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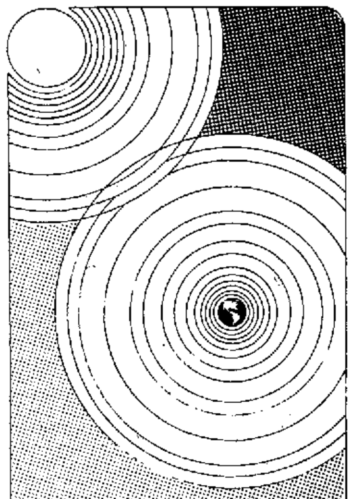
POSSIBLE RELATIONSHIPS BETWEEN SOLAR ACTIVITY AND METEOROLOGICAL PHENOMENA



Dedicated to Dr. Charles Greeley Abbot

Edited by
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and
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NASA-Goddard Space Flight Center
Greenbelt, Maryland

Proceedings of a Symposium held November 7-8, 1973
at the NASA-Goddard Space Flight Center*

June 1974

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ERRATA - Page 136

Unfortunately, several lines and a paragraph separation were omitted beginning on the last line of Page 136. The last two paragraphs should read (the underlined words are those that were omitted in the Proceedings):

Bremsstrahlung radiation could also contribute to changes in the atmospheric composition as a result of the ionization produced at altitudes primarily in the 25- to 90-km range. Although a change in the atmospheric composition has been suggested as a possible mechanism to link solar activity to meteorological processes (see Roberts and Olson, 1973b), no generally accepted hypothesis has emerged.

If precipitating energetic electrons are found to be important in meteorological processes, some control of the precipitation rates, and thus of the meteorological processes may eventually prove to be feasible. Brice (1970, 1971a, b) and others (see Cornwall, 1972) have suggested that particle precipitation from the radiation belts should be feasible using cold gas injection into the magnetosphere. Also, an experiment is presently being conducted to precipitate energetic electrons from the radiation belts using VLF electromagnetic waves transmitted from Siple, Antarctica (Helliwell, 1973).

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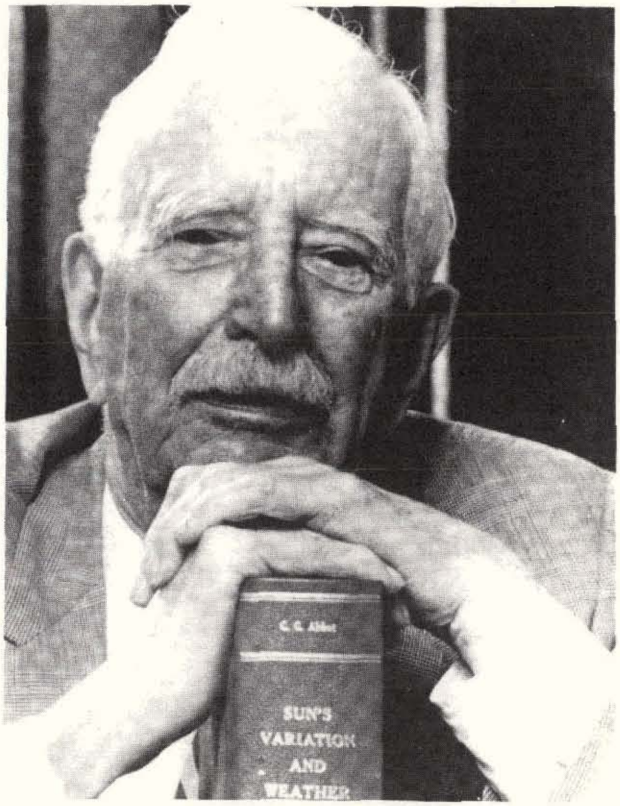
Possible Relationships Between Solar Activity and Meteorological Phenomena
Proceedings of a Symposium held November 7-8, 1973 at the NASA-Goddard Space Flight Center

EDITOR'S NOTE

This volume contains the unrefereed manuscripts of Symposium presentations. In that respect their appearance here does not constitute formal publication, and certain contributions may appear elsewhere in appropriate professional journals.

The requirement for the use of the International System of Units (SI) has been waived for this document under the authority of NPD 2220.4, paragraph 5.d.

DEDICATION



To Dr. Charles Greeley Abbot, preeminent pioneer worker in the field of measurement of the solar constant and the search for solar-weather relationships, this Symposium on Possible Relationships Between Solar Activity and Meteorological Phenomena is respectfully dedicated.

Dr. Abbot passed away on December 17, 1973, at the age of 101. An active scientist throughout his long and productive lifetime, Dr. Abbot expressed a wish to travel from his home in Hyattsville, Maryland to attend the opening of the Symposium at the nearby Goddard Space Flight Center. His remarks delivered personally to the attendees set an inspiring tone for the entire meeting.

PREFACE

This volume constitutes the proceedings of the Symposium on Possible Relationships Between Solar Activity and Meteorological Phenomena that took place on November 7 and 8, 1973, at the NASA, Goddard Space Flight Center in Greenbelt, Maryland.

The Symposium was dedicated to a pioneering investigator in this field, Dr. Charles Greeley Abbot of the Smithsonian Institution. Despite his age—101 years—Dr. Abbot addressed the Symposium and remained at the Center to hear the lecture by Dr. W. O. Roberts. It was to be perhaps Dr. Abbot's last major public appearance; he passed away on December 17, 1973. In the short time since then, the subject of peaceful applications of solar energy, to which Dr. Abbot also devoted much effort, many years ahead of his time, has become a matter of preeminent concern to the nation.

The Symposium was sponsored by the Laboratory for Solar Physics (since renamed Laboratory for Solar Physics and Astrophysics) and the Meteorology Program Office, both of Goddard Space Flight Center, in cooperation with the University Corporation for Atmospheric Research (UCAR) and the American Meteorological Society. The organizing committee, chaired by Morris Tepper of NASA Headquarters, included Goetz K. Oertel, also of NASA Headquarters; Walter Orr Roberts, UCAR; and John M. Wilcox, Stanford University, in addition to the editors of this volume. Six young scientists, five of them graduate students, were selected in a national competition and given the opportunity to attend and to prepare a brief summary of the conference for publication in the Bulletin of the American Meteorological Society (J. S. Levine et al., February 1974). The summary also appears in these proceedings.

The question and answer sessions and the panel discussions are reproduced here from tape recordings and have not been checked by the respective speakers.

Greenbelt, Maryland
February 15, 1974

S.P.M.
W.R.B.

CONTENTS

Page

DEDICATION iii

PREFACE v

INTRODUCTION xiii

SYMPOSIUM SUMMARY xv

RECOGNITION OF DR. CHARLES GREELEY ABBOT BY THE HON. JAMES C. FLETCHER, ADMINISTRATOR, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION xxvii

RESPONSE BY DR. CHARLES GREELEY ABBOT xxix

SESSION 1: WHAT IS THE EVIDENCE? 1

RELATIONSHIPS BETWEEN SOLAR ACTIVITY AND CLIMATE CHANGE
Walter Orr Roberts 3

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF WALTER ORR ROBERTS 22

SOLAR ACTIVITY AND THE WEATHER
John M. Wilcox 24

MAGNETOMETEOROLOGY: RELATIONSHIPS BETWEEN THE WEATHER AND THE EARTH'S MAGNETIC FIELD
J. W. King and D. M. Willis 52

KIDSON'S RELATION BETWEEN SUNSPOT NUMBER AND THE MOVEMENT OF HIGH PRESSURE SYSTEMS IN AUSTRALIA
E. G. Bowen 56

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF E. G. BOWEN 59

CONTENTS (continued)

Page

PROPOSED GEOMAGNETIC CONTROL OF SEMIANNUAL WAVES IN THE MESOSPHERIC ZONAL WIND
A. D. Belmont, G. D. Nastrom, and Hans G. Mayr 60

CERTAIN REGULARITIES OF GEOMAGNETIC AND BARIC FIELDS AT HIGH LATITUDES
S. M. Mansurov, G. S. Mansurov, and L. G. Mansurova. . . . 71

ON POSSIBLE INTERACTIONS BETWEEN UPPER AND LOWER ATMOSPHERE
Bruce C. Macdonald and Elmar R. Reiter. 81

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF BRUCE C. MACDONALD 101

A SPECTRAL SOLAR-CLIMATIC MODEL
H. Prescott Sleeper, Jr. 102

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF H. PRESCOTT SLEEPER, JR. 115

A POSSIBLE CORRELATION BETWEEN MAXIMA OF THE FAR ULTRAVIOLET SOLAR IRRADIANCE AND CENTRAL MERIDIAN PASSAGES OF SOLAR MAGNETIC SECTOR BOUNDARIES
Donald F. Heath and John M. Wilcox 116

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF DONALD F. HEATH. 121

THE AURORA AS A SOURCE OF PLANETARY-SCALE WAVES IN THE MIDDLE ATMOSPHERE
Y. T. Chiu and J. M. Straus 122

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF Y. T. CHIU. 129

DIRECT SATELLITE OBSERVATIONS ON BREMSSTRAHLUNG RADIATION AS A TECHNIQUE TO INVESTIGATE ITS ROLE IN METEOROLOGICAL PROCESSES
R. G. Johnson and W. L. Imhof 130

CONTENTS (continued)

Page

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF R. G. JOHNSON 140

SESSION 2: VARIABILITY OF SOLAR INPUT TO THE EARTH'S ATMOSPHERE 141

SOLAR FLUX AND ITS VARIATIONS
Elske v.P. Smith and David M. Gottlieb 143

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF ELSKE v.P. SMITH 186

GEOMAGNETIC RESPONSES TO THE SOLAR WIND AND TO SOLAR ACTIVITY
Leif Svalgaard 188

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF LEIF SVALGAARD 229

SOLAR MODELS IN RELATION TO TERRESTRIAL-CLIMATIC VARIATIONS
A. G. W. Cameron 231

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF A. G. W. CAMERON 236

POSSIBLE RELATIONSHIPS BETWEEN SOLAR ACTIVITY AND ATMOSPHERIC CONSTITUENTS
Robert G. Roosen and Ronald J. Angione 239

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF ROBERT G. ROOSEN 249

FUTURE MONITORING OF CHARGED PARTICLE ENERGY DEPOSITION INTO THE UPPER ATMOSPHERE AND COMMENTS ON POSSIBLE RELATIONSHIPS BETWEEN ATMOSPHERIC PHENOMENA AND SOLAR AND/OR GEOMAGNETIC ACTIVITY
D. J. Williams, R. N. Grubb, D. S. Evans, and H. H. Sauer . . 250

CONTENTS (continued)

Page

ON CLIMATIC CHANGES RELATED TO THE 22-YEAR SOLAR CYCLE
C. J. E. Schuurmans 258

APPARENT RELATIONSHIP BETWEEN SOLAR-SECTOR BOUNDARIES AND 300-mb VORTICITY: POSSIBLE EXPLANATION IN TERMS OF UPWARD PROPAGATION OF PLANETARY-SCALE WAVES
Raymond J. Deland 260

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF RAYMOND J. DELAND 265

HIGH LATITUDE IONOSPHERIC WINDS RELATED TO SOLAR-INTERPLANETARY CONDITIONS
J. P. Heppner 266

SOLAR MODULATION OF ATMOSPHERIC ELECTRIFICATION THROUGH VARIATION OF THE CONDUCTIVITY OVER THUNDERSTORMS
Ralph Markson 272

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF RALPH MARKSON. 286

SOLAR LUMINOSITY VARIATIONS AND THE CLIMATE OF MARS
Owen B. Toon, Peter J. Gierasch, and Carl Sagan. 287

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF OWEN B. TOON 295

SESSION 3: IN SEARCH OF PHYSICAL MECHANISMS 297

SOME PROBLEMS IN COUPLING SOLAR ACTIVITY TO METEOROLOGICAL PHENOMENA
A. J. Dessler 299

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF A. J. DESSLER 311

CONTENTS (continued)

Page

NUMERICAL EXPERIMENTS ON SHORT-TERM METEOROLOGICAL EFFECTS OF SOLAR VARIABILITY
R. C. J. Somerville, J. E. Hansen, P. H. Stone, W. J. Quirk, and A. A. Lacis 319

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF R. C. J. SOMERVILLE 336

AURORAL EFFECTS IN THE D REGION OF THE IONOSPHERE
Syun-Ichi Akasofu 340

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF SYUN-ICHI AKASOFU 358

RELATING TERRESTRIAL ATMOSPHERIC CIRCULATION TO SOLAR DISTURBANCES
C. O. Hines 360

CORRELATIONS AND LINKAGES BETWEEN THE SUN AND THE EARTH'S ATMOSPHERE: NEEDED MEASUREMENTS AND OBSERVATIONS
William W. Kellogg. 365

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF WILLIAM W. KELLOGG 383

SESSION 4: PANEL DISCUSSION—WHAT FUTURE CRITICAL MEASUREMENTS, EXPERIMENTS, AND THEORETICAL WORK ARE NEEDED, AND WHICH OF THESE CAN BE ACCOMPLISHED BEST FROM SPACE? 387

SUMMARY OF HIGHLIGHTS OF THE SYMPOSIUM
S. I. Rasool 419

CONCLUDING REMARKS
Morris Tepper 427

LIST OF ATTENDEES 431

INTRODUCTION

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An enormous literature on the subject of this Symposium has developed over the years. Scientists continue to differ on the reality of claimed relationships between the phenomena of solar activity and those of terrestrial meteorology and climatology. The root of the controversy is basically an energy argument: The changes in the total solar energy arriving at the earth that can be ascribed to solar activity events and cycles are small compared to the typical energies involved in the meteorological processes with which some authors would associate them.

However, the energy released by solar activity can be very large, compared to the quiet sun emission in certain restricted domains of radiation wavelength or particle energy, and it is selectively deposited in restricted regions of the terrestrial atmosphere. Thus, the possibility exists that this energy can trigger events in those regions that in turn may influence the more energetic processes of the troposphere.

Further, in recent years a vast expansion of our knowledge of solar physics and global meteorology has resulted from research conducted in space, notably by automated spacecraft such as the Orbiting Solar Observatories, the Interplanetary Monitoring Platforms, the Nimbus and Television and Infrared Observation (TIROS) satellites, and most recently by the highly successful Skylab missions. Thus, it seemed appropriate to convene a multidisciplinary group of scientists to address these key questions: (a) What is the evidence concerning possible relationships between solar activity and meteorological phenomena? (b) Are there plausible mechanisms to explain these relationships? (c) What kinds of critical measurements are needed to further determine the nature of solar-meteorological relationships and/or the mechanisms to explain them, and which of these measurements can be accomplished best from space?

The reader will judge how well we have succeeded. It does seem that there are now at least a few physical mechanisms in this field that are amenable to further theoretical investigation. It is also obvious that the wealth of new data is raising at least as many new questions as it is answering older ones.

SYMPOSIUM SUMMARY

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A Symposium on Possible Relationships Between Solar Activity and Meteorological Phenomena was held at the Goddard Space Flight Center (GSFC) on November 7 and 8, 1973, sponsored by NASA in co-operation with the University Corporation for Atmospheric Research (UCAR) and the American Meteorological Society. The 200 scientists attending the symposium included meteorologists, aeronomers, solar and plasma physicists, and astrophysicists, attesting to the truly interdisciplinary nature of this area. Participants included researchers from England, Australia, the Netherlands, Germany, and the U.S.S.R.

In his welcome and opening remarks, Dr. James C. Fletcher, NASA Administrator, dedicated the Symposium to Dr. Charles Greeley Abbot, for his preeminent pioneering work in the measurement of the solar constant and the search for solar-meteorological relationships. Dr. Abbot, who in 1972 celebrated his one-hundredth birthday, accepted from Dr. Fletcher a model of Robert H. Goddard's first rocket, which flew in 1926. Dr. Abbot was a strong supporter of Goddard's early rocket research, as well as a strong and long-time advocate of solar activity influences on weather. The hypothesis that meteorological phenomena respond to variations in solar activity was not widely accepted when Dr. Abbot began his research some three-quarters of a century ago and is still not universally accepted today even though well over one thousand papers have been published on the subject. The response of the troposphere to solar activity variations is not presently used operationally in forecasting, but solar variations may prove to be an important operational tool once such responses are positively identified. The evidence for solar activity-deduced meteorological phenomena is often localized, isolated and contradictory, and the investigations in this field do not lend themselves to direct comparison due to the diversity of independent and dependent parameters employed by different investigators. Furthermore, a widely accepted physical mechanism has not yet emerged and many scientists refuse to admit the possibility of an appreciable influence of solar activity on the weather in the absence of an accepted physical mechanism.

The Symposium addressed itself to three fundamental questions:

1. What is the evidence concerning possible relationships between solar activity and meteorological phenomena?

2. Are there plausible physical mechanisms to explain these relationships?

3. What kinds of critical measurements are needed to further determine the nature of solar meteorological relationships and/or the physical mechanisms to explain them, and which of these measurements can be accomplished best from space?

Joel S. Levine

SESSION 1

The underlying theme for the initial session, chaired by Ralph Shapiro of the Air Force Cambridge Research Laboratories, was a challenge for the presentation of convincing evidence in support of solar-terrestrial relationships.

In the opening invited paper, Walter Orr Roberts cited the recent Russian wheat sale as an example of how weather-related events, in this case a drought, can impact on world events and shoppers' pocketbooks. He acknowledged the lack of plausible physical mechanisms to explain any such phenomena and called for the generation of such mechanisms and their subsequent testing. The "energy problem"—that of obtaining large tropospheric responses from small energy deposition at much higher altitudes—was cited as the biggest hurdle to be overcome.

Droughts, in Dr. Roberts' opinion, appear to present some of the most convincing correlations with solar activity. A review of several efforts relating droughts in the central U.S. with sunspots indicated that severe droughts in the High Plains follow the minimum after the minor maximum in the double (22-year) sunspot cycle. Other data, e. g., temperature increases during drought conditions, also show this relationship, lending further support to the hypothesis of a physical link rather than merely a chance relationship. In Dr. Roberts' opinion, however, the most convincing evidence will be the events of the near future (1974 to 1978) when the next High Plains drought should occur. No deficiencies have yet been observed; in fact, many places last spring were abnormally wet. An increase in solar activity during the past year may have delayed the drought onset—only time will tell. Dr. Roberts presented a climatological picture of the wind patterns associated with a High Plains drought and a method to stratify the data to assist in the identification of a suitable mechanism.

Dr. Roberts concluded his presentation by suggesting a possible mechanism by which changes in solar activity could affect the lower atmosphere. His mechanism relies on the sudden formation of cirrus clouds following solar activity. Such clouds may modify the atmospheric radiation budget at the tropopause producing up to 1°C per day change in temperature—enough to be dynamically significant. Observations supporting the sudden formation of cirrus clouds after various types of solar activity then followed, as did a suggestion to carefully investigate satellite IR data for further evidence.

John Wilcox presented evidence to support the existence of shorter time scale terrestrial responses. Common threads running through all such studies were noted: meteorological responses occur within 2 or 3 days after geomagnetic activity, these responses are most pronounced in winter, and continental responses are opposite to those over the oceans.

As evidence of short time scale responses to solar activity by the atmosphere, Dr. Wilcox reviewed the studies relating geomagnetic activity to the development of wintertime 300-mb troughs in the Gulf of Alaska. Such troughs formed in (or entering) this region 2 to 4 days following a rise in geomagnetic activity tend to be larger than average (as measured by the vorticity area index). Further evidence was furnished by the results relating the change in hemispheric vorticity area index and the passage of a magnetic sector boundary. Using the time of boundary passage as zero time in a superposed epoch analysis, it was found that a decrease in vorticity area index began approximately one day prior to boundary passage, reached a minimum about one day after and returned to its original value by four days following boundary passage. The results are similar if the data are stratified by polarity change, by separating the first half of the winter period from the second half or by dividing the early years of the period from the late years.

Also, it was noted that, according to F. W. Berko and R. A. Hoffman, the frequency of 2.3-keV electron precipitation events in the auroral zone is twice as high in winter as in summer.

Dr. Wilcox noted that in the past it has been difficult to compare investigative studies and reports. He suggested using the magnetic sector boundary passage as a timing device upon which to base and thus compare future solar-terrestrial relationship investigations. A. J. Hundhausen of the High Altitude Observatory urged caution, stating that such a timing mechanism might cause one to overlook certain effects of the fine structure within a typical sector, for example, those with more than one velocity maximum. A. J. Dessler of Rice University argued that in addition to stressing sector boundary passages, some emphasis should also be placed on the non-boundary responses to better ascertain possible differences.

David Willis read the first contributed paper for J. W. King, of the Radio and Space Research Station, Slough, England, relating changes in the length of the growing season with the solar cycle. E. G. Bowen of the Embassy of Australia demonstrated how the track of anticyclones across Australia and rainfall at several Australian locations correlated with the solar cycle. S. M. Mansurov of IZMIRAN, U.S.S.R. presented evidence that the atmospheric pressure at the surface of the earth polar regions varies regularly with changes in the polarity of the interplanetary magnetic field.

A. D. Belmont of Control Data Corporation suggested a possible relationship between the semiannual variation in the geomagnetic field and two semiannual waves observed in the zonal wind at altitudes between 30 and 65 km. A significant shrinking of the stratospheric vortex following geomagnetic events was reported by Bruce C. Macdonald of Colorado State University. H. Prescott

Sleeper of Northrop Services, Inc. attempted to provide a better understanding of variations within and among solar cycles by representing the solar cycle as the sum of many subcycles of varying durations and intensities.

Donald F. Heath of Goddard Space Flight Center reported that enhanced UV emissions appear to be correlated with central meridian passages of solar magnetic sector boundaries. Y. T. Chiu of the Aerospace Corporation suggested that the energy injected into the atmosphere by an auroral substorm is of a scale size sufficient to trigger instabilities in middle atmospheric circulation systems which in turn cause a response in the lower atmosphere.

The final paper, contributed by R. G. Johnson of the Lockheed Palo Alto Research Laboratory, reported that variations due to bremsstrahlung from auroral electrons constitute a minor effect when compared to ionization by cosmic rays - Richard G. Hendl.

SESSION 2

The second session of the Symposium was introduced by Robert W. Noyes of the Smithsonian Astrophysical Observatory. The governing idea was to elucidate the main features of the sun-earth system, features which would have to be considered in seeking an extraterrestrial influence.

The initial invited paper, by Elske v. P. Smith of the University of Maryland, summarized the current knowledge of the electromagnetic solar spectrum and radiant energy output for conditions of quiet and active sun. She discussed the temporal behavior and occurrence of solar phenomena such as active regions, calcium plages and flares, X-rays, UV and other energetic emissions, and their relationship to 11- and 22-year solar cycles.

The second invited paper by Arthur J. Hundhausen of the High Altitude Observatory at NCAR provided a clear review of particle emissions from the quiet and active sun. Solar wind protons are an important form of particle emission because of their great abundance and high integrated energy flux. Since the magnetic field pattern defines the interplanetary sector structure, either 2 or 4 sectors normally, the high-velocity stream of the solar wind is found within the forward part of the rotating sector. Solar wind properties are not necessarily related to flare activity or the Zurich sunspot number but are intimately linked to the pattern of magnetic field lines at the photosphere.

Dr. Lief Svalgaard of Stanford University discussed the interaction of solar wind, rotating sector structure, and solar electromagnetic flux with the magnetosphere of the earth. Radiant flux in the UV and X-ray region determines the ionospheric conductivity while the interaction between the terrestrial magnetic field and solar wind plasma produces the magnetopause, bow shock, and magnetotail. Energy is provided by annihilation of field lines in the magnetotail and this release of energy results, through the energetic deposition of electrons and protons in the upper atmosphere, in the excited energy states and emissions of the polar atmosphere, which are the visible aurora.

Dr. Wolfgang Priester of Bonn University, a pioneer researcher in the field of the response of the upper atmosphere to variations in solar activity, referred to the sixties as the decade of the satellite drag measurements and predicted the seventies would be the decade of the mass spectrometric exploration of the upper atmosphere. Dr. Priester reported that for a given level of solar activity, the temperature of the upper atmosphere can be readily determined. Dr. Priester described the preliminary results of the new ESRO IV mass spectrometer experiment, dealing with the variation of atmospheric constituents with solar activity.

A. G. W. Cameron of Harvard University presented the results of efforts to model the behavior of the solar neutrino output by modifying the degree of mixing in the solar core. Current solar models suffer in that the predicted high neutrino flux has not been observed. To solve this discrepancy, a rapid mixing the core was postulated leading to an increased rate of burning and expansion of the core decreasing the luminosity. However, Dr. Cameron expressed pessimism regarding periodicity in solar luminosity as an explanation for the neutrino shortage.

The final invited paper of the second session was presented by Robert G. Roosen of NASA/GSFC Laboratory for Solar Physics, New Mexico Station. His historical discussion of Dr. Abbot's early Smithsonian Observations of solar parameters with spectrobolometric techniques was very appropriate due to the dedication of the conference to Dr. Abbot. In addition to the solar constant, which was measured to within 0.1 percent of the currently accepted value using the most modern techniques, seasonal variations in aerosols, water vapor, volcanic activity, and air pollution were carefully monitored and correlations with solar activity computed.

The seven contributed papers in this session partially continued the fundamental descriptions of the sun-earth system while others presented evidence of solar weather effects. D. J. Williams of NOAA reported on plans to monitor energy deposition in the upper atmosphere by future operational satellite systems. Ralph Markson of State University of N.Y. at Albany suggested that the modification of the conductivity of the lower atmosphere by solar flares and resultant changes in thunderstorm frequency could serve as a mechanism for extraterrestrial influence. Raymond J. Deland of the Polytechnic Institute of N.Y. critically examined the selection process for sector structure boundary crossings used in the vorticity correlation studies and assessed the possible influence of ascending planetary scale waves. James Heppner of GSFC presented evidence showing that the direction of ionospheric winds at 200 km could be related to the direction of the inter-planetary magnetic field. C. J. E. Schuurmans of the Royal Netherlands Meteorological Institute presented evidence showing a difference in frequency of occurrence of Icelandic lows between the two halves of the double sunspot cycle. Roger Olson of the National Oceanic and Atmospheric Administration (NOAA) provided evidence that the key dates used by Roberts and Olson are related to the sector boundary dates used by Wilcox, et. al. In particular, the decrease in the average hemispheric vorticity index would show up around zero days of the sector boundary analysis, and also shows up around zero days of the geomagnetic dates. As the final contributed paper, Owen B. Toon of Cornell suggested, by use of Mariner-9 photographs, that possible climatically-caused changes in surface features on Mars may be a useful indicator of solar luminosity variations. - Henry P. Cole.

SESSION 3

The third session, chaired by E. N. Parker of the University of Chicago, focused on possible physical mechanisms that could link solar activity to meteorological phenomena. Unfortunately, C. O. Hines, University of Toronto, was unable to attend and present models of two newly proposed mechanisms for transferring angular momentum from ionospheric heights to the vicinity of the tropopause. However, the mechanisms described in the abstract of his paper provoked much discussion throughout the session. The first mechanism consists of a viscous coupling of the upper atmosphere to the troposphere and the second requires changes in the reflection of planetary waves by the thermosphere. This second mechanism is very appealing because it makes active use only of energy derived from the lower atmosphere itself, with solar activity directly modifying only the thermospheric reflectivity.

A. J. Dessler, Rice University, discussed some of the difficulties encountered in seeking coupling mechanisms. He cautioned the audience that establishing a scientific correlation requires not only the simultaneous occurrence of phenomena but also the establishment of a physical mechanism linking them in a causal relationship. On the other hand, he offered encouragement to researchers by citing instances where causal relationships have been established between phenomena that eminent scientists had previously "proved" to be unrelated.

A major restraint on coupling mechanisms is the negligible amount of energy absorbed from the solar wind by the magnetosphere (5×10^{-2} TW = 5×10^{10} watts) or released in a large geomagnetic storm (10^2 TW) compared to the sunlight incident upon the earth (10^5 TW). Dr. Dessler estimated the power driving a typical vorticity change to be 2.7 TW, so solar influence is energetically feasible for this phenomenon. However, viscous coupling between the ionosphere and lower atmosphere is weak since the atmospheric mass above 105 km is only 10^{-12} the mass above the 300-mb level. Consequently, drag interactions between the two regions would result in little momentum exchange and the energy transferred would merely result in joule heating. Dr. Dessler judged other proposed downward transport mechanisms to be inadequate. As noted by previous speakers, tropopause ionization by auroral electron bremsstrahlung is negligible compared to the steady cosmic ray ionization. Highly energetic solar cosmic rays produce significant ionization at this height, but occur infrequently. Dr. Dessler agreed that particle heating of the thermosphere had been established but doubted whether energy could be efficiently transported downward by gravity waves or infrared radiation.

Dr. Dessler asked for clarification of the apparent discrepancies between the 11-year cycle of precipitation and the 22-year tree-ring cycle, which should be simply related and would be expected to have identical cycles. In addition, he was puzzled by the fact that the vorticity effect is a winter phenomenon while tree-ring growth is a spring/summer effect. It should be determined whether the vorticity index exhibits an 11- or 22-year cycle.

Richard Somerville, Goddard Institute for Space Studies (GISS), presented the results of numerical experiments on short-term effects of solar variability using a global model developed by himself, Robert Jastrow, and co-workers at GISS. They tested effects of changes in atmospheric ozone content and changes in the solar luminosity. The model includes surface heat balance, detailed radiative transfer, and a hydrologic cycle, and is thought to be effective on time scales of days to months. A sensitivity experiment was run in which the short-term (8- to 12-day) atmospheric evolution with normal solar luminosity and ozone content was compared with four atmospheric evolutions obtained by changing luminosity by factors of 2/3 and 3/2 and doubling and removing all atmospheric ozone. Quite surprisingly, no significant changes occurred as a result of these unrealistically large variations. Such lack of atmospheric response is probably due to the large thermal inertia of the atmosphere with a tropospheric radiative relaxation time of about 30 days and to the fact that sea surface temperature and snow cover are prescribed in the model. Dr. Somerville concluded from these studies that any causal relationship between solar activity and the weather on time scales less than two weeks depends either on agents other than variation in solar luminosity or ozone content or on mechanisms not included in the numerical model.

S. I. Akasofu, University of Alaska, discussed in detail the physical phenomena associated with the interaction between auroral particles and electromagnetic fields, auroral energy flow, and the propagation of auroral effects to low altitudes. He reiterated the conclusion that energy deposition of soft auroral X-rays would be negligible at stratospheric altitudes. New data from incoherent backscatter measurements of neutral winds in the auroral region indicate a lack of correlation between stratospheric winds and winds in the auroral ionosphere. Dr. Akasofu also used magnetograms to show that sector-boundary crossings with a time scale of approximately one hour (as opposed to the sector structure itself with a time scale of several days) do not couple effectively with the magnetosphere and are not significant energy inputs to it.

William W. Kellogg of NCAR concluded the third session with a summary of needed measurements and observations. He noted that as soon as correlations are established one needs to identify the sequence of processes leading from change in solar input to change in tropospheric circulation and weather. Changes in the solar electromagnetic radiation have to be carefully monitored since variations over the solar cycle are small (less than one percent). Dr. Kellogg offered the suggestion that changes in the ionization at the Pfotzer maximum could influence the formation of thunderstorms by changing the electric potential gradient. This could be checked by measuring the global atmospheric electric field. As an example of spacecraft observations, a worldwide distribution plot of nocturnal thunderstorms compiled from OSO-5 data by Sparrow and Ney was shown. Dr. Kellogg noted that no obvious correlation with solar data had been found, but the time span of the data was rather limited and more sophisticated observation techniques could be used. He recommended continuous and careful monitoring of the input of electromagnetic and particle radiation into the earth's atmosphere (especially during solar events), ozone distributions in the region above 30 km, and wind systems in the mesosphere and lower thermosphere. In addition, special phenomena suspected to be important in the causal chain, such as cirrus cloud formation at high latitudes and thunderstorm activity, should be monitored on a global basis. - Richard R. Vondrak.

SESSION 4

The final session of the symposium was chaired by Morris Tepper of NASA Headquarters. There was a panel discussion followed by comments from the audience concentrating on which future measurements, experiments, and theoretical work would be most useful. Emphasis was given to determining the role of spacecraft in making critical measurements. Panel members were: Dr. Akasofu, Dr. Dessler, Dr. Kellogg, Dr. Julius London of the University of Colorado, Dr. William Nordberg of GSFC, Dr. Parker, Dr. Roberts, and Dr. Wilcox.

Several speakers emphasized the need for a more organized approach in presenting observations. Dr. Dessler suggested that future observations be compared with the work previously reported and that observations be designed to build upon past ones. Dr. Akasofu noted that more comprehensive statistical analysis of the many observations and the many aspects of solar activity should be made so that the range of parameters can be narrowed. Dr. Wilcox suggested that solar sector boundaries be included as a correlation in all future solar-related weather studies. The time of boundary crossing serves as an accurate time mark and is definitely not of terrestrial origin or affected by it. Moreover, it may be possible to locate the times of sector boundary passage in the pre-satellite era for comparisons with older data. Dr. Dessler pointed out that the differences in development of solar storms not located near sector boundaries should be studied. Dr. Hundhausen emphasized that sector boundaries are not a causal mechanism. Some phenomena might therefore have no correlation with boundaries, and correlated phenomena may not all have the same ultimate cause. He suggested that correlations be made with specific causal agents.

The sun is fundamental to this problem. Dr. London pointed out that satellite observations of the time variation of the solar constant and the variation in spectral distribution of energy are absolutely essential. Dr. Wilcox remarked that further satellite studies of the relation of solar sectors to interplanetary properties of the solar wind and magnetic field lines are necessary. Remarks by Dr. Noyes and Dr. Hundhausen emphasized this point and the suggestion was made that a knowledge of the solar origin of the sector structure and variable activity might eventually lead to forecasting of solar-influenced weather many days in advance. Dr. Wilcox pointed out that Stanford and the Crimean Astrophysical Observatory intend to study the sun and its magnetic field to relate to effects observed in the interplanetary magnetic structure.

Several suggestions were made for organized studies attempted to isolate the mechanism which might link solar activity to meteorological phenomena. Dr. London said that variation in the total amount and vertical distribution of ozone should be inspected. He outlined two possible ozone related mechanisms: 1) low latitude middle UV penetration could cause hydroxol formation from water vapor, which would destroy ozone and 2) high latitude particle-induced ionization could promote either ozone formation or ozone destruction, depending on whether molecular oxygen or nitrogen is more extensively ionized. He suggested that more groups should investigate the correlations between UV variations and sector boundary passages. Dr. Akasofu also suggested the possible importance of ozone and of trace constituents in the mesosphere. He pointed out that further work in understanding the magnetosphere and its effects on upper atmosphere energy input is needed, and that the effects of auroral activity on ozone should be investigated. Dr. Nordberg suggested that artificial modifications of ozone in the stratosphere could be made and the effects on the lower stratosphere and upper troposphere monitored. Dr. Dessler remarked that volcanic eruptions might provide a natural mechanism for this experiment.

Another set of experiments has been designed to look for connections between cloud cover and solar activity. Dr. Roberts suggested that global IR flux data might be correlated with solar activity. As a check for a mechanism he suggested geiger counter flights to look at ionization increases with solar activity, and laboratory studies of the generation of freezing nuclei using ionization processes. Dr. Nordberg pointed out that in order to account fully for cloud effects, not only cloud area but also optical depth, height, water content, albedo, and geographic location must be observed. These measurements will be difficult to make, and there is no possibility of determining all these parameters from satellites now, although observing techniques are being developed for future space missions.

Mechanisms need to be investigated that might lead to a correlation between thunderstorm activity and solar activity. Ralph Markson suggested that the effects of solar activity upon the conductivity of the atmosphere, particularly the stratosphere, and the resultant interactions with thunderstorm activity be studied. Dr. Roberts stated the need for thunderstorm frequency data in which care is taken to eliminate bias. A discussion followed involving Drs. Roberts, Akasofu, Kellogg, Nordberg, Polk, and Markson on the feasibility of measuring thunderstorm activity from spacecraft observations of regions of lightning discharges. Other suggestions were made for ground-based measurements of variables such as the ionospheric potential, which might provide a thunderstorm activity index. The question of the technique that was most practical and free from bias went unresolved.

Another mechanism that needs to be investigated is the possible importance of large-scale gravity waves. C. O. Hines was unable to attend the Symposium so that despite the high interest in his theory no suggestions could be made for its future investigation.

Dr. Bowen suggested that increased dust input to the atmosphere from extraterrestrial sources might lead to increased storm activity. Dr. Parker pointed out that historical observations of sunspot numbers have not fully been correlated with climatic history and more can be done in this area.

A final important suggestion by Dr. Roberts was that if mechanisms for relating solar activity to weather are identified they should be tested by including them in large numerical global circulation models. Dr. Sommerville indicated that this would be of interest and would be feasible if the correct models were chosen and if the mechanism for relating solar activity to weather could be quantified. - Owen B. Toon and Howard P. Hanson.

The Symposium concluded with some comments on future research by Ichtiaque Rasool, NASA Headquarters, who cautioned against the current practice of correlating solar activity variations with localized, isolated weather effects instead of global responses. The importance of the stratosphere as a buffer for solar meteorological responses and the need for realistic stratospheric models was stressed by Dr. Rasool. He commented that due to its tremendous inertia the relaxation time of the troposphere is so large that short-term tropospheric responses cannot easily be identified. Dr. Rasool added that fundamental deficiencies in our knowledge include the possible variations over the entire solar cycle of both the solar constant and the solar spectral distribution, particularly in the near and extreme UV and the response of stratospheric ozone to such variations. - Joel S. Levine

It was felt by many at the symposium that although we are still without any definite physical mechanisms, the Symposium was an important step in stressing the importance to relating meteorological and purely solar parameters. The attendance at the symposium pointed up the fact that the area is attracting new and enthusiastic researchers from several different disciplines. The outlook for resolution of the outstanding problems looks promising if only because of the increased interest of both older and newer workers from a wide variety of fields.

RECOGNITION OF DR. CHARLES GREELEY ABBOT BY THE HON. JAMES C. FLETCHER, ADMINISTRATOR, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

It is my pleasure to participate in the opening of the Symposium on Possible Relationships Between Solar Activity and Meteorological Phenomena, and I am especially honored to dedicate this Symposium to one of the pioneer research workers in this field, Dr. Charles Greeley Abbot.

Some of the older scientists in this room were beginning college students in the mid 1930's, by which time Dr. Abbot had completed the development of his silver disk pyrheliometer, and with it and other instruments had already carried out more than two decades of brilliant research on the spectral properties of the sun and establishing the size, value, and constancy of the sun's total radiation.

Dr. Abbot's research interests range far beyond the measurement of the solar constant. He did brilliant work on atmospheric transmission, but was also deeply interested in the practical utilization of solar energy, a very popular subject these days. Many decades ago, at the Mount Wilson Observatory, he built a small solar cooker and could cook gingerbread, I'm told, in 35 minutes. It must be very gratifying to see the great revival of interest in solar energy at this time.

Dr. Abbot was born 101 years ago, May 31, 1872, in Wilton, New Hampshire, and he graduated from MIT in 1894, at the age of 22. The aspect of his long and brilliant career for which we honor him today is his work in relating the variable activity of the sun to meteorological phenomena, the subject of this Symposium. Work in this field is, and has long been, challenging. The reality of solar weather relationships and the possible mechanisms by which changed solar activity might influence climate and weather have long been debated.

Dr. Abbot has been a persistent searcher for indications of solar influences, either cyclical or quasi-cyclical in nature, in the rainfall, temperature, and other meteorological records of specific cities and regions. He persistently pushed his analyses on this score, sometimes convincing his critics and sometimes not. But he was always prepared to describe his work openly and freely to all who were interested, and his publications were numerous and extensive. Moreover, he was always generous in his encouragement to younger scientists interested in entering this field, and some who profited from that encouragement are in this room today.

Dr. Abbot, it does honor to the sponsors of this Symposium, the American Meteorological Society, the University Corporation for Atmospheric Research, and to us in NASA to dedicate to you the efforts we make in these two days. We shall be exploring new approaches to the field to which you have brought great distinction. In our deliberations we shall endeavor to bring to bear upon a long-standing question the new potentialities of space science and technology. We thank you for being with us at this opening ceremony.

Perhaps it's not known to those of us who are new in the space field that Dr. Abbot arranged with the Smithsonian Institution for funds to support the early work on rockets by Dr. Robert H. Goddard, after whom this Center is named. Therefore, it seems especially fitting to present to Dr. Abbot on this occasion a model of the world's first liquid-fueled rocket launched by Dr. Goddard on March 16, 1926, a cornerstone of modern space exploration.

RESPONSE BY DR. CHARLES GREELEY ABBOT

I thank you all for your kind words. I wrote in my book, "Adventures in the World of Science," about my experiments and observations along with my philosophical ideas. These have granted me a long and pleasant lifetime.

It has been enjoyable to me to recall many friendships of almost forgotten men. The revolutionary expansion of scientific utilities and pleasures and of our knowledge of the universe was never paralleled in any half century before. Well, it bids fair to be far outstripped in that which is about to come, if only peace can reign. Posterity may never know of the happy times in the latter part of the nineteenth century, but they are bound to see wonderful events coming that we cannot even imagine at this time. I am quite content to have lived between 1870 and 1970. Thank you very much.

SESSION 1

WHAT IS THE EVIDENCE ?

Ralph Shapiro, Chairman
Air Force Cambridge Research Laboratories

N74-29073

RELATIONSHIPS BETWEEN SOLAR ACTIVITY AND CLIMATE CHANGE

Walter Orr Roberts
University Corporation for Atmospheric Research
Boulder, Colorado

ABSTRACT

Climate change is of extreme importance in world affairs. Therefore, we should forcefully pursue all avenues of research leading to improved understanding of the underlying causes of climate change. One such avenue involves the possible effects of variable solar activity on regional and world climates. A major obstacle to theories that seek to relate climate to varying solar activity is the extremely small energy involved in such variations. Thus "trigger mechanisms" will have to be invoked if progress is to be made.

Vast numbers of apparent solar-climate relations have been advanced. I have chosen to review only a few, including one that apparently relates recurrent droughts in the High Plains of the United States to the double sunspot cycle. Some of the pitfalls of such analyses are reviewed. There is a common thread emerging in research, however, that suggests that high solar activity is generally related to increase in meridional circulations and blocking patterns at high and intermediate latitudes, especially in winter. I offer a speculative suggestion that the effect is related to the sudden formation of cirrus clouds during strong geomagnetic activity that originates in the solar corpuscular emission.

INTRODUCTION

Climate changes vitally affect world affairs. One need only consider the "domino effect" of the summer droughts of 1972 to realize the dependence of humanity on seasonal weather anomalies. The intense Moscow area drought and heat in the spring and summer of 1972 was serious enough to impel the Soviet Union to purchase wheat from Canada and U.S.A. This unusual need coincided with new demands elsewhere that conspired to wipe out our surpluses. The result was skyrocketing domestic and international grain prices, with dire consequences for meat and poultry prices that no American household now ignores. The impact in India, the sub-Sahara and elsewhere was far more tragic, as millions of people went hungry because of the exhaustion of world grain reserves at the same time as their own fields dried up with spreading droughts.

Small wonder, thus, that there is a quickened interest in climate research the world over. The need to predict and to plan is just too important to world welfare for us to leave any new research leads unexploited. And, indeed, the time is now scientifically favorable for new initiatives in climate research. There have been great improvements in the understanding of the general circulation of the atmosphere and the oceans in recent years. These findings have come at a time when earth-orbiting satellites have given us new means for observing the global behavior of the oceans, the atmosphere, the land cover and the ice; these factors, together, open genuine promise of advances in the understanding of climate changes. So for the years immediately ahead it is a matter of urgency to find the people who will do this climate work and to give them the support that the problem deserves. In our country climate research had been an underdeveloped science in recent years. The time has come for us to become a rapidly developing nation in this field of research which so critically applies to human needs.

One of the many contending theories of climate change involves variations of the solar input to the earth's atmosphere and surface. This is the subject of my paper. There are, of course, many different ideas about the origins of climate change. Many factors have been looked upon as potential causes: vulcanism, sea surface, temperature changes, changes in CO_2 content of the atmosphere, oscillations in Arctic ice and sea depth, atmospheric turbidity changes due to man-made dust or wind-blown soil and sand.

These theories, including the solar one, share the difficulty that they have not yet reached the stage where convincing experimental verification is possible. It may turn out that climate changes occur for a number of different reasons, and that more than one theory will ultimately be verified. Meanwhile, it is important to follow forcefully all promising leads that have any chance to advance our climate forecasting skills and to devise critical experiments and analyses to discriminate which leads are the most significant.

Probably the reason so few talented scientists have worked on climate theory is that real progress appears to most meteorologists to be very difficult. Success has seemed unlikely until other tasks have first been accomplished in short-term weather forecasting research. But this may not necessarily be so. It may be that the atmosphere's mean properties respond sensitively to long-term changes in rather small forcing functions, such as increased ocean evaporation due to anomalously warm sea surface temperatures over large areas. In such a circumstance it may be easier to make progress by looking at monthly, seasonal or annual mean circulations than it is with day-to-day meteorological changes. In another research area, it may be possible to do explicit numerical dynamical modeling of climatic properties effectively, and this may be a more fruitful approach to climate modeling than integrating up the usual general circulation models over long periods of time. Be that as it may, my purpose here is to look at one aspect of climate theory, namely that having to do with the effect on climate of variable solar activity, if indeed there is one. For this paper I'll confine my attention to climate changes that manifest themselves as anomalies of meteorological parameters of seasonal, annual or decadal time span. I shall not look at climate changes in the time frame of centuries or millenia, important as they may be. Nor will I look at day-to-day solar-weather effects; that is the subject of the next paper. Indeed, I suspect that the most important climate effects are simply the aggregations of persistent day-to-day weather effects, as Professor Hurd Willett pointed out long ago.

Finally, let me say that I do not plan to do a comprehensive survey of the vast literature on the subject of suspected influences of variable solar activity on climate. There are good summaries of this available (Pokrovskaya, 1970; Lamb, 1972). My purpose, instead, is to discuss critically a few selected findings which seem to show a real effect of variable solar activity.

OBSTACLES

The subject of solar-weather relationships is spiced with strong language. To be sure, a great deal of uncritical work was done, especially in the 1950's, by workers whom Lamb (1972, p. 441) had characterized as "over-optimistic or naive amateurs working in isolation and without adequate criticism of either data or results." Andrei Monin (1972) has some sharp words for "heliogeophysics enthusiastics" working on suspected influences of solar activity on weather: "Most of the information concerning such an influence fortunately produces only an impression of successful experiments in auto-suggestion; the hypotheses proposed concerning the physical mechanisms of the influence of solar activity on the weather lack convincing substantiation." He says "fortunately" because he thinks that to find such a result would be almost a tragedy for meteorology, since then one would have to predict the solar activity in order to predict the weather. And he thinks we've got enough problems without that!

But the matter won't go away that easily; and if indeed solar activity is a significant factor in weather and climate, it will not advance research progress simply to wish it away. If it is not a significant factor, we will be better off to know that as we seek theoretical explanations for climate change. I am convinced, however, that there is good evidence, on some occasions at least, that certain weather and climate phenomena are significantly linked with solar activity or with upper atmospheric phenomena generally considered to be caused by solar activity.

It must, nonetheless, be frankly stated that the literature of efforts to find links between variable solar activity and meteorological phenomena is spotty. Many of the publications in this field are vague, and sketchy. Some are very poorly done. We have more than the normal share of such papers, I fear. They hurt the reputation of all workers in the field. Few of the published research works deal effectively with the physical mechanisms that must, sooner or later, be subjected to critical tests if we are to develop confidence in our understanding of empirically-discovered connections. In my view, the most important step that must now be taken by those seriously interested in the solar-weather field is to generate some plausible physical explanations and then to test them quantitatively against observational data. I hope that this symposium will be a step in this direction.

A serious obstacle facing hypothesis-makers in this field is the energy problem. It is a hang-up that has been recognized for a long time. The problem, simply stated, is this. There are large potential and kinetic energy transformations involved in changes of the large-scale dynamical features of the general circulation of the stratosphere and its interactions with the troposphere. The changes in solar energy incident upon the atmosphere as a result of changes in solar activity, on the other hand, are orders of magnitude smaller. It is hard to imagine a plausible scheme to have this tiny tail wag the huge dog. But that is the essence of the problem. Many authors appeal to "trigger mechanisms" but these are, of course, very difficult to deal with quantitatively and logically. If trigger mechanisms are at work (and unless I am wrong about the reality of solar-weather influences there must be such processes going on), then we have a serious responsibility to find ways to assess the collateral consequences of any given trigger mechanism, and to use them to increase the susceptibility of the hypothesis to quantitative test. That is the most important item on our agenda now, as I see it.

It is obvious enough that variable solar activity controls many important ionospheric phenomena. In some instances very high ionospheric winds are produced. But these offer no easy solution to the energy problem, because the atmosphere at the levels of solar control has so little density that its kinetic energy is still trivial, in spite of the high velocity, by comparison with that needed to push around the lower atmosphere.

When one is addressing questions of solar activity and climate he faces still another obstacle. This is, briefly put, the very unsatisfactory state of affairs in regard to theories of climate change. Only in most recent years have we begun to give explicit attention to the forcing mechanisms that are almost certainly involved in climate change even though their short-term weather implications are small. Atmospheric scientists are now beginning to give the appropriate attention to the radiative balance implications of increased atmospheric CO_2 or scattering aerosols. They are now also starting to look carefully at the interactions between polar ice, ocean flow and the atmosphere. These are examples of important steps in climate research. Only when our general understanding of climate change improves greatly, I suspect, will we make substantial progress in understanding the true role of variable solar activity as an influence upon climate. It is, moreover, likely that climate change is not uniquely determined, but that different or even contrasting initial influences may alter world climates in similar ways. This will not simplify our task!

REVIEW OF SELECTED SOLAR-CLIMATE EFFECTS

There is an enormously abundant literature dealing with research work purporting to relate changes of solar activity to various aspects of climate change. I shall select only a few of the published works to discuss critically in the minutes to follow. My choice is designed to concentrate on just a very few items from among the many that are probably relevant. And I have selected those research findings that seem to me to be the securest empirical-statistical evidences for an influence of solar activity on climate change.

RECURRENT DROUGHTS IN THE HIGH PLAINS AREA OF THE UNITED STATES

The best-established result of statistical studies showing apparent effects of variable solar activity on climate, so far as I am aware, is that relating solar activity to severe droughts in the High Plains of the Central United States in the first 500 or 600 kilometers east of the Rocky Mountains. Various authors have called attention to this coincidence (Borchert, 1971; Marshall, 1972; Thompson, 1973). There is a striking tendency for the droughts in this region during the last 150 years to recur with a periodicity of about 20 to 22 years, and with a reasonably constant phase relationship to the alternate minima of the solar activity cycle.

The easiest representation on which to visualize this, probably, is that used by Thompson (1973). Figure 1, adapted from his paper, shows the sunspot numbers for this century plotted in such a way that the alternate maxima are plotted as negative numbers. There is no physical reason to interpret alternate cycles as negative numbers. But it has long been known that there is a very real sense in which the "true" sunspot cycle is about twenty to twenty-two years, rather than ten to eleven, namely: the magnetic fields of the leader spots of sunspot pairs are opposite in the opposite hemispheres of the sun during a given ten-year spot cycle, but both reverse at the start of a new cycle. This fact was noted many years ago by the solar physicist G. E. Hale, and the 20-22 year quasi-cycle of sunspot activity is often termed the "Hale double sunspot cycle" or simply the "double sunspot cycle." The physical reason for this behavior is still a matter of speculation.

For illustration, in the cycle from 1934 to 1944 the leader spots in the solar northern hemisphere were north-seeking; in the cycle from 1944 to 1954, the leader spots in this same hemisphere were south-seeking. It was not until the cycle beginning after 1954 that the spots had the same polarities as they did after 1934. Things were exactly opposite in the solar southern hemisphere. Thus, there is a very real sense in which the behavior of the sun may be considered quasi-cyclical with a period of approximately 20-22 years. Drawing the sunspot diagram as Thompson has done in Figure 1 simply calls attention to this fact.

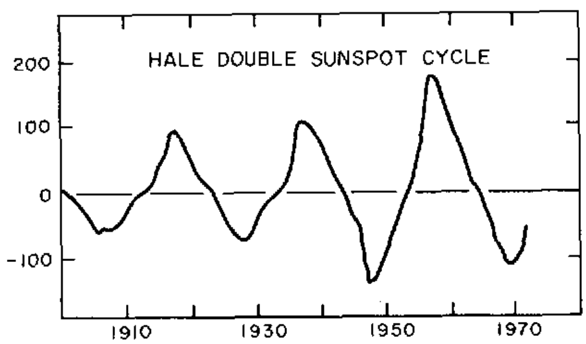

Figure 1. The Hale double sunspot cycle. The alternate maxima in the 10- to 11-year sunspot cycle are plotted with opposite sign. Plotted below the horizontal zero line are the alternate maxima whose amplitudes have tended to be smaller.

In addition, the polarity of the magnetic field of the sun near the poles (sometimes loosely called the "dipole field" because it roughly resembles a dipole in shape near the poles) is generally believed to reverse each ten or eleven years, but there is great irregularity in the time of reversal, and uncertainty regarding its relation to the sunspot cycle. Sometimes both poles carry the same sign for extended times, as one polar region lags the other in reversing. There are also surprisingly substantial day-to-day changes in the poloidal fields. During the sunspot maximum of the IGY, which occurred in 1958, the solar poloidal field was anti-parallel to the earth's, having reversed in 1957.

There is, moreover, a tendency in the recent spot cycles for the alternate halves of the twenty-year cycle to be systematically different in magnitude. This can be seen in the fact that the spot numbers plotted negatively in Figure 1 are slightly smaller, on the average, than those plotted positively.

It is customary, then, to refer to the eleven-year cycles plotted negatively as "minor," and those plotted positively as "major." It would perhaps be better to call these "odd" and "even" cycles, because before 1880 some of the negatively plotted maxime are larger than the positive ones.

Figure 2, reproduced from Thompson (1973), shows the sunspot numbers plotted as above, but carried all the way back to about 1750. It also shows by horizontal bars the years from 1800 onward for which the tree growth ring analyses of Weakly (1962) indicated droughts in Nebraska. It is rather striking that there is evidence for a drought at eight successive times very close to the sunspot minimum that follows the minor sunspot maximum. It is also notable that no severe droughts occurred in this region as the major maximum drew to a close.

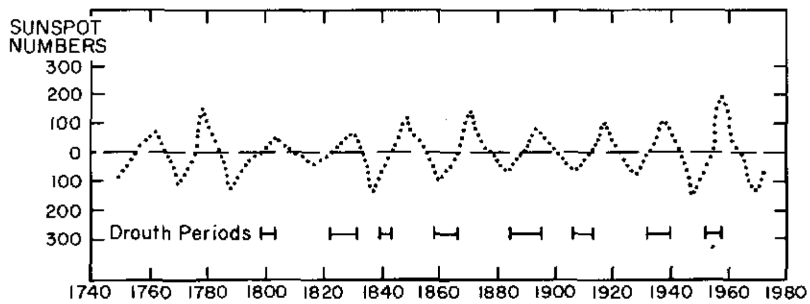

Figure 2. Solar cycle and drought in western Nebraska (Thompson, 1973). Drought periods in Garden County, Nebraska, are shown by horizontal bars below the sunspot numbers plotted as in Figure 1. All droughts published by Weakly (in 1962 and 1943) are included.

To illustrate the matter with independent data, I have adapted Figure 3 from the Ph.D. Thesis of Marshall (1972). A vertical line is drawn at the center date of each of the droughts in his analysis, which was based on drought data from other workers. Figure 3 shows that all of the major droughts of the available time period came remarkably close to the solar activity minima that followed the minor peaks. Moreover, there were no major, extensive droughts at dates other than the ones shown, giving us a one-to-one correspondence during the period under study.

Two nagging questions come to mind: (1) are these coincidences since 1800 accidental, and simply the result of selection due to a long search for a correlation in a vast body of global weather records, and (2) are the droughts related to the 20-year solar activity cycle, or are they evidences of a natural terres-

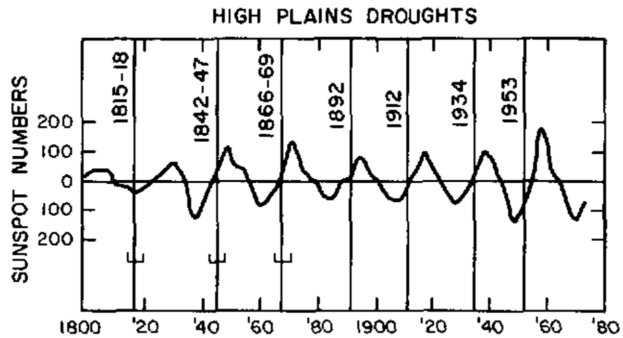

Figure 3. High Plains droughts. This figure is adapted from the Ph.D. thesis of Marshall (1972). The vertical lines correspond to the center dates of all droughts cited by Marshall from rainfall data over the High Plains region. The three earliest droughts are less reliably determined; for them the horizontal bars show approximate beginning and ending dates. Note that every drought occurs near the sunspot minimum following the negatively plotted sunspot maximum.

trial oscillation of about 20 years period that happens by chance, just now, to hold an approximately constant phase with the solar cycle? The distinguished climatologist, J. Murray Mitchell, Jr. (1964) has given serious attention to both questions, and has also given us some very apt warnings about the many pitfalls of seeking periodicities in climate records. He even has some pungent words about the subject: "Hasty and uncritical acceptance of the reality of evidence of cycles in climate has evidently been the source of more waste effort in meteorology than any other kind of scientific misjudgment." And a very similar criticism could be leveled at solar activity versus climate correlation analysis, as Mitchell so cogently points out.

At my suggestion, Mitchell recently (unpublished) resurrected some drought data for eastern Kansas developed by Wayne C. Palmer, his former colleague in NOAA. He has now plotted severe drought years on two types of harmonic dials: (1) a strict 20-year recurrence dial, and (2) a dial based on the double sunspot cycle (of approximately 20 to 22 years length). The data embrace nearly the full time span of available records, reaching back to about 1850 and forward to 1960, with some serious uncertainties about the earliest data. The region was chosen by Palmer because he believes it partook in each of the major High Plains droughts since 1850. The data are taken from mean climatological division statistics developed by NOAA. Except for the earliest drought (1852), for which there are some uncertainties in the data, all of the worst years of the severe droughts have tended to cluster near the rising branch of the sunspot cycle following the minor cycle. Figure 4 shows the harmonic dial for these data, which I have adapted from the one given me by Mitchell. Note that half of the dial is completely free of drought indications. The worst drought years listed here tend to cluster slightly later in phase than those in the results which I showed in Figures 2 and 3. But this is not surprising, since I suspect that the extreme years of a given drought period are likely, other things being equal, to come near the end of the cumulative effect of several successive dry years.

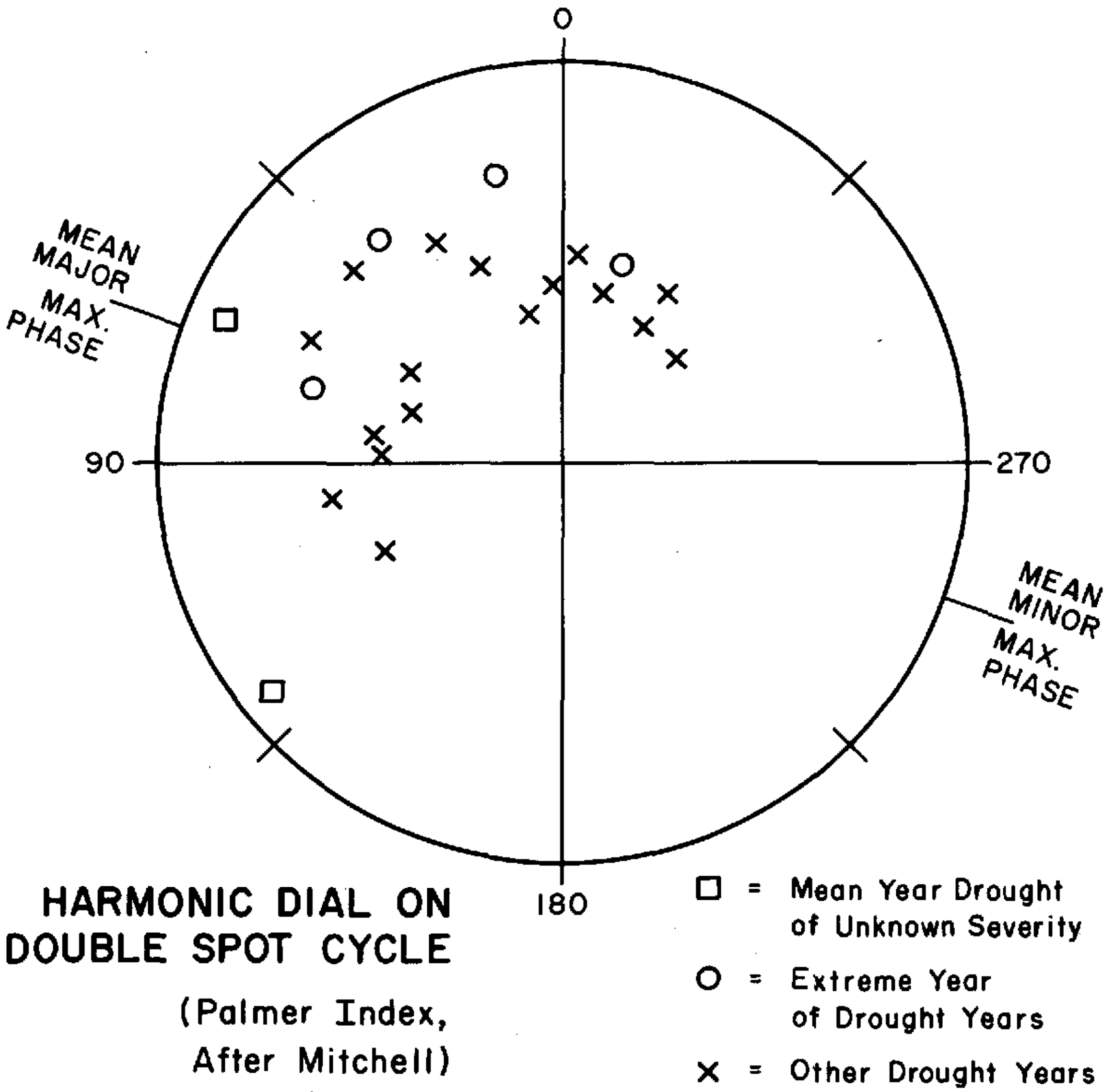

Figure 4. Harmonic dial showing drought dates of differing amplitude for western Kansas as measured by Palmer (Mitchell, 1964). The minimum sunspot phase following the negatively plotted sunspot maximum is as phase 0°. Note clustering of droughts one half of the dial between phases 45° and 225°.

Mitchell next asks whether it is possible, with these same drought data of Palmer, to discriminate between a strict 20-year recurrence and the double sunspot cycle. Figure 5, also adapted from one given me by Mitchell, shows a harmonic dial to test this. The clustering tendency is approximately the same, except that the 1852 drought falls better into line. One must not forget, however, that in choosing a strict 20-year period because it seems to fit the data, he has taken advantage of one additional free parameter for the analysis. Nonetheless, the dial shows that one cannot, with the available data span and with these data, safely discriminate between the hypothesis that the double sunspot cycle associates with the droughts, and the hypothesis that the droughts are approximately 20-year recurrent.

To bring to bear the data in Figure 2 on this question, I have made two additional harmonic dials. I have plotted points from Weakly's original data and represented them in Figure 6, which shows the drought years in Nebraska according to phase in the double sunspot cycle, just as is done in Figure 4. I have picked the middle year of the drought, and weighted it according to the indicated length of the drought to give the amplitude in the harmonic dial.

It is clear that the harmonic dial for the phase relative to the double spot cycle, Figure 6, has a significant clustering near the minimum after the minor sunspot maximum. This is what one would expect from Figure 1. The double sunspot cycle orders the data slightly better than does a 20-year cycle, although I have not reproduced the 20-year harmonic dial here. A cycle slightly longer than 20 years would organize the data just about as well as does the sunspot cycle. So, once again, it is not possible to distinguish in this length of record between a periodic recurrence of Nebraska droughts with a cycle length of about 22 years, and a recurrence in phase with the double sunspot cycle. On the other hand, we have no good reason to suspect any physical process of purely terrestrial origin that would produce a periodic fluctuation of High Plains droughts with a 22-year period. We do have, on the other hand, a valid a priori reason to look for the double sunspot cycle, namely our suspicion that some feature of the quasi-cyclical behavior of solar activity causes the drought.

Other high plains parameters show a similar 22-year recurrent behavior; for example, Thompson has reproduced July-August temperatures in the "corn belt" of the U.S., and it shows a warming trend in the same phase as the drought years (Thompson, 1973). I do not think, however, that it is worthwhile to spend any major effort to do additional statistical-empirical searches for teleconnections to this drought region though I am sure there are many. What is far more important to do is to search for possible physical mechanisms to explain the apparent effect in terms of variable solar activity—and then to test candidate mechanisms against available observations.

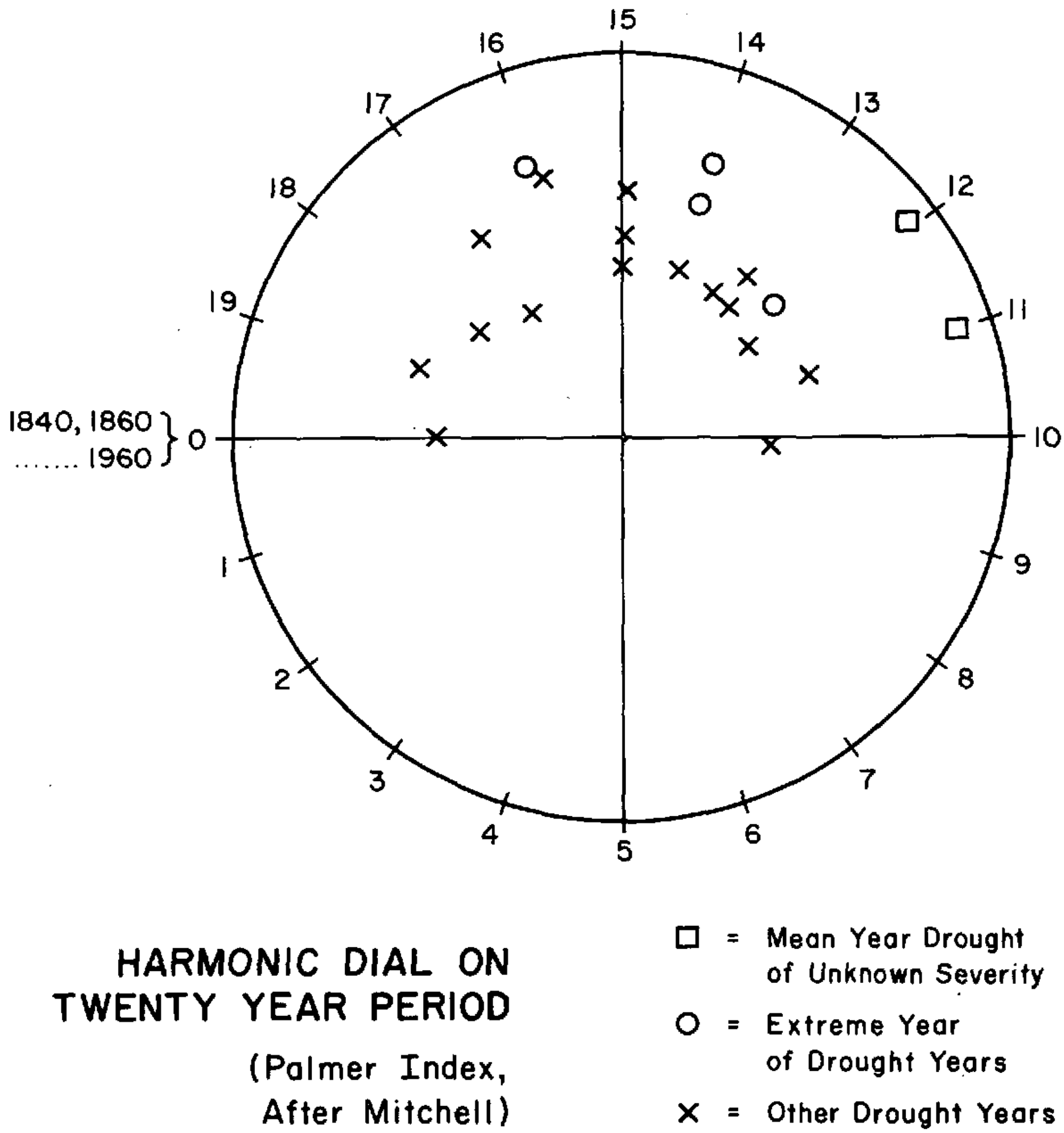

Figure 5. Harmonic dial showing drought dates in Figure 4 compared with 20-year periodicity (Mitchell, 1964). Note absence of droughts in alternating decades 1840 to 1850, 1860 to 1870, . . ., 1960 to 1970. This figure and Figure 4 illustrate that western Kansas drought recurrence since 1840 can be explained equally well by association with the double spot cycle or a 20-year recurrence tendency.

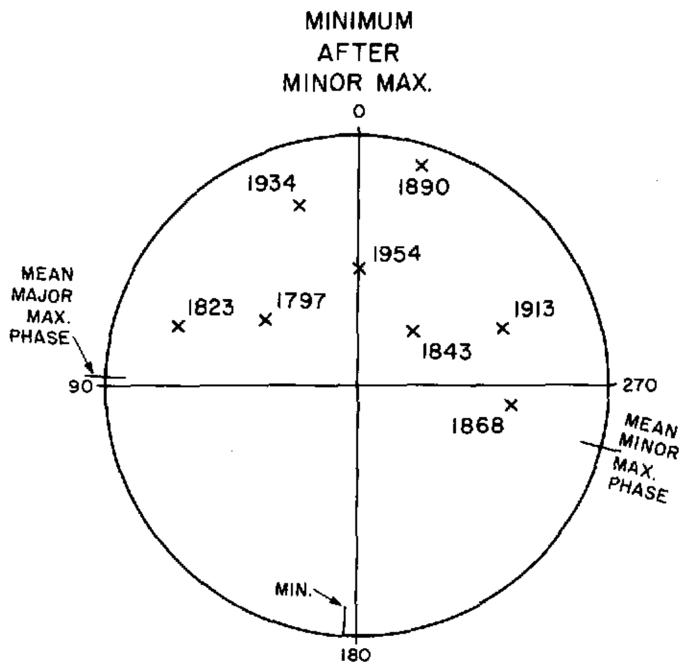

Figure 6. Harmonic dial, western Nebraska droughts reported by Weakly versus double sunspot cycle, 1800 to 1970. Note significant clustering in the upper half of the dial, corresponding to a centering on the minimum following the negatively plotted sunspot cycles. This graph agrees approximately with Figure 4, though the droughts lag slightly in phase compared to Figure 4. Amplitudes correspond to drought duration. Drought dates are shown beside drought points.

I'd like to make some additional points before leaving the High Plains. First, it will be extremely interesting to see what happens in this region in the period 1974 to 1978. In recent years the double sunspot cycle has averaged a bit under 21 years. A 21-year recurrence would place the start of a High Plains drought right about 1973; none has occurred, and in fact the spring of 1973 was a growing season of abundant moisture. On the other hand, in August 1972 solar activity took a sharp spurt upward from its decline toward minimum, with a large outbreak of flares, sunspots and other active sun phenomena, and substantial activity has continued until this writing (October 1973). It looks, therefore, as if the solar activity minimum after the recent minor maximum may be delayed. If the drought is correspondingly delayed, this will be a strong boost to the hypothesis that the droughts are causally connected to solar activity.

Secondly I want to comment on the earlier western Nebraska drought data of Weakly (1962) not analyzed by Thompson. Sunspot data are available back to the time of Galileo's discovery of the phenomenon around 1610, although reliable and regular sunspot measurements date only from about 1700. In Figure 7 I have reproduced a harmonic dial like that of Figure 6 for the period 1610 to 1800. I have assumed, in making this dial, that the double sunspot cycle alternated as it has in more recent times. This is not an entirely safe assumption because there are some indications that long-term phase anomalies in the spot cycle occur. And, of course, no spot magnetic field observations or other direct solar activity records exist for these earlier periods. The dial does not lend any very strong independent support to the hypothesis of a relationship of the double sunspot cycle to droughts in western Nebraska. It is not a clear negation of this hypothesis, however, because there is some clustering near and after the minimum that follows the minor maximum. Moreover the anomalously long 1698 drought, which was over 20 years in duration, is the one latest in phase. I mentioned above that late phase relationships for center dates or long droughts also showed up in the more recent data.

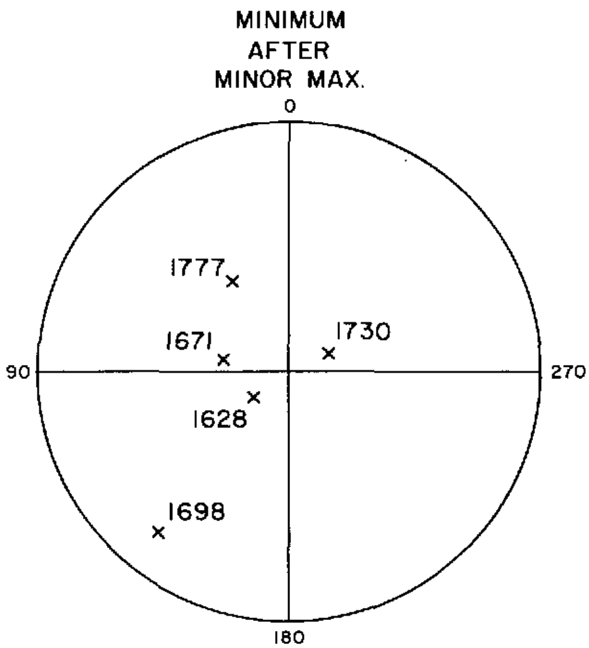

Figure 7. Harmonic dial, western Nebraska droughts reported by Weakly versus double sunspot cycle, 1610 to 1800. Drought data for 1610 to 1800 plotted on same basis as Figure 6, but with expanded amplitude scale. The 1698 drought, which is late in phase, was also very long (20 years), necessitating the expanded amplitude scale compared to Figure 6. Paucity of data leads to inconclusive results regarding double sunspot cycle association with droughts in this time period.

The data do not, however, show that a distinct drought accompanies every one of the minima following the minor sunspot maxima, as was the case for the period from 1800 on. We are probably straining too hard, however, when we try to push both the sunspot and drought data all the way back to the discovery of sunspots, especially in view of the fact that the distinction of major and minor maxima is not clear in these earlier periods. In any event, we cannot draw from these earlier data much evidence for or against the apparent High Plains drought relationship to solar activity that is so marked from 1800 on.

Finally, I'd like to say a word about what the climatological picture for a High Plains drought might be, in hope that it will contribute to the search for a mechanism. My concept is perhaps too simpleminded and therefore I'd be glad to have some more sophisticated experts shoot it down. My reasoning goes as follows. For a spring or summer drought to occur in the High Plains of the U.S.A., it would seem to me reasonable that the large-scale circulation should have a persistent anomaly that would lessen the prospect for warm moist Gulf of Mexico air to penetrate northwestward to the lee of the Rockies where its contact with cold Canadian air thrusting southward results in precipitation.

A likely mechanism for this would, in my opinion, be a strengthening of the jet-stream westerlies over the Colorado Rockies; so that there'd be a relatively warm, strong, dry, west wind on the lee side of the mountains. In this case, the Gulf air would be pushed appreciably farther east and its precipitation would occur perhaps 1000 km or so downwind from the Rockies, say from St. Louis eastwards. On this assumption, one might search directly for a solar activity correlation in strong winds at the troposphere and at the surface, and for a corresponding reordering of precipitation patterns eastward. If this were verified, it would focus attention on a strong westerly wind as a step in the explanation.

Reliable wind data for this region over any appreciable time span may be hard to come by. It is certainly true, within the memory of present-day farmers of the region, that the "dust bowl years" of the 1930's and the drought years of the 1950's were characterized by high surface winds, and no one contests that this greatly promoted soil erosion in spring and early summer. Weakly (1962) reports that in the extreme drought that ended in 1562, the trees in his test area of western Nebraska were buried in nearly 3 meters of wind-blown soil. Even though long-term wind data are hard to acquire, it may be possible to find jet-stream wind and rainfall associations with solar activity that are operative on a short time scale of perhaps week-to-week changes; such findings would encourage us to surmise what would happen if the changes were to be persistent in one pattern or another over a season or a year or a series of years.

In fact, it was in hope of finding such a lever to understanding climate changes that I decided, many years ago, to look at short-term changes in the 300-mb circulation over the North Pacific and North America to see if they were connected to changes in the geomagnetic disturbance activity. The findings from that work appear generally to support the notion that low solar activity is a time of stronger and less meridionally-perturbed westerlies, but it says nothing about the difference between the two minima of the double sunspot cycle. I suspect that it should be possible to look more directly at the Rockies and the High Plains, and from data covering as few as 30 years to produce differential 300-mb circulation maps for two-week or one-month periods characterized by different phases of the spot cycle, and also characterized by differing aspects of other features of solar activity or geomagnetism. Such a study will be especially attractive a few years hence, when we pass through the coming minimum of the double spot cycle, since it is the one for which we have some empirical reasons to expect a high plains drought to recur.

SOLAR ACTIVITY AND WARM (COLD) PERIODS

There are numerous studies of solar activity indices and their possible relation to the occurrence of colder or warmer climates. These are summarized by H. H. Lamb (1972, page 443 ff.) and I shall not go extensively into detail here. However, Lamb is of the opinion, in spite of the welter of complex and often confusing results, that warmer weather in most regions appears to have occurred significantly more often during the years of high solar activity. He quotes J. R. Bray (1968), one of the most active workers in the field, as believing that "75-80% of all known glacier advance events and other indicators of cold climate in late glacial and post-glacial time occurred during intervals of weak solar activity, and a similar percentage of glacier recession and warm climate indicators occurred with high solar activity." Bray's results cover a wide range of latitudes and encompass data from both hemispheres.

There are, however, very great complexities in long-term temperature trends as related to solar activity. Work of Suess (1968), for example, illustrates this. Over very long periods, Suess determined solar activity from the cosmic ray production of natural radiocarbon deposited in wood samples of known age. His results show suggestive relationships with temperatures in some regions and periods, but very confusing results, and unlikely time lags in others. The story is obviously far from simple, and it is no wonder that results of this character have caused many workers to shy away from the field, believing the evidence of real solar-climatic relations insufficient to merit major research effort on their parts.

PRESSURE PATTERN DIFFERENCES BETWEEN SOLAR ACTIVITY MAXIMUM AND MINIMUM

Many investigators have sought sunspot-cycle-related features of regional or global pressure patterns and circulation systems. Wexler (1950) did a thorough study seeking mean surface pressure differences between maximum sunspot years and minimum for the northern hemisphere over a 40-year period and confirmed an earlier finding of Clayton that high latitudes show higher average pressures at spot maximum than at minimum. Wexler did not, however, consider the results conclusive. In today's context they appear more significant, perhaps, than he thought.

Willett (1965) did perhaps the most extensive modern study of the matter, using several indicators of solar activity, such as geomagnetic storm activity. He concluded that at high solar activity there is a mass displacement of air toward high latitudes, consistent with Wexler's and Clayton's findings. He also found abundant but complex evidences, especially in North American climate data, for the effects of the double sunspot cycle in temperatures, rainfall, and other phenomena. Abstracting his findings, Willett has said, ". . . analysis of the double sunspot solar-climatic cycle indicates that this cycle is . . . pronounced in middle and high latitudes, particularly in the winter season. It is suggested that this cycle probably reflects a change of the transmissive properties of the atmosphere, i.e., a greenhouse effect, in such a manner as to sharpen or suppress the relative heat and cold sources of the continental-maritime monsoonal cells of the general circulation." Willett suggested varying atmospheric ozone as the causative factor, a notion that has gained some support from recent work of Angell and Korshover (1973).

Schuurmans (1969) has carried out an interesting study of the relation of solar activity to the relative frequencies of different types of weather patterns over Western Europe. He used the "Grosswetterlagen" classification system introduced in 1952 by the German meteorologists, Hess and Brezowsky in their "Katalog der Grosswetterlagen Europas." In this system there are three principal types of circulation characterized as: Z = zonal, H = half meridional, and M = meridional or blocking. Schuurmans found that the meridional circulations are most frequent and the zonal types least frequent during highest solar activity. The effect is strongest in winter and spring. Moreover, he finds that both the frequency and duration of the meridional or blocking circulation increases at maximum solar activity. He concludes as follows: "Therefore we might say that increased solar activity, quite apart from having an influence on the development of meridional type circulations, strengthens the persistence (i.e., continuation tendency) of meridional or blocking type circulations, while on the other hand it interrupts spells of westerly zonal circulation, which are normally quite long."

There are many supporting evidences for these conclusions of Willett and Schuurmans. I regret that time does not permit me to go further into their discussion.

A FEW WORDS ABOUT MECHANISMS

Other parts of our symposium will deal with the search for mechanisms. My job was to lay out some evidences for the reality of effects in climate and to discuss these critically. However, I'd like to say a few words about mechanisms.

My first comment stems from the work of Schuurmans (1969, p. 114) which suggests that the atmospheric reaction to solar activity (in his case, solar flares) shows a maximum at the tropopause and that it "is not propagated downwards from a higher level in the stratosphere but is initiated in situ, most likely through a cooling mechanism near the tropopause level." As he points out, if an effect originates near the 300-mb level, it can propagate downwards causing the circulation to become more meridional after a few days. It is not surprising, if such a mechanism is operative, that the magnitude of the reaction is, as Schuurmans and others have observed, dependent on the initial atmospheric conditions at the time of the solar activity intervention.

To me the most promising place to search for mechanisms operative at the tropopause is in modification of the atmospheric radiation budget through the sudden formation of cirrus clouds following solar activity. It seems reasonable to expect that a cirrus cloud could produce, near its level, either a heating or a cooling. As Roberts and Olson and I (1973) have pointed out, for example, a reasonably solid cirrus deck overlying a relatively warm ocean surface during high latitude winter could easily lead to a heating of 1°C/day, enough to be dynamically significant.

What evidence is there to suggest that solar activity could produce such cirrus? The evidence is slender, but not totally lacking. A. von Humboldt, way back in 1845, called attention to an apparent connection between the polar aurora and subsequent cirrus clouds in a paper now mainly of historical interest. More recently, Dauvillier (1954) wrote: "It is invariably found that after the phosphorescent final stage of an auroral storm the sky rapidly loses its limpidity and that it becomes covered with a light veil of cirrostratus giving rise to lunar halos." Dauvillier also states the following: "Tromholt found that observations at Godthaab from 1857-1873 showed a strong correlation between the number of halos observed and the number of aurorae. At dawn the sky is seen to be full of cirrus. These clouds always follow auroral display."

I have some personal doubts about the "invariably" and the "always". But perhaps these questions should be reexamined by modern techniques. I find this particularly so in the light of the provocative but very short-term study of Barber (1955) that suggested a light-scattering layer over England following magnetic storms. I am also impelled in the same direction by the analysis by Vassy (1956) of Danjon's analyses of the shadow of the earth on the eclipsed moon which led Vassy to conclude that there is an increase in light-scattering aerosols in the earth's atmosphere during periods of strong solar corpuscular emission associated with high solar activity and strong auroras. Finally, there is the work of Tilton (1934), based on a long series of observations beginning in 1844, purporting to show a change in atmospheric refractive index as a function of solar activity.

Perhaps satellite IR data will give us an opportunity to settle definitively, in a few years, the existence of this kind of a solar-modulated IR budget from high terrestrial latitudes that might account for the climate phenomena that apparently display a measure of control by variable solar activity. Be this as it may, there is sufficient evidence, in the light of our compelling need to understand and predict climate change, to justify greatly enhanced research attention, by scrupulously critical workers, to study of the effects of variable solar activity on climate phenomena.

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF WALTER ORR ROBERTS

MR. ROBERTS: The question was could I give some numbers about the disparity in energy from the sun and the energy required, through a brute-force mechanism, to produce some kind of circulation change in the lower atmosphere. All right. I hope there will be some further discussion of this later because I know some people here have done some new calculations on this. But the work that I did, of a very qualitative sort, some years ago, shows that while the solar constant produces a flux into the top of the atmosphere in a direction normal to the direction of the sun of the order of ten to the sixth ergs per square centimeters per second, the features of variable solar activity precipitate into the atmosphere something only of the order of the few ergs, or a few tens of ergs, occasionally maybe as high as a thousand ergs per square centimeter per second.

It is very difficult—at least, for a non-meteorologist like me—to calculate what amount of energy would be required in a brute-force way in order to produce, for example, a substantial trough amplification over one of the large-scale planetary wave types of circumstances or a large blocking high like those that produce themselves in the winter season in certain regions of the earth. But it looks to me as if the energy required to do this in some brute-force way is of the order of ten to the fourth or greater.

QUESTION: You mentioned the drought and you seemed to emphasize spring and summer in that discussion, but later you seemed to think that the place to look is in the winter. Now, in those drought years, is there a variation with seasons?

MR. ROBERTS: I think I mentioned late winter and spring, for the most part, but I'm not sure. But in any event, in this region, from the Rockies to about a thousand kilometers to the east and from South Dakota down into the Texas Panhandle, the drought appears to be well-established in the early spring or late part of the winter, and to continue right on into the summer. So if you take whole growing season integrated drought data, or if you take data for the period March, April, and May, you get about the same results. This has been done month-by-month, for example, by Marshall.

MR. RASOOL: One thing that bothers me in these correlations between solar activity and the phenomena on the earth is why should we take only the local phenomena, as in Kansas. If anything is going to happen because of the solar activity, it should be planet-wide, so why can't you take the measurements from all over the globe?

MR. ROBERTS: Okay. First of all, there is very abundant literature on searches for drought in various latitudes and longitudinal regions all the way from, for example, looking at something like the level of Lake Victoria as an isolated instance in Africa. I chose to pick just a few selected instances and it seems to me very, very clear that the influence on climate is one that has a very regional character because it appears to be associated with the change in the wave number or intensity of the large-scale planetary wave features of the circulation, the Rossby wave regime.

And it seems clear to me, for example, that if there is any systematic change in the wavelength of the Rossby waves as a function of solar activity cycles, then in some regions it will produce drought and in other regions it may produce increased rainfall. Therefore, it seems important to concentrate your studies in a particular region that has some particular relationship to these circulation features, and a second way of saying it is that some regions appear to show a much simpler and more straightforward relationship to solar activity than other regions. But I could have picked regions showing different kinds of relationships. This seems to me to be the one that is most clear-cut and the most pronounced.

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SOLAR ACTIVITY AND THE WEATHER

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ABSTRACT

The attempts during the past century to establish a connection between solar activity and the weather are discussed. Some critical remarks about the quality of much of the literature in this field are given. Several recent investigations are summarized. Use of the solar-interplanetary magnetic sector structure in future investigations is suggested to perhaps add an element of cohesiveness and interaction to these investigations.

INTRODUCTION

"That there is a causal connection between the observed variations in the forces of the sun, the terrestrial magnetic field, and the meteorological elements has been the conclusion of every research into this subject for the past 50 years. The elucidation of exactly what the connection is and the scientific proof of it is to be classed among the most difficult problems presented in terrestrial physics. The evidence adduced in favor of this conclusion is on the whole of a cumulative kind, since the direct sequence of cause and effect is so far masked in the complex interaction of the many delicate forces in operation as to render its immediate measurement quite impossible in the present state of science. Before attempting to abstract the results of this research on these points a brief resume of the views held by the leading investigators will be given, especially with the object of presenting the status of the problem to those who are not fully acquainted with this line of scientific literature. The bibliography is large—covers a century—and embraces such names as . . . Gauss, Sabine, . . . Faraday, Wolf, . . . Stewart, Schuster, . . . Airy, . . . Kelvin, and many others." (Bigelow, 1898)

These words appear to provide a modern and contemporary introduction to an essay on solar activity and the weather, but in fact they were written 75 years ago. During this interval of 75 years, well over one thousand papers have been published on the subject. It may be fair, then, to ask exactly what has been accomplished.

An appreciable influence of solar activity on the weather is not widely accepted, and is not in every day use for forecasting purposes. The literature on the subject tends to be contradictory, and the work of the authors tends to be done in isolation. It is often very difficult to compare the claims of one author with those of another. Many times an author starts from scratch, rather than building on the work of his predecessors in the classical pattern of science. A widely accepted physical mechanism has not yet emerged.

Nevertheless, there are a few common threads that appear so widely in the otherwise disparate literature as to suggest that they probably have some validity: 1) Meteorological responses tend to occur two or three days after geomagnetic activity. 2) Meteorological responses to solar activity tend to be the most pronounced during the winter season. 3) Some meteorological responses over continents tend to be opposite from the responses over oceans.

Many scientists refuse to admit the possibility of an appreciable influence of solar activity on the weather in the absence of an accepted physical mechanism. Such scientists presumably do not use aspirin. This viewpoint is to some extent valid, and we certainly will never rest until we understand the physical mechanisms involved. We may perhaps learn a lesson from history at this point.

In his famous presidential address in 1892 to the Royal Society, Lord Kelvin said a few words regarding terrestrial magnetic storms and the hypothesis that they are due to magnetic waves emanating from the sun. He considered in particular the magnetic storm of June 25, 1885, and drew the following conclusions: "To produce such changes as these by any possible dynamical action within the sun, or in his atmosphere, the agent must have worked at something like 160 million, million, million, million horsepower (12×10^{35} ergs per second), which is about 364 times the total horsepower (3.3×10^{33} ergs per second) of the solar radiation. Thus, in this eight hours of a not very severe magnetic storm, as much work must have been done by the sun in sending magnetic waves out in all directions through space as he actually does in four months of his regular heat and light. This results, it seems to me, is absolutely conclusive (emphasis added) against the suposition that terrestrial magnetic storms are due to magnetic action of the sun; or to any kind of dynamical action taking place within the sun, or in connection with hurricanes in his atmosphere, or anywhere near the sun outside. It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sunspots is unreal, and that the seeming agreement between the periods has been a mere coincidence." (Kelvin, 1892)

These words of an eminent physicist, stated with the absolute assurance that has not completely deserted the profession today, were correct within the frame of reference in which they were uttered. What Lord Kelvin did not know about, and therefore did not take into account in his calculations, was of course the solar wind, which extended the sun's magnetic field lines out past the earth with the field strength decreasing less rapidly than $1/r^2$ rather than as $1/r^3$ as Lord Kelvin had assumed. We may ask today whether there may be an as yet unknown physical process related to solar activity and the weather that is comparable in importance and extent to the solar wind.

A meteorologist's opinion of the subject matter of this Symposium is given in the following quotation from Monin (1972):

> The greatest attention should be devoted to the question of whether there is a connection between the earth's weather and the fluctuations in solar activity. The presence of such a connection would be almost a tragedy for meteorology, since it would evidently mean that it would first be necessary to predict the solar activity in order to predict the weather; this would greatly postpone the development of scientific methods of weather prediction. Therefore, arguments concerning the presence of such a connection should be viewed most critically.

INVESTIGATIONS OF THE EFFECT OF SOLAR ACTIVITY ON THE WEATHER

Having been unable to find in the voluminous literature a single coherent structure to describe and discuss in this paper, I shall proceed by citing a few recent reviews as sources for a bibliography, and then discuss a few recent representative investigations. Some recent reviews and discussions include Rubashev (1964), Schuurmans (1969), Markson (1971), Roberts and Olson (1973a) and Svalgaard (1973). A good cross-section of current activity in the field was given by the papers at the IUGG Symposium on "Solar Corpuscular Effects on the Stratosphere and Troposphere," Moscow, August 1971. The Symposium papers are in press. Fifty reports and communications were presented at the first All-Union Conference on the problem "Solar-Atmospheric Relationships in the Theory of Climate and Weather Forecasting" held in Moscow in 1972. A short description of this conference is included as Appendix 1.

A prominent line of investigation during the past decade or longer has been led by W. O. Roberts with the participation of R. H. Olson, N. J. Macdonald, D. D. Woodbridge and T. W. Pohrte. I shall describe only the recent work of Roberts and Olson, but this, of course, has benefited from the earlier contributions. Roberts and Olson (1973b) have studied the development of 300-mb low pressure trough systems in the North Pacific and North America region. They find that troughs which enter (or are formed in) the Gulf of Alaska two to four days after a sharp rise of geomagnetic activity tend to be of larger than average size. In this investigation each trough is characterized by an objectively-derived vorticity area index, which is defined as the area of the trough for which the absolute vorticity $\geq 20 \times 10^{-5}$ s^{-1} plus the area $\geq 24 \times 10^{-5}$ s^{-1}. The study included the winter half-years 1964 to 1971. Some results of this investigation are shown in Figure 1. During three to five days after the geomagnetic key day the troughs preceded by a sharp rise in geomagnetic activity have on the average about 40 percent larger vorticity area index than the troughs preceded by a geomagnetically quiet ten-day period. The statistical analysis given by these investigators appears to be compelling and to eliminate any probability of the results being associated with a statistical fluctuation.

The investigations of Roberts and Olson (1973b) were extended by Wilcox et al. (1973a). The vorticity area index was summed over the portion of the northern hemisphere north of 20° N, and the time at which an interplanetary magnetic sector boundary was carried past the earth by the solar wind was used as the

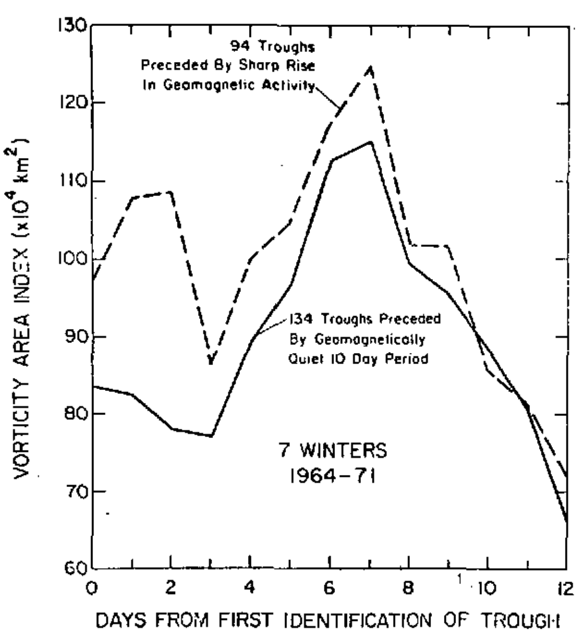

Figure 1. Mean vorticity area index for troughs preceded by sharp geomagnetic activity increases and for troughs preceded by a 10-day geomagnetically quiet period. (For the key troughs add 3 days, on the average, to the lags shown, in order to ascertain the number of days since the geomagnetic rise that led to the designation as a key trough.) (Roberts and Olson, 1973b)

zero time in a superposed epoch analysis. We emphasize again that the sector boundary provides a well defined time, but that the meteorological response is associated with the large-scale sector structure during the interval of several days before and after the passing of the boundary, as discussed in more detail below. The results of the investigation shown in Figure 2 indicate that the

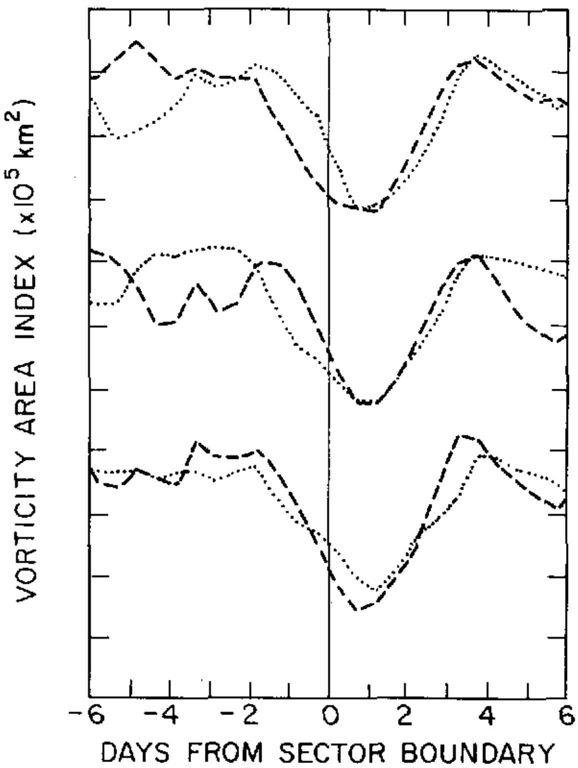

Figure 2. Average response of the vorticity area index to the solar magnetic sector structure. Sector boundaries were carried past the earth by the solar wind on day 0. The analysis includes 54 boundaries during the winter months of November to March in the years 1964 to 1970. The boundaries were divided into two parts according to the magnetic polarity change at the boundary, the first or last half of winter, and the yearly intervals 1964 to 1966 and 1967 to 1970. (a) The dotted curve represents 24 boundaries in which the interplanetary magnetic field polarity changed from toward the sun to away, and the dashed curve, 30 boundaries in which the polarity changed from away to toward. (b) The dotted curve represents 32 boundaries in the interval November 1 to January 15, and the dashed curve, 22 boundaries in the interval January 16 to March 31. (c) The dotted curve represents 26 boundaries in the interval 1964 to 1966, and the dashed curve, 28 boundaries in the interval 1967 to 1970. The curves have been arbitrarily displaced in the vertical direction, each interval on the ordinate axis being 5×10^5 km^2 (Wilcox et al., 1973).

vorticity area index reaches a minimum about one day after the passing of the sector boundary, followed by an increase in magnitude approximately 10 percent during the next two or three days. The result persists essentially unchanged as the list of sector boundary times is divided in two in three different ways. In a continuation of this investigation Wilcox et al. (1973b) found that the effect is present at all levels in the troposphere but only in the lowest portion of the stratosphere. The effect is not confined to a single interval of longitude or of latitude. Since this meteorological response is related to a well-defined solar structure it is not subject to the criticism of Hines (1973) discussed below.

Another prominent investigation during the past decade or longer is the work of E. R. Mustel (1972 and earlier work cited therein). Mustel has investigated the response of the ground level atmospheric pressure to geomagnetic moments based on the first day when an isolated geomagnetic storm becomes sufficiently strong. Mustel finds that in some regions of the globe the atmospheric pressure increases after the geomagnetic moment, whereas in other places the pressure decreases. The reaction time is about three days, and tends to increase with decreasing latitude. Figure 3 shows a representative result obtained by Mustel (1972) for the months December, January and February of the years 1890 to 1967. Large contiguous areas represented by the black circles have an increase in atmospheric pressure after geomagnetic disturbance, while other large areas represented by the open circles have a decrease. The mean statistical curves for the corresponding regions I, II, . . . are shown at the bottom of Figure 3.

Interplanetary magnetic field lines directed away from the sun can connect most readily with geomagnetic field lines directed into the northern polar cap, and interplanetary magnetic field lines directed toward the sun can connect most readily with geomagnetic field lines directed out of the southern polar cap. Thus in a given polar cap one might perhaps find changes in meteorological phenomena depending on the polarity of the interplanetary magnetic field. Mansurov et al. (1972) have found such an effect in the atmospheric pressure, using observations obtained during 1964. At a northern polar cap station (Mould Bay, near 80° N) they found that the average pressure was higher when the interplanetary magnetic field was directed toward the sun, and at a conjugate southern polar cap station (Dumond d'Urville, near 80° S) the average pressure was higher when the interplanetary magnetic field was directed away from the sun. Using only days in the first half of each interplanetary sector they obtained the results shown in Table 1.

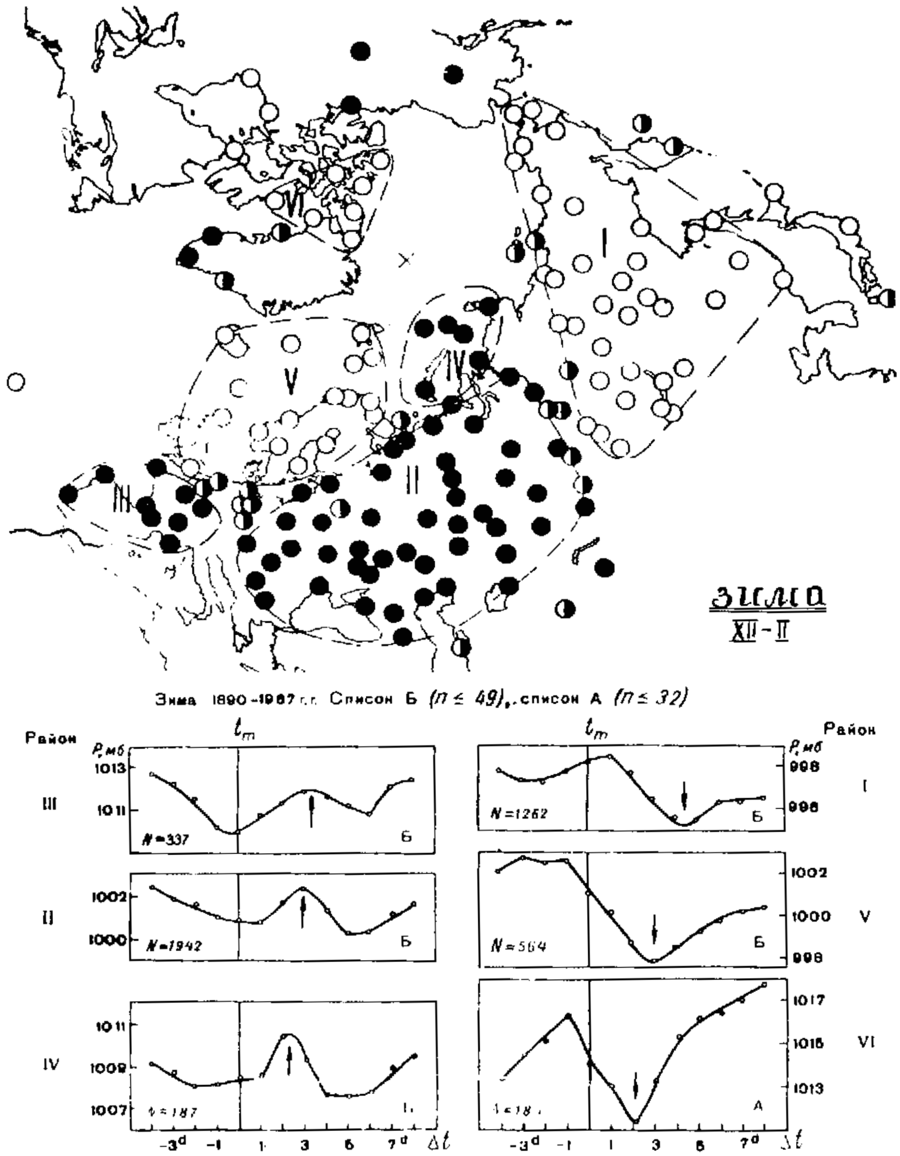

Figure 3. Hemispheric distribution of the change of atmospheric pressure after a geomagnetic storm for the months of December through February and the years 1890 to 1967. The black circles correspond to an increase in pressure and the open circles, to a decrease in pressure. At the bottom of the figure the mean statistical curves for the regions I, II, . . . are given (Mustel, 1972).

Table 1
Average Atmospheric Pressures Resulting from Variations in Interplanetary Magnetic Field Direction

	Interplanetary Field	Pressure
Northern Polar Station	Away	1011.1
	Toward	1016.3
Southern Polar Station	Away	986.2
	Toward	982.7

When the entire interplanetary sectors were used (not just the first half of each) the same results were found, but the magnitude of the differences decreased. This is consistent with the observed properties of the interplanetary sector structure, because the average solar wind velocity and interplanetary field magnitude are larger in the first half of the sectors. The authors state that the results are valid with a statistical probability in excess of 99.5 percent.

Schuurmans (1969) has studied the influence of solar flares on the tropospheric circulation. The mean change in height of atmospheric constant pressure levels during the first 24 hours after a flare is greater than may be expected from mere random fluctuations in height. Average positive height changes are found to occur in the mid-latitude belts of 45° to 65°, while average negative height changes prevail poleward of 70° latitude. The maximum effect is found at approximately the 300-mb level and the effect appears to be stronger in winter than in the other seasons of the year. Significant mean height changes are found to occur only during the first 24 hours after a flare except at the ground level where significant changes do not appear until the third day after a flare. Schuurmans ascribes the causal agent to the corpuscular radiation of the flare rather than to UV radiation. A representative result is given in Figure 4, showing that zonal averages of the pattern of 500-mb height changes as a function of latitude are approximately the same in the northern and the southern hemispheres.

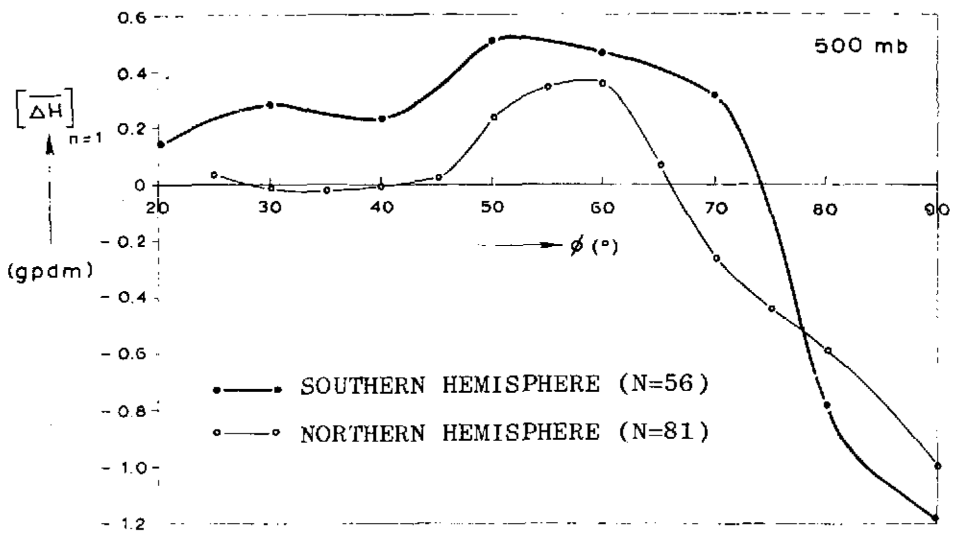

Figure 4. Zonal averages of the difference in height of the 500-mb level between the first aerological observation after a flare and the observation 24 hours earlier as a function of latitude for both hemispheres (Schuurmans, 1969).

Shapiro and Stolov (1972) have found significant increases in westerly winds at the 700-mb level in the longitude belt from 90° W to 180° approximately three or four days after magnetic storms. The effect results mainly from pressure falls in higher latitude (70° N) but also results partly from pressure rises at lower latitudes (20° N), and as usual is strongest in winter. Shapiro (1972) has also found a heightened persistence of sea level barometric pressure over North America and Europe in the first week after a geomagnetic storm, followed by decreased persistence in the second week.

Markson (1971) has studied thunderstorm activity as a function of the earth's position in a solar magnetic sector during 15 solar rotations in 1963 and 1964. The results shown in Figure 5 suggest a maximum in thunderstorm activity when the earth was at the leading edge of a sector with magnetic field directed toward the sun and at the trailing edge of a sector with magnetic field directed away from the sun; that is, that thunderstorms maximized when the earth was crossing from an away sector into a toward sector. Bossolasco et al. (1972) have found that in the third and especially in the fourth day after the occurrence of an Hα flare the global thunderstorm activity becomes higher than normal,

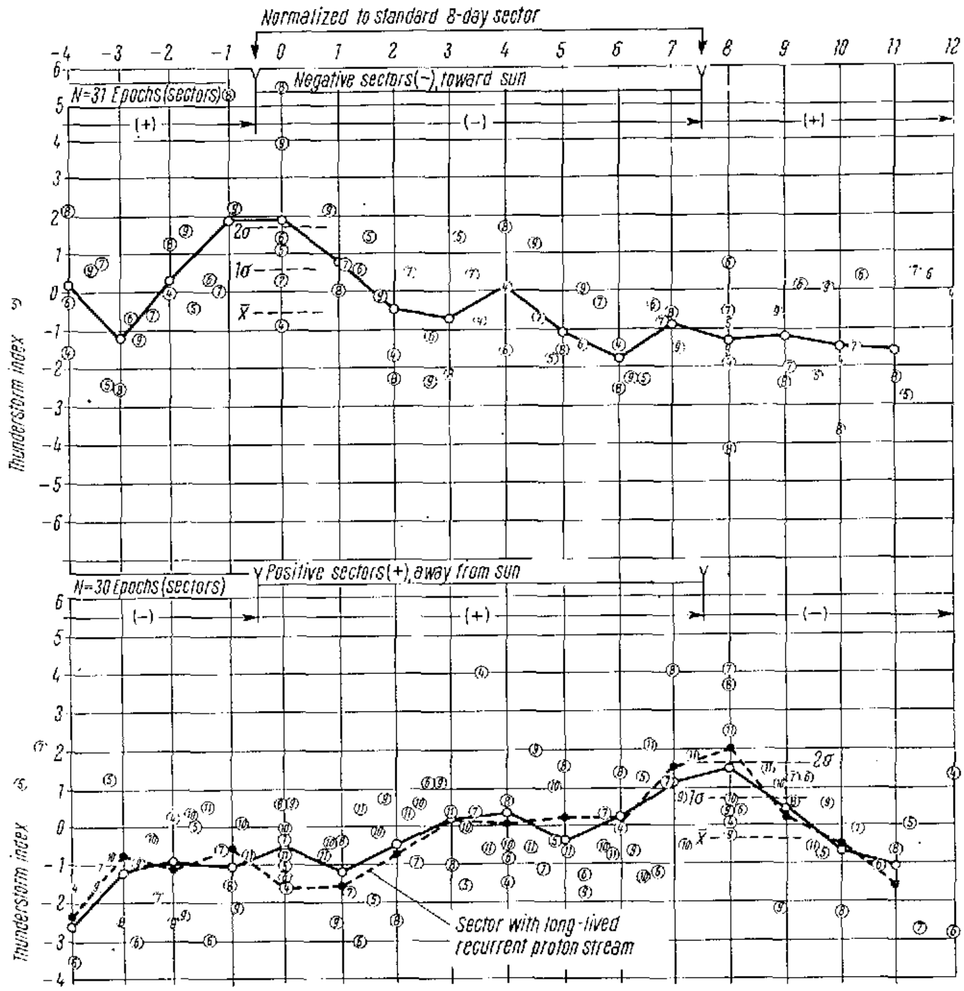

Figure 5. Thunderstorms as a function of the earth's position in a solar sector: negative sectors (top curve); positive sectors (bottom curve); transitions to adjacent sectors of opposite sign seen at days 0 and 8; all points shown to indicate variance in data; curves drawn through locus of points closest to each daily increment of time; numbers in points give days in sector being normalized, that is, each point is average for all sectors of that length at that increment of the sector's length (Markson, 1971).

increasing, on the average up to 50 to 70 percent, as shown in Figure 6. Reiter (1973) has found an increase in the frequency of influxes of stratospheric air masses down to 3 km after the occurrence of Hα flares. This is detected through an increased concentration of the radionuclides Be7 and P32 at the measuring station at Zugspitze Peak in the Bavarian Alps. These radionuclides are preponderantly generated in the lower stratosphere. Some results are shown in Figure 7.

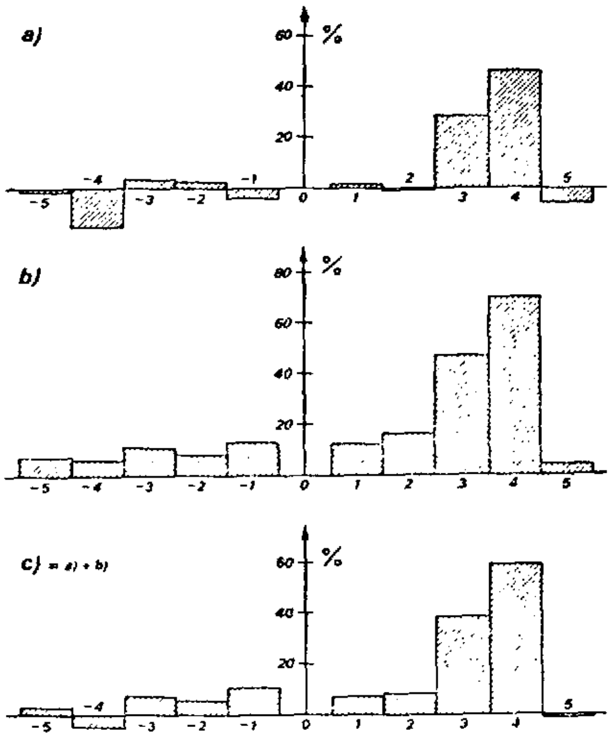

Figure 6. Superposed-epoch analysis of the thunderstorm activity before and after Hα flare day (with Hα flare day as a key-day). Data are expressed in terms of percentage differences from the value corresponding to the key-day: (a) = 1961 to 1965, (b) = 1966 to 1970 (Bossolasco et al., 1972).

The largest meteorological response to solar activity occurs during winter. This is such a prominent and persistent feature in the literature that any magnetospheric or geomagnetic effects that show a large variation between winter and summer should be carefully considered in the search for physical mechanisms. For example, Berko and Hoffman (1973) have studied high-latitude field-aligned 2.3 keV electron precipitation data from OGO-4 at heights of approximately 800 km during the interval July 1967 through December 1968. This precipitation was found to occur primarily in a roughly oval shaped region, with the greatest number of field-aligned events observed in the interval $67.5^\circ \leq$ magnetic latitude $\leq 72.5^\circ$ and 22 hours $\leq$ mean local time $\leq$ 01 hour. Figure 8 shows the probability of this 2.3 keV electron precipitation being field-aligned for the four seasons as a function of altitude, with the largest probability at high latitudes observed during winter. This result is interpreted by the authors in terms of a possible seasonal dependence in the altitude of double charge layers that may accelerate the electrons.

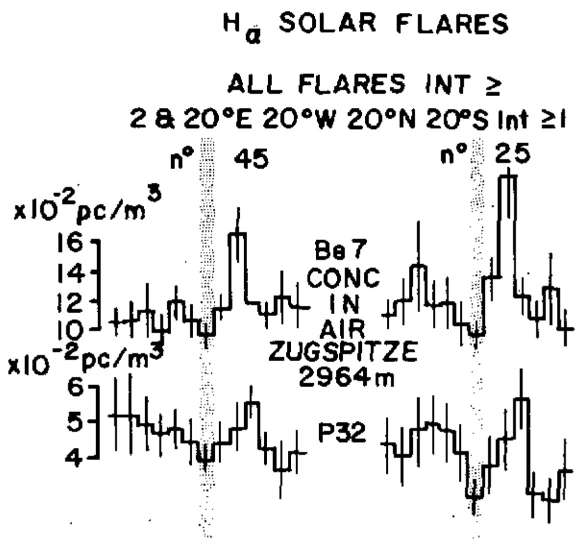

Figure 7. Superposed epoch analysis of Be7 and P32 concentrations in air at 3 km above sea level and various solar and geophysical data; key days (n): solar H flares of different intensity and solar positions; vertical bars: standard deviation (Reiter, 1973).

If other spacecraft experimenters could be encouraged to analyze their data in terms of the four seasons it seems possible that valuable clues to the physical mechanisms involved in the effects of solar activity on the weather might result.

The investigations described above represent a tiny fraction of the voluminous literature. I do not claim that they are necessarily the most significant. Indeed, it is quite clear that the most important papers on the subject of solar activity and the weather remain to be written. It appears reasonable to expect that the next few years may see more solid progress than has occurred in the previous 75-year interval.

THE SOLAR-INTERPLANETARY MAGNETIC SECTOR STRUCTURE

Having criticized the existing literature as being fragmented, disconnected and unrelated, I would like to suggest a possible remedy. We should utilize the large advances in solar-terrestrial physics that have occurred during the past decade due to the advent of spacecraft, much improved ground-based observations, and the availability of large computers. A common organizing influence to which many of the existing investigations could be related is the solar and interplanetary magnetic sector structure. I will give a brief description of this structure, and then comment on its possible advantages for investigations of solar activity and the weather. The following discussion is taken from Wilcox et al. (1973b).

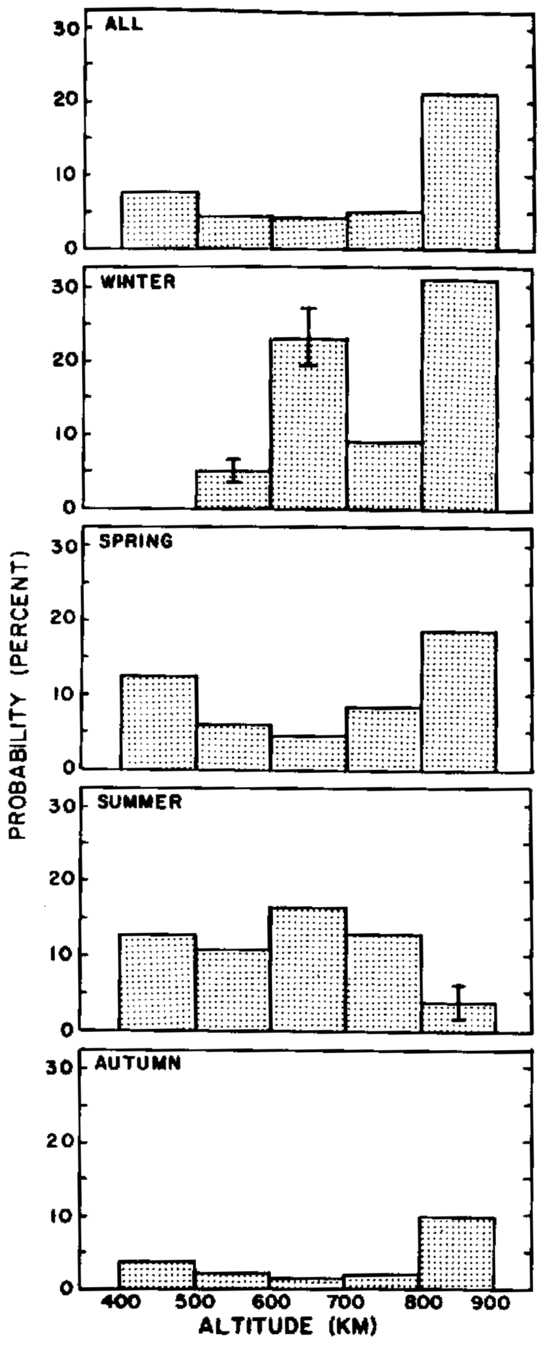

Figure 8. Probability of 2.3-keV electron precipitation being field-aligned for the four seasons as a function of altitude in the mean local time interval of 22 hours to 01 hour. The seasons are defined as equal time intervals around the equinoxes and the solstices. During winter at high altitudes the probability is much larger than during the other seasons. (Berko and Hoffman, 1973).

Figure 9 shows spacecraft observations of the polarity (away from or toward the sun) of the interplanetary magnetic field observed near the earth during two and one-half solar rotations. The plus (away) and minus (toward) signs at the periphery of the figure represent the field polarity during three-hour intervals. The four Archimedes spiral lines coming from the sun represent sector boundaries inferred from the spacecraft observations. Within each sector the polarity of the interplanetary field is predominantly in one direction. The interplanetary field lines are rooted in the sun, and so the entire field pattern rotates with the sun with an approximately 27-day period. The solar magnetic sector structure is extended outward from the sun by the radially flowing solar wind. The sector boundaries are often very thin, sometimes approaching a proton gyroradius in thickness. The time at which such boundaries are swept past the earth by the solar wind can therefore often be defined to within a fraction of an hour.

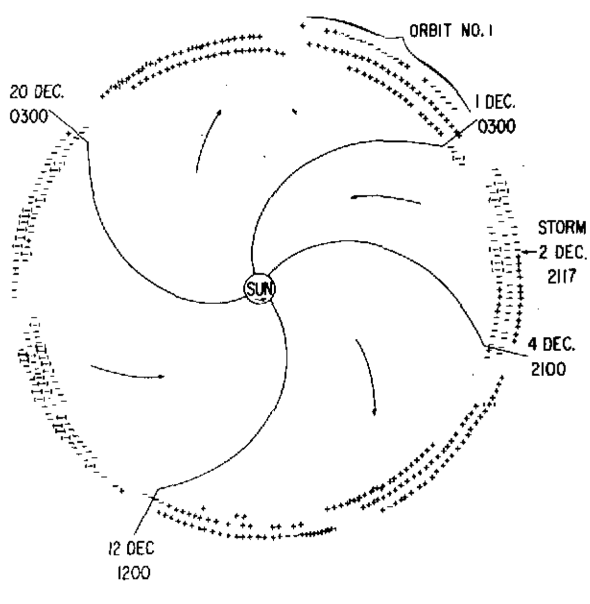

Figure 9. The inner portion of the figure is a schematic representation of a sector structure of the interplanetary magnetic field that is suggested by observations obtained with the IMP-1 spacecraft in 1963. The plus signs (away from the sun) and minus signs (toward the sun) at the circumference of the figure indicate the direction of the measured interplanetary magnetic field during successive 3-hour intervals. The deviations about the average streaming angle that are actually present are not shown (Wilcox and Ness, 1965).

What would a sector boundary shown in Figure 9 look like on the visible solar disk? Wilcox and Howard (1968) have compared the interplanetary field observed by spacecraft near the earth with the solar photospheric magnetic field deduced from the longitudinal Zeeman effect measured at the 150-foot solar tower telescope at Mount Wilson Observatory. This analysis suggested that an average solar sector boundary is similar to the schematic shown in Figure 10. The boundary is approximately in the north-south direction over a wide range of latitudes on both sides of the equator. A large area to the right of the boundary has a large-scale field of one polarity and a large-scale region to the left of the boundary has a field of the opposite polarity.

Suppose we observe the mean solar magnetic field when the configuration is as shown in Figure 10. The mean solar magnetic field is defined as the average field of the entire visible solar disk, that is, the field of the sun observed as though it were a star. In the circumstances shown in Figure 10, such an observation would yield a field close to zero, since there would tend to be equal and opposite contributions from the left and right sides of the figure. One day later the boundary will have rotated with the sun 13° westward, and the visible disk will be dominated by the sector at the left in Figure 10. A mean field observation will now yield a field having the polarity appropriate to the dominant sector. This same polarity will be observed during several subsequent days, until the next sector boundary passes central meridian and reverses the polarity of the observed mean solar field.

Figure 11 shows a comparison of the mean solar field observed at the Crimean Astrophysical Observatory with the interplanetary magnetic field observed with spacecraft near the earth (Severny et al., 1970). In this comparison, the mean solar field has been displaced by four and one-half days to allow for

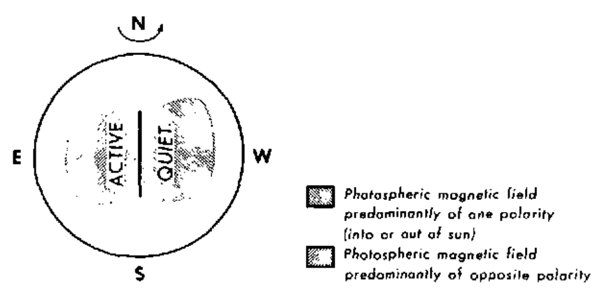

Figure 10. Schematic of an average solar sector boundary. The boundary is approximately in the north-south direction over a wide range of latitude. The solar region to the west of the boundary is unusually quiet and the region to the east of the boundary is unusually active (Wilcox, 1971).

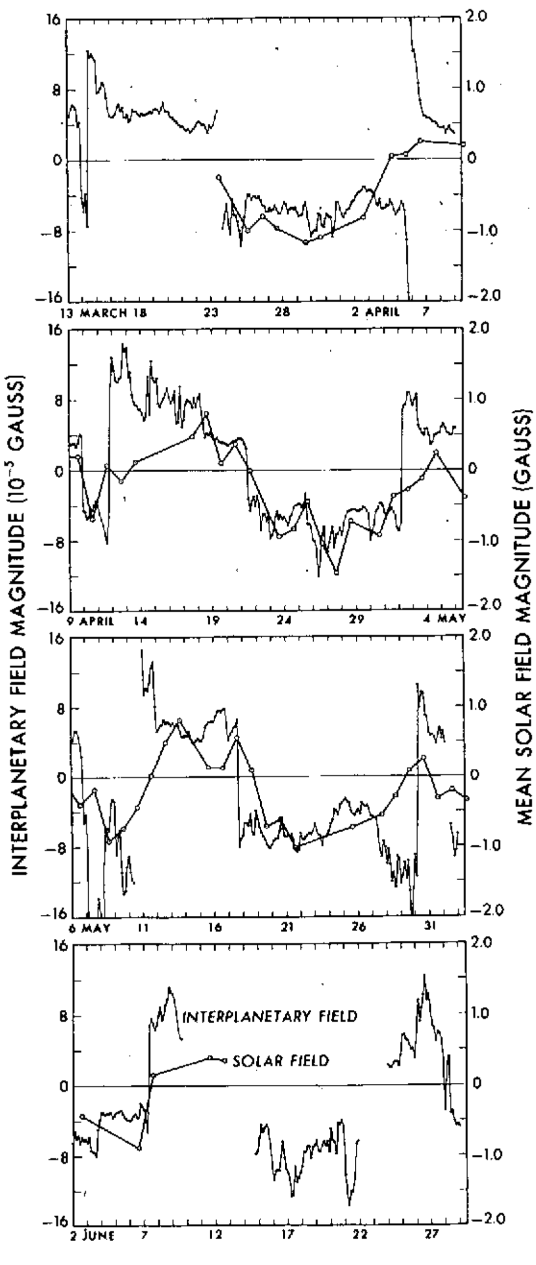

Figure 11. Comparison of the magnitude of the mean solar field and of the interplanetary field. The open circles are the daily observations of the mean solar field, and the dots are 3-hour average values of the interplanetary field magnitude observed near the earth. The solar observations are displaced by 4-1/2 days to allow for the average sun-earth transit time. The abscissa is the time of the interplanetary observations (Severny et al., 1970).

the average transit time from near the sun to the earth of the solar wind plasma that is transporting the solar field lines past the earth. We see in Figure 11 that in polarity and also to a considerable extent in magnitude the interplanetary field carried past the earth is very similar to the mean solar magnetic field. If we use the observed interplanetary field to investigate effects on the earth's weather, we are using a structure that is clearly of solar origin but is observed at precise times near the earth.

In addition to the sharp, well-defined change of polarity at the boundary, the sector structure has a large-scale pattern. During several days before a boundary is observed to sweep past the earth (or equivalently we may say during several tens of degrees of heliographic longitude westward of a boundary) conditions on the sun, in interplanetary space, and in the terrestrial environment tend to be quieter than average. Similarly after the boundary these conditions tend to be more active than average. A specific example of this is shown in Figure 12, which shows a superposed epoch analysis of the average effect on the geomagnetic activity index Kp as sector boundaries sweep past the earth. In the days before a boundary, the average geomagnetic activity has a monotonic decline to a minimum about one day before the boundary. Activity then

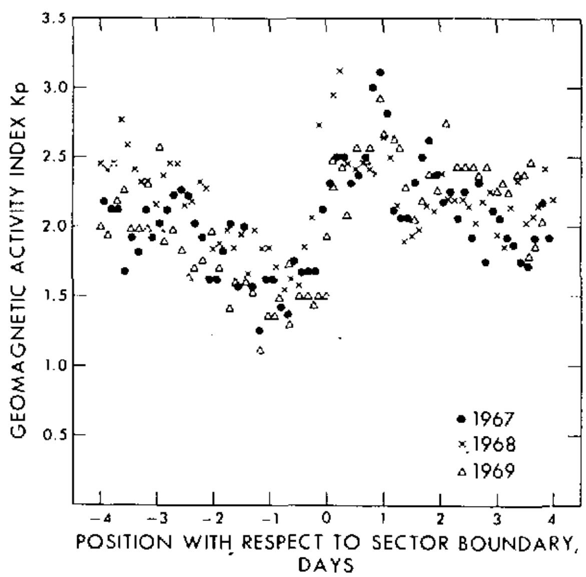

Figure 12. Superposed epoch analysis of the magnitude of the planetary magnetic 3-hour range indices Kp as a function of position with respect to a sector boundary. The abscissa represents position with respect to a sector boundary, measured in days, as the sector pattern sweeps past the earth (Wilcox and Colburn, 1972).

rises to a peak a day or two after the boundary, and then resumes its decline (Wilcox and Colburn, 1972). The Van Allen radiation belts "breathe" inward and outward as the sector structure sweeps past the earth (Rothwell and Greene, 1966). Several other examples of the large-scale geomagnetic response to the sector structure have been given by Wilcox (1968). We emphasize that although the moment at which a sector boundary is carried past the earth provides a well-defined timing signal, the terrestrial effects are related for the most part to the large-scale structure existing for several days on each side of the boundary.

From the above discussion, it appears reasonable to use the solar magnetic sector structure in an investigation of possible effects on the earth's weather. The use of the sector structure for this purpose has several advantages. We are using a fundamental large-scale property of the sun. There can then be no doubt that any observed atmospheric response to the passing of a sector boundary is ultimately caused by the solar magnetic sector structure. We emphasize that "solar magnetic sector structure" is a name for the entire structure discussed above. When we say that an atmospheric response is caused by the solar magnetic sector structure, we include possibilities that the effect has been transmitted through interplanetary space in the form of magnetic fields, solar wind plasma, energetic particles or radiation. Similarly, an atmospheric effect observed in the troposphere may flow through the higher atmospheric layers in an exceedingly complex manner.

We discuss some further advantages of the sector structure for such investigations. In the sense discussed above, a tropospheric response does not have its ultimate cause in other atmospheric processes. Some earlier investigations of solar activity and the weather have been criticized in this respect by Hines (1973). Because of the four- or five-day transit time of the solar wind plasma from the sun to the earth, we can have, by observing the mean solar magnetic field, a four- or five-day forecast of that time at which a sector boundary will sweep past the earth. By improving the solar observation procedure, we may be able to detect a sector boundary two or three days after it has rotated past the eastern limb of the sun. This would add an additional four or five days to the forecast interval.

From one solar rotation to the next, the sector structure usually does not change very much. In the course of a year there are often significant changes in the sector structure, which appears to have significant variations through the 11-year sunspot cycle (Svalgaard, 1972). All of these regularities and recurrence properties may be of significant assistance in forecasting. As the solar magnetic sector structure and its interplanetary and terrestrial consequences become better understood in the coming years, the possibilities of using solar data in weather forecasting should also improve.

A list of observed and well-defined sector boundaries is given in Appendix 2. If it were possible for investigators in this field to agree on the use of this list for at least one small part of their investigations, an important element of cohesiveness and interaction might be added to the literature.

Having started with a quotation from Bigelow written in 1898, I would like to end with a quotation from E. N. Parker from the Calgary Conference on Solar Terrestrial Relations in 1972:

> The information on hand indicates a strong and important connection between geomagnetic activity and weather. So if the statistics need improving, let us improve them through further studies. If a physical connection is missing, then we have before us the fascinating task of discovering it. Then perhaps in a few years we can bring a significant improvement to the forecasting of weather in the populated areas of Canada and the United States. We may suppose that a similar connection between geomagnetic activity and the formation of storms exists in other parts of the world too. And can be discovered if sought after.

ACKNOWLEDGMENTS

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APPENDIX 1

CONFERENCE ON SOLAR-ATMOSPHERIC RELATIONSHIPS

The first All-Union Conference on the Problem "Solar-Atmospheric Relationships in the Theory of Climate and Weather Forecasting" was held recently in Moscow. It was called on the initiative of the Main Administration of the Hydrometeorological Service of the USSR Council of Ministers. Scientific specialists from the USSR Hydrometeorological Center; Main Astronomical Observatory, USSR Academy of Sciences; Institute of Terrestrial Magnetism; Ionosphere and Radio Wave Propagation, USSR Academy of Sciences; Main Geophysical Observatory; Arctic and Antarctic Scientific Research Institute; Central Aerological Observatory; Institute of Biology of Internal Waters, USSR Academy of Sciences; Marine Hydrophysical Institute Academy of Sciences, Ukrainian SSR; Institute of Applied Geophysics; and Leningrad and Kazan' State Universities; as well as the Advanced Marine Engineering Institute imeni Admiral S. O. Makarov; the Scientific Research Heliometeorological Station, Gornaya Shoriya; and the Kherson Agrometeorological Station, presented different reports at its sessions.

Fifty reports and communications were presented at the conference, which lasted three days. Representatives of different scientific research institutes and laboratories participated in their discussion.

In a lengthy resolution, the conference noted that investigations of different aspects of the "Sun-Earth's Atmosphere" problem investigated over a period of several decades in the USSR and abroad make it possible to assert with assurance that solar activity and other space-geophysical factors exert a substantial influence on atmospheric processes. Allowance for these factors is of great importance in preparing weather forecasts.

It was noted at the conference that the Soviet scientists M. S. Eygenson, V. Uy. Vize, L. A. Vitel's, B. M. Rubashov, A. I. Ol', I. V. Maksimov, A. A. Girs, T. V. Pokrovskaya, M. N. Gnevyshev, A. V. D'yakov, P. P. Predtechenskiy, E. R. Mustel' and R. F. Usmanov have made a substantial contribution to study of these problems. Many interesting and promising investigations have been made by the younger generation of scientists.

While noting the considerable attainments of Soviet science in solving the problem of solar-terrestrial relationships, and in taking into account their role in the practical activity of the USSR Hydrometeorological Service, the conference nevertheless pointed out serious shortcomings.

For example, in the USSR Hydrometeorological Service and in the USSR Academy of Sciences there is still no organization for coordinating and planning work of solar specialists or for putting into practice the results already achieved by them. We have not properly organized the collection, processing, and routine use of solar and geophysical information in weather forecasting work. As a result, in the development and improving of forecasting methods allowance is unfortunately not made for the role of solar-atmospheric relationships; they are usually ignored when preparing weather forecasts by synoptic and numerical methods.

Accordingly, the conference deemed it desirable to broaden work on the study of the influence of a complex of space-geophysical factors on the atmosphere and weather, one of the most important problems facing the USSR Hydrometeorological Service. The conference has laid out a broad program of investigations, for these purposes using the latest instruments, rockets, space vehicles, electronic computers, and so on.

In the conference's resolution it was especially noted that there must be the fastest possible training of highly skilled specialists on the problem "Sun-Lower Atmosphere" through the graduate-school level; there is also an urgent need for organizing annual courses on heliometeorology for workers in scientific, academic, and operational units of the USSR Hydrometeorological Service.

Beginning with 1973 plans call for publication of specialized collections of articles on heliometeorology and broadening of publication of materials on solar-terrestrial relationships in the journals Meteorologiya i Gidrologiya and Fizika Atmosfery i Okeana. The Hydrometeorological Center USSR, Main Geophysical Observatory and Arctic and Antarctic Institute have been delegated the task of generalizing investigations on this problem and preparing a systematic manual for operational workers in the USSR weather forecasting service.

The conference deemed it desirable to create in the key institutes of the Hydrometeorological Service a network of heliometeorological stations (observatories) and at some universities and hydrometeorological institutes—departments of solar-terrestrial relationships. Solar specialists expect great assistance from the institutes of the USSR Academy of Sciences and the academies of science of some union republics, particularly in the plan for forecasting solar activity.

Considering the results of the First All-Union Conference, it has been decided to issue a collection of articles by its participants and in the future to hold such conferences regularly, every two or three years, and in the time intervals between them to hold working conferences on individual aspects of the problem.

In its resolution the conference especially noted the positive role which was played by discussion of the problem of solar-terrestrial relationships and their prediction on the pages of the newspapers Sel'skaya Zhizn', Pravda, and Literaturnaya Gazeta (June-October 1972). The questions raised in the press and the critical comments made by the newspapers have favored a broader discussion of this problem and its role in weather forecasting.

The conference was concluded by words from Academician Ye. K. Fedorov, chief of the Main Administration of the Hydrometeorological Services of the USSR Council of Ministers.
(Excerpts: "Sun, Climate, Weather," by B. Lesik; Moscow, Sel'skaya Zhizn', November 11, 1972, p. 2)

APPENDIX 2

LIST OF OBSERVED AND WELL-DEFINED SECTOR BOUNDARIES

The date, sign change (+ away, - toward), and time (in three-hour intervals) is given for all observed sector boundaries with at least four days of opposite field polarity on each side of the boundary. The notation 8-1 means that the boundary occurred between the last three-hour interval of that day and the first three-hour interval of the next day.

Year	Day of Year	Sign	Date	Time
1962	253	+, -	September 10	8-1
	269	-, +	September 26	3-4
	281	+, -	October 8	4-5
	293	-, +	October 20	8-1
1963	336	-, +	December 2	8-1
	346	+, -	December 12	4-3 (gap)
	354	-, +	December 20	1-2
1964	007	+, -	January 7	7-8
	016	-, +	January 16	2-2 (gap)
	023	+, -	January 23	3-4
	035	+, -	February 4	2-3
	284	-, +	October 10	6-7 (1 day gap)
	291	+, -	October 17	7-8
	297	-, +	October 23	6-8 (1 day gap)
	306	+, -	November 1	5-6
	312	-, +	November 7	2-1 (gap)
	320	+, -	November 15	5-6
	325	-, +	November 20	3-2 (gap)
	332	+, -	November 27	7-8
	341	-, +	December 6	4-5
	345	+, -	December 10	8-1
	349	-, +	December 14	8-1
	361	+, -	December 26	1-2
1965	002	-, +	January 2	1-2
	008	+, -	January 8	1-2
	012	-, +	January 12	2-3

Year	Day of Year	Sign	Date	Time
1965	032	+, -	February 1	8-1
	125	+, -	May 5	4-5
	153	+, -	June 2	8-1
	161	-, +	June 10	2-3
	230	-, +	August 18	7-6 (gap)
	235	+, -	August 23	5-7 (gap)
	259	-, +	September 16	2-3
1966	001	+, -	January 1	6-7 (1 day gap)
	032	+, -	February 1	4-5
	043	-, +	February 12	2-3
	062	+, -	March 3	3-4
	067	-, +	March 8	2-3
	089	+, -	March 30	2-3
	099	-, +	April 9	1-2
	127	-, +	May 7	8-1
	249	-, +	September 6	5-6
	257	+, -	September 14	6-7
	276	-, +	October 3	6-7
	285	+, -	October 12	2-3
	303	-, +	October 30	5-6
	312	+, -	November 8	4-5
	331	-, +	November 27	7-8
	338	+, -	December 4	3-4
1967	001	+, -	January 1	7-8
	013	+, -	January 13	3-4
	018	-, +	January 18	2-3 (1 day gap)
	081	-, +	March 22	7-8
	216	-, +	August 4	5-6
	242	-, +	August 30	2-3 (1 day gap)
	249	+, -	September 6	6-7
	270	-, +	September 27	3-4
	276	+, -	October 3	1-2
	297	-, +	October 24	2-3
	324	-, +	November 20	4-5
	338	+, -	December 4	5-6

Year	Day of Year	Sign	Date	Time
1968	001	+, -	January 1	6-5 (gap)
	028	+, -	January 28	8-1
	042	-, +	February 11	3-4
	057	+, -	February 26	6-7
	070	-, +	March 10	4-5
	083	+, -	March 23	5-6
	096	-, +	April 5	7-8
	112	+, -	April 21	3-4
	123	-, +	May 2	1-2
	138	+, -	May 17	5-6
	185	-, +	July 3	3-4
	191	+, -	July 9	8-1
	199	-, +	July 17	4-5
	207	+, -	July 25	4-5
	213	-, +	July 31	7-8
	226	-, +	August 13	7-8
	234	+, -	August 21	2-3
	263	+, -	September 19	2-3
	290	+, -	October 16	5-6
	318	+, -	November 13	2-3
	334	-, +	November 29	6-8 (gap)
	345	+, -	December 10	2-3
	359	-, +	December 24	6-7
1969	006	+, -	January 6	5-6
	023	-, +	January 23	8-1
	033	+, -	February 2	5-6
	050	-, +	February 19	2-3
	090	+, -	March 31	6-7
	110	-, +	April 20	7-1 (gap)
	119	+, -	April 29	3-4
	127	-, +	May 7	6-3 (gap)
	132	+, -	May 12	8-2 (gap)
	138	-, +	May 18	6-7
	147	+, -	May 27	1-2
	165	-, +	June 14	3-4
	192	-, +	July 11	2-3
	202	+, -	July 21	5-6
	219	-, +	August 7	6-7
	248	-, +	September 5	3-4

Year	Day of Year	Sign	Date	Time
1969	303	-, +	October 30	8-1
	330	-, +	November 26	5-6
	343	+, -	December 9	1-2
	356	-, +	December 22	7-8
1970	040	-, +	February 9	7-8
	067	-, +	March 8	8-1
	120	-, +	April 30	3-4
	131	+, -	May 11	6-7
	158	+, -	June 7	6-7
	243	+, -	August 31	8-5 (gap)
	309	-, +	November 5	3-4
	328	+, -	November 24	3-4

N74-29075

MAGNETOMETEOROLOGY: RELATIONSHIPS BETWEEN THE WEATHER AND THE EARTH'S MAGNETIC FIELD

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A comparison of meteorological pressures and the strength of the earth's magnetic field suggests that the magnetic field exerts, through some unknown process, a controlling influence on the average pressure in the troposphere at high latitudes (King, 1974). For example, the contour pattern showing the average height of the 500-mb level in the northern hemisphere during winter and the contours of constant magnetic field strength are very similar. There are two regions in the northern hemisphere where low pressure is associated with high magnetic intensity, whereas there is only one such region in the southern hemisphere. Figure 1 shows a comparison of the longitudinal variations at 60°N of averaged 500-mb data and magnetic intensity data. The similarity between the two curves is striking except that the magnetic-B curve is displaced about 25° towards the west. Certain features of the "permanent" atmospheric pressure system appear to have moved westwards during some decades of the present century and this movement may be associated with the westward drift of the non-dipole component of the earth's magnetic field. No attempt has been made, however, to correct the curves presented in Figure 1 to allow for this drift; in any case, the "phase" of the meteorological variation depends on the height and latitude to which it relates and further curves such as those in Figure 1 may well reveal the origin of the magnetic-field-dependent "driving force" on the atmosphere.

If the earth's magnetic field influences meteorological phenomena, long-term changes in the geomagnetic field should produce corresponding changes in climate. Figure 2 shows, in the upper section, the variation of the magnetic inclination at Paris since about 700 A.D. The lower section shows 50-year averages of the temperatures prevailing in central England since about 900 A.D. These two sets of data exhibit similar variations; the "Little Ice Age" (Lamb, 1966) that occurred in Britain during the period 1550 to 1700 A.D. is clearly associated with an epoch of high magnetic inclination. More work obviously needs to be done to determine the extent to which climatological changes are associated with magnetic field changes.

One possible way in which the earth's magnetic field may affect the weather is by its controlling influence on the precipitation of charged particles from the magnetosphere. In this context it is worth noting (King, 1973) that contours showing the average height of the 850-mb surface in July over the Canadian Arctic region during the period 1964 to 1972 are nearly parallel to

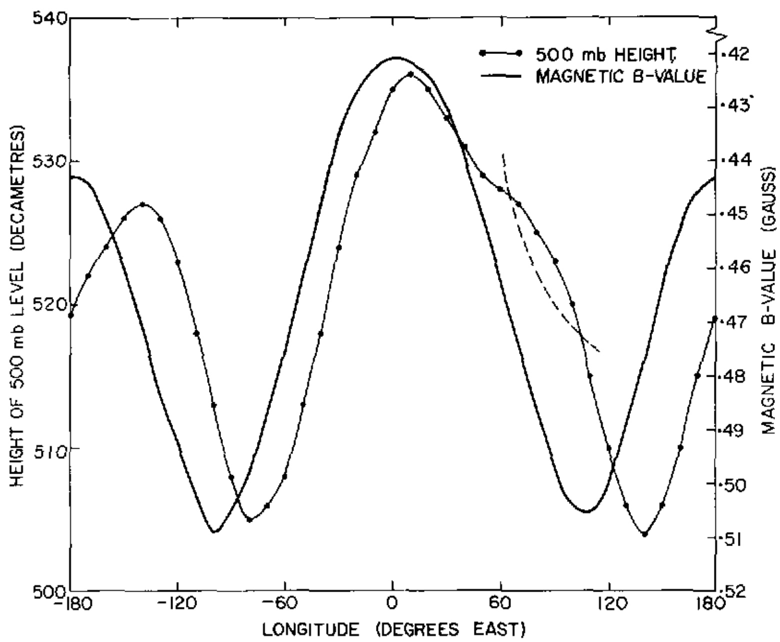

Figure 1. Curves showing the longitudinal variations at 60° N of the magnetic field strength and the height of the 500-mb level. The short broken curve draws attention to some of the pressure data which may be anomalously high (King, 1974). The magnetic data relate to 1965 and the meteorological data to the epoch 1918 to 1958.

contours of constant invariant latitude. The southeastern area of this region is, however, dominated by a ridge of high pressure that occurs at invariant latitudes between 76° and 79°; these are the latitudes at which solar wind particles penetrate into the atmosphere most easily, having gained access to the magnetosphere through the northern magnetospheric "cleft." While the single comparison described certainly does not prove that meteorological pressures can be affected by precipitated charged particles, it does point to the need for further studies of this kind.

It is well known that physical processes occurring in the magnetosphere and ionosphere vary with solar activity and many authors have conjectured that certain features of the weather vary during the solar cycle. It is interesting, for example, that the length of the annual "growing season" (defined as the

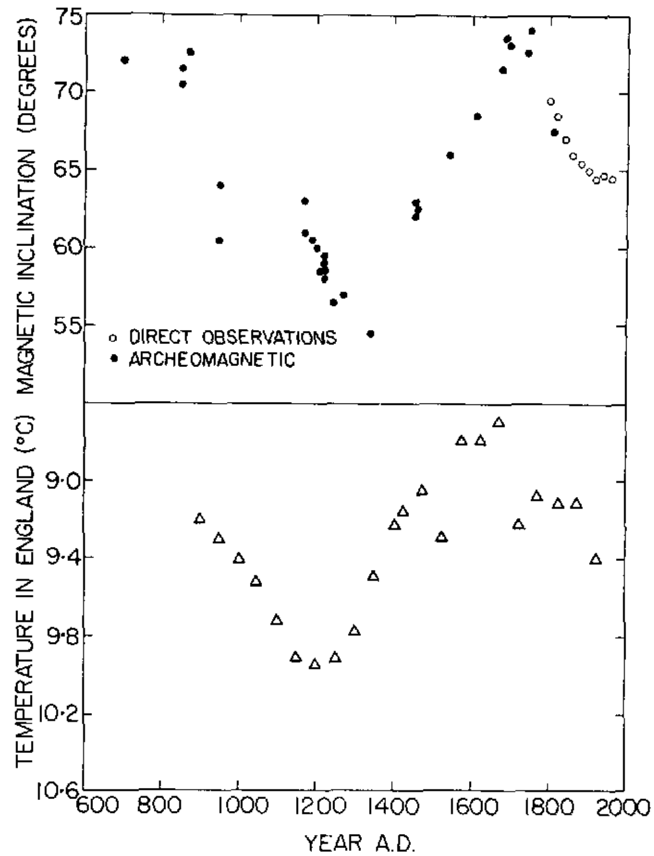

Figure 2. Upper section: Magnetic inclination at Paris since 700 A.D. (after Thellier, 1970). Lower section: Average temperature in central England since 900 A.D. (after Lamb, 1966).

portion of the year during which the air temperature at 1.25 m above ground exceeds 5.6°C) at Eskdalemuir (55°N, 03°W) in Scotland appears to have been influenced by changes of solar radiation associated with the solar cycle during the period of 1916 to 1969 (King, 1973). This conclusion is based on an apparent association between the length of the growing season and the yearly mean sunspot number: on average, the growing season is about 25 days longer near sunspot maximum than near sunspot minimum. A detailed comparison of the growing season and the solar data reveals the geophysically interesting fact that the growing season tends to be longest about a year after sunspot maximum.

Starr and Oort (1973) have made a comprehensive study of meteorological temperatures, using about ten million individual measurements of temperature, to derive the average temperature of the bulk of the atmospheric mass in the northern hemisphere for each of the 60 months between May 1958 and

April 1963. If the mean seasonal variation is subtracted from the monthly values to yield the residual temperatures, it is found that the spatially-averaged temperature fell by about 0.60°C during the five years. A comparison of the temperatures with the monthly mean sunspot numbers during the same period suggests that the declining temperature trend may be associated with the decline in solar activity. This suggestion is supported by the fact that smoothed variations of temperature and sunspot number are both relatively flat during the first and last years of the five-year period. Alternatively, it appears that the earth's magnetic dipole is moving slowly into the northern hemisphere (Nagata, 1965) and the magnetic field, is, on average, gradually increasing there; this behaviour may lead, in some unknown way, to the decrease of the northern hemisphere meteorological temperatures.

Many attempts have been made in the past to relate changes in solar radiation to meteorological phenomena; similarly, many different explanations have been offered of climatic changes. We fully appreciate the pitfalls that abound in this area of research and we are also cognizant of the speculative nature of the suggestion that spatial and temporal variations of the earth's magnetic field may be associated with climatic changes. Nevertheless, we believe that the evidence presently available is sufficient to warrant further investigations in the field of magnetometeorology.

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N74-29074

KIDSON'S RELATION BETWEEN SUNSPOT NUMBER AND THE MOVEMENT OF HIGH PRESSURE SYSTEMS IN AUSTRALIA

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Anyone who looks for a simple relation between sunspots and elementary meteorological quantities like rainfall or pressure is most unlikely to find it. At best one might conceivably find a connection with one of the broader atmospheric parameters like the number of waves in the circumpolar pattern or the rate at which that pattern rotates.

One connection between sunspots and the movement of pressure systems has been in the literature for a long time, but it does not seem to be generally known in the U.S.A. This was published by Kidson* in 1925 and may be described briefly as follows.

A characteristic of Australian weather is the regular march of high pressure systems across the continent in the direction of New Zealand. They cross the East Coast anywhere between latitudes 30° and 40° S as shown in Figure 1, which is taken directly from Kidson's paper.

Kidson defined a quantity R which was simply the N-S range of movement of the anticyclones in any one year. He showed that R is highly correlated and in phase with sunspot number as shown in Figure 2.

Other workers (Deacon and Das, private communication) have since extended these data to the 1950's, that is, for another thirty years, and the relationship stands up.

An interesting consequence of this can be seen in rainfall, if one is prepared to dig for it.

In the first place it will be clear from the above that if one looks for a 10- or 11-year period in the rainfall of Australian stations within the 30° to 40° S latitude belt, one will find a very complex situation; on investigation this is indeed found to be the case.

* Kidson, "Some Periods in Australian Weather," Bulletin No. 17, Bureau of Meteorology, Melbourne, March 1925.

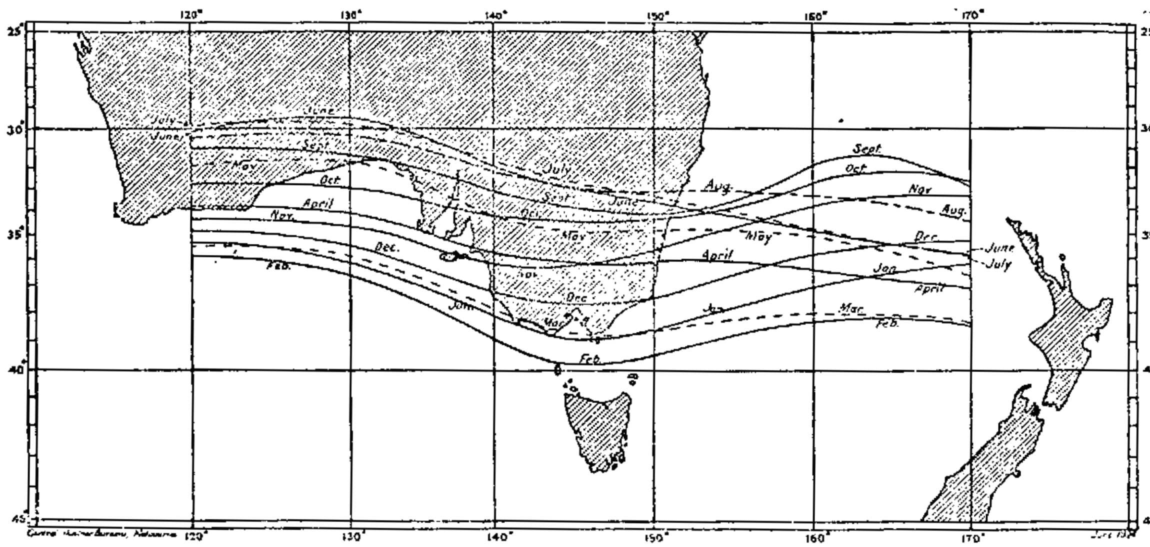

Figure 1. Mean monthly tracks of anticyclones.

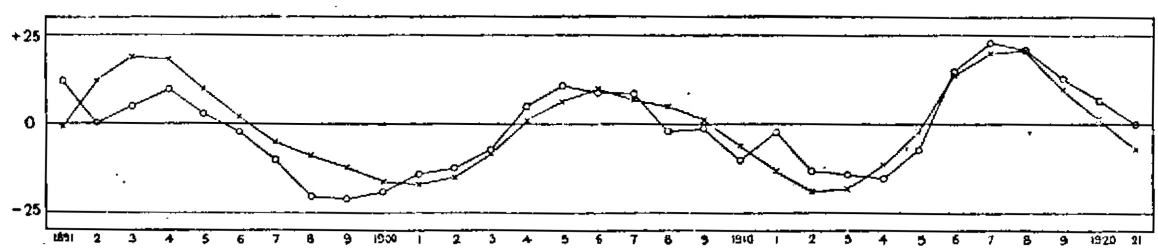

Figure 2. Consecutive three-yearly means of deviations from normal.

However, if one goes outside that range of latitudes, for example, Cairns at latitude 15° S and Hobart at 45° S and applies a numerical filter (8- to 15-year broadband filter) to the annual rainfall totals, the result shown in Figure 3 is obtained.

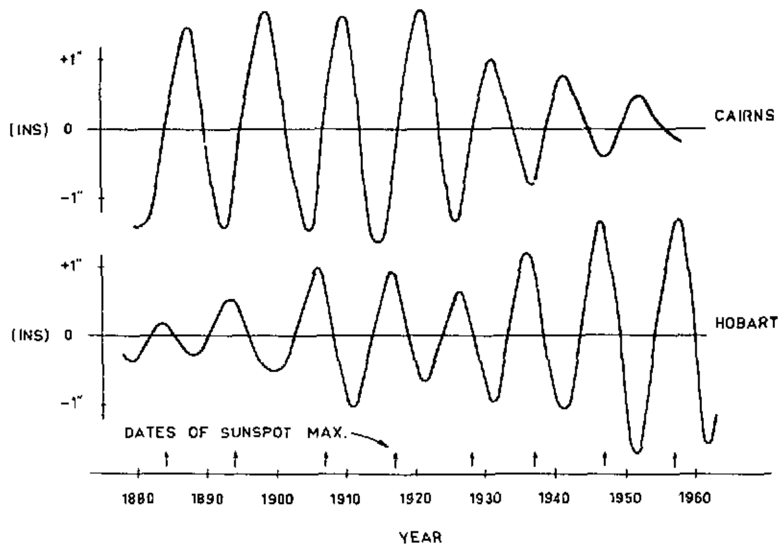

Figure 3. Annual rainfall totals at Cairns and Hobart.

That is, the 10- and 11-year components are almost exactly out of phase. This is in spite of the fact that within the year there is virtually no connection between Hobart weather and the weather of Cairns. The rainfall of Cairns is dominated by the southward movement of tropical cyclones down the Queensland coast and has virtually no winter rainfall. Hobart is influenced by low pressure systems off the southern ocean and has mostly a winter rainfall with a relatively dry summer. A few years ago, a paper was published in Russia showing that an exactly similar antiphase relationship existed between the rainfall of Archangel and Athens.

In conclusion, if a relation is found between sunspots and weather, it is likely to appear in the march of high and low pressure systems around the poles.

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF E. G. BOWEN

MR. DESSLER: Can you describe the frequency response of the filter that you ran the rainfall data through?

MR. BOWEN: The half-valleys of the filter are 15 and 8 years. There is not much of a flat top; essentially it's a bandpass filter.

MR. DESSLER: Well, the comment I would make — and I would have to test it — is that I think if you ran white noise through a filter like that you would get something that was in the middle, something between 8 and 15, close to 11-year periodicity that was amplitude-modulated; the amplitude would change with a periodicity of something like 7 cycles. Every 7 cycles you would go through a maximum or a minimum, and the data look consistent with running white noise through a filter like that.

MR. BOWEN: The answer is best given by the similar analyses I have done for rainfall data in the intermediate regions in Australia that don't show any effect like that at all.

N74-29077

PROPOSED GEOMAGNETIC CONTROL OF SEMIANNUAL WAVES IN THE MESOSPHERIC ZONAL WIND

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ABSTRACT

The polar semiannual oscillation in zonal wind can explain midwinter weakening of the polar vortex and the relatively short stratospheric and mesospheric summer easterlies. The phase of the wind oscillation is equinoctial, as is the phase of the semiannual component in magnetic storm activity. For a given altitude, the contours of amplitude of the semiannual wind oscillation have less variability in geomagnetic than in geographic coordinates. It is suggested that the polar wind oscillations are caused by the semiannual maxima in magnetic storm activity which lead to electron dissociation of O_2 into O, in turn increasing ozone more rapidly than the dissociation of N_2 destroys ozone, and thereby inducing a semiannual variation in the thermal and wind fields. This implies that geomagnetic processes may cause or affect the development of sudden warmings. As the tropical semiannual wind oscillation is symmetric about the geomagnetic equator, the same processes may also influence the location of the tropical wind wave.

INTRODUCTION

Two new distinct polar centers of the semiannual oscillation of the mesospheric zonal wind have recently been identified (Groves, 1972; Belmont et al., 1973). The well-known tropical center is centered near the geographic equator at about 45 km, while a northern center is near 60°N at about 65 km, and a southern is near 70°S at 60 km. Original attempts to explain the tropical oscillation attributed it to the semiannual variation of insolation at the equator due to changes of the solar zenith angle (Webb, 1966). This mechanism, however, would inherently demand equatorial symmetry which, in Figure 1, is not found to exist (Belmont and Dartt, 1973). Furthermore, energy and momentum considerations have shown that some other process is forcing this oscillation. Meyer's (1970) study of the dynamics of the tropical semiannual oscillation show that an eddy momentum flux by tidal motions could furnish the necessary energy. However, because of the rapid variations of tidal phase with altitude, he concludes that other mechanisms also probably contribute in driving the tropical wave. This will be considered later.

POLAR CENTER

The newly described polar center of the semiannual oscillation is of great interest for several reasons. It can help explain the long-observed weakening of the intense, winter polar westerlies as seen on time sections (Belmont and Dartt, 1970). This decrease in winter westerlies was attributed by Webb (1966) to the intrusion of the summer hemisphere easterlies into the winter hemisphere, that is, to the semiannual wave in the tropics, although no direct influence could be measured. The existence of the separate polar semiannual oscillation, however, can now directly explain this phenomenon as can be seen in Figure 2. This wave is also probably related to the winter polar sudden warmings.

The polar semiannual oscillation can also explain the relatively short duration of the stratospheric summer easterlies, as can be seen in Figure 2 where the annual (A) and semiannual (SA) are superposed on the long-term mean to produce a resultant (R) yearly cycle. Amplitude and phases used in the figure are for 55°N at 60 km, from Belmont et al. (1973). This short summer effect varies with location and altitude, being a function of the relative amplitude and phase lag between annual and semiannual waves.

POSSIBLE MECHANISMS

It is interesting that the phases of both the tropical and polar semiannual oscillations are equinoctial (Belmont and Dartt, 1973). While they are separated by more than a scale height in altitude, they could very well be influenced by the same mechanism because of their similarity of phase. No explanation has yet been offered for the polar wave. Its location, in the auroral zone, and its altitude, just below auroral heights, are intriguing however, and a possible relation should be examined. The semiannual component in magnetic storm activity also has equinoctial phase (Chapman and Bartels, 1940) and has recently been explained by Russell and McPherron (1973) as arising from the interaction between the magnetosphere and the interplanetary magnetic field. A coupling between the geomagnetic field and atmospheric circulation has long been accepted. The dynamo theory relating geomagnetic fluctuations to winds in the ionosphere was hypothesized long before direct observations were available, and is still accepted in modified forms (Fejer, 1965). Also, Flohn (1952)

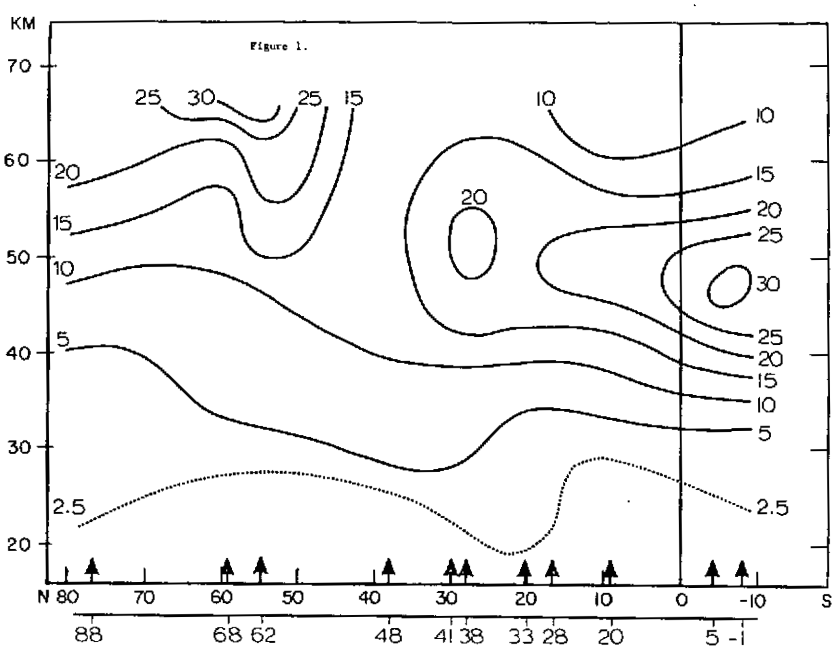

Figure 1. Amplitude of the semiannual wave in zonal wind (mps) for stations near 80°W. Arrows indicate rocket stations. Bottom scale is geomagnetic latitude.

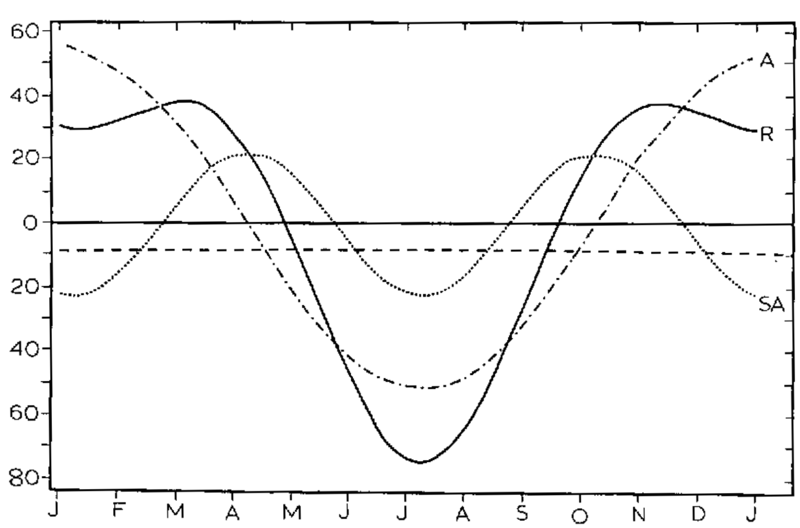

Figure 2. Yearly wind cycle (R) in mps resulting from addition of annual (A) and semiannual (SA) waves at 60 km at Primrose Lake (55° N).

demonstrated a striking similarity between the mean flow at 200 mb and the horizontal intensity of the geomagnetic field and between the mean position of the Inter Tropical Convergence Zone and the geomagnetic equator. Due to the extremely large energy involved, he concluded that the similarity was due to atmospheric influence upon the geomagnetic field although there is no apparent explanation for this. So in the ionosphere and the troposphere, for both short-period changes and the long-term mean, the atmosphere appears to influence the geomagnetic field. That the reverse applies to the mesosphere-stratosphere is suggested next.

In Figure 3 the amplitude of the semiannual wave at 50 km is plotted in geomagnetic mercator coordinates; Figure 4 shows the same data in geographic mercator coordinates. Note that the north-south variations of the contours are smaller in geomagnetic, rather than geographic, coordinates. Figures 5 and 6 present the same data in geomagnetic and geographic polar coordinates, respectively. Once again, note the greater symmetry of the contours in geomagnetic coordinates. This suggests that the semiannual oscillation is coupled with the geomagnetic, rather than geographic, coordinate system. Rocket stations depicted by dots on the figures and the corresponding amplitude of the semiannual wave at 50 km are listed in Tables 1 and 2. Amplitudes are as in Belmont et al. (1973), except for those new stations marked by an asterisk; the sources of original rocket data for these four additional stations are World Data Center A, Asheville, North Carolina, and the Pakistan Space and Upper Atmosphere Research Committee (1971).

Since the maximum of the semiannual wind oscillation coincides with that of the geomagnetic coordinate system, and as the phases of the semiannual wind and magnetic variations are the same, and since the magnetic storm semiannual variation is due to extra-terrestrial causes (Russell and McPherron, 1973), and thus not to the atmosphere, the coincidences require an explanation. Direct magnetic field control of the circulation at mesospheric altitudes can be rejected from energy considerations. However, the magnetic field might still indirectly influence the mesospheric circulation.

Large-scale circulation features, such as the semiannual wind oscillation, must be the result of large-scale temperature gradients. Joule dissipation heating of the lower thermosphere is a major heat source at high altitudes (Ching and Chiu, 1973; Hays et al., 1973) and could be the source that drove the meridional circulation postulated by Mayr and Volland (1971) from their analysis of the meridional component in meteor wind data. Joule dissipation, however, is generally important above 100 km, while the heat source driving the semiannual wind oscillation must be near 75 km. An empirical description of an observed heat source is shown in Groves (1972), as a polar maximum near 75 km in the semiannual temperature oscillation.

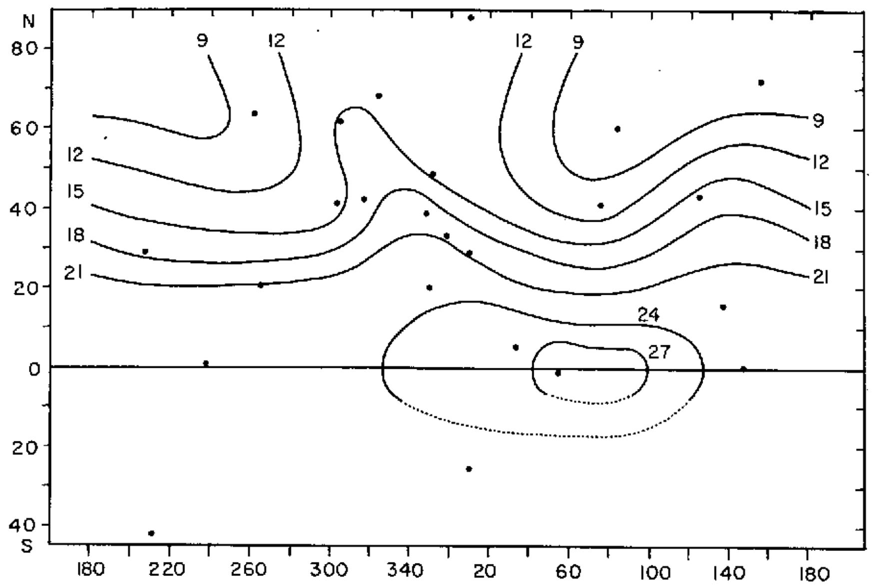

Figure 3. Amplitude (in mps) of the semiannual wave at 50 km, in geomagnetic Mercator coordinates. The amplitude of stations shown by dots is given in Tables 1 and 2.

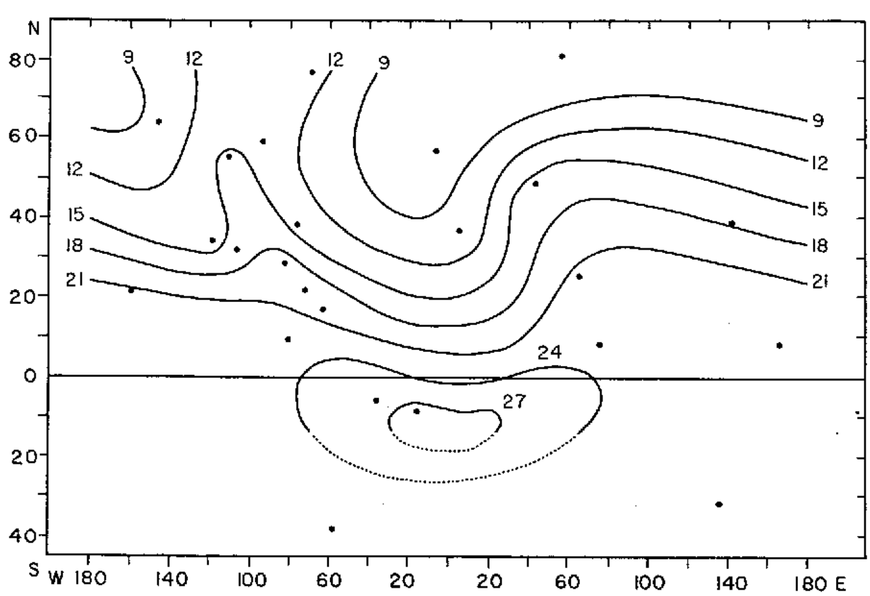

Figure 4. Same as Figure 3 in geographic Mercator coordinates.

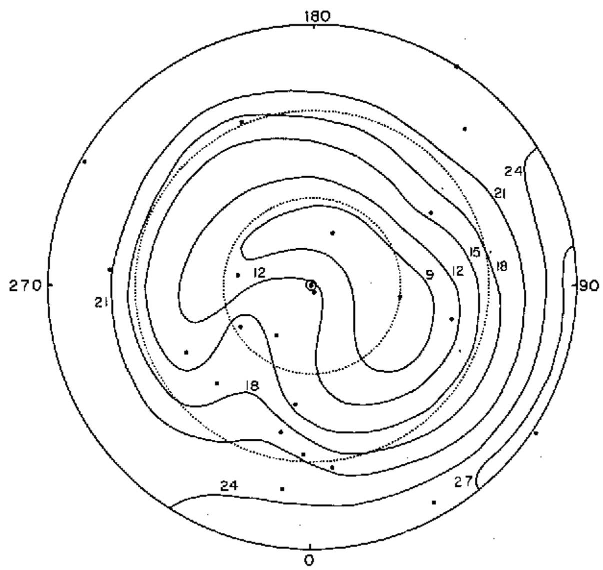

Figure 5. Same as Figure 3 in geomagnetic polar coordinates. The dotted latitudes are 30° and 60° .

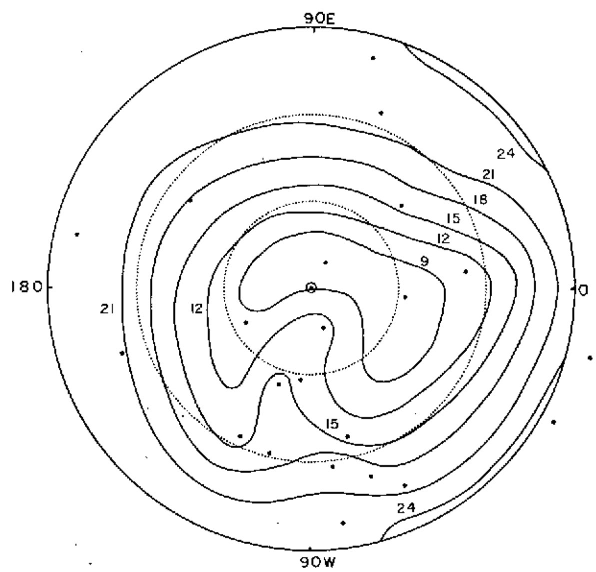

Figure 6. Same as Figure 3 in geographic polar coordinates. The dotted latitudes are 30° and 60°.

Table 1
Stations Near 80° W

	Latitude	Longitude	Geomagnetic Coordinates	Amplitude (m/s)
Thule	76° 33'N	68° 49'W	88°N 10°	12.1
Churchill	58° 44'N	93° 49'W	68°N 324°	12.4
Primrose Lake	54° 45'N	110° 03'W	62°N 305°	15.3
Wallops	37° 50'N	75° 29'W	48°N 351°	13.9
Cape Kennedy	28° 27'N	80° 32'W	38°N 347°	20.3
Grand Turk	21° 26'N	71° 09'W	33°N 357°	16.9
Antigua	17° 09'N	61° 47'W	28°N 10°	20.7
Fort Sherman	9° 20'N	79° 59'W	20°N 350°	22.1
Natal	5° 45'S	35° 10'W	5°N 34°	26.6
Ascension Island	7° 59'S	14° 25'W	1°S 55°	28.5

Table 2
Other Rocket Stations

	Latitude	Longitude	Geomagnetic Coordinates	Amplitude (m/s)
Heiss Island	80° 37'N	58° 03'E	72°N 156°	7.1
Fort Greely	64° 00'N	145° 44'W	64°N 261°	10.8
West Geirnish	57° 21'N	7° 22'W	60°N 84°	4.8*
Volgograd	48° 41'N	44° 21'E	43°N 125°	17.1
Ryori	39° 02'N	141° 50'E	29°N 207°	17.4*
Arenosillo	37° 06'N	6° 44'E	41°N 76°	10.9*
Point Mugu	34° 07'N	119° 07'W	41°N 302°	14.1
White Sands	32° 23'N	106° 29'W	42°N 317°	16.1
Sonmiani	25° 12'N	66° 45'E	16°N 137°	22.6*
Barking Sands	21° 54'N	159° 35'W	21°N 265°	21.1
Kwajalein	8° 42'N	167° 42'E	1°N 238°	22.8
Thumba	8° 32'N	76° 52'E	0° 146°	23.3*
Woomera	31° 58'S	136° 31'E	42°S 211°	9.6
Mar Chiquita	37° 45'S	57° 25'W	26°S 10°	15.4

* Stations added since Belmont et al. (1973).

A coupling of the magnetosphere and thermosphere with the mesosphere could occur however, through influence upon the radiation field as follows: The semiannual component in the occurrence of magnetic storms leads to semiannual auroral activity. Through particle precipitation associated with this activity, energy is dissipated in the lower thermosphere down to the mesopause. But, more importantly, the particle precipitation may lead, at these levels, to production of O through electron impact dissociation of O_2, which in turn increases ozone through three-body recombination (Maeda, 1968; Maeda and Aiken, 1968). This process, though, is somewhat compensated by production of N through electron impact dissociation of N_2 which in turn increases NO which increases destruction of ozone (Strobel et al., 1970). However, the influence of NO upon O_3 is small above 70 km (Hunt, 1973). This leads to a semiannual control of ozone, and through its absorption of UV, to a semiannual oscillation in the temperature and wind fields. Although enough measurements have been made to preliminarily identify an annual variation in ozone at these levels (Evans and Llewellyn, 1972), observational verification of a semiannual component in ozone is not yet available. We leave theoretical verification of this theory to atmospheric chemists and radiation physicists who are aware of the latest estimates of reaction rates and the many interdependent processes which are now being discussed so actively in the literature. If geomagnetic activity is indeed the cause of the polar semiannual wave, this implies it may thus influence the development of sudden warmings which are disturbances of the thermal field and which progress downward from about 50 km.

The tropical wind oscillation appears located closer to the geomagnetic than the geographic equator (Figures 1, 3 and 4). Also, note that the presently known extreme maximum of the tropical oscillation is centered near the anomalously weak magnetic field in the South Atlantic and Brazil. At tropical latitudes the most particle precipitation occurs in the region of relatively weakest magnetic field (Reagan and Imhof, 1970; Trivedi et al., 1973). Also, Cole (1971) suggested that near the equator increased electric field activity during terrestrial magnetic storms could lead to energy dissipation, with more energy dissipated in regions of relatively weak magnetic field at a given altitude. Could it be that the semiannual component in magnetic storm activity influences the tropical wind field so as to shift the tropical semiannual wind oscillation toward the geomagnetic equator? This could then help resolve the dynamic modeling problem encountered by Meyer (1970).

CONCLUSIONS

1. The polar semiannual wind wave can help explain the decrease in strength of the midwinter stratospheric and mesospheric westerlies, and the shorter summer season in the stratosphere.

2. The phases of both the polar and tropical semiannual wind oscillation are very similar to the phase of the semiannual component in magnetic storm activity and the amplitude, at a given level, of the semiannual wind oscillation appears more symmetric in geomagnetic, rather than geographic, coordinates.

3. It is suggested that the polar semiannual wind centers are caused by that UV heating of mesospheric ozone, which is contributed semiannually by particle precipitation during magnetic storms. The same process may influence the random occurrence of sudden warmings.

4. The tropical semiannual wind center may be influenced enough by similar processes to account for its apparent symmetry in the geomagnetic coordinate system.

These hypotheses are offered in the hope of stimulating investigation of the chemistry and dynamics of the mesosphere with regard to the semiannual variation in magnetic storm activity.

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CERTAIN REGULARITIES OF GEOMAGNETIC AND BARIC FIELDS AT HIGH LATITUDES

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The value of the north component, χ', of geomagnetic field at the stations, which get under cusps on the sunlit side of the magnetosphere, depends on the polarity of interplanetary magnetic field sectors. Under otherwise identical conditions, in the north hemisphere χ' is greater when the earth is in the positive sector, while in the south hemisphere, χ' is greater when the earth is in the negative sector (north-south asymmetry). The difference, $\Delta\chi'$, resulting from the change of sector polarities is greater in both hemispheres in spring than in autumn (spring-autumn asymmetry).

Similar regularities are revealed in the distributions of atmospheric pressure, ρ, in the near-earth layer at the conjugate stations Mould Bay and Dumont d'Urville in 1964.

Resemblance of regularities in the distribution of χ' and ρ is conditioned apparently by a common cause: a zonal magnetospheric convection and related circumpolar ionosphere current vortices which appear now in south, then in north hemispheres depending on the sector polarity.

During some phases of the solar activity cycle the sectors of one polarity are predominant for a long time. This may cause an accumulation of weak impulses of the same sign, conditioned by solar wind, which sometimes get in resonance with oscillation processes in the atmosphere and in the ocean, thus changing the course of the processes which determine the weather and climate.

The existence of a relation between the variations of magnetic field at the earth's surface in nearpole regions and the sector structure of interplanetary magnetic field (IMF) is generally accepted and is considered as the evidence of influence of the solar wind with its magnetic field on the processes proceeding in the magnetosphere.

The notion on outer display and physical essence of this relation, the idea about the so-called geomagnetic effect of IMF sector structure is given in the work by Wilcox (1972). This work, however, does not show the following two peculiarities of the relation between geomagnetic and interplanetary fields: north-south and spring-autumn asymmetry. The both peculiarities are important for understanding of the mechanism of solar-plasma magnetosphere interaction, and hence, for the study of solar-terrestrial relations. The essence of these peculiarities consists in the following:

At the stations which at day-time get under the magnetospheric cusps, at the geomagnetic latitude $\phi_c \approx \pm(78°-80°)$, the dependence of the earth's surface magnetic field on the polarity of IMF sectors (under otherwise identical conditions) is expressed by inequalities:

$$\begin{array}{ll} \text{in north hemisphere} & M\left(X_N^{1+}\right) > M\left(X_N^{1-}\right) \\ \text{in south hemisphere} & M\left(X_S^{1+}\right) < M\left(X_S^{1-}\right) \end{array} \qquad (1)$$

where $M\left(X_N^1\right)$ and $M\left(X_S^1\right)$ are the averaged for a certain interval of time values of north X^1 component of the geomagnetic field in Hakura's system of coordinates (Hakura, 1965) in south (S) and north (N) hemispheres, calculated separately for days with IMF directed away from the sun (+) and toward the sun (-). Thus, the geomagnetic effect of IMF sector structure is displayed in the fact that under otherwise identical conditions X' is greater : in north hemisphere - when the earth is within the positive sector of IMF, and in south hemisphere - when the earth is within the negative sector of IMF.

Inequalities (I) have the greatest values if the sample X' is made by near-midday hours of local magnetic time in summer. In the behaviour of (X') calculated from the data of all hours of the day, the following has been revealed : magnitudes $M\left(X_N^{1-}\right)$ and $M\left(X_S^{1+}\right)$ obtained as a result of a successive averaging of the data for two-months period keep their levels nearly unchanged during a year, while the magnitudes obtained by the same way $M\left(X_N^{1+}\right)$ and $M\left(X_S^{1-}\right)$ are changing regularly and forming an annual wave with the maximum in local summer. As in the behaviour of magnitudes $M(X')$ in north and south hemispheres similar features are observed at different IMF directions, then this peculiarity of the relation between geomagnetic field and interplanetary magnetic field is called "the north-south asymmetry". It is the evidence of an essentially different (depending on the sign of IMF sector) response of northern and southern parts of magnetosphere to the solar wind.

In both hemispheres the following inequalities are observed for the samples selected during equinoctial periods:

$$\begin{array}{l} \left[M\left(X_N^{1+}\right) - M\left(X_N^{1-}\right)\right]_{\text{III-IV}} > \left[M\left(X_N^{1+}\right) - M\left(X_N^{1-}\right)\right]_{\text{IX-X}} \\ \left[M\left(X_S^{1-}\right) - M\left(X_S^{1+}\right)\right]_{\text{III-IV}} < \left[M\left(X_S^{1-}\right) - M\left(X_S^{1+}\right)\right]_{\text{IX-X}} \end{array} \qquad (2)$$

Inequalities (2) show that the difference $\Delta X'$ appearing with the change of sector polarity (in other words, the magnitude of geomagnetic effect of IMF sector structure) in both hemispheres is greater in local spring than in autumn ("spring-autumn asymmetry").

Figure 1 represents the histograms of the geomagnetic field north component X' mean magnitudes in gammas for March-April and September-October 1964, for the stations Dumont d'Urville (above) and Mould Bay (below) of two three-hour groups: the beforenoon and the afternoon ones for the IMF directed away from the Sun and that one directed toward the Sun (shaded). Calculations of X' according to observations made at the stations X and Y (projections of horizontal component on geographical meridian and parallel) are made by the formulas:

for the station Dumont d'Urville $\quad X' = 0,87X + 0,49Y$

for the station Mould Bay $\quad X' = 0,69X + 0,72Y$

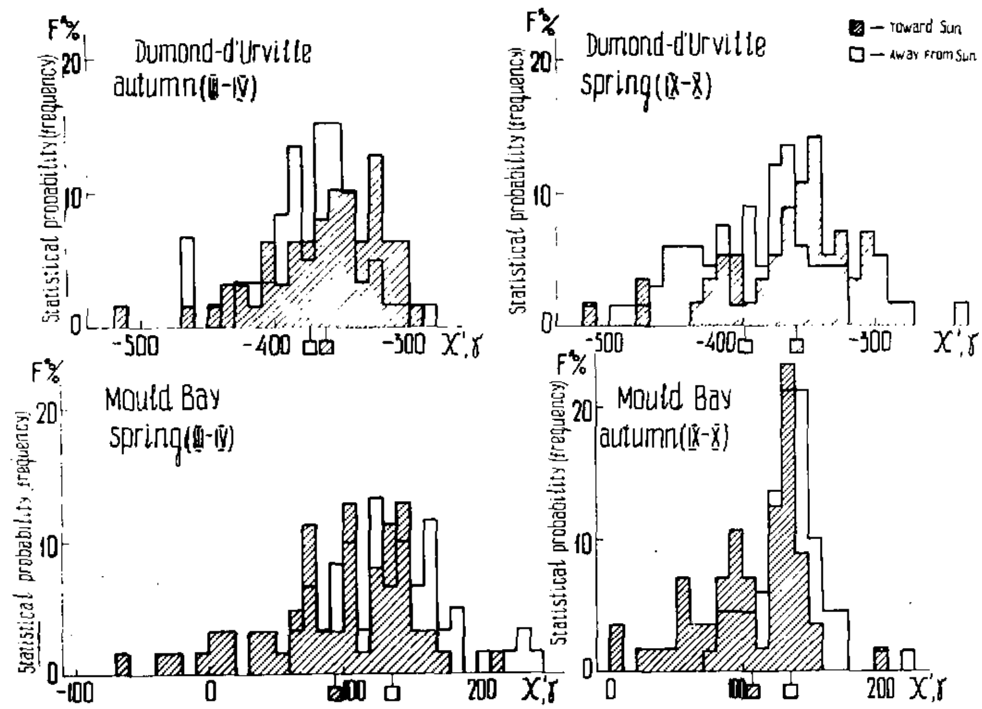

Figure 1. Histograms of the geomagnetic field north component X' mean magnitudes in gammas.

The both peculiarities of the relation of geomagnetic and interplanetary fields are represented at the histograms. Average values M (χ') given in the Table satisfy the inequalities (1) and (2).

III-IV	IX-X	III-IV	IX-X
		Dumont d'Urville	
Autumn r	Spring r	Autumn r	Spring r
$M(\chi^{1-}_S)$ -362	62-359 56	$M(\rho^-_S)$ 975.6 248	969.9 224
$M(\chi^{1+}_S)$ -374	59-398 66	$M(\rho^+_S)$ 979.7 240	984.1 264
$\Delta\chi'$ 12	39	$\Delta\rho$ 4.1	14.2
		Mould Bay	
Autumn r	Spring r	Autumn r	Spring r
$M(\chi^{1+}_N)$ 136	60 136 66	$M(\rho^+_N)$ 1013.5 240	1015.8 264
$M(\chi^{1-}_N)$ 95	62 107 56	$M(\rho^-_N)$ 1017.3 248	1016.9 224
$\Delta\chi'$ 41	29	$\Delta\rho$ 3.8	1.1

Here r is the sample size.

Control of the significance of the results of analysis by the method of mathematical statistics showed that the distribution of magnitudes χ' at positive and negative directions of IMF in 1964 were different with a probability no less than 99 percent (according to Kholmogorov's and Wilcox's criteria) both for March-April and September-October periods at the station Mould Bay. At the station Dumont d'Urville the distribution of χ' was different with the same probability (no less 99 percent) only for the period of local spring (September-October). For the period of local autumn (March-April) it was different with the probability no less 90 percent, according to Kholmogorov's criterion, and no less 94 percent—according to Wilcox's and Pirson's criteria. Thus, one may consider with much confidence that the distributions of χ' are various at different directions of IMF. The application of t - criterion to estimate the reliability of the difference between the average values χ' for these two samples showed that the average values χ' in local spring at both stations and in local autumn at the station Mould Bay differed with the probability equal to 99.9 percent. This difference in local autumn at the station Dumont-d'Urville is less probable (its probability is about 80 to 90 percent).

In the works by Smirnov (Смирнов , 1972), Mansurov et al. (Мансуров и др. 1972) and Wilcox et al. (1973) there are indications to a noticeable influence of IMF sector structure upon the near-earth atmospherical layers and upon the stratosphere. Therefore, the below-mentioned result of analysis of the atmosphere pressure data ρ in near-earth layer at magnetically conjugate stations Dumont d'Urville and Mould Bay (which can be expressed by inequalities (3) and (4) analogous to inequalities (1) and (2)) does not seem occasional. This dependence is of the form:

$$\begin{array}{ll} \text{in north hemisphere} & M\left(\rho_N^+\right) < M\left(\rho_N^-\right) \\ \text{in south hemisphere} & M\left(\rho_S^+\right) > M\left(\rho_S^-\right) \end{array} \quad (3)$$

and

$$\begin{array}{l} \left[M\left(\rho_N^-\right) - M\left(\rho_N^+\right)\right]_{III-IV} > \left[M\left(\rho_N^-\right) - M\left(\rho_N^+\right)\right]_{IX-X} \\ \left[M\left(\rho_S^+\right) - M\left(\rho_S^-\right)\right]_{III-IV} < \left[M\left(\rho_S^+\right) - M\left(\rho_S^-\right)\right]_{IX-X} \end{array} \quad (4)$$

where M (ρ) are the average values of atmospheric pressure for the stations of south (S) and north (N) hemispheres, calculated on eight synoptic terms per day separately for the days with positive (+) and with negative (-) polarity of sectors for the sample sizes for each pair of equinoctial months.

Figure 2 represents the histograms of the distribution of atmosphere pressure ρ values in millibars for March-April and September-October 1964 at the two stations for eight synoptical terms per day with the IMF directed toward the sun (shaded) and away from the sun. It is seen that the both peculiarities of pressure value distributions depending on IMF-structure (north-south and spring-autumn asymmetry) as well as in the case of χ' distribution (Figure 1) are clearly revealed. Average values $M(\rho)$ given in the Table satisfy the inequalities (3) and (4).

The control of reliability of the obtained results showed that the distributions of ρ are different during the equinoctial period at both stations with a probability no less than 99 percent (according to Kholmogorov's and Wilcox's criteria) when the IMF sector polarity is different.

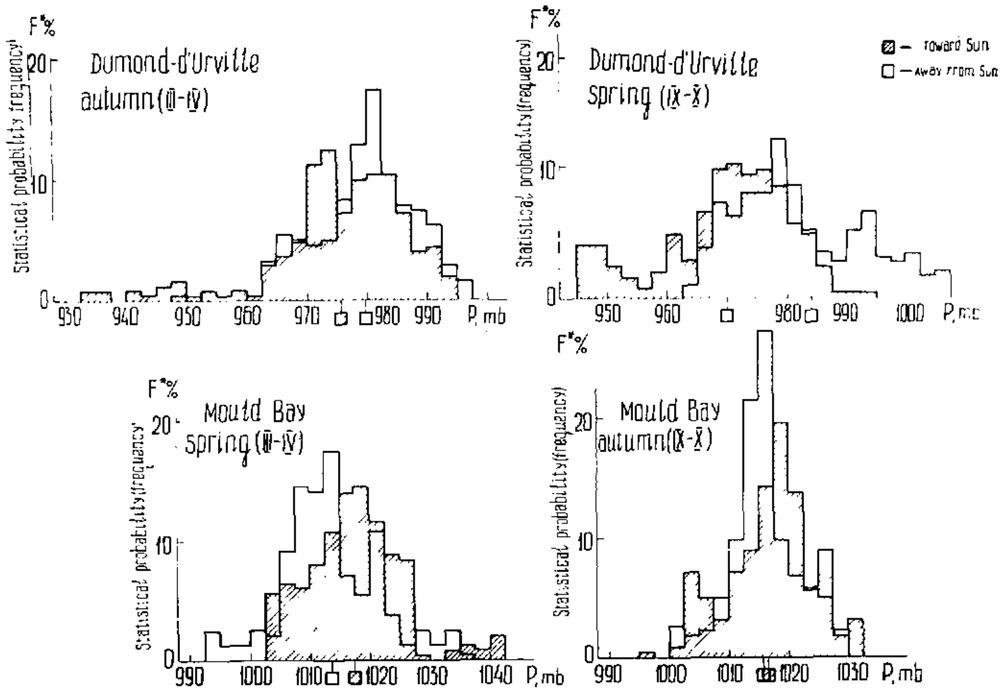

Figure 2. Histograms of the distribution of atmospheric pressure (P) values in millibars.

The estimation of difference between the average values of pressure for different IMF directions by means of t-criterion showed that average pressure values are different with the probability 99.9 percent in spring and in autumn at the station Dumont d'Urville and in spring (March-April) at the station Mould Bay. In autumn the average values ρ are different with the probability equal to 95 percent at the station Mould Bay.

The resemblance of distribution regularity of X' and ρ depending on the sign of IMF-sector at magnetically conjugate high-latitudinal stations may be the result of the influence of solar wind and its magnetic and electric fields upon the ionosphere, and the influence of ionosphere upon the neutral atmosphere. Apparently, there exist many mechanisms of such influence. The complex of geophysical phenomena which display relations with IMF sector structure (among which one may mention the absorption in auroral zones studied in detail by Hargreaves, 1969) implies that in these mechanisms an important role is played by bremsstrahlung radiation. Such an assumption was first made by Roberts and Olsen (1973) while they were explaining the revealed relation between the baric field and geomagnetic disturbances. According to Ioshida's et al. information (1971) that there is a north-south asymmetry in cosmic rays intensity which depends on IMF sector sign, our results are in agreement with Sazonov's (**Сазонов** , 1972) conception concerning the cosmic ray effects upon the atmosphere lower layers.

Smirnov (Смирнов , 1972) indicated that the relation between the thermobaric field of lower atmosphere and large-scale inhomogeneities of interplanetary medium tends to be revealed more distinctly at coast regions where the so-called "coast effects" are observed by Sen'ko (Сенько , 1959) and by Mansurov (Мансуров , 1958). It means that in the mechanism of relation between upper and lower parts of atmosphere, together with wave oscillation, which may occur as a result of the upper atmosphere heat and then may pass to the lower atmosphere, as assumed by Reshetov (Решетов , 1972) an essential role is played by electromagnetic induction. Therefore one may expect that during some phases of the solar activity cycle when the sectors of IMF of the same polarity are predominant for a long time (Svalgaard, 1972), weak impulses of one sign which appear by induction, may be accumulated, and, getting in resonance with oscillation processes in the atmosphere and in the ocean, may cause a change in the direction of air and oceanic flows which determine the weather and the climate. Such possibility ensues from the fact that the zonal magnetospheric convection appears now in one hemisphere, then in another, depending on the sign of IMF sector. The notion on zonal convection is given in Figure 3.

Figure 3 shows the distribution of vectors of ΔH difference $S_a^- - S_p^+$ for south hemisphere (above) and $N_a^+ - N_p^-$ for north hemisphere (below) between the meanhour values of horizontal component of the geomagnetic field, calculated separately for samples at positive (S_p^+ and N_a^+) and negative (S_a^- and N_p^-) directions of IMF for two equinoctial periods of 1964 of two-months duration.

In Figure 3 which shows the geomagnetic effect of the sector structure of IMF in horizontal component, the spring-autumn asymmetry of the effect is well seen, which is displayed in the baric field.

The authors are grateful to Dr. Wilcox and Dr. Roberts for their king attention to the work and discussion, as well as to other members of the Symposium Organizing Committee for being given the possibility to make this report.

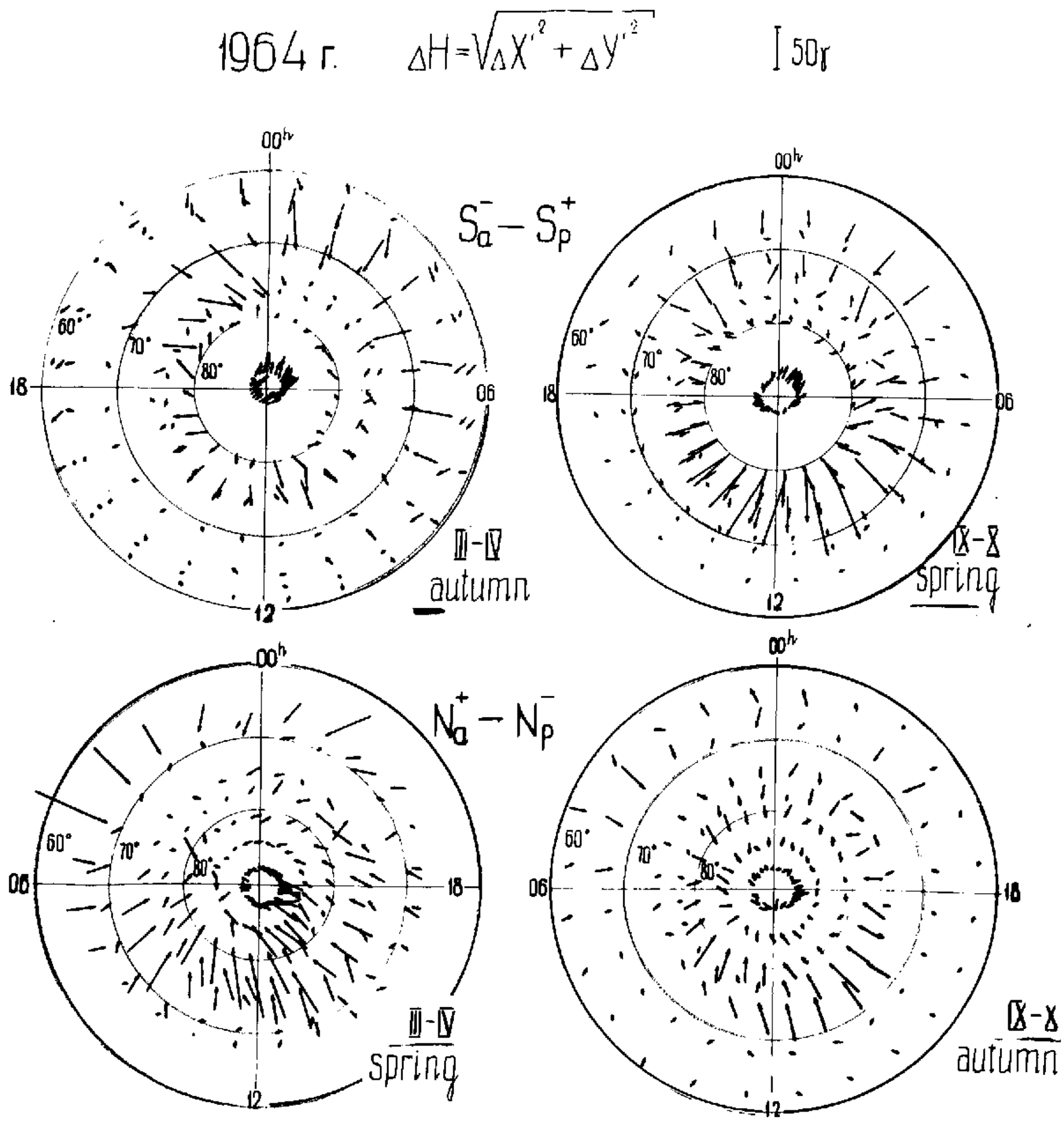

Figure 3. Geomagnetic effect of the sensor structure of IMF in horizontal component.

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ON POSSIBLE INTERACTIONS BETWEEN UPPER AND LOWER ATMOSPHERE

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ABSTRACT

Comparing geomagnetic data with data on tropospheric and stratospheric circulation characteristics, we find a statistically highly significant shrinking in areal extent of the stratospheric vortex from the third to the eighth day following a "geomagnetic storm." The meridionality of the 30,640-m contour line at 10 mb increases markedly from five to eight days after the storm.

During the contraction of the polar vortex edge, the mean height of the vortex central contour decreases only slightly. This indicates that a stratospheric warming event is associated with a steepening of the contour gradient rather than a warming over the entire area of the stratospheric polar vortex.

The troposphere reacts to these weak, but nevertheless significant stratospheric warming events by a shrinkage of the area of the 500-mb cold air pool. This shrinkage commences about three days after the stratospheric warming.

Our investigation also indicates that the energy input into the stratosphere which is received in conjunction with the geomagnetic disturbance has to come at a propitious time, that is, when the stratospheric-tropospheric circulation system is not already undergoing a major readjustment because of an inherent dynamic instability. It can be shown that the observed warming of the stratosphere that follows a geomagnetically disturbed key day, cannot be explained by simple radiation absorption.

INTRODUCTION

The complex reaction of the atmosphere to solar geomagnetic activity has become the subject of an increasing number of research studies. Macdonald and Roberts (1960) found that 300-mb troughs which enter or move into the Gulf of Alaska amplified several days after the earth was bombarded with unusually intense solar corpuscular emission. Macdonald and Roberts (1961) and Twitchell (1963) obtained similar results of trough intensification at the 500-mb level.

Reiter and Macdonald (1973) indicated that fluctuations in area of the tropospheric cold pool ($T \leq -30°C$ at 500 mb) and in size of the polar vortex at 10 mb are coupled by a feedback mechanism. They found that sudden warmings in the stratosphere tend to precede warmings in the troposphere, and a portion of this paper will investigate this stratospheric forcing further. Roberts and Olson (1973) indicated that 300 mb troughs over North America tended to intensify with a lag time from a geomagnetic event to maximum vorticity development of about five to seven days. They define a geomagnetic event as: a daily A_p index greater than or equal to 15 along with an increase of this value over the previous daily value at least as large as the monthly average value of A_p.

THE GEOMAGNETIC, STRATOSPHERIC, AND TROPOSPHERIC DATA AND THEIR INTERCOMPARISONS

The superposed epoch method was employed to investigate a possible relationship between geomagnetic activity and both the wintertime stratospheric polar vortex and the tropospheric cold pool. This method compares two sets of data: key events are parameterized and selected from one set, and the mean action or reaction of the other set surrounding these key events are noted. In this paper, 29 days surrounding each key event are used in each single epoch. These range from the 14th day preceding the event to the 14th day following it. These dates are noted as D_{-14}, D_{-13}, ..., D_{-1}, D_0, D_1, ..., D_{14}. The key event occurs on D_0.

Specifically, we employed a set of geomagnetic activity data to be used in determining the key events. We developed two separate sets of data of "reacting" events, one dealing with the polar troposphere and the other with the polar stratosphere. These three sets of data will be described first, and their comparisons and results using the superposed epoch method will follow.

THE DATA

To develop an objective method for determining a sudden increase in geomagnetic activity, we used the daily planetary geomagnetic activity index A_p, as published by the National Geophysical and Solar-Terrestrial Data Center. This is a daily global index of geomagnetic activity and is generally considered to be linear to its severity. Key dates of this activity, called "Geomagnetic Key Dates," were selected according to two criteria: The daily A_p value must be greater than or equal to 15, and the increase from the previous daily value must be at least as large as the monthly average value of A_p. These are the same two criteria used in the paper by Roberts and Olson (1973). The key dates cover 17 years from 1953 through 1969 and therefore are available for all winters for which we have tropospheric and stratospheric data available.

Our set of data for the stratosphere parameterizes the size and convolution of the polar vortex at 10 mb. It is identical to that used in the previous study by Reiter and Macdonald (1973). The 30,640-m contour at this pressure level generally lies near the edge of the polar vortex during the months from November through March. The latitude value of this contour at 30° longitude intervals is noted for each day, giving 12 such values. The mean of these latitudes give a rough idea of the daily areal extent, although not of the intensity, of the vortex. The standard deviation of these values gives an indication of the convolution or ellipticity of the vortex. For each day in the 12 cold seasons (November through March) 1957-58 through 1968-69 we obtained a mean latitude value as well as a standard deviation value for this contour line.

The tropospheric data deal with the daily size of the 500-mb cold pool. Generally the -30°C isotherm lies near the polar front at this level, and the area enclosed by this isotherm should give an indication of the areal extent of the cold pool. We planimetered the area enclosed by this isotherm from maps published by the U. S. Weather Bureau for each day in 10 cold seasons, 1953-54 through 1962-63. Values for two of the seasons, 1961-62 and 1962-63, were taken from operational charts while the others were taken from the Daily Series Synoptic Weather Maps published by the U. S. Weather Bureau. Portions of this area which occasionally broke away from the main cold pool were disregarded unless they "rejoined" the pool at a later time. This data set consists of the daily area of the 500-mb cold pool in arbitrary units.

THE COMPARISONS OF GEOMAGNETIC DATA WITH STRATOSPHERIC AND TROPOSPHERIC DATA

First let us compare the Geomagnetic Key Dates with the mean latitude and standard deviation of the polar vortex, our stratospheric data. Ninety-eight key dates were selected from nine cold seasons, 1960-61 through 1968-69. The mean values of these two sets of stratospheric data for the 98 epochs surrounding the key events are shown in Figure 1. Note the significant increase in mean latitude of the 30,640-m contour, indicating a shrinkage of the polar vortex, from the third to the eighth day following the geomagnetic event. The Wilcoxon Rank-Sum Test shows that the D_1 through D_{14} mean latitudes are statistically separate from the D_{-14} through D_{-1} means at the 99 percent significance level. Most perplexing is the slight increase in mean latitude along with a corresponding sharp increase in standard deviation preceding the Key Date. To investigate this situation, we reduced our Key Dates to only those which were preceded by at least nine non-key dates. This eliminates the "pre-event" compounding effects of sequences of key events. Forty Key Dates met this new criterion, and the mean values of the mean latitude and standard deviation for these epochs are shown in Figure 2. It was noticed, however,

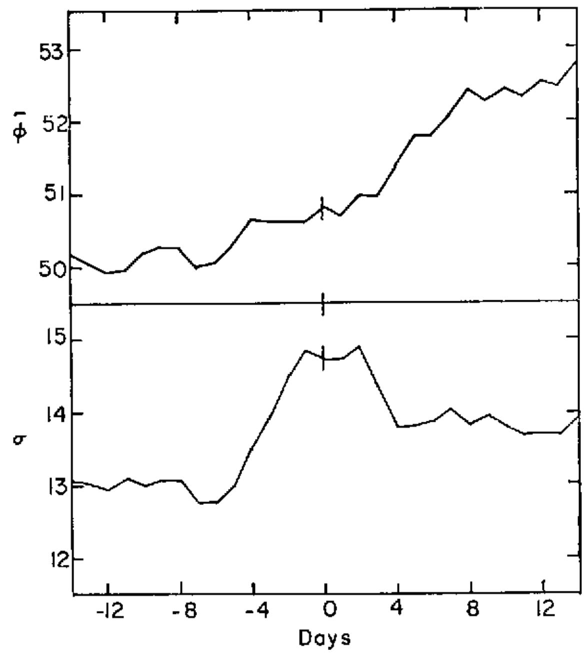


Figure 1. Superposed epoch averages of the daily mean latitude, ϕ (top diagram), and the daily standard deviation, σ (bottom diagram), of the 30,640-m contour line at 10 mb surrounding key geomagnetic dates. Data averaged were taken from 98 cases in 9 cold seasons (November through March) for the years 1960-61 through 1968-69.

that a sudden break-up of the polar vortex circulation occurred during two of these epochs: the mean latitude of the 30,640-m contour fluctuated by as much as 20° in one day, in these two cases. The mean latitudes of these two individual epochs are shown in Figure 3. After eliminating these sequences, we are left with the mean values of 38 epochs which are shown in Figure 4. Note the rapid increase in mean latitude from D_3 through D_7. Also, the standard deviation of the vortex jumps most markedly from D_5 through D_8. These figures indicate that a four- to five-day shrinkage of the polar vortex follows a Key Geomagnetic Data by about three days, with a slight increase in the ellipticity of, or meridional transport by, the polar vortex later in the period of the shrinkage.

Returning to the 98 original epochs and taking them individually, we tried to determine the statistical significance of the D_7 through D_{11} mean latitudes compared with some pre-key event values. Specifically, we used the D_{-10} through D_{-1} mean latitudes for the pre-event data, giving a total of 15 values to be compared for each epoch. A simple rank-sum test was used to compare

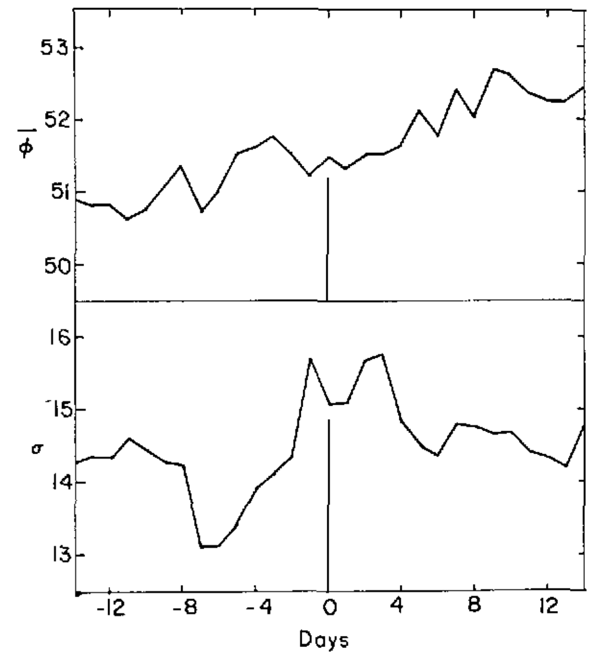


Figure 2. Key geomagnetic dates which were preceded by at least nine non-key geomagnetic dates (40 cases) in 9 cold seasons (November through March) for the years 1960-61 through 1968-69.

these two sets of data and to determine the statistical significance of their separation. In 52 of the 98 epochs the mean latitude of the D_7 through D_{11} data is greater than the pre-event values at the 95 percent significance level. In other words, in more than half of the key epochs this D_7 through D_{11} increase in mean latitude following the key event is significant.

Three seasons with stratospheric and geomagnetic data (1957-58 through 1959-60) remain, and we used this data to determine whether the same trend will develop from new independent data. Thirty-one Key Geomagnetic Dates were chosen from this sample, and the results of the superposed epoch method of mean latitude and standard deviation are shown in Figure 5. Again we selected only those key dates which were preceded by at least nine non-key dates, of which there were 14, and the results of the superposed epoch for these events are shown in Figure 6. Note a similar trend toward an increase in mean latitude following the geomagnetic event (in this case from six to eight days following the key date). The large increase in standard deviation preceding the key date is due mostly to a single event, while the increase preceding D_8 is more general.

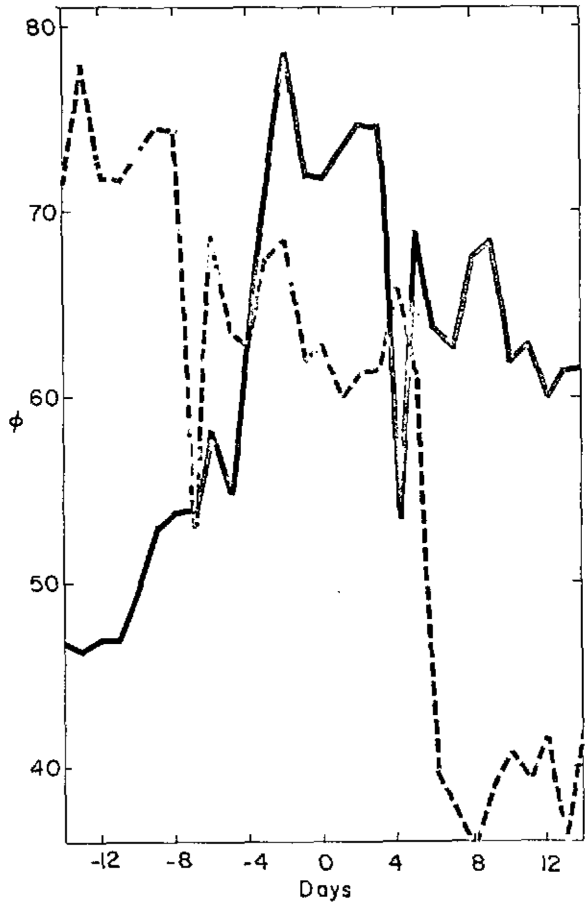


Figure 3. The daily mean latitude values of the 30,640-m contour at 10 mb surrounding the key geomagnetic dates of January 30, 1963, (solid line) and February 10, 1973 (dashed line).

Also we tried to determine a mean 500-mb cold pool response surrounding similar geomagnetic events. Since the tropospheric data and the stratospheric data cover different seasons, the key dates are not exactly the same, however, the criteria used in selecting them remain identical. The 10 cold seasons which were used ran from 1953-54 through 1962-63, and 113 days were selected as key geomagnetic dates from this period. The mean values of the area within the -30° C isotherm surrounding the key dates are shown in Figure 7(a). No statistically significant variation can be determined from this data. Selecting only those key dates which were preceded by at least nine non-key dates, we noted the mean area variations which are given in Figure 7(b). Again, no significant variation is apparent.

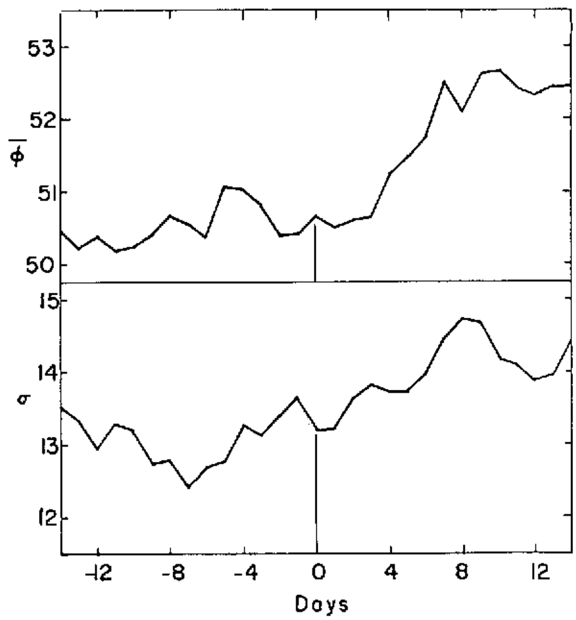


Figure 4. The daily mean latitude values at 10 mb (38 cases).

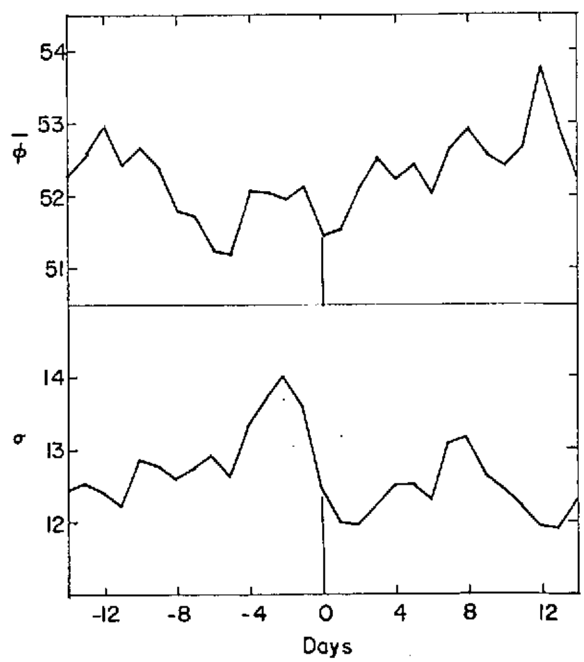


Figure 5. Superposed epoch averages of the daily mean latitude ϕ, and the daily standard deviation, σ, of the 30,640-m contour line at 10 mb surrounding key geomagnetic dates for the 1957-58 through 1959-60 cold seasons (31 epochs).

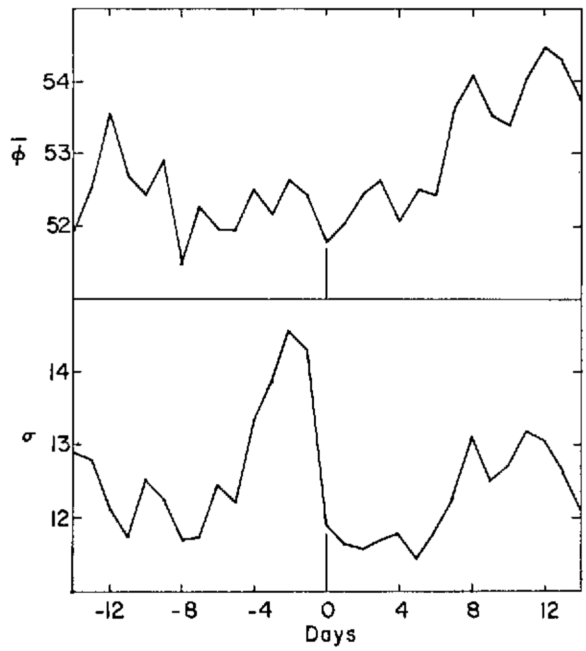
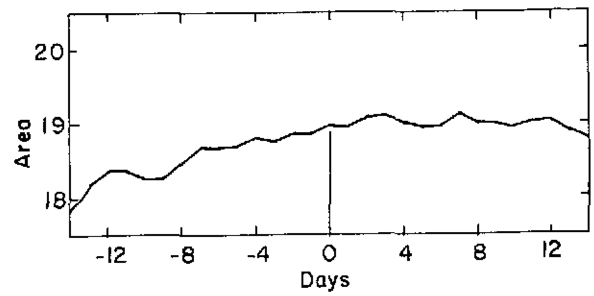


Figure 6. Key geomagnetic dates which are preceded by at least nine non-key dates for the 1957-58 through 1959-60 cold seasons (31 epochs).

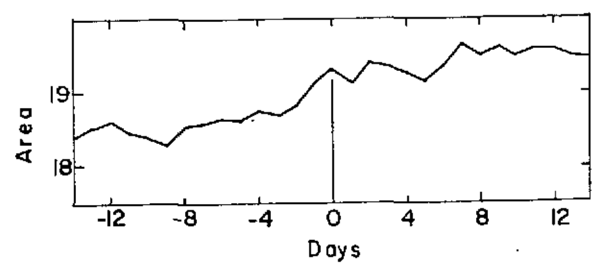
SECTOR EVENTS

Occasionally, and often at the time of a geomagnetic event, the orientation of the interplanetary magnetic field switches. Wilcox et al. (1973) observed a vorticity minimum in the troposphere and lower stratosphere north of 20° N latitude about one day following the passage of a sector boundary. No overlap of our tropospheric data and sector data was available, but we wanted to determine whether such a switch had an effect on the stratospheric polar vortex at 10 mb. Forty-two dates of this switch, whether from positive to negative or vice versa, were selected from the cold seasons 1963-64 through 1968-69. These were called Sector Key Dates, and the superposed epoch method was used to determine a mean stratospheric reaction surrounding these dates. The mean of the 30,640-m contour mean latitude and the mean of its standard deviation surrounding these key events are shown in Figure 8.

Note the slight decrease in mean latitude (expansion of the polar vortex) following the key date, with relatively lower values from D_3 through D_7. Using a simple rank sum test, we compared the values for these five days with those of the D_{-10} through D_{-1} segment separately for each of the 42 sequences. In 14 of the cases, the D_3 through D_7 sample was lower than the pre-key date sample at the 95 percent significance level. In 16 of the cases, however, this D_3 through D_7 sample was actually greater than the pre-key date sample above the 95 percent significance level. Thus we could establish no statistically significant trend.



(a)



(b)

Figure 7. (a). Superposed epoch averages of the daily area (in arbitrary units) of the cold pool (T≤-30°C) at 500 mb surrounding key geomagnetic dates. Such dates (113 in all) were selected from November through March in the seasons 1953-54 through 1962-63. (b). Superposed epoch averages of the daily area (in arbitrary units) of the cold pool (T≤ -30°C) at 500 mb surrounding key geomagnetic dates. Key dates include only those preceded by at least nine non-key dates (45 cases) and were selected from November through March in the seasons 1953-54 through 1962-63.

TROPOSPHERIC RESPONSE TO THE STRATOSPHERE

We have shown that there appears to be a stratospheric reaction to geomagnetic activity, but there appears to be no similar significant response in the troposphere. Reiter and Macdonald (1973) indicated that the troposphere reacts to sudden, strong warmings in the stratosphere and that these tropospheric warmings tend to occur about two days later (see Figure 9). We wanted to include the effects of weaker and less sudden warmings in the stratosphere in this study, however. Using our stratospheric data for the six seasons in which it overlapped the tropospheric data (1957-58 through 1962-63), we took every possible nine-day sequence in each season and separated it into three three-day sequences. Key stratospheric warming events were determined in the following manner: The 30,640-m contour mean latitude in the second three-day sequence must be greater than the mean of the first three-day

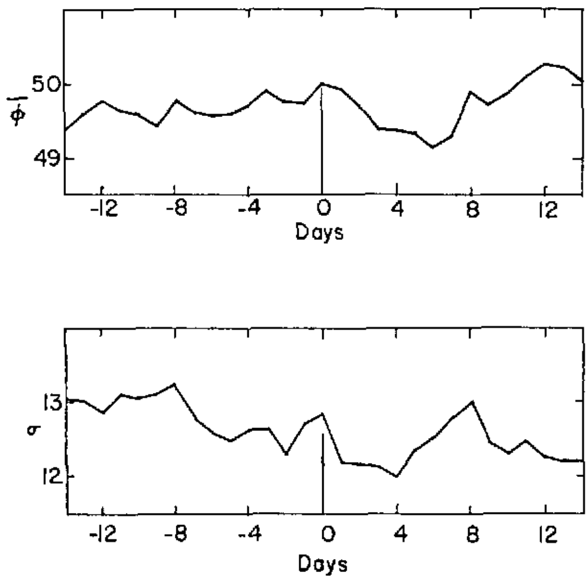


Figure 8. The superposed epoch averages of the daily-mean latitude, ϕ, and the daily standard deviation, σ, of the 30,640-m contour at 10 mb surrounding key sector dates. Forty-two cases were included from November through March 1963-64 through 1968-69.

sequence by two degrees of latitude or more, and similarly the mean of the third three-day sequence must also be greater than the second by 2° or more. Key dates were arbitrarily called the fifth day (the middle day) of the nine-day sequence, and 52 such sequences in the six seasons met both criteria. Using the superposed epoch method, we determined the mean response of the tropospheric cold pool area surrounding these key dates. The mean values of the polar vortex mean latitude (the controlled event) and the 500-mb cold pool area are given in Figure 10. Note the shrinkage of the cold pool following the stratospheric warming, with the most significant shrinkage beginning about three days after the stratospheric warming. To test the statistical significance of this decrease in area we again used a simple rank-sum test separately for each of the 52 sequences. We compared the area values of the D_{-5} through D_{-1} sequence with those of the D_8 through D_{12} sequence. In 32 of the 52 epochs, the latter sample was statistically less than the former sample at the 95 percent significance level or better. In 40 of the cases, the numerical mean of the D_8 through D_{12} sequence was less than the mean of the earlier sequence. This confirms a forcing upon the tropospheric cold pool size by stratospheric warmings which are weaker than those discussed by Reiter and Macdonald (1973).

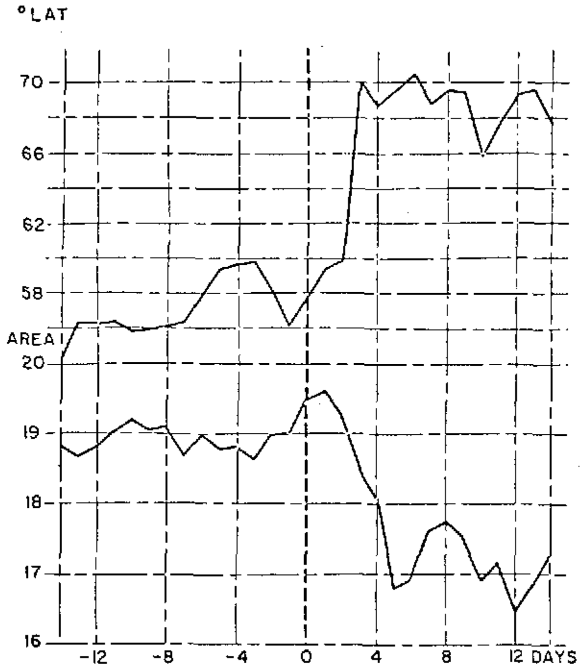


Figure 9. Superposed epoch averages of four cases of stratospheric vortex breakdown measured by an increase in the mean latitude of the 30,640-m contour at 10 mb (top diagram) and the mean area (arbitrary units) of the cold air ($T \leq -30°C$) at 500 mb (lower diagram). (From Reiter and Macdonald, 1973).

We speculate that the reason that no tropospheric response to geomagnetic activity could be shown directly is that the intermediary action of the stratosphere tends to mask this effect over the time scales considered here. This would cause the tropospheric reaction to be spread over a greater length of time with respect to the Key Geomagnetic Date; and therefore, it would be more difficult to detect in a statistical sense.

The results presented in this section indicate that the stratosphere responds more significantly to geomagnetic activity than does the troposphere, and that the resulting stratospheric warming is in turn forced upon the troposphere. This forcing has been the subject of several earlier papers (Austin and Krawitz, 1956; Tewels, 1958; Reiter and Macdonald, 1973).

POSSIBLE MECHANISMS

THE POLAR VORTEX CENTER

Before determining the mechanism which brings about the shrinkage of the polar vortex discussed in the preceding section, it is important to examine

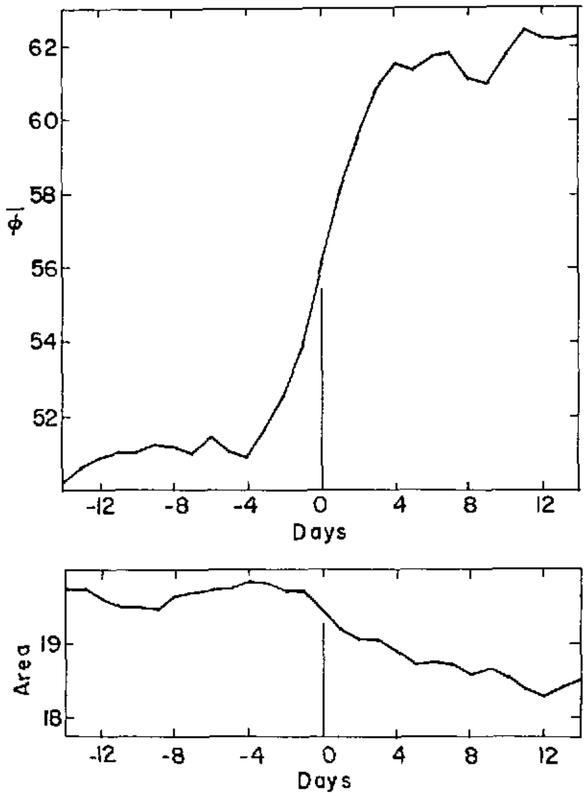


Figure 10. Superposed epoch averages of the 30, 640-m contour mean latitude, ϕ, at 10 mb surrounding an increase in mean latitude of 4° or more in nine days (upper curve). The superposed epoch averages of the area of the cold air ($T \leq -30\ ^{\circ}C$) in arbitrary units surrounding such events are shown in the lower curve.

the fluctuations of the vortex center surrounding such warming events. If the center contour at 10 mb shows a marked increase at the time that the edge of the vortex shrinks, a mechanism of large scale subsidence would suggest itself. A schematic indication of a typical event of this type, if it exists, is shown in Figure 11. On the other hand, if the center contour remained essentially at the same value or became numerically less during shrinkage, a steepening of the contour gradient near the edge of the vortex would be associated with a contraction of the vortex edge. Some mechanism, such as mass importation or warming only along a rather narrow belt, would be indicated. Figure 12 shows a schematic interpretation of an event of this type.

We examined the fluctuations in central contour value during a 29-day epoch surrounding a contraction of the vortex edge. As before we used the criterion in which the mean latitude of the 30-640-m contour at 10 mb increased by 4° or more in nine days using the method with the three day means described in

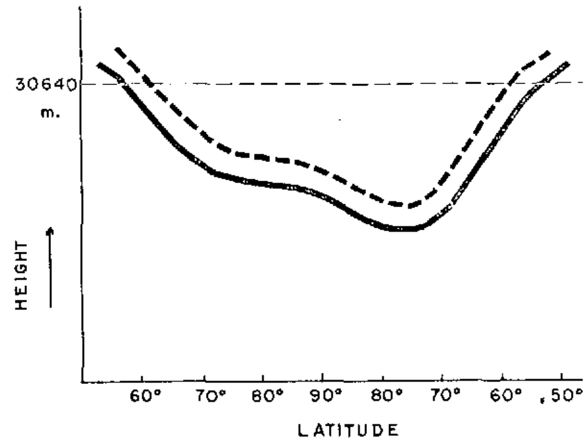


Figure 11. Meridional cross section of the 10-mb surface surrounding an increase in mean latitude (shrinkage or the polar vortex) of the 30,640-m contour, if it is associated with large-scale warming or subsidence. The solid line represents the 10-mb heights preceding the shrinkage, and the dashed curve represents height values following the shrinkage.

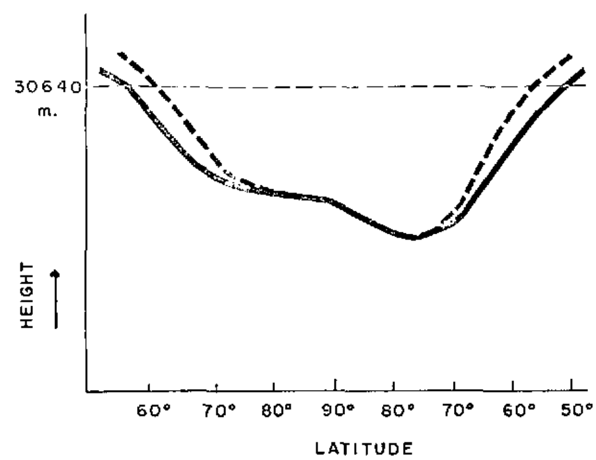


Figure 12. Meridional cross section of the 10-mb surface surrounding an increase in mean latitude (shrinkage of the polar vortex) of the 30,640-m contour, if it is associated with a steepening of the contour gradient along the vortex edge. The solid line represents the 10-mb heights preceding the shrinkage, and the dashed curve represents height values following it.

the previous section. The superposed epoch method was employed with the key date again chosen as the middle day of such nine day sequences. In the 12 seasons for which we have 10-mb data, 76 nine-day sequences met the criterion. The means of the 30,640-m mean latitude values for these events

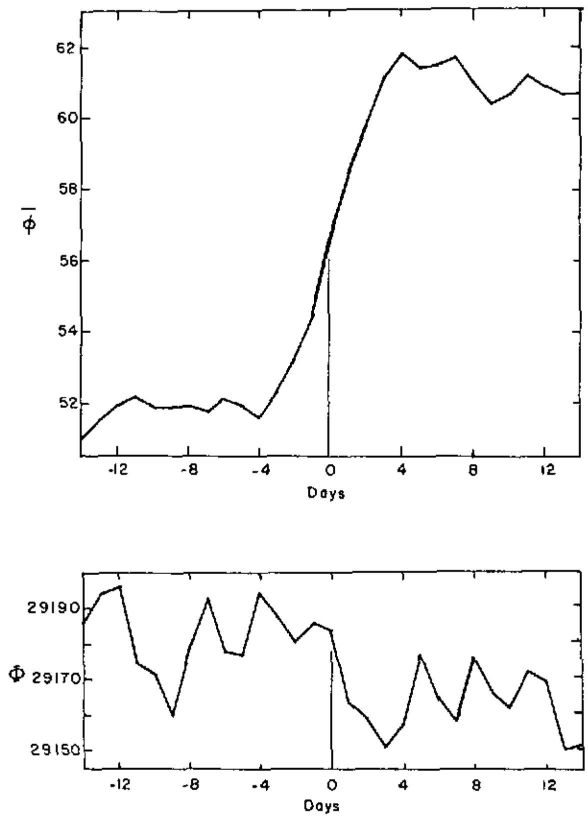


Figure 13. Superposed epoch averages of the 30, 640-m contour mean latitude, $\bar{\phi}$, at 10 mb surrounding an increase in mean latitude of 4° or more in nine days (upper curve). The superposed epoch averages of the value (in meters) of the polar vortex central contour at 10 mb are shown in the lower curve.

are shown in Figure 13. The means of the central contour value at 10 mb during these epochs are also shown in Figure 13. Note that no increase in height of this pressure surface is even remotely suggested; in fact a mean decrease of about 20 m is implied. On the basis of these results we can rule out any mechanism which promotes large scale subsidence as being responsible for a shrinkage of the polar vortex. We are forced to rely on a mechanism which causes a steepening of the contour gradient (on a constant pressure surface) near the edge of the polar vortex to bring about the observed contraction.

DIRECT ABSORPTION

One possibility of warming the polar vortex edge at 10 mb would be through collisional excitation and ionization of the atmospheric molecules during the geomagnetic storm, i.e., direct absorption of energy. Certainly the fact that auroras occur along a latitude belt which is near the polar vortex edge gives impetus to an investigation of this possibility. We will present some calculations showing that this mechanism cannot supply the required energy to bring about the observed contraction.

According to Matsushita and Campbell, (1967) we can assume that the auroral absorption takes place primarily in a latitude band 10° wide, averaging 5000 km in length in both hemispheres. The rate of dissipation due to auroral processes during a magnetic storm is about 10^{17} to 10^{18} erg $\cdot$ s^{-1}. The area of one of these bands is about 5.6×10^{16} cm^2, and we will assume that 10^{18} erg $\cdot$ s^{-1} are absorbed over one of these bands during a magnetic storm. A cursory examination of the contour gradient at 10 mb near the polar vortex edge in midwinter yields a mean contour gradient of about -80 m (degree latitude)$^{-1}$, shown schematically in Figure 14. If we assume uniform heating of a 10° latitude band (from 50° N to 60° N) only, a 4° increase in mean latitude of the 30,640-m contour line would require a uniform 320-m increase in height of the 10-mb surface over this latitude band. If this increase is due totally to heating in, say the 30 to 10 mb layer, the calculations shown in Appendix 1 indicate a required mean warming of about 10°C in this layer. Also in Appendix 1, calculations of energy required to carry on this heating compared with energy available from a long (10^{+4} s) geomagnetic event show that simple absorption and redistribution of the auroral energy could not possibly account for the noted heating.

DISCUSSION

It is apparent that simple absorption of the radiative energy associated with a geomagnetic storm cannot account for the observed warming at 10 mb following such an event. Some mechanism involving the dynamics and transport processes along the vortex edge should be investigated. In particular, adiabatic sinking motion and eddy transport processes in the area might account for the observed warming. Calculation of the adiabatic subsidence in the 30 to 10 mb layer required to produce such a warming are shown in Appendix 2. The result (0.14 cm $\cdot$ s^{-1}) is within the realm of variability in vertical motion at 50 mb reported by Mahlman (1966). He indicates that mean vertical motion during a "Stratospheric Warming" changed from -0.06 cm $\cdot$ s^{-1} preceding the period to -0.14 cm $\cdot$ s^{-1} during it. The increase in standard deviation of the 30,640-m contour at 10 mb (see Figure 4) indicates that the effect of eddy transport processes is increasing after a geomagnetic key date, and this too may account for some of the observed warming.

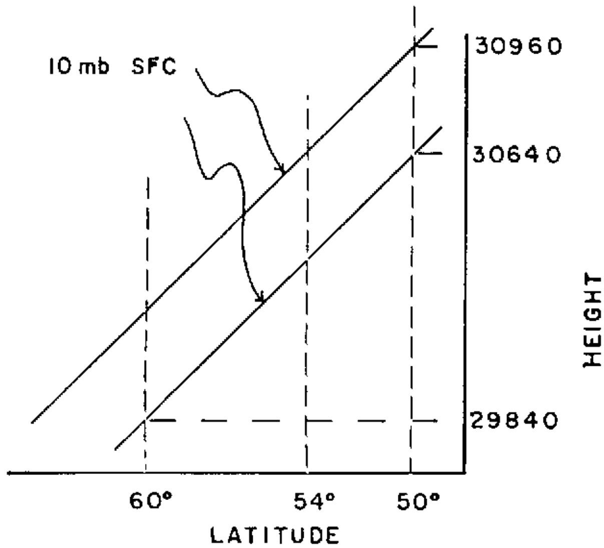


Figure 14. A schematic diagram of 10-mb surfaces with latitudinal gradient of -80 m per degree latitude.

ACKNOWLEDGMENT

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APPENDIX 1

1. Assume a mean temperature of 218° K -55° C in the 30 to 10 mbar layer.

2. Given the formula from the Smithsonian Tables:

$$\Delta\Phi = 67.442\ (273.16 + t'_{mv})\ \log_{10}\frac{P_1}{P_2}$$

where: $\Delta\Phi$ = thickness of the layer (gpm)

t'_{mv} = mean adjusted virtual temperature of the layer (°C)

P_1 = pressure at the base of the layer

P_2 = pressure at the top of the layer

3. Using this formula with the values given in (1.) above,

$$\Delta\Phi = 7020 \text{ gpm.}$$

4. If we increase the thickness of this layer by 320 gpm and reapply the equation in (2.),

$$t'_{mv} = -45°\text{C.}$$

5. Therefore, corresponding to an increase of 320 gpm in the 30 to 10 mb layer, the mean virtual temperature must increase by 10°C.

6. From the text, we had assumed that the area of the latitude band in which auroral energy is absorbed in 5.6×10^{16} cm^2.

7. The mass of air in the 30 to 10 mb layer over this band is $(20\ g \cdot cm^{-2})$ $(5.6 \times 10^{16}\ cm^2) = 1.1 \times 10^{18}$ g.

8. Given the specific heat of air $c_p = 10\ erg \cdot g^{-1}\ °K^{-1}$.

9. The energy required to bring about this observed warming = (total mass to be heated) (specific heat of the mass) (change in temperature required), or from (7), (8), and (5) above. Energy required = $(1.1 \times 10^{18}\ g)$ $(10^6\ erg \cdot g^{-1}\ °K^{-1})$ $(10°K) = 1.1 \times 10^{25}$ erg.

10. From Matsushita and Campbell (1967), assume that the energy of an auroral absorption is 10^{18} erg • s^{-1}.

11. Assume that this strong absorption lasts ~3 hours or 10^4 s.

12. Then the total energy involved in the aurora is

$$(10^{18} \text{ erg} \cdot s^{-1}) (10^4 \text{ s}) = 10^{22} \text{ erg}.$$

13. Comparing the results from (9) and (12), note that the energy involved in an aurora is much less than is required to produce the noted heating.

APPENDIX 2

Assume a four-degree increase in mean latitude of the 30,640-m contour at 10 mb, and assume that this is brought about by the 10 K warming in the 30 to 10 mb layer noted in Appendix A.

Differentiating Poisson's equation and holding $d\theta = 0$ where P = 20 mb, T = 223°K, let dT = + 10°K

$$d\theta = dT \frac{1000}{P}^{K} + = KT(1000)^{K} P^{-K-1} dp$$

then dp = 3.1 mb

Using the hydrostatic approximation, this corresponds to a change of about 1070 gpm.

Therefore a parcel of air which sinks adiabatically from the 20-mb level, T = 223°K, and warms 10°K must experience a change in geopotential of ~1070 gpm.

If this change in geopotential is experienced over a period of nine days (7.78×10^5 s), then the mean vertical motion which accounts for this warming is about $-0.14\ cm \cdot s^{-1}$.

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF BRUCE C. MACDONALD

MR. SHAPIRO: Could you define a little more precisely the nature of your magnetic key day selection?

MR. MACDONALD: We used a planetary A_p index to determine these key dates. It had to be at least 15, and the increase over the previous day had to be greater than or equal to the mean monthly A_p value.

MR. SHAPIRO: That's similar to something that Walter Roberts has done.

MR. MACDONALD: That's exactly the same criterion he used, yes.

MR. AIKEN: Have you made any analysis on whether the polar vortex ever breaks up in association with geomagnetic activity?

MR. MACDONALD: Yes. In fact, it did break up. A breakup occurred near a key date twice, I believe. We excluded that data from these charts because it tended to mask any other values which we observed from, say, the other 38 key dates, but we only had 12 years of this data and we could detect no real correlation, for example, with a massive breakup of the polar vortex following that key date.

QUESTION: What time of the year did the breakup occur?

MR. MACDONALD: There were two breakups that occurred near a key date, and they were both in January. Our data runs from November through March.

N74-29080

A SPECTRAL SOLAR-CLIMATIC MODEL

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INTRODUCTION

The problem of solar-climatic relationships has been the subject of speculation and research by a few scientists for many years. Understanding the behavior of natural fluctuations in the climate is especially important currently, due to the possibility of man-induced climate changes (Study of Man's Impact on Climate, 1971, Study of Critical Environmental Problems, 1970). This paper consists of a summary of pertinent research on solar activity variations and climate variations, together with the presentation of an empirical solar-climatic model which attempts to clarify the nature of the relationships.

The study of solar-climatic relationships has been difficult to develop because of an inadequate understanding of the detailed mechanisms responsible for the interaction. The possible variation of stratospheric ozone with solar activity has been discussed by Willett (1965) and Angell and Korshover (1973). The empirical evidence for statistically significant effects of solar flares on the earth's weather has recently been summarized by Roberts and Olson (1973). A brief summary of solar-climatic effects has been given by Bray (1971), and more complete discussions have been given by Rubashev (1964) and Lamb (1972) Recent developments in the field of solar-climatic relationships have been discussed by Willett (1965), Suess (1968), Damon (1973), Mitchell (1973), and Stuiver (1972).

SOLAR ACTIVITY BEHAVIOR

Summaries of the state-of-the-art in solar activity analysis and forecasting have been given by Vitinskii (1962, 1969). Recent attempts to improve our understanding of solar activity variations have been based upon planetary tidal forces on the sun (Bigg, 1967; Wood and Wood, 1965), or the effect of planetary dynamics on the motion of the sun (Jose, 1965; Sleeper, 1972). Figure 1 presents the cunspot number time series from 1700 to 1970. The mean 11.1-year sunspot cycle is well known, and the 22-year Hale magnetic cycle is specified by the positive and negative designation. The magnetic polarity of the sunspots has been observed since 1908. The cycle polarities assigned prior to that date are inferred from the planetary dynamic effects studied by Jose (1965). The

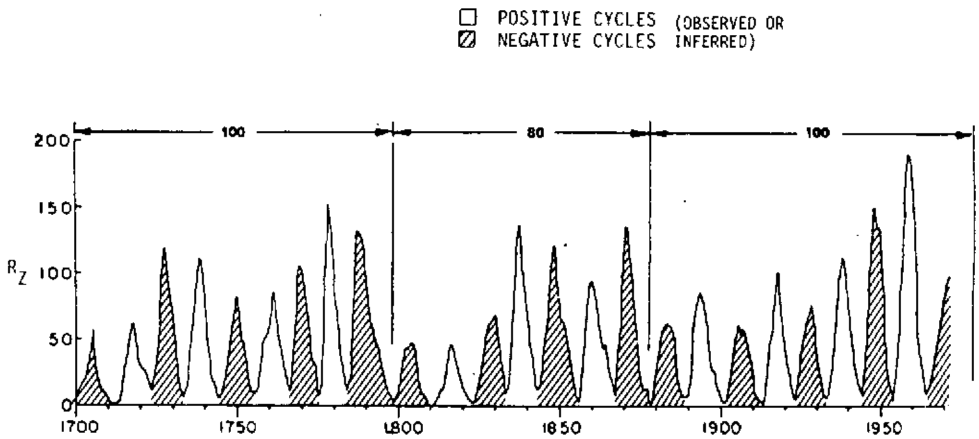

Figure 1. Observed sunspot variations from 1700 to 1970.

sunspot time series has certain important characteristics which are summarized below.

SECULAR CYCLES

The sunpot cycle magnitude appears to increase slowly and fall rapidly with an 80- to 100-year period. Jose has identified a basic 180-year period associated with the resonance structure of the planets, and 80- and 100-year subperiods related to planetary dynamics and the resulting orbit of the sun about the center of gravity of the solar system. The center of gravity moves from the sun's center as much as 2 solar radii (Jose, 1965). Secular solar cycles started about 1700, 1800, 1880, and a new one is expected by 1980.

INTRASECULAR CYCLES

The secular cycles can be further analyzed into shorter epochs of 30 to 40 years duration, depending on mean cycle magnitude or other characteristic criteria. The most recent intrasecular epoch of potential importance is the interval from about 1920 to 1961. According to Svalgaard (1973), the geomagnetic data available from 1926 to 1973 indicate a possible cyclic fluctuation of solar wind sector structure with a period of about 40 years. The solar wind structure is related to the sun's corpuscular emissions, with a corresponding influence on the earth's magnetic field fluctuations (Wilcox, 1968).

DECADAL CYCLES

The decadal cycles consist of 11-year cycles of opposite magnetic polarity, positive and negative. The mechanism for the magnetic field reversal of successive cycles has been described by Babcock (1961) in terms of an empirical dynamo model, with the interaction of toroidal and poloidal magnetic fields generated by the sun's surface differential rotation. Jose's analysis suggests that the simple 22-year cycle breaks down every 80 to 100 years. According to his model, the next 11-year cycle will be of negative magnetic polarity, the same as cycle 20. The sun's dipole magnetic field may change sign about three years after the maximum sunspot activity (Wilcox and Scherrer, 1972), although there is considerable evidence for reversal near sunspot maximum.

SUBCYCLES

There is some substantial evidence indicating that the nominal mean 11-year solar cycle is a superposition of two or three subcycles, closely related to the corpuscular emission from the sun. These subcycles of 4-7 years duration, are further discussed by Sleeper (1972). Differences in subcycle structure may account for differences in shape of positive and negative magnetic cycles. A new dynamo theory, derived from first principles, leads to a subcycle structure, with periods of less than 11 years in duration (Nakagawa, 1971).

CLIMATE VARIABLE BEHAVIOR

Climate variables of temperature, precipitation, pressure, wind direction, trough or ridge position, have been used to study climate fluctuations over periods of several hundred years. Instrumental measurements have been available for only about 200 years. Other sources of climate variation such as tree ring growth, carbon-14 variation and glacier ice-core oxygen isotope ratios have been used to extend the range of measurement to thousands of years. Evidence for climatic cycles is briefly summarized below.

SECULAR CYCLES

Evidence of secular cycles has been found in climate-related variables. Johnsen et al. (1970) studied variations in the O^{18}/O^{16} oxygen isotope ratio as a function of depth in a Greenland ice core. From their age calibration, they determined characteristic periods of 78 and 181 years. They also found periods of 400 years and 2400 years. Further evidence for a period of 180 years has been discussed by Lamb (1972) and Damon (1973).

INTRASECULAR CYCLES

There have been numerous discussions in the literature of climate cycles or epochs with periods of about 40 years. Dzerdeevski (1966) discussed a fluctuation which initiated about 1922. Troup (1962) pointed out that there was a reasonable correlation between equatorial temperatures and the 11-year sunspot cycle until about 1922, and then the correlation failed or reversed. Namias (1969) pointed out that there appeared to be a substantial change in general circulation in 1961, associated with significant changes in North Pacific Ocean temperature. Davis (1972) has shown that the last date of spring in England changed significantly about 1920, and changed back near 1960. Sleeper (1973) discussed these and other atmospheric and solar changes in 1961 which may indicate the termination of an intrasecular epoch in both the sun's and the earth's atmosphere.

DECADAL CYCLES

Searches have been made for a simple 11-year period in climatic variables. The data in which such variation was evident were equatorial surface temperatures and African lake levels (Mitchell, 1961). However, this simple correlation breaks down about 1920, (Mitchell, 1961), and has caused considerable confusion. This breakdown appears to be closely related to the intrasecular epoch initiated in the general circulation about 1920, and terminated in 1961. This particular epoch appears to have been a short duration climatic optimum, with a sudden onset and a sudden termination. It is possible that the general circulation has returned to the state where the climate is again sensitive to the 11-year solar cycle at the equator. This may account for the rainy African equatorial conditions in the 1960's and the relatively dry conditions in the early 1970's.

Evidence for a nominal 22-year cycle has been found in climate variables in the midlatitudes. Bollinger (1945) found evidence for a 22-year period in the rainfall in Kansas and Oklahoma. This is related to the 20-year drought cycle in the great plains. Willett (1965) found a 22-year cycle in continentality, and related it to ozone variations in the atmosphere. Sleptsov-Shevlevich (1972) found a 22-year period in high-latitude, sea-level pressure variations. Spar and Mayer (1973) found a 20.8-year period in the New York City January temperatures since 1870. They did not recognize that this period corresponds with the mean 20.8-year solar magnetic cycle forcing function since 1870. A. I. Ol' (1969) has presented other evidence for a 22-year period in midlatitude climate variables.

SUBCYCLES

In the study of the 22-year cycles, Bollinger (1945) and Sleptsov-Shevlevich (1972) found evidence for subcycles of a few years duration, with substantial fluctuation in precipitation and atmospheric pressure. Thus a one or two year very rainy epoch could appear in the middle of a drought period of several years duration, or vice versa.

A SPECTRAL SOLAR-CLIMATIC MODEL

Meteorologists have studied climatic changes on the basis of observations of a series of irregular, quasi-random fluctuations superimposed on a general trend for a given climate variable. These irregular, but important changes were of unknown origin. A number of models for climate change have been suggested based on the effect of volcanic dust, man-made CO_2, ocean temperature and solar activity. While there are undoubtedly effects due to volcanic dust, man-made dust, CO_2, and ocean temperature, the fundamental effects will be assumed to be due to changes in solar activity.

Typical decadal and secular fluctuations are presented in Figure 2 for several climatic variables over the last 100 years. The fluctuation of the mean world temperature (after Mitchell, 1971), indicates a secular cycle of about 100 years, from 1870 to 1965. The data show a rapid drop in temperature in the 1870's, a relatively low value until 1920, and then a sudden rise to 1940, with a subsequent fall. The sudden rise about 1920 appears to signal a very warm intrasecular epoch, and may be related to a corresponding intrasecular epoch on the

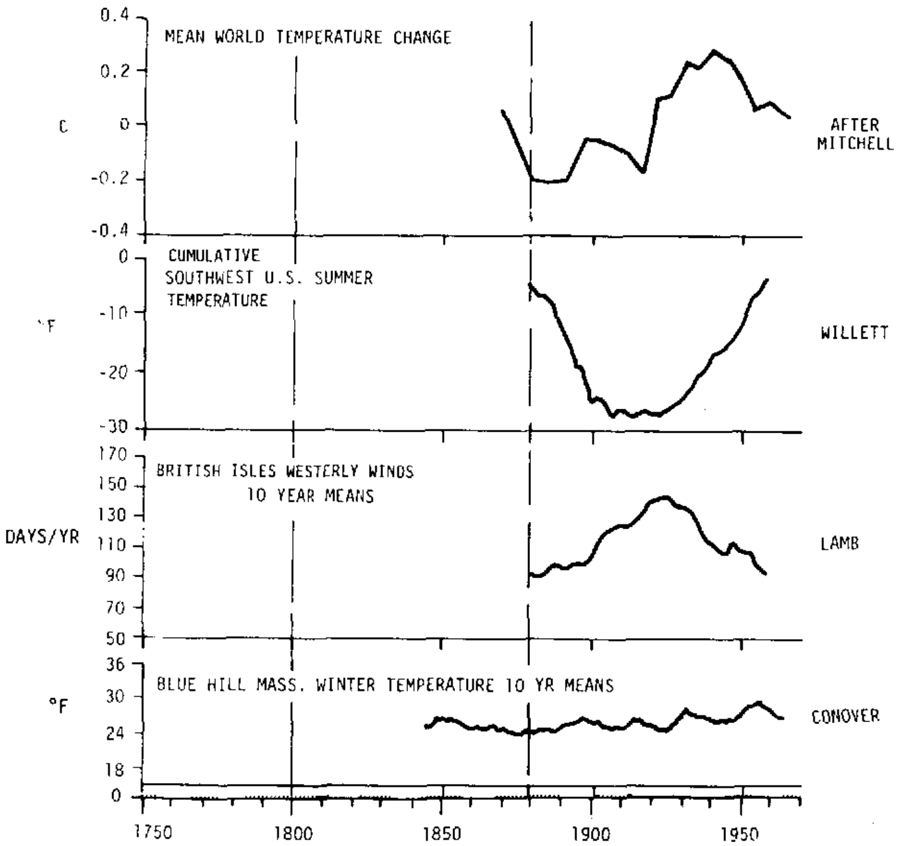

Figure 2. Observed climate variations.

sun. Willett (1965) showed that the cumulative summer temperature change for representative cities in the Southwestern United States decreased rapidly from 1880 to about 1900, stayed nearly constant until 1920, and increased steadily until 1960. Lamb (1967) demonstrated a secular change in frequency of westerly winds over the British Isles, with a noticeable change from increasing to decreasing frequencies about 1920. Conover's (1967) 10-year mean winter temperatures for Blue Hill indicate a small decrease from 1850 to 1880 and a noticeable increase from 1880 to 1960, together with a substantial indication of a 20-year periodicity. This nominal 20-year periodicity in the Northeastern United States winter temperatures, since 1880 has also been studied by Spar and Mayer (1973). The abrupt decadal fluctuations are not apparent in most of the above parameters, because 10-year means have been used to display the data.

The sudden decadal changes are more clearly demonstrated in Figure 3. Namias (1970, 1969) showed an abrupt change in San Diego sea level in 1957, and a change in the mean Atlanta winter temperature in 1947, 1957 and 1970.

New York City mean temperatures for January and February also indicated an abrupt increase after 1947, and a decrease about 1957. The changes subsequent to this date are not as abrupt as for Atlanta. This may be due in part to the local moderating effects of the ocean near New York City. The crosshatched regions are epochs when the solar wind was changing its structure from that characteristic of one sign of solar dipole field to the opposite (Wilcox and Scherer, 1972). The crosshatched regions correspond with the epochs when the annual modulation of the solar wind structure was uncertain, or changing phase. With the exception of the anomaly in 1961, this change in solar wind structure seems to be a characteristic of the 22-year solar magnetic cycle. These epochs of uncertain solar wind phase may be related to local climate shifts, and may serve as indicators or precursors of such climatic shifts. Recently these climate mode switches have occurred near the 11-year solar cycle maximum.

Qualitative evidence for an intrasecular warm epoch from about 1922 to 1961 is summarized in Figure 4. Flohn (1969) has demonstrated that the Lake Victoria level had an 11-year fluctuation from 1900 to 1922, and then changed variance structure until 1961. Davis (1972) demonstrated a sudden change in the mean final date for spring near 1920, and a return to the early conditions by 1965. The abrupt change in world mean temperature about 1920 has already been mentioned (Mitchell, 1971), and Budyko (1969) showed a change in direct solar radiation near 1920 and a change back to lower levels by 1960.

Theoretical approaches to the study of climate stability have been made on the basis of simplified models. Budyko (1972), Faegre (1972) and Sellers (1973)

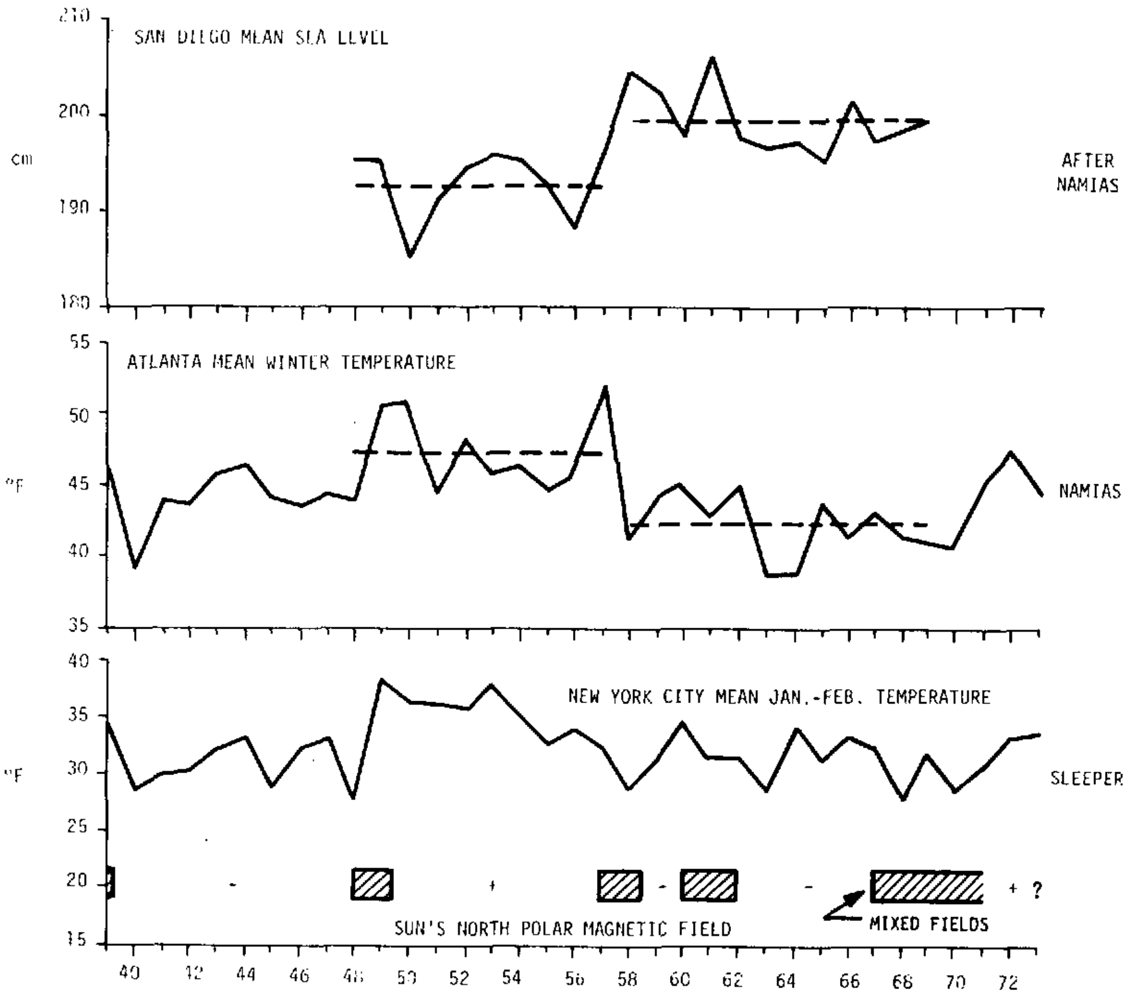

Figure 3. Decadal changes in geophysical variables.

have studied different but related models which suggest that the climate can exist in one of several quais-stable states, from an ice-free world to an ice-covered world. Changes from one quasi-stable state to another can occur relatively abruptly. On the basis of those studies, and the above empirical data on solar activity and climate cycles, a working hypothesis for a new solar-climatic model has been developed. This model views the small changes as abrupt shifts from one stable climatic mode to another, and assumes that they correspond to a change in solar activity. Some of the changes are small, but they are abrupt changes within a general trend.

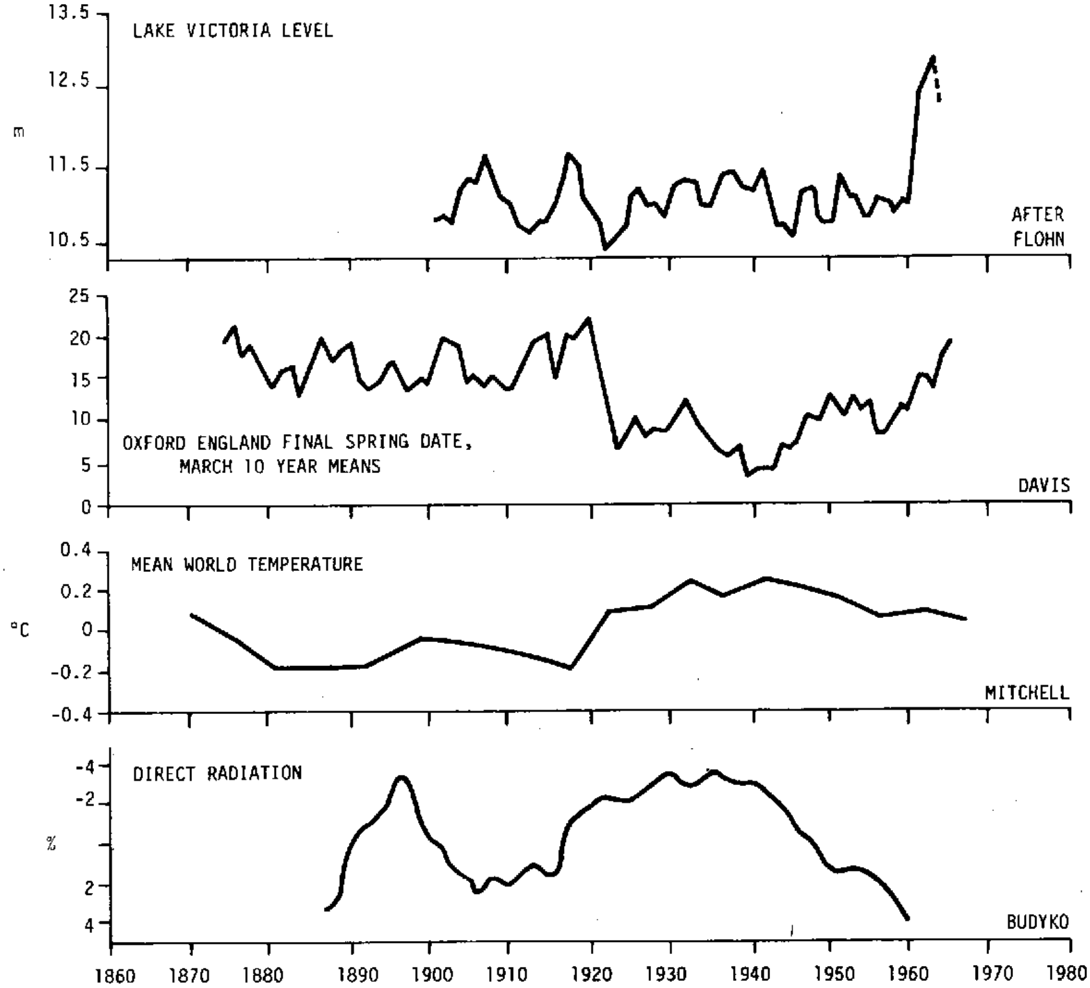

Figure 4. Intrasecular epochs in geophysical variables.

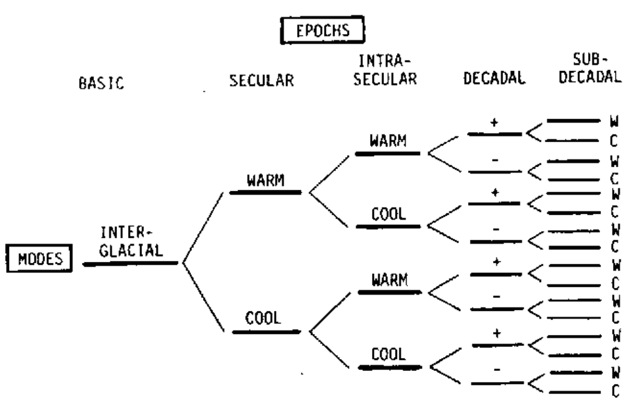

Figure 5. Spectral solar climatic model.

The basic assumptions are as follows:

- Both the sun and the earth's atmosphere operate in a succession of pairs of stable states or modes. A consecutive related pair of these states, of any duration, constitutes a solar or climatic cycle.

- The change from one mode to another in the climate can frequently be related to a similar change on the sun. The interval from one mode change to another is called a solar or climatic epoch.

The general scheme for the model is shown in Figure 5. In this scheme, the basic condition is either a glacial or interglacial state or mode. Only the present interglacial mode is shown. The figure shows the relationship of the different modes of various time durations within the interglacial state, i.e., 80- to 100-year (secular), 40-year (intrasecular), 11-year (decadal), and shorter epochs (subdecadal). In general, two closely related modes are designated warm and cool. The decadal or 11-year modes are designated as positive or negative and may be related to the magnetic cycles on the sun. These decadal modes appear to be related to shifts in long wave structures in the midlatitudes, with corresponding changes in mean temperature at a given location, such as the East Coast of the United States.

The general features of this working model appear to allow correlation of changes on the sun and in the earth's atmosphere. A more thorough analysis of this model will have to be made before it is generally accepted as a useful tool. The diagram is only schematic. In practice, some of the numerous subdecadal modes may overlap in average temperature.

DISCUSSION

Some of the concepts which have been described may be applied to the current state of the climate in the United States and the world. The model specifies various discrete modes, with corresponding states for both the sun's and the earth's atmosphere. Mode switches on the earth appear to depend on mode switches on the sun.

The results of these studies, and the new solar-climatic model, lead to the following tentative conclusions:

- The epoch from 1800 to 1880 was a cool secular mode, and the epoch from 1880 to ~1980, is a warm secular mode. A new cool secular epoch is likely to be initiated by 1980 and will extend to about 2060.

- The epoch from about 1920 to 1961 was a warm intrasecular mode (~40 years).

- In the absence of more definite information, we will assume that in 1961 the atmosphere reverted to the same secular mode as prior to 1920. However, it should be remembered that this "warm" secular mode included such anomalies as the cold U.S. winter of 1917-1918 and the extreme winter of 1899.

- In the Eastern United States, the decadal mode switched from warm to cool in 1957, and from cool to warm in 1970. These switches are associated with changes in North Pacific Ocean temperature, Southern California sea level, and Atlanta winter temperatures.

- The current climate anomalies of less than 11 years in length are such that we may be observing 100-year or 180-year extremes in such variables as northward shift of storm track, and very low atmospheric pressure levels, with attendant heavy precipitation, violent thunderstorms, tornado activity, and potential extreme hurricane generation.

- The anomalous character of the present solar cycle (20) is such that a breakdown is expected in the simple "20-year" period in midlatitude climatic variables which has been observed for the last 100 years. Corresponding anomalies may develop in the sun's dipole magnetic field structure, the solar wind annual phase structure, and the nominal "20-year" drought and east coast cold winter behavior. The solar cycle sunspot minimum is not expected until about 1977.

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF H. PRESCOTT SLEEPER, JR.

MR. STURROCK: I was very interested to note in your first slide that you give the type of the solar cycle, that is, whether it is major or minor. What do you do to get that way back in the sixteenth and seventeenth centuries? I wonder how you infer the sign of the field way back then.

MR. SLEEPER: Yes, that's a key question. How do we infer magnetic polarity for cycles occurring, say, 100 to 200 years ago when no magnetic measurements were available? The answer is, of course, we cannot determine them absolutely. The determination was inferred by some studies from Paul Jose in which he showed a change in the center of gravity of the solar system moving outside the surface of the sun by two solar radii and having a characteristic period of 80 and 180 years, and associating these with changes in the 22-year period of the sun.

N74-29081

A POSSIBLE CORRELATION BETWEEN MAXIMA OF THE FAR ULTRAVIOLET SOLAR IRRADIANCE AND CENTRAL MERIDIAN PASSAGES OF SOLAR MAGNETIC SECTOR BOUNDARIES

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Greenbelt, Maryland
and
John M. Wilcox
Stanford University
Stanford, California

The question of the possible existence of a causal relationship between solar activity and meteorological phenomena has been the subject of many investigations. Recently there have been a series of papers reporting a connection between passages of solar magnetic field sector boundaries past the earth and certain meteorological phenomena. That work with ample references to past work has been reported in detail by Wilcox (1974) as a part of the proceedings of the "Symposium on Possible Relationships Between Solar Activity and Meteorological Phenomena."

It is the purpose of this work to describe the relationship which has been observed between enhancements in the far UV solar irradiance and the position of the solar magnetic sector boundaries. The UV observations have been made with the Monitor of Ultraviolet Solar Energy (MUSE) experiments which were launched aboard Nimbus-3 in April 1969 and Nimbus-4 in April 1970. The Nimbus-4 experiment is still operating. A summary of the circumstances of observed and well-defined sector boundaries is contained in the work by Wilcox (1974).

The MUSE experiment has been described in detail by Heath (1973) and it consists of five broadband photometers which respond to solar radiation from 115 nm to 300 nm. Since the instrument was flown on the sun-synchronous Nimbus-3 and -4 satellites it has been possible to observe the intrinsic variability of the sun as a UV variable star. The persistent regions of solar variability that are related to the rotation of long-lived active regions are shown in Figure 1. Each point gives the solar longitude of the central meridian for the day number when the UV solar irradiance (principally, H. Lyman-alpha) was observed to be a maximum. The different symbols simply indicate the different active regions by virtue of their clustering about preferred solar

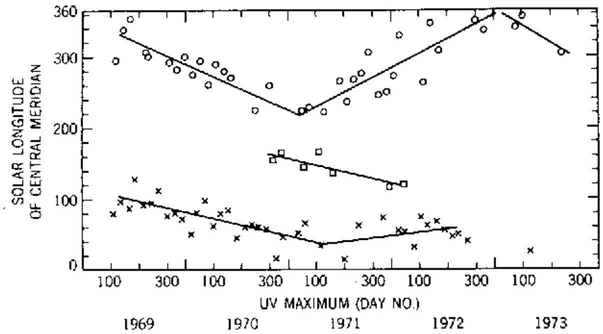

Figure 1. Carrington solar longitude of the central meridian on days of observed UV maximums in irradiance. The different symbols represent regions on the basics of groupings in longitude.

longitudes. The nature of these curves is outside the scope of this paper and is used only to illustrate the fact that there are two very long lived regions of UV activity which were separated by about 180° in solar longitude in 1969.

Figure 2 shows the polarity of the interplanetary magnetic field as observed by spacecraft orbiting the earth (Wilcox and Colburn, 1972). The grey shaded area represents field directed away from the sun and the black indicates field directed toward the sun. The days on which the UV solar irradiance peaked during a solar rotation are indicated by the same symbols that were used in Figure 1.

Since there is a delay of about 4 1/2 days between the time a sector boundary is at central meridian on the sun and the time at which the solar wind carries it past the earth (Wilcox, 1968), the sector boundaries shown in Figure 2 should be shifted backward by about 4 1/2 days to give the time at which they were near central meridian on the sun. When this is done one notes that the ultraviolet peaks marked with circles are very close to the time when an away-toward boundary was near central meridian, and the UV peaks marked with X's are very close to the time when a toward-away boundary was near central meridian.

This relation is quantitatively displayed in Figure 3, which shows a histogram of the time in days of the UV peaks with respect to the time at which a sector boundary was near central meridian. A clustering of the UV peaks near the sector boundaries is evident. We reserve judgement on the small difference between away-toward and toward-away boundaries until more observations have been analyzed.

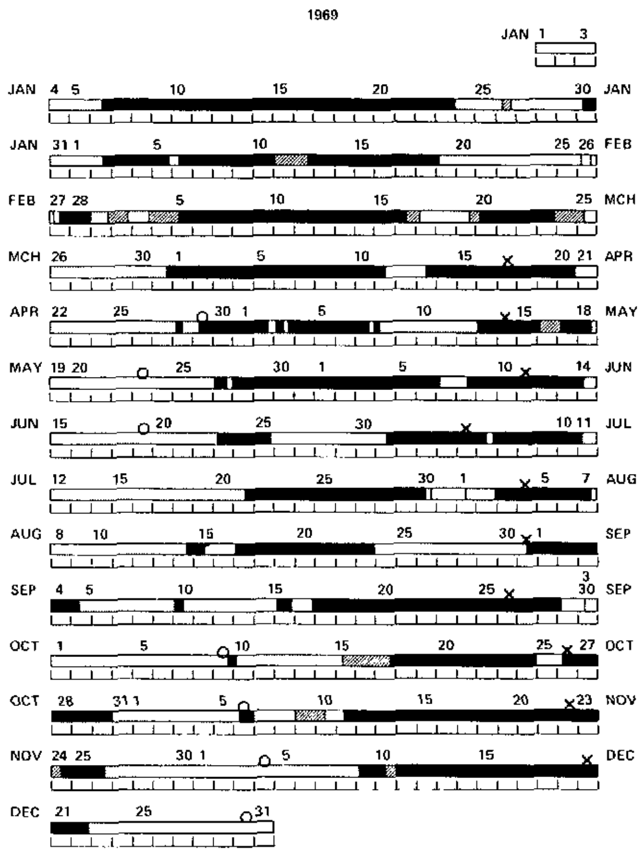

Figure 2. Representation of the sectors of the large-scale solar photospheric magnetic field carried radially outward by the solar wind as it sweeps by the earth. The dotted or grey regions are the away field and the black regions are the toward field. Times of solar UV enhancements are indicated with the same symbols used in Figure 1. The sector boundaries were near central meridian on the sun about 4 1/2 days before the times shown in the figure at which the boundaries were observed by spacecraft orbiting the earth.

Typical increases in the solar UV above the minimum during a solar rotation which were observed with the MUSE experiment in 1969 were typically: 25 percent at H. Lyman-alpha, 5 percent at 175 nm, and 1 percent at 295 nm. In terms of the equivalent width of the photometer channels this would correspond to increases above the minimum during a solar rotation of: 1.6 ergs/cm^2 s at H. Lyman-alpha, 1.0 erg/cm^2 s at 175 nm, and 230 ergs/cm^2 s at 295 nm. In other words, variations per solar rotation are typically greater than the annual variation below 175 nm and less than above 175 nm. This representative increase associated with the solar rotation of UV active regions should be considered when considering possible physical causes to explain the observed correlations between passages of the solar magnetic sector boundaries past the earth and meteorological phenomena.

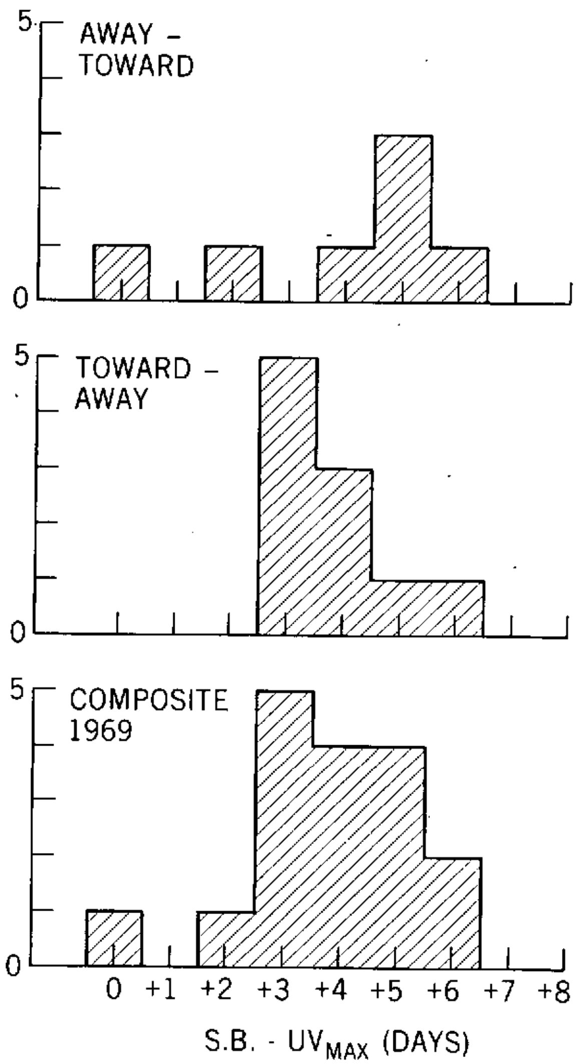

Figure 3. Histogram of the time delay in days between an observed UV solar enhancement (UV max) and a corresponding central meridian passage of the solar magnetic field sector boundary.

In summary, satellite observations of the sun over almost five years have shown that principally two UV active longitudes have persisted over a significant portion of this observational period. A comparison between the position of solar magnetic sector boundaries and UV enhancements of the sun seems to show, at least during the year of 1969, that the UV maxima tend to occur near the times when a solar sector boundary is near central meridian. An estimate of the magnitude of the variable UV solar energy input into the atmosphere resulting from the rotation of active solar longitudes is that for wavelengths less than 175 nm and down to H. Lyman-alpha it exceeds the annual variation, whereas at longer wavelengths it is less. The total observed peak-to-peak variation in the UV irradiance from 120 to 300 nm over a solar rotation is typically at least 230 $ergs/cm^2$ s.

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF DONALD F. HEATH

MR. LONDON: The Nimbus-3 observations showed, for some of the filtered measurements in the ultraviolet, a fairly pronounced solar rotation period in the shorter wave ultraviolet. Was there a similar solar rotation period in the Nimbus-4 observations? And, if the ultraviolet is related to magnetic sector fluctuations, should there not then be a semirotation period in the variation rather than a solar rotation period? Should there not be a 14-day rather than a 27-day period?

MR. HEATH: The variations are similar both on Nimbus-3 and -4 and, at times when you have the two active regions, they are separated by about 180 degrees in solar longitude.

QUESTION: As I remember, what was shown in the Nimbus-3 results was a full solar rotation period in the fluctuation, not a 14, but on the order of 27-day.

MR. HEATH: (Referring to figure — Ed.) Two curves in Figure 1 represent the two very long-lived active regions, and they are about 180 degrees apart in solar longitude, so there is UV enhancement essentially twice per solar rotation.

MR. RASOOL: What were these enhancements?

MR. HEATH: In the case of Lyman-alpha, typical variation in 1969 was the order of enhancement of 25 percent above the normal background during that solar rotation. In the case of 1750 angstroms, it was of the order of 5 to 6 percent enhancement over one solar rotation; that is, per each active region. If there were two, you would have two peaks of that magnitude, and, for the longest wave length, 2900 angstroms, it was only during the very high period of solar activity during the spring of 1969 that we saw an enhancement of the order of 1 percent at 2900 angstroms.

MR. RASOOL: How is this related to your statement about the order of magnitude increase at 2900 angstroms?

MR. HEATH: If I use the same sensor which gives these data, and I compare the absolute values of the solar radiance which are derived from the rocket flight in 1966, at solar minimum with the satellite data beginning in 1969 at solar maximum and continuing into 1970, then the difference is about an order of magnitude at 2900 and also at 1750 angstroms but not at Lyman-alpha.

N74-29082

THE AURORA AS A SOURCE OF PLANETARY-SCALE WAVES IN THE MIDDLE ATMOSPHERE

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ABSTRACT

Photographs of global-scale auroral forms taken by scanning radiometers onboard U.S. Air Force weather satellites in 1972 show that auroral bands exhibit well-organized wave motion with typical zonal wave number of 5 or so. The scale-size of these waves is in agreement with that of well-organized neutral wind fields measured by the 1967-50B satellite in the 150- to 200-km region during the geomagnetic storm of May 27, 1967. Further, the horizontal scale size revealed by these observations is in agreement with that of high-altitude traveling ionospheric disturbances. It is conjectored that the geomagnetic storm is a source of planetary and synoptic scale neutral atmospheric waves in the middle atmosphere. Although there is, at present, no observation of substorm-related waves of this scale size at mesospheric and stratospheric altitudes, the possible existence of a new source of waves of the proper scale-size to trigger instabilities in middle atmospheric circulation systems may be significant in the study of lower atmospheric response to geomagnetic activity.

The dynamics of the upper stratosphere, and perhaps the lower thermosphere as well, have been shown to be strongly affected by the interaction of mean zonal winds with planetary Rossby waves (Charney and Drazin, 1961; Newell and Dickinson, 1967; Finger et al., 1966; Dickinson, 1968; Matsuno, 1970). Clearly, a source of Rossby waves in the stratosphere would be that associated with large-scale tropospheric weather systems. However, if a second source of such planetary or synoptic scale waves were to exist, then it would be of considerable interest to workers concerned with upper atmospheric dynamics. In particular, if such a second source of neutral atmospheric waves were related to geomagnetic activity, and if suchwaves were of the proper dimensions to interact with the upper atmospheric circulation, then they may act as the initiating perturbations to trigger latent aerodynamic instabilities in the upper atmosphere.

In this paper, we would like to suggest, by invoking recent satellite observations of planetary-scale variations of auroral forms (Morse et al., 1973), as well as direct satellite observations of polar upper atmospheric winds during magnetic storms (Feess, 1968; Chiu, 1972), that auroral substorms may be a source of planetary waves in the 100-km altitude region. It is understood that numerous observations of ionospheric and atmospheric disturbances associated with geomagnetic activity have been reported from time to time; however, upon examination, most of these are either in the high altitude regions (~350 km) or of such local nature that the lateral extent of the disturbance cannot be ascertained.

Traveling ionospheric disturbances occurring in the 200- to 800-km altitude region have been observed for many years (Thome, 1968; Davis and daRosa, 1969). Well correlated ionospheric disturbances of ~2000-km horizontal scale and of ~1- to 2-hr periods have been observed to propagate from the auroral zone at speeds of ~500 m/s. These disturbances have been interpreted generically as due to the passage of gravity waves. Since the horizontal scale and wave speed are so large, being reminiscent of long waves in the ocean, at least two intriguing questions must be raised. First, since aurorae occur at the 100-km level, it would be of interest to ask if these high-altitude ionospheric disturbances may be related to variations of the low-altitude aurorae and associated neutral disturbances. Second, if such large scale disturbances were indeed neutral waves, then it would be of interest to investigate the effects of sphericity and the latitudinal variation of the Coriolis force on their propagation. These questions will be considered in some detail here in order that the peculiar properties of these waves in the auroral region may be exploited for observational purposes. In this respect, it is perhaps relevant to note that, while meridional propagation of ionospheric disturbances has been studied thoroughly in the midlatitude region, observations of the horizontal scale and propagation of such disturbances in the auroral region do not seem to be available.

Figure 1 shows an extensive auroral form detected by scanning radiometers on board a U.S. Air Force weather satellite (Morse et al., 1973). The most important feature revealed by this unique observation of planetary scale auroral forms is that the aurora shows coherent spatial variations typical of a wave with zonal wave number 3 to 6. Since auroral substorms show typical temporal variations of, say, 1 to 2 hours, these observations suggest clearly that auroral substorms, as a source of atmospheric heating in the vicinity of 100 km, must be rich in Fourier components of these zonal wave numbers and wave periods. Indeed, there is theoretical reason to believe that such spatial and temporal variations of the aurora are related to waves in the auroral current (Hasegawa, 1970). Given the existence of such wave-like variations of auroral heating, it is reasonable to consider meridional and vertical propagation of such planetary waves, to lower latitudes and to higher altitudes, in the interpretation of traveling ionospheric disturbances.

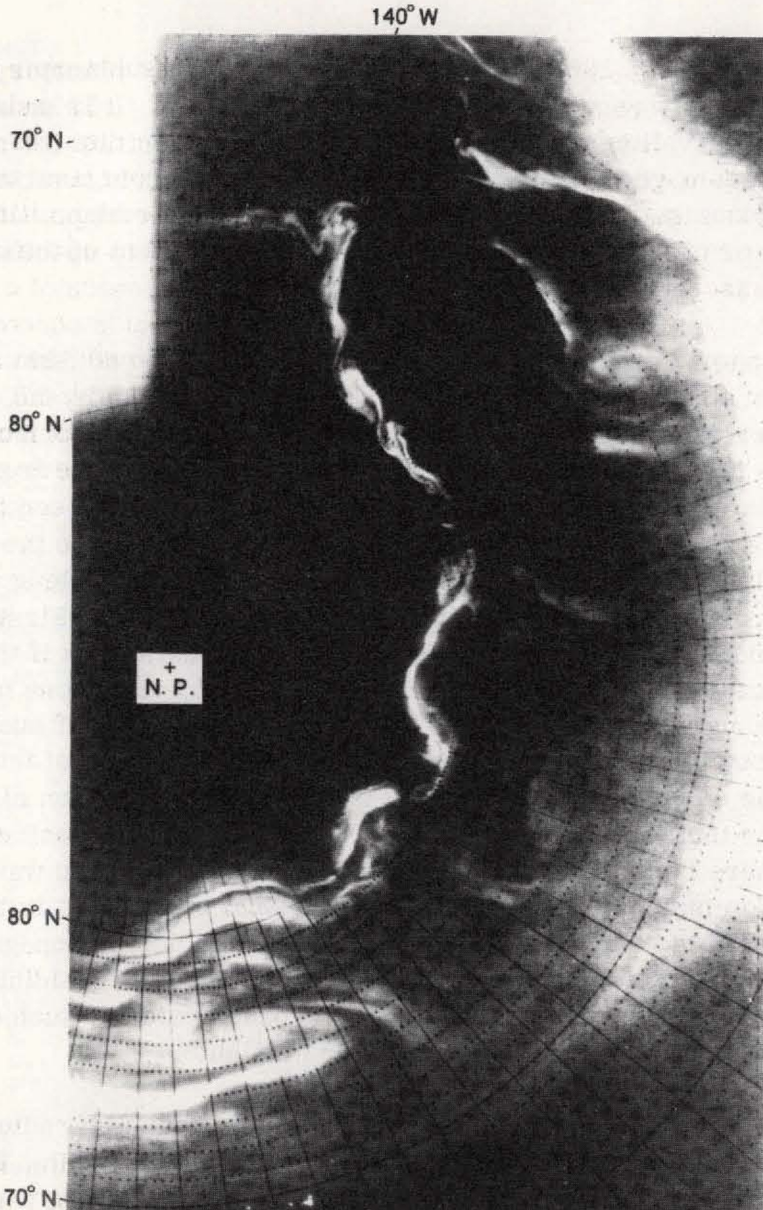

Figure 1. An extensive auroral form observed by scanning radiometers on board a U.S. Air Force weather satellite near the north auroral zone at 13.51 GMT on August 1, 1972. The origin of the grid on the photograph is the north geographic pole. It is seen that, aside from small scale variations of <100-km horizontal scale, the auroral form exhibits planetary scale variations with zonal wave number ~5. The coherent extensiveness of the associated auroral heating is particularly significant. (Courtesy E.H. Rogers and D.F. Nelson, The Aerospace Corporation.)

Despite the observation of clearly wave-like variation of planetary scale auroral heating, direct observations of the neutral wind field associated with such wave motion would be desirable in order to substantiate the suggested relation between the characteristics of auroral forms and traveling ionospheric disturbances. In short, are there in situ satellite observations of upper atmospheric wind fields in the auroral region directly related to specific geomagnetic storms? In this regard, we wish to point out that the pattern of cross-track wind components, deduced from accelerometer and attitude control activity on board the 1967-50B satellite at altitudes between 150 and 220 km before and after the onset of a very large geomagnetic storm on May 27, 1967, are of particular interest (Feess, 1968). Figure 2 shows data from selected orbits in which well organized cross-track wind variations were encountered.

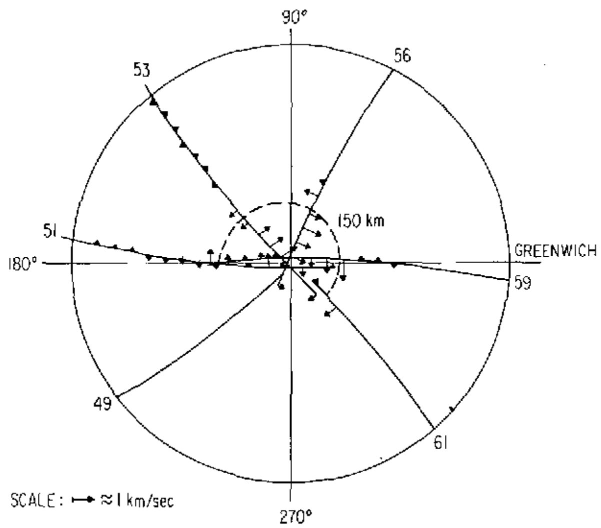

Figure 2. Lower thermospheric winds deduced from accelerometer and attitude control activity on board the satellite 1967-50B on May 27, 1967 near the north geographic pole, the origin of the figure. The satellite paths are labeled by the orbit numbers (49-61) and the dashed curve indicates the locus of points for which the satellite altitude is 150 km. The polar plot shows the measurements for the northern hemisphere. The magnetic storm onset was at the 50th orbit. It is seen that well-organized wind components with a horizontal scale of ~2000 km seem to be associated with an extremely disturbed but stationary structure at the pole. These features are particularly well-illustrated on orbits 51, 53, and 59. It should be noted that both features are coherent and planetary in scale. (After Feess, 1968; for summary see also Chiu, 1972.)

Although the major stationary structure near the pole may involve convective over-turning of the atmosphere (Chiu, 1972), the coherent wind variations of smaller magnitude, which change from orbit to orbit, are likely to be propagating waves of ~2000 km horizontal scale. These structures are particularly evident at or near satellite orbits 51 and 53.

The next question then is how the stratosphere responds to the same magnetic storm. In this regard, it is a fortunate coincidence that detailed radiosonde data exists for Berlin during the same period (Scherhag, 1967). Figure 3 shows Scherhag's data for the period March to June 1967. The top three curves show the stratospheric temperature at 30, 35, and 37 km. The bottom curve shows the thickness between the 5 and 10 mb levels in decameters. Scherhag noted that all four curves show a rapid rise to a peak during the period May 25-26, 1967. This becomes somewhat more evident if we take the sum of all four curves so that the random signal is reduced. Indeed, the sum shows 3 clear events (April 24, May 3, and May 26) which interestingly occurred during the most magnetically disturbed days of the period (ΣK_p = 32, 47, and 51 respectively).

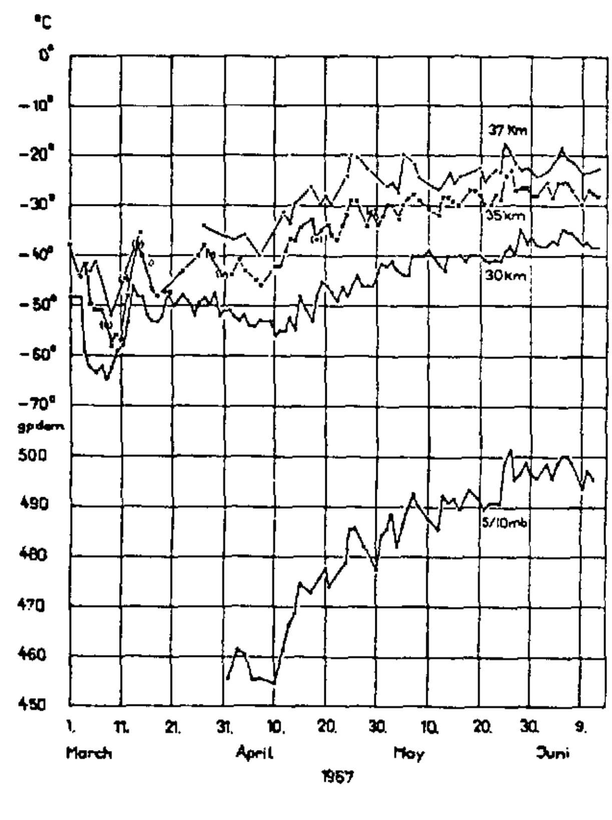

Figure 3. Stratospheric temperatures at 30, 35, and 37 km and the 5- to 10-mb thickness for the period March to June 1967 (Scherhag, 1967).

In conclusion, there seems to be some in situ evidence that the auroral substorm is a source of planetary waves in the 100 km region neutral atmosphere. These neutral wind disturbances may have caused some stratospheric response, although data from a wider area would be required to confirm it. In any event, we emphasize that detailed testing of any theoretical mechanism reduces, in the final analysis, to an in situ layer by layer correlation study of the responses from thermospheric levels to the stratospheric levels.

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF Y. T. CHIU

MR. AKASOFU: I don't think you can associate that type of picture of the aurora with Rossby waves because in a matter of 10 minutes, the pattern of the aurora might change drastically. I understand that Rossby waves are a much more stable phenomenon. These are very high-latitude phenomena at geographic latitudes above approximately 70; and I am sure that Rossby waves are at something like latitude 50.

MR. CHIU: I agree that the phenomenon is not a Rossby wave. The point, however, is that the auroral heating would have a spatial structure of 2000 kilometers, even though it changes in a few minutes. If you consider the aurora, or the particle deposition associated with it, as a heating source which produces waves, then it would be rich in the Fourier components in spatial structure of 2000 km. I am not trying to associate Rossby waves with the auroral waves.

N74-29083

DIRECT SATELLITE OBSERVATIONS ON BREMSSTRAHLUNG RADIATION AS A TECHNIQUE TO INVESTIGATE ITS ROLE IN METEOROLOGICAL PROCESSES

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ABSTRACT

It has been suggested by Roberts and Olson that bremsstrahlung radiation associated with strong auroras (in turn associated with geomagnetic disturbances) may cause increased ionization near the 300-mb level which in turn leads to the formation of cirrus clouds. These clouds could then modify the outgoing blackbody radiation rates and thus influence weather patterns. Recently, the first satellite observations on bremsstrahlung produced in the atmosphere by precipitating energetic electrons have been reported by Imhof, Nakano, Johnson, and Reagan. This type of observation affords the possibility of directly monitoring the bremsstrahlung energy input to the lower atmosphere over large segments of the earth and at frequent intervals. Detailed measurements on the spatial and energy distributions of the bremsstrahlung are feasible with present techniques and satellite data on widespread bremsstrahlung events are presented and discussed. From comparison of the ion production rates from cosmic rays with those calculated for bremsstrahlung from precipitating energetic electrons, it is concluded that bremsstrahlung is a negligible contributor to the ionization near the 300-mb level.

Recent results on the correlations between interplanetary magnetic sector boundaries and weather patterns (Wilcox, 1973) have provided added support for earlier evidence (Roberts and Olson, 1973a) of connections between solar activity and weather. The evidence for these connections has recently been reviewed by Roberts and Olson (1973b). Although various hypotheses have been advanced for the physical processes connecting the two phenomena, none have been generally accepted for lack of adequate experimental data and for lack of detailed understanding of atmospheric and magnetospheric processes. The purpose of this paper is to assess the validity of one such hypothesis and to discuss satellite observations and techniques that are pertinent to the investigation of the role of bremsstrahlung radiation in meteorological processes.

The first satellite observations on bremsstrahlung produced in the atmosphere by precipitating energetic electrons have recently been reported by Imhof, Nakano, Johnson and Reagen (1974). The bremsstrahlung measurements were obtained with a 50-cm^3 germanium spectrometer (a second spectrometer failed at launch) placed on the low-altitude, polar-orbiting satellite 1972-076B. The satellite was launched on October 2, 1972, into a sun-synchronous noon-midnight orbit (inclination = 98.4°) with a perigee of 736 km and an apogee of 761 km. The satellite is spin stabilized with a rotation period of approximately five seconds and an on-board tape recorder provides capability for nearly worldwide coverage. The Ge(Li) detector cooling is achieved with a solid CO_2 cryogen system, and pulse-height analysis of the detector output provides energy spectra of the bremsstrahlung above 50 keV. The instrument is collimated to ±45° with a high-density (predominantly tungsten) shield and plastic-scintillator anticoincidence counter and is oriented at 75° to the spin axis of the satellite. The collimator is ~20 cm long, providing a relatively sharp cutoff angle and a geometric factor of 27 cm^2 s. Several energetic particle spectrometers provide spectral measurements on the energetic electron and proton fluxes. The details of the instrumentation are provided in other reports (Nakano et al., 1974; Bakke et al., 1974; and Imhof et al., 1974).

The geometry for observing the bremsstrahlung associated with electron precipitation is shown schematically for two spectrometers in Figure 1 to illustrate that even at altitudes near 750 km a large fraction of the region of electron precipitation at high magnetic latitudes can be observed. Since the satellite is spinning with a period that is very small compared to the time for traversal over a region of interest, the gamma-ray spectrometer scans the bremsstrahlung source distribution repeatedly. During a pass of the satellite over the polar cap successive triangulations are made on each point within a large portion of the precipitation region. In Figure 1 the shaded "circles" indicate schematically the fields-of-view of the spectrometers for different positions of the spinning satellite and the shaded "band" indicates schematically a region from which bremsstrahlung is observed from electrons precipitating into the atmosphere. For future payloads designed especially to observe the bremsstrahlung, the extent of the region observed could be increased by widening the fields-of-view of the sensors or by increasing the satellite altitude. Thus, with current technology, the bremsstrahlung produced in the atmosphere by precipitating energetic electrons at the higher latitudes could be observed at all longitudes from a satellite about every two hours. From the energy distributions of the observed bremsstrahlung, the ion production rates as a function of altitude could then be calculated.

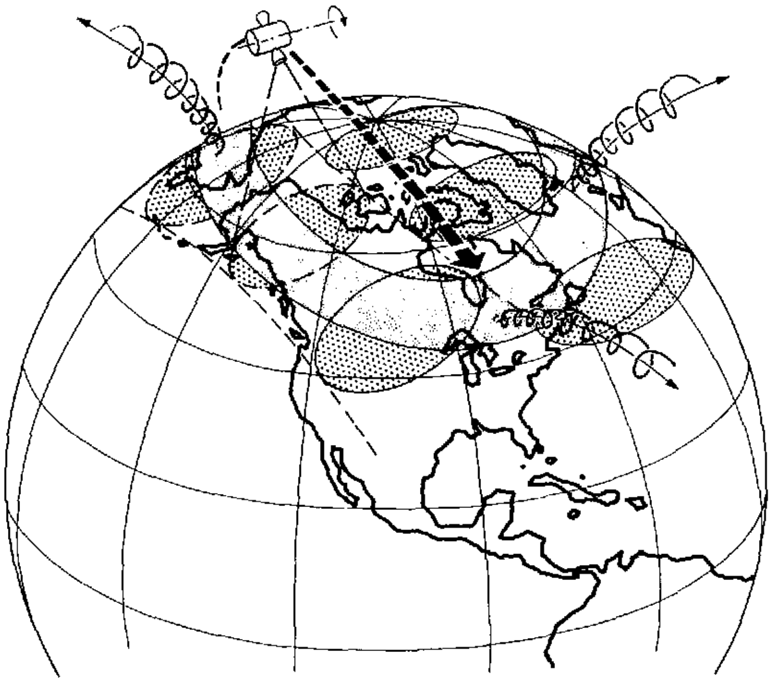

Figure 1. Schematic illustration of the geometry for observing the bremsstrahlung associated with electron precipitation at high latitudes. The shaded "circles" indicate schematically the fields-of-view of the spectrometers for different positions of the spinning satellite and the shaded "band" indicates schematically a region from which bremsstrahlung is observed.

An example of the bremsstrahlung and electron observations from the 1972-076B satellite is shown in Figure 2. These data are from a pass over the northern polar region, and the location of the outer Van Allen radiation belt can be seen from the top curve showing a detector response to electrons with energies greater than 160 keV. The second curve from the top is the gamma-ray spectrometer response to X-rays in the energy range from 50 to 75 keV. The large gamma-ray response in the outer radiation belt is primarily from bremsstrahlung produced by the trapped electrons striking the shielding covering the collimator entrance. This response is generally modulated twice per spin period reaching a maximum each time the spectrometer is oriented at 90° to the earth's magnetic field line. However, the gamma-ray spectrometer shows an additional response on each side of the outer belt that is found from the satellite orientation data to come from below the satellite and to occur when the spectrometer is viewing regions of the atmosphere where electrons are precipitating. The third and fourth sections from the top show data from the polar cap region on expanded scales to illustrate the angular variation of the response with satellite position. The bottom sections are averaged over 24 successive spins to improve statistics. These data were

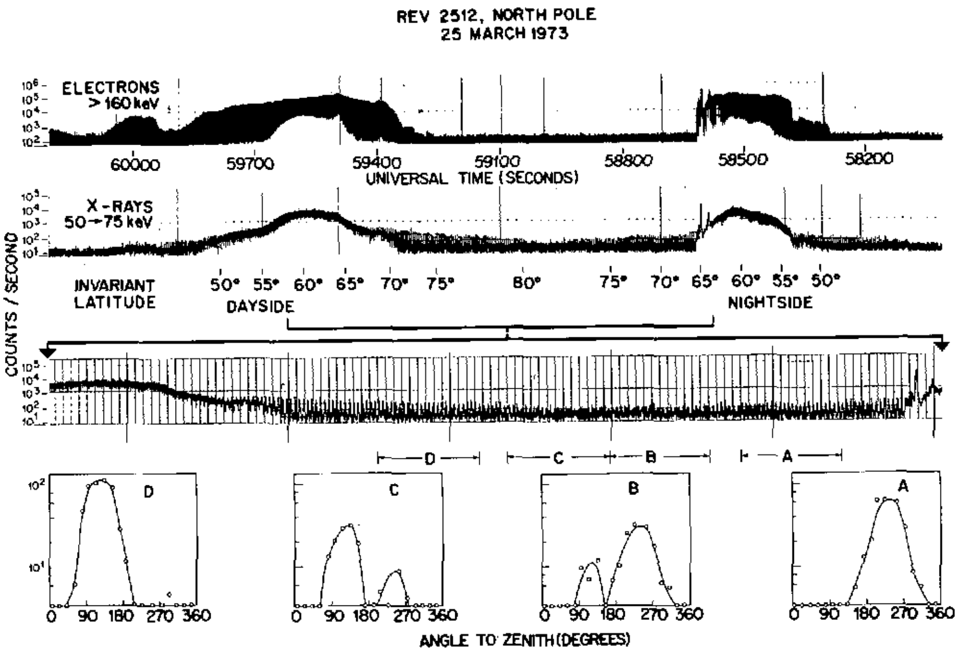

Figure 2. The responses of the electron and gamma-ray spectrometers during passage of the satellite over the north polar region at a time of great magnetic disturbance. The counting rates of X-rays in the energy range 50 to 75 keV are also shown for two different expanded time scales. In the bottom row the counts have been grouped in angle intervals of 18° and each angular distribution is summed over 24 spins.

taken during a magnetically-disturbed period; normally the levels of bremsstrahlung from the atmosphere are near or below the detectability threshold for the spectrometer. Since the energy threshold of the present gamma-ray measurements is higher than that employed in many of the balloon observations and since the electron energy spectra are generally quite soft, the present data, in contrast to the bulk of the balloon measurements, are more representative of very intense and more energetic precipitation from the outer radiation belt. Bremsstrahlung from auroral electrons, whose energy flux is typically dominated by electrons with energies below 20 keV (Sharp, Carr, and Johnson, 1969), would not be observed in the present experiment.

Using the measured gamma-ray counting rate profiles and the known geometries of the gamma-ray detector and the satellite, it is feasible to obtain information on the local time distribution of the bremsstrahlung from the atmosphere. Several examples of the local-time dependences of the precipitation levels as derived from the bremsstrahlung observations by least-squares-fitting techniques are shown in Figure 3 (Imhof et al., 1974). The

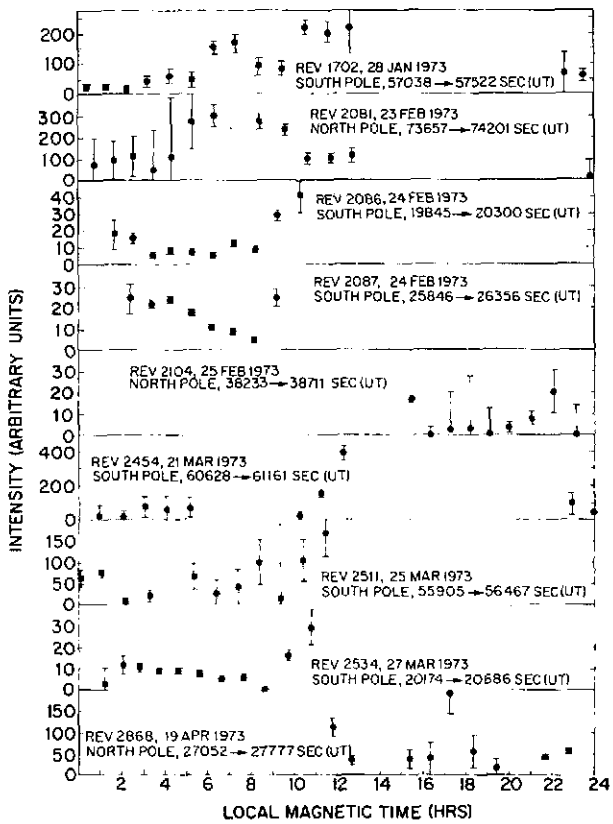

Figure 3. The best fit intensities obtained from the least-squares-fits to the bremsstrahlung data plotted as a function of local magnetic time.

majority of these cases favor coverage in the morning hours. Since the satellite is in a noon-midnight orbit (descending node in daylight) and the viewing cone of the spectrometer is centered about a vector pointing 15° to the right of the satellite orbit plane, in the majority of passes the spectrometer responds primarily to sources located in the midnight-to-noon interval. Coverage with the spectrometer of the afternoon and early-evening portions of the precipitation region is generally possible only for selected longitudes which are favorable as a result of the geomagnetic field axis being offset from the earth's spin axis. With the data from two spectrometers pointing in somewhat different directions, as illustrated schematically in Figure 1, all local times can be covered with nearly equal probability.

In the limited number of cases shown, the bremsstrahlung is found to be widespread in local time (or longitude) and the local time profiles display large variations in character. However, the precipitation levels near local noon are generally greater than in the early morning hours. In this regard the average time profiles of these individual intense and large-scale events are generally consistent with the time-averaged profiles obtained from localized measurements of the precipitation of greater than 40-keV electrons (Imhof et al., 1974).

To explain the correlation between geomagnetic disturbances and weather cell characteristics, Roberts and Olson (1973a) have suggested that bremsstrahlung radiation associated with strong auroras may cause increased ionization near the 300-mb level which in turn could lead to the formation of cirrus clouds. To test this hypothesis, the ion production rates from bremsstrahlung radiation have been calculated as a function of altitude for several typical spectra of electrons precipitating into the atmosphere and for some of the bremsstrahlung spectra observed from the 1972-076B satellite. The general agreement between the observed bremsstrahlung spectra and the bremsstrahlung spectra calculated from the precipitating electron fluxes measured on the same satellite have been reported by Imhof et al. (1974). Two examples of the ion production rate calculations along with the cosmic ray ion production rate at solar maximum (Webber, 1962) are shown in Figure 4. The cosmic ray production at high latitudes during solar minimum is about three times higher. The ion production rate for bremsstrahlung from the "auroral" electrons is shown for an electron energy distribution that is exponential in form and has a characteristic energy, E_o, of 6 keV. The intensity of 10 ergs/cm^2 -s corresponds to an aurora of moderate intensity and is about a factor of ten higher than the average nightside auroral particle energy input for the magnetic latitudes of 65° to 70° during a four-day period that was moderately active magnetically (K_p varied from 0_+ to 8_o) (Sharp, Carr, and Johnson, 1969). The characteristic energy, E_o, for these data, when fit with an exponential spectral form, averaged about 6 keV. It is seen from Figure 4 that the ion production rate resulting from the "auroral" electron spectrum is about 10 percent of the cosmic-ray ion production rate at 37 km and the percentage decreases rapidly at lower altitudes. The direct ionization from the auroral electrons occurs principally at altitudes above 90 km.

The calculated ion production rate is also shown in Figure 4 for an electron spectrum of exponential form with E_o equal to 100 keV and a flux of 1.3 x 10^6 electrons/cm^2 -s. This intensity is the median value of the maximum encountered on several satellite passes during times of high geomagnetic disturbance on February 23, 1973 and March 20, 1973. Although the precipitating fluxes are sometimes larger by an order of magnitude (Imhof et al., 1973b; Rosenberg et al., 1972), such fluxes occur relatively infrequently compared to those used in the calculations. It is seen that the direct ion production rate by these electrons is larger than the cosmic ray ion production rate down to about 55 km. The ion production rate from the bremsstrahlung produced by these electrons becomes 10 percent of the cosmic ray ion production rate at about 28 km and the percentage decreases rapidly at lower altitudes.

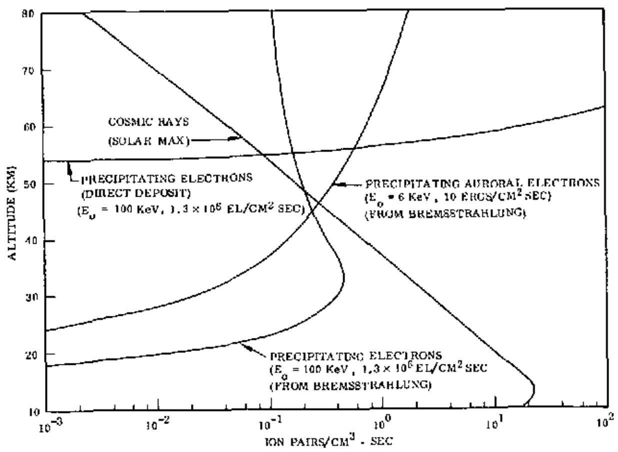

Figure 4. The ion production rate as a function of altitude from the bremsstrahlung and the direct deposit of energy by precipitating electrons with e-fold energies of 6 keV and 100 keV, respectively. The cosmic-ray ion production rate at solar maximum is also shown (Webber, 1962).

From the foregoing calculations and from comparisons of the measured bremsstrahlung spectra with calculations of the bremsstrahlung production from typical radiation belt electrons, we conclude that the ion production rate from bremsstrahlung produced by energetic electrons precipitating into the atmosphere is a negligible fraction of the cosmic ray ion production rate near the 300-mb level. Thus, we conclude that bremsstrahlung is not an important factor in influencing weather patterns via the formation of cirrus clouds near the 300-mb level as proposed by Roberts and Olson (1973a,b).

It is evident from the foregoing considerations that bremsstrahlung radiation from precipitating electrons can at times significantly increase the ionization in the atmosphere at altitudes above about 25 km. Since this increased ionization will increase the atmospheric conductivity, bremsstrahlung radiation may be important in processes suggested by Markson (1973) for influencing the atmospheric electricity and the related development of thunderstorms. He suggests, however, that the most likely mechanism involves the variation in the conductivity over thunderstorms at somewhat lower levels, namely in the 10- to 20-km height range. Changes in the conductivity by a factor of two at 41.5 km due to bremsstrahlung radiation during a magnetic storm have been measured in a balloon-borne experiment (Williamson, 1973).

Bremsstrahlung radiation could also contribute to changes in the atmospheric composition as a result of the ionization produced at altitudes primarily in the 25- to 90-km range. Although a change in the atmospheric composition has been suggested as a possible mechanism to link solar activity to meteorological processes, some control of the precipitation rates, and thus of the meteorological processes may eventually prove to be feasible. Brice (1970, 1971a, b) and others (see Cornwall, 1972) have suggested that particle precipitation from the radiation belts should be feasible using cold gas injection into the magnetosphere. Also, an experiment is presently being conducted to precipitate energetic electrons from the radiation belts using VLF electromagnetic waves transmitted from Siple, Antarctica (Helliwell, 1973).

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF R. G. JOHNSON

MR. RASOOL: What is the flux difference in cosmic rays from solar maximum to solar minimum?

MR. JOHNSON: It is relatively small. I think it is of the order of 10 or 20 percent kind of effect. In this connection, one should bear in mind that the variation of the interplanetary medium is sufficient to cause modulation of the cosmic rays of the order of a few percent, so as soon as the bremsstrahlung contribution drops to a few percent, they would be of comparable magnitudes. If bremsstrahlung is important as a dynamic effect, one would suspect that that must occur at altitudes above which the bremsstrahlung is more than a few percent of the cosmic rays.

SESSION 2

VARIABILITY OF SOLAR INPUT TO THE EARTH'S ATMOSPHERE

Robert W. Noyes, Chairman
Smithsonian Astrophysical Observatory

N74-29084

SOLAR FLUX AND ITS VARIATIONS

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INTRODUCTION

This paper is intended to be a review of what we know about the photon flux from the sun at all wavelengths, and its variations. The emphasis has been placed on coming up with values for the solar constant (total electromagnetic energy flux from the sun incident on the earth), the solar irradiance (wavelength distribution of the flux) of use to workers in the geophysical-meteorological field, and the variation of the irradiance as a function of solar activity. Accordingly, emissions shortward of 2 Å and longwards of 2 cm have been ignored, as the total energies involved are exceedingly low.

We shall begin with a review of the general nature of the solar spectrum. At radio and infrared wavelengths (10,000 Å to 2 cm), the solar spectrum is essentially a continuum, with the bulk of the emission occuring from progressively higher regions in the solar atmosphere at the longer wavelengths. Below 10,000 Å, occasional absorption lines appear superimposed on a photospheric continuum, becoming more and more numerous as we go towards the UV. Around 5000 Å, about 10 percent of the continuum flux is blocked by lines; near 3500 Å, about 40 percent. The continuum flux drops off sharply below 4000 Å, but the fraction of the energy absorbed in lines remains high until about 2100 Å. Here, a sharp decrease in continuum flux occurs, coincident with the Al I ionization edge, and the absorption lines all but disappear. The photospheric continuum flux continues to drop off, and emission lines begin to appear around 1750 Å. The last absorption lines die out near 1500 Å, and the photospheric continuum itself dominates over the emission lines only until 1300 to 1400 Å. Shortward of this wavelength, chromospheric and coronal emission lines dominate until the coronal continuum begins to make itself felt below 100 Å. From 2 to 100 Å, one finds a mixture of continuum and lines; both are coronal in origin. Special mention should be made of the extremely strong Lyman-alpha emission line of HI at 1216 Å. The flux from just this line usually exceeds the combined flux from all shorter wavelengths.

In the next section we discuss the solar spectrum of the quiet sun in detail and in Part III we investigate variations, especially in X-rays and UV emissions, caused by flares, plages, and other effects.

THE QUIET SUN

FLUX VERSUS SPECIFIC INTENSITY

Two types of measurements of solar radiation are commonly made: the flux from the entire disk, and the specific intensity measured over a small area at the center of the disk.

The quantity we need is the solar irradiance (the solar flux at 1 A.U.) which can be derived directly from the total solar flux according to:

$$H = \pi(r^2/R^2)\ F = 6.80 \times 10^{-5}\ F$$

where H is the solar irradiance, F is the total solar flux, r is the radius of the sun, and R is 1 A.U. We use the units $W/m^2 \cdot Å$ to specify H.

Converting specific intensity to solar irradiance requires knowledge of the limb darkening at each wavelength. Such data are not always available, especially in the far UV. We have deduced limb darkening values at many wavelengths below 1800 Å where direct observational data are very incomplete.

Once limb darkening is known, the flux can be calculated by:

$$F = \frac{1}{\pi} \int I\,(o)\ \ L(\theta)\ \cos\theta\ dw$$

where I(o) is the specific intensity at the center of the disk, θ is the angle between the sub-earth point and position on the disk, and $L(\theta) = I\ (\theta)/I(o)$ is the limb darkening.

THE VISIBLE REGION: 3300 TO 10,000 Å

In the wavelength region 3300 to 10,000 Å we adopt the data of Labs and Neckel. They made specific intensity measurements of over one hundred 20 Å bandpasses at Jungfraujoch during 1961 to 1964 (Labs and Neckel, 1967). The authors estimate their errors to be everywhere less than about 1 percent. Labs and Neckel (1968) later combined their data with limb darkening data from David and Elste (1962) to obtain the solar irradiance in 100 Å bands. Finally, Labs and Neckel (1970) report a minor revision to transform their values to the International Practical Temperature scale of 1968, incorporating the revised value of the melting point of gold. It should be noted that there is an error in the caption to Table 7 of Labs and Neckel, 1970, in that the units given should read $\mu W/cm^2$.

Other observations of the solar flux at visible wavelengths have been made, for example, by Arvesen et al. (1969), Drummond et al. (1968); see also Laue and Drummond (1968). The Labs and Neckel data are in good agreement with most of those observations; further, they marshall very good arguments in favor of their values, based on reanalyses of previous data. Moreover, the Labs and Neckel results are almost precisely identical to the Willstrop (1965) data for the G^2 V star, HD 20766.

For these reasons, we have adopted the Labs and Neckel data from 3300 to 10,000 Å.

THE NEAR INFRARED: 10,000 TO 24,000 Å

The Labs and Neckel data end at 12,000 Å; longward of this wavelength we rely on measures by Arvesen et al. (1969) and Pierce (1954).

Pierce's data are on a relative scale, but the absolute calibration was provided by Labs and Neckel (1968). The scaling was done by adjusting Pierce's data to the models of Gingerich, et al. (1971) and Holweger (1967).

When the data were plotted (see Figure 1), it became clear that they could be fit with a series of straight lines of the form

$$\log F = \alpha + \beta \log \lambda$$

where λ is the wavelength in Å, F is the irradiance in $W/m^2Å$, and α and β are listed in Table 1.

LONGER WAVELENGTHS: 25,000 Å TO 2 cm

Above 25,000 Å, data have been taken from several sources. Farmer and Todd (1964) used spectra to get one data point at 45,000 Å. Koutchmy and Peyturaux (1970) report measurements from the Pyrenees Mountains for seven wavelengths from 38,000 to 200,000 Å. Murcray et al. (1964) have balloon data for 40,000 to 50,000 Å, and Saiedy and Goody (1959) and Saiedy (1960) report three measurements near 100,000 Å.

The gap between the far infrared and the radio region is bridged by four data points from Eddy et al. (1969), who used a NASA aircraft for their observations. Linsky (1973) has published a compendium and recalibration of work from 0.1 to 2 cm and then derived a mean relation.

In many cases, the data are given as a brightness temperature, but this can be converted to irradiance by:

$$H = \frac{8.09 \times 10^{-21}}{\lambda^5 (e^{1.44/\lambda T} - 1)}$$

where λ is the wavelength in cm, T is the brightness temperature in °K, and H is the irradiance in $W/m^2 Å$.

The data are presented in Figures 1 and 2. Once again, they are fit by straight line segments, as above, and the value of the coefficients is given in Table 1.

THE NEAR ULTRAVIOLET: 2100 TO 3300Å

For this spectral region, we adopt the Broadfoot (1972) rocket data. Unfortunately, his data extend only from 2100 to 3200Å, with the last 100 Å being rather uncertain. Labs and Neckel (1968, 1970) data extend down only to 3300 Å. To bridge this gap, and to determine if the two sets of data are consistent, we use the Arvesen et al. (1969) data from 3000 to 3300 Å, first scaling these data by a factor of 0.87 to get them to the Labs and Neckel scale. Table 2 presents the results. The scaled Arvesen data points from 3100 to 3300 Å have been adopted. For 3000 to 3100 Å, the agreement of the data is very encouraging, and so shortward of 3100 Å, we use Broadfoot's data.

THE FAR ULTRAVIOLET: 1400 TO 2100 Å

In this region of the spectrum, the absorption lines fade out, emission lines begin, but the photospheric continuum dominates the flux.

Relatively good intensities are available from 1400 to 1900 Å from Bruckner and Nicolas (1973), Rottman (1973) as quoted in Donelly and Pope (1973), and Parkinson and Reeves (1969).

We prefer these data to the higher values obtained by Bonnet and Blamont (1968) and Widing et al. (1970). The adopted lower values, besides being very self-consistent, yield a value of 4400 °K for the temperature minimum in agreement with infrared data. Further, Carver et al. (1972) report on some 50 Å resolution data from WRESAT I ion chambers which are also in good agreement with the adopted data. We used the Bonnet and Blamont limb darkening curves together with values derived from Dupree and Reeves (1971) data to convert the intensities to irradiances. Figure 3 depicts the data and the limb darkening (F/I) values used.

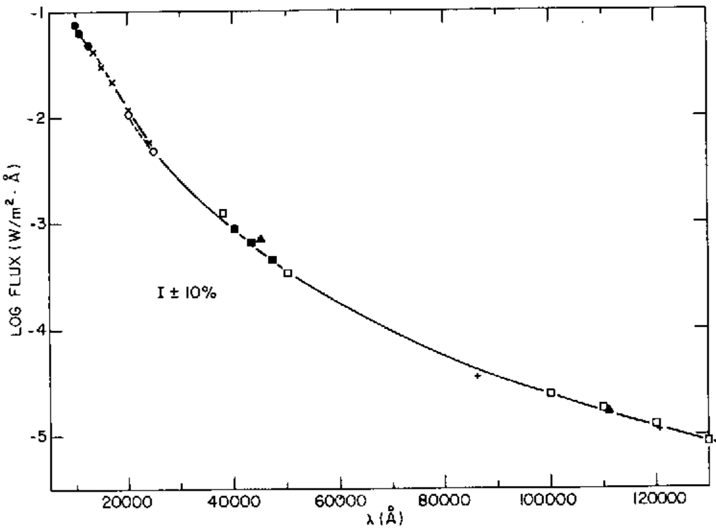

Figure 1. The solar flux in the infrared. Data is from: filled circles, Labs, and Neckel, 1968; x, Arvesen, et al. 1969; open circles, Pierce 1954; open squares, Koutchmy and Peyturaux 1970; filled squares Murcray 1969; filled triangles Farmer and Todd 1964; plus signs Saiedy 1960; filled triangle near 100,000 Å, Saiedy and Goody 1959.

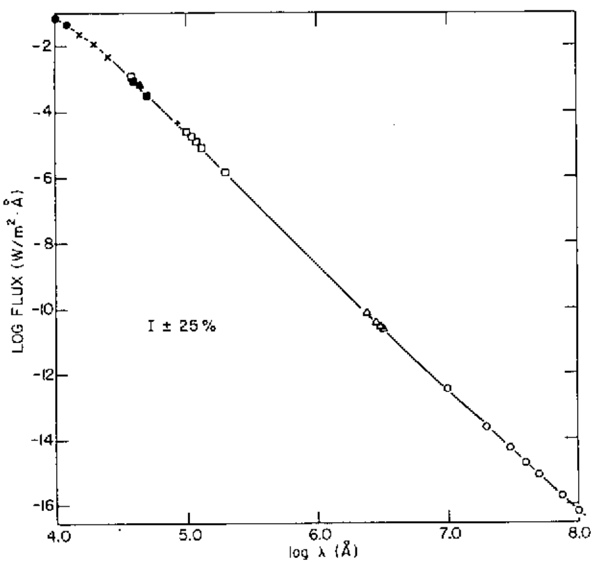

Figure 2. Solar irradiance in the microwave region. Solid line is the adopted fit. Data is from: filled circles, Labs and Neckel 1968; x, Arvesen et al. 1969; open squares, Koutchmy and Peyturaux 1970; filled squares, Murcray 1969; filled triangles, Farmer and Todd 1964; plus signs Saiedy 1960; open triangles, Eddy et al. 1969; open circles, Linsky 1973.

Above 1900 Å we have less reliable data. We use the shape, but not the absolute calibration, of the Bonnet and Blamont (1968) and Widing et al. (1970) data, and scale them to fit both Figure 3 and Broadfoot's (1972) data. The very abrupt rise in flux from 2075 to 2100 Å is real. This corresponds to the Al I ionization edge, and appears clearly in spectra.

THE EXTREME ULTRAVIOLET: 500 TO 1400 Å

Below 1400 Å, the solar spectrum is dominated by chromospheric and coronal emission lines. Contributions are also made by the continua of CI, HI, and He I.

Virtually all available data is from the OSO satellites. Irradiance values come from OSO-3 (Hall and Hinteregger, 1970) and OSO-4 (Reeves and Parkinson, 1970). Specific intensities from OSO-6 (Dupree, et al., 1973) are available for more lines and probably at better accuracy. Dupree and Reeves (1971) have some additional specific intensities from OSO-4.

Since we wish to base our evaluation on the OSO-6 data, some knowledge of limb darkening is necessary. Fortunately, the effect is small for most lines (Noyes and Kalkofen, 1970; Withbroe, 1970a, 1970b). However, for some high ionization potential lines, there is limb brightening.

To evaluate F/I we have compared the OSO-6 data to the fluxes from Reeves and Parkinson (1970). Here I is defined as the flux as if there were no limb effect. F/I turned out to be a function of ionization potential and wavelength:

F/I =	1.201 + 0.0114 I.P. (eV)	800 - 1400 Å
	1.350 + 0.0068 I.P. (eV)	600 - 800 Å
	1.069 + 0.0014 I.P. (eV)	500 - 600 Å

Table 3 presents the irradiances for each line.

We made allowance for the continua of CI, HI, and He I, as well as a correction to allow for the extended wing of HI (Δ1216 Å). The data used were from Dupree and Reeves (1971).

The HI (Δ1216 Å) line is by far the strongest present. A profile of the line is given by Bruner and Rense (1969).

SOFT X-RAYS: 2 TO 500 Å

The coronal continuum contributes significantly to the total solar flux below 100 Å, but from 100 to 500 Å the flux comes almost entirely from emission lines.

What is meant by "quiet" sun becomes a critical consideration at these wavelengths. In general, a "quiet" sun would have a sunspot number of $R \sim 10$ to 40 and no large plages. Such conditions occur routinely near solar minimum and sporadically at other times.

By "active," we mean $R \sim 100$, but no flares present. An "active" sun is typical around solar maximum.

X-ray data come from a variety of satellite and rocket measurements. At the shorter wavelengths, we rely heavily on Wende's 1972 recalibration of earlier data. Culhane et al. (1969) and Kreplin and Horan (1969) also provide some data. Figure 4 shows these results for 1 to 11 Å and presents our adopted values for the active, moderate, and quiet sun.

For wavelengths longward of 20 Å, we use Freeman and Jones (1970), Argo et al. (1970), Manson (1972), and Malinovski and Heroux (1973). Figure 5 shows the results.

THE SOLAR CONSTANT

Table 4 presents the results of this section in the form of solar irradiance averaged over small wavelength intervals. Figure 6 depicts much of the same information; here, however, we include several short-wavelength curves to indicate the effect of solar activity on the flux. Table 5 presents the percentage of the total solar flux emitted shortward of each of a number of wavelengths for the four conditions indicated in Figure 6.

The total solar constant (quiet sun) which we derive is 1357.826 W/m^2 at 1 A.U. (= 1.947 cal/cm^2 min). A comparison of this value with previously derived values as presented in NASA Report SP-8005 (1971) is made in Table 6. Note that our value is towards the upper end of the high altitude results and near the lower end of the ground-based results.

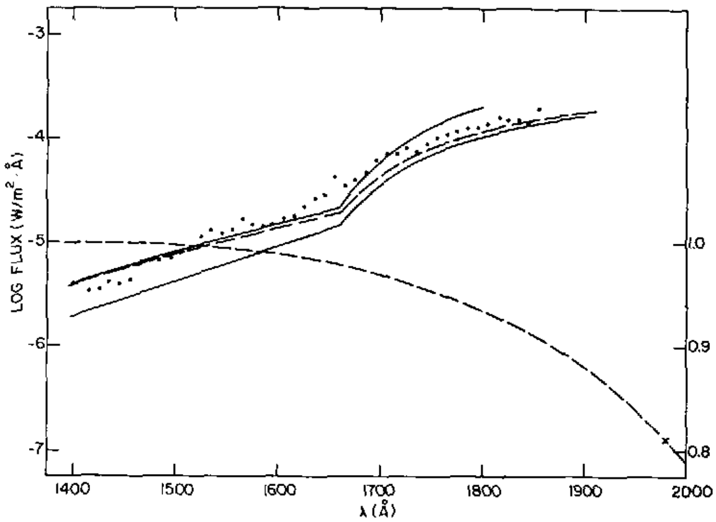

Figure 3. Solar irradiance in the ultraviolet. The dash line is the adopted limb darkening (scale at right). The dots are from Rottman 1973; the upper solid line is from Nicolas 1973, the lower solid line is from Parkinson and Reeves 1969, and the dash line between the two is the adopted limb darkened solar irradiance.

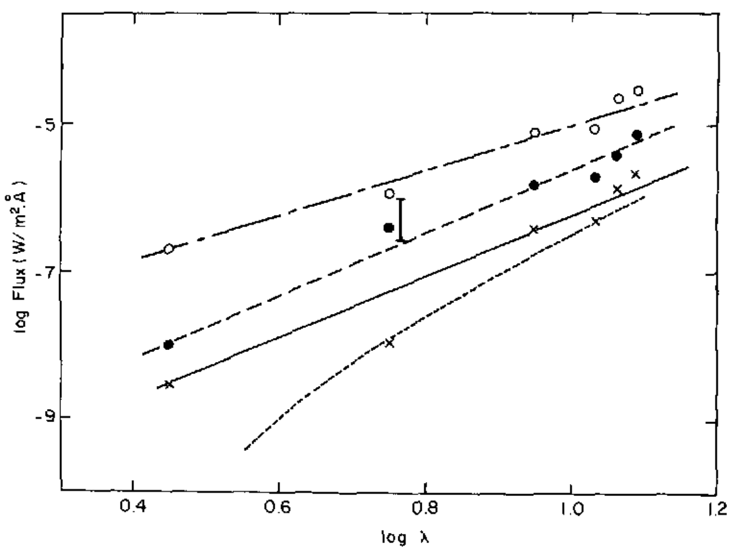

Figure 4. Solar irradiance in the X-rays. Open circles are Wende's (1972) his active sun, filled circles are his moderate sun, and x's are his quiet sun. Lines through the data are the adopted fits. The vertical bar is from Kreplin and Horan 1969, at a time of moderate activity. The dashed line towards the bottom is from Culhane et al. 1969, for an extremely quiet sun.

VARIATIONS DUE TO SOLAR ACTIVITY

INTRODUCTION

Solar flux variations fall into natural categories determined by their time scales. Flares have the shortest life times—of the order of minutes. The slowly varying component encompasses changes over hours to days, and is due to the appearance, development and disappearance of active regions. Closely related to this is the 27-day period, which results from the reappearance of active regions as the sun rotates. Finally, the 11-year cycle reflects the correlation of all solar activity with the sunspot cycle.

FLARES

We start our discussion with the shortest-lived and most energetic phenomena: flares. Flares are traditionally observed in (and, in fact, are defined by) the enhancement of the Hα radiation, even though flux increases are frequently proportionally higher for X-rays and for the far ultraviolet. The coincidence of Hα flares with short wavelength radiation enhancements is by no means one-to-one. While many investigators have found a strong correlation of Hα flares with X-ray bursts, some X-ray bursts may be associated with other short-lived chromospheric phenomena, such as active prominences (Hoover, Thomas, and Underwood, 1972).

Optical flares are classified according to the area and brightness of the Hα radiation. Table 7 summarizes this classification system. The frequency of occurrence depends on the phase of the 11-year solar sunspot cycle; flares are most numerous during sunspot maximum. During solar maximum flares of importance 1 or greater appear on the average every 2 to 2 1/2 hours. For X-ray bursts, Drake's (1971) analysis yields approximately the same figure, as his threshold of detection was at a value typical of an importance 1 flare.

Smith and Booton (1961) found that approximately 79 percent of all flares of importance 1 or greater are of importance 1; 19 percent are of importance 2, and about 2 percent are of importance 3 or greater. The proportion of high importance flares should probably be revised downwards, however, on the basis of new data and more reliable classifications (Dodson and Hedeman, 1971). These proportions vary little, if any, with phase of the solar sunspot cycle (Smith, 1962).

Small, low importance flares occur in far greater abundance than the large bright importance 3 or 4 flares. Small events (subflares or other chromospheric events that may trigger X-ray emission) are even more prolific, especially during solar maximum. Good statistics on these are not available. Undoubtedly the lower the threshold, the larger the number of events. We do not concern ourselves unduly with small events, as the fluxes involved are not substantial; however, they may be of use as predictors of larger events.

Any average figures on flare occurrence are, however, somewhat misleading, for some active regions are far more flare productive than others. Frequently, several major flares occur within a few days out of the same active region. An outstanding example of such a multiple series of events is represented by the August 1972 flares. Furthermore, one solar cycle may be far more flare productive then another. Cycle 19 (1954 to 1963) produced 77 proton flares, but cycle 20 produced less than half as many.

Nor can we use the sunspot number to predict frequency of flare occurrence. Major flares are less closely correlated with sunspot number than are lesser flares. Since the major flares are responsible for the most dramatic variations in flux, this makes it virtually impossible to predict X-ray flux in terms of the sunspot number, except on the most general statistical basis. To make matters even worse, the cycle for major events, such as proton flares, may be doubly peaked, with the second maximum occurring during the decline of the sunspot cycle (Gnevyshev, 1967; also see below). The resurgence of activity represented by the August 1972 flares in cycle 20 is quite analogous to the post-maximum phase of activity in cycles 17, 18, and 19 (Dodson and Hedeman, 1973).

To further complicate the attempt to give a figure for the frequency of occurrance of major flares, it is now apparently accepted that proton flare producing regions are not distributed randomly in solar longitude (see The 27-Day Period below). The distribution of sunspots, however, does not portray such a nonrandom organization.

All these qualifications should be kept in mind when interpreting Table 8, which summarizes our knowledge of the frequency of flares over the sunspot cycle. Most of the data used to prepare Table 8 comes from Smith and Smith (1963) and Dodson and Hedeman (1971). We now examine in further detail the characteristics of flares in several wavelength intervals.

Characteristically, soft X-ray bursts have a rise time close to 4 minutes, and a decay time of 12 minutes (Drake 1971). Many bursts have a superimposed short impulsive phase, of one or two minutes duration, occurring near the start of the flare. For hard X-rays (~1 Å or shorter) this phase consists

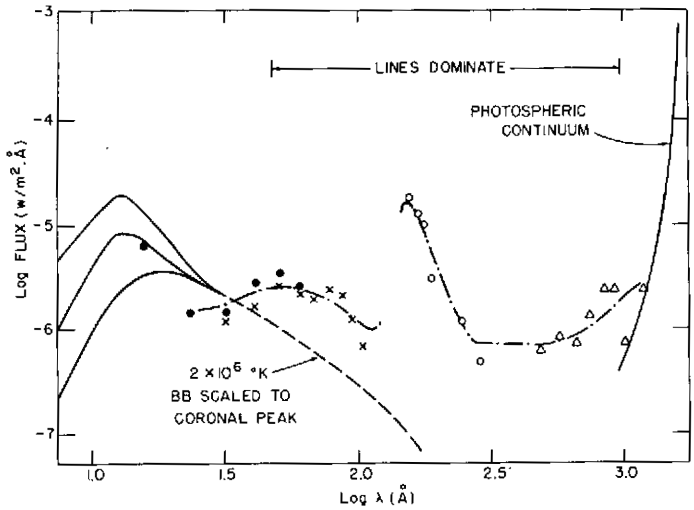

Figure 5. Solar irradiance in the ultraviolet and X-rays. Data is from: Solid line to left is from Figure 4; solid line to right is from Nicolas 1973; filled circles and open circles, Freeman and Jones 1970; x, Manson 1972; open triangles, various OSO results. The dashed-dotted line is an arbitrary fit.

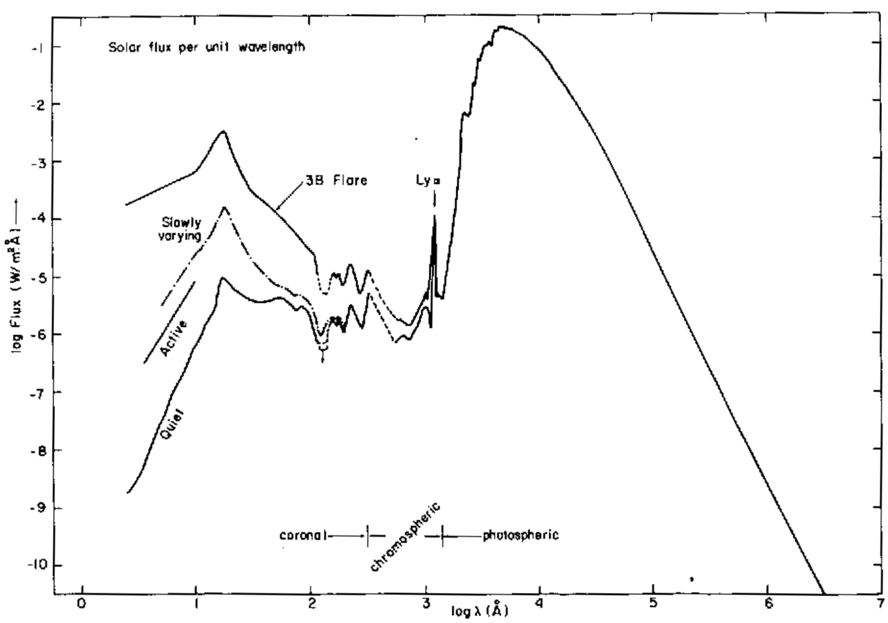

Figure 6. Summary of solar irradiance at all wavelengths.

of numbers of even shorter spikes, with time scales from under 1 second up to 10 seconds. The impulsive phase dominates increasingly with hardening of the X-rays (Frost, 1969). Another way of stating this is that the hardness of the X-rays decreases with time after the onset of an event. Figure 7 is an example of an X-ray event at several wavelengths.

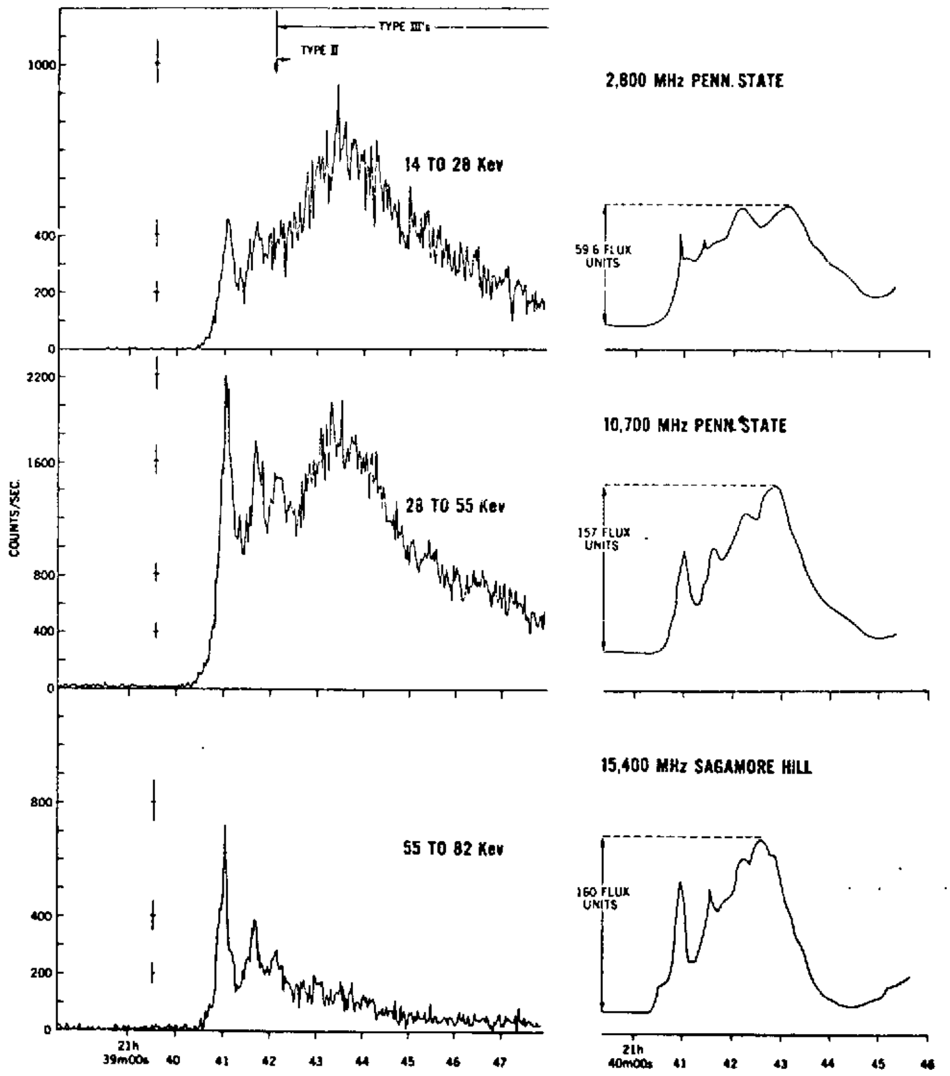

Figure 7. X-ray spectrum of a solar flare at three wavelengths from Frost 1969.

The relationship between soft X-ray peak flux (2 to 20 Å) and Hα flare importance classification has been ambiguous, for there are large deviations from the mean relation between them. Nevertheless, analyses of significant numbers of flares (Hoover, Thomas, and Underwood, 1972; Drake, 1971) point to the existance of such a relationship, particularly with the brightness of the Hα flare (Krieger et al., 1972) as opposed to its area. Large deviation from the mean correlation may be partly explained by the fact that the X-ray flux is also affected by the general level of solar activity and nature of the plage region in which the flare occurs (Hoover et al., 1972). In general, though, we may state that large bright Hα flares frequently produce large X-ray fluxes. Small flares never produce large X-ray bursts. Conversely, strong X-rays are always accompanied by some Hα event, though it may occur behind the solar limb (implying a coronal origin for the X-rays).

We obtain typical soft X-ray peak fluxes in large flares from the data of Dere et al. (1973), who used the NRL Solrad-10 satellite to observe the series of large flares in August 1972. These data also provide useful information on the fluxes of smaller flares. Table 9 presents the results. Although coronal emission lines between 2 and 20 Å arising from highly ionized ions are very greatly enhanced during a flare, most of the contribution to the flux in this spectral region is due to the continuum (Neupert, 1971).

From 20 to 1400 Å emission lines dominate the spectrum. Unfortunately, we are not aware of any published data on overall EUV enhancements at the time of major flares, and it is of course risky to extrapolate. The estimated enhancement and fluxes in Table 5 are based on extrapolations, using the enhancement in the X-ray wavelengths, Hall's (1971) measurements of several emission lines, and Heath's (1969) measures at HI Lyman-α (1216 Å) and longer wavelengths.

For the EUV line emission from 300 to 1400 Å the enhancement varies widely from one line to another, depending on the ionization potential and the wavelength. Highly ionized ions are present but weak in the quiet sun spectrum. During flares, the integrated emission in these lines from the entire sun increases by a factor of two or three (Neupert, 1967). Chromospheric lines show considerable enhancement over the flare area (Wood and Noyes, 1972; Hall, 1971), but when the small fraction of the solar disk covered by the flares is taken into account, the total enhancement only amounts to about 1 to 2 percent for a subflare, 10 percent or less for an importance 1 flare, and 25 to 50 percent for an importance 2 flare.

Hall (1971) found an empirical relationship between the enhancement of EUV lines in terms of Hα flare areas, namely $E \propto kA^{3/2}$, where Å is the Hα flare area and k is a constant of proportionality which ranges from less than 0.4 for HI, HeI, and some coronal lines to 2.4 and 2.8 for chromospheric lines like SI III λ 1206 and O VI λ 1032. Caution must be exercised in using this relationship, however, for it is based on relatively little data and does not allow for the large known differences between flares.

The two types of flares discussed above under X-rays exist in the EUV as well (Kelly and Rense, 1972). The impulsive EUV events are associated with the impulsive nonthermal X-ray events (Wood and Noyes, 1972). The time of maximum for such events is nearly the same at all wavelengths (Wood et al., 1972). Time scales run around 2 minutes.

The gradual EUV burst is associated with the gradual thermal X-ray bursts (Wood and Noyes, 1972). The time of maximum in the EUV is about one or two minutes before the X-ray or Hα maximum (Wood et al., 1972; Hall, 1971). Time scales are around 5 to 10 minutes.

Lyman-α of HI is of course the strongest line in the EUV, and is treated separately from the general EUV flux, though the data are surprisingly sparse. The profile shown in Figure 8 is a quiet sun profile due to Bruner and Rense (1969). Measurements by Heath (1973) and Hall (1971) indicate an overall enhancement from the entire disk in Lyman-α of 16 to 18 percent for an importance 3 flare.

At longer wavelengths the enhancement due to flares becomes negligible. Heath (1969) observed a 3B flare on April 21, 1969, with intermediate band filters centered around 1800 and 2950 Å. Any enhancement was less than 1 percent.

Note that only a small fraction of even the brightest Hα flares are known to be visible in white light. DeMastus and Stover (1967) measured the white light enhancement of a band centered around 5800 Å during a 3B flare. They found a 16 percent enhancement in a small kernal covering around 10^{-5} of the solar surface. Using these data, we estimate maximum enhancements in the visual and near infrared (4000 to 12500 Å) to be about 10^{-5} to 10^{-6} for even major flares. Nevertheless, three absorption lines in the visible spectrum are affected sufficiently to warrant mention: Hα and the H and K lines of Ca II.

Zirin and Tanaka (1973) measured the Hα flux for the August 4 and August 7, 1972, importance 3B flares and find total energies of 2.0×10^{30} and 2.5×10^{30} ergs. These figures are an order of magnitude lower than previous estimates for similar flares. The authors attribute the discrepancy to the fact that earlier estimates assumed that the wide line widths and high central intensities prevailed over the entire area of the flare and for most of its lifetime. These observations show that much of the Hα emission is concentrated into bright short-lived kernels and that the excessive line width (12 Å or more) occurs only in these kernels. The above quoted energies represent an Hα total disk enhancement of about 0.1 percent in the central 1 Å passband, where the emission may be as great as three times the local continuum (Jefferies et al., 1954; Smith and Smith, 1963). It is much less, of course, in the neighboring wavelengths.

The H and K lines of Ca II ($\lambda \sim 390$ Å) are also enhanced in flares. We can only estimate the enhancement in the basis on the basis of flare line profile information (for example, Smith and Smith, 1963). Peak intensities may exceed the local continuum by a factor of 3 within 1 Å of the line center. The whole disk enhancement is then about 0.5 percent.

THE SLOWLY VARYING COMPONENT (NONPERIODIC)

The term "slowly varying component" was originally used to refer to the day-to-day changes of the solar radio flux. The radio emission responsible for the overall increased flux was identified with regions lying above chromospheric plages. These plages are best observed in the visual as areas of enhanced Hα or CaII K-line emission. X-rays and ultraviolet radiation exhibit variations similar to those in the radio region, hence the term "slowly varying component" has been applied to these radiations also. The entire volume encompassing visual, X-ray and radio plage, enhanced magnetic fields, sunspots, and coronal enhancements constitutes an "active region."

A rapid rise in flux and a slow decay characterizes the slowly varying component as it does all solar activity, from flares to the 11-year cycle. An active region may last as long as several solar rotations, but its most active phase is early in its life.

According to Sawyer (1968), the increase in total visible solar radiation due to a single plage is miniscule, amounting to about 0.1 percent; however, it may be as much as 100 percent in certain EUV emission lines and 50 percent at ratio frequencies. The major effect of a plage however, occurs for X-rays. As a rule, the shorter the wavelength, the greater the amplitude.

SOLRAD data (Friedman and Kreplin, 1969; Kreplin, 1970) extend over several years and are ideal for studying variations on a time scale from hours to months

In March 1966, near solar minimum, there was only a single active region on the solar disk; thus it was possible to ascertain the flux enhancement caused by one typical active region. Kreplin (1970) found that the overall solar flux increased by a factor of 100 in the 0-to-8-Å range and a factor 50 in the 8-to-20-Å band as the region rotated into view on the solar disk.

Typical month-to-month variations due to the slowly varying component would be a factor of 15 at 16 Å and a factor of 1.7 at 50 Å (Kreplin, 1970). We might be expect, occasionally, factors of 100 at 5 Å. The month-to-month variation will be greatest during the rise to and decline from maximum of the solar cycle. During minimum, the scarcity and weakness of active regions prevent large variations; during maximum, the large number of active regions present forces a statistical "constancy" on the total flux.

In addition to the variations caused by the appearance and disappearance of active regions as the sun rotates, the slowly varying component also includes a contribution due to the development of an active region. For example, Krieger et al. (1972) found an increase of a factor of 20 in a 4-hour period at 10 Å, while Kreplin (1970) reported a similar decrease over 2 days at 16 Å. Both of these variations were due to changes in the structure of an active region.

The amplitude of enhancements in the EUV is far less, down to a factor 1.5 at 50 Å (Hall and Hinteregger, 1970), 1.1 at 1350 Å, and 1.05 at 1700 Å (Heath, 1973). At longer wavelengths, there is probably no substantial variation, based on an extrapolation of Heath's (1969) flare data. Since this region is dominated by line rather than continuum emission, the strengthening of a few strong lines plays a major role.

Reeves and Parkinson (1972) find that typical chromospheric lines (with excitations up to about that of Fe X) vary about 10 percent. Chapman and Neupert (1973) also find a 10 percent average variability for lines from 140 to 400 Å for a change of 10-cm flux corresponding to quiet-to-active. They would increase this to 20 percent for the shorter wavelength lines. The variation for Lyman is of the order of 30 percent (Vidal-Madjar, et al., 1973).

In strong contrast, the total flux from the high ionization lines of Fe XVI (335 Å) and Fe XV (284 Å) change by a factor 4 because of the appearance or disappearance of an active region (Neupert, 1967).

Figure 9 shows the peak variations observed as a function of wavelength based mainly on the SOLRAD data. Note that the slowly varying component falls approximately mid-way between the 3B flare curve and Wende's (1972) "typical active sun."

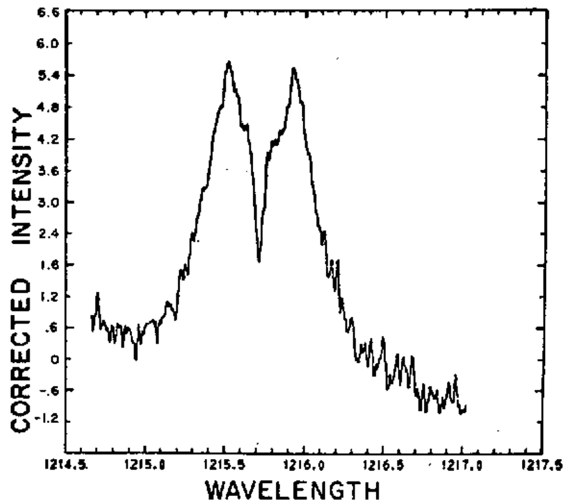

Figure 8. The profile of the Lyman alpha line, from Bruner and Rense, 1969.

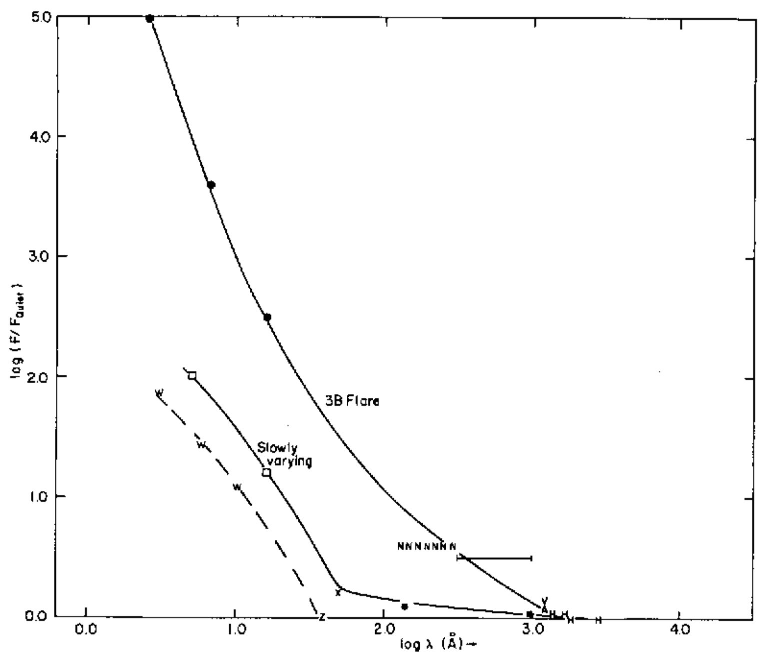

Figure 9. Variations in the solar irradiance. Data is from: filled circles, Dere et al., 1973; horizontal bar, Hall, 1971; V, Vidal-Madjar et al., 1973; A, Heath 1969, Lyman alpha; H, Heath and Heath 1973; open squares, Kreplin 1970; X, Hall and Hinteregger 1970; stars, Reeves and Parkinson 1972; W, Wende 1972; Z, from Figure 5.

In the visual, the largest-fluctuations occur in the H- and K-lines of CaII. On the basis of the increased Ca II K-line emission in plages, which is on the average 20 percent of the continuum (Smith, 1960), and the area of a plage (up to half a percent of the disk) one can estimate that the overall enhancement in the line cores due to an active region may be at most 5 percent.

The Mg II lines at 2803 and 2795 Å behave very similarly to the Ca II lines; Fregda (1971) found a correlation coefficient of 0.92 between the intensities of the Mg II K line (Δ2795) and the Ca II K line. The emission cores are far more pronounced in the Mg II lines than the Ca II lines, so that the percentage enhancement due to active regions is somewhat greater.

As to the visual continuum, we use Rogerson's (1961) work on faculae, the photospheric counterpart of plages. Faculae are only visible near the limb, and reach a maximum contrast of $I_{facula}/I_{photosphere} = 1.6$ at a heliocentric distance of $\cos\theta = 0.2$. Even for a large facula that would cover 5×10^{-3} of the solar disk when at central meridian, this still produces an enhancement of only 0.1 percent.

Variations in any other part of the visible spectrum, including Hα, are dwarfed by those in the H- and K-lines, and can safely be ignored. The same is true for the infrared. Not until one reaches the radio frequencies do we find that plages make a significant contribution to the overall flux. However, the energies and fluxes at radio radiations are so low as to be insignificant.

THE 27-DAY PERIOD

Whereas the slowly varying component is due largely to the growth and decay of active regions, the 27-day period is caused strictly by the rotation of the sun.

The existence of a 27-day period is quite evident at X-ray wavelengths, but how long it persists in phase, and what the exact value is for the period, are more difficult questions.

Since a single active region may survive for several rotations, a periodicity in the X-ray (and EUV) flux is produced by its appearance and disappearance around the solar limb. This periodicity would persist only for the active lifetime of the region—no more than three or four rotations. However, new active regions tend strongly to form out of the remnants of old ones (Bumba and Howard, 1965). Consequently, localized activity may extend to perhaps a year or so (Heath, 1969).

The existence of a single 27-day period over longer extents of time depends upon the recurrence of major active regions at, or near, the same longitude over extended timescales. The existence of a correlation of major sunspot groups with solar longitude has been pointed out by numerous writers, for example, Sawyer (1968), Haurwitz (1968), Levitsky (1967), Wilcox and Schatten (1967), Sakurai (1966), Warwick (1965), and Guss (1964). The correlation does not exist for normal-size active regions, spot groups or flares, but appears clearly for the most energetic flares and the largest spot groups and active regions. Haurwitz's data goes back the longest (over 100 years), and she determines a period of 27.213 days, which is slightly shorter than the Carrington period of 27.275 days. Of course, the solar rotation period is a function of latitude and altitude, but the shortness of Haurwitz's period, relative to even the fastest of these, is very interesting.

This correlation does not predict any long-enduring 27-day period for the minimum monthly flux in the EUV or in X-rays, but is evidence for a 27-day quasi-periodicity of the very large flares and concurrent strong X-ray bursts, at least over time spans of about 100 years.

Direct observational evidence for a long-enduring 27-day period is limited, but studies of up to a couple of years duration have been reported in the X-ray region by Teske (1971) and Parkinson and Pounds (1971). Radio emission is also known to follow a 27-day period.

The amplitude of the 27-day period can be inferred directly from the data presented in the section on the Slowly Varying Component, since the cause of the periodicity is the appearance and disappearance of active regions around the solar limb.

THE 1-YEAR PERIOD

The varying distance of the earth from the sun over its orbit is cause for a substantial variation in the solar flux. Table 10 presents appropriate factors by which one should multiply the fluxes given here to correct to a certain time of year. The following sine curve approximation for this factor is proportional to the solar distance squared and is accurate to within 0.3 percent at all times:

$$r^2 = 1.0004 + 0.0334 \sin(\text{day} - \text{April } 4)$$

Note that for near ultraviolet, visible and infrared wavelengths this variation swamps those due to flares, the slowly-varying component, and the 27-day and 11-year cycles.

THE 11-YEAR CYCLE

The 11-year sunspot cycle is defined in terms of the periodicity in the number of sunspots and spot groups. The Wolf number, or Zurich number, R, is a function of a combination of the total number of spots and the number of spot groups: $R = K (10g + f)$, where K is a personal factor to bring all measurements to the same scale; g is the number of groups, and f is the number of spots. A closely related datum is the sunspot area (for example, see Tandbert-Hanssen 1967). It varies in phase with R.

Actually, the polarity of the leading spot in a group changes from one cycle to the next, leading to the designation of a "22-year" sunspot cycle. There is little reason to believe that the polarity flip affects any other parameter of the 11-year "subcycle." However, the overall solar magnetic field changes polarity in a similar manner. Thus, the solar and terrestrial magnetic fields are alternately parallel and antiparallel for alternate 11-year solar cycles.

Successive solar maxima differ quite considerably. It has been suggested that alternate maxima have higher R values, but this is by no means clear cut. The IGY (International Geophysical Year) solar maximum of Cycle 19 turned out to be unique in that it was exceptionally active. Since this was a well studied maximum, much of the data obtained there is often assumed to be typical of all solar maxima. Caution should be exercised because of the uniqueness of the activity during this period.

The sunspot number is the most easily measured index of solar activity and in fact, has been traced back to the mid-18th century.

The question is sometimes raised whether the presence of a large number of sunspots does not measurably decrease the solar flux in the visible portion of the spectrum. It is therefore instructive to make some estimates.

An extremely large sunspot may have an umbral area of 600 millionths of the solar disk. The intensity may be as low as a tenth of the photospheric intensity at 500 Å (Zwaan, 1968). The total reduction in flux from such a sunspot is therefore well below 0.1 percent. One can argue that a more realistic estimate must take into account the fact that at solar maximum there are many spots on the solar surface. When the Zurich sunspot R number is 200, the total <u>area</u> of all the sunspots is of the order of 4000 millionths (using upper limits: for example, see Tandberg-Hanssen, 1967). If one makes the extreme assumption that this whole area is umbra at a tenth the photosphospheric intensity, one still only obtains a diminution of 0.4 percent of the total solar flux. Actually, only about one sixth of the sunspot area is umbra, for the larger fraction is the penumbral contribution, with an intensity of about 0.7 the photospheric intensity. So we again arrive at the result that sunspots cause at most a 0.1 percent fluctuation in visible flux. Furthermore brightening in the plage region near large spot groups will make up for part of this deficiency.

Many laymen, and even scientists in related fields, attribute certain effects to sunspots that should properly be attributed to flares or other aspects of solar activity. This confusion arises in large part to the fact that the cycle of solar activity is closely associated with the sunspot cycle. For example, the number and area of Ca II or Hα plage regions is closely related to the sunspot number. Similarly, the correlation with R number of He II λ 304 flux, nonflare X-ray flux at all spectral wavelengths, and radio emission, especially at 10 cm, is very good.

It seems safe to conclude that the 11-year cycle in X-rays, for example, is largely due to the variation in the number of active regions.

There is a strong indication, however, that superimposed on this phenomenon, is a variation of X-ray and EUV emissions from similar active regions over the 11-year solar sunspot cycle (Parkinson and Pounds, 1971; Kreplin, 1970). This is in the sense that emission tends to be greater near solar maximum. An explanation may lie in the higher coronal densities observed near solar maximum, which could amplify the effects of any solar activity present, especially at X-ray wavelengths.

It should be emphasized that the importance and intensity of flares correlates only poorly with sunspot number; therefore, data from such correlations should be used only in the broadest statistical manner.

Kreplin (1970) reports SOLRAD satellite data for the period 1964 to 1969. Solar minimum in the X-rays occurred around July 1964 when the flux at 50 Å was about 2×10^{-6} W/m^2 Å and the flux at 16 Å was below threshold intensity for the experiment ($< 2 \times 10^{-8}$ W/m^2 Å). Van Gils and DeGraaff (1967) have similar data. Maximum occurred around mid-1970 with the monthly-minimum 16 Å flux at that time 25 percent higher than in 1968 or in 1971 (Horan and Kreplin, 1972).

Gibson and Van Allen (1970) used Explorer 33 and 35 measurements to demonstrate a 150 percent rise at 10 Å from July 1966 to December 1968. Using Culhane et al. (1969) to scale the data from one wavelength to another, we find that there should have been another 50 percent rise at 10 Å from December 1968 until maximum in 1970. July 1966 probably presented conditions not too different from minimum.

Thus, for cycle 20, the monthly minimum flux at 10 Å probably rose about 225 percent from minimum to maximum; at 16 Å, the rise was probably about 125 percent.

Allowing for some rise from 1964 to 1966 (previously ignored), and the fact that cycle 20 had a rather low maximum, we estimate that monthly minima will vary by a factor of 3 to 5 at 10 Å and 2 to 3 at 16 Å, from solar minimum to solar maximum.

At longer wavelengths, we have only correlations of fluxes with such things as R and the 10-cm flux to go by in determining the amplitude of variation over the 11-year cycle. As we stated previously, these correlations are very imperfect. The major emission line strengths have been correlated with R. The flux from the He II line at 304 Å, for example, increases by 15 percent as R goes from 50 to 200 (Timothy and Timothy, 1970). This is typical of solar minimum-to-maximum. Vidal-Madjar et al. (1973) report an identical result for Lymanα. Hinteregger (1970) does his correlations with 10-cm flux and gets similar results for other chromospheric lines; however, high excitation coronal lines may vary by a factor of 5 to 10 more.

In the visible regions, no measurements have been made over extended time periods. However, observations of similar stars have failed to turn up any variations (limiting accuracy about 1 percent) over times of about 20 years. We conclude that, longward of 1500 Å or so, there is no variation over the 11-year solar sunspot cycle.

LONGER PERIODS

Periodic variations in the solar flux over time scales greater than 11 years can, for the most part, only be indirectly deduced, as no accurate astronomical observations were made until well into the 20th century. Further, we restrict ourselves to astronomical data in this paper and have not considered geological data to any extent.

Since sunspot numbers are, however, available for several hundred years; some authors have analyzed them for long-term periodicity. If such periods exist, there <u>may</u> be a similar period in solar flux, especially for X-rays.

Numerous analyses of the sunspot number for an 80-year period have been done. Kopecky (1962) reviews some of these. More recently, Hartmann (1971) has used untreated, unsmooth R value from 1700-1950. By plotting alternate cycles as positive and negative, he obtains a convincing portrayal of an 80-year cycle in R. The most recent maximum was in 1950. The amplitude of variation is about 100 in the R number at solar maximum.

Longer-period cycles have been suggested (for example, Henkle, 1972), but the evidence for them is necessarily very weak.

A curious periodicity deduced from the R numbers by Shapiro and Ward (1962) with a 25 to 26 month period may provide an example of the confusion of cause and effect. Shapiro and Ward's power spectrum of the R numbers showed a small, but according to them significant, peak at around 25 to 26 months. This coincides with a similar periodicity for the strength of the stratospheric winds (Veryard and Ebdon, 1961) and other terrestrial phenomenon (Heath, 1973). It has been suggested that the variation in the winds might be due to the sunspot number periodicity (for example, Westcott, 1964); however, it seems more likely to us that the sunspot number periodicity is the result of varying photographic quality of images of the solar disk caused by the atmospheric changes.

THE 26,000-YEAR PERIOD

The procession of the earth's orbit with a period of 26,000 years produces a change in the amount of solar energy received at a given terrestrial latitude. Currently, aphelion occurs very near the middle of northern hemisphere winter; in 13,000 years this situation will be reversed.

LONG-TERM SECULAR CHANGES

While we have omitted theoretical arguments from most of this paper, it seems appropriate to mention that models of stellar evolution, borne out by observations of star clusters, indicate that the sun has been brightening and getting slightly hotter over the past 5 billion years, and will continue to brighten (at near constant temperature) for the next 4 billion years. The rate of brightening is about 1 percent in 50 million years and the rate of solar effective temperature rise has been about 1 K per 25 million years.

ACKNOWLEDGMENT

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Table 1

Coefficients for the Linear Relation Between Log Flux and Log Wavelength

Wavelength Range	Alpha	Beta
10,000 - 12,460 Å	7.670	-2.198
12,460 - 15,000 Å	8.702	-2.450
15,000 - 24,000 Å	13.026	-3.485
24,000 - 40,000 Å	13.820	-3.667
40,000 - 50,000 Å	15.781	-4.093
50,000 - 100,000 Å	14.736	-3.870
100,000 - 200,000 Å	15.534	-4.030
.02 - .238 mm.	15.291	-3.984
.238 - .312 mm.	15.828	-4.068
.312 - 1.0 mm.	13.510	-3.711
1.0 - 3.0 mm.	14.297	-3.824
3.0 - 10.0 mm.	13.598	-3.730
10.0 - 20.0 mm.	12.991	-2.654

Table 2

Various Values of the Solar Irradiance in the Ultraviolet
(The Arvesen data has been scaled to Labs and Neckel)

Wavelength Range (Å)	Solar irradiance (W/m^2 - 100 Å) Arvesen	Broadfoot
3000 - 3100	5.09	5.18
3100 - 3200	6.35	5.82
3200 - 3300	7.81	----

Table 3
Ultraviolet Emission Lines and Their Strengths

Wavelength (Å)	Ion	Irradiance (W/m²)	Wavelength (Å)	Ion	Irradiance (W/m²)
468	----	1.9 (-6)	707	----	9.5 (-7)
469	Ne IV	5.7 (-7)	712	S VI	2.7 (-7)
476	----	8.8 (-8)	718	O II	16. (-6)
482	Ne V	6.2 (-7)	728	S III	1.9 (-7)
489	Ne III	1.4 (-6)	736	Mg IX	3.2 (-7)
499	Si III	7.5 (-6)	744	S IV	4.8 (-7)
507	O III	3.7 (-6)	750	S IV	8.7 (-7)
515	He I	8.8 (-7)	760	O V	3.4 (-6)
521	Si XII	5.6 (-6)	764	N III/N IV	8.1 (-6)
525	O III	1.6 (-6)	770	Ne VIII	6.2 (-6)
537	He I	4.1 (-6)	775	N II	3.0 (-7)
542	Ne IV	7.7 (-7)	780	Ne VIII	3.0 (-6)
550	A1 XI	5.1 (-7)	787	O IV	8.2 (-6)
554	O IV	1.0 (-5)	790	O IV	9.9 (-6)
559	Ne VI	9.3 (-7)	834	O II/O III	1.7 (-5)
562	Ne VI	1.1 (-6)	859	----	1.5 (-6)
568	A1 XI/Ne V	6.3 (-7)	904	C II	5.2 (-6)
572	Ne V	6.5 (-7)	923	N IV	6.4 (-6)
580	O II	7.0 (-7)	931	H I	4.8 (-6)
584	He I	3.2 (-5)	933	S VI	2.9 (-6)
592	----	2.2 (-7)	937	H I	6.1 (-6)
599	O III	3.0 (-6)	944	S VI	1.8 (-6)
609	Mg X	1.8 (-5)	949	H I	9.0 (-6)
616	O II	4.3 (-7)	959	----	3.9 (-7)
625	Mg X	7.7 (-6)	973	H I	1.8 (-5)
629	O V	5.3 (-5)	977	C III	1.4 (-4)
639	Ca VII	3.6 (-7)	988	----	6.2 (-6)
644	O II	4.6 (-7)	991	N III	9.2 (-6)
649	----	1.2 (-7)	1010	C II	1.8 (-6)
657	S IV	4.0 (-7)	1021	S III	1.3 (-6)
661	S IV	1.1 (-6)	1025	H I	6.8 (-5)
671	N II	2.3 (-7)	1031	O VII	4.7 (-5)
681	Na IX	1.4 (-6)	1037	O VI	4.2 (-5)
685	N III	2.8 (-6)	1045	----	6.6 (-7)
692	----	2.5 (-7)	1063	S IV	1.3 (-6)
694	Na IX	5.4 (-7)	1068	----	1.6 (-6)
703	O III	8.1 (-6)	1077	S III	2.6 (-6)

Table 3 (continued)

Wavelength (Å)	Ion	Irradiance (W/m^2)	Wavelength (Å)	Ion	Irradiance (W/m^2)
1085	N II	7.9 (-6)	1215	H I	8.5 (-3)
1122	Si IV	5.1 (-6)	1238	N V	1.3 (-5)
1128	Si IV	5.1 (-6)	1242	N V	1.1 (-5)
1134	N I	2.7 (-6)	1264	Si II	1.7 (-5)
1139	A1 XI/Ne VI	1.2 (-5)	1277	C I	4.0 (-6)
1148	----	3.1 (-6)	1302	O I	3.1 (-5)
1152	O I	3.9 (-6)	1305	O I	8.0 (-5)
1157	C II	4.3 (-6)	1309	Si II	7.1 (-6)
1175	C III	3.8 (-5)	1329	C I	6.4 (-6)
1190	Si II	2.2 (-6)	1335	C II	1.3 (-4)
1194	Si II	6.9 (-6)	1351	----	8.3 (-6)
1199	N-I	1.1 (-5)	1356	O I	7.3 (-6)
1206	Si III	6.9 (-5)	1393	S IV	3.5 (-5)

Table 4
A Summary of the Solar Irradiance at all Wavelengths
(Column 2 gives the per Å irradiance; column 3 gives the total irradiance shortward of and including that interval, and column 4 gives the percentage of the total irradiance occurring at or shortward of that interval.)

Wavelength Range (Å)	Solar Irradiance (W/m^2) per Å	total	percent
2-3	1.8 (-9)	1.8 (-9)	00.000
3-4	5.6 (-9)	7.4 (-9)	00.000
4-5	2.0 (-8)	2.7 (-8)	00.000
5-6	5.0 (-8)	7.7 (-8)	00.000
6-7	1.0 (-7)	1.8 (-7)	00.000
7-8	1.8 (-7)	3.6 (-7)	00.000
8-9	3.2 (-7)	6.8 (-7)	00.000
9-10	5.6 (-7)	1.24 (-6)	00.000
10-11	8.0 (-7)	2.04 (-6)	00.000
11-12	1.12 (-6)	3.16 (-6)	00.000
12-13	1.78 (-6)	4.94 (-6)	00.000
13-14	2.24 (-6)	7.18 (-6)	00.000
14-15	2.64 (-6)	9.82 (-6	00.000
15-20	9.55 (-6)	5.76 (-5)	00.000
20-30	4.57 (-6)	1.03 (-4)	00.000
30-40	3.47 (-6)	1.38 (-4)	00.000
40-50	3.80 (-6)	1.76 (-4)	00.000
50-60	4.17 (-6)	2.18 (-4)	00.000
60-70	3.39 (-6)	2.52 (-4)	00.000
70-80	2.69 (-6)	2.79 (-4)	00.000
80-90	3.09 (-6)	3.09 (-4)	00.000
90-100	2.46 (-6)	3.34 (-4)	00.000
100-110	1.29 (-6)	3.47 (-4)	00.000
110-120	7.1 (-7)	3.54 (-4)	00.000
120-130	near 0	3.54 (-4)	00.000
130-140	near 0	3.54 (-4)	00.000
140-150	1.41 (-6)	3.68 (-4)	00.000
150-160	1.70 (-6)	3.85 (-4)	00.000
160-170	1.41 (-6)	3.99 (-4)	00.000
170-180	1.82 (-6)	4.17 (-4)	00.000
180-190	1.29 (-6)	4.30 (-4)	00.000
190-200	1.00 (-6)	4.40 (-4)	00.000
200-250	3.16 (-6)	5.98 (-4)	00.000

Table 4 (continued)

Wavelength Range (Å)	Solar Irradiance (W/m^2)		
	per Å	total	percent
250-300	1.26 (-6)	6.61 (-4)	00.000
300-350	2.00 (-6)	7.61 (-4)	00.000
350-500	7.9 (-7)	8.80 (-4)	00.000
500-600	6.9 (-7)	9.49 (-4)	00.000
600-700	9.1 (-7)	1.04 (-3)	00.000
700-800	7.8 (-7)	1.12 (-3)	00.000
800-900	1.53 (-6)	1.27 (-3)	00.000
900-1000	2.52 (-6)	1.52 (-3)	00.000
1000-1100	2.82 (-6)	1.80 (-3)	00.000
1100-1200	1.26 (-6)	1.93 (-3)	00.000
1200-1300	8.71 (-5)	1.06 (-2)	00.001
1300-1400	4.47 (-6)	1.11 (-2)	00.001
1400-1500	5.62 (-6)	1.16 (-2)	00.001
1500-1600	1.05 (-5)	1.27 (-2)	00.001
1600-1700	1.78 (-5)	1.45 (-2)	00.001
1700-1800	7.96 (-5)	2.24 (-2)	00.002
1800-1900	1.63 (-4)	3.86 (-2)	00.003
1900-2000	4.00 (-4)	7.86 (-2)	00.006
2000-2100	1.10 (-3)	1.89 (-1)	00.014
2100-2200	4.69 (-3)	6.58 (-1)	00.048
2200-2300	6.41 (-3)	1.30	00.096
2300-2400	5.72 (-3)	1.87	00.138
2400-2500	6.42 (-3)	2.51	00.185
2500-2600	9.05 (-3)	3.42	00.252
2600-2700	2.10 (-2)	5.52	00.406
2700-2800	2.04 (-2)	7.56	00.557
2800-2900	2.90 (-2)	1.05 (+1)	00.770
2900-3000	5.24 (-2)	1.57 (+1)	01.156
3000-3100	5.18 (-2)	2.09 (+1)	01.538
3100-3200	6.35 (-2)	2.72 (+1)	02.005
3200-3300	7.81 (-2)	3.50 (+1)	02.580
3300-3400	9.00 (-2)	4.40 (+1)	03.243
3400-3500	8.94 (-2)	5.30 (+1)	03.902
3500-3600	9.49 (-2)	6.25 (+1)	04.601
3600-3700	10.51 (-2)	7.30 (+1)	05.375
3700-3800	10.40 (-2)	8.34 (+1)	06.141
3800-3900	9.45 (-2)	9.28 (+1)	06.836
3900-4000	11.34 (-2)	1.04 (+2)	07.672

Table 4 (continued)

Wavelength Range (Å)	Solar Irradiance (W/m²)		
	per Å	total	percent
4000-4100	16.31 (-2)	1.20 (+2)	08.873
4100-4200	17.00 (-2)	1.37 (+2)	10.125
4200-4300	16.59 (-2)	1.54 (+2)	11.347
4300-4400	16.72 (-2)	1.71 (+2)	12.578
4400-4500	19.28 (-2)	1.90 (+2)	13.998
4500-4600	20.06 (-2)	2.10 (+2)	15.475
4600-4700	19.86 (-2)	2.30 (+2)	16.938
4700-4800	19.89 (-2)	2.50 (+2)	18.403
4800-4900	18.88 (-2)	2.69 (+2)	19.793
4900-5000	19.56 (-2)	2.88 (+2)	21.234
5000-5100	19.02 (-2)	3.07 (+2)	22.635
5100-5200	18.31 (-2)	3.26 (+2)	23.983
5200-5300	18.59 (-2)	3.44 (+2)	25.352
5300-5400	19.17 (-2)	3.63 (+2)	26.764
5400-5500	18.56 (-2)	3.82 (+2)	28.131
5500-5600	18.41 (-2)	4.00 (+2)	29.487
5600-5700	18.28 (-2)	4.19 (+2)	30.833
5700-5800	18.34 (-2)	4.37 (+2)	32,184
5800-5900	18.08 (-2)	4.55 (+2)	33.515
5900-6000	17.63 (-2)	4.73 (+2)	34.814
6000-6100	17.41 (-2)	4.90 (+2)	36.096
6100-6200	17.05 (-2)	5.07 (+2)	37.351
6200-6300	16.58 (-2)	5.24 (+2)	38.573
6300-6400	16.37 (-2)	5.40 (+2)	39.778
6400-6500	15.99 (-2)	5.56 (+2)	40.956
6500-6600	15.20 (-2)	5.71 (+2)	42.075
6600-6700	15.55 (-2)	5.87 (+2)	43.220
6700-6800	15.16 (-2)	6.02 (+2)	44.337
6800-6900	14.89 (-2)	6.17 (+2)	45.433
6900-7000	14.50 (-2)	6.31 (+2)	46.501
7000-7100	14.16 (-2)	6.46 (+2)	47.544
7100-7200	13.85 (-2)	6.59 (+2)	48.564
7200-7300	13.56 (-2)	6.73 (+2)	49.562
7300-7400	13.16 (-2)	6.86 (+2)	50.532
7400-7500	12.84 (-2)	6.99 (+2)	51.478
7500-7600	12.65 (-2)	7.12 (+2)	52.409
7600-7700	12.36 (-2)	7.24 (+2)	53.320
7700-7800	12.07 (-2)	7.36 (+2)	54.209

Table 4 (continued)

Wavelength Range (Å)	Solar Irradiance (W/m^2)		
	per Å	total	percent
7800-7900	11.83 (-2)	7.48 (+2)	55.080
7900-8000	11.61 (-2)	7.59 (+2)	55.935
8000-8100	11.36 (-2)	7.71 (+2)	56.771
8100-8200	11.04 (-2)	7.82 (+2)	57.585
8200-8300	10.75 (-2)	7.93 (+2)	58.376
8300-8400	10.51 (-2)	8.03 (+2)	59.150
8400-8500	10.06 (-2)	8.13 (+2)	59.891
8500-8600	9.86 (-2)	8.23 (+2)	60.617
8600-8700	9.68 (-2)	8.33 (+2)	61.330
8700-8800	9.47 (-2)	8.42 (+2)	62.028
8800-8900	9.24 (-2)	8.51 (+2)	62.708
8900-9000	9.20 (-2)	8.61 (+2)	63.386
9000-9100	8.98 (-2)	8.70 (+2)	64.047
9100-9200	8.74 (-2)	8.78 (+2)	64.691
9200-9300	8.57 (-2)	8.87 (+2)	65.322
9300-9400	8.41 (-2)	8.95 (+2)	65.941
9400-9500	8.23 (-2)	9.04 (+2)	66.547
9500-9600	8.06 (-2)	9.12 (+2)	67.141
9600-9700	7.89 (-2)	9.20 (+2)	67.722
9700-9800	7.73 (-2)	9.27 (+2)	68.291
9800-9900	7.56 (-2)	9.35 (+2)	68.848
9900-10000	7.39 (-2)	9.42 (+2)	69.392
10000-11000	6.82 (-2)	1.01 (+2)	74.417
11000-12000	5.58 (-2)	1.07 (+2)	78.530
12000-13000	4.64 (-2)	1.11 (+2)	81.943
13000-14000	3.85 (-2)	1.15 (+2)	84.777
14000-15000	3.23 (-2)	1.18 (+2)	87.154
15000-16000	2.67 (-2)	1.21 (+2)	89.118
16000-17000	2.14 (-2)	1.23 (+2)	90.697
17000-18000	1.75 (-2)	1.25 (+3)	91.983
18000-19000	1.44 (-2)	1.26 (+3)	93.042
19000-20000	1.20 (-2)	1.28 (+3)	93.923
20000-30000	5.53 (-3)	1.33 (+3)	97.998
30000-40000	1.53 (-3)	1.35 (+3)	99.125
40000-50000	5.71 (-4)	1.35 (+3)	99.546
50000-60000	2.54 (-4)	1.35 (+3)	99.733
60000-70000	1.32 (-4)	1.36 (+3)	99.830
70000-80000	7.56 (-5)	1.36 (+3)	99.886

Table 4 (continued)

Wavelength Range (Å)	Solar Irradiance (W/m^2)		
	per Å	total	percent
80000-90000	4.64 (-5)	1.36 (+3)	99.920
90000-100000	3.01 (-5)	1.36 (+3)	99.942
(microns)			
10-11	2.02 (-5	1.36 (+3)	99.957
11-12	1.40 (-5)	1.36 (+3)	99.967
12-13	9.97 (-6)	1.36 (+3)	99.975
13-14	7.30 (-6)	1.36 (+3)	99.980
14-15	5.47 (-6)	1.36 (+3)	99.984
15-16	4.18 (-6)	1.36 (+3)	99.987
16-17	3.25 (-6)	1.36 (+3)	99.990
17-18	2.56 (-6)	1.36 (+3)	99.992
18-19	2.05 (-6)	1.36 (+3)	99.993
19-20	1.66 (-6)	1.36 (+3)	99.994
20-30	7.03 (-7)	1.36 (+3)	99.999
30-40	1.72 (-7)	1.36 (+3)	99.999
40-50	6.16 (-8)	1.36 (+3)	100.000
50-60	2.73 (-8)	1.36 (+3)	100.000
60-70	1.39 (-8)	1.36 (+3)	100.000
70-80	7.83 (-9)	1.36 (+3)	100.000
80-90	4.74 (-9)	1.36 (+3)	100.000
90-100	3.04 (-9)	1.36 (+3)	100.000
100-110	2.04 (-9)	1.36 (+3)	100.000
110-120	1.42 (-9)	1.36 (+3)	100.000
120-130	1.01 (-9)	1.36 (+3)	100.000
130-140	7.46 (-10)	1.36 (+3)	100.000
140-150	5.61 (-10)	1.36 (+3)	100.000
150-160	4.30 (-10)	1.36 (+3)	100.000
160-170	3.35 (-10)	1.36 (+3)	100.000
170-180	2.65 (-10)	1.36 (+3)	100.000
180-190	2.12 (-10)	1.36 (+3)	100.000
190-200	1.72 (-10)	1.36 (+3)	100.000
200-300	7.28 (-11)	1.36 (+3)	100.000
300-400	1.80 (-11)	1.36 (+3)	100.000
400-500	6.89 (-12)	1.36 (+3)	100.000
500-600	3.23 (-12)	1.36 (+3)	100.000
600-700	1.73 (-12)	1.36 (+3)	100.000
700-800	1.01 (-12)	1.36 (+3)	100.000

Table 4 (continued)

Wavelength Range (microns)	Solar Irradiance (W/m^2)		
	per Å	total	percent
800-900	6.34 (-13)	1.36 (+3)	100.000
900-1000	4.18 (-13)	1.36 (+3)	100.000
1000-1100	2.84 (-13)	1.36 (+3)	100.000
1100-1200	2.00 (-13)	1.36 (+3)	100.000
1200-1300	1.46 (-13)	1.36 (+3)	100.000
1300-1400	1.08 (-13)	1.36 (+3)	100.000
1400-1500	8.24 (-14)	1.36 (+3)	100.000
1500-1600	6.38 (-14)	1.36 (+3)	100.000
1600-1700	5.02 (-14)	1.36 (+3)	100.000
1700-1800	4.01 (-14)	1.36 (+3)	100.000
1800-1900	3.24 (-14)	1.36 (+3)	100.000
1900-2000	2.65 (-14)	1.36 (+3)	100.000
2000-3000	1.16 (-14)	1.36 (+3)	100.000
3000-4000	3.07 (-15)	1.36 (+3)	100.000
4000-5000	1.17 (-15)	1.36 (+3)	100.000
5000-6000	5.49 (-16)	1.36 (+3)	100.000
6000-7000	2.92 (-16)	1.36 (+3)	100.000
7000-8000	1.71 (-16)	1.36 (+3)	100.000
8000-9000	1.07 (-16)	1.36 (+3)	100.000
9000-10000	7.03 (-17)	1.36 (+3)	100.000
10000-11000	4.86 (-17)	1.36 (+3)	100.000
11000-12000	3.48 (-17)	1.36 (+3)	100.000
12000-13000	2.57 (-17)	1.36 (+3)	100.000
13000-14000	1.94 (-17)	1.36 (+3)	100.000
14000-15000	1.49 (-17)	1.36 (+3)	100.000
15000-16000	1.17 (-17)	1.36 (+3)	100.000
16000-17000	9.29 (-18)	1.36 (+3)	100.000
17000-18000	7.49 (-18)	1.36 (+3)	100.000
18000-19000	6.11 (-18)	1.36 (+3)	100.000
19000-20000	5.04 (-18)	1.36 (+3)	100.000

Table 5
Summary of theSolar Irradiance for the Quiet Sun,
a Typical Active Sun, the Maximum Enhancement due to the
Slowly Varying Component, and An Importance 3B Flare

Wavelength Range (Å)	Solar Irradiance (W/m^2)							
	Quiet Sun		Active Sun		Slowly-Varying		3B Flare	
	per Å	total	per Å	total	per Å	total	per Å	total
2-3	1.8 (-9)	1.8 (-9)	1.5 (-7)	1.5 (-7)	4.5 (-7)	4.5 (-7)	1.78 (-4)	1.78 (-4)
3-4	5.6 (-9)	7.4 (-9)	4.0 (-7)	5.5 (-7)	1.26 (-6)	1.71 (-6)	2.34 (-4)	4.12 (-4)
4-5	2.0 (-8)	2.7 (-8)	8.3 (-7)	1.38 (-6)	2.40 (-6)	4.11 (-6)	3.16 (-4)	7.28 (-4)
5-6	5.0 (-8)	7.7 (-8)	1.58 (-6)	2.96 (-6)	3.71 (-6)	7.82 (-6)	3.64 (-4)	1.09 (-3)
6-7	1.0 (-7)	1.8 (-7)	2.51 (-6)	5.47 (-6)	6.30 (-6)	1.41 (-5)	4.17 (-4)	1.51 (-3)
7-8	1.8 (-7)	3.6 (-7)	3.80 (-6)	9.27 (-6)	1.00 (-5)	2.41 (-5)	4.78 (-4)	1.99 (-3)
8-9	3.2 (-7)	6.8 (-7)	6.02 (-6)	1.53 (-5)	1.41 (-5)	3.82 (-5)	5.25 (-4)	2.51 (-3)
9-10	5.6 (-7)	1.24 (-6)	7.95 (-6)	2.32 (-5)	2.34 (-5)	6.16 (-5)	5.89 (-4)	3.10 (-3)
10-11	8.0 (-7)	2.04 (-6)	1.12 (-5)	3.44 (-5)	2.82 (-5)	8.98 (-5)	6.31 (-4)	3.73 (-3)
11-12	1.12 (-6)	3.16 (-6)	1.41 (-5)	4.85 (-5)	3.71 (-5)	1.27 (-4)	1.00 (-3)	4.73 (-3)
12-13	1.78 (-6)	4.94 (-6)	1.78 (-5)	6.63 (-5)	4.47 (-5)	1.32 (-4)	1.26 (-3)	5.99 (-3)
13-14	2.24 (-6)	7.18 (-6)	1.90 (-5)	8.53 (-5)	6.31 (-5)	2.35 (-4)	1.78 (-3)	7.77 (-3)
14-15	2.64 (-6)	9.82 (-6)	2.00 (-5)	1.05 (-4)	7.94 (-5)	3.14 (-4)	2.24 (-3)	1.00 (-2)
15-20	9.55 (-6)	5.76 (-5)	2.40 (-5)	2.25 (-4)	1.58 (-4)	1.10 (-3)	3.16 (-3)	2.58 (-2)
20-30	4.57 (-6)	1.03 (-4)	1.02 (-5)	3.27 (-4)	3.24 (-5)	1.43 (-3)	5.13 (-4)	3.09 (-2)
30-40	3.47 (-6)	1.38 (-4)	6.17 (-6)	3.89 (-4)	1.18 (-5)	1.54 (-3)	2.04 (-4)	3.30 (-2)
40-50	3.80 (-6)	1.76 (-4)	5.63 (-6)	4.45 (-4)	8.51 (-6)	1.63 (-3)	1.59 (-4)	3.46 (-2)
50-60	4.17 (-6)	2.18 (-4)	5.37 (-6)	4.99 (-4)	6.92 (-6)	1.70 (-3)	1.09 (-4)	3.57 (-2)
60-70	3.39 (-6)	2.52 (-4)	4.37 (-6)	5.43 (-4)	5.49 (-6)	1.76 (-3)	7.08 (-5)	3.64 (-2)
70-80	2.69 (-6)	2.79 (-4)	3.22 (-6)	5.75 (-4)	4.17 (-6)	1.80 (-3)	4.68 (-5)	3.68 (-2)
80-90	3.09 (-6)	3.09 (-4)	3.80 (-6)	6.13 (-4)	4.68 (-6)	1.84 (-3)	4.57 (-5)	3.73 (-2)
90-100	2.46 (-6)	3.34 (-4)	2.88 (-6)	6.42 (-4)	3.63 (-6)	1.88 (-3)	3.09 (-5)	3.76 (-2)

Table 5 (continued)

Wavelength Range (Å)	Solar Irradiance (W/m^2)							
	Quiet Sun		Active Sun		Slowly-Varying		3B Flare	
	per Å	total	per Å	total	per Å	total	per Å	total
100-110	1.29 (-6)	3.47 (-4)	1.48 (-6)	6.57 (-4)	1.91 (-6)	1.90 (-3)	1.44 (-5)	3.77 (-2)
110-120	7.1 (-7)	3.54 (-4)	7.9 (-7)	6.64 (-4)	1.02 (-6)	1.91 (-3)	7.08 (-6)	3.78 (-2)
120-130	near 0	3.54 (-4)	near 0	6.64 (-4)	near 0	1.91 (-3)	near 0	3.78 (-2)
130-140	near 0	3.54 (-4)	near 0	6.64 (-4)	near 0	1.91 (-3)	near 0	3.78 (-2)
140-150	1.41 (-6)	3.68 (-4)	1.41 (-6)	6.79 (-4)	1.95 (-6)	1.93 (-3)	1.10 (-5)	3.79 (-2)
150-160	1.70 (-6)	3.85 (-4)	1.70 (-6)	6.96 (-4)	2.29 (-6)	1.95 (-3)	1.23 (-5)	3.81 (-2)
160-170	1.41 (-6)	3.99 (-4)	1.41 (-6)	7.10 (-4)	1.91 (-6)	1.97 (-3)	9.32 (-6)	3.81 (-2)
170-180	1.82 (-6)	4.17 (-4)	1.82 (-6)	7.28 (-4)	2.45 (-6)	2.00 (-3)	1.15 (-5)	3.83 (-2)
180-190	1.29 (-6)	4.30 (-4)	1.29 (-6)	7.41 (-4)	1.70 (-6)	2.01 (-3)	7.10 (-6)	3.83 (-2)
190-200	1.00 (-6)	4.40 (-4)	1.00 (-6)	7.51 (-4)	1.32 (-6)	2.03 (-3)	5.62 (-6)	3.84 (-2)
200-250	3.16 (-6)	5.98 (-4)	3.16 (-6)	9.09 (-4)	4.07 (-6)	2.23 (-3)	1.58 (-5)	3.92 (-2)
250-300	1.26 (-6)	6.61 (-4)	1.26 (-6)	9.72 (-4)	1.58 (-6)	2.31 (-3)	5.25 (-6)	3.94 (-2)
300-350	2.00 (-6)	7.61 (-4)	2.00 (-6)	1.07 (-3)	6.17 (-6)	2.62 (-3)	1.77 (-5)	4.00 (-2)
350-500	7.9 (-7)	8.80 (-4)	7.9 (-7)	1.19 (-3)	9.6 (-7)	2.76 (-3)	4.47 (-6)	4.07 (-2)
500-600	6.9 (-7)	9.49 (-4)	6.9 (-7)	1.26 (-3)	8.1 (-7)	2.84 (-3)	1.55 (-6)	4.09 (-2)
600-700	9.1 (-7)	1.04 (-3)	9.1 (-7)	1.35 (-3)	1.07 (-6)	2.95 (-3)	1.77 (-6)	4.10 (-2)
700-800	7.8 (-7)	1.12 (-3)	7.8 (-7)	1.43 (-3)	9.1 (-7)	3.04 (-3)	1.38 (-6)	4.12 (-2)
800-900	1.53 (-6)	1.27 (-3)	1.53 (-6)	1.58 (-3)	1.70 (-6)	3.21 (-3)	3.24 (-6)	4.15 (-2)
900-1000	2.52 (-6)	1.52 (-3)	2.52 (-6)	1.83 (-3)	2.82 (-6)	3.49 (-3)	4.78 (-6)	4.20 (-2)
1000-1100	2.82 (-6)	1.80 (-3)	2.82 (-6)	2.12 (-3)	3.09 (-6)	3.80 (-3)	5.01 (-6)	4.25 (-2)
1100-1200	1.26 (-6)	1.93 (-3)	1.26 (-6)	2.24 (-3)	1.35 (-6)	3.94 (-3)	1.62 (-6)	4.26 (-2)
1200-1300	8.71 (-5)	1.06 (-2)	8.71 (-5)	1.09 (-2)	9.34 (-5)	1.33 (-2)	1.07 (-4)	5.33 (-2)
1300-1400	4.47 (-6)	1.11 (-2)	4.47 (-6)	1.14 (-2)	4.77 (-6)	1.37 (-2)	5.02 (-6)	5.38 (-2)

Table 6
Comparison of Our Value for the Solar Constant with Other Values

Source	Solar Constant (W/m^2)
Our value	1358
Ground-based measurements:	
Nicolet 1951	1380
Aldrich and Hoover 1952	1352
Stair and Johnston 1954	1428
Johnson 1954	1395
Allen 1958	1380
Gast 1965	1390
Stair and Ellis 1968	1369
Labs and Neckel 1968	1365
Makarova, et. al., 1969	1418
High-altitude measurements:	
Thekaekara, 1970	1352
(various instruments)	1349
	1343
	1358
	1338
Murcray 1969	1338
Kondratyev, et. al., 1970	1353
Drummond and Hickey 1968	1360
Plamondon, 1969	1353

Table 7
Definition of Importance Classes for Flares

Importance	Area (solar disk)
S	less than 10^{-5}
1	$1.0 - 2.5 \times 10^{-5}$
2	$2.5 - 6.0 \times 10^{-5}$
3	$6.0 - 12 \times 10^{-5}$
4	more than 12×10^{-5}

Table 8
Frequency of Occurrence of Flares as a Function of
Importance and Phase of the Solar Cycle

Year	Flares per day			Total
(after maximum)	Importance 1	2	3	4
o	0.050	1.0	9.0	10
1	0.045	0.9	8.0	9
2	0.035	0.7	7.3	7
3	0.015	0.3	2.7	3
4	0.010	0.2	1.8	2
5	0.005	0.1	0.9	1
6	0.002	0.05	0.5	0.5
7	0.001	.01-.05	.1-.5	.1-.5
8	0.005	0.1	0.9	1
9	0.025	0.5	4.5	5
10	0.045	0.9	8.0	9

Table 9
Summary of Wende's 1972 Data on X-Ray Flux from Solar Flares

Flare Type	log flux (W/m^2-Å)		
	2.5 Å	6.5 Å	16 Å
1N	-5.8	-5.7	-5.0
1B	-5.0	-4.7	-4.5
2B	-4.6	-4.4	-4.4
3B	-3.5	-3.2	-3.0
Quiet	-8.5	-6.8	-5.5

Table 10
Factors for the Conversion of Mean Irradiance to Irradiance at any Given Day (To convert, divide mean irradiance by these numbers.)

Day	Factor
Jan. 1	0.9669
Feb. 1	0.9710
Mar. 1	0.9819
Apr. 1	0.9988
May 1	1.0155
June 1	1.0284
July 1	1.0337
Aug. 1	1.0304
Sep. 1	1.0189
Oct. 1	1.0024
Nov. 1	0.9851
Dec. 1	0.9722

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF ELSKE v. P. SMITH

MR. RASOOL: Do we understand the mechanism of the 11-year cycle?

MRS. SMITH: There are some who think they understand it, but I think the answer is no, we don't really understand it.

MR. RASOOL: Is there any reason why there should be a 22-year cycle?

MRS. SMITH: Well, the 22-year cycle is because of the change in the polarity. We have the increase in the number of sunspots every 11 years, but the polarity of the leading sunspots changes with every 11-year cycle, and so, on that basis, we have a 22-year cycle. Babcock has presented a model that explains how the magnetic flux lines get twisted, producing the active regions and the rise of the magnetic flux to the surface of the sun. It breaks through and we see the sunspots and the surrounding magnetic regions that are responsible for the plages.

MR. PRIESTER: Since the radio radiation of the sun has been left out of this talk, I would like to report some very recent results which have been obtained with the 100-meter fully-steerable radio telescope at Bonn, which is located at Effelsberg. The telescope has provided pictures of the sun measured at a wavelength of 2.8 centimeters, where we can clearly see beautiful coronal condensations, which are also the source of X-ray radiation. I would like to point out the persistence of these features, even the small features. These data were taken at a time when the Skylab astronauts monitored the sun, too, on August 30, 1973. By 24 hours later, a fully-developed new coronal condensation has appeared right in the center of a very active group of four condensations.

Also striking, is the persistence of even the smaller features over longer periods of time; further, we don't find any limb brightening, which should be expected at this wavelength, given the beam-size of one minute of arc.

I would like to point out that 30 percent of the observing time with the Bonn radio telescope has been set aside for foreign guest observers.

MRS. SMITH: The variations from one day to the next are, of course, what we would call the slowly-varying component that we also find in the X-rays.

QUESTION: Of course, meteorologists have been fascinated by the idea that the solar constant can change, and I thought you said that, in principle, we would get as much as a 2 percent change in the visible. If I misunderstood, what is the maximum that you would guess for the change in the solar constant, the solar activity?

MRS. SMITH: This has to be explained. The figure of 2 percent variation applies not to the solar constant or the total visible light. It refers to the total light from the solar disk that is emitted within certain narrow spectral bands, such as the cores of the K-line of ionized calcium and the H-alpha line of hydrogen.

MR. MITCHELL: I'm a little puzzled by one thing about the solar constant variation. This is something I commented on years ago. If you have a large sunspot crossing the sun, it has an effect on reducing the photospheric emission from the region of the spot by something like half, as I understand it. This is in the umbra. If the spots are big enough, that figures out to be up to something like one-half of one percent of the total radiation emitted from the photosphere.

Why wouldn't it follow that the radiation in the visible actually is a negative function of sunspot number? How do we know that the rest of the solar disk increases in radiation by an amount that just compensates for the shadowing effect, if you will, of individual sunspots? I'm referring to some statistics on very large sunspots which occurred around 1946, and maybe some other dates. The total areas of all sunspots on the disk can get up to a fraction of one percent during high sunspot maxima.

MR. ROOSEN: Dr. Abbot, whom we honored today, actually did publish a lot of work on the solar constant, and in his publication (Smithsonian Miscellaneous Collections, No. 4545) the variation in solar constant values that he got over a solar cycle is roughly about two-tenths of one percent, and he did, indeed, also point out that as a large sunspot group crossed the central meridian of the sun, the ultraviolet flux did drop substantially. The drop that he published is a little bit larger than I think anyone would believe from observations made in 1920, but he did find that the ultraviolet flux (in the sense of ground-based observations, 0.35 microns or so) increased.

The ultraviolet flux increased with increasing sunspot numbers, but as a large spot crossed the central meridian, the ultraviolet flux dropped.

MR. NOYES: I think we will have to agree that these early observations are pioneering ones. It would be very interesting to repeat this with modern equipment.

GEOMAGNETIC RESPONSES TO THE SOLAR WIND AND TO SOLAR ACTIVITY

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ABSTRACT

This paper presents a unified overview of our present knowledge of the geomagnetic response to the dynamic solar wind. Physical understanding rather than observational details is emphasized. Following some historical notes, the formation of the magnetosphere and the magnetospheric tail is discussed. The importance of electric fields is stressed and the magnetospheric convection of plasma and "frozen-in" magnetic field lines under the influence of large-scale magnetospheric electric fields is outlined. Inonospheric electric fields and currents are intimately related to electric fields and currents in the magnetosphere and the strong coupling between the two regions is discussed. The energy input of the solar wind to the magnetosphere and upper atmosphere is discussed in terms of the reconnection model where interplanetary magnetic field lines merge or connect with the terrestrial field on the sunward side of the magnetosphere. The merged field lines are then stretched out behind the earth to form the magnetotail, so that kinetic energy from the solar wind is converted into magnetic energy in the stretched out field lines in the tail. Localized collapses of the cross-tail current, which is driven by the large-scale dawn-dusk electric field in the magnetosphere, divert part of this current along geomagnetic field lines down to the ionosphere, causing substorms with auroral activity and magnetic disturbances. The collapses also inject plasma into the radiation belts and build up a ring current. Frequent collapses in rapid succession constitute the geomagnetic storm. The merging model emphasizes the importance of the interplanetary magnetic field and especially the north-south component, because the merging efficiency is strongly dependent on the amount of southward flux. The solar sector structure with its organized magnetic field and embedded high speed plasma streams is identified as the source of the recurrent geomagnetic disturbances while flare-associated interplanetary shock waves are the source of most violent and sporadic geomagnetic storms.

An appendix contains numerical estimates of some relevant physical quantities related to intensities of fields and currents in the magnetosphere and the ionosphere.

HISTORICAL NOTES

In 1843, Swabe discovered the 11-year sunspot cycle from 17 years of regular observations of the sun commencing in 1826. Following this, in 1852 Sabine announced his discovery of a strong positive correlation between the number of sunspots and the disturbance variation of the declination of the geomagnetic field measured in Toronto, Canada, during the years 1841 to 1848, not covering even one full sunspot cycle. It was concluded on this limited statistical evidence that the geomagnetic environment was strongly influenced by solar activity. Over a century of subsequent monitoring of solar and geomagnetic activity have confirmed these early conclusions, although the first indication of an explicit event on the sun with direct terrestrial response was observed as early as 1859 by the renowned solar astronomer Carrington. While observing a large spot group on the sun, he saw an intense outburst of white light from the sunspot group. The event lasted only a few minutes, but at the same time all three components of the earth's magnetic field recorded at Kew Magnetic Observatory became abruptly disturbed, followed about 18 hours later by a great geomagnetic storm that surpassed in intensity and duration all previous observations. For several days auroral displays of almost unprecedented magnificence were observed and telegraph communication was widely interrupted, because of currents induced in the wires.

While Carrington cautiously proposed a connection between this solar and the terrestrial events, it was difficult for the scientific world to accept any such idea. In 1905, Maunder drew attention to the 27-day recurrence pattern of the magnetic activity and Chree removed every doubt about the existence and significance of this 27-day period. Since the synodic rotation period of the sun is also near 27 days, the 27-day recurrence period was additional evidence that its ultimate cause is resident in the sun. Chree and Stagg noted in 1927 that "The exhibition of a 27-day interval in groups of days of all types, from the most highly disturbed to the quietest, seems to imply that there is no exceptional phenomenon on highly disturbed days, but merely increase in the activity of some agent always more or less active. If magnetic disturbance is due to radiation from the sun, then (...) the radiation must always be going on."

Chapman and Ferraro in a series of papers in the 1930's examined theoretically the effect of a plasma stream emanating intermittently from the sun and impinging on the earth to interact with the earth's magnetic field and causing geomagnetic storms. Their basic ideas were largely correct except that, as pointed out by Chree and Stagg and later by Bartels, the geomagnetic field is always somewhat disturbed, indicating a continuous rather than intermittent mode of interaction. Activity never ceases completely and auroras can always be seen somewhere. The realization and general acceptance that the sun continuously emits a tenuous, magnetized plasma which at all times interacts with the earth and its magnetic field has come slow and had to await direct in situ probing by spacecraft in 1962. From studies of movements and directions of comet tails, Bierman in 1951 proposed that the sun emits "corpuscular radiation" in essentially all directions at essentially all times, and Parker in 1958 proposed a hydrodynamic model of the solar corona from which the material flowed out as a natural consequence of the million degree temperature of the corona. Parker named this phenomenon the "solar wind," by which name it has been known ever since. But final acceptance of the existence of an essentially continuous solar wind came first after measurements made on board the Venus probe, Mariner 2, in 1962. The principal features of the solar wind as reported by Neugebauer and Snyder were:

- A detectable solar wind was present at all times.
- The average solar wind speed was 500 km.
- The speed varied between 300 and 860 km and was correlated with geomagnetic activity.
- The average proton density was $5/cm^3$.
- Several streams of high-speed plasma were found to reoccur at 27-day intervals, and
- The plasma was found to possess a weak magnetic field.

The discovery of the magnetized solar wind and the concept of a continuous interaction of the wind with the terrestrial magnetic field are the basis for our understanding of the geomagnetic response to solar activities.

THE MAGNETOSPHERE

In the presence of a weak interplanetary magnetic field, the solar wind plasma behaves as a supersonic continuum fluid over scale lengths which are large compared with the proton gyroradius (typically 100 km for solar wind plasma near the earth). The earth's magnetic field thus presents an obstacle to the solar wind flow. To a first approximation the solar wind flow around this obstacle can be treated fluid-dynamically. The magnetic pressure in the dipolar geomagnetic field falls off as $(r^{-3})^2 = r^{-6}$ and eventually becomes comparable with the directed gas pressure, p, of the solar wind. Close to the geomagnetic field, there is a region where the magnetic pressure $B^2/2\mu_o$

(where B denotes the magnetic flux density and μ_o is the permeability of free space) is much larger than p, but in the free solar wind p is much larger than the magnetic pressure of the weak interplanetary field. The boundary between these two regions is called the magnetopause and the region inside the magnetopause which confines the geomagnetic field is called the magnetosphere.

Because the magnetic pressure of the geomagnetic field varies rapidly with distance, the magnetopause can be adequately represented by a tangential discontinuity, in which there is no solar wind plasma on the magnetosphere side of the magnetopause and no magnetic field on the solar side. In this approximation, the gas pressure, p, in the solar wind must balance the magnetic pressure, $B^2/2\mu_o$, just inside the magnetopause, and solar wind particles are specularly reflected from the magnetopause. From these assumptions the shape and size of the magnetopause can be computed using an iterative method to solve what is essentially a free-boundary problem: both the boundary and the conditions which determine it are to be found.

A standing shock front or bow wave would be expected at some distance upstream in the solar wind. This is because the geomagnetic field is an obstacle in a supersonic (more precisely, super-Alfvénic) flow. A transition to subsonic flow is necessary for the solar wind to flow smoothly around the earth as required by the zero flow velocity normal to the magnetopause. A supersonic solar wind cannot receive knowledge of the obstacle ahead so the wind must undergo an upstream shock transition to subsonic flow. The position and shape of this bow shock can be calculated using conventional equations of fluid dynamics for a solid obstacle of the same shape as the magnetopause.

The region between the shock and the magnetopause is called the magnetosheath, and contains shocked solar wind plasma with increased density and temperature and also somewhat disturbed interplanetary magnetic field. Given the interplanetary field the average configuration of the magnetic field in the magnetosheath can finally be computed assuming that field lines move with the streaming plasma and taking the boundary condition that the field, $\underline{b}_{norm}$, normal to the magnetopause vanishes. For an interplanetary field directed along a 45° spiral-angle the calculated geometry and extent of the magnetosphere and magnetosheath regions on the dayside of the earth is shown in Figure 1. Several comparisons of theory and measurements made in space have confirmed the adequacy of the continuum fluid model for predicting even quantitatively the location and shape of both the magnetopause and the bow shock wave, and for explaining the observed properties of the flow of the solar wind plasma in the magnetosheath. In fact, the agreement between theory and observation is surprisingly good, considering both the gross simplifications that are necessary to make the problem tractable and the lack of a rigorous justification for applying fluid concepts to a collisionless, weakly magnetized plasma.

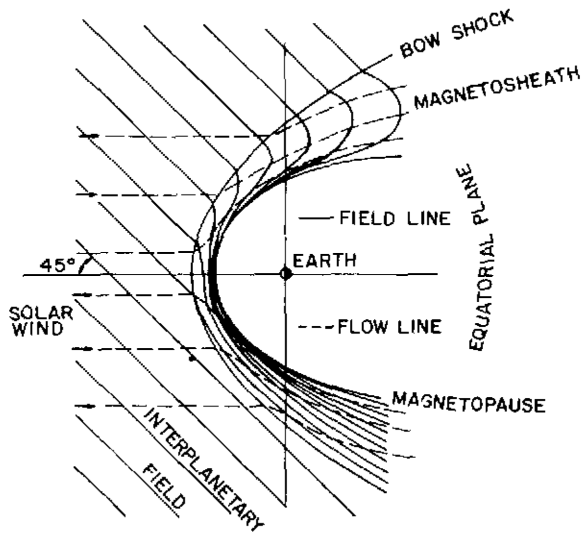


Figure 1. Flow lines of the solar wind around the geomagnetic field confined within the magnetosphere. Interplanetary magnetic field lines corresponding to a spiral angle of 45°are draped around the magnetopause. The geomagnetic dipole is assumed perpendicular to the plane of the figure and to the solar wind flow.

The treatment of the solar wind as a cold plasma flow leads to the formation of a magnetosphere which is open in the antisolar direction with its flanks stretching asymptotically to the solar wind flow direction. At great distances from the earth, the dynamic flow pressure on the magnetopause tends to zero together with the magnetic field inside the magnetosphere. In the more realistic case, where the solar wind pressure includes both the directed dynamic pressure of the flow and the more nearly isotropic thermal pressure due to nonzero plasma temperature, the magnetosphere will be closed in the antisolar direction at some distance from the earth. In this case the magnetosphere is expected to extend in the solar wind flow direction (corrected for the small aberration due to the orbital movement of the earth around the sun) to three or four times the standoff distance on the sunward side of the earth. This extension, the magnetospheric tail, has also been observed to exist by in situ spacecraft measurements.

The observed properties of the tail are, however, not understood in terms of the fluid dynamic approach which was so successful in describing the sunward regions of the magnetosphere. Figure 2 summarizes the observational results. Field lines in the tail beyond about 10 earth radi are roughly parallel to the sun-earth line. The tail itself approximates a long cylinder. In the northern half of the cylinder the field lines are directed toward the sun, and in the southern half their direction is away from the sun. The length of the tail and its eventual termination is not well known but is at least several hundred earth radii, and is therefore very much larger than predicted. It is important to note that the tail field lines all come from fairly small regions around the magnetic poles inside the classical auroral zones. High fluxes of keV plasma are observed in the so-called plasma sheet separating the oppositely directed fields in the tail lobes. The thickness of this plasma sheet varies greatly with geomagnetic activity but is typically 5 earth radii, and the sheet extends most of the way down the tail. The plasma sheet surrounds a region of very weak fields, the neutral sheet, where the tail field reverses. To maintain the tail configuration of oppositely directed field lines, a current must flow in the neutral sheet across the tail. Figure 3a shows a north-south cut through the magnetotail. Figure 3b shows a schematic cross section of the tail. The field directions above and below the neutral sheet require a tail current flowing in the sheet from dawn to dusk.

That the tail is much longer than predicted by the continuum fluid model is obviously the result of forces (external or internal) exerted on the magnetic field to stretch out the field lines. We do not know precisely what these forces are. The pressure of the quiet solar wind is about an order of magnitude larger than the tension in the tail so it is natural to assume that interactions between the solar wind and the magnetosphere at the magnetopause provide the necessary tangential stresses to pull out the tail in the antisolar direction.

Turbulence in the solar wind could produce such interactions because it ripples the magnetopause with a phase velocity exceeding the Alfvén speed, thereby generating waves which propagate into the magnetosphere. Another possibility is that the magnetopause is not a perfect separation of interplanetary and geomagnetic field lines. If field lines cross the magnetopause then the solar wind "may blow away the magnetic lines of force like smoke from a chimney." However, we can in this case not relate the magnetopause to a boundary separating different field lines since these cross the magnetopause. Moreover, solar wind plasma may penetrate the boundary and equalize the concentration on both sides of the boundary. In the case of an isotropic velocity distribution of the solar wind particles, the plasma concentration along magnetic field lines would be constant and there would be no

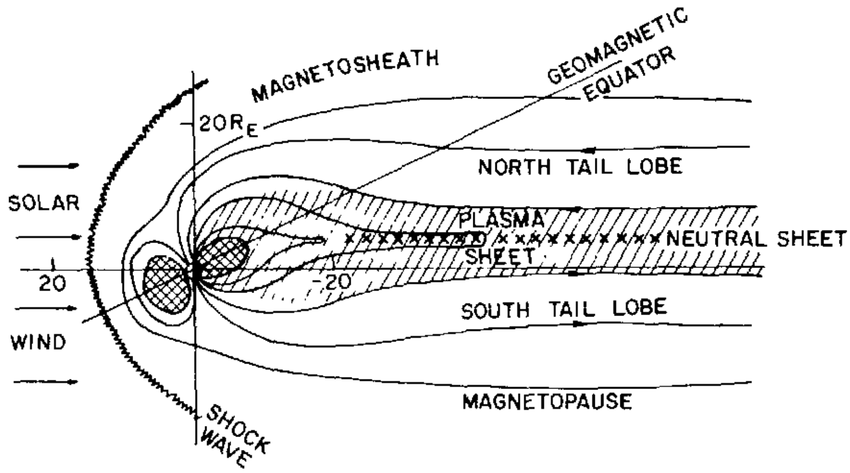


Figure 2. Observed properties of the magnetotail. The distant tail is approximately aligned with the solar wind flow direction independent of the inclination of the geomagnetic equator to the ecliptic plane. Field lines in the northern tail lobe are directed towards the earth, and field lines in the southern tail lobe are directed away from the earth. The plasma sheet separates the two tail lobes and the field reversal takes place in the neutral sheet which then contains a very weak net northward magnetic field. The inner part of the magnetosphere (crosshatched) contains plasma of mainly terrestrial origin. This plasmasphere corotates with the earth, while the rest of the magnetosphere stays roughly fixed in relation to the sun-earth line.

near-stationary magnetopause. But since the directed energy for solar wind particles greatly exceeds their thermal energy, we have a very highly anisotropic velocity distribution and the majority of the particles will be reflected back by a region of increasing magnetic field. This region where the magnetic field intensity increases rapidly could then be considered to be the magnetopause. Energetic particles from solar flares penetrate easily into the magnetosphere due to the much higher degree of isotropy of these particles which simply do not recognize any magnetopause. In some sense the magnetopause could be considered "magnetoporous" to magnetic field lines and isotropic particles.

ELECTRIC FIELDS AND CONVECTION

A plasma always sets itself in motion such as to oppose any external electric field in order that there be no electric field in the rest frame of the plasma. Switching on an electric field causes the particles to drift so that they do not see any electric field. One might say that collisionless plasmas abhor

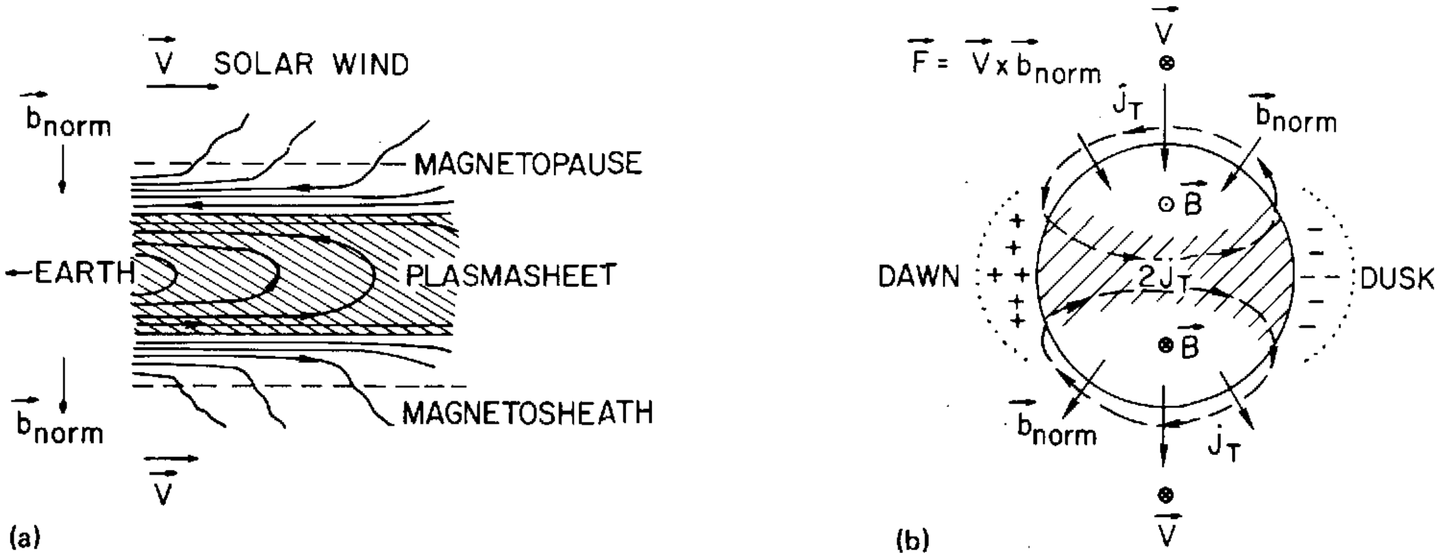


Figure 3. (a) North-south cut through the magnetotail. Field lines in the central plasma sheet connect with field lines from the other tail lobe. Field lines outside the plasma sheet connect to the interplanetary magnetic field thus providing a field component $\underline{b}_{norm}$ normal to the magnetopause. (b) Cross-section of the magnetotail as viewed from the earth. The plasma sheet is indicated by shading in the middle of the tail. The electromotive force, $\underline{V} \times \underline{b}_{norm}$, of the magnetospheric dynamo drives a current, J_T, around each tail lobe and accumulates positive space charge on the dawn side magnetosphere and negative space charge on the dusk side. The electric field resulting from the charge separation is discharged through the cross tail current, $2J_T$, keeping the two lobes apart.

electric fields, so that

$$\underline{E} + \underline{v} \times \underline{B} = 0 \quad (1)$$

or alternatively

$$\underline{v} = \underline{E} \times \underline{B}/B^2 \quad (2)$$

where $\underline{E}$ is electric field strength, $\underline{B}$ is magnetic flux density, and v is the resulting plasma drift velocity. Similarly, magnetic field lines in a highly conducting plasma move with the plasma because the electromotive force around any closed loop must vanish, and hence, the flux through the loop cannot change. We can therefore, to a good approximation, consider field lines as "frozen" into the ionospheric and magnetospheric plasma and also to be frozen into the conducting interior of the earth. But they are not "frozen-in" in the neutral atmosphere and as a result, two magnetic tubes of force may be interchanged as shown in Figure 4. The inner flux tube must be stretched to go into the position of the outer tube, which requires work, but the outer tube shortens upon moving to the position of the inner tube and gives up just as much energy as the other consumes. So there is no tendency for the tubes to interchange or to resist interchange. Moving the frozen-in flux tubes amounts to interchanging the plasma in the tubes.

Field lines passing through the ionosphere are embedded in a plasma which is highly conducting, and a potential difference between any two points in the ionosphere must exist everywhere along the two field lines containing these points. This is because the field lines are approximately equipotential due to the plasma lying along any of them, and therefore a potential difference between two points in the ionsphere must be maintained all along the magnetic field lines. This means that there is an electric field between these two field lines, and the plasma tied to the field lines must then drift with a velocity

$$\underline{v} = \underline{E} \times \underline{B}/B^2$$

in order that there be no electric field in the rest frame of the plasma. This drift is called convection of frozen-in field lines in the presence of an electric field, and has proven to be of fundamental importance in the dynamics of the magnetosphere.

Within the E-region (90 to 150 km altitude) of the ionosphere, electrons drift freely but the motion of ions is strongly impeded by collisions with neutral particles, because the relations between the collision frequency, ν and the gyrofrequency, ω , are such that $\upsilon_{electron} < \omega_{electron}$ and $\upsilon_{ion} > \omega_{ion}$. Therefore the ions move essentially with the neutral gas except for a small drift parallel to the electric field in the sense of a direct (Pedersen) current that discharges this field. The electrons still satisfy Equation (1) and can be considered as remaining frozen to the field lines. The drift of the electrons results in a Hall current that flows perpendicular to the electric and the magnetic fields. Throughout the E-region the Hall conductivity is much larger than the Pedersen conductivity, so that in this region the major ionospheric currents can be considered as being Hall currents to a fair approximation. This is important because it enables us to infer the aproximate direction and (with an estimate of the conductivity) the magnitude of electric fields in the ionosphere, and since magnetic lines of force are almost equipotentials, also roughly to determine the distribution of electric potential in the magnetosphere.

Although the Pedersen current is not important in producing magnetic variations, it is significant in that it is dissipative. The energy dissipation, which can be considered as being due to friction between the charged and the neutral constituents of the atmosphere, is so effective that electric fields in the magnetosphere which are not maintained by some driving mechanism are discharged in a few seconds. Constantly maintained convective motions in the magnetosphere are therefore normally accompanied by a substantial amount of ionospheric heating.

If interplanetary and geomagnetic field lines are connected across the magnetopause there will be a component, $\underline{b}_{norm}$, of magnetic field normal to the magnetopause as shown in Figure 3a. The electromotive force, $\underline{F} = \underline{V} \times \underline{b}_{norm}$, where $\underline{V}$ is the solar wind velocity, caused by the solar wind flow along the magnetopause drives electric currents of intensity j_T as indicated in Figure 3b. The current builds up a positive space charge on the dawn side of the magnetopause and a negative space charge on the dusk side, and completes its circuit by the current across the tail in the neutral sheet where the magnetic field is very weak. In a sense we can regard the magnetosphere as a very large lossy capacitor which acts as a load for the solar wind electric generator. The dawn and dusk sides are the two capacitor plates, and the magnetosphere, particularly the plasma sheet, is the dielectric between them. Geomagnetic and auroral activity constitute loss mechanisms, or resistive elements, or maybe at times short circuits.

The existence of this large-scale magnetospheric electric field directed from dawn to dusk has been verified by a variety of techniques including satellite, rocket and balloon observations. This magnetospheric electric field has been found to be a permanent feature of the magnetosphere and it is now generally accepted that it plays a central role in magnetospheric processes. The separated charges causing this electric field are located in a thin layer immediately adjacent to the magnetotail surface. A boundary layer of plasma less dense than the magnetosheath plasma and flowing anti-sunward at less than magnetosheath flow speed has been observed by satellites; it exists at all times on both the morning and evening sides and probably extends completely around the surface of the tail. Plasma from this boundary layer drifts into the tail, thereby maintaining the plasma sheet. Once these particles are on tail field lines in the plasma sheet they feel the influence of the magnetospheric electric field and drift toward the earth as the result of the net northward magnetic field across the plasma sheet and the dawn-dusk electric field. This drift under the influence of the electric field accelerates the plasma particles adiabatically because of the increasing magnetic field as the plasma comes closer to the earth. If the energy gain is large enough the plasma may penetrate deep into the ionosphere before mirroring back and may be precipitated due to Coulomb scattering, collisions, and wave-particle interaction.

The above considerations can be summarized by noting that plasma flows down the tail near the tail surface and back again towards the earth in the plasma sheet within the tail. This large-scale circulation of the plasma is commonly referred to as the deep magnetospheric convection and is expressed in terms of convection of frozen-in magnetic field lines. Figure 5 shows a schematic of these convective motions of the magnetic field lines and associated particles in the equatorial plane of the earth. This convective circulation is often described in rather loose terms by saying that magnetospheric field lines are carried by the solar wind from the dayside, over the polar caps, and into the nightside magnetosphere, wherefrom they return to the dayside having their foot-points flowing through the subpolar or auroral zone ionosphere.

Because of viscosity, the neutral atmosphere largely rotates with the earth. In the lower ionosphere the neutral atmosphere interacts with the ions by collisions to set the ionosphere in corotational motion. In the frame of reference of the rotating earth, the ionospheric plasma at subauroral zone latitudes is not appreciably affected by the deep magnetospheric convection and is approximately at rest, so the electric field is zero. The electric field in a nonrotating frame of reference then becomes

$$\underline{E}_c = -\underline{v}_c \times \underline{B}$$

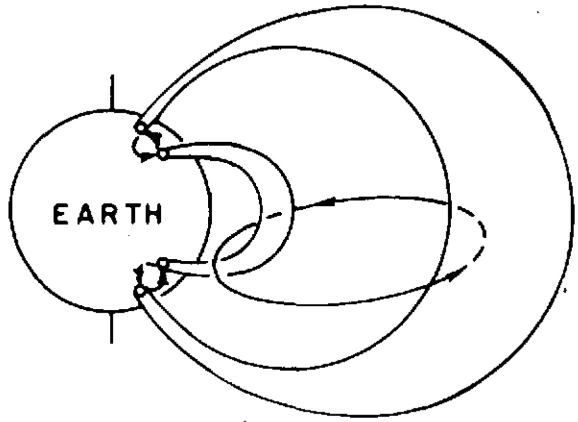


Figure 4. Interchange of tubes of magnetic field lines. The inner tube can be stretched to go into the position of the outer tube, but the outer tube shortens upon moving to the position of the inner tube. In the absence of dissipative forces no work is done by interchanging flux tubes.

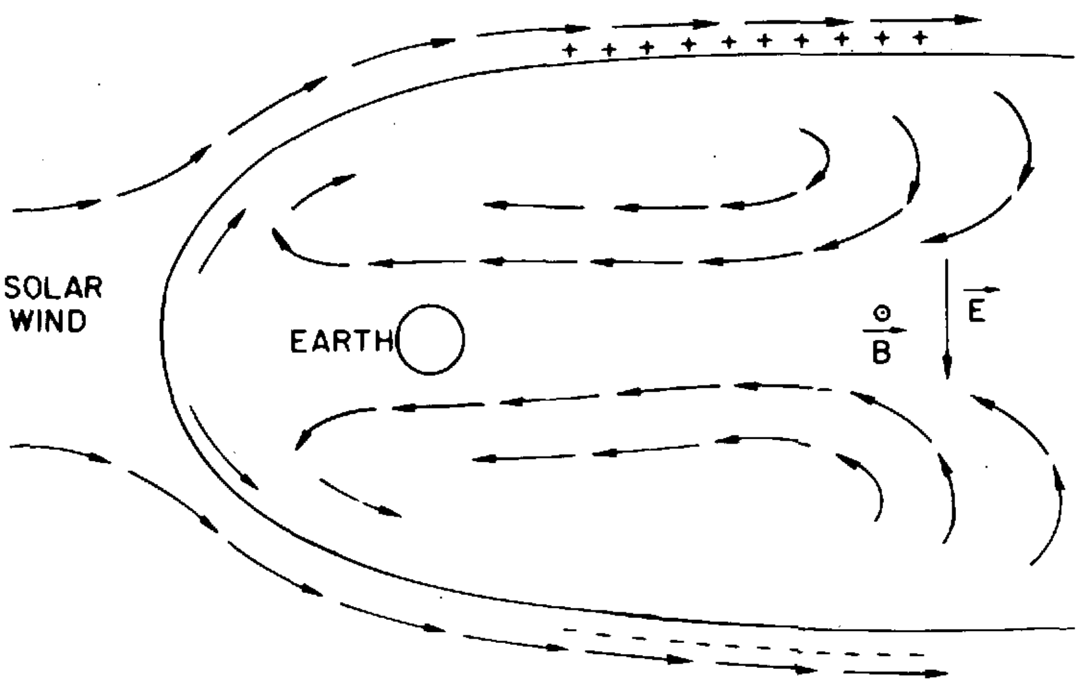


Figure 5. Large-scale magnetospheric circulation of plasma and "frozen-in" field lines in the equatorial plane. Solar wind plasma flows down the tail near the magnetopause and towards the earth in the plasma sheet within the tail.

where $\underline{v}_c$ is the corotation velocity and $\underline{B}$ is the magnetic field of the earth. For a dipolar $\underline{B}$, the magnitude of the ionospheric, corotational electric field is

$$E_C = 0.014 \cos\theta \, (1 + 3 \sin^2\theta)^{1/2} \, V\, m^{-1}$$

In the approximation that the magnetic field lines are equipotentials, the ionospheric corotation electric field persists along field lines into the magnetosphere causing the inner magnetosphere to corotate with the earth. This inner part of the magnetosphere contains cold (~1 eV) plasma that has evaporated from the dayside ionosphere onto the corotating magnetic field lines.

Even if the earth's rotation and the solar wind were turned off, the upper atmosphere would move because of thermal and tidal effects from the sun and the moon. The motions couple to the ionospheric plasma through collisions to set it in motion, and the resulting currents partially polarize the ionosphere to create an electric field. The precise effect of this field depends on the large-scale upper atmospheric wind system, which is poorly known; but in any case, the electric field at a given location has a 24-hour variation due to the diurnal solar heating and ionozation of the upper atmosphere. The existence of these ionospheric dynamo currents was suggested by Balfour Stewart in 1882 to account for the observed small (0.1 percent) diurnal variations of the geomagnetic field, the so-called Sq variations. Direct low-latitude magnetic and electric field measurements by rocket and radar techniques have proved the existence of the Sq currents, explaining the first geomagnetic variations to be physically understood.

The relative importance of the ionospheric electric fields produced by rotation of the earth, by tidal motions of the upper atmosphere, and by interaction of the magnetosphere with the solar wind is illustrated in Figure 6. At latitudes below 45°, the dynamo and magnetospheric electric field strength are much less than the corotation field strength so that the plasmasphere clearly rotates with the earth. At high latitudes the ionospheric electric field is dominated by magnetospheric processes that cause the plasma to flow in the antisolar direction in the polar cap and toward the sun at somewhat lower latitudes.

The high latitude electric field has recently been directly observed by low altitude spacecraft and also from active experiments injecting Barium vapor into the F-layers of ionosphere where it is ionized by sunlight; the electric field can then be inferred from the $\underline{E} \times \underline{B}$ drift of the sunlit Barium cloud.

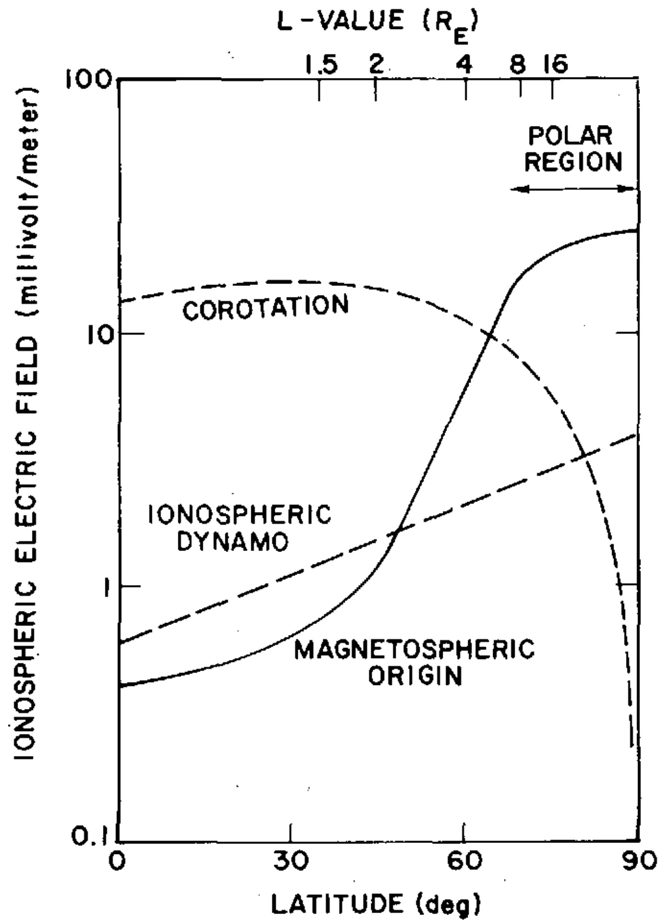


Figure 6. Survey of the relative importance of ionospheric electric fields of different origins as a function of latitude. At low latitudes the corotation and ionospheric dynamo electric fields dominate, while electric fields of magnetospheric origin are most important in the polar regions.

Figure 7a shows the electric field observed on a polar pass of the OGO-6 satellite after subtraction of the $\underline{V} \times \underline{B}$ fields from both the motion of the satellite and the rotation of the earth. The field seems to be quite uniform across the polar cap directed towards the evening side. Field reversals are seen at the polar cap boundary. Figure 7b shows typical drifts of Ba^+ clouds released in the F2-layer plotted in a coordinate system of corrected (taking into account the nondipolar parts of the field) geomagnetic latitude and local magnetic time. The Ba^+ ions drift antisunward over the polar cap and toward the sun at lower latitudes in accordance with the expected convection pattern. A schematic summary of the high latitude electric fields and the associated convection is given in Figure 7c.

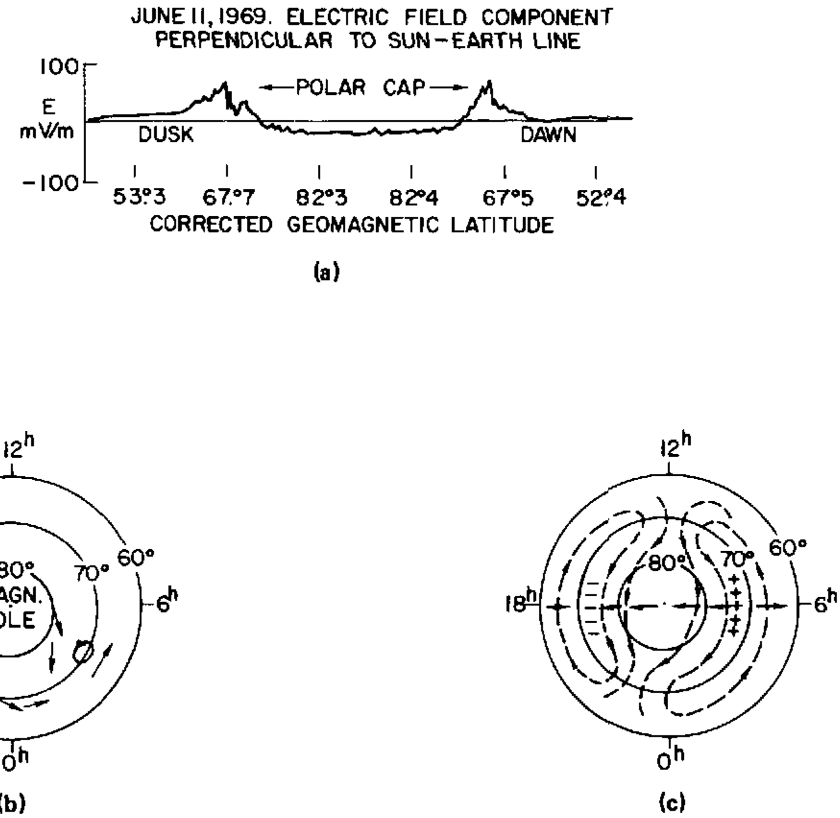


Figure 7. (a) Ionospheric electric field dusk-dawn components measured by OGO-6 satellite passing over the north polar region. A rather uniform electric field is found in the polar cap with reversals near the auroral zone. (b) Typical drifts of Ba^+ clouds in the F2-layer in a coordinate system of corrected geomagnetic latitude and local magnetic time. The direction to the sun is from the magnetic pole to the tick mark labeled 12^h. (c) Summary of electric fields and convection pattern in the polar regions. The direction of the electric field shown in panel (a) is shown as a series of arrows along the 6^h to 18^h meridian. Regions of positive space charge (source) and negative space charge (sink) are shown at the electric field reversals. Hall currents circulating around these regions are indicated by dashed curves. The geomagnetic field is nearly vertical over the polar regions, directed downwards over the northern pole.

The convection pattern can be described as consisting of two vortices, one in the morning and one in the evening. Since normally the electrons and not the atmospheric ions participate in the convection in the lower ionosphere, the result is a Hall current in the E-region flowing in the opposite direction to the convection flow. Since the electric field is strongest at auroral latitudes surrounding the polar cap (see Figure 7a) and since the ionospheric conductivity is highest there, the Hall currents can become quite concentrated and intense at latitudes around and just below 70°, and are referred to as the auroral electrojets. Figure 8a shows a schematic of the two-celled current system with the electrojets indicated by heavy arrows, while Figure 8b is an example of current vectors as inferred from magnetometers on the ground. Such configurations would be expected if the convection is in balance, that is when the return flow in the auroral zone equals the anti-sunward flow over the polar cap.

FIELD LINE MERGING

There is an increasing understanding that most geomagnetic and related activity result from nonbalance of the convection rates on time scales less than typical reaction times of various parts of the coupled magnetosphere-ionosphere system. Understanding of the processes which govern the convection rates in different regions within the magnetosphere is therefore extremely important but is largely lacking or at best phenomological and qualitative in nature. The necessary tangential stresses on the magnetopause to stretch the field lines back into the tail could be provided or at least aided by connecting interplanetary magnetic field lines to geomagnetic field lines. This connection or merging of field lines could take place at an X-type magnetic neutral point. As plasmas with oppositely directed magnetic fields are pressed together as illustrated in Figure 9, pairs of magnetic field lines such as ab and cd, identified via the plasma frozen to them, flow toward a point where the magnetic field vanishes in an electric discharge. At that point the field lines merge to form a new pair of lines a'c' and b'd'. The plasma is squeezed out and accelerated away from the neutral point, aided by the tendency of the new field lines to reach a lower energy state by shortening themselves. Exactly how the merging takes place is poorly understood, but the process can be made to work in laboratory plasmas. As the plasma on the newly merged field lines flows away from the neutral points more field lines can be merged, and so on. If the interplanetary magnetic field has a southward component, the geometry at the subsolar point of the dayside magnetopause is that of an X-type neutral point as indicated in Figure 10a. The interplanetary field lines and the geomagnetic field lines merge at A, and the magnetosheath plasma flow carries the field lines in the anti-solar direction. The numbers 1 to 7 on Figure 10a indicate successive positions of an interplanetary field as it connects to the geomagnetic field. Even if the field lines are not strictly antiparallel merging can still occur but with lower efficiency, so field lines connected across the magnetopause can be a permanent feature not exclusively dependent on the presence of a southward field.

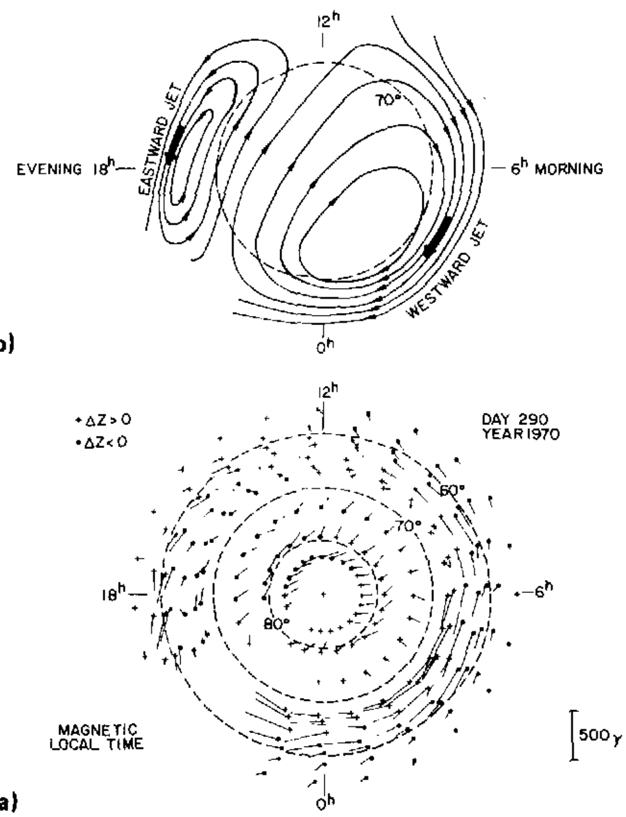


Figure 8. (a) Schematic overhead equivalent currents flowing in the polar ionosphere. Equivalent currents are not necessarily real currents but simply model currents at constant altitude which could produce the observed magnetic variations on the ground. The current system is plotted as a function of corrected geomagnetic latitude and local magnetic time and is constructed assuming that the current pattern is fixed in space and time with the earth rotating below it. (b) Observed current vectors at a chain of ten polar region magnetic observatories. For a given hourly interval the average directions of the equivalent currents are platted as lines originating in the observing stations having a length proportional to the observed magnetic perturbation. By plotting these current vectors for successive hourly intervals we can construct the total equivalent current system. The data were chosen for a day where geomagnetic activity was moderately high and nearly constant throughout the day, to minimize temporal variations of the current strength. The sign of perturbations of the vertical component, Z, of the geomagnetic field is given at each point as a "+" for positive and a dot for negative disturbances. Construction of equivalent current systems is a commonly used tool in geomagnetic physics. Interpretation of the current systems is often difficult and the distinction between equivalent and real currents is not always emphasized. Other examples of equivalent ionospheric currents are shown in Figure 22.

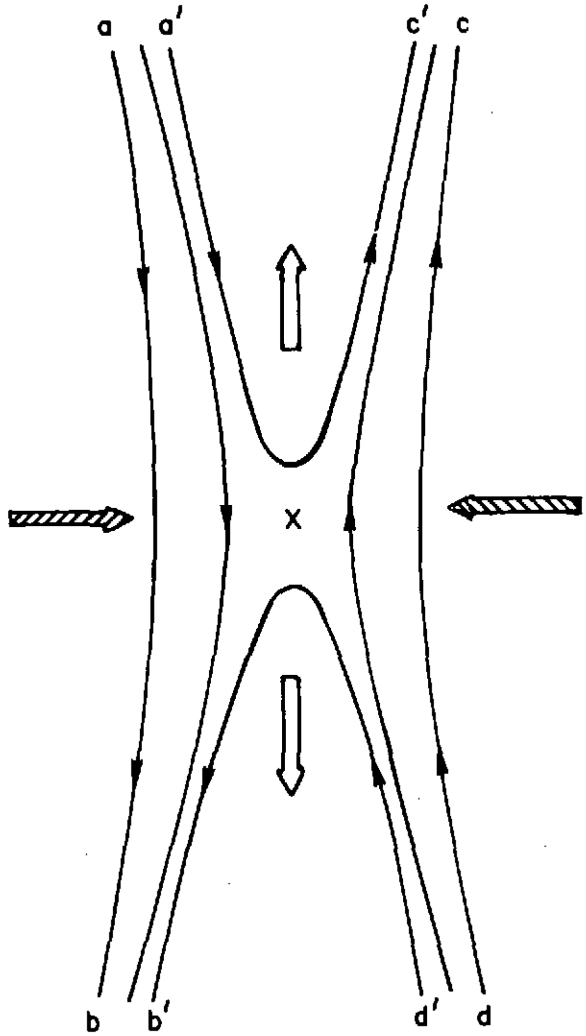


Figure 9. Reconnection of oppositely directed magnetic field lines embedded in a plasma. If the plasma is compressed (shaded arrows) field lines merge at the X-type neutral point and plasma flows away (open arrows) from the reconnection region carrying the connected field lines. Field lines ab and cd eventually assume the new configuration a'c' and b'd'.

Merging of field lines has the effect that we must distinguish three classes of magnetic field lines near the earth : 1) interplanetary field lines, such as AA' in Figure 10b, which are unlinked with the geomagnetic field lines, 2) open field lines such as BB' which link the two fields, and 3) closed terrestrial field lines, C and D, which are not linked to the interplanetary magnetic field. The use of the descriptive terms open and closed geomagnetic field lines refers in an incorrect but obvious manner to an important topological

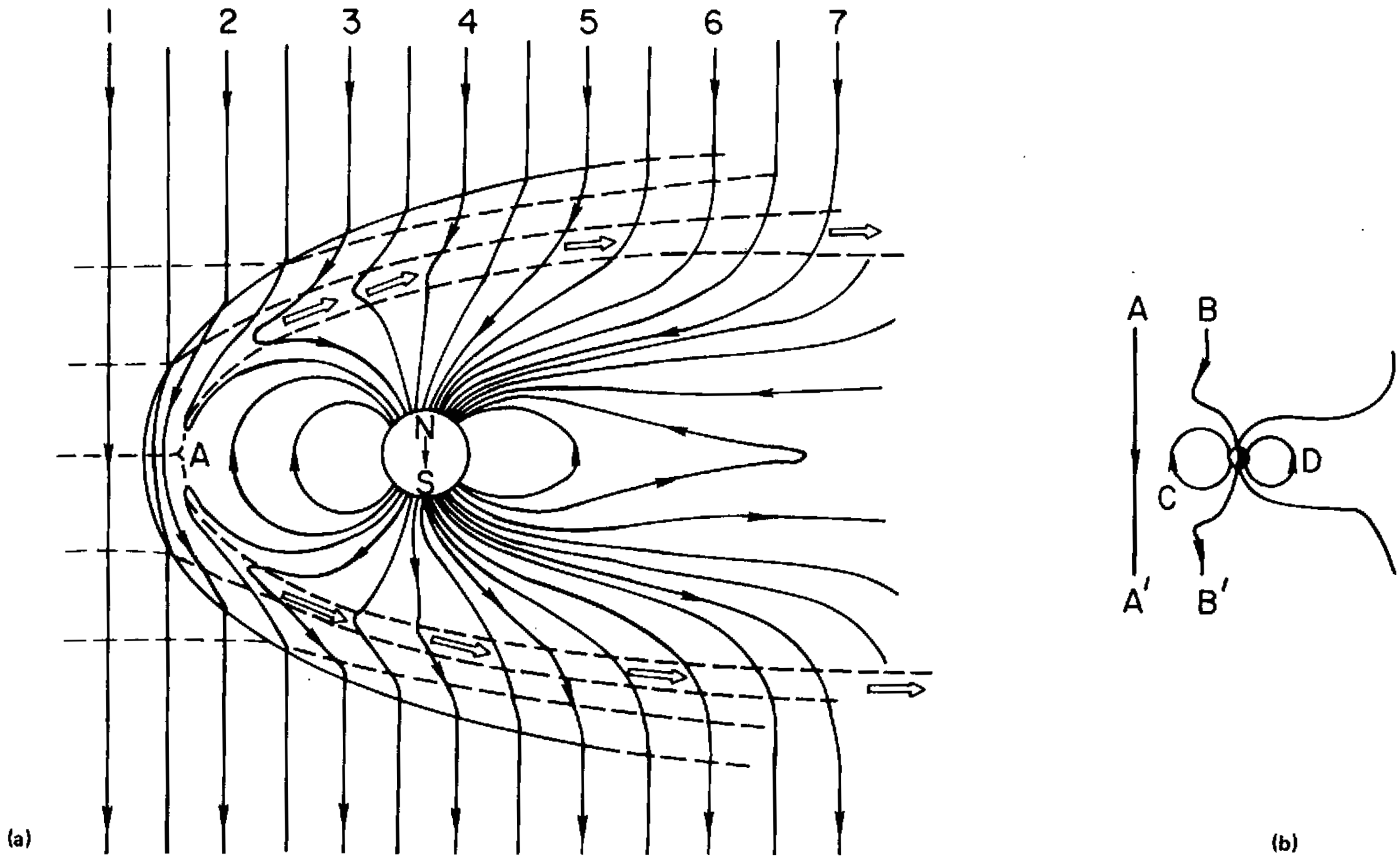


Figure 10. (a) Successive stages (1 to 7) in the linkage of a southward directed interplanetary magnetic field line with the terrestrial field as the linked lines are carried past the earth by the magnetosheath flow (open arrows). (b) Classes of magnetic field lines with different terrestrial relationships: AA′ is an unlinked interplanetary field line; BB′ is an open terrestrial field line connected to the interplanetary field; C and D are closed terrestrial field lines not linked to any external field.

property of the field line. On open field lines, solar wind particles and electric fields have direct access to the earth, and ionospheric plasma can directly escape into interplanetary space. It is much more difficult for particles to diffuse across field lines onto closed field lines, and once they are there, the particles are trapped and cannot easily be removed. This trapping region on closed field lines is indicated by cross-hatching on Figure 2 and coincides roughly with the outer part of the plasmasphere.

When interplanetary field lines have just merged on the dayside with the previously outermost closed terrestrial field lines, magnetosheath plasma suddenly gets access to these field lines and can penetrate to low altitudes into the ionosphere before mirroring back. Some of the plasma precipitates and causes a subvisual band of 6300 Å emission. Satellite observations both at low altitude and also out in the magnetosphere show the existence of large fluxes of magnetosheath plasma on geomagnetic field lines near the dayside boundary between open and closed field lines. The region containing this plasma is called the magnetospheric cleft or the polar cusp and is shown in Figure 11a as a funnel shaped connection between the magnetosheath and the earth. As indicated on Figure 11b the cleft has a large longitudinal extent adjacent to most of the dayside polar cap boundary. The field lines extending into the plasma sheet are in a similar manner located near the nightside polar cap boundary. The observed properties of the plasma in the magnetospheric cleft strongly support the idea that terrestrial field lines there do connect to the solar wind magnetic field. The location of the cleft has also been found to depend on the strength of the north-south component B_z of the interplanetary magnetic field. A strong southward B_z persisting for some time causes an equatorward movement of the cleft as if more terrestrial field lines have been "peeled" off and transported into the tail. This erosion of the geomagnetic field on the dayside is closely related to B_z: particle observations of position of the cleft show that a persistent 6γ southward B_z for 45 minutes is enough to move the cleft 5°equatorwards. The amount of magnetic flux added to the tail during that interval can then be estimated to be about 10 percent of the total southward flux impinging on the magetosphere.

We have discussed how the merging of the geomagnetic field lines with southward directed interplanetary field lines provides a normal component of the magnetic field across the magnetosphere and therefore a potential difference across the magnetotail. The currents around the tail then tend to accumulate positive space charges along the dawn side of the magnetopause and negative space charges along the dusk side Figure 4. The resulting electric field drives an electric current from dawn to dusk in the "neutral sheet" and is also responsible for the downtail convection of the newly merged magnetic tubes of force containing magnetosheath plasma. When these field tubes

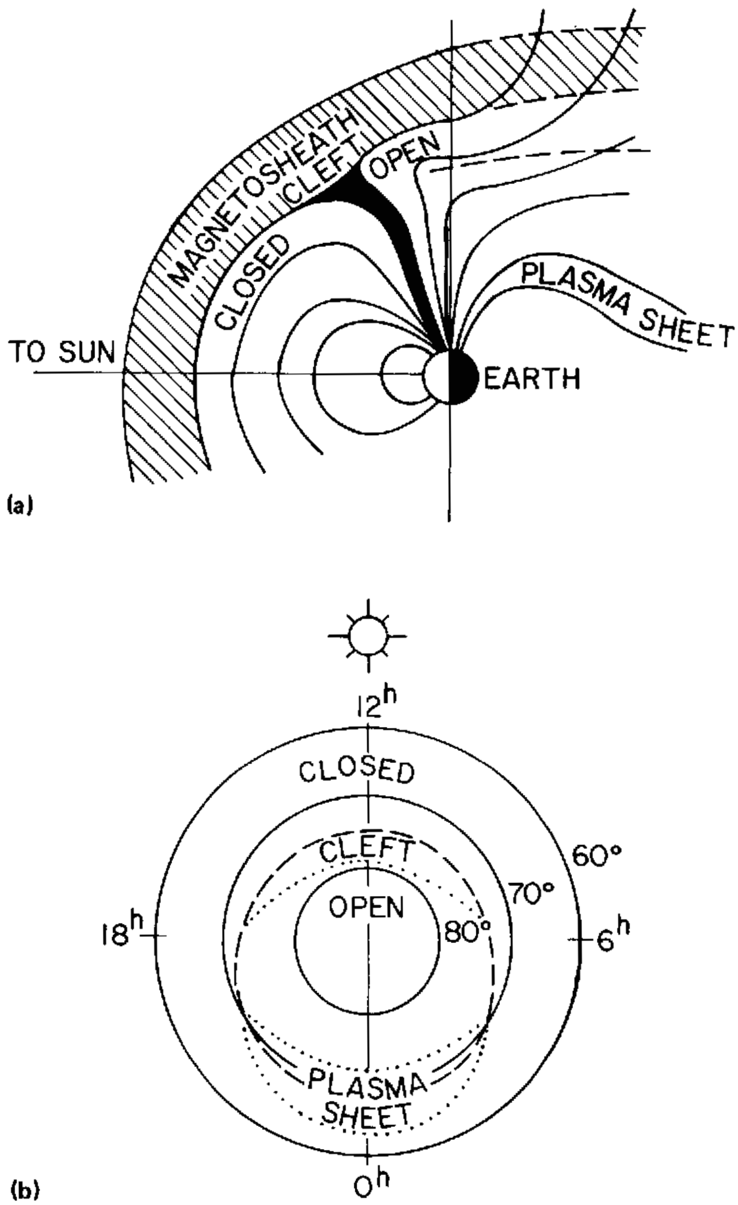
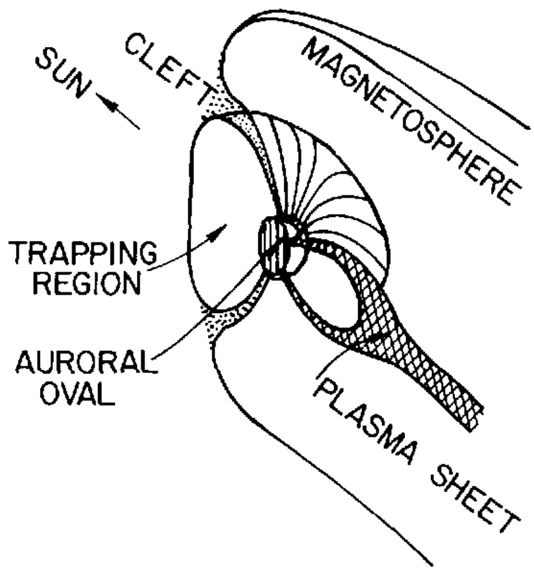


Figure 11. (a) The position of the magnetospheric cleft in a north-south section of the magnetosphere. Various magnetospheric regions are indicated. The cleft is shown as the heavy black funnel-shaped region at the boundary between open and closed dayside field lines. (b) The boundary on the ground (in corrected geomagnetic latitude and local magnetic time coordinates) between the regions of the closed and open field lines is indicated by the dashed oval-shaped curve, which is closer to the pole on the dayside than on the nightside. The plasma sheet maps down to the night side oval tapering out as we approach the dayside.

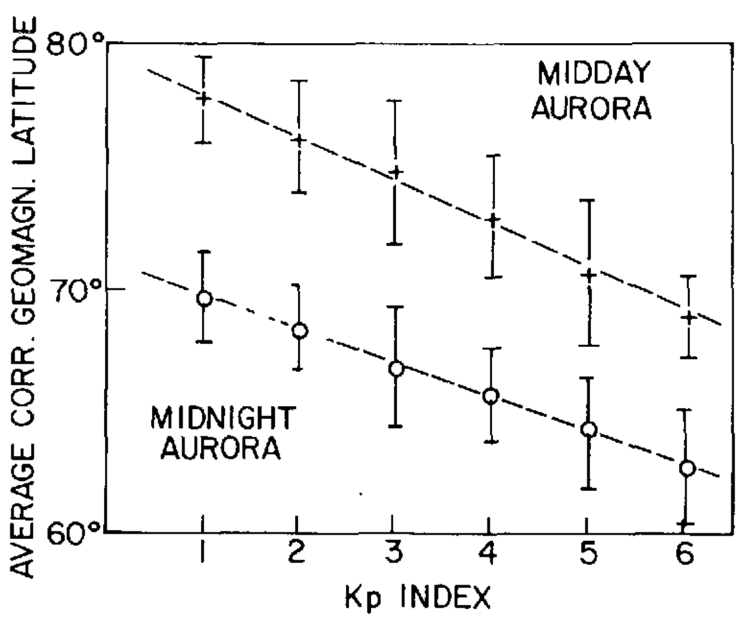
reach the distant tail and meet the corresponding ones from the opposite hemisphere, reconnection is again likely to take place because two plasmas with oppositely directed fields are being pressed together. After the reconnection in the tail, the field tubes are convected back toward the earth due to the northward component across the neutral sheet. During this convective motion, the field lines resume a more dipolar configuration, as they approach the earth, and the kinetic energy of the plasma increases because of increasing magnetic field and progressive shortening of the field lines. Magnetic energy stored in the stretched-out field in the tail is then converted into kinetic energy of the charged particles. Electrons precipitated into the atmosphere where the field lines from the plasma sheet and the cleft reach the earth cause auroral displays along an oval-shaped belt, the auroral oval, around the magnetic pole. Figure 12a shows a noon-midnight cross-section of the magnetosphere indicating the relationship between the auroral oval and the cleft, the plasma sheet and the outer boundary of the trapping region. The auroral oval is a permanent feature even during extremely quiet conditions. As geomagnetic activity increases, the oval expands away from the pole as seen in Figure 12b. In view of the merging model we would explain this by saying that when more field lines are piled up in the tail and the polar cap therefore is large corresponding to an expanded oval, then the magnetosphere contains more energy and any release of that might result in enhanced geomagnetic disturbance. As we shall see, activity in itself tends to expand the oval further.

SUBSTORMS

At times the flux transport to and back from the tail can take place smoothly and balanced. Fluctuations in B_z are then just manifested as fluctuations in the convection and in particular in the ionospheric electric currents and their magnetic effects. An example of such correlated fluctuations is shown in Figure 13a. There seems to be about 30 minutes delay in the ionospheric response, which is reasonable for such a large circuit as the magnetosphere. At other times, the response to enhanced tail flux as the result of a steady southward B_z is much more dramatic. Intense magnetic and auroral activity may develop. Figure 13b shows a sudden southward turning of the interplanetary field followed by the magnetic signature of enhanced convection. The auroral electrojets were intensified for some time after the southward turning, and just before 7^h UT, magnetograms from auroral zone stations (Figure 14) near local midnight showed a rapid decrease of the horizontal component: a magnetic substorm is now progressing. At the same time a quiet auroral arc along the midnight portion of the auroral oval suddenly brightened and started to move rapidly polewards while new bright auroral forms were forming behind it. This is the onset of an auroral substorm.



(a)



(b)

Figure 12. (a) Noon-midnight "cut away" schematic of the magnetosphere showing the auroral oval as the region where the cleft and the plasma sheet intersect the ionosphere. (b) Average corrected geomagnetic latitude of auroras in the midday and midnight parts of the auroral oval as function of geomagnetic activity as given by the K_p index. Both parts of the oval move toward lower latitude as the activity increases.

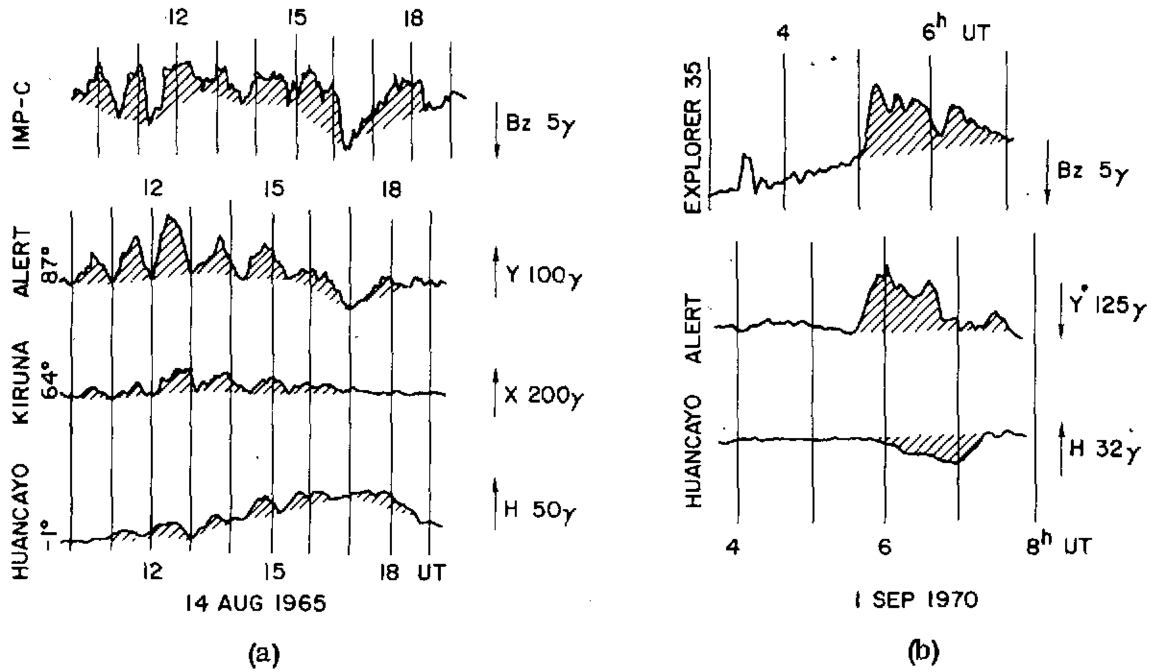


Figure 13. (a) Coherent fluctuations in the north-south component of the interplanetary magnetic field (IMP-C) and in the horizontal component of the geomagnetic field at Alert near the pole (87° corrected geomagnetic latitude), at Kiruna in the auroral zone (64°) and at Huancayo near the equator (-1°). The fluctuations on the ground seem to be delayed ≈45 min. This day (August 14, 1965) is also shown in the bottom panel of Figure 21b, where fluctuations in the east-west component of the interplanetary magnetic field correlate with fluctuations in the vertical component of the geomagnetic field at Thule (86°) after a delay of ≈30 min. (b) Response of the geomagnetic field at Alert and Huancayo to a sudden southward turning of the interplanetary field. The responses have the opposite sign of the responses shown in Figure 13a because of different (≈9^h) time of day.

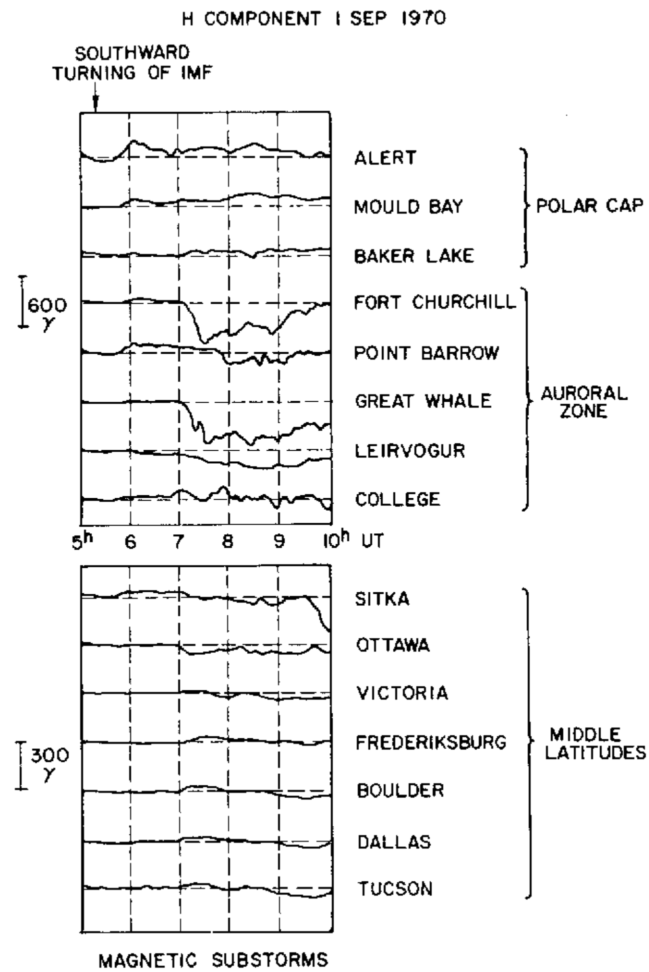


Figure 14. Horizontal component magnetograms from several observatories for the interval following the southward turning of the interplanetary magnetic field shown in Figure 12b. In the polar cap the horizontal component in the direction of the corrected geomagnetic pole is increased after the event. This is indicative of an enhancement of the cross-polar-cap convection. In the midnight sector of the auroral oval (Fort Churchill and Great Whale stations) a magnetic substorm becomes evident at about 7^h UT. At middle and lower latitudes a positive perturbation at the same time is seen at, for example, Boulder and Tucson. The complex variations can be explained as the effects of the (real) current system shown in Figure 15. The uniform midlatitude positive perturbation is an indication of eastward current flow at large distances. A disruption (disappearance) of a part of the (westward) magnetotail current is equivalent to temporarily superposing such an eastward current.

We may understand the phenomenon by considering the effect of an increased dawn-dusk electric field due to the increased magnetic flux in the tail. The earthward convection of the plasma in the plasma sheet increases, thereby removing plasma from the sheet in an earthward motion. This progressive thinning of the plasma sheet, together with the added magnetic pressure in the tail, increases the reconnection rate drastically with resulting increased plasma flow both toward the earth and also toward the distant tail away from the reconnection point. The process may be described as a local collapse or disruption of the magnetotail current because there is no plasma to carry it. The magnetic configuration in the near-earth tail changes suddenly to a more dipolar configuration from a stretched "tail-like" state. The plasma moving rapidly towards the earth is partly injected into the trapping region and partly spirals down along fieldlines into the auroral oval ionosphere where precipitating electrons cause brilliant, rapidly moving auroras. Thus, the disrupted magnetotail current establishes a new circuit from the dawnside tail to the dawnside auroral oval along the geomagnetic field lines, flows then in the ionosphere to the duskside oval and finally up to the duskside magnetotail as shown in Figure 15. An intense westward current develops in the midnight auroral ionosphere and the ionization of the ionosphere is greatly enhanced by precipitating plasma particles.

In lower latitudes the magnetic effect of the currents along the field lines is seen as magnetic bays on the magnetograms. Birkeland suggested in 1913 that an intense westward ionospheric current connected via field-aligned currents to a current circuit located at great distance beyond the earth could explain the magnetic variations associated with substorms or "elementary disturbances" as he called them. Recent rocket and satellite observations do indicate that the concept of field-aligned electric currents is fundamental in understanding magnetic substorms: disruptions of the magnetotail divert part of the magnetotail current down through the ionosphere and temporarily relax the load on the magnetosphere converting magnetic energy in the tail to heating and ionization of the upper atmosphere. Often the tail collapse progresses in a step-wise fashion as if several localized disruptions take place successively; the whole process can exhibit extraordinary complexity and diversity with series of rapidly moving and very bright loop-like auroral displays. The rapid earthward movement of the plasma leads to jet-like injection of hot plasma into the trapping region. This injection may be described as a convection under the influence of an intense induction electric field corresponding to the rapid changes in magnetic configuration when the near-earth tail field becomes more dipolar.

Once injected the particles will drift around the earth due to gradient and curvature of the magnetic field. The drift direction depends on the charge of the particles, and electrons tend to move towards the morning side, while protons are drifting toward the evening side as sketched in Figure 16a. The drifting particles constitute a net westward ring current. The magnetic field produced by this current is opposite to the dipole field (see Figure 16b) and is observed as a decrease of the horizontal component, H, at the ground in low and middle latitudes. Furthermore a strong ring current deforms the magnetospheric field in the trapping region and therefore changes the structure of the inner magnetosphere. In particular, it shrinks the inner radius of the trapping region and shifts the auroral oval towards the equator. The injected particles are rapidly lost again to the atmosphere, partly due to various instabilities as they interact with the plasmasphere. To build up a strong ring current, a number of successive injections is required or, stated differently, a number of substorms must occur in rapid succession.

GEOMAGNETIC STORMS

Identification of the basic magnetospheric processes driven by the continuous and continuously changing solar wind has been the clue to our understanding of the magnetospheric response to the more violent manifestations of solar activity: solar storms. A solar storm starts with a solar flare in a magnetically complex active region. Intense X-ray, UV, radio, H_α, and in rare cases even white light emissions mark the beginning of the storm. The solar atmosphere over the active region is violently disturbed; shock waves are generated and travel through the solar wind plasma, and part of the solar atmosphere is ejected into interplanetary space at high speed. When the shock front reaches the earth the geomagnetic field is suddenly exposed to a shocked solar wind with increased speed, density, temperature and magnetic field, resulting in a sudden compression of the magnetosphere. Thus the magnetic field intensity inside the magnetosphere increases suddenly. Ground magnetograms show this sudden storm commencement (ssc) almost simultaneously over the globe. Figure 17a shows the effect of the passing of an interplanetary shock wave where the solar wind pressure increased by a factor of 8 and stayed high for many hours after the shock. The horizontal component at Honolulu increased suddenly by 30γ, maintaining the increase during the initial phase of the storm for about 9 hours. When the shock-driving plasma reached the magnetosphere and the turbulent interplanetary field had developed a strong southward component, the energy input to the compressed magnetosphere increased rapidly by enhanced merging of field lines on the front side. A number of substorms followed in rapid succession, each of them increasing the strength of the ring current causing the main phase decrease of the field. When the solar wind returns to its quiet state and most of the magnetic energy stored in

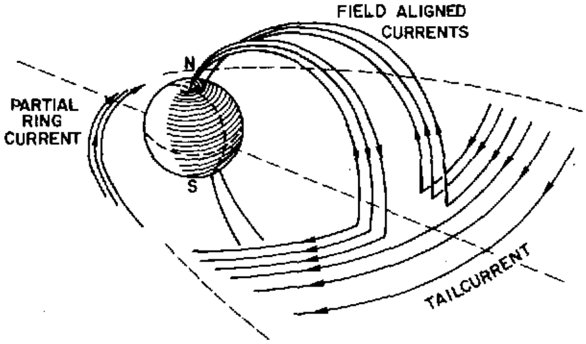


Figure 15. Currents within the magnetosphere during a magnetospheric substorm. The magnetotail current is disrupted and the magnetospheric currents establish a new circuit down the field lines to the ionosphere and back again to the tail. The intensity of the ring current becomes enhanced. There are some indications that currents also flow along field lines from the ring current to the ionosphere (this circuit is not shown in the figure).

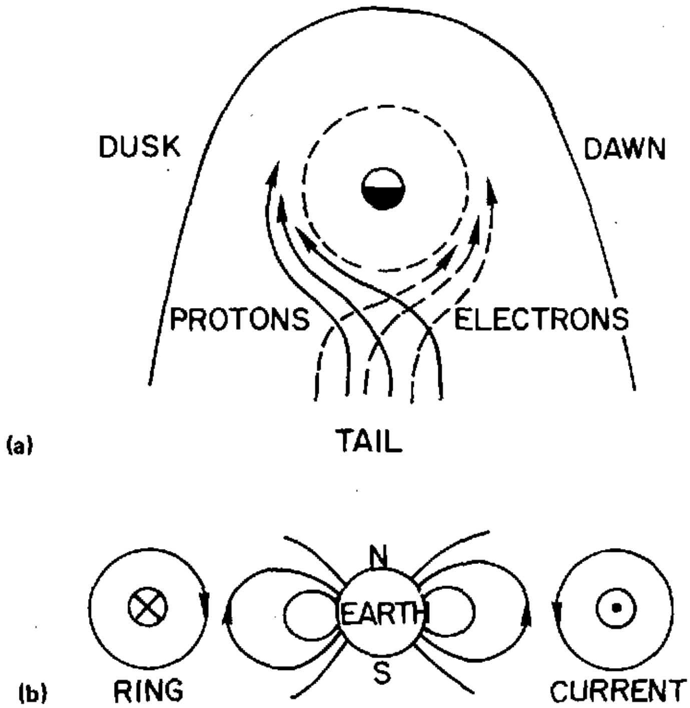


Figure 16. (a) Injection of plasma from the tail into the trapping region. The protons tend to drift westward, while the electrons tend to move eastward. The net result is a westward ring current as shown in panel (b). (b) The ring current and its magnetic effect which is opposite the dipole near the earth.

the magnetotail has been released by the intense substorm activity, the storm enters its recovery phase with the field slowly returning to its normal value. This is because the ring current particles injected into the trapping region and compressing the plasmasphere are steadily being lost and the inner magnetosphere is returning to its quiet state as shown in Figure 17b.

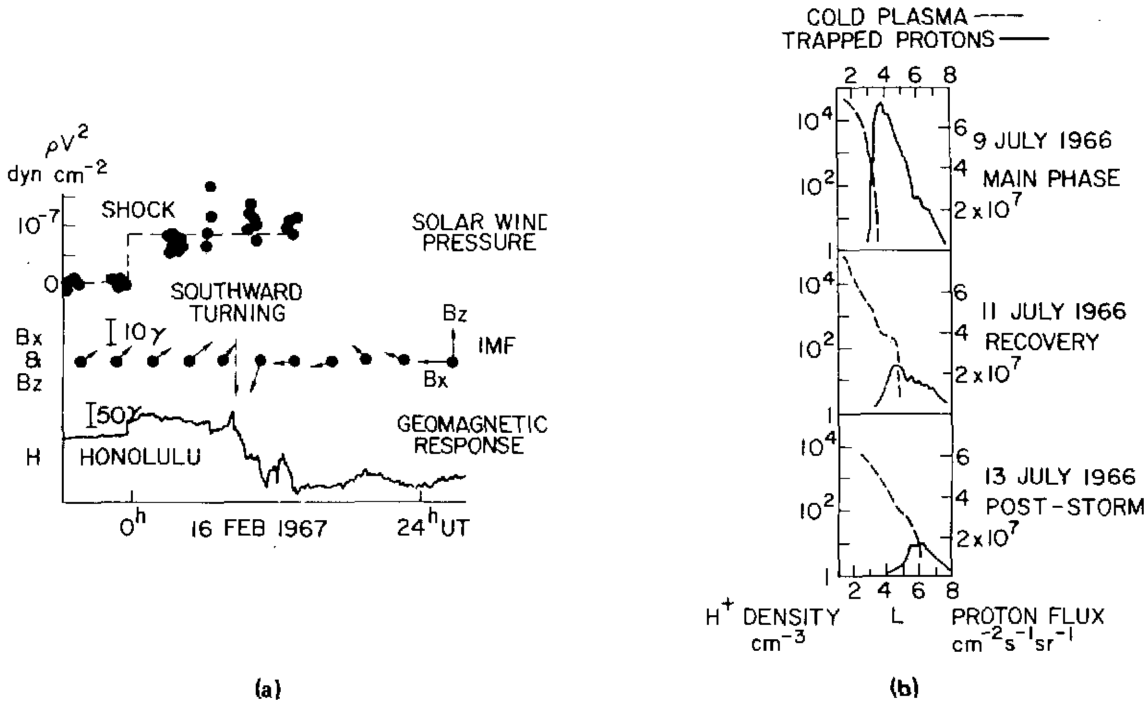


Figure 17. (a) A geomagnetic storm on February 16, 1967, following an interplanetary shock. The solar wind pressure increased eight-fold compressing the geomagnetic field. The interplanetary magnetic field in the north-south plane is shown in the center panel. After a southward turning of the field the main phase decrease in the horizontal component, H, at Honolulu is observed. (b) Changes in the size of the plasmasphere and the flux of protons (solid line) in the trapping region during a geomagnetic storm. The H^+ density in the plasmasphere decreases abruptly at a geocentric distance of 3 earth radii during the main phase, while significant density is found out to more than 5 earth radii in the post-storm phase. The "L" parameter on the abscissa is characterizing the field lines on which the plasma is trapped. For $L = 3$ the field line crosses the geomagnetic equatorial plane at a geocentric distance of 3 earth radii. High fluxes of trapped protons are found at $L = 4$ during the main phase; later the fluxes are much smaller and have moved out to $L \approx 6$.

Geomagnetic storms show a considerable variety. Some storms have no clear indication of the sudden onset and no initial compression of the magnetosphere but the main phase progresses essentially in the same way as for storms with a sudden storm commencement and a well developed initial phase. This may be related to the diversity of interplanetary shocks. At times there is no great change in the solar wind pressure across the shock but instead the magnetic field parameters change drastically, or in other cases a rarefaction region follows the shock with resulting expansion of the magnetosphere instead of the usual compression. The geometry of the shock front in connection with the position on the sun of the solar storm seem to determine the overall structure of the magnetospheric storm. Solar storms in the eastern part of the solar disk produce geomagnetic storms with a sudden commencement but not with a large main phase. Western storms cause in general very complicated magnetic storms sometimes with multiple onsets, while storms near the central meridian usually cause typical geomagnetic storms with a well-defined ssc, initial compression phase, and a large main phase decrease. Figures 18 and 19 show further examples of geomagnetic storms. In Figure 18 horizontal component magnetograms from low latitude and auroral zone stations are superposed separately to bring out the difference in the storm morphology in the two regions. The impulsive occurrence of substorms in high latitudes is clearly evident, while an ssc, a main phase, and the recovery phase can be discerned in the low latitude records. The figure also illustrates the definition of the D_{st} magnetic index as the average difference between the actual field and its quiet undisturbed level for the low latitude stations. The AE index is defined as the field difference between the upper and lower envelopes of the superposed high latitude records. The variation of these two indices during September 1957 is shown in Figure 19. The variability of the low latitude storm signature D_{st} and the impulsive nature of the high latitude substorm index AE is evident.

The plasma driving the interplanetary shock is highly turbulent and so, in particular, the north-south component of the interplanetary magnetic field, B_z, is quite irregular both spatially and temporally and may develop quite large southward values. Thus, during the passage of the turbulent plasma, many substorms are expected to occur; especially when the magnetosphere is compressed and the tail field therefore is increased. In the quiet solar wind, the interplanetary magnetic field vector is mainly in the solar equatorial plane and the average B_z is usually small. It is important, however, to note that the dipole axis generally is not perpendicular to the solar equatorial plane but is inclined to it at an angle, which has both diurnal and semi-annual variations. Even if the interplanetary field had a constant B_z perpendicular to the solar equatorial plane, there would still be a varying component which was anti-parallel to the geomagnetic dipole so that diurnal and semiannual modulations of the field line merging efficiency would be expected. On the other hand, the radially outflowing solar wind forming the magnetosphere aligned with the sun-earth line, would tend to diminish these modulations. It is at present not clear what are the relative importance of all these effects, but semiannual and diurnal modulation of geomagnetic activity are in fact deserved.

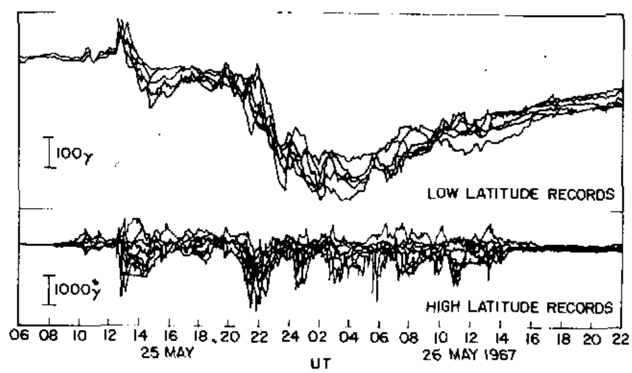


Figure 18. Horizontal component magnetograms for a magnetic storm on May 25 and 26, 1967. The traces are superposed for a number of low latitude stations and for a number of auroral zone stations separately. The quiet level before the storm has been used as a common zero-level. The difference between the actual field intensity and the zero-level for the low latitude stations defines the equatorial ring current index D_{st}. The difference (in gammas) between the upper and lower envelopes of the superposed high latitude record defines the auroral electrojet index AE.

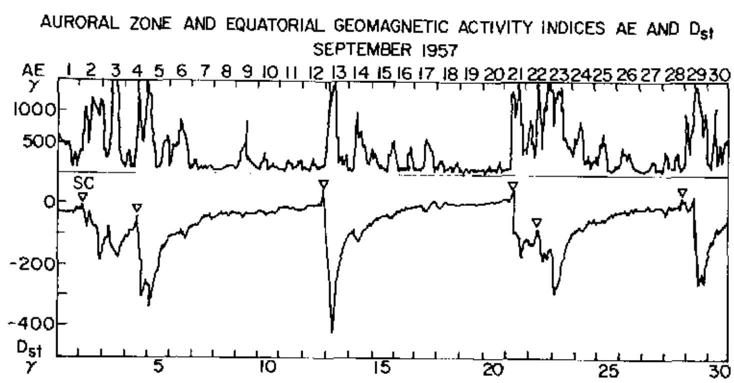


Figure 19. Variations of the AE index and the D_{st} index during the very disturbed month of September 1957. Sudden storm commencements are marked by open triangles.

SECTOR STRUCTURE EFFECTS

While it has long been clear that large geomagnetic storms are closely related to solar storms in conspicuous active regions on the sun, the solar source of the lesser geomagnetic disturbances is not easily distinguished. The pronounced 27-day recurrence tendency of moderate geomagnetic activity strongly suggests some semipersistent solar regions or features responsible for the activity. The magnetic field structure in the solar wind also shows marked 27-day recurrence, in some cases for several years. The interplanetary magnetic field tends to be directed predominantly toward or away from the sun along the basic spiral configuration for intervals of several days at a time. The tendency for these intervals of organized polarity to recur with a period near 27 days has led to the concept of a long-lived interplanetary magnetic sector structure that rotates with the sun. Regions with opposite polarity are separated by quite narrow sector boundaries which may sweep by the earth in a few minutes. The sector structure implies that the solar wind within each magnetic sector emanated from a coronal region of similarly organized magnetic polarity. Often the solar wind parameters have an organized structure within each sector. The flow speed and the magnetic field strength tend to be low near the sector boundary, rising to a maximum one or two days after the boundary, and then declining towards the end of the sector. If the sector is very broad, that is lasting for, say, 14 days, this organized structure may be found twice within the sector suggesting a time scale of about a week for the basic structure, corresponding to 90° of solar longitude. Near a sector boundary, where the field changes direction, we may expect it to be somewhat disturbed and turbulent thereby increasing the probability of substorm occurrence or at least of readjustments of the state of the magnetosphere. The increased solar wind speed and the enhanced magnetic field following the sector boundary in itself increases the energy input to the magnetosphere, hence we would expect geomagnetic activity to be organized in a similar manner within a sector. Figure 20 shows that this is indeed the case. The geomagnetic field is usually most quiet just before the boundary and increases to a maximum approximately one day after the boundary. We therefore identify the source of the long-lived 27-day recurrent geomagnetic activity with the magnetic sector structure and ultimately with the corresponding large-scale organization of the magnetic fields on the sun.

The direct responsiveness of the magnetosphere to the ever changing interplanetary magnetic field environment is maybe best illustrated by the recently discovered effect of the east-west or azimuthal component, B_y, of the interplanetary field on the geomagnetic field at very high latitudes in the heart of the polar caps. The effect is most easily seen in the vertical component, Z, very near to the magnetic poles. Figure 21a shows the average variation

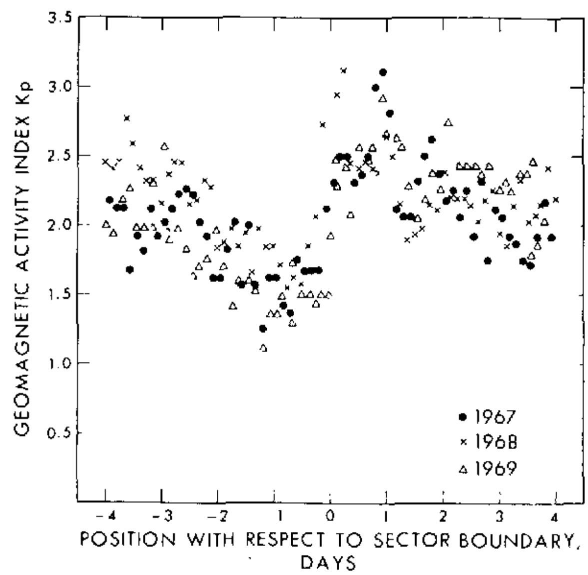


Figure 20. Average response of the geomagnetic activity index K_p to passage of an interplanetary sector boundary. The response is shown separately for three different years as the response averaged for all sector boundaries occurring in each year.

during the day of Z at Vostok in the southern and Resolute Bay in the northern polar cap; in both cases about 600 km from the corrected geomagnetic pole. The hourly means of Z are divided into three classes depending on the average value of B_y during the hour. If the east-west component B_y is small there is very little variation of Z because the two stations are near the center of the electrojet system, but for nonzero B_y significant perturbations of the vertical component is observed at both stations. The perturbations are of opposite sign when B_y changes sign and are observed in the opposite part of the day in opposite hemispheres. Since positive B_y is associated with sectors with magnetic polarity away from the sun and negative B_y is associated with toward polarity and because the vertical component is positive when directed towards the earth, we can summarize the effect by noting that central polar cap Z perturbations are predominantly directed away from the earth during sectors with polarity away from the sun, and towards the earth during sectors with magnetic polarity directed towards the sun. From Figure 21b it may be seen that this remarkable correlation is not only seen in a statistical sense for long period variation but also extends to individual fluctuations as short as 30 minutes or less during the interval 10^h to 22^h UT.

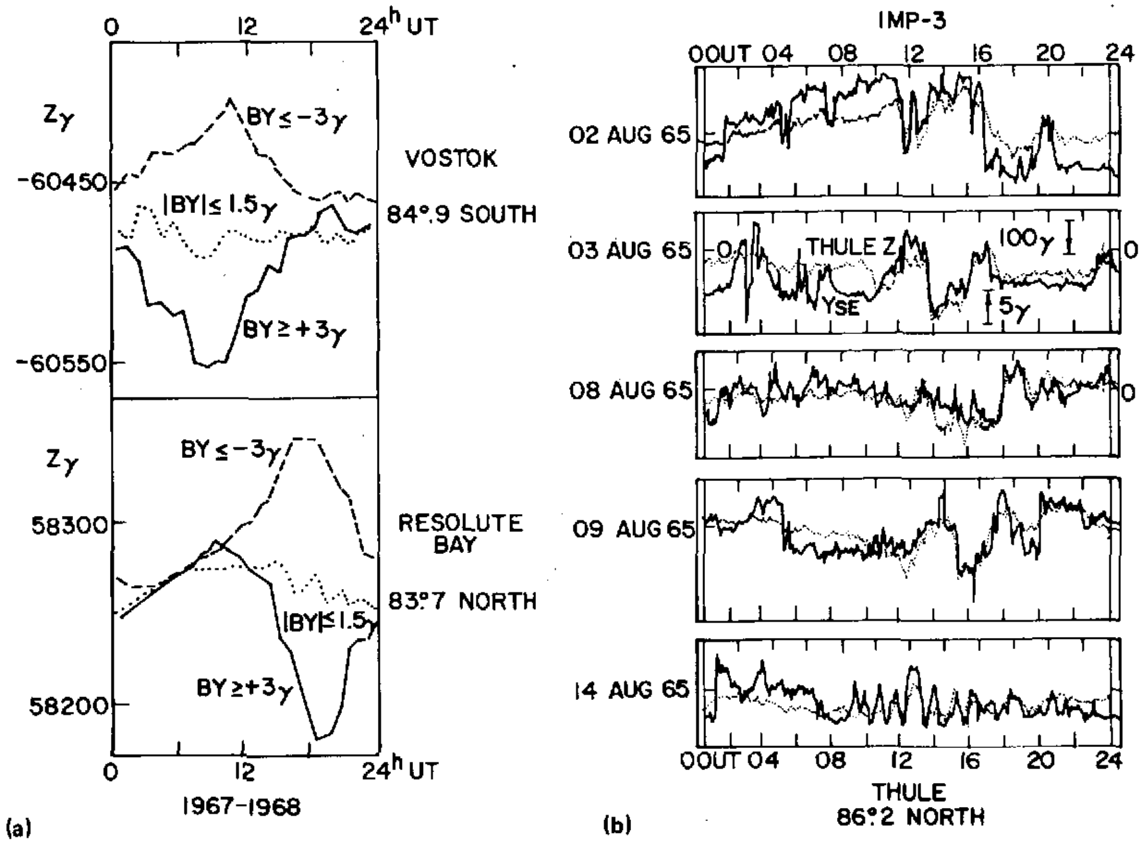
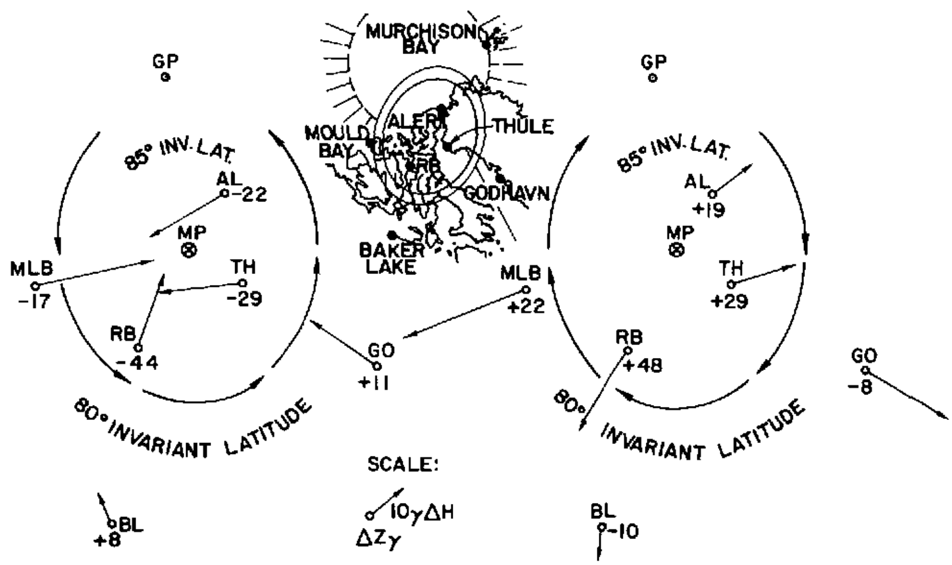


Figure 21. (a) Diurnal variation of the vertical component, Z, at Vostok and Resolute Bay during 1967 and 1968. All hours where the hourly average of the interplanetary east-west component (solar magnetospheric coordinates) BY was less than -3γ were averaged for each UT hourly interval to yield the dashed curves. When BY is greater than +3γ the solid curves result, while the dotted curves were computed for times where BY was near zero ($|BY| \leq 1.5\gamma$). (b) Corresponding fluctuations of the Z component at Thule (dotted trace plotted positive downwards) and the east-west component (solar ecliptic coordinates) Y_{SE} of the interplanetary magnetic field (solid trace). The fluctuations are well correlated in the interval 10^h to 24^h UT with the fluctuations on the ground delayed about 25 min.

A note about coordinate systems: The X axis points towards the sun. In magnetospheric coordinates the XZ plane contains the geomagnetic dipole. In ecliptic coordinates the XY plane contains the ecliptic. The third axis completes the normal righhanded orthogonal system. When discussing the interaction with the magnetosphere the interplanetary magnetic field is normally expressed in magnetospheric coordinates. For our purpose the distinction is not important.

There seems to be a delay of about 20 minutes before the response of the polar cap field. The figure clearly demonstrates that the sector structure may exhibit a high degree of variance, and that the polar cap Z-component responds to variations of the sector structure on a time scale of a few tens of minutes.

Further analysis of this response has shown that at a somewhat larger distance from the magnetic poles the horizontal components begin to respond to variations of B_y. The effects can be described as the magnetic effects of an ionospheric current flowing around the magnetic pole at a corrected geomagnetic latitude of 80° to 82°, as indicated on Figure 22. The sense of the current is clockwise for negative B_y and anti-clockwise for positive B_y. Passage of a sector boundary thus causes an abrupt reversal of the current.



POLAR CAP DISTURBANCES AT 18^h UT FOUND DURING IMF AWAY POLARITY.

POLAR CAP DISTURBANCES AT 18^h UT FOUND DURING IMF TOWARD POLARITY.

Figure 22. Typical polar cap magnetic disturbances observed for the two opposite polarities of the east-west component, B_y, of the interplanetary magnetic field. Two synoptic maps are shown with disturbance vectors corresponding to positive B_y (normally within "away" sector) at the left and to negative B_y ("toward" sector) at the right. The vectors showing the horizontal perturbations are drawn from the positions of each six northern polar cap stations. An insert shows the geographical locations of these stations. Signed numbers next to the station circles denote the Z perturbations. The positions of the geographical pole (GP) and of the corrected magnetic pole (MP) are indicated. Parts of equivalent currents which could produce the magnetic variations are sketched. The perturbations (and the current) reverse when B_y reverses sign.

The physical reason for the existence of this polar cap current is presumably some modification of the convection pattern caused by the azimuthal component of the interplanetary field, but no clear picture of the precise nature of the effect and of its mechanism has emerged yet. One thing is, however, clear, namely that the magnetosphere is directly affected by the interplanetary field; the existence of this response is also a good indication that geomagnetic and interplanetary field lines are connected.

CONCLUDING REMARKS

A tremendous advance in our understanding of the properties of the solar wind and its interaction with the terrestrial environment has been achieved in recent years through intensive observational and theoretical programs. Enough observational evidence has been in hand to guide the theory along realistic paths, and enough theory has been developed to interpret data that are characteristically incomplete in coverage. The explorative phase of magnetospheric research is coming to an end, and the basic magnetospheric processes are identified. The basic structure of the magnetosphere—the bow shock, the magnetosheath, the magnetopause, and the magnetotail—has been unveiled. The importance of the continuous interaction between the solar wind and the magnetosphere is realized and the concept of the magnetospheric substorm constitutes a basic framework for our understanding of the major disturbances within the magnetosphere.

The interplanetary magnetic field—although having an energy density two orders of magnitude less than the solar wind plasma—is essential in controlling the solar wind interaction with the earth. It gives the collisionless plasma fluid properties over scale lengths comparable to (or less than) the size of our planet. The interplanetary field connects with the geomagnetic field to provide efficient solar wind-magnetosphere coupling to drive the magnetospheric dynamo. Solar wind kinetic energy is then converted into magnetic energy stored in the magnetotail. Instabilities in the system release part of the stored energy and convert it into kinetic energy of magnetospheric plasma particles. The upper atmosphere acts as a sink for this kinetic energy as it is converted into radiation and heating.

ACKNOWLEDGMENTS

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APPENDIX

ESTIMATES OF SOME RELEVANT PHYSICAL QUANTITIES FOR THE SOLAR WIND INTERACTION WITH THE GEOMAGNETIC FIELD

The electromotive force, $\underline{\epsilon} = \underline{w} \times \underline{b}_n$, supplied by the solar wind to the magnetospheric dynamo is of the order

$$\epsilon = wb_n$$

where w is the solar wind speed. The normal component b_n of the magnetic field connecting the magnetospheric tail and the interplanetary field can be estimated by assuming that the magnetic flux M_P from the polar cap is connected to the interplanetary field along the surface A_T of the tail. With a polar cap radius r_P and a polar cap field B_P, we get $M_P = \pi r_P{}^2 B_P$. Taking the length of the tail as S_T, we have $A_T = \pi R_T S_T$, where R_T is the radius of the tail. Hence

$$b_n = \frac{M_P}{A_T} = r_P{}^2 B_P / R_T S_T$$

With $r_P = 15^\circ = 1.7 \times 10^6$ m, $B_P = 55{,}000\gamma = 00.55 \times 10^{-4}$ Wb/m^2, $R_T = 20\ R_E =$ 1.3×10^8 m, and $S_T = 500\ R_E = 3.2 \times 10^9$ m, we get $b_n = 3.7 \times 10^{-10}$ Wb/m^2 = 0.37γ. One earth radius is $R_E = 6.38 \times 10^6$ m. Taking the solar wind speed as $w = 420$ km/s $= 4.2 \times 10^5$ m/s, we find

$$\epsilon = 1.6 \times 10^{-4}\ \text{V/m}$$

The total potential difference across the tail then becomes

$$\Phi = \epsilon \pi R_T = 6.4 \times 10^4 \text{V} = 64\ \text{KV}$$

and the electric field in the polar cap is

$$E_i = \frac{\Phi}{2\ r_P} \approx 20 \times 10^{-3}\ \text{V/m} = 20\ \text{mV/m}$$

We can also write

$$\Phi = wb_n \pi R_T = wM_P \pi R_T / A_T = wM_P / S_T$$

The field strength in the near earth tail (before too much flux has leaked out) can be estimated to be

$$B_T = \frac{M_p}{\frac{1}{2}\pi R_T^2} = 2B_P \frac{r_p^2}{R_T^2} = 19 \times 10^{-9} \text{Wb/m}^2 = 19\gamma$$

The typical quiet time convection velocity over the polar cap can be obtained from $\underline{v}_c = \underline{E} \times \underline{B} / B^2$ as

$$v_c = E_i / B_P = 360 \text{ m/s}$$

The time to convect the foot-points of the tail field lines across the polar cap is now

$$t_c = \frac{2r_P}{v_c} = 9250 \text{ s} = 2.6 \text{ hours}$$

In that time the interplanetary end of the field line moves wt_c which then is also an estimate of the length of the tail

$$S_T = wt_c = w2r_P B_P / E_i = 3.8 \times 10^9 \text{ m} = 600 \text{ R}_E$$

For a line current (auroral electrojet) at height h over the ground to give a magnetic substorm effect of $B_A = 1000\gamma = 10^6 \text{ Wb/m}^2$ the current strength must be of the order

$$i_A = 2\pi h B_A / \mu_o$$

Taking $h = 110 \text{ km} = 1.1 \times 10^5 \text{m}$, we get $i_A = 550,000$ ampere. If n_T is the current density of the tail current estimated by treating each half of the tail as a solenoid: $n_T = B_T / \mu_o$, we find that the extent of the tail current disruption is of the order of

$$k_d = i_A / n_T = 3.7 \times 10^7 \text{m} \simeq 6 \text{ R}_E$$

Assuming that the energy in this part of the tail was stored as magnetic energy, we get for this

$$U_d = \frac{B_T 2}{2\mu_o} \text{ volume} = \frac{B_T^2}{2\mu_o} \frac{\pi R_T 2}{2} k_d = B_T \pi R^2{}_T i_A / 4$$

But we have also $U_d = \frac{1}{2} Li^2$ so that the inductance of the circuit becomes

$$L = \mu_0 \frac{B_T}{B_A} \frac{R_T}{4h} = 890 \text{ henry}$$

The resistance, R, in the circuit is essentially that of the ionosphere: $R = \Phi / i_A = 0.12$ ohm, so the time constant of the circuit can be estimated as

$$t = L/R = 7.4 \times 10^3 \text{ s} \simeq 2 \text{ hours}$$

This shows us that the magnetotail certainly contains enough energy to drive a substorm which lasts, say, 1 hour. The energy dissipated in the ionosphere alone by the substorm current is of the order

$$P = i_A \Phi = 3.5 \times 10^{10} \text{ watt}$$

Taking into account also the current in the southern hemisphere we get a total rate at which work is being done of the order of 10^{11} watts. If the substorm lasts for one hour the total amount of energy dissipated in the currents is then about 3×10^{14} joules. The additional energy deposited in the auroral substorm by the precipitating electrons can be estimated from the auroral luminescence and is about 2×10^{14}J. Therefore the total substorm energy dissipation amounts to 5×10^{14} joules corresponding to an earthquake of magnitude 6.7 on the Richter scale.

We can estimate the total magnetotail current J_T by setting the average magnetic field in the tail to $B_T/2$. We do this because the field decreases down the tail as more and more field lines are connected to the solar wind and leak out of the tail (see Figure 4a). Hence the average current density: $\bar{n}_T = \frac{1}{2} n_T = B_T / 2\mu_0$, so that $J_T = J_{northern} + J_{southern} = 2S_T \bar{n}_T = S_T B_T / \mu_0 = 5 \times 10^7$ ampere. The total amount of energy drawn from the solar wind by the current J_T over a potential difference Φ is then

$$P_S = J_T \Phi = 3 \times 10^{12} \text{ watts (J/s)}$$

The energy deposited in a substorm corresponds to about 2 minutes of solar wind input. We see that *substorms are not major collapses of the magnetosphere*, but rather have the character of minor internal adjustments to changing external conditions.

The kinetic energy of the solar wind falling on the magnetosphere is essentially

$$K = \pi R_T^2 w \tfrac{1}{2} n m_p w^2$$

where $m_p = 1.67 \times 10^{-27}$ kg is proton mass and $n = 5$ protons/cm^3 = 5×10^6 m^{-3} is the number density. We find $K = 1.6 \times 10^{13}$ watts, which is 5 times the energy in the magnetotail. From energy considerations the solar wind thus seems capable of driving the magnetospheric dynamo and maintaining the magnetotail.

QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF LEIF SVALGAARD

MR. SCHMERLING: I am having some difficulty bridging the sharp discontinuity between one speaker and another, and I wonder if somebody can help me by providng a 1 A.U. matching transform. In particular, what bothers me is that in one view — and that is primarily the view of the sun in the interplanetary medium — what is important is the field structure in the ecliptic plane, and what appears to be important for triggering some of the terrestrial events is whether the field, as it arrives at the earth out of the ecliptic plane, is north-south or south-north. More specifically, I can look at that picture that you have drawn on the board and imagine that with precisely the same kind of ecliptic plane projection I can have north-south or south-north fields, depending simply on whether some of the structure is a little bit above or a little bit below the ecliptic plane.

MR. SVALGAARD: Part of the answer is that the important thing is the fluctuations of the field. A field line is not really like a straight line; it is wiggling all around. And so, as seen from the earth, that field line is carried past us, and it appears as a wiggly line that changes direction — it runs east, it runs west, it runs north, and it runs south. And when it "decides" to go southward, the energy input to the magnetosphere, due to the connection of the field lines across the magnetopause, goes up, and if it is fluctuating enough, then it goes southward a lot and you have a lot of input to the magnetotail.

MR. MANKA: It seems to me that you discussed a lot of mechanisms which might provide energy input, ultimately, into the atmosphere. If the solar wind flow velocity is related to position in the sector structure, there is a direct plasma energy input and then you have a magnetic connection.

It seems to me that, in a sense, basically you are dealing with whether it is a plasma energy input, ultimately, or a field input. You also have the interplanetary electric field which will be related to the magnetic field strength and the flow velocity. When it gets to the earth, if the interplanetary electric field creates polarization and cross-tail field, then you could convert that field energy into a plasma input via currents down the field lines, or we may have the magnetospheric electric field, itself, mapping down the magnetic field lines, and then driving currents in the atmosphere.

So it seems to me that a possible approach might be to try to track through the sequences and see whether it is the field or the plasma which is, in a sense, the cause, and which is the effect. Do you have any feel for this? Which of these processes might dominate? Which one might be a key one in relationship to the magnetic sector structure?

MR. SVALGAARD: That is a difficult question to answer straight away, but I think that (to be very brief) the kinetic energy of the solar wind plasma is, via this reconnection, stored up as magnetic energy in the tail, and then instabilities in the tail sooner or later release that energy, and so we have a conversion of plasma kinetic energy into magnetic energy, and then later from that magnetic energy again into plasma energy. It is that latter plasma which has the effect on the earth. There is very little solar plasma which comes directly from the solar wind and goes directly down, down to the ground.

So one could say that the solar wind acts from the sun on the sunward side of the earth, but then it is the tail which really gives the action on the night side, and I think the crucial thing here is to note that the energy is stored up in stretched magnetic field lines of the tail, and that stretching out is presumably done by the magnetic field of the solar wind.

MR. MARKSON: There have been studies that indicate that, on one hand, the moon's position may have something to do with weather, and also that the moon's position may have something to do with geophysical parameters, such as Stolov's studies relative to the position from the ecliptic. I wonder if you could comment on how important this might be and how it might happen.

MR. SVALGAARD: The moon passes through the tail, and therefore might upset the balance in the tail. However, the tail is extremely large and the moon is very small, and I think the consensus right now is that the moon has very little, if any, effect at all. Maybe in another 55 years or so, there will be a conference on lunar influences on the weather!

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SOLAR MODELS IN RELATION TO TERRESTRIAL-CLIMATIC VARIATIONS

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ABSTRACT

One of the suggested possibilities to explain the lack of observation of solar neutrinos is that the sun may have undergone a thermal expansion at the center, lasting a few million years, with an accompanying decrease in luminosity, producing an ice age. A critical examination is given of this hypothesis.

Most of the papers at this meeting have dealt with relatively small changes in the state of the sun which may or may not be accompanied by relatively small changes in the state of the earth's atmosphere. The present paper deals with the possibility of occasional much larger changes in the state of the sun, lasting for some millions of years, which might be responsible for producing more drastic changes in the earth's climate, called ice ages. I have recently given a more complete summary of this situation, and the reader interested in more details and references is referred to this (Cameron, 1973).

For some years, Raymond Davis, Jr., of the Brookhaven National Laboratory, has been attempting to detect neutrinos emitted from the sun. He has been utilizing a large tank underground in a mine in South Dakota, which contains some 100,000 gallons of commercial cleaning fluid, C_2Cl_4. The expected action of the more energetic solar neutrinos is to convert some atoms of ^{37}Cl into atoms of ^{37}Ar, which is a radioactive nuclide. Periodically, every month or two, the tank is purged of rare gas atoms, which are collected, the argon separated out, and any radioactive argon atoms are then detected by a carefully shielded counter. The great sensitivity of this experiment may be judged from the fact that Davis is looking for the production of only a few radioactive argon atoms per month in this large tank.

Davis' experimental results are usually quoted in terms of a unit depending in part on the expected neutrino interaction cross section with ^{37}Cl atoms. This unit is called the solar neutrino unit, or SNU for short. When the experiment was first designed, model calculations had predicted that Davis should obtain a signal equivalent to about 30 or 40 SNUs. However, he did not detect any signal, and with added effort which has involved increasing his detector sensitivity greatly, he has pushed down the limit to the point where the solar neutrino flux is not greater than about one SNU. Meanwhile, there have been some revisions in nuclear reaction cross sections, whose redetermination has been motivated by these experimental results, and current solar models predict that he should detect a signal of about seven SNU. It is this discrepancy which has led to an intense search for aspects of nuclear astrophysics, stellar physics, or neutrino physics, which might be an error. Here I shall deal with only one of these suggested methods for evading the solar neutrino difficulty, that involving a temporary thermal expansion of the center of the sun. This idea was originally suggested by W. A. Fowler.

Suppose that a considerable amount of thermal energy is suddenly dumped into the center of the sun. This heats up the gas, increasing the pressure, and causing the center of the sun to expand. This expansion, in turn, adiabatically cools the gas to a temperature lower than that which the center of the sun would normally have. This cuts down the rate of the thermonuclear reactions occurring there, and hence it will also greatly cut down the emission of neutrinos from the central regions of the sun. This excess energy will diffuse out of the center of the sun over the course of a few million years, allowing the central region to relax back toward the normal condition.

There have been a number of discussions in the last two years of a possible way in which such a sudden energy release might take place. To show schematically how this happens, it is necessary to consider the basic energy-producing reactions in the sun and their temperature sensitivities. I shall give here only the first of the so-called "proton-proton reaction chains" which is probably responsible for most of the energy generation in the sun, but which is not responsible for producing neutrinos to which the Davis detector is sensitive.

The first step is the proton-proton reaction: $^{1}H(p, \beta^{+} \nu)^{2}D$. This reaction, involving a β decay, is a rare one and has a relatively low temperature sensitivity in the center of the sun, about the fourth power of the temperature. This reaction is immediately followed by another: $^{2}D(p, \gamma)^{3}He$. The deuterium formed in the first reaction is almost instantaneously removed and converted to ^{3}He by this reaction. The ^{3}He builds up until there is enough of it present for it to react with itself: $^{3}He(^{3}He, 2p)^{4}He$. This reaction has a much higher temperature sensitivity, something like the twentieth power of the temperature near the center of the sun.

As a result of the different temperature sensitivities of these reactions, the amount of ^3He which will be present under steady-state conditions will increase as one goes away from the center of the sun. This results from the fact that much larger amounts of it are needed to compensate the relatively smaller reaction rate at lower temperatures in the sun.

Therefore it is evident that if some mechanism could produce a large-scale and sudden mixing of the central regions of the sun, the amount of ^3He at the center would be greatly increased. The amount would then be much in excess of that needed to produce ^4He at the steady-state rate established by the basic proton-proton reaction. Hence the excess ^3He would more rapidly be destroyed in the central region of the sun, releasing energy at higher than the normal rate, and providing the source for the relatively sudden release of energy which has been postulated.

It is necessary to emphasize that we do not know of a suitable mixing mechanism which would be needed to produce this effect. The only detailed mechanism suggested is an oscillatory overstability of the central regions of the sun, leading to mixing, proposed by Dilke and Gough. However, this mechanism has come under severe criticism by Ulrich and others. Thus at the present time we have nothing to suggest for a driving mechanism that would cause the mixing, and this is the fundamental weak point in this whole approach. All we can do is suppose that the mixing happens, and inquire as to the consequences. This simply recognizes that there is a considerable amount of strange behavior associated with they dynamics of rotating fluids that we do not yet understand, so that perhaps it may be possible in the future to find a driving mechanism for the mixing if the consequences should look interesting.

Let me cite a specific numerical example, calculated by Ezer and Cameron (1972). In this experiment, 56 percent of the central mass of the sun was suddenly mixed, which meant that its composition was rendered uniform. This led to an increase of ^3He near the center, and the additional energy released by destruction of this nuclide caused the center of the sun to expand over a period of about two million years. Following an initial neutrino flash immediately after the mixing, the neutrino production fell off markedly throughout the sun, and the expected detection by Davis dropped to about 0.5 SNU. The photons then gradually diffused out of the center of the sun, allowing the solar core to relax back toward normal conditions over the following four million years. The total time involved in the core expansion was thus six million years, and during this period of time the solar luminosity dropped to a minimum of about two-thirds of normal. There was a small overshoot in luminosity at the end of the recovery period, which would gradually die out over a somewhat longer period.

It is reasonable to expect that the large decrease in luminosity of the sun would produce an ice age. We are presently involved in an ice age, which has lasted for a few million years. As long as the poles of the earth are covered by ice, this is to be regarded as an ice age, and we are not concerned with the motion of the ice sheet back and forth between high and low latitudes. It appears that the earth was free of polar icecaps throughout most of geologic history. Thus the numerical example that I have just cited cannot be expected to be truly representative of the situation. If something like this were to happen, we would identify the present as a period of reduced solar luminosity, so that the normal solar luminosity would be considerably higher than at the present time, perhaps 50 percent greater. This would have burnt more hydrogen in the central region of the sun, leading to a rising level of the normal solar neutrino flux, and the current dip in this neutrino flux would not be as great as indicated in the above example. A more realistic calculation would probably bring the minimum down only comparable with the Davis upper limit on the neutrino flux.

To judge from the geologic record, this sort of mixing would have to occur about four times per billion years throughout the history of the sun.

If this should prove to be an explanation for the terrestrial ice ages, then I wish to emphasize the restrictions imposed on the process by these calculated time scales. These calculations seem to pin down the total duration involved in the luminosity excursion quite well; I would not expect this duration to be much affected by any details of the mixing mechanism that might be determined in the future, with the exception noted below.

Therefore it is important that the geologic record does not seem to give clear-cut determinations of the general duration of ice ages, nor does it seem to give very precise evidence for the time at which the present ice age began. I, at least, have been unable to find any precise determinations of these quantities in my somewhat cursory examination of the literature. Thus, this picture for the production of ice ages would certainly be in trouble if it were found that the present ice age had extended for much longer than three or four million years. I have seen a report in the popular press that recent drilling in the Antarctic ice sheet has indicated an age much greater than this, perhaps of order 20 million years; until details of this should appear in the scientific literature, it is not possible to judge the validity of such reports.

If it should be decided that one wishes to preserve this mechanism for accounting for the earth's ice ages and also to accommodate longer durations of these ice ages, then there is one possible way in which this might be done. If the hypothetical mixing mechanism has a longer time period associated with it than six million years, so that the excess ^{3}He is driven toward the center of the sun on this longer time scale, then the duration of the luminosity dip in the sun could be extended. However, the amplitude of the luminosity dip would be correspondingly decreased. Under these circumstances, it would no longer be possible to reduce the solar neutrino flux down to the limit indicated by the Davis experiment, and the entire motivation for this suggestion would disappear.

At the present time, I am rather pessimistic about the possibility that this suggested mechanism will solve the solar neutrino problem and provide an explanation of the ice ages. The lack of a suitable mixing mechanism despite the interest generated by this suggestion is one cause for such pessimism. The sharply limited duration possible for such ice ages is another. Nevertheless, I think it is well worthwhile to carry out additional work on this suggestion, particularly with regard to calculations of general worldwide climatic conditions under conditions of a higher-than-normal solar luminosity, and additional investigations of the dynamics of rotating fluids. Unfortunately, astronomical evidence for such major luminosity variations is unlikely to be found, since the temperature and luminosity of the sun change in such a way as to drive the sun stright down the main sequence, so that other stars undergoing these changes would simply now appear to be of lower than normal mass but otherwise normal in all respects. Meanwhile, if some other explanation of the solar neutrino puzzle should prove to be successful, then we would no longer have a motivation for belief in the present suggested mechanism.

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF A. G. W. CAMERON

MR. RASOOL: The luminosity of the sun has changed over billions of years. Can you give the present thinking of how this evolution has taken place?

MR. CAMERON: The standard kind of solar models would make the solar luminosity increase from the time when the sun was on the zero edge main sequence to now by, I think, it is something like 35 percent, 50 percent, of that order, in a sense of gradually increasing. And, of course, if you believe in time variation of G and things like that, you can actually make the solar luminosity gradually decrease over all of that period of time. If you believe in the Brans-Dicke theory, you can do anything you want. But if you don't, then the solar luminosity has increased by an order of 40 or 50 percent since the time the sun was formed.

MR. BOOK: Is it possible that there are neutrino absorbers somewhere in the sun that are far more effective because there is far more mass in the sun, than in Davis' experiment? How does one know that there isn't a lot of chlorine or some other neutrino absorber somewhere in the sun, since not very much is known about its constitution?

MR. CAMERON: There is nothing special about chlorine except that is happened to lead to a convenient rare gas radioactivity at the detector. The neutrino cross sections are pretty well calculated and they are known in some cases experimentally, at least at the higher energies. The standard calculations say that the mean free path for absorption of typical solar neutrinos is something like 80 light years of ordinary lead. That is a measure of how transparent matter ordinarily is to the passage of such neutrino fluxes. This is why Ray Davis can have a hundred thousand gallons of cleaning fluid down in the mine and only detect a few atoms per month. The stuff is really terribly transparent.

It would be far more upsetting to physics to say that there was some sort of neutrino absorber in the sun that to assume that the sun behaves in the way I suggested. So it is a matter of choosing which field you want to do drastic things in.

I should have mentioned that the idea that we are now in an ice age on the earth has been picked up by Carl Sagan and some of his colleagues who say that Mars is also in an ice age. One of the other things that he suggested, though, I would like to lay to rest: that is that when the sun changes this way, it would have the effect of broadening the distribution of stars (which are also doing this) on the main sequence which one can measure for a cluster or something like that.

When we look at, in fact, how the temperature and radius of the sun change together, it turns out that the sun, when it decreased in luminosity, moved exactly down the main sequence. Therefore this does not produce any broadening of the main sequence, so this is not an effect that one can look for astronomically.

QUESTION: How fast do you think the solar luminosity changes?

MR. CAMERON: These calculations, as I remember, the time scale for a luminosity decrease occurred in just a little less than one million years, and most of the recovery occurred in about a two-million year period.

QUESTION: Yes, but that would be the rate of change for this particular process. How fast do you think it could change by, you know, if you just perturbed it in some way? What would be the lower limit for changing of solar luminosity, due to maybe other forces? How fast can a big thing like that change?

MR. CAMERON: If you make any major perturbation in the structure, the relaxation time is basically the Kelvin-Helmholtz relaxation time. When one is dealing with the core, it is just like five or six million years. If one is dealing with the outer envelope of the sun, it is rather longer, maybe 50 million years, so you can get the fastest response if you just deal with the core. In terms of the neutrino problem, just doing something to the envelope isn't going to help you.

MR. ARKING: Can we have an explanation of why you have to have such a drastic change in luminosity if you were to, say, alter the rate at which you are producing energy in the center of the sun? Or another way of looking at it, if you suddenly turn off the energy-producing reactions in the center of the sun, wouldn't the sun continue to be luminous at approximately the same solar constant for millions of years before the effect would be seen on the surface?

MR. CAMERON: That's right. If you turned off all the nuclear reactions in the sun, the sun would keep shining and it would keep contracting, and the luminosity would in fact follow pretty much the horizontal branch — that is, it would stay level as the sun shrunk and as the surface temperature increased.

MR. ARKING: So why do you need a 30-percent change in luminosity?

MR. CAMERON: Well, the whole question is what do you have to do to the sun to shut off the neutrinos enough not to violate the Davis experiment, and the argument is that you have to cause the center to expand and therefore you have to dump energy into it, and it is a natural consequence of the response of the sun to dumping that energy into the core which decreases the luminosity.

QUESTION: Would a strong magnetic field in the interior of the sun have any effect, a very strong field, millions of gauss, something like that?

MR. CAMERON: Such a field would help a little bit. It would not help nearly as much as you need if you wanted to try to cure the neutrino problem strictly with such a field.

MR. DAVIS: I'm curious where you got your 20 million year figure for the Antarctic Ice Cap because, as I recall, the ice at the bottom of the core at Byrd Station has a radiocarbon date of about 40 to 50 thousand years, which would probably fit your theory better.

MR. CAMERON: It would be fitted very much better. All I remember is that sometime this summer I read an interview with somebody who had done a measurement, and it was quoted as 20 million years. I haven't seen it in the literature, all I have seen it in is a popular report. And so I don't know how good that number is. Other people have tried to look at ocean temperatures and have said that they seem to have been steadily decreasing over the last 50 million years, for example, and I don't know how good those numbers are. If one can say that the duration is longer than about six million years, the basic point I am trying to make is that one is in trouble with this explanation no matter what you do because, even if you make the sun behave this way, it won't cure the neutrino problem. Maybe there is some other explanation for the neutrino problem and the sun still behaves this way, but we still don't know of a driving mechanism that would make it behave this way, so that is a very fundamental weakness, too.

N74-29087

POSSIBLE RELATIONSHIPS BETWEEN SOLAR ACTIVITY AND ATMOSPHERIC CONSTITUENTS

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ABSTRACT

The large body of data on solar variations and atmospheric constituents collected between 1902 and 1953 by the Astrophysical Observatory of the Smithsonian Institution (APO) is examined. Short-term variations in amounts of atmospheric aerosols and water vapor due to seasonal changes, volcanic activity, air pollution, and frontal activity are discussed. Preliminary evidence indicates that increased solar activity is at times associated with a decrease in attenuation due to airborne particulates.

INTRODUCTION

In 1902 a series of observations was begun at the Smithsonian Institution's Astrophysical Observatory, generally called the APO. Their intention was to make daily determinations of the solar constant and correlate variations in the observed values with variations in rainfall, temperature, and other meteorological phenomena.

Until about 1920 the so-called "long method" was used, in which the result was fundamentally dependent on daily spectrobolometric determinations of the transmission of the earth's atmosphere at over 40 places in the solar spectrum covering a wavelength range from about 0.35 to 2.5 microns. In succeeding years the work came to rely on a "short method" based on tables using pyranometric and pyrheliometric observations along with observed values of precipitable water vapor to estimate the effective atmospheric transmission over the entire wavelength region. This method was regularly checked by the spectrobolometric long method. Observations were continued from 1920 to 1955 on a full-time basis at sites in both northern and southern hemispheres.

The techniques used and results obtained are extensively documented in the Annals of the Astrophysical Observatory (Abbot, 1908, 1913; Abot, Fowle, and Aldrich, 1922; Abbot, Aldrich, and Fowle, 1932; Abbot, Aldrich, and Hoover, 1942; Aldrich and Hoover, 1954), hereinafter referred to as Annals. Other interesting summaries and descriptions of the work were also written by Abbot (1929, 1963). The Annals report long method spectrobolometric determinations of atmospheric transmission at various sites for over 3500 days, and short method results for over 10,000 days. The sheer bulk of the observational results gives some idea of the crusading nature of this program as well as the problems of scale that arose with data reduction and correlation analyses. When we consider that the program was carried out entirely without the aid of electronic computers, a project of such magnitude appears in retrospect to be impossible.

Nevertheless the work was carried out and we have been left with a legacy of measurements of solar and atmospheric parameters completely unparalleled in terms of accuracy, homogeneity, quantity, and historical baseline. Application of modern computing equipment and techniques to this body of data is certain to be of great value in answering many of the questions raised at this Symposium.

It is not our intention here to re-discuss relations between solar activity, weather, and climate already documented in great detail by Dr. Abbot. But we would like to make two points concerning their relevance.

First, the APO's final mean value for the solar constant (Aldrich and Hoover, 1952) agrees to within one-tenth of one percent with the value adopted by NASA in 1971 based on the most modern available equipment and techniques — including aircraft and rocket observations (Thekaekara, 1971).

Second, based on his analyses of solar variations and the water levels of the Great Lakes, Abbot (1963) has predicted that a great drought will occur in this country beginning in the year 1975. This morning Dr. Roberts discussed predictions of such a drought made in the last few years. Dr. Abbot's prediction was first published in the year 1938.

SHORT-TERM VARIATIONS IN ATMOSPHERIC CONSTITUENTS

Before discussing possible relationships between solar activity and atmospheric constituents, we would like to give an idea of the size of the variations that occur naturally. We should point out that since these results are from solar observations, all of the work reported on here was done when the sun was not obscured by clouds — producing a rather obvious selection effect.

Figure 1 shows the annual variation in atmospheric transmission at 0.4 and 1.6 microns as measured at the Astrophysical Observatory in Washington, D. C., during the period from 1902 to 1907. Since these wavelengths were chosen to avoid molecular absorption bands, essentially all of the variations can be ascribed to variations in the amount of particulate matter (that is, aerosols) in the atmosphere.

People are often surprised to learn that any variations occur at all. A surprisingly large amount of photometric work has been based on the assumption of constancy. It is plain from Figure 1 that monthly means yield only a slightly better idea of the true situation. The curves shown here are sine curves fit by the method of least squares. They serve to demonstrate our conclusion that in general atmospheric transmission tends toward a maximum in midwinter and a minimum in midsummer (Roosen, Angione, and Klemcke, 1973).

The primary natural sources of atmospheric aerosols are usually considered to be hydrocarbons from trees and plants (Went, 1966), windblown dust, sea spray, volcanoes, and forest fires (Hidy and Brock, 1971). To these we can add man-made effects such as smoke from slash and burn agriculture and other air pollution (Hidy and Brock, 1971). Determining the makeup of the atmospheric aerosol burden at any given place and time is an excruciatingly complex problem, but the results that we will show here are almost certainly due only to naturally produced aerosols.

Large perturbations can occur with the eruption of some volcanoes. An eruption such as that of Mount Agung in 1963 can inject many cubic kilometers of dust into the stratosphere, which could drive the observed values of atmospheric transmission off the bottoms of graphs like Figure 1.

Figure 2 shows observed values of atmospheric precipitable water vapor for sites on mountain tops in both northern and southern hemispheres. Daily and seasonal variations are once again strongly apparent. Variations in atmospheric total ozone are not unlike those shown here for aerosols and water vapor, except that the maximum tends to occur in the spring — at least in the northern hemisphere. We will not show any results for ozone here because we are not satisfied with our reductions yet, but the APO data do contain substantial amounts of information on ozone.

The general question of energy balance in the atmosphere on any given day is very difficult, but the effects of the variations that we have shown here are very likely at the level of tens of percent. The large majority of these variations are almost certainly due to changes in the weather, but it is necessary to have a quantitative idea of the scatter involved before discussing correlations involving changes of only a few percent in long-term averages.

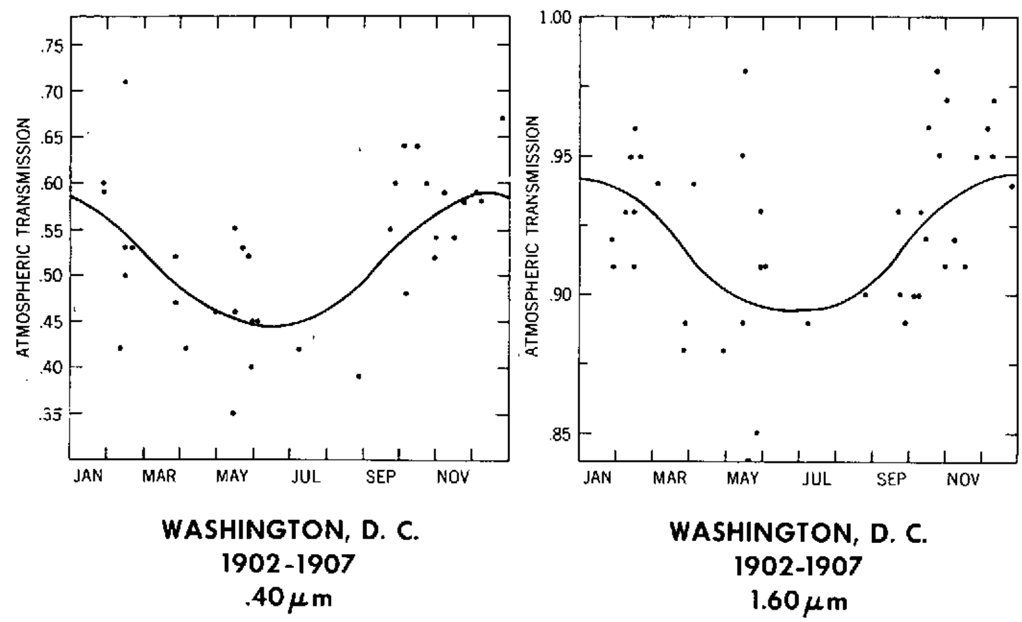


Figure 1. Observations of atmospheric transmission at Washington, D.C.

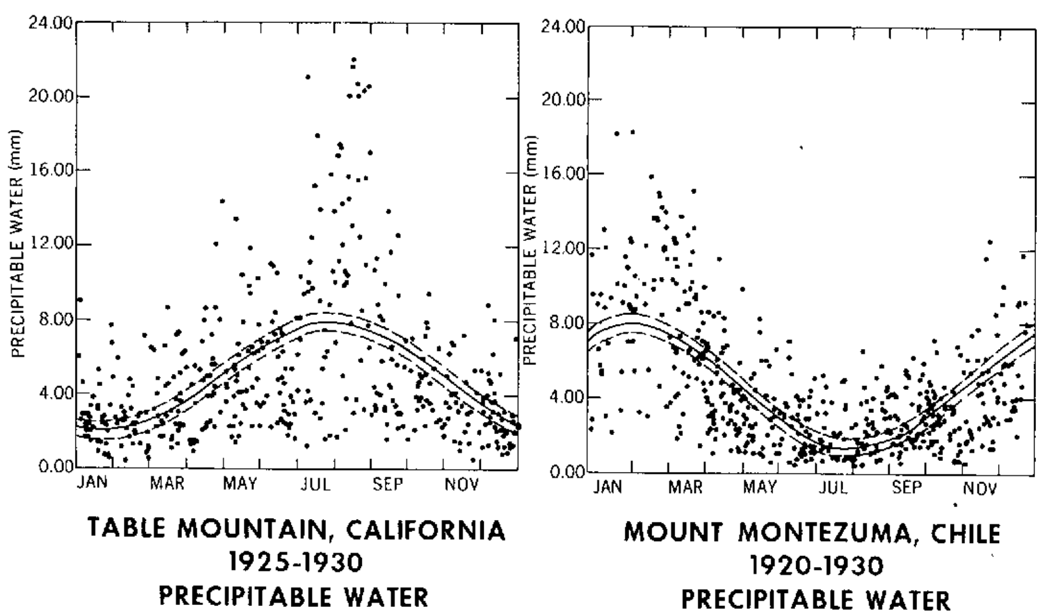


Figure 2. Observations of atmospheric precipitable water vapor at the two main APO sites.

CORRELATION WITH SOLAR ACTIVITY

In large part the previous remakrs were meant to give an idea of the caution that we feel in approaching our subject. We spent more than three years writing our paper that merely describes some of the variations in atmospheric constituents (Roosen et al., 1973). In contrast we have spent only about six months addressing the question of correlations with solar activity.

Viewed in that light, the results that we describe in this section should really be considered as a case study. We feel that they are important, but we cannot guarantee that they are truly representative.

We have applied the shotgun approach of taking annual means and then looking for correlations between solar and geomagnetic parameters on the one hand and atmospheric constituents on the other. We found a number of intriguing possibilities, the best of which is presented here.

Figure 3 shows the variations with time of annual means of atmospheric precipitable water vapor as observed at the APO's primary mountaintop observatories. The curve at the top shows the annual means of the Zurich sunspot numbers. The correlation between sunspot numbers and precipitable water vapor at Table Mountain is .02, which we will call zero for short. The correlation at Mount Montezuma is apparent to the eye. The computer says that it is -.20.

Figure 4 is a plot of sunspot numbers versus observations at Mount Montezum Chile, of solar brightness at an altitude of 30° corrected to mean solar distanc The correlation coefficient between these two quantities is .56. The observed brightness certainly seems to increase with increasing solar activity. Since the observed solar brightness depends directly on the amount and size of aerosols in the earth's atmosphere, this figure indicates that increased solar activity is associated with decreased attenuation due to atmospheric aerosols. The only reported effects of volcanic activity are represented by the plus sign in the lower left-hand corner of the graph. This point represents the year 19: during which at least five separate volcanoes erupted in the Chilean Andes. W believe this to be the only year in this study that is significantly affected by volcanic dust.

Figure 5 is a plot of sunspot numbers versus observed brightness in the part of the sky near to but not including the sun. These observations were made with a completely separate instrument than that used for the previous figure. The correlation coefficient in this case is -.51. This figure tells us that scattered light near the sun decreases with increasing solar activity. The

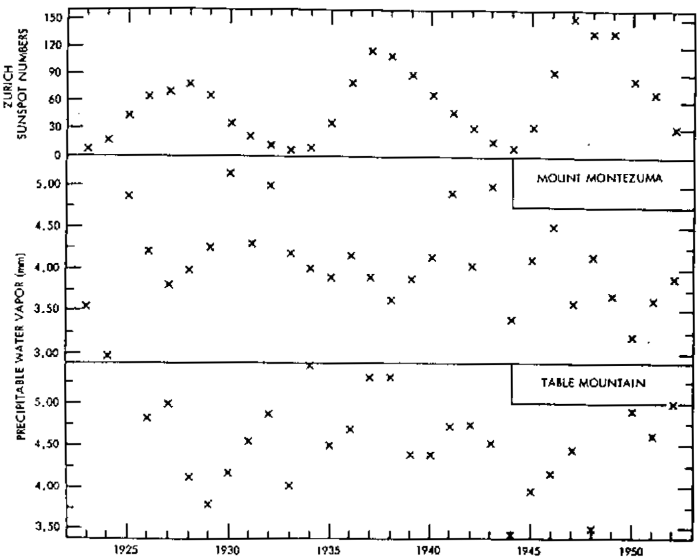


Figure 3. Annual means of precipitable water vapor and sunspot numbers.

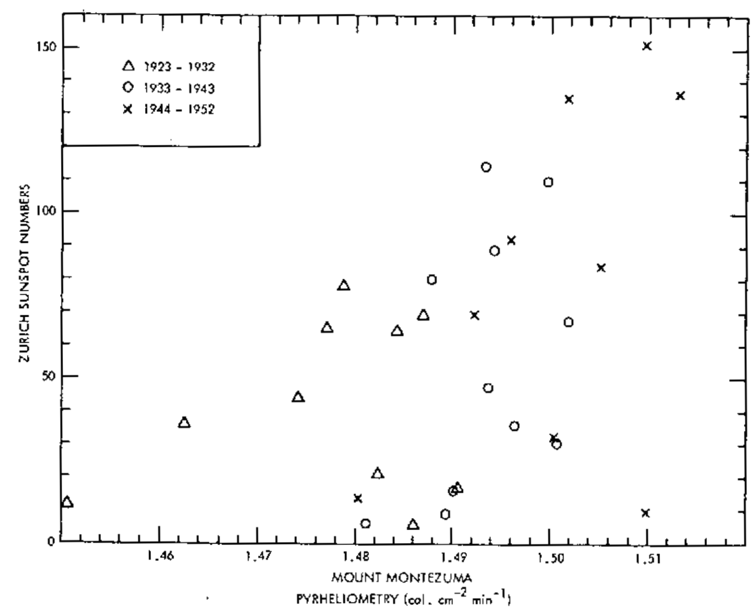


Figure 4. The relation between annual means of direct solar brightness at 30° altitude corrected to mean solar distance and sunspot numbers at Mt. Montezuma.

obvious interpretation is similar to that for the solar brightness observations. Namely, increasing solar activity is associated with decreasing amounts of atmospheric particulates.

Figure 6 shows observed precipitable water vapor versus sunspot numbers for Mount Montezuma. Remember that the correlation coefficient is minus .20 and that increasing solar activity is associated with decreasing amounts of precipitable water.

Figure 7 shows plots of precipitable water vapor versus the astronomical extenction coefficient, which is an indicator of the amount of light removed from the direct solar beam by atmospheric constituents (Roosen et al., 1973). More water vapor leads to a lower observed solar brightness. The strong correlation between precipitable water vapor and atmospheric attenuation shown here points up the possible importance of the fairly weak correlation between atmospheric water vapor and solar activity shown earlier. It is possible that most of the aerosols above Mount Montezuma are hygroscopic and swell in the presence of higher humidity. Hence the observed correlations between solar activity and aerosol scattering may be due in part to a change in the size of the aerosols rather than the total amount.

Analysis of the Table Mount, California, observations shows correlations between solar brightness, sky brightness, and sunspots that are similar to but not as strong as those found for Mount Montezuma. We believe that the differences between the two sites emphasize the main problem presented by research into the effects of solar activity on the earth's weather and climate — separation of variables.

Table Mountain is located 40 miles east of the Los Angeles basin and is surrounded by pine trees and other vegetation. We have reason to believe that the air above it is filled with dust particles of many different origins, both organic and inorganic. The relationship between solar activity and production of organic aerosols by trees and other plants may well be quite different than that with production of inorganic aerosols. Hence, by observing from a desert site it may well be possible to eliminate some variables and make the problem that much more tractable.

Mount Montezuma certainly meets this criterion. As Dr. Abbot (1929) described it, "Hardly ever does rain fall near the observatory. It lies in one of the most barren regions of the earth. Neither tree nor shrub, beast nor bird, snake nor insect, not even the hardiest of desert plants is found here."

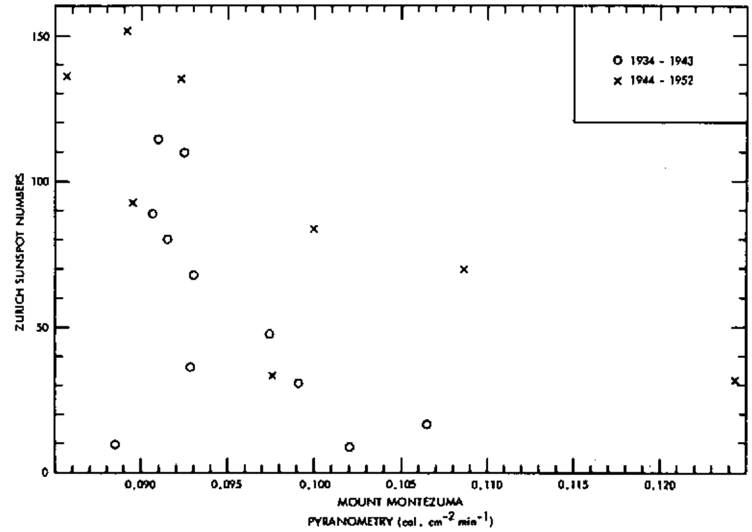


Figure 5. The relation between annual means of scattered light near the sun at 30° altitude and sunspot numbers at Mt. Montezuma.

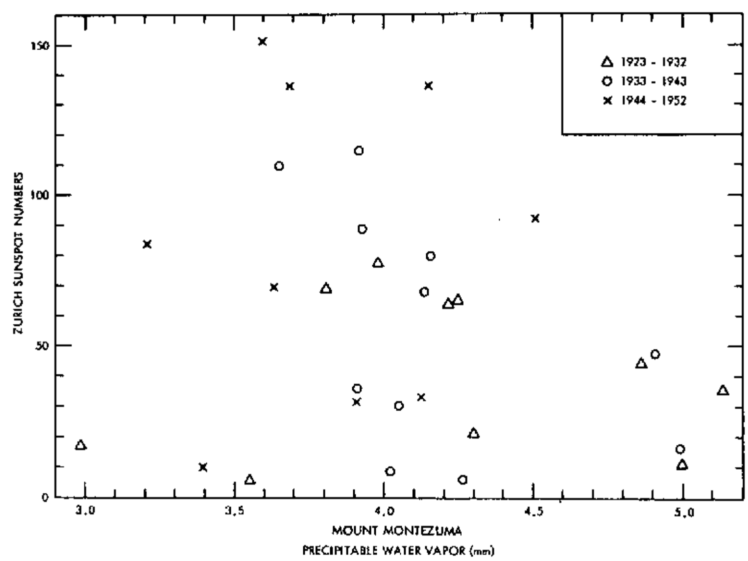
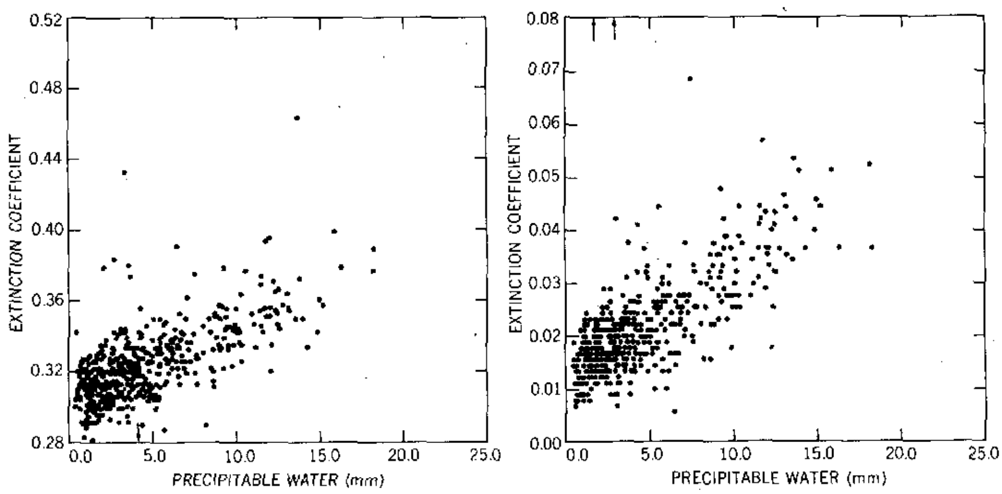


Figure 6. The relation between atmospheric precipitable water vapor and sunspot numbers at Mt. Montezuma.



MOUNT MONTEZUMA, CHILE
1920-1930
.395 μm

MOUNT MONTEZUMA, CHILE
1920-1930
1.214 μm

Figure 7. The relation between atmospheric extinction and atmospheric precipitable water vapor at Mt. Montezuma. The extinction coefficient k (λ) = −2.5 $\log_{10}$ T(λ), where T(λ) is the atmospheric transmission.

CONCLUSION

We have found evidence that (as seen from a high altitude desert site) increased solar activity is associated with a decrease in attenuation due to airborne particulates. It may also be associated with a decrease in the average amount of water vapor in the air above that particular site. Further, it appears that the results for any particular site are strongly dependent on a great number of variables, only some of which have been isolated.

In any case, we are firmly convinced of one thing. That is, Dr. Abbot and the staff of the APO have presented all of us with a superb body of observational material to help solve the problems of solar variations, weather, and climate.

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF ROBERT G. ROOSEN

MR. LONDON: It is good to hear of the care that was taken in reviewing the Abbot measurements. I wonder if you have an estimate that you can give us of the probable error of those measurements, and whether or not you have an estimate of any change in probable error with time as a result of the improvement of the instruments.

MR. ROOSEN: That is one of the reasons that we took three years before we would say anything at all. There were, indeed, changes in the instrumentation. Every effort was made in the spectrobolometry to continue to refer all spectrobolometric observations back to the scale of 1913.

As to the probable error of the spectrobolometric transmission results, my own estimate, from working on the data, is that it is probably better than one percent for individual determinations, if you keep in mind the fact that these are done by the so-called Bouger-Langley method of observing the sun as it rises,and changes in atmospheric transmission during that period are often very hard to weed out. In terms of the probable error of the individual solar constant observations, I don't think it is appropriate for me to comment. Dr. Abbot, in Smithsonian Publication 4545, said that he felt that the individual solar constant determinations were accurate to about one-half of one percent, and he wished that they were accurate to one-tenth of one percent, and I wish that I could do one-tenth as good as he did.

MR. LONDON: Well, our experience, as one went through in time, was that as the accuracy of the instrument increased, so did the variation of the solar constant decrease.

MR. ROOSEN: I would be very pleased to discuss that with you later.

N74-29088

FUTURE MONITORING OF CHARGED PARTICLE ENERGY DEPOSITION INTO THE UPPER ATMOSPHERE AND COMMENTS ON POSSIBLE RELATIONSHIPS BETWEEN ATMOSPHERIC PHENOMENA AND SOLAR AND/OR GEOMAGNETIC ACTIVITY

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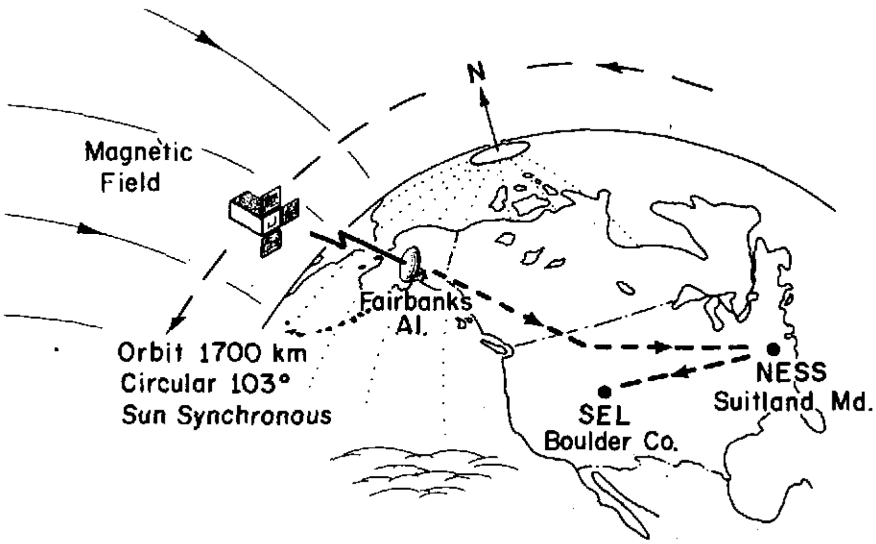
Boulder, Colorado

ABSTRACT

The National Oceanic and Atmospheric Administration has been carrying out routine monitoring of the earth's atmosphere for several years utilizing the ITOS series of low altitude, polar-orbiting weather satellites. A space environment monitoring package has been included in these satellites to perform measurements of a portion of the earth's charged particle environment. We describe briefly in this note the charged particle observations proposed for the new low altitude weather satellites, TIROS-N, which will provide the capability of routine monitoring of the instantaneous total energy deposition into the upper atmosphere by the precipitation of charged particles from higher altitudes. Such observations may be of use in future studies of the relationships between geomagnetic activity and atmospheric weather pattern development. Estimates are given to assess the potential importance of this type of energy deposition. Discussion and examples are presented illustrating the importance in distinguishing between solar and geomagnetic activity as possible causative sources. Such differentiation is necessary due to the widely different spatial and time scales involved in the atmospheric energy input resulting from these various sources of activity. Examples also are given illustrating the importance of thoroughly investigating all physical mechanisms which may potentially link the lower atmosphere to the varying energy inputs at high altitudes.

I am happy to have this opportunity to describe and comment briefly on the type and usefulness of charged particle measurements to be performed on the proposed TIROS-N environmental satellite program. These measurements, concerning the energy deposition in the upper atmosphere due to charged particles, should be of use in future considerations of atmospheric weather phenomena and their relationship to solar and/or geomagnetic activity. It should be noted that the TIROS-N environmental satellite program has not yet been approved and is presently under review by the Office of Management and Budget.

Figure 1 is a schematic showing the orbit of the TIROS-N spacecraft. The proposed orbit is circular at an altitude of 1700 km with a 103° inclination which



Launch Schedule

TIROS N Mid 1977

Follow on Operational Spacecraft at 1-2 year intervals.

Figure 1. TIROS-N spacecraft orbit.

maintains it in a sun-synchronous attitude. A currently operating real-time data transmission system is illustrated in the figure. Data are available at the Space Environment Laboratory in near real-time and are immediately placed into an operational real-time data base made up of data collected throughout the solar-terrestrial environment. In addition, the satellite data recorded throughout the orbit are available on a longer time basis for research and archiving.

The satellite is oriented at high latitudes so that the charged particle detectors are able to obtain a measure of the particle pitch angle distribution at these altitudes. A set of detectors looks normal to the field line thereby measuring particles with a local pitch angle of 90°. An additional set of detectors is oriented to look upwards nearly along the field line thereby measuring particles whose local pitch angles are very small. It is these latter particles which precipitate directly into the upper atmosphere and are directly responsible for such phenomena as polar cap absorption, auroral displays, and possibly phenomena in the lower atmosphere. The charged particle observations aboard TIROS-N therefore allow the measurement of the total instantaneous energy deposition to the local atmosphere due to charged particles.

Figure 2 shows the energy range to be covered. This range extends from several hundred eV to $\geq 10^9$ eV. A variety of detectors (thin scintillators, solid

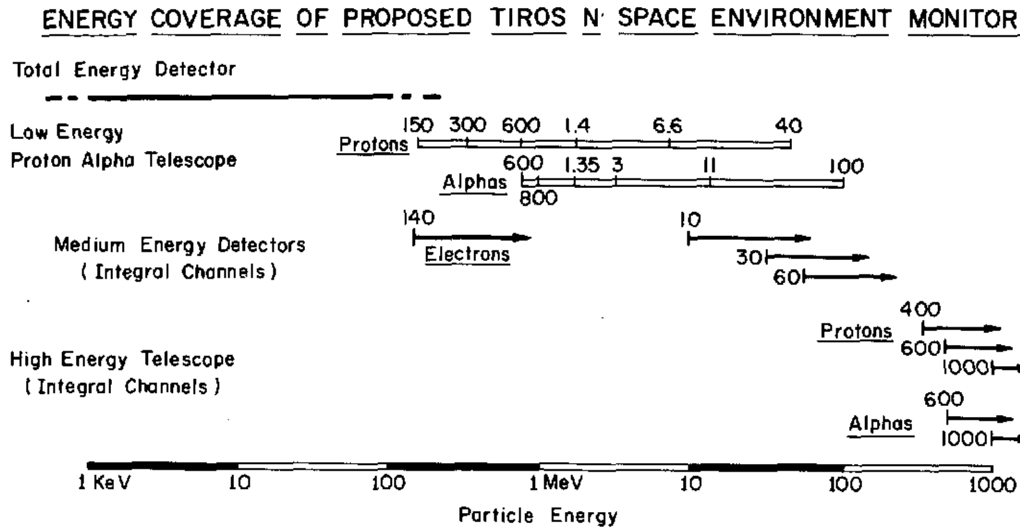


Figure 2. Energy coverage of proposed TIROS-N space environment monitor.

state detectors, and Cerenkov detectors) will be used to cover this energy range and will be sized to measure energy inputs $\geq 10^{-2}$ ergs/cm^{2}s. Details of how the various energy ranges will be covered and details of instrument design can be obtained from the Space Environment Laboratory, Boulder, Colorado.

Since we are proposing to monitor on a routine basis the energy deposition at the top of the atmosphere due to charged particles, let us try to assess its importance. In Figure 3, we show a photograph of an aurora obtained from the DoD DAPP satellite on January 11, 1973. Included in the figure is a summary of estimates of energy deposited by such an aurora into the upper atmosphere. The upper portion of the auroral photograph is in the dawn hemisphere, the broad diffused band near the right-hand portion is near local midnight and the two line structures extending to the lower left of the photograph are in the local evening sector. Aurora also can be seen over the polar cap aligned in the noon-midnight direction.

The area of the photograph is approximately 1.4 by 10^7 km^2 with approximately 20 percent of the area covered with auroral glow. A modest energy influx during an aurora is ~ 4 ergs/cm^{2}s. This value yields a total energy influx in Figure 3 of approximately 10^{17} ergs/s $= 10^{10}$ W.

We also can estimate the total power dissipation through Joule heating due to ionospheric current flow at the 115-km level. Using an ionospheric integrated Pederson conductivity for moderate levels of disturbance of

$$\Sigma\sigma \simeq 20 \text{ mhos/m}$$

ESTIMATES OF ENERGY
DEPOSITED BY AURORAL PROCESSES

Estimated area of aurora in the satellite picture on the right:

$\simeq 2.8 \times 10^6 \ km^2$

For a commonly occurring 'moderate' aurora which will last for several hours the particle energy deposition is:

$\simeq 4.0 \ ergs/cm^2/sec$

or a total power input of:

$\simeq 1.1 \times 10^{10}$ Watts

The ohmic losses due to the Pedersen currents flowing at 110-120 km may be

$\simeq 1 \times 10^{10}$ Watts

If these processes heat the neutral atmosphere at 115km the resultant heating rate would be:

> 1000 °K / Day

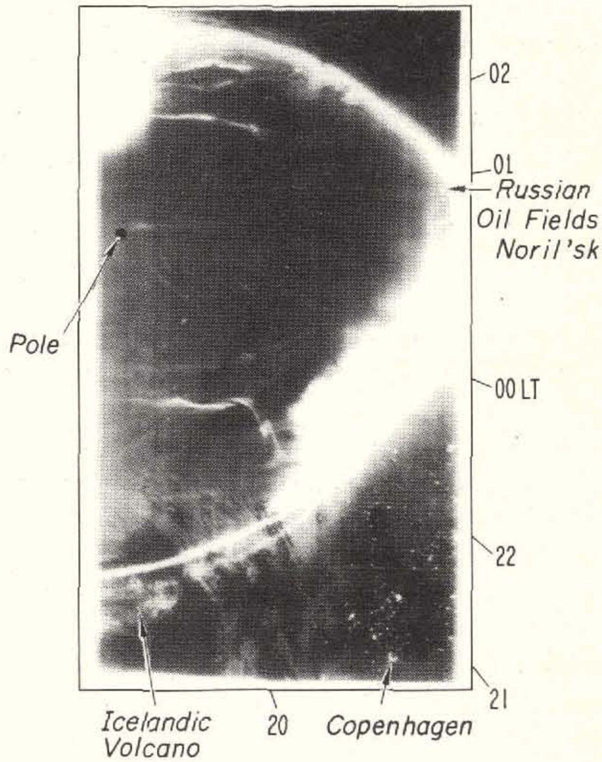


Figure 3. Aurora obtained from DAPP satellite on January 11, 1973.

and a nominal potential difference of about 0.015 V/m, a power dissipation of $\sim 4.5 \times 10^{-3}$ W is obtained for a column of 1 m^2 cross section. If this current is flowing within the auroral glow shown in Figure 3, a total power dissipation of approximately 10^{10} W exists.

Using these estimates, considering the possibility of current along geomagnetic field lines, and estimating the volume energy deposition rates due to auroral particle precipitation, heating rates of more than 1000 K per day (1.4×10^{-2} K/s) result if the assumption is made that this energy heats the neutral atmosphere at these altitudes (110 km to 125 km). Thus it is apparent from such estimates that the energy deposition into the atmosphere at altitudes above 110 km due to magnetospheric processes exceeds that due to solar energy flux at high geomagnetic latitudes. This should not only cause considerable heating of the high altitude neutral atmosphere but may also generate significant neutral winds at these altitudes.

The preceding estimates were concerned with intense particle precipitation due primarily to geomagnetic processes. Let us consider an example of such effects due to solar flare activity. In contrast with auroral particle precipitation, which is confined to a relatively narrow latitude band ($\leq 10^\circ$) and may last for hours, particles released from a solar flare impinge on the earth's atmosphere over the entire polar cap region and last for several days. Thus the time scales for the energy input are longer and the atmospheric spatial scales over which the energy input occurs are greater for solar flare particles than for auroral processes. In contrast, however, the frequency of occurrence is greater for auroras than it is for particle-emitting solar flares.

We shall use the solar flare activity occurring in August 1972 to obtain an estimate of energy dissipation into the upper atmosphere over one polar cap. For the several days during which intense solar particle activity occurred during the August 1972 solar events, a peak energy dissipation rate into the polar cap of ~ 2 ergs/cm^{2}s occurred for a 1/2-hr period. For the remaining several days of this solar activity, the energy dissipation rate due to flare-associated particles was less than ~ 0.2 ergs/cm^{2}s. Using a polar cap area of approximately 2.5×10^{17}cm^2 yields a peak energy dissipation rate over one polar cap of 5×10^{17} ergs/s = 5×10^{10} W. Using the 1/2-hr time interval for the event peak yields a total peak power of 3×10^7 kW hours deposited in an altitude range of 40 to 70 km. This could give a mean heating of the order of 1° to 3° over the altitude range of deposition.

Again, we see evidence for significant energy deposition in the earth's upper atmosphere, due in this case to particles emitted during a solar flare. Consequently, the routine observations of such energy depositions may play an important role in delineating mechanisms responsible for correlations between atmospheric weather and solar and/or geomagnetic activity.

In such correlations, it is extremely important to distinguish between solar activity and geomagnetic activity because of the vast differences in the spatial and temporal scales of the energy input into the earth's upper atmosphere. At this conference, we are hearing of potential atmospheric responses ranging in time from several days (corresponding to the development of atmospheric storm systems) to 11 to 22 years (corresponding to correlations with the solar cycle) and on to many millenia (corresponding to hypotheses concerned with glacial advances and recessions). Similarly, the spatial scales in the atmosphere vary from more or less localized continental storm systems to global climatic changes.

If causes related to variations in the solar terrestrial realm are sought, it is important that the necessary energy input be compatible with the atmospheric phenomena being studied. For example, any variation in the electromagnetic emission of the sun (X-ray, UV, visible, IR, radio, and such) produces a global variation throughout the earth's sunlit hemisphere. Consequently, slight changes in the solar constant over long periods of time might provide a more appropriate mechanism to explain long-term global climatic variations.

Table 1 is a rough attempt to block out atmospheric spatial and temporal scale sizes associated with a few examples of solar and geomagnetic activity. It is not intended to imply cause and effect but simply to emphasize the spatial and temporal scales of atmospheric energy input associated with various solar and geomagnetic activity.

Finally, in attempting to understand many of the correlations being presented, it is necessary to examine all possible mechanisms which may conceivably provide a connection between the lower atmosphere (≤10 km) to solar and/or geomagnetic activity. For example, it has been long known that atmospheric turbulence is capable of producing upward traveling, acoustic gravity waves which can carry significant amounts of energy into the high altitude (≥100 km) regions. If this occurs under conditions of marginal stability in the geomagnetic particle population, these waves could conceivably create turbulence in the ionosphere at the foot of the geomagnetic field lines and initiate instabilities leading to enhanced particle precipitation. Note that such possibilities are maximized when enhanced geomagnetic activity is imminent and when large atmospheric storm systems are developing, and would naturally lead to positive correlations under conditions set forth in many reported studies. Ionospheric effects of this type apparently have been observed (Bauer, 1957, 1958; Davies and Jones, 1971, 1973) and, in one case, interpreted as upwards propagating acoustic gravity waves setting the ionosphere at 200 km altitude into large-scale vertical oscillations having periods of several minutes (Davies and Jones, 1973).

Mechanisms such as the above should be identified, assessed in importance, and clearly separated in correlations of atmospheric weather development with solar and/or geomagnetic activity. Only then will the reality of solar activity and geomagnetic effects on the earth's weather and climate be established.

Table 1
Spatial and Temporal Considerations of Energy Inputs to Atmosphere Associated with Solar and Geomagnetic Activity

	Extra-atmospheric Activity	Time Scale	Atmospheric Spatial Scale	Potential Atmospheric Effects
Solar	Overall change in electromagnetic emission from the sun (includes possible changes in solar constant)	?Millenia?	Global, direct[1]	Long-term worldwide climatic changes. Glacial advances and recessions.
Solar	Overall change in emitted solar wind	?Millenia?	Global, indirect	Long-term worldwide climatic changes. Glacial advances and recessions.
Solar	Number of sunspots[2]	Solar cycle 11-22 years	Global, direct, indirect	Shorter term climatic changes. 20-22 cycle of U.S. high plains droughts. Motion of atmospheric jet stream.
Solar	Solar flare particle emission	Days	Polar regions, direct	Atmospheric storm system development. Isolated, unique atmospheric phenomena.
Solar	Solar flare shock wave	Hours	Global, indirect	Atmospheric storm system development. Isolated, unique atmospheric phenomena.
Geomagnetic	Aurora (precipitated particles and currents in substorms)	Hours	Narrow latitude band (≤10°) at high latitudes. Nightside. Direct.	Atmospheric storm system development. Isolated, unique atmospheric phenomena.
Geomagnetic	Magnetic storms	Days	Wide latitude band at mid-latitudes. Global. Direct.	Atmospheric storm system development. Isolated, unique atmospheric phenomena.

1. Direct = energy from given phenomena applied directly to atmosphere.
   Indirect = energy from given phenomena applied indirectly to atmosphere, for example, solar wind energy applied through magnetospheric coupling to atmosphere.
2. Number of sunspots used simply as indication of overall solar activity.

ACKNOWLEDGMENTS

We would like to acknowledge the United States Air Force, Air Weather Service, and the World Data Center A, NOAA, Boulder, Colorado, for providing the DAPP satellite photo in Figure 3.

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N74-29089

ON CLIMATIC CHANGES RELATED TO THE 22-YEAR SOLAR CYCLE

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INTRODUCTION

In extratropical regions, the character of climatic fluctuations on a time scale of years or decades differs from the character of climatic changes on a time scale of a century. Whereas in the former case the changes at two different places at the same latitude may be opposite in sign, in the latter a whole latitude belt is affected by changes in one and the same direction.

It has been pointed out that climatic changes of relatively long duration are caused by changes in the prevailing circulation regime, which in their turn are caused by latitudinal displacements of the subtropical, high pressure belts. Climatic fluctuations of relatively short duration (years to decades), which have their maximum amplitude at the temperate to high latitudes, may well be due to longitudinal displacements of the semipermanent lows (Iceland Low and Aleutian Low). It is quite probable that the two types of climatic changes are independent of each other and that their ultimate causes are independent as well. Nevertheless, there may be a possibility that both types of changes do originate from the effects of the sun's activity on the earth's atmosphere.

As far as the latitudinal displacements of the subtropical high pressure belts are concerned, a relation has been suggested with the 80 to 90 year solar cycle. (See, for example, Willett, 1965.)

THE 22-YEAR CYCLE

Nobody may have thought of the 22-year or double sunspot cycle as a cause for the longitudinal displacements of the atmospheric semipermanent "centers of action." However, if this solar cycle has any effect, there are reasons to believe that it is strongest at the higher latitudes of the earth, mainly since the charged particle radiation of the sun is involved in this cycle.

Some investigations have already been made to show that the 22-year cycle is present in mid- and high-latitude climate. Newman (1965), for example, has found that winter temperatures at Boston exhibit a 20 to 22 year periodicity.

In view of the above, I have started an investigation on the location of the low pressure center near Europe in alternate sunspot cycles. The low is most often located near Iceland, especially in winter. In some winters, however, the center moves quite persistently into the Scandinavian area. Circulation types showing this feature are well-defined and make up, on the average, some 10 percent of the total number of days.

In the following table the mean frequency of occurrence of such types (symbolically indicated by NWz, TrM, and Nz, according to the German system of "Grosswetterlagen Europas") in the winters of each of the last eight sunspot cycles is given. (The first year mentioned for each cycle is the year of minimum sunspot number.)

1888-1900	8.1 percent	1901-1912	10.8 percent
1913-1922	5.5 percent	1923-1932	8.4 percent
1933-1943	8.7 percent	1944-1953	14.8 percent
1954-1963	8.9 percent	1964-1973	13.4 percent

It may be concluded from the table that each second cycle has more circulation types with Scandinavian lows in winter than the foregoing cycle.

The mean frequency of occurrence of circulation types with lows near Iceland (Grosswetterlagen Wz and SWz) is largest in the winters of the years in the left side of the table, as is to be expected. However, the number of days with circulation types having high pressure over the Icelandic area (Grosswetterlagen HNa, HNz, HNFa, HNFz, NEa, NEz, TM*) is also largest in the winters of the years in the left side of the table: the average number of days per winter season (December, January, February) being 12 for the years in the left side and 8 for the years in the right side of the table. This would suggest some pressure oscillation in winter, which in one sunspot cycle has its largest amplitude mostly over the Icelandic area, whereas in the next cycle it is more often located over Scandinavia.

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*These circulation types usually cause very severe winter conditions over Western Europe.

N74-29090

APPARENT RELATIONSHIP BETWEEN SOLAR-SECTOR BOUNDARIES AND 300-mb VORTICITY: POSSIBLE EXPLANATION IN TERMS OF UPWARD PROPAGATION OF PLANETARY-SCALE WAVES

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INTRODUCTION

It appears to be well-established that large-scale variations of pressure fields in the troposphere and stratosphere are propagated up to ionospheric levels, to at least the E-region (Brown and Williams, 1971; Deland and Cavalieri, 1973; and many other authors). Correlations between large-scale stratospheric variations and ionospheric parameters are illustrated in Figure 1, taken from Deland and Cavalieri (1973). It seems possible that the resulting changes in the ionosphere could cause variations in the magnetosphere, and thus cause variations in geomagnetic parameters such as A_p. It therefore appears likely that at least some of the observed correlations between geomagnetic variations and meteorological variations may be due to meteorological effects on the geomagnetic variables, rather than due to a common solar origin for the variations in both geomagnetic and meteorological variations, as commonly presumed. Partly because of these considerations, the correlations between the solar sectors and large-scale atmospheric vorticity in the lower atmosphere reported by Roberts and Olson (1973) and Wilcox et al. (1973), are of great interest since the solar-sector data appear to be independent of any terrestrial influences. It is shown in this paper that even these solar data, as analyzed by Wilcox et al., 1973, may be affected by geomagnetic properties, and a method of removing such influences is suggested.

WELL-DEFINED BOUNDARIES AND THE BOW SHOCK

In their comparison of solar sectors and 300-mb vorticity, Wilcox et al. used the times of passage of well-defined boundaries as key days in a superposed-epoch analysis. The well-defined boundaries were specified by Wilcox and Colburn (1969) as those for which the magnetic polarity was the same for at least 4 days before the boundary and of the opposite sign for at least 4 days after. According to Ness and Wilcox (1967), the gaps in the data corresponding to the satellite crossing the magnetosheath and magnetosphere were partly compensated for as follows: "Whenever such a perigee gap has a given field polarity both before the satellite entered the magnetosphere and after the satellite returned to the interplanetary medium, the gaps have been filled with that polarity."

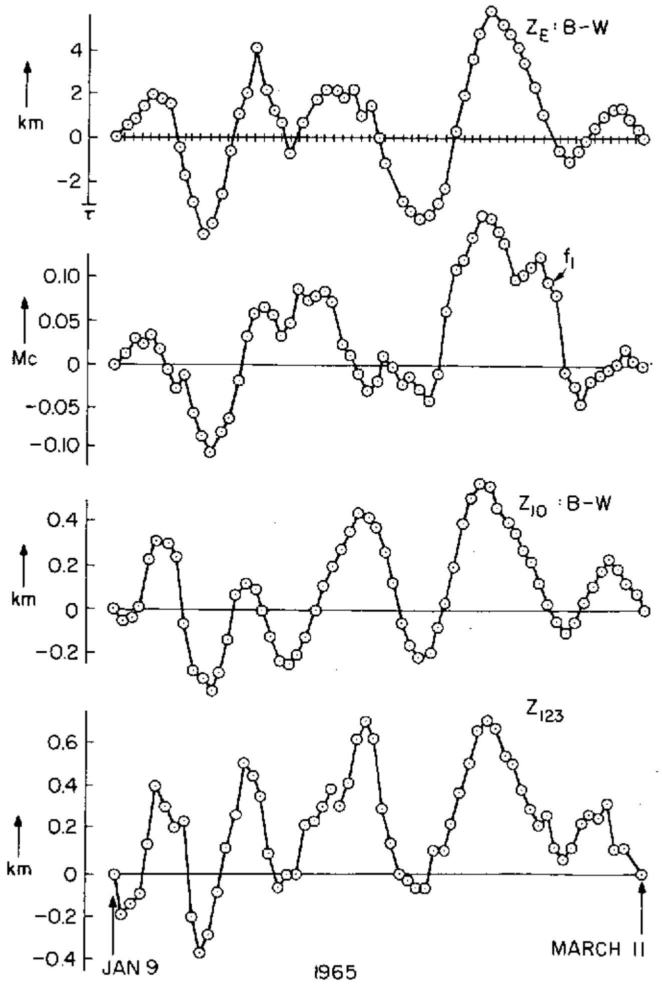

Figure 1. Simultaneous variations of ionospheric and stratospheric variables over Aberystwyth from January 9 to March 11, 1965, taken from Deland and Cavalieri (1973): Z_E is height of a constant electron density surface in the E-region (Brown and Williams, 1971); f_1 represents smoothed variations of f-min; Z_{10} is the height of the 10-mb surface over Aberystwyth (Brown and Williams, 1971); and Z_{123} is the smoothed variations of 10-mb height corresponding to the first three zonal wave numbers.

Autocorrelations for the magnetic field polarity observed by the satellite along its trajectory have been published by Ness and Wilcox (1967) and Wilcox and Colburn (1969). The autocorrelation function falls off quite rapidly for 2 or 4 days lag, as of course it must in view of the tendency of the polarity to be repeated after 7 to 10 days, according to the characteristic sector structure described by Wilcox, Ness, and their coworkers. The observed autocorrelation at a given lag can be considered to be an estimate of the quantity (2P - 1)*, where P is the probability of observing the same polarity at a given time and at a time τ later. It follows that the probability of observing a given polarity, assuming that the same polarity was observed a few days previously, varies with the time delay.

In Figure 2, a schematic diagram of the earth's bow shock and satellite orbit such as that of IMP-3 is shown. Since the figure is schematic, it is not meant to be realistic. In the figure, (2) and (3) denote points just outside the bow shock, which fall within 4 days after passing X. Let us assume that there is a (-+) crossing at X, so that there is positive polarity at (1), and that the previous 4 days were all negative. The probability that the boundary crossing at X will be recorded as well-defined is then the probability that positive polarity is recorded for the following 4 days. This will depend on the probability of recording positive polarities at points (2) and (3), conditional on positive at (1), for the polarity at both must be positive for a well-defined boundary to be recorded. These probabilities in turn will depend on the position of the bow shock for this will determine the time lags between point (1) and the points (2) and (3). For instance, the wider the bow shock the less likely it is that the polarity at both points (2) and (3) will be positive and thus enable continuity of polarity across the gap to be recorded as specified by Ness and Wilcox (1967).

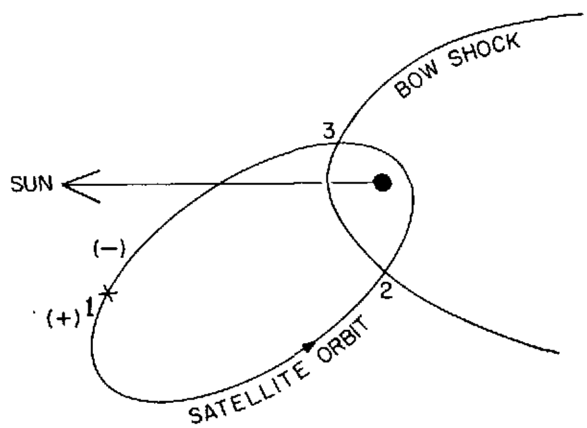

Figure 2. Schematic diagram of a satellite orbit and the bow shock, showing the possibly well-defined boundary of a magnetic sector at X. Point 1 is just after the sector boundary, and points 2 and 3 just before and after the satellite encounters the bow shock.

*In the presentation of the paper I incorrectly stated that the autocorrelation is equal to the probability P.

It follows from the above that the probability of a well-defined boundary being recorded will depend to some extent on the width of the perigee gap. This will be so for all the boundaries recorded by the satellites with periods of 8 days or less, and for a varying fraction of the boundaries for all other satellites. As a consequence, the well-defined boundaries may include a higher proportion of cases for which the bow shock and magnetopause were relatively close in to the earth, and fewer for a relatively disturbed (perhaps) "pushed out" magnetosphere. If the latter occurs in part due to atmospheric influences, the possibility of bias due to a positive correlation arising from accidental selection of the data is apparent.

CONCLUSION AND RECOMMENDATIONS

The possibility that the correlations reported by Roberts and Olson (1973) may be due to accidental selection of the solar-sector data is sufficiently serious that further analysis of this type should be undertaken with special care to avoid the problems discussed in this paper. One method is to avoid all selection, that is, include all boundary crossings in the analysis. This is difficult to do because of the perigee gap: this approach might easily lead to more boundary crossings with a smaller gap than with a larger one. The only way to be certain appears to be to use only those boundary crossings for which the satellite was some fixed distance, such as 20 earth radii, ahead of the earth for 4 days before and 4 days after, which would ensure that the selection is not affected by the bow shock or magnetosphere.

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF RAYMOND J. DELAND

MR. WILCOX: We thank Dr. Deland for his interest in our work, but I don't believe that the remarks are relevant to it. The sector pattern is well defined almost all the time, being either two sectors or four sectors per solar rotation, as seen on, say, spacecraft going out to Venus where one will have continuous observations for several months. And you simply see that within a given sector you have the field completely in one direction, except for filaments of a few hours' width, and then you have a boundary, and then you have the next sector.

And so I just don't see the relevance of all this. I could comment that the particular autocorrelation that you chose for 1965 was the one interval of a few months out of the ten years now observed in which the sector pattern was less well defined than the others. There are a number of other published autocorrelations, for example, any of which you could have chosen which would have had a considerably longer time to go down to zero. But it seems to me the basic point is just that spacecraft observations well away from the earth establish very clearly that one has either a two-sector or a four-sector pattern with a very sharp boundary.

If there is a suggestion of a selection effect, which was in the abstract at least, it would seem like the clearest way to remove that possibility was to not have any selection at all. Now, we worked with 54 boundaries that were well observed by spacecraft. The interplanetary field for four days on each side of the boundary was unidirectional. For this particular interval, I sat down and used the sector charts and counted the total possible number of boundaries during this interval, which came out to be 74.

And so we repeated the analysis, using all 74 boundaries, in which case I don't think there could be any selection effect. It seems to me that if you have 54 out of 74 you are not in a problem with selection in any case.

MR. DELAND: Dr. Wilcox's point is well taken. However, I am still concerned that, even with the 74 boundaries, there is still some problem with the interpolation across the perigee gap, but I have not had time yet to look into this procedure. And I still stick to my point, that if you really want to be sure you should essentially stay clear of the earth, and any possible statistical contamination.

N74-29091

HIGH LATITUDE IONOSPHERIC WINDS RELATED TO SOLAR-INTERPLANETARY CONDITIONS

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ABSTRACT

Treated jointly, two recent results imply that the distribution of winds in the polar ionosphere should change as a function of the direction of the interplanetary magnetic field. (1) From the motions of chemically released ion and neutral clouds, it is apparent that neutral winds in the high latitude ionosphere are driven principally by ion drag forces. (2) OGO-6 electric field measurements have demonstrated that there are definite relationships between the time-latitude distribution of ionospheric plasma convection and interplanetary magnetic field parameters, and also that the distribution is most sensitive to the azimuthal angle of the interplanetary field. Thus, although direct neutral wind to interplanetary magnetic field comparisons are not available, logic clearly implies a close relationship. The lower altitude, meteorological effects of these externally driven ionospheric winds are not known. However, observations of infrasonic waves following sudden ionization enhancements indicate the existence of momentum transfer.

The intent of this short contribution is to note results from recent Goddard Space Flight Center measurements which permit one to deduce that there must be a relationship between the solar wind sector structure and the spatial distribution of energy and momentum inputs to the high latitude ionosphere. It is also appropriate to note that ion drag effects can apparently be detected at the earth's surface in the form of infrasonic waves.

Above 110 km at magnetic latitudes >60° it has become apparent that the integraged effects of ion drag, caused by the convective electric field, dominate both the heat input and the momentum flux. By "integrated effects" one means not only space-time integration over the convecting region, but also the inclusion of all energy dissipation mechanisms that depend directly on the existence of the convection electric field, $\underset{\sim}{E} = -\underset{\sim}{v} \times \underset{\sim}{B}$, where $\underset{\sim}{v}$ is the plasma velocity and $\underset{\sim}{B}$ is the magnetic field. For example, joule heating which arises from ionospheric current flow transverse to $\underset{\sim}{v}$, tending to short-out the field $\underset{\sim}{E}$, is an ion drag effect. Accurate numbers for the total energy dissipation and momentum flux cannot be given because of the high degree of variability of the ion drag both in time and in spatial distribution. Between quiet and moderately disturbed times the integrated $\underset{\sim}{E}$ (that is, the potential drop) commonly varies by a factor of 5 (Heppner, 1973). The coupling of ion and neutral motion which is determined by the plasma density and its altitude distribution is, however, a much greater variable. Density factors of 100 between sunlit and dark regions and between regions with and without auroral particle precipitation are quite common. Representative numbers for the local, columnar energy dissipation most commonly fall within the range 1 to 100 ergs/cm^{2}s. Typically, numbers in the literature tend to be conservative as a consequence of considering relatively stable model conditions. For example, and discussions of mechanisms, papers such as Walbridge (1967), Cole (1971), and Fedder and Banks (1972) should be consulted. Their numbers for the energy dissipation, and the range 1 to 100 given above, can be compared with other energy inputs discussed in this Symposium. In doing this it is important to also keep in mind that unlike the localization of auroral particles or the restriction of EUV absorption to the sunlit ionosphere, ion drag exists over the entirety of the polar regions.

Confidence that a relationship exists between solar wind sector structure and the spatial distribution of inputs to the high latitude ionosphere is based on: (a) observations which demonstrate that the spatial distribution of $\underset{\sim}{E}$ is related to the sector structure, and (b) neutral wind observations which demonstrate that mass motions of the high latitude thermosphere are primarily a response to collisions with the convecting plasma (that is, ion drag).

Item (a) is based on OGO-6 electric field measurements (Heppner 1972, 1973). These clearly showed that the distribution of antisolar convection over the north polar cap shifts toward the evening (dusk) or morning (dawn) hours, respectively, depending on whether the interplanetary magnetic field is directed toward the west of the sun ($270° < \phi < 360°$) or away and to the east of the sun ($90° < \phi < 180°$). They further showed that this relationship is reversed in the south polar region. Figure 1 is drawn for northern high latitudes; for southern high latitudes the sector headings would be interchanged. The reader should consult the journal publications for examples and discussions of the great variety of deviations from the Figure 1 idealizations, and also how these shifts in the $\underset{\sim}{E}$ pattern provide a physical explanation for the Svalgaard-Mansurov findings relating sector structure to polar magnetic variations.

Item (b) is based on high latitude chemical releases from rockets. Since 1967, five launching sites between 65° and 81° have been used, and 100 barium ion and barium and strontium oxide neutral clouds have been released between 180 and 310 km from 27 rockets. Seven of these rockets also released TMA/TEA neutral trails extending from 180 km down to 80 km. Observations of the simultaneous motions of ion and neutral clouds provide a powerful tool for evaluating ion drag. An analysis of the first 15 flights appears in Meriwether et al. (1973). This analysis and subsequent data show that most of the observed motions

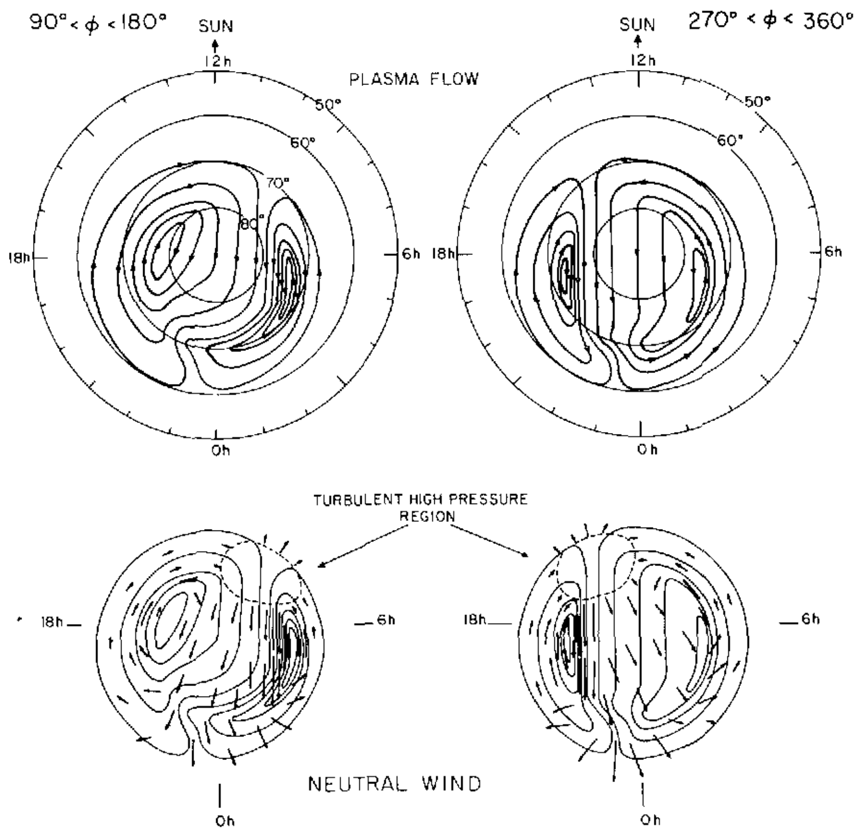

Figure 1. (Top) Idealized polar patterns of the convective plasma flow for "away" and "toward" sectors of the interplanetary magnetic field. Streamlines, the direction of v, are lines of constant electric potential; thus the spacing between lines is inversely proportional to the magnitude of E or v. Coordinates are magnetic local time and invariant latitude. (Bottom) Idealized vector representation of neutral winds above 180 km relative to the plasma flow patterns.

above 180 km fit very well with motions expected from ion drag forces. Apparent discrepancies, in the form of neutral wind vectors not aligned with the ion flow, appear consistently in the post-midnight auroral belt, but these can be attributed to the inertia of the wind system. In effect, the neutral flow across the polar cap has too much inertia to suddenly change direction. There are other important details that cannot be discussed here. In a gross way they have influenced the idealized wind pictures shown at the bottom of Figure 1.

The Figure 1 neutral wind idealizations are based on observations where possible and on expectations in time-latitude regions were observations have not been conducted. For this crude modeling it is assumed that there is a narrow band of auroral ionization within the sunward convection and that the ionosphere is sunlit to the dayside of the 18^h to 6^h meridian. Thus, ion-neutral coupling is relatively negligible over the dark portion of the antisolar convection. In addition to the general tendency for the neutral motion to follow the ion motion, an important point to note is that a "turbulent, high pressure region" is created on the dayside (see Figure 1). The existence of this region is a prediction, not an observation. The convergence of sunward, east-west flows is the primary cause of the high pressure, and nonuniformity of these flows with variable inertia will produce a turbulent behavior. A further point is that these regions are also regions where the electric field measurements suggest very strong turbulence (not represented in the Figure 1 idealizations). Through ion drag, the plasma turbulence will also produce a wind turbulence, but feedback effects are also operative and it becomes impossible to determine whether the electric field or the neutral wind turbulence is primary. The important point for the present is that the flow away from this high pressure tends to add to the antisolar wind from ion drag; thus it adds to the sector-dependent asymmetry.

The Figure 1 wind pictures are representative for altitudes greater than 180 km. In the lower ionosphere the winds become more complex as the time lag for the neutrals to respond to changes in ion drag increases (that is, the neutral mass motion is more sluggish). The ratio of ion to neutral densities and the duration of a unidirectional ion drag force determines how closely the local low altitude winds resemble the higher altitude winds. However, on the scale of the entire polar region there will be a dawn-dusk asymmetry in the momentum transferred to the neutral gas depending on the sector of the interplanetary magnetic field.

We do not claim to know if or how the momentum transferred to the neutral gas at ionospheric levels influences the lower atmosphere. However, it does appear that effects can be detected in the form of infrasonic waves which Wilson (1972) has observed in Alaska for many years. Figure 2 is Wilson's illustration of the frequency of occurrence of waves seen by microbarographs at three latitudes. The lines, emanating at 20° intervals from each site, point at the direction from which the waves arrive, and their lengths are proportional to the number of occurrences from that direction. If these lines are flipped 180°, such that they point in the direction of propagation, their mean pattern in the night hours closely resembles the neutral wind vectors in Figure 1. As discussed by Wilson (1972), a complete causative picture to explain these winds involves a number of complex considerations. Our view is that there are at least two essential conditions: (1) having a high velocity, antisolar wind blowing into the midnight auroral belt from the polar cap, and (2) having a sudden increase in the auroral ionization such that the antisolar wind hits a new wall of dense plasma.

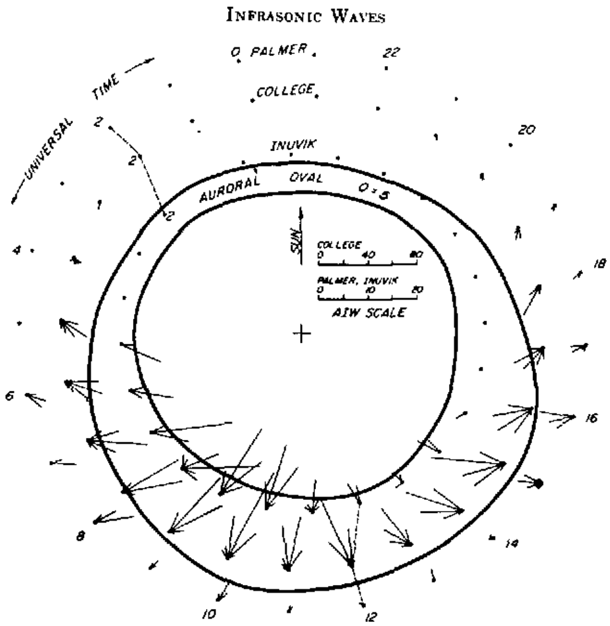

Figure 2. Wilson's (1972) illustration of the frequency of occurrence of auroral infrasonic waves. Vectors point toward the directions from which the waves came.

If an infrasonic shock is produced by the above conditions it raises a more general question; that is, whether or not a similar momentum transfer is taking place all the time, but that it is not identified relative to the noise background when the auroral ionization is changing less abruptly. Although this appears plausible, a more comprehensive understanding of the generation mechanism is required. Infrasonic waves appear, however, to be the only directly observed atmospheric effect of ionospheric electrodynamics.

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SOLAR MODULATION OF ATMOSPHERIC ELECTRIFICATION THROUGH VARIATION OF THE CONDUCTIVITY OVER THUNDERSTORMS

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ABSTRACT

There have been numerous reports indicating that solar activity somehow modulates the earth's electric field and thunderstorm activity. This paper suggests that variations of the current in the global atmospheric electrical circuit can be produced through regulation of the resistance between the tops of thunderclouds and the ionosphere. Long- and short-term changes in the conductivity of this region occur due to changes in the ionization rate resulting from solar activity. Previous suggestions that the phenomena might be due to conductivity variations in the fair-weather part of the world or an influx of space charge to the upper atmosphere are discussed and considered unlikely. It might be possible to test the proposed mechanism by measuring the temporal variation of the ionospheric potential during disturbed solar periods. Another approach would be to measure simultaneously the variation in ionization rate and electric current over thunderstorms. Several ways in which changes in atmospheric electrification might influence other meteorological phenomena are mentioned.

INTRODUCTION

Statistical evidence has been accumulating suggesting that the electrification of the atmosphere is controlled to some extent by solar activity. The findings can be divided into two categories:

a) Long-term (secular) effects in which worldwide thunderstorm activity, as inferred by the ionospheric potential and air-earth current density in the upper atmosphere, varies inversely with solar activity over a solar cycle.

b) Short-term effects characterized by increases in potential gradient, air-earth current density, and thunderstorm activity for several days following solar flares.

It has been difficult to explain how extraterrestrial radiation could modulate atmospheric electrification or the electrical elements near the ground inasmuch as the radiation variations are confined to the upper atmosphere (Markson, 1971).

This paper suggests that solar controlled conductivity variations in the stratosphere could cause the observed atmospheric electrical effects through control of electrical currents flowing between the tops of thunderclouds and the ionosphere.

It will be helpful in the discussion to follow to review the classical picture of atmospheric electricity. The basis of the proposed mechanism is contained in the "global circuit" first defined by Wilson (1920). Figure 1 depicts this dc series circuit. The generator is worldwide thunderstorm activity. There are on the order of 2000 thunderstorms at a given time producing currents averaging about 1 ampere per storm. This generator maintains the ionospheric potential (V_I) at approximately +250 kV relative to earth. Local generators, which contribute minimally to the global circuit current, are also shown. Thunderstorms can be considered as dipoles with the positive pole at the top. Positive charge leaves the earth under thunderstorms due to corona discharge and cloud-to-ground lightning. It is transported up to the cloudbase and through the cloud by a combination of lightning, precipitation, convection, and conduction currents. The relative importance of each is subject to debate. From the cloud tops, it flows upward by conduction to the ionosphere where it rapidly becomes distributed laterally around the earth. In non-thunderstorm regions, over 99 percent of the earth's surface, the charge returns to the ground in the air-earth conduction current. The current density (J) is about 3×10^{-12} A m^{-2}. Because high conductivity exists in the upper atmosphere, the region at a height of about 60 km, called the "ionosphere" for our purposes, can be considered an equipotential surface and the outer conductor of a capacitor formed by two concentric spherical shells, the inner conductor being the earth. Between the conductors, the atmosphere constitutes a leaky dielectric in which conductivity increases approximately exponentially with height. Conduction currents can flow through the atmosphere because ions are present. The ionizing radiation is mostly galactic cosmic radiation supplemented at times by solar cosmic radiation and near the ground by radioactive gases and emanations from the soil.

The ionospheric potential is a good measure of worldwide thunderstorm activity and the electrification of the atmosphere.

PROPOSED MECHANISM

Because of variations in solar activity, conductivity variations occur in one element of the global circuit which, containing most of the total circuit resistance, would exert strong control over the global circuit current. This element is the path between the tops of thunderclouds and the ionosphere. Thunderstorm clouds generally extend up to altitudes in the 10- to 20-km height range.

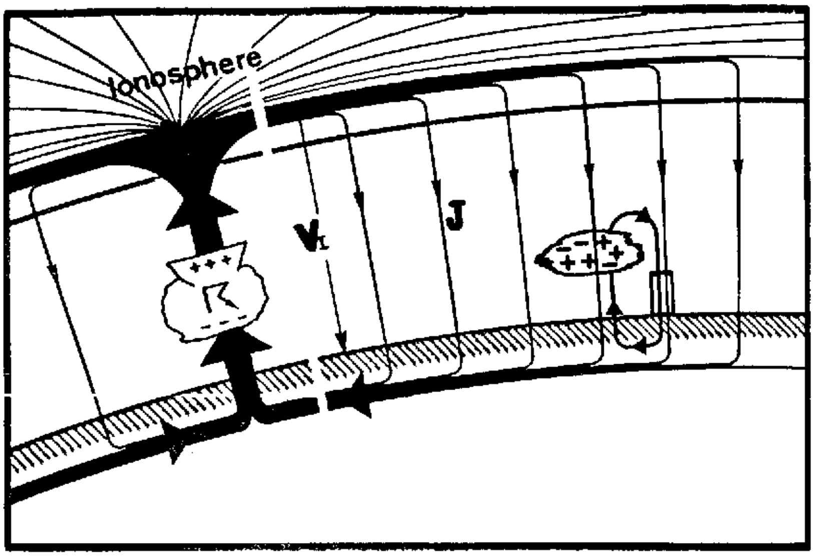

Figure 1. The basic elements of the atmospheric electrical global circuit: thunderstorms, the ionospheric potential, and the fair-weather conduction current. (after Mühleisen and Fischer, 1967)

Conductivity variations are sufficiently large in the environment of the tops of thunderclouds that global electrification should be affected.

Long-term conductivity variations at these altitudes through a sunspot cycle, caused by changes in galactic cosmic radiation, are on the order of a few tens of percent (Dubs et al., 1965). However, following solar flares, solar corpuscular radiation can cause short-term increases in conductivity to three times the normal value (Hake, Pierce, and Viezee, 1973).

The more the circuit resistance is concentrated in the element above thunderstorms, the better the mechanism will work. Dolezalek's (1972) estimates for a typical thunderstorm of area 2×10^8 m^2 with a cloud base at 2 km and top at 12 km will be used. The resistance between the top and the upper atmosphere is 2×10^7 ohms. This gives 10^4 ohms for 2000 storms constituting the global generator. (Note: they are in parallel.) Under a thunderstorm the estimated resistance is 3×10^5 ohms, or 150 ohms for the global generator. This value was derived by increasing the normal fair-weather conductivity in this region by three orders of magnitude because of the presence of point discharge ions. With an ionospheric potential of 250 kV and an air-earth current density of 3×10^{-12} A m^{-2}, the resistance of the fair-weather return path over the 5×10^{14} m^2 area of the earth is 160 ohms.

Thus, the resistance over the generator is two orders of magnitude larger than the resistance in the other parts of the circuit external to the generator. The thunderstorm's resistance given in the reference was 1.5×10^6 ohms, or 750 ohms for the global generator; but this estimate was intentionally conservative. However, it is questionable whether the ohmic concepts of conductivity and resistance should be applied in more than a qualitative manner to a thundercloud, or the region beneath it, since the flow of charge in these regions depends on many variables other than just the electric field intensity and is not linearly related to the latter (Vonnegut, 1963).

While it is realized that conductivities within and beneath thunderclouds are not accurately known, it seems reasonable to assume a large portion of the total circuit resistance lies above thunderstorms. It is suggested that this region in effect is a variable resistor and can function as a valve controlling current flow in the global circuit. Solar controlled changes in this resistance should therefore regulate the ionospheric potential and the electrification of the atmosphere. The mechanism should be more effective with higher thunderstorms since solar controlled conductivity variations increase with altitude. However, detailed predictions cannot be made until we have more information about thunderstorm electrification processes.

The question of how an increased flow of charge to the thunderstorm might influence its function as a generator must be considered. Whether this will enhance or diminish the storm's ability to separate charge depends on the electrification mechanism. There is no consensus on this basic problem of atmospheric electricity and many theories exist. If convection is important, in accordance with the models of Grenet (1947), Vonnegut (1955), or Wilson (1956), the electrification process will be enhanced. If increased currents are dissipative, as stated by Schonland (1932), in accordance with the numerous models where charged particles are produced by hydrometeor interactions (Chalmers, 1967), the generator could weaken.

Finally, we should consider the possible influence of the fair-weather field on thunderstorm formation. Several thunderstorm theories (Elster and Geitel, 1885; Wilson, 1929; Vonnegut, 1955; Sartor, 1965) depend on polarization of cloud droplets in the fair-weather field during the initial stages of electrification. Thus, a change in thunderstorm currents could lead to a corresponding variation in the number of thunderstorms. In sum, there are two possibilities for feedback in the proposed mechanism.

IONIZING RADIATION

WHICH RADIATION IS RESPONSIBLE ?

Solar corpuscular particles are more likely to influence atmospheric electricity than solar electromagnetic radiation. Wave radiation with sufficient energy to ionize air molecules, for example, Lyman-alpha and X-rays, does not penetrate below 50 km (Hake, Pierce, and Viezee, 1973). In order to have a significant influence on the thunderstorm generator, ionizing radiation must reach altitudes below 20 km. Secondary cosmic radiation (created by solar and galactic cosmic radiation) has this property and is almost exclusively the ionizing agent from the top of the mixing layer through the stratosphere. Solar corpuscular radiation also plays a critical role in modulating the flux of galactic cosmic radiation reaching the atmosphere through variation of the screening properties of the interplanetary magnetic field (Hines et al., 1965).

STRATOSPHERIC CONDUCTIVITY VARIATIONS

Primary cosmic radiation from the galaxy and its secondary radiation are the ionizing agents in the stratosphere. There is an inverse correlation between galactic cosmic radiation and solar activity through a sunspot cycle. While the exact cause of this is not well understood, the galactic particles apparently are magnetically deflected by kinks and irregularities in the interplanetary magnetic field (Wilcox, 1968). Therefore the ionization of the upper atmosphere varies inversely with solar activity over a sunspot cycle. The cosmic radiation modulated secular variation in conductivity is minimal in the lower atmosphere but becomes significant at higher altitudes. Comparing ion production rates at solar maximum (cosmic ray minimum) in 1958 to solar minimum (cosmic ray maximum) in 1954, there was a 25-percent increase at 10 km, a 50-percent increase at 15 km, and an 80-percent increase at 20 km (Dubs et al., 1965). Since conductivity is proportional to ion density, and the latter is proportional to the square root of the production rate, the conductivity increases would have been 12 percent at 10 km, 22 percent at 15 km, and 34 percent at 20 km.

However, there are short period increases in stratospheric ionization of as much as one order of magnitude due to bursts of energetic solar particles (Hake, Pierce, and Viezee, 1973). A series of solar flares over tens of hours or several days, such as might occur during a period of intense solar activity, could maintain enhanced conductivity in the stratosphere over a similar period with a delay for the transit time of the particles.

We will next examine the variations in atmospheric electricity as a function of solar activity.

ATMOSPHERIC ELECTRICAL RESPONSES TO SOLAR ACTIVITY

SECULAR VARIATIONS

In searching the literature it is possible to find both positive (Bauer, 1926), negative (Rao, 1970), and null (Hogg, 1955) correlations between long-term time series comparing atmospheric electrical parameters measured on the ground and solar activity. Because atmospheric electrical data gathered at the earth's surface are sensitive to local influences, they are relatively unreliable indicators of global electrical activity compared to measurements of ionospheric potential and air-earth current density well above the earth's surface (to be discussed later).

An inverse relationship between ionospheric potential and long-term solar activity is suggested by Figure 2. This data from Mühleisen (1969) depicts the variation of ionospheric potential over a solar cycle. Similarly, an inverse correlation between air-earth current density in the stratosphere (directly proportional to ionospheric potential) and solar activity during the period of 1965 to 1972 has been observed (D. E. Olson, personal communication, 1973). Since galactic cosmic radiation is inversely correlated with solar activity, and since this radiation is the primary source of atmospheric ionization, these findings suggest the importance of galactic cosmic radiation in modulating the intensity of the global electric generator through conductivity variations.

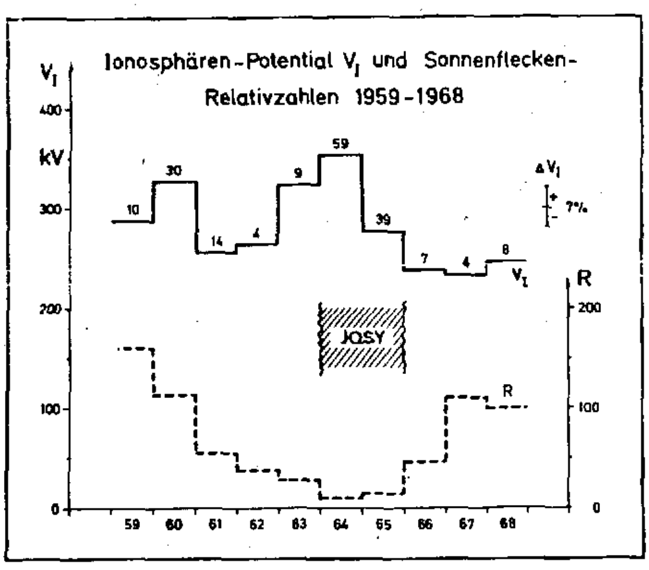

Figure 2. The variation of ionospheric potential through a solar cycle; numbers on line are total balloon soundings that year. (after Mühleisen, 1969)

Additional support for this conclusion is seen in Lethbridge's (1969) comparison of galactic cosmic radiation, as monitored by neutron counts at Chicago, with United States thunderstorm frequency. This study shows that high counts correspond to high thunderstorm frequency and low counts to low thunderstorm frequency.

SHORT-TERM VARIATIONS

While the secular variation in solar activity seems to be inversely related to ionospheric potential, the opposite is noted for short-term variations. Increases in potential gradient and air-earth current density on 3-km high mountains in Hawaii and Germany following solar flares have been reported by Cobb (1967) and Reiter (1960, 1969, 1971). Sao (1967) shows a correlation between 1000-MHz solar flux (a measure of solar activity) and potential gradient measured in the arctic. Bossolasco et al. (1972) report an increase in thunderstorm activity in the Mediterranean area three and four days after solar flares. These reports indicate an increase in terrestrial electrical activity apparently associated with the radiation from solar flares. There is a lag of one to several days between the occurrence of flares and the electrical effects on earth in agreement with the time it would take solar corpuscular radiation to reach earth.

Thus, the evidence suggests that both galactic cosmic radiation as well as solar corpuscular radiation modulate the electrification of the atmosphere. This could explain the apparent contradiction that long-term variations in global electrification appear to be inversely correlated with solar activity while short-term electrical variations are positively correlated with solar activity. If the electrical charge of the atmosphere is controlled by conductivity over thunderstorms, the variation of galactic ionizing radiation controls the secular change in atmospheric electrification, while short-term atmospheric electrical increases are due to the enhancement of conductivity caused by particles from solar flares.

DISCUSSION OF PREVIOUS SUGGESTED MECHANISMS

VARIATION OF COLUMNAR RESISTANCE

In trying to explain how solar radiation might influence atmospheric electricity, Sao (1967) suggested that, during times of enhanced solar activity, increased ionization in the upper portion of the columnar resistance in fair-weather regions would concentrate the ionosphere-to-earth potential difference in the lower portion of the atmosphere and increase the potential gradient there. This seems unlikely. Since 90 percent of the columnar resistance lies below

10 km and 98 percent below 20 km, an increase in conductivity in the stratosphere would not significantly change the total columnar resistance and thereby the electrical conditions in the lower atmosphere. The ionizing radiation would have to penetrate to about the 3-km level, through one-third of the columnar resistance, to have an appreciable influence on atmospheric electricity through fair-weather columnar resistance variations; such occurrences are rare. It would be necessary for the columnar resistance above 3 km to undergo an unrealistically large 30-percent decrease to produce a 10-percent increase in air-earth current and potential gradient near the ground. This line of reasoning led Cole and Pierce (1965) and Cobb (1967) to speculate that since solar-induced atmospheric electrical effects in the lower atmosphere could not be caused by conductivity variations, they might be the result of an influx of space charge to the stratosphere, for example, from a stream of solar protons.

SPACE CHARGE

The ionization of the atmosphere above the mixing layer is caused by secondary cosmic radiation showers produced in the 15- to 35-km region when primary cosmic radiation in the BeV energy range contacts air molecules. Some of the charge carried by the primaries is deposited in this region and a fraction of it is carried to lower altitudes. However, the flux of galactic cosmic radiation is about 1 particle $cm^{-2}s^{-1}$. While flare-produced solar corpuscular radiation (sometimes called solar cosmic radiation) can have flux densities in the thousands, these are mostly in the low MeV energy range and would be screened by the magnetosphere from the atmosphere except in the auroral zones. As previously mentioned, some of the solar particles (they are mostly protons) have sufficient energy to produce an increase in stratospheric ionization of, at the most, one order of magnitude lasting a few hours (Hake, Pierce, and Viezee, 1973). This means that a maximum flux of 10 elementary charges $cm^{-2}s^{-1}$ might reach the stratosphere. Because of high conductivity in the upper part of the columnar resistance, most of the incoming charge would be conducted toward the ionosphere and not significantly contribute to the air-earth conduction current in the lower atmosphere. Considering that this current is about 1500 elementary charges $cm^{-2}s^{-1}$, the small influx of space charge to the upper atmosphere which could be carried by extraterrestrial radiation is orders of magnitude too small to influence atmospheric electricity near the ground. About 1500 positive elementary charges $cm^{-2}s^{-1}$ would have to reach 10 km to cause a 10-percent increase in the fair-weather conduction current and potential gradient in the lower atmosphere.

TESTING THE MODEL

MEASURING THE VARIATION OF IONOSPHERIC POTENTIAL

It may be possible to identify the extraterrestrial particles and mechanism(s) which modulate atmospheric electricity by correlating the variation of ionospheric potential, a measure of the intensity of the global generator, with geophysical parameters. Reiter's (1972) attempt to do this with data obtained on a 3-kim high mountain indicates that even under the most ideal circumstances it is very difficult with electrical data taken at the earth's surface. Kasemir (1972) reports with measurements made on a ship in mid-ocean (the cleanest air possible), at least one week's data was necessary for statistical averaging in order to detect the well-known diurnal variation which follows worldwide thunderstorm activity. The noise in ground level measurements is caused by variations in columnar resistance plus local conductivity and space charge fluctuations. These are due to many natural and manmade elements such as radioactive gases, condensation nuclei, and pollution transported by the wind and convection. An additional limitation with ground data is that the response time of the local electric field, here defined as the time to reach 90 percent of the new equilibrium value, is about 30 minutes.

Most of the noise in such measurements can be eliminated by making them from an airplane flying at constant altitude well above the mixing layer under selected meteorological conditions over the ocean (Anderson, 1969: Markson and Vonnegut, 1971). With this technique, the diurnal variation in potential gradient and air-earth current density is seen in just one day's record and simultaneous measurements made from two aircraft 7000 km apart showed high correlation (Dolezalek, 1972). These results demonstrate the possibility of recording continuously the temporal variation of ionospheric potential. The temporal resolution is determined by the altitude of the measurement — at airplane flight levels the response time is less than 1 minute.

AIRPLANE MEASUREMENTS

It may be possible to test the proposed mechanism in two different ways utilizing atmospheric electrical measurements from aircraft platforms. The first approach would be to measure the variation of ionospheric potential and ionization rate at one location and altitude in fair-weather regions over extended periods following solar flares. This would allow comparison of global electrification with solar controlled geophysical events. An increase in ionospheric potential at the time of a magnetic storm or PCA event would suggest the importance of solar corpuscular radiation. A decrease coincident with a Forbush decrease (in galactic cosmic radiation) would point to this as the cause. If the measurements were made at a location reached by ionizing radiation, increases in the ionization rate might accompany increases in ionospheric potential. However, increases in ionospheric potential alone might occur if the radiation enters the atmosphere in an area remote from the aircraft where it increases thunderstorm currents. The correlation of stratospheric ionization and ionospheric potential may only be observable at low latitudes since most of the world's thunderstorms, particularly the largest ones, reside in the tropics, and magnetic screening allows only the most energetic cosmic radiation access to this region.

It also would be of interest to examine the variation of ionospheric potential as a function of the earth's position in a solar magnetic sector. Markson (1971) suggested that since the sector structure of the solar magnetic field controls extraterrestrial particles, the analysis of extraterrestrial effects on weather should consider the earth's position in a solar sector. Using this approach, a relationship was found between solar sector position and thunderstorms in the United States. Subsequently, Wilcox et al. (1973) found striking evidence for atmospheric vorticity relating to the earth's solar sector position. Solar and galactic cosmic radiation reaching the earth is a function of the earth's position in a solar sector (Wilcox, 1968).

A second approach would be to measure electrical currents and ion production rates above thunderstorms. If the model is correct, thunderstorm currents for comparable storms (height, depth, and location) would be positively correlated with ionization. Comparisons between solar maximum versus solar minimum would be of interest; if conductivity controls thunderstorm currents, they should be greater at solar minimum.

It is recognized that making such an evaluation may be difficult because of noise in the data. Previous investigators have observed considerable structure in flights across the tops of thunderclouds (Gish and Wait, 1950; Stergis et al., 1957). Many measurements may be required for statistical evaluation. The noise may be lessened by using a slow flying airplane capable of remaining over one thunderstorm location — preferably a turret where the masking effect of the screening layer is minimized (Vonnegut et al., 1966). This would have the additional advantage of minimizing variations due to changes in the aircraft's position relative to charge in the thunderstorm, thus allowing the temporal variation to be observed better. If the noise is not too great, measurements made at judicious times after solar flares may "catch" the arrival of ionizing radiation for comparison with the thunderstorm current.

THE INFLUENCE OF ATMOSPHERIC ELECTRIFICATION ON METEOROLOGY

As previously discussed, a variation in the global circuit current would be expected to affect the electrification of the thunderstorm generator as a function of the charging mechanism. Changes in electric field intensity could influence microphysical processes within a thundercloud. Vonnegut (1963) has assembled from the literature several different ways in which precipitation formation and cloud dynamics might be affected.

It is difficult to estimate the influence of thunderstorm activity on synoptic meteorology, but several large-scale physical processes occur which could have consequences in atmospheric dynamics. Thunderstorms transport momentum, heat, and water from the lower atmosphere to the stratosphere. Ice crystals from their tops can form extensive cirrus-like cloud shields which would modulate radiational heating.

Variations in solar activity controlling the weather through modulation of thunderstorm activity would be important to the extent that thunderstorms are an important part of the earth's weather.

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF RALPH MARKSON

MR. DESSLER: Would the fair-weather electric field at the surface of the earth (in terms of your model) be maximum at sunspot maximum? The way you have it now, the total potential is minimum at sunspot maximum, is that correct?

MR. MARKSON: The ionospheric potential?

MR. DESSLER: Relative to the earth, is the minimum at sunspot maximum?

MR. MARKSON: That is correct.

MR. DESSLER: Now, the fair-weather electric field in volts per meter at the earth's surface ...

MR. MARKSON: This is also essentially proportional to ionospheric potential.

MR. DESSLER: Not necessarily, if you are lowering the effective height of the ionosphere, which I understand you are doing, then it could go the other way.

MR. MARKSON: Assuming I maintain the same kind of conductivity distribution in both cases (solar maximum and minimum), the potential gradient near the earth would be less when the ionospheric potential is less.

MR. DESSLER: But I thought you were changing the conductivity distribution.

MR. MARKSON: No. The point is that the big variations occur in the 10- to 20-kilometer region.

This soups up the current. If you have a model that doesn't bleed the thunderstorm down, if it can maintain its potential, this would increase the strength of the generator, which in turn would increase ionospheric potential, which in turn would increase the gradient near the ground, which could initiate additional thunderstorm activity.

N74-29093

SOLAR LUMINOSITY VARIATIONS AND THE CLIMATE OF MARS

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ABSTRACT

Attempts to resolve the solar neutrino flux problem have led to suggestions of large-scale oscillations in the solar luminosity on a geological time scale. A simple climatological model of Mars indicates that its climate may be much more sensitive to luminosity changes than the Earth's because of strong positive feedback mechanisms at work on Mars. Mariner-9 photographs of Mars show an abundance of large sinuous channels that point to an epoch of higher atmospheric pressures and abundant liquid water. Such an epoch could have been the result of large-scale, solar luminosity variations. However, our climatological model suggests that other less controversial mechanisms, such as obliquity or polar albedo changes, also could have led to such an epoch. As more becomes known about Mars, it may prove possible to formulate a history of Martian climate. By discovering effects that cannot be due to other mechanisms one may be able to form a chronology of solar luminosity variations to compare with data from the Earth.

Attempts to explain the current low solar neutrino flux have led to suggestions of oscillations of solar luminosity on a geological time scale. Luminosities during the bulk of Cambrian time may have been 7 to 35 percent greater than present (for example, Ezer and Cameron, 1972). Great ice ages, such as the one during the last few million years, would correspond to relatively short epochs of reduced luminosity. Evidence that luminosity fluctuations of this magnitude might actually occur comes from studies of the color-magnitude diagram of the galactic star cluster Praesepe (Sagan and Young, 1973).

Luminosity variations would have affected Mars as well as the Earth. Figure 1 illustrates a variety of large-scale Martian surface features that have been interpreted as dried out river valleys. Other evidence including cratering statistics and widespread hydration of surface materials also suggests a wetter epoch in the Martian past (see Sagan et al., 1973). An important point is that the current Martian atmospheric pressure is below the triple point of water. This makes it impossible to have permanent bodies of liquid water on present-day Mars and suggests a higher atmospheric pressure in past epochs.

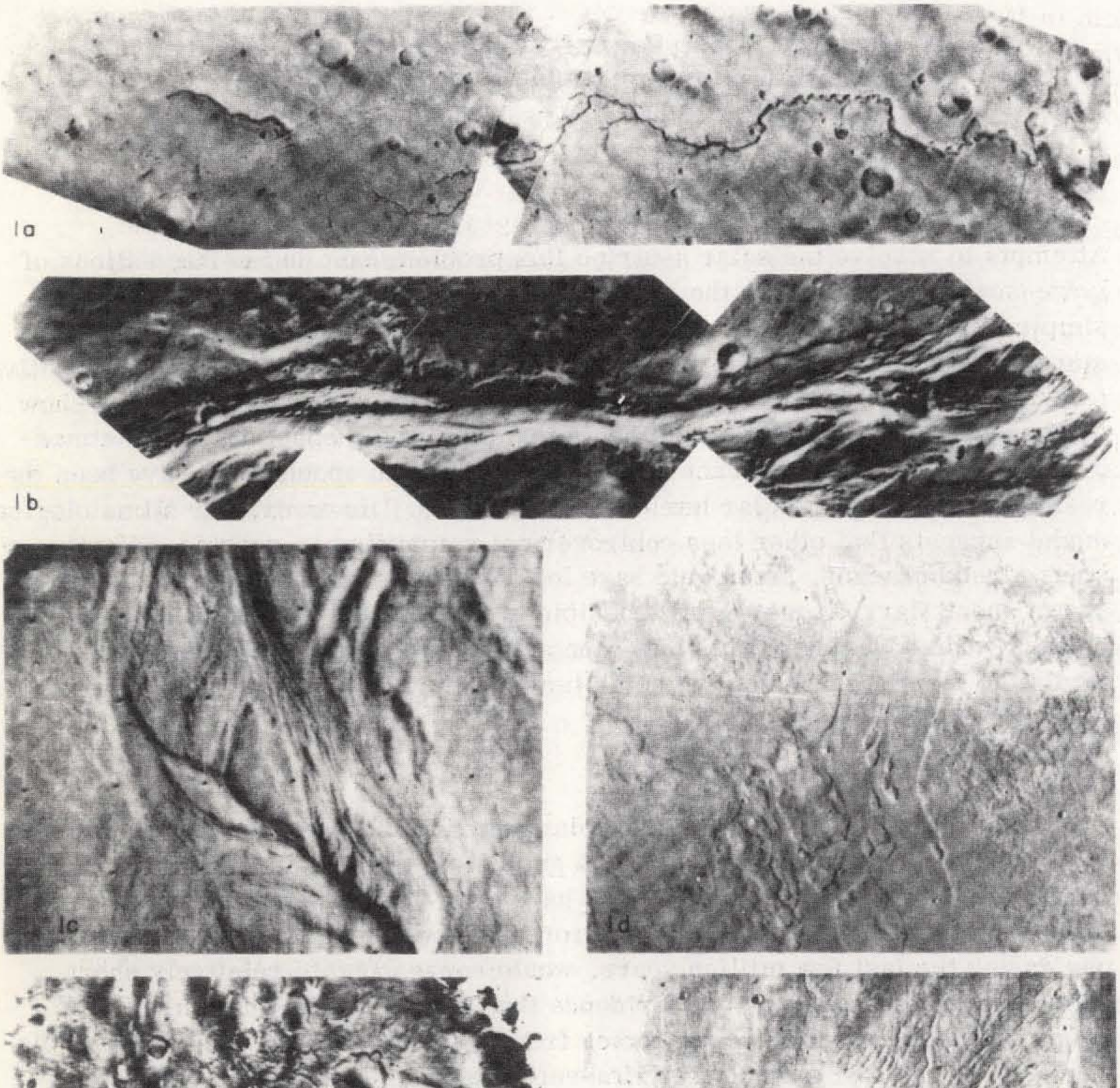
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Figure 1. Mariner-9 photographs indicative of running water on Mars. The details of flow — for example, whether produced by rainfall or underground rivers — differ from case to case. (a) Mosaic of sinuous dendritic channel system in Mare Erythraeum (29° S, 40° W), ~1000 km long. Note the evidence of tributaries buried under sand and the possible covered segment of the main channel at left (Image Processing Laboratory product, pictures 122/6354843, 131/6283032, 211/9160800). (b) Mosaic of about one-third (~120 km) of the Amazonis-Memnonia channel. This segment, exhibiting banks, bars, and braids, is centered at 7° S, 151° W (Mission Test Video System product, revolution 458, pictures 12499650, 12499720, 12499790). (c) Narrow-angle (B-frame) closeup of braided portion of Amazonis-Memnonia channel at 6° S, 150° W. The feature, about 40 km across, is reminiscent of the results of episodic flooding in terrestrial river systems (MTVS product, picture 224/9628649). (d) Teardrop-shaped islands ~5 km long in a channel between Aetheria and Elysium (31° N, 229° W) (IOP product, picture 204/8910729). Similar streamlined islands in the Lunae Palus channel darkened during the Mariner-9 mission, probably due to deflation of bright overlying dust by winds coursing down the channel (3). (e) Network of gullies in Sabaeus Sinus (10° S, 330° W) on old cratered terrain, suggestive of cutting by rainfall. The field of view is ~600 km across (MTVS product, picture 423/116205331). (f) Possible mountain drainage system in Alba (45° N, 116° W). This is not a perfect replica of terrestrial mountain drainage systems because some of the flow appears to be uphill, which poses interpretation problems with all hypothesized liquids. The field of view is ~70 km across (MTVS product, picture 152/7039903). This figure is adopted from Sagan et al. (1973).

The basic question that needs to be answered, then, is what can lead to higher atmospheric pressures on Mars? An important feature of Martian climatology is that the atmospheric pressure seems to be just the vapor pressure of CO_2 at Martian polar temperatures. Thus the atmospheric pressure is a sensitive function of polar temperature. A recent study (Gierasch and Toon, 1973; Sagan et al., 1973) shows that an instability is possible. A small increase in polar temperature due, for example, to orbital perturbations, polar albedo variations, or solar luminosity changes leads to an increase in atmospheric pressure. However, atmospheric heat transport to the polar ground increases with atmospheric mass so there is a strong positive feedback leading to further increases in polar temperature. Because of the strong positive feedback, Martian climate is probably much more sensitive to long-term solar luminosity variations than the Earth's. Figure 2 shows the results of solving a simple heat balance equation which contains these ideas (Gierasch and Toon, 1973). One discovers that the annual average solar heating at the poles

$$S = \frac{S_0(1-A)\sin\delta}{\pi a^2(1-e^2)^{1/2}}$$

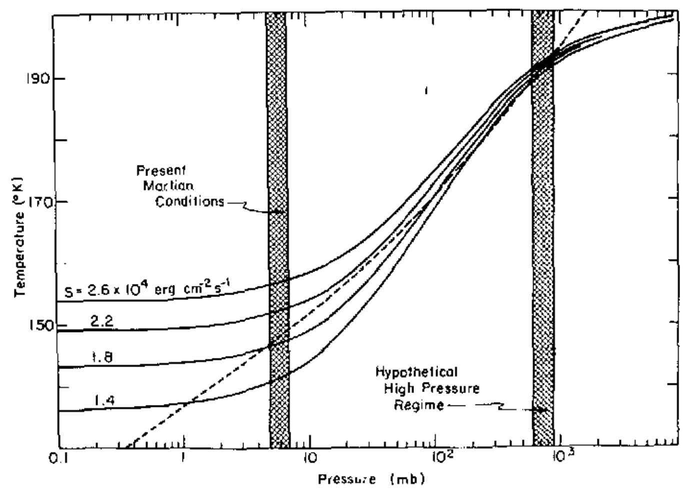

Figure 2. A solution of a simple climatological model of Mars. The dashed line is the vapor pressure curve of CO_2. The solid line is a solution of a simple energy balance model which includes parameterizations of heat transport from atmosphere to polar ground by conduction and radiation, and heat transport from equator to pole by baroclinic waves. The axes are atmospheric pressure and polar ground temperature. An equilibrium climate requires that dashed and solid curves intersect. Current conditions on Mars require that $S \cong 1.8$ and this is a reasonable value for S to take. If S increases to 2.2 there is no equilibrium climate until pressures near 1 bar are reached. To increase S this much, δ must increase by about 6°, A must decrease by about 0.05, or S_0 must increase by about 15 percent. The model is discussed more fully in Gierasch and Toon (1973).

is critical. The semimajor axis of Mars, a, and the eccentricity of the orbit, e, do not change enough to affect S. However, obliquity, δ , changes and albedo, A, changes are large enough to lead to very large changes in atmospheric pressure as are the changes in the solar constant, S_0, predicted by solar neutrino flux theories.

The obvious features that indicate climatic change on Mars, such as the channels shown in Figure 1, could have easily been caused by changes in albedo or obliquity rather than by more speculative changes in S_0. Definitive evidence for solar luminosity variations may still exist, however, in more subtle features. Some of these may hopefully be understood without extensive future observations.

The polar albedo may be changed during epochs characterized by global dust storms. Dust storms in turn may be favored by times when perhelion insolation is high so that the polar albedo may vary with a few million year period

(Murray et al., 1973). Likewise, the obliquity of Mars undergoes very large oscillations ($\pm 10^\circ$) with a period on the order of a few million years (Ward, 1973). The period of solar luminosity variations, which would be the time between great ice ages on the earth, is a hundred times greater than the period of albedo or obliquity oscillations. There may be features on Mars which reflect very long term oscillations in contrast with the shorter ones. Figure 3 shows a small part of an interesting set of features, known as the polar laminae, which are found in both north and south polar regions. Unfortunately, how these features were formed, what they are made of, and how

Figure 3. A view of the polar laminae. These features are found in both polar regions. The finest dark bands are thought to be about 30 meters thick. The distance across the layered region is about 5 km at the widest part. The laminae are thought to contain both dust and a volatile, probably H_2O. Their regular structure and the fact that they occur in both polar regions indicate that their formation may be controlled by climatic changes. (MTVS product, picture 4213-21, DAS 08080243).

old they may be is unknown at present. It is likely that their formation is influenced by climatic changes, and they do show evidence of doubly periodic formation with tens of laminae adding to form distinct plates. It is the edge of one plate which is shown in Figure 3. Figure 4 shows the North Pole of Mars and the dark bands seen in the ice illustrate the edges of several plates which are arranged one on top of the other. Future studies of the laminae and plates may provide us with a climatic history of Mars.

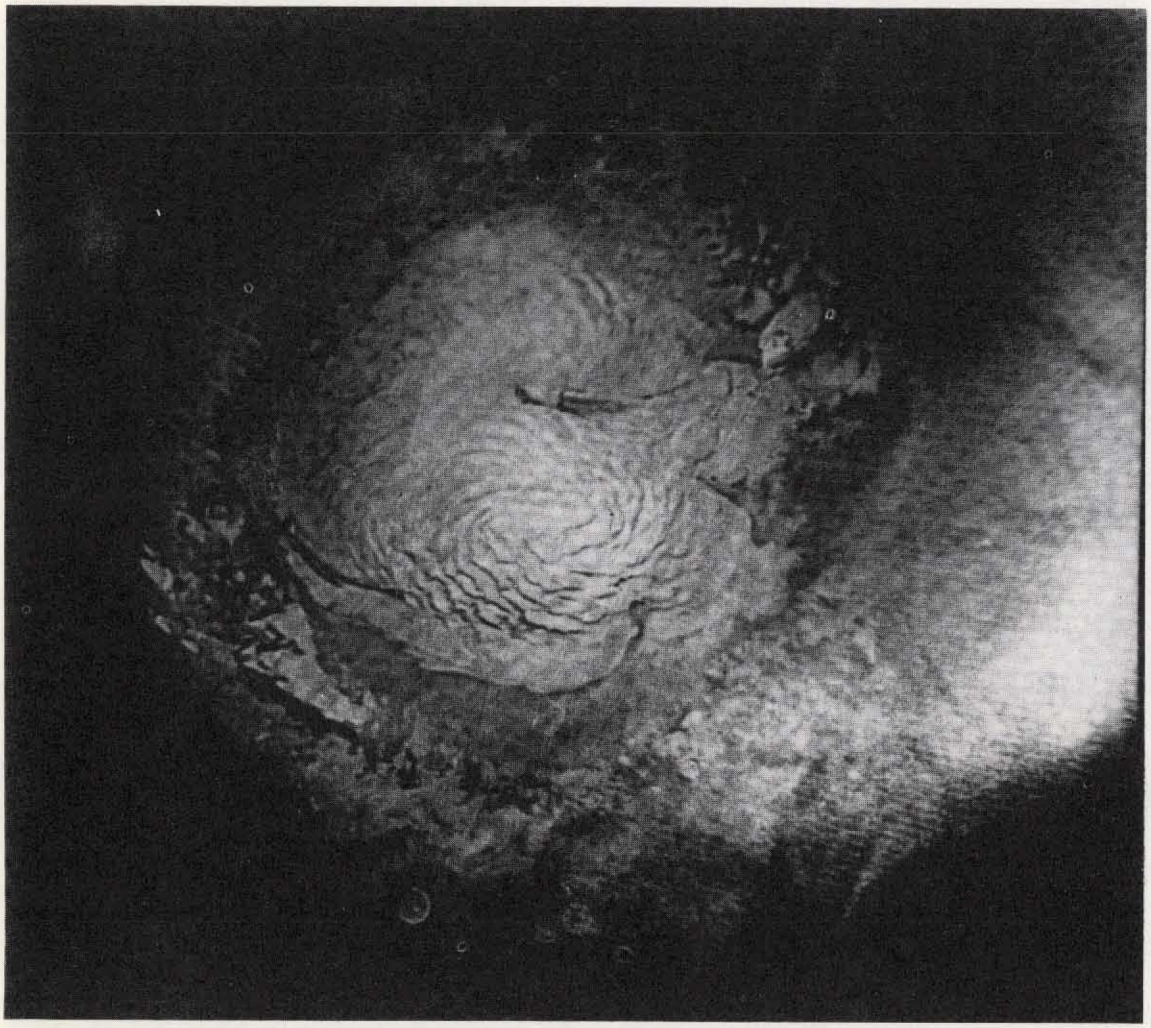

Figure 4. A view of the North Pole of Mars. The circular, concentric dark bands are the edges of plates. Each plate is composed of many tens of laminae as seen in the previous figure. The plates lie one on top of the other and extend far out from the poles in both hemispheres (MTVS product, picture 529/13028127).

As we pointed out, the river valleys seen by Mariner 9 seem to require a much higher atmospheric pressure for their formation. They do not require higher planetary temperatures, however (Sagan et al., 1973). There is some indirect evidence for rainfall on Mars (Sagan, et al., 1973). The conditions required for rainfall are not yet well understood. However, from terrestrial experience, it seems likely that higher Martian equatorial temperatures will be required. It is possible that a CO_2, H_2O greenhouse effect may be enough to provide this (Gierasch et al., in press). If this is not the case, then solar luminosity variations will become attractive since they both raise the planetary mean temperature and lead to increased pressures through the instability we have described.

Mars is climatologically simpler than the Earth in many ways. There are no oceans and at present there is no rainfall. Moreover, strong positive feedbacks accentuate climatic changes on Mars. These factors partly compensate for the remoteness of the planet from Earth, and we have now entered an era when studies of the planet may be of real use in understanding the Earth. There is some hope that an understanding of the more subtle features we have observed on Mars may provide information about possible solar luminosity variations, and that such an understanding can be achieved in the relatively near future.

The climate of the Earth has undergone changes on many time scales other than the one we have concentrated on in this paper. If any of these climatic changes has been caused by extraterrestrial mechanisms there may be evidence of similar climatic changes on Mars. Exciting discoveries undoubtedly await us in our future explorations of the planets.

ACKNOWLEDGMENT

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF OWEN B. TOON

QUESTION: Can the finer divisions be annual variations?

MR. TOON: I think it is very unlikely that there are annual variations. The thickness of the finer layers is about 30 meters. So it is pretty hard to think of anything annual that could occur that would make a 30-meter thickness layer of dust. They are very uniform in thickness, and they are remarkably uniform in thickness one layer compared to the next.

SESSION 3

IN SEARCH OF PHYSICAL MECHANISMS

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N74-29094

SOME PROBLEMS IN COUPLING SOLAR ACTIVITY TO METEOROLOGICAL PHENOMENA

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ABSTRACT

The development of a theory of coupling of solar activity to meteorological phenomena has to date foundered on the two difficulties of (1) devising a mechanism that can modify the behavior of the troposphere while employing only a negligible amount of energy compared with the energy necessary to drive the normal meteorological system, and (2) determining how such a mechanism can effectively couple some relevant magnetospheric process into the troposphere in such a way as to influence the weather. If such a mechanism exists, it appears that we may not be able to define it without understanding much more than we do now about long-range weather behavior. A clue to the nature of the interaction between the weather and solar activity might be provided by the fact that most solar activity undergoes a definite 11-year cycle, while meteorological phenomena undergo either no closely correlated variation, or an 11-year variation, or a 22-year variation.

INTRODUCTION

It is safe to suppose that the search for correlations between occurrences in the heavens and events on the earth dates into prehistory. Many such efforts come to mind, including, for example, the hypothesis that the position of the sun, moon, and planets controls human destiny (for example, astrology), or the practice of beating tom-toms during an eclipse to restore the sun (a correlation that has been conclusively verified by thousands of independent experiments). Some such searches lead to fruitful outcomes. For example, the connection between sunspot number and geomagnetic activity was suggested almost as soon as both phenomena could be clearly identified. Schwabe's discovery of the sunspot cycle was announced in 1851 after he personally had collected two cycles of data. The next year, Sabine (1852) reported results showing that geomagnetic activity appeared to vary cyclically as did the sunspot number. There was a setback to this line of research when Kelvin (1892), who at the time held the powerful position of President of the British Royal Society, denounced this correlation (illustrated in Figure 1) as a "mere coincidence." The concept survived handily, however, because the result could be reproduced cycle after cycle.

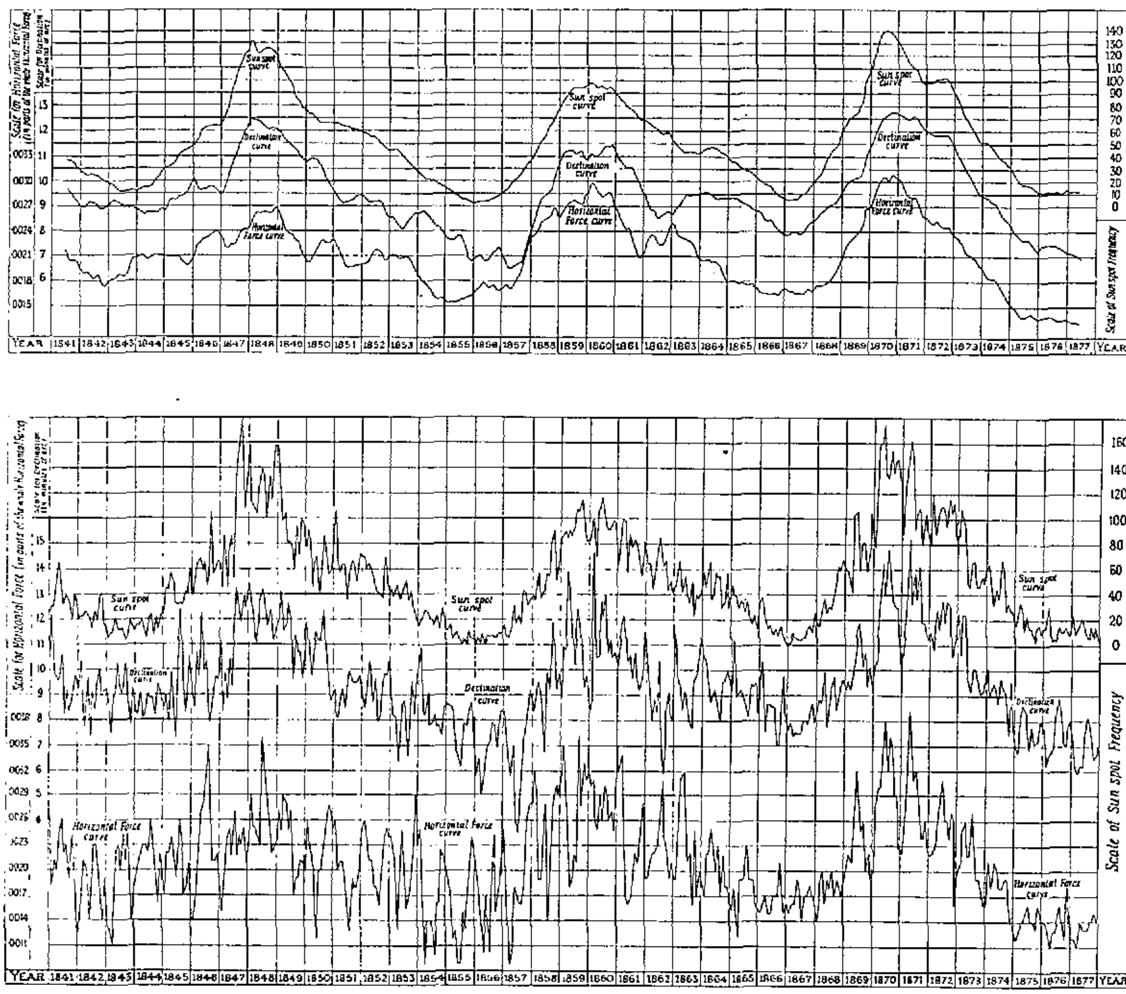

Figure 1. Sunspot number and geomagnetic activity are plotted for the time period between the years 1841 to 1877 (after Chapman and Bartels, 1940). The correlation between solar and geomagnetic activity is obvious.

Following this correlation there were attempts to establish a relationship between sunspot number and a variety of items, as for example, the occurrence of the aurora, animal and plant growth, stock market prices, the temperature of the thermosphere, the frequency of volcanic outbursts (see Figure 2), cosmic radiation, suicide rates, variations in the solar constant, and, of course, the subject of this conference — the weather. Of these items listed, only the aurora, the temperature of the thermosphere, and the solar-cycle variation of the low-energy component of the cosmic radiation are accepted and generally understood. It appears that correlations in geophysics are not easily established.

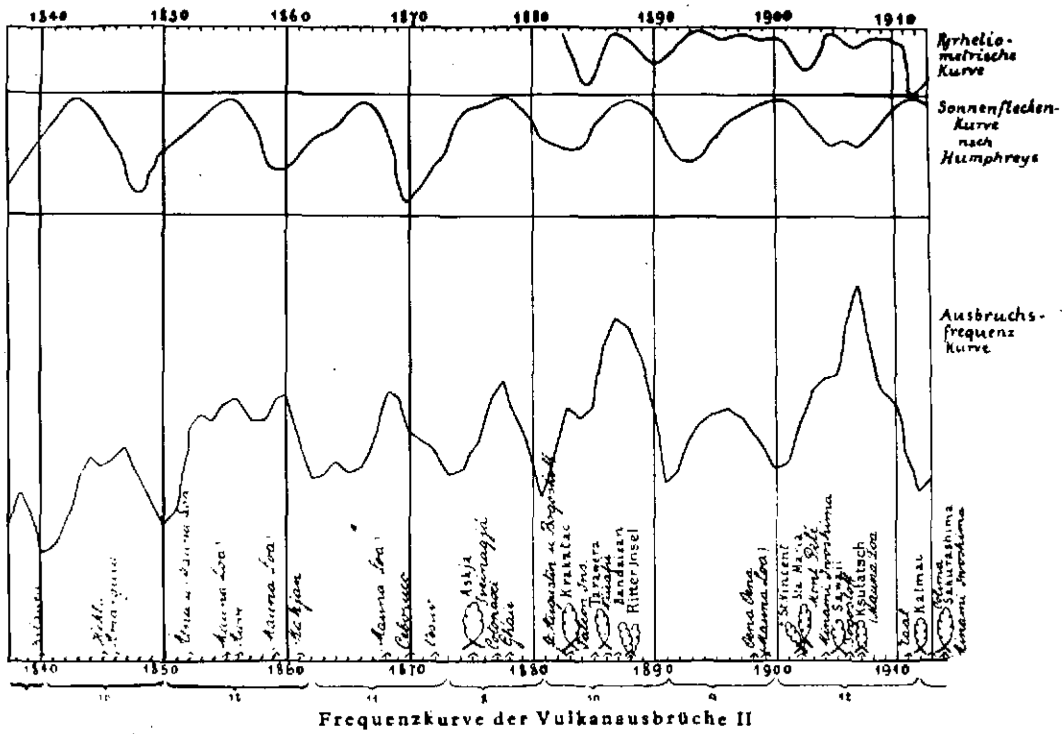

Figure 2. Sunspot number and frequency of volcanic outbursts are plotted for the time period between the years 1838 to 1914. The correlation between solar and volcanic activity, while not as obvious as the correlation of Figure 1, is "not bad."

CORRELATIONS IN GEOPHYSICS

Why is it that, with few exceptions, one finds such difficulty in establishing a causal relationship between two geophysical phenomena, or even in saying what regularity might govern the time-dependent behavior of a single variable? There are several factors we must consider:

(1) Most geophysical phenomena have a high intrinsic noise level. Their first order behavior is erratic. The phenomena we are looking for change slowly with time. For example, Schwabe was well into his second solar-cycle data set before he could demonstrate the systematic cycle. It took 20 years to establish the 11-year sunspot cycle.

(2) There usually is no acceptable theory to help organize the data into a manageable search. The theory usually follows the recognition of the phenomenon from observations. One must have great patience and perseverance. A good example is shown by Kepler's work that resulted in his laws of planetary motion. He had the data that Tycho Brahe had gathered over his lifetime of painstaking

observations. Kepler labored for more than six solid years; by trial and error he groped in the dark with no possible glint of theory to illuminate his search, until finally he chanced on the correct relationships. Patience, hard work, and extensive runs of reliable data are necessities.

(3) Finally, there are scoffers, like Kelvin, who delight in strangling new hypotheses in their infancy. The record shows that, although Kelvin was often wrong in his prolific criticisms, he was quite influential in slowing progress in several fields of research. Such people often rely on what is sometimes referred to as Bates' Principle, "Never believe an observational result until it is confirmed by theory" (Bates, 1974).

COUPLING BETWEEN SOLAR ACTIVITY AND THE WEATHER

I am not aware of any viable theory at present that proposes a coupling between solar activity and some meteorological phenomenon. However, many good, relevant data are at hand. Researchers in this field thus need only the patience of Kepler, a good sense of humor to handle the Kelvins among us, and a little luck to lead them to the right parameters.

Let us look at a few of the difficulties a theory must overcome before it can be regarded as a hopeful candidate for explaining a relationship between solar activity and some meteorological phenomenon.

ENERGY

The energy source for meteorological phenomena is (virtually) entirely provided by sunlight absorbed at the earth's surface. This energy flux is $U_{EM} = \pi r_E^2 F\ (1-A)$, where r_E is the radius of the earth, F is the solar constant, and A is the earth's albedo. If we assume the earth has an albedo $A = 0.5$, we find that $U_{EM} = 8.9 \times 10^{16}$ W $= 8.9 \times 10^4$ TW, where TW signifies a terrawatt $= 10^{12}$ W. Essentially all of this energy is ultimately radiated back out into space. But much of it first becomes involved in the tropospheric weather system where it establishes temperature differentials to drive convective systems and evaporates large quantities of water to provide for interesting instabilities within these convective systems.

To compare this energy flux with the solar-wind energy flux, we note that the solar wind, carrying an embedded magnetic field, strikes the geomagnetic field with a total energy flux of

$$U_s = \pi r_M^2 \left(\frac{1}{2} \rho V_s^2 + \frac{B^2}{2\mu_o} \right) V_s$$

where r_M is the radius of the magnetosphere, ρ is the mass density of the solar wind, V_s is its velocity, and B is the strength of the interplanetary magnetic field. Calculations made using various space and ground-based observations indicate that less than 1 percent of this energy, on the average, penetrates the geomagnetic field. Let us estimate U_c, the value of the corpuscular and magnetic energy flux that is pumped into the geomagnetic field. We will assume $U_c = 10^{-2} U_s$. For $r_M = 12 r_E$, $\rho = 8 \times 10^{-21} kg/m^3$, $V_s = 400$ km/s, and $B = 10$ nanotesla (that is, 10 gamma), we find that $U_c = 5 \times 10^{-2}$ TW, and the ratio $\frac{U_c}{U_{EM}} = 6 \times 10^{-7}$. Thus the available energy flux of the solar wind and interplanetary magnetic field is less than one millionth that of the solar-electromagnetic-energy flux absorbed by the earth.

One can improve this ratio quite a bit by choosing conditions when U_{EM} is small (for example, wintertime or nighttime) and when U_c is magnified by short but intense bursts of geomagnetic activity that draws on stored energy within the geomagnetic tail. Snow and cloud cover may cause the average albedo on the illuminated portion winter hemisphere to reach 0.9, and the winter polar cap is not illuminated at all. For the winter hemisphere, $U_{EM(min)}$ might drop to 6×10^3 TW. If we wish to raise the corpuscular energy flux to a maximum, we should consider the period during an intense magnetic storm when energy that had been stored in the geomagnetic tail by the solar wind is dissipated so that, in the order of 10^4 seconds; approximately 10^{18} joules of energy is fed into the magnetosphere in the form of aurora, ionospheric currents, ring currents, and particle energization. Thus, during a magnetic storm, U_c could increase to $U_{c(max)} = 10^2$ TW. This leaves us with

$$\frac{U_{c(max)}}{U_{EM(min)}} = 1.7 \times 10^{-2}$$

which might be just barely large enough to do some good.

These calculations indicate that, unless there is some energetic component in the solar wind of which we have no knowledge, we should look for ways to use the energy of the solar wind and interplanetary magnetic field as a trigger that subtly switches the lower atmosphere from one quasi-stable mode of operation into another. This is, in principle, feasible, since weather systems, once started, run largely on internal energy derived from heat of condensation and crystallization.

In a paper presented elsewhere in this meeting, Hines (1973a) has proposed a theoretical model that may well be the breakthrough we have been looking for. It is energetically feasible. (But, as we shall see later, the coupling is weak.) The idea is that magnetospheric convective motions, which are intensified during magnetic storms, change the vorticity of the lower atmosphere at or near auroral latitudes by viscous coupling. This theoretical suggestion is directed toward explaining the observations of such vorticity changes as reported by Roberts and Olson (1973a).

The change in vorticity is characterized by an increase in the angular velocity of the air at and above the 300-mb level following certain geomagnetic storms. The rate at which energy must be supplied to accomplish this change can be estimated as follows: Assume a disk of air above the 300-mb level with a radius $R = 500$ km whose angular velocity, ω, increases from 4×10^{-5} rad/s to 6×10^{-5}/s. (These parameters are typical of the observed vorticity changes (W. O. Roberts, private communication)). The moment of inertia, I, of the disk is $\pi R^4 \rho/2$ where ρ is the column density of air above the 300-mb level, $\rho = 3 \times 10^3 \text{kg/m}^2$. Substituting these values we obtain $I = 2.9 \times 10^{26}$ kg-m^2. The energy of the rotating system is $E = 1/2\ I\omega^2 = 5.3 \times 10^{17}$ Joules for $\omega = 6 \times 10^{-5}$ s. This is comparable to the energy of a magnetic storm. The power input required to increase ω from 4×10^{-5}/s to 6×10^{-5}/s in 24 hours is

$$U_r = \frac{dE}{dt} = I\omega \frac{d\omega}{dt} = 2.7 \text{ TW}$$

The increase in energy of rotation is 2.3×10^{17} J. This power value is to be compared with $U_{c(max)} = 10^2$ TW, derived earlier as dissipated within the magnetosphere during a magnetic storm. Thus there appears to be enough power within the magnetosphere to cause such changes in vorticity if the power can be directed and coupled effectively. We will now discuss problems with this and other processes.

SHIELDING

The troposphere is well shielded by the earth's magnetic field from particle bombardment by the magnetosphere (except in auroral and polar regions) and by the overlying atmosphere (even in auroral and polar regions). For example, at an altitude of 16 km (the top of the tropopause at low latitudes), the shielding is 100 g/cm^2. Electrons or protons would require energies greater than about 10^8 eV to penetrate this barrier. The flux of particles either in the solar wind or within the magnetosphere having such energies is negligible. Direct measurements of X-ray fluxes beneath auroral displays show that the flux of auroral X-ray that penetrate to 16 km altitude is seldom detectable above cosmic-ray background. Again, the atmospheric shielding, roughly equivalent to a lead shield 9 cm thick, effectively screens out any penetration. The shielding problem is actually more critical than discussed above since in auroral and polar latitudes, where we might expect more effective particle penetration, the top of the troposphere drops to an altitude of about 10 km. Here the atmospheric shielding is nearly 300 g/cm^2. Thus, if we wish to suggest direct particle interaction, or even the less efficient X-ray conversion interaction, we must propose that it is the stratosphere, extending up to about 50 km, (or perhaps it is even higher levels such as the ionosphere) that provides the link to meteorological phenomena.

It has been well established that auroral and geomagnetic activity cause marked increases in the temperature of the atmosphere above about 120 km altitude (for example, Newton et al., 1965; Jacchia et al., 1967). A significant portion of the heating is accomplished by direct particle bombardment in the auroral zone. An intense auroral beam has an energy flux of only about 1 W/m^2 or less than 1/1000 that of sunlight. The heat capacity of the upper atmosphere is so small that the effect of absorbing this energy flux is profound. However, the upper atmosphere is thermally isolated from the lower atmosphere by two temperature minima, one at an altitude of 80 km and the other at about 15 km. Some energy is converted to forms that can penetrate through these temperature minima to the troposphere, for example, infrared radiation and infrasonic noise. But with a power input of only 1/1000 that of sunlight, it is hard to imagine that the small fraction of this energy that would go into either componer would provide a sensible perturbation to the tropospheric system.

Finally, to return to the mechanism suggested by Hines in which ionospheric winds might set the lower atmosphere in motion, we find the coupling is too weak. There are two ways to calculate the drag that the upper atmosphere exerts on the lower. They give similar results, so only the simplest one will be shown as follows:

The convective motions in the magnetosphere encounter a drag motion in the ionosphere that produces ionospheric currents. These currents, which may reach an integrated value of $J = 10^6$ amps as an upper limit, exert a force $\overline{J} \times \overline{B}$ per meter of length on the neutral atmosphere. For the polar value of $B = 6 \times 10^{-5}$ T, $\overline{J} \times \overline{B} = 60$ N/m. If this force is integrated over the diameter of the disk of air that was discussed earlier and applied in the most favorable way to this disk, an angular acceleration of $d\omega/dt = 2JBR^2/I = 10^{-13}/s^2$ is the result. This acceleration is to be compared with the acceleration of $2 \times 10^{-10}/s$ that is necessary to make the process fit the phenomena reported by Roberts and Olson (1973a). While there is enough available energy, there is not enough coupling force to utilize this energy by a factor of about 10^3. C. Hines (private communication) has calculated the magnitude of this drag force by a different method and arrived at an answer in reasonable agreement with the one presented here. The more optimistic tone in his abstract reflects a more generous view of the seriousness of the discrepancy and slightly different assumptions.

CLIMATE THEORY

The two points discussed above have implications that are relevant to theories of climate. We wish to develop a theory in which some particle effect in the stratosphere (or perhaps even higher?) somehow couples to the troposphere to cause a significant change. It is here that we appear stuck for the time being. Present theories of climate are quite primitive. For example, there is no accepted theory for the ice age, which, geologically speaking, occurred only yesterday. Nor is there an accepted theory for the quasi-stable states of the troposphere, with the required trigger mechanism, that was alluded to earlier. This would seem to me to present a formidable handicap to anyone who wished to propose a detailed solar activity/meteorological coupling mechanism. It would seem that, at a minimum, it would be necessary to be able to forecast weather one or two weeks in advance with reasonable reliability. Then changes triggered by solar activity could be detected by matching the "bad" forecasts against unusual solar activity. The next step would be to postulate something about the trigger mechanism and the nature of the bistable states of the troposphere and devise experimental tests of the hypotheses.

But I have gone too far. We do not know if there is, or even if we need, a bistable atmosphere of the type described. The point is, we know so little about these aspects of the meteorological system that we find it hard to ask good questions. Asking good questions is essential to the development of a reasonable theory. This last point can be illustrated by pointing to the aurora, a phenomenon which, in recent times, has had no shortage of theories because the phenomenon is reasonably well defined in an input/output sense. The task of the auroral theorist is to explain something of what is going on in a well-defined black box. Solar activity as related to meteorology has not reached this stage of definition yet.

CORRELATIONS WITH GEOMAGNETIC ACTIVITY

Figure 1 shows that solar activity (as indicated by sunspot number) and geomagnetic activity are correlated. The search for a similar correlation between sunspot number and the weather has been carried on up to the present time. The principal problem encountered was that there is apparently no consistent 11-year cycle in the weather. Reports of either no sunspot correlation or a 22-year cycle have tended to confuse the issue. That is, rainfall, winds, and temperatures vary from year to year, sometimes showing persistent behavior (as in an ice age or a long drought) but these parameters do not consistently exhibit an 11-year cyclic pattern. There is presently a claim that three rings show an 11-year pattern. If this is true, the 11-year, rather than a 22-year, pattern would be established, Trees respond principally to springtime rain, temperature, and sunshine. (See Fritts (1971) and Fritts et al. (1971) for a review of the uses of tree rings in climate research.)

Recently Shapiro (1972) and Wilcox et al. (1973) have presented results showing a correlation between geomagnetic storms and winds and pressure troughs. These papers are reviewed by Roberts and Olson (1973b).

There is perhaps a clue to a possible mechanism arising from this work. If there is no 11-year cycle in the meteorological phenomena they are testing against, perhaps there is a special type of geomagnetic storm that should be sought that also does not have an 11-year cycle. For example, recurrent geomagnetic storms do have a much smaller variation over the sunspot cycle than do the great storms. According to Newton and Milsom (1954), the frequency of recurrent storms varies by a factor of 2.5 over the solar cycle while the large storms vary by a factor of 7.3. If meteorological variables could be correlated against only recurrent geomagnetic storms, we could see if the basically different nature of these storms was important to meteorological phenomena.

The existence of an unvarying base frequency of a special type of geomagnetic activity might explain why Shapiro (1972) found an improved correlation when he eliminated the years of sunspot maximum from his data — if there is no 11-year variation in his meteorological data, elimination of the geomagnetic data from sunspot maximum would tend to eliminate the 11-year cycle in geomagnetic activity. This point has been taken up by Hines (1973b) who points out that the remaining correlation may actually be caused by the meteorological phenomena sending energy to the ionosphere (Bauer, 1958) by means of gravity waves (Georges, 1973). These waves will cause currents to flow in the ionosphere, which can be detected as geomagnetic activity (Hines, 1965). Thus Hines suggests that cause and effect are reversed. (See also Shaprio, 1973.)

The approach of Wilcox et al. (1973) is different in that they have chosen the sector boundary structure of the interplanetary magnetic field to correlate with a vorticity index derived by Roberts and Olson (1973a) for pressure troughs in the northern hemisphere. The number of sector boundary crossings per year should show an 11-year cycle. Does the vorticity index show a similar 11-year variation? If not, it would be important to learn which sector boundaries at sunspot maximum were not effective in causing a change in vorticity index. The answer to this question might lead to an understanding of what is essential and what is not in order for the interplanetary medium to affect the troposphere.

CONCLUSION

As Roberts and Olson (1973b) have pointed out, "it has now become a matter of high scientific priority to develop and test working hypotheses for the empirically established (solar-activity/meteorological) relationships." But nothing viable seems to be forthcoming from the theorists. This lack of theoretical development may be caused by our lack of understanding of how the weather really works on time scales of a week to ten days. On the other hand, we may be in much the same predicament as the unfortunate Lord Kelvin who was completely unaware of the existence of dominant physical processes (such as the solar wind, which could transport energy from the sun to the geomagnetic field). Perhaps the developments of the next few years in determining why there is no pronounced 11-year cycle in meteorological phenomena while there is one in geomagnetic phenomena will provide the clue we need to establish some hypotheses that can be tested.

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF
A. J. DESSLER

MR. DELAND: Ray Deland, Polytechnic Institute of New York. I would like to defend the statistical approach a little bit, because this is my own approach. Certainly if you correlate A and B, you find A is correlated with B, as so many of these studies have shown. One doesn't know whether A is causing B in the sense of fluctuations in A propagating some energy that is transferred to B or vice versa. Neither do you know whether something else is causing both A and B.

One approach applies, I think, in this situation — based only on the hypothesis that if you have a transfer of energy from A to B there is usually some sort of signal velocity involved, and there is a time delay of the effect on B compared to A — is lag correlation studies.

That is, correlate A delayed by plus or minus a few days with B. My own experience with this, unfortunately, is that, when one does that, one finds the best correlation usually when you take zero lag which makes it very difficult.

Again, gradually building up some experience that most things go up rather than come down in terms of the correlations between weather changes and what is upstairs, you get the better correlations with a delay of what happens upstairs compared to what happens downstairs.

MR. LONDON: Now, I have a follow-up to that, and that is, in the magnetosphere observations, is there any way that we can recognize one cycle from another except for polarity, supposing you were given a long trend and asked to identify them?

MR. DESSLER: That's a good point, because in geomagnetic activity, auroral activity, and things like that, there is no trace of the 22-year cycle that I am aware of. Solar wind interaction with the geomagnetic field is beginning to be understood, and there in no way do appearances depend on the spot wave.

So that is something we haven't thought of yet, and this recalls again what happened to Lord Kelvin. In each case, the mistake he made was based on insisting that he knew everything. But there were things he didn't know about, like the atom is not indestructible, and there were other things along that line that he didn't know about, and he was wrong on the age of the earth. He didn't know about radioactivity, and he didn't know about solar winds and made a mistake on the correlation.

So there is something in the solar wind, the component of the solar wind we don't know about, that somehow depends on the polarity of the sunspots going wild like that. Then maybe it will do something to the weather, but it sure doesn't do anything markedly significant that is observable and detectable and noticeable, either in the aurora or geomagnetic storms. They have an 11-year cycle, not a 22-year cycle.

QUESTION: Can you describe in a few words what actually happens when the boundary sector passes the earth, physics-wise?

MR. DESSLER: I will give you the party line, and the evidence for it is reasonable enough but a lot of it is circumstantial: there is a connection between the interplanetary magnetic field and geomagnetic field, which draws a lot of magnetic field into the tail. And magnetic pressure builds up in the tail. The plasma sheet which has separated the two halves of oppositely-directed field in the tail disappears, and all of a sudden you get a lot of magnetic field being annihilated.

Net energy from annihilating the magnetic field drives the remaining plasma sheet into the geomagnetic field where it causes the auroral ring current. The plasma moves in so far before it creates the ring current, and it energizes the particles by betatron acceleration, so then they can precipitate as the aurora. And so it is a pretty straightforward chain. A lot of details need to be explained.

MR. HUNDHAUSEN: This question is really addressed to two members of the audience. I think it is appropriate at the moment. The persistent change in the sector pattern has been inferred for several solar cycles from ground-based measurements.

However, is it now true that this pattern develops in the same way in all cycles? In other words, there is not a change in interplanetary polarity pattern with the major and minor solar cycles, so if we emphasize the use of solar sectors in studying these effects we seem to be limiting ourselves, therefore, to the 11-year and not the 22-year cyclic phenomenon.

MR. ROSNER: You are quite correct. There is no 22-year variation in the sector.

MR. PARKER: How is it known, insofar as the polarity is concerned, though?

MR. ROSNER: Well, we can determine what the polarity is since on any given day by looking at geomagnetic polar disturbances, and so we know what the polarity is. There is no 22-year cycle.

MR. DESSLER: Again, I don't believe the sector structure's peak will occur coincident with the solar cycle's peak. I think there will be a four-year displacement, because they are the source of recurrent storms, and recurrent storms peak four years later.

MR. NORDBERG: Let me try another elementary freshman-class magnetosphere question. What is the cycle of the sector boundary sweep across here? I assume there are about four sectors, and so it's four divided into twenty-seven?

MR. DESSLER: Either two or four, yes, and it would be two into twenty-seven or four into twenty-seven. Now, at times it gets more complex when the solar structure gets complex and you have — well, I should answer that "yes," I guess, but stop me if I am wrong. But during some intermediate stages, as new sectors are being created, you may not have such a simple division, but generally, that is right, either two or four divided into twenty-seven.

MR. NORDBERG: In that case, since you raised the question of what to look for in 22 years, 11 years, 3 days, or what not, I have a wild idea here. If it turns out four into twenty-seven, then it just falls right that you have about six- or seven-day passages of the sector boundaries. That is very closely coincident with the life-cycle of planetary waves, or the generation cycle of planetary waves. How about some kind of a resonance mechanism here?

Whenever a sector boundary happens to sweep when conditions are ripe for cyclogenesis, that one old wave has just died and you generate a new one, that could match that vorticity correlation with the sector boundary sweep. And it is understandable that sometimes and in some places it works exceedingly well, and in other places it doesn't work where you have a mismatch.

MR. DESSLER: So I guess you could take the time when there are only two sector boundaries and see whether every other vortex that was generated was weaker or later or somehow showed the effects and noneffects of the vortex.

QUESTION: Considerations of both energy and momentum you have shown as weakly-coupled to the atmosphere, and one has to consider them as triggering mechanisms.

MR. DESSLER: Well, there are other things that could serve as triggering mechanisms, for example, like volcanic eruption.

QUESTION: I was wondering, could you give for comparison the energy involved in volcanic eruption — what is the correlation between, say, volcanic eruptions and weather phenomena?

MR. DESSLER: I am afraid I don't know offhand. The volcanoes are very, very energetic, and at the time I knew it I was impressed at how powerful they were. But I showed you a slide that showed what I thought was not a bad correlation between frequency of volcanic outbreak and sunspot number. You didn't like that?

MR. HEPPNER: I think you may have confused our nonmagnetospheric-physicist types here when you related sector structure to rate of reconnection. Sector structure is the east-west component, reconnection is usually attributed to the north-south component. I don't know of any theories that relate sector structure to rate of reconnection. I think you called that the party line.

MR. DESSLER: Yes, that's why I said that, because geomagnetic activity rises at the sector boundary crossing. And, as you said, it is a north-south component that explains the rate of reconnection and geomagnetic activity. So I was going through a real weak point there, which is true. As you know, I am not very sympathetic with the party line, but I feel obliged to follow it at the present time.

MR. ROBERTS: This is on your comments about, for example, trying to distinguish between an 11-year cycle and a 22-year cycle in the vorticity index, particularly if it is integrated up over the northern hemisphere, as we did in sector boundary studies. This probably isn't going to be a terribly fruitful way to go.

First of all, it is going to take a long time to get enough data on the vorticity index to be able to do something that will satisfy Lord Kelvin. And moreover, we have a tremendous wealth of variation of much shorter term between various types of magnetic disturbance and sector boundaries and vorticity in particular areas, and so on. But it does seem to me that the emphasis on the difference between the 11- and 22-year cycles might be a fruitful thing to look at in terms of some kind — as Bill Nordberg suggested — of resonance in the terrestrial system. Because it is perfectly possible, for example, that due to time constants and ocean temperature changes or something like that, a 22-year cycle could be driven by an 11-year forcing function.

QUESTION: You brought in one pseudo-correlation with no explanation, that is, solar relation to volcanic activity. But you ignored one suggestion which has been made a number of times, namely, that the cosmic-ray change, which is really due to solar activity, could in turn change the magnetic field, and this could relate to weather.

Remember that the ionization change due to the cosmic-ray change is something like an order of magnitude. As you go up in the atmosphere it's around the tropopause, or around 20 kilometers. So this is a good relationship and I would like to hear your comment.

MR. DESSLER: Well, I did pass over very quickly the cosmic-ray variations in the soft component around a few BeV. And it comes into the polar cap where it's ionization peak is at about 22 kilometers altitude. The tropopause in the polar cap is at 10 kilometers, and at this altitude there is just no change. There is almost nothing reaching there now.

If you've got an effect where you can use production of ions or maybe some gas chemistry ten kilometers above the tropopause, then that would be great. But, unfortunately if the cosmic-rays come in at the equator where the tropopause is higher, amplified through maximum, then you would be in business. But I see the shielding layer above the polar cap tropopause, and I don't see any good way to get around it.

MR. PARKER: Well, at middle latitudes we are talking about 10-percent variations in the cosmic-ray intensity. The other thing you might suggest, along this same line, is that there are occasionally enormous proton flares, which every few years at least produce rather enormous amounts of energy, of ionization, sometimes down to at least middle latitudes if not low latitudes. But again, there is the same question as to elevations at which you produce the ionization.

MR. DESSLER: Now, those unusual events will just do everything, but they are once every five years. They are a funny kind of flare that, in my opinion, show no relationship to the solar cycle. They just appear once every three, four, five, six years. There is some evidence that they avoid solar maximum and minimum, but it is not that clear, there have been so few of them. You can't have a weather effect of the kind that has been talked about in the meeting that relies on a rare event like that.

MR. WOODBRIDGE: You mentioned that in the sector structure that we have four or two sectors, except at times when we have changes. Has anybody looked at what is occurring at these times? If geomagnetic storms are associated with the sector boundaries, then when these changes are occurring — it seems like everyone has passed over this point — may be the most important times.

Are they associated with the 11-year cycle? How often do they occur? How violent are they? Or are they associated with the 20-year cycle?

MR. DESSLER: I think that clearly these changes are associated with an 11-year cycle.

MR. WILCOX: In the first approximation, one has two or four sectors all the time coming around very clearly. Now, having said that, we can say that during the time observed by spacecraft in part of 1965, this pattern was not quite as clear. It was somewhat more broken up. But I think, in terms of trying to understand the weather, we shouldn't worry about those few months but should consider the ten years in which just very regularly the boundaries sweep past the earth.

VOICE: Why?

MR. WILCOX: Based on the work of Lief Svalgaard, it seems that around sunspot maximum there may be a tendency to have two boundaries per rotation for a few years. And the rest of the time, particularly, say, going into minimum, it is four. As to why, we don't know.

MR. HUNDHAUSEN: In fact, as you all know from my talk yesterday, I am no foe of simplification to try to understand some basic physical phenomena. But I think we have to be very careful here and not talk about interplanetary space as though such a structure were the only thing present. Now in fact, during this period in early 1965 when the sector structure seemed to appear, and at least for one month, there were no sector crossings, there were still geomagnetic disturbances. And in that case, as I showed at the Chapman Symposium in June, there were high-speed solar windstreams, and the geometric changes were pretty well correlated with the stream structure that remained even when there were no sector boundaries.

During the period of the solar cycle, when there may be two sectors, there are often two streams per sector, and in most cases there still were back in the Mariner-2 data geomagnetic peaks when the different streams came by, even within a sector. So the sector structure has proven very useful in many ways, both in relating interplanetary phenomena to the sun, and in doing superimposed epoch analyses with the terrestrial pheonmena. But let's not regard all of interplanetary space as organized purely by the sector structure. There are other obvious influences on geomagnetic activity, and one should not ignore the fact that there may well be other important physical driving mechanisms for the rest of the atmosphere.

MR. DESSLER: Well, that's why I wanted to see what happens with the non-sector boundary, to remove the sector boundary storms, because most of the storms are not sector boundary storms. I want to repeat the total of the storms from max to min, varied by a factor of 7.5 in number of currents per month.

Whereas the sector boundary storms, which would be presumably the recurrent storms, vary by a factor of about 2.5 from sunspot maximum to minimum. So, most of the storms are not sector boundary storms.

MR. DELAND: The sector boundaries, in fact, seem to be fairly periodic. Bill Nordberg suggested that I say something about a 7-day periodicity in planetary waves. However, if you look at them carefully, you find there is a whole spectrum of frequencies, just as there is a whole spectrum of wavelengths. I want to really emphasize that anything involving the planetary waves is very far from periodic. This is partly because people have jumped to that conclusion at times. And in looking for resonances, we had better be very careful.

MR. LONDON: Since we are talking about mechanisms, and there has been no discussion of one particular mechanism so far, but the question of cosmic rays has come up, I thought it would be important here to mention an idea that is being developed now by Max Ruderman and Joe Chamberlain, on a solar-weather relationship, and the mechanism by which this could be caused. This has to do with cosmic rays being modulated in a solar cycle period, coming down to a meteorologically important level, that is, down to about 20 to 30 kilometers, and there spreading nitrogen so that one can reform nitric oxide. We now know that nitric oxide can be deleterious to ozone concentrations.

At 20 to 30 kilometers, the ozone concentration has its maximum. It also has its maximum in high polar latitudes. If cosmic rays, therefore, in an indirect but understandable way, can affect the ozone concentration at, let's say, 25 kilometers, this can affect the radiation budget at that level. The difficulty is to find out whether there is sufficient energy in the cosmic rays to produce enough NO, which will produce enough destruction of ozone. Here is something that can be tested by numerical models very easily.

Let me say just one other thing, and that is there is, however, a counter-mechanism that has been suggested, also invoking cosmic rays. And that is if there is ionization of O_2 at these levels, then there can be dissociative recombination. And in that case one can produce atomic oxygen. As everybody knows, it's atomic oxygen that then forms ozone.

Se we have two counter-processes. Now, that doesn't seem so silly, because one can put both of these into a numerical scheme, knowing what the relaxation times or kinetic rates are for these, and actually get some kind of solution, at least in situ. So I think that this is a mechanism that one has to consider in terms of cosmic-ray modulation.

MR. DESSLER: This would be very slow. It wouldn't be a geomagnetic storm effect.

MR. DELAND: Goodwin and Chamberlain used this mechanism for a so-called, or presumed, solar cycle variation in ozone. We are not sure that there is one, but if there were to be one, then they have this mechanism to account for the 11-year period.

MR. MARKSON: I would like to discuss Kellogg's and London's suggestion about the importance of cosmic rays, because I agree that you have to look for something that gets down to meteorological altitude. And the ion production maximum is at 16 kilometers. I think some numbers that would answer an earlier question about looking into this are that at 10 kilometers the variation from solar minimum to solar maximum, between 1954 and 1958, was 30 percent. At 15 kilometers it was 50 percent. Now, what I would like to have meteorologists consider is whether, assuming thunderstorms are modulated in the way I suggested yesterday, the energy released by thunderstorms contributes to synoptic scale meteorological variation.

MR. R. JOHNSON: Concerning London's suggestions about Chamberlain's work on the chemistry being involved, I would just like to comment that the ionization produced by the bremsstrahlung from energetic electrons also comes down to altitudes of, say, the order of 30 kilometers. That is a significant fraction of the cosmic-ray ionization rate. Therefore, one could tie this in to the magnetic storm effect.

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NUMERICAL EXPERIMENTS ON SHORT-TERM METEOROLOGICAL EFFECTS OF SOLAR VARIABILITY

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ABSTRACT

A set of numerical experiments has been carried out to test the short-range sensitivity of a large atmospheric general circulation model to changes in solar constant and ozone amount. On the basis of the results of 12-day integrations with very large variations in these parameters, it is concluded that realistic variations would produce insignificant meteorological effects. Thus any causal relationships between solar variability and weather, for time scales of two weeks or less, will have to rely upon changes in parameters other than solar constant or ozone amounts, or upon mechanisms not yet incorporated in the model.

INTRODUCTION

The study of possible physical mechanisms by which solar variability might influence weather (on time scales of a few days or weeks) is difficult both because the effects are apparently weak and because the causes are probably complicated. Recent examples of the types of effects for which explanations are sought include statistical relationships between atmospheric vorticity indices and either geomagnetic storms (Roberts and Olson, 1973) or the solar magnetic sector structure (Wilcox et al., 1973). Because the energetic variations associated with solar variability are percentage-wise small, and because the more direct effects are likely to occur in the high atmosphere, it has long been recognized that any causal chain of physical mechanisms is likely to involve trigger effects or coupling processes (London, 1956; Monin, 1972).

In the present work we have investigated two possible influences on weather by numerical experiments with a large atmospheric general circulation model. In terms of physical completeness, overall realism, and sheer computational complexity, such models represent current state-of-the-art capability for large-scale weather forecasting and climate simulation. However, they do not include many proposed possible physical mechanisms connecting solar variability and weather. It seems worthwhile, nevertheless, to explore the sensitivity of such a model to those influences which it does attempt to take into account. We have therefore tested the response of our model to changes in atmospheric ozone content and to changes in the solar constant.

THE MODEL AND ITS LIMITATIONS

The model used in this study is a nine-level primitive equation general circulation model with a horizontal finite-difference grid spacing of 4° in latitude and 5° in longitude (see Somerville et al., 1974, for a detailed description). The domain is global, and a realistic distribution of continents, oceans, orography, and snow and ice cover is included. The model contains detailed computations of the heat balance at the surface and of the hydrologic cycle in the atmosphere, and its calculations of energy transfer by solar and terrestrial radiation make use of model-generated fields of cloud and water vapor. The solar radiation parameterization (Lacis and Hansen, 1974) includes ozone absorption, the diurnal variation of solar zenith angle, and the diurnal and seasonal variation of solar flux. The model's ozone amount and vertical distribution are based on results summarized by Manabe and Möller (1961) and vary latitudinally and seasonally.

This model has produced a realistic simulation of tropospheric January climatology (Somerville et al., 1974) and has demonstrated two-day forecasting skill equal to that of current operational numerical weather prediction models (Druyan, 1974). The model is thus appropriate for the time scales (up to about two weeks) involved in the present work.

The model is limited, for the purpose of this study, primarily by a vertical resolution of about 110 mb, by a top at 10 mb, and by the omission of any coupling with the very high atmosphere. Additionally, a climatological distribution of sea surface temperature is prescribed. The model is therefore unsuitable for investigating processes involving changes in sea surface temperature, but such changes occur typically on time scales which are long compared to those which characterize the statistical relationships cited above between solar or geomagnetic variables and meteorological ones.

EXPERIMENTAL PROCEDURE

In view of the above capabilities and limitations of the model, we have employed the following procedure to determine the sensitivity of the model atmospheric evolution to changes in solar constant and ozone amount: We first perform a control run by integrating the model from a particular initial condition, specified by meteorological observations at 0000 GMT, December 20, 1972, as supplied by the National Meteorological Center. We integrate the model for 12 days. Next, we carry out a second integration to measure the natural variability of the model atmosphere. This integration differs from the control run only in that the initial state is created by modifying that of the control run by random perturbations with RMS amplitudes of 1 K in temperature and 3 m/s in wind at all grid points, and 3 mb in pressure at all surface grid points. Because such pairs of integrations can be used to estimate the effect of observational uncertainty on atmospheric predictability, we denote this second integration as the predictability run.

Since we anticipate that realistic changes in solar constant and ozone amount would cause effects too weak to be detected except by a Monte Carlo procedure involving many model integrations (Leith, 1973), we artificially increase the signal-to-noise ratio by performing several integrations with unrealistically large changes in solar constant and ozone amount. Such sensitivity studies can establish upper bounds on the magnitude of the effects. If the very large input changes produce large effects, subsequent integrations can be carried out with smaller input changes; while if only small or negligible effects are produced by large input changes, we may conclude that much smaller input changes would have even smaller effects.

Accordingly, we carry out four more integrations which differ from the control run only in the value of solar constant or ozone amount. The values of solar constant employed are 2/3 and 3/2 the normal value, and the values of ozone amount are zero and twice the normal value. The specifications of the six integrations are given in Table 1.

RESULTS OF OZONE EXPERIMENTS

Figures 1 to 3 show maps of 500-mb geopotential height in a region surrounding North America at 11.5 days after the start of the integrations. The upper maps shown in each case are for the various perturbation experiments (PREDIC, OZ = 0, and OZ = 2), while the lower map is for the control experiment (OZ = 1) and is the same in each of the figures. It is clear that the map least resembling the control run is that of the predictability run. The ozone changes apparently produce no effect above the noise level of natural variability of the model, as measured by the difference between control and predictability runs.

Table 1
Specifications of Integrations

Name of Run	Initial State	Normalized Solar Constant	Normalized Ozone Amount
Control (also called S=1 or OZ=1	Standard (0000Z December 20, 1972)	1	1
Predictability (PREDIC)	Perturbed (see text)	1	1
OZ = 0	Standard	1	0
OZ = 2	Standard	1	2
S = 2/3	Standard	2/3	1
S = 3/2	Standard	3/2	1

Figures 4 to 7 show the time evolution of the global integrals of the four basic forms of atmospheric energy, for the same four integrations. Again, the ozone changes give no significant effect.

Table 2 compares the time evolution, for the four integrations, of global atmospheric temperature, mean temperature in the highest model layer, mean temperature in the lowest model layer, and global cloud cover. Only in the highest layer (centered at about 65 mb) do the ozone changes have a significant effect.

RESULTS OF SOLAR CONSTANT EXPERIMENTS

Figures 8 to 10 are the 500-mb maps for the three experiments (PREDIC, S = 2/3, S = 3/2) compared with the control run (S = 1) in a format similar to that of Figures 1 to 3, but at 8 days after the start of the integrations. The effect of the solar constant changes appears insignificant, although significant changes do occur after 8 days.

Figures 11 to 14 display the time evolution of the four energy integrals for the four cases. These do show an effect, principally in zonal available potential energy (Figure 11), essentially a measure of the pole-equator temperature

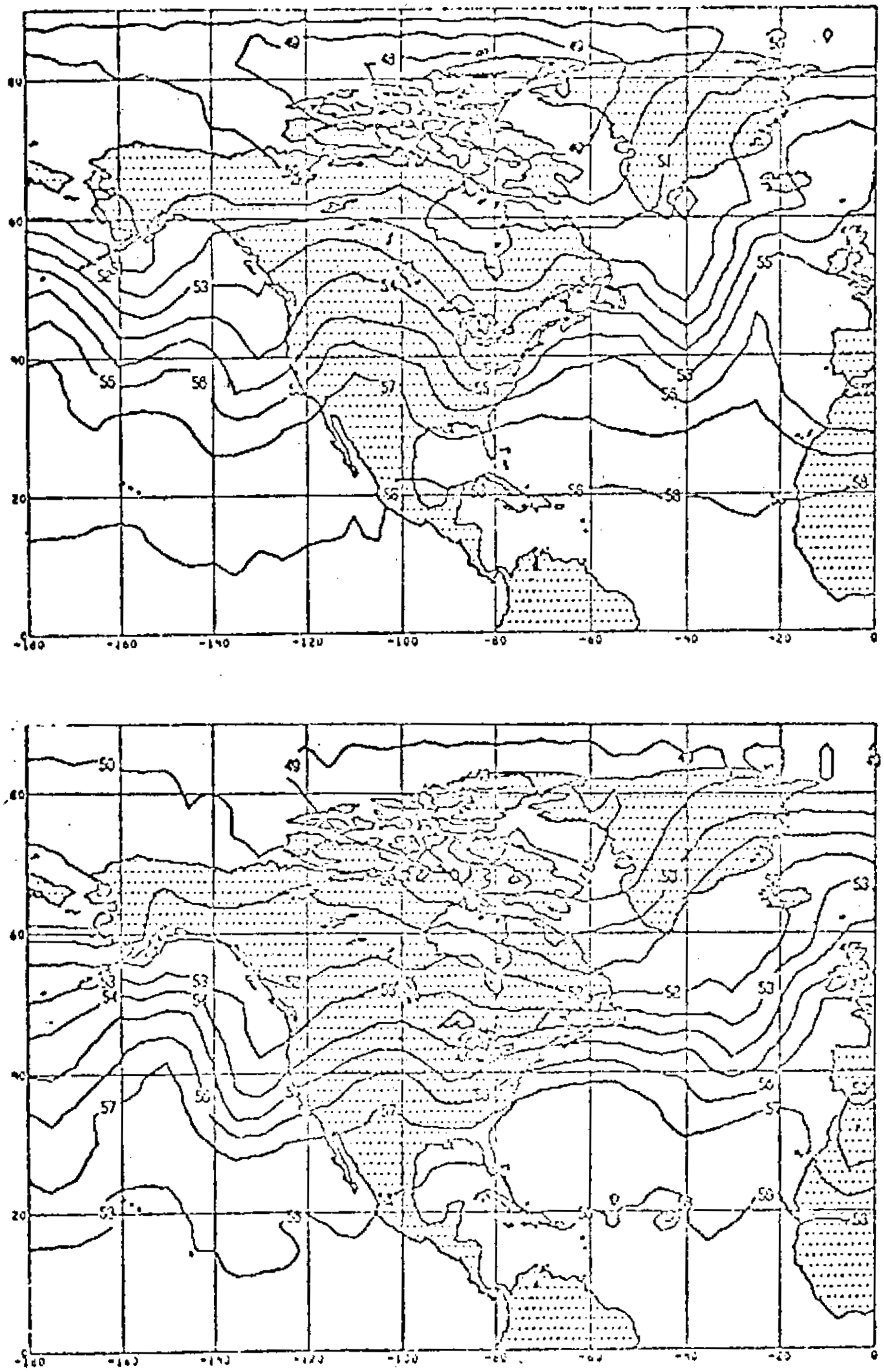

Figure 1. 500-mb maps at 11.5 days. Upper: PREDIC; lower: Control (OZ=1).

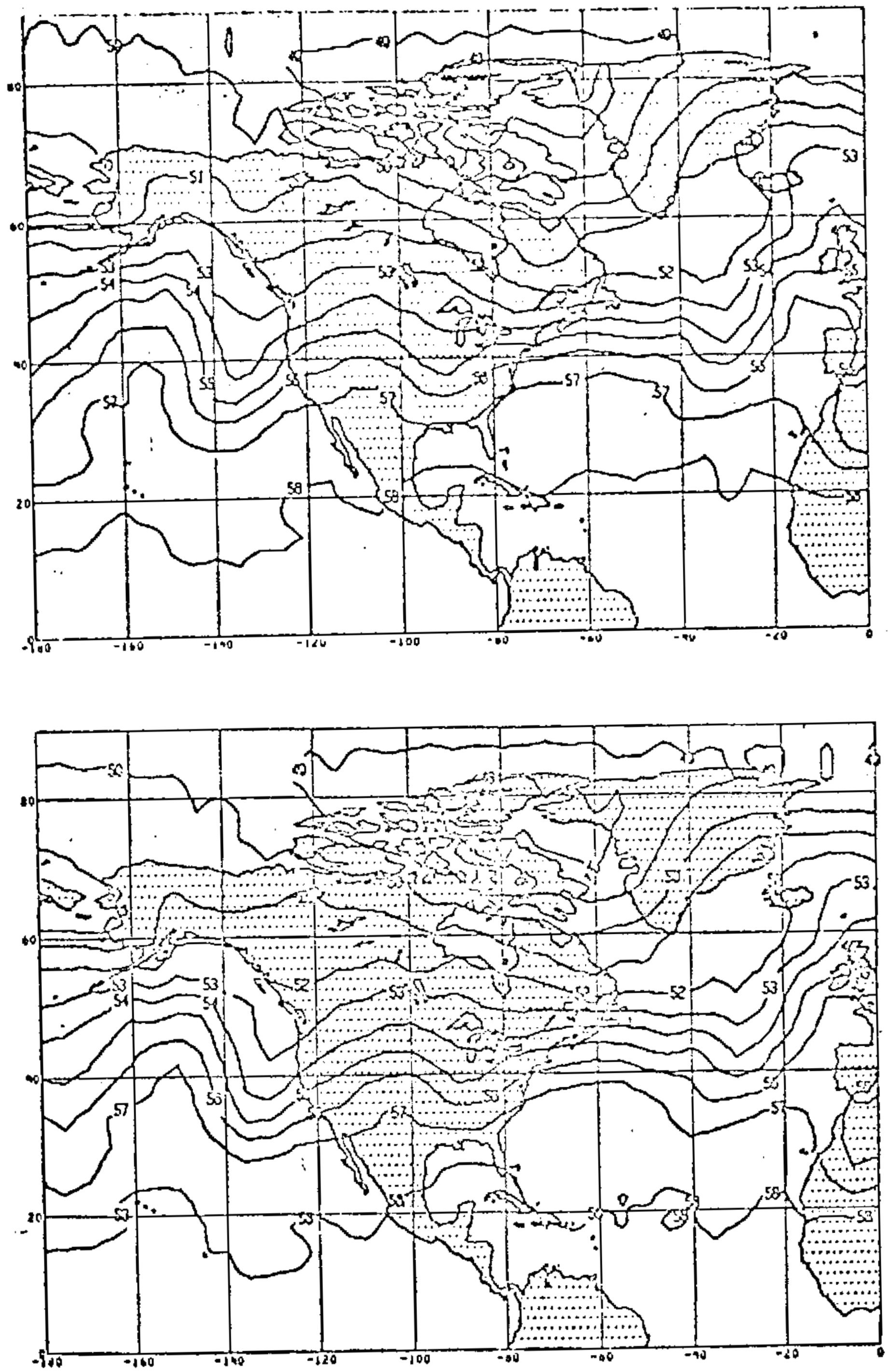

Figure 2. 500-mb maps at 11.5 days. Upper: OZ=0; lower: OZ=1.

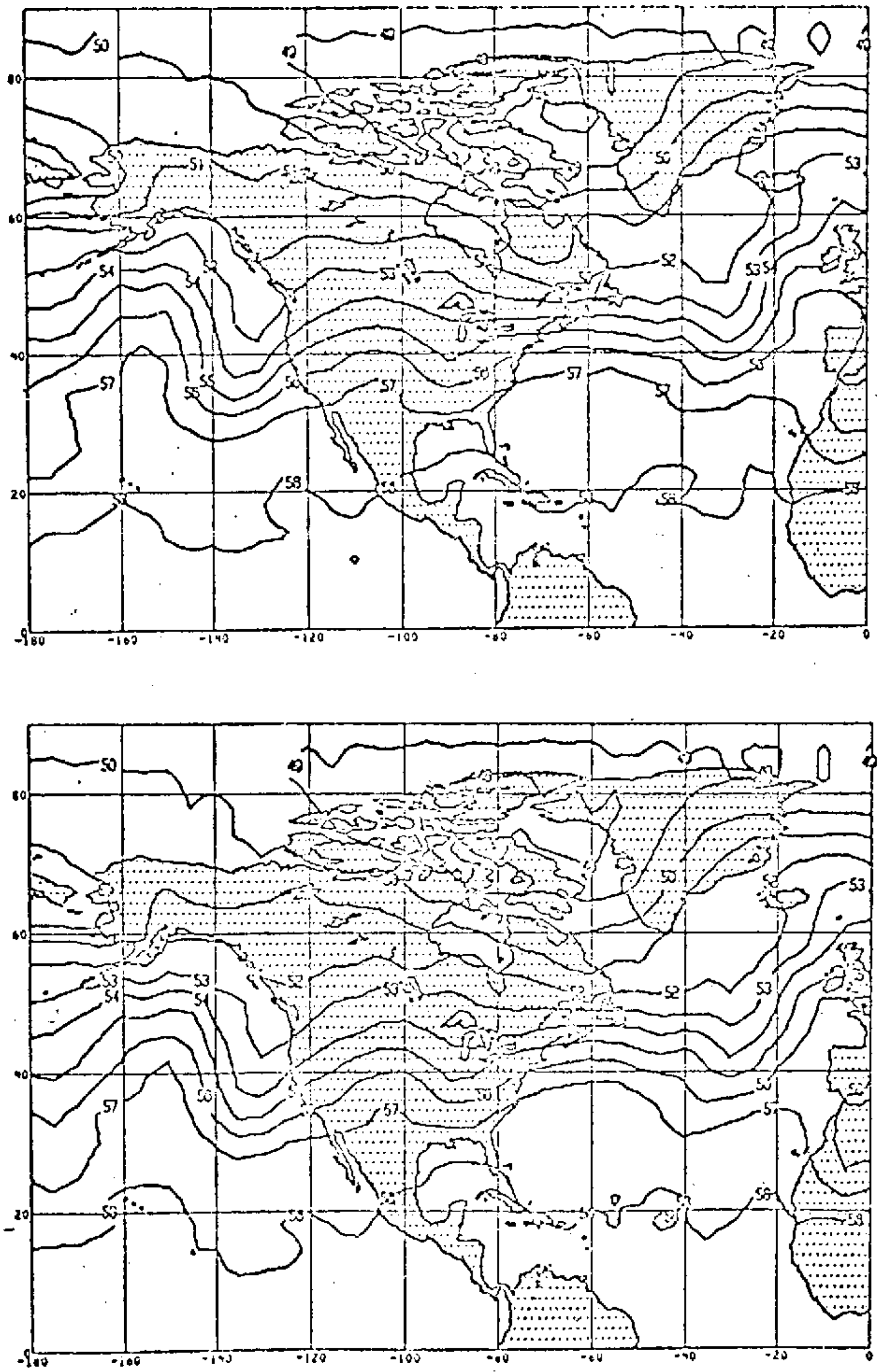

Figure 3. 500-mb maps at 11.5 days. Upper: OZ=2; lower: OZ=1.

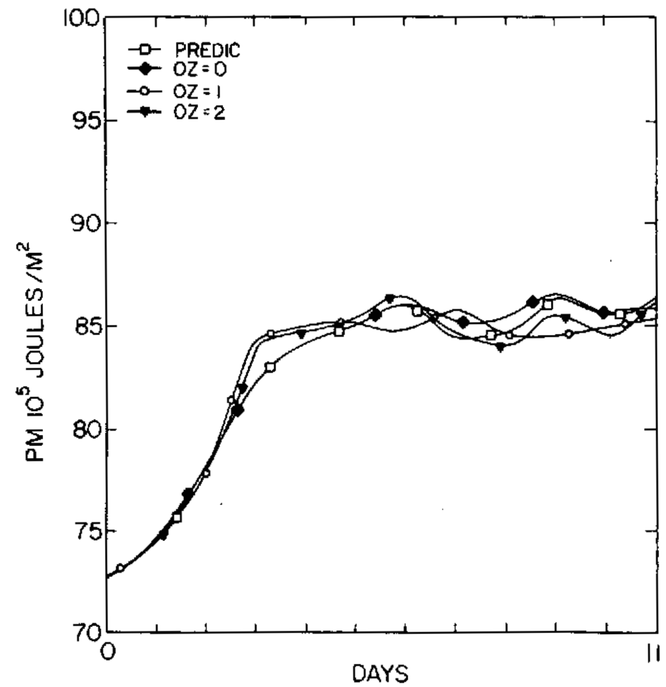

Figure 4. Time evolution of globally-integrated zonal available potential energy (PM) for the ozone experiments.

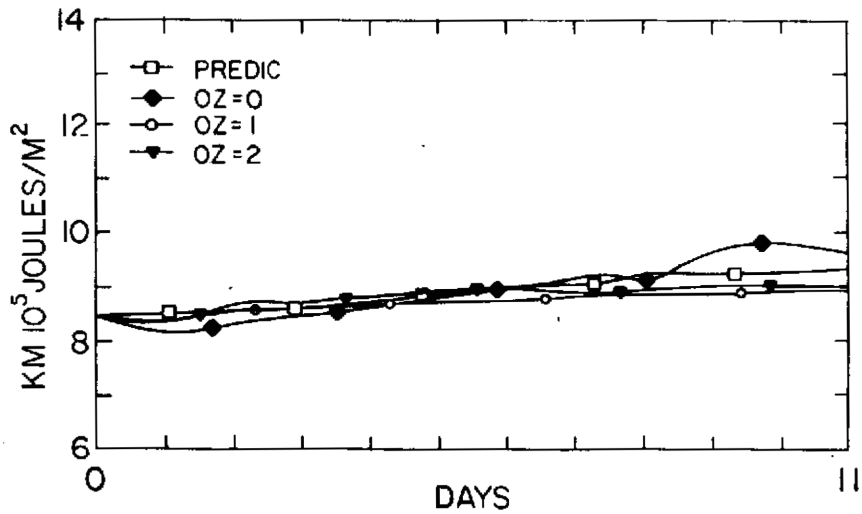

Figure 5. Time evolution of globally-integrated zonal kinetic energy (KM) for the ozone experiments.

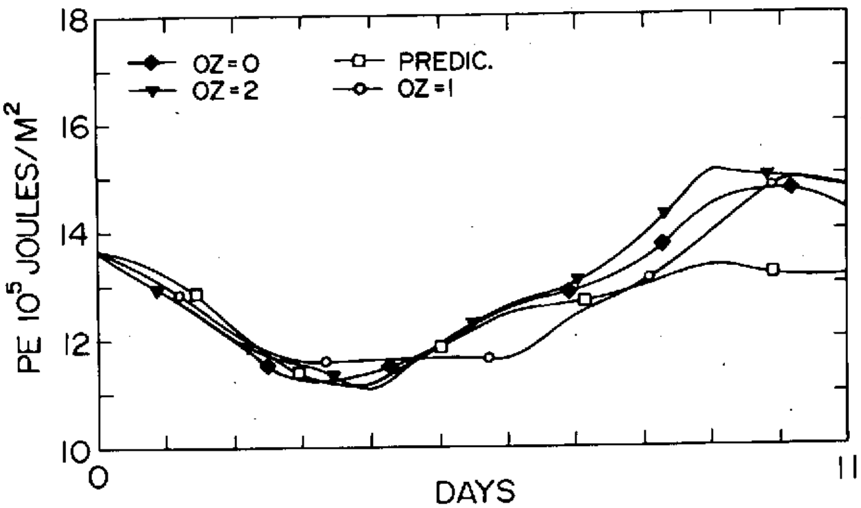

Figure 6. Time evolution of globally-integrated eddy available potential energy (PE) for the ozone experiments.

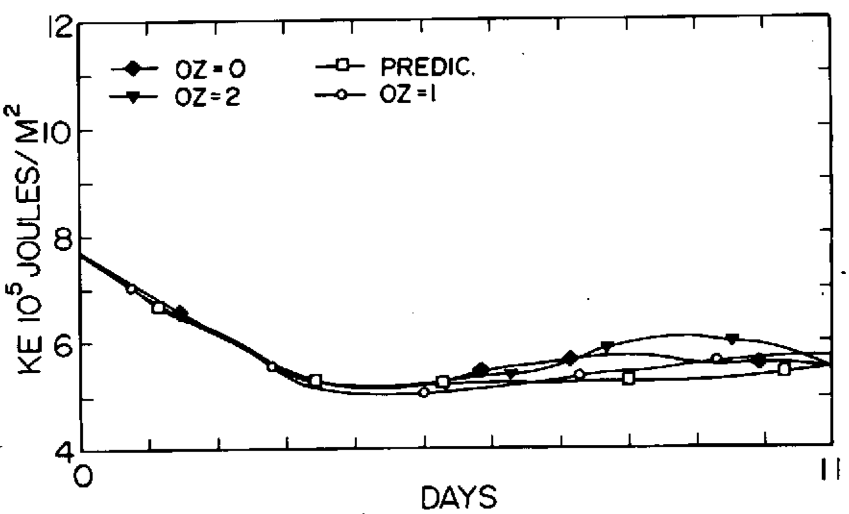

Figure 7. Time evolution of globally-integrated eddy kinetic energy (KE) for the ozone experiments.

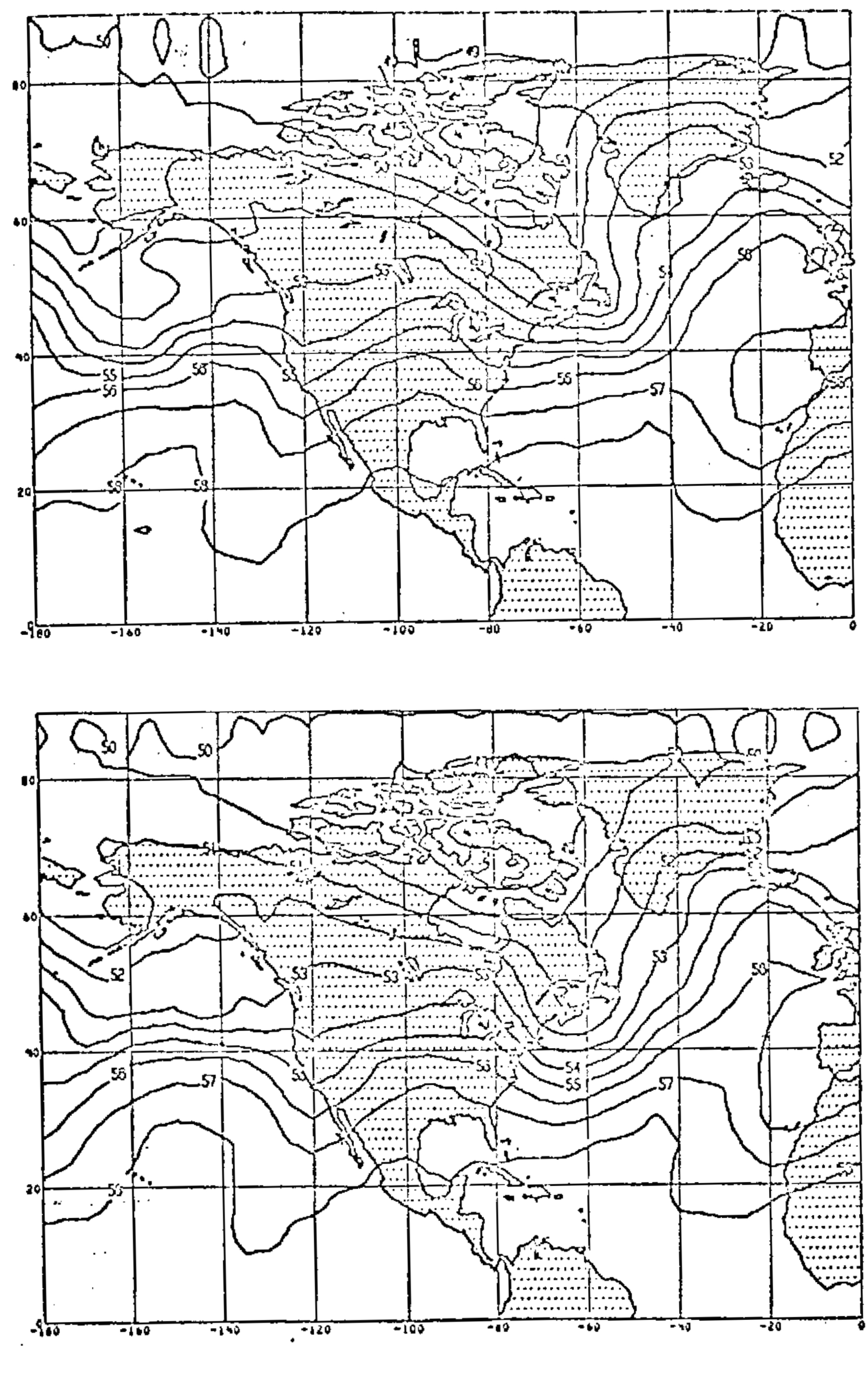

Figure 8. 500-mb maps at 8 days. Upper: PREDIC; lower: control (S=1).

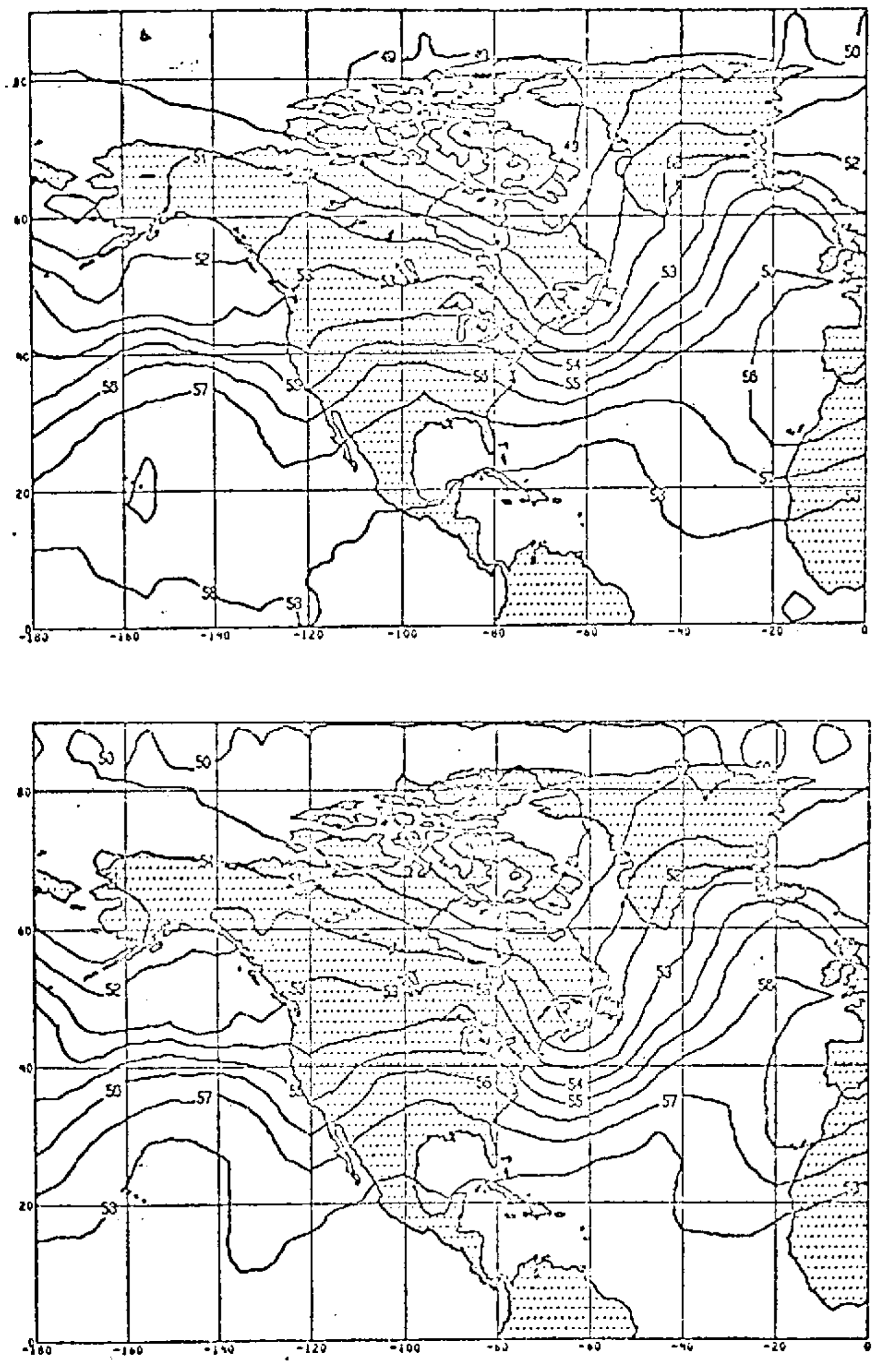

Figure 9. 500-mb maps at 8 days. Upper: S=2/3; lower: S=1.

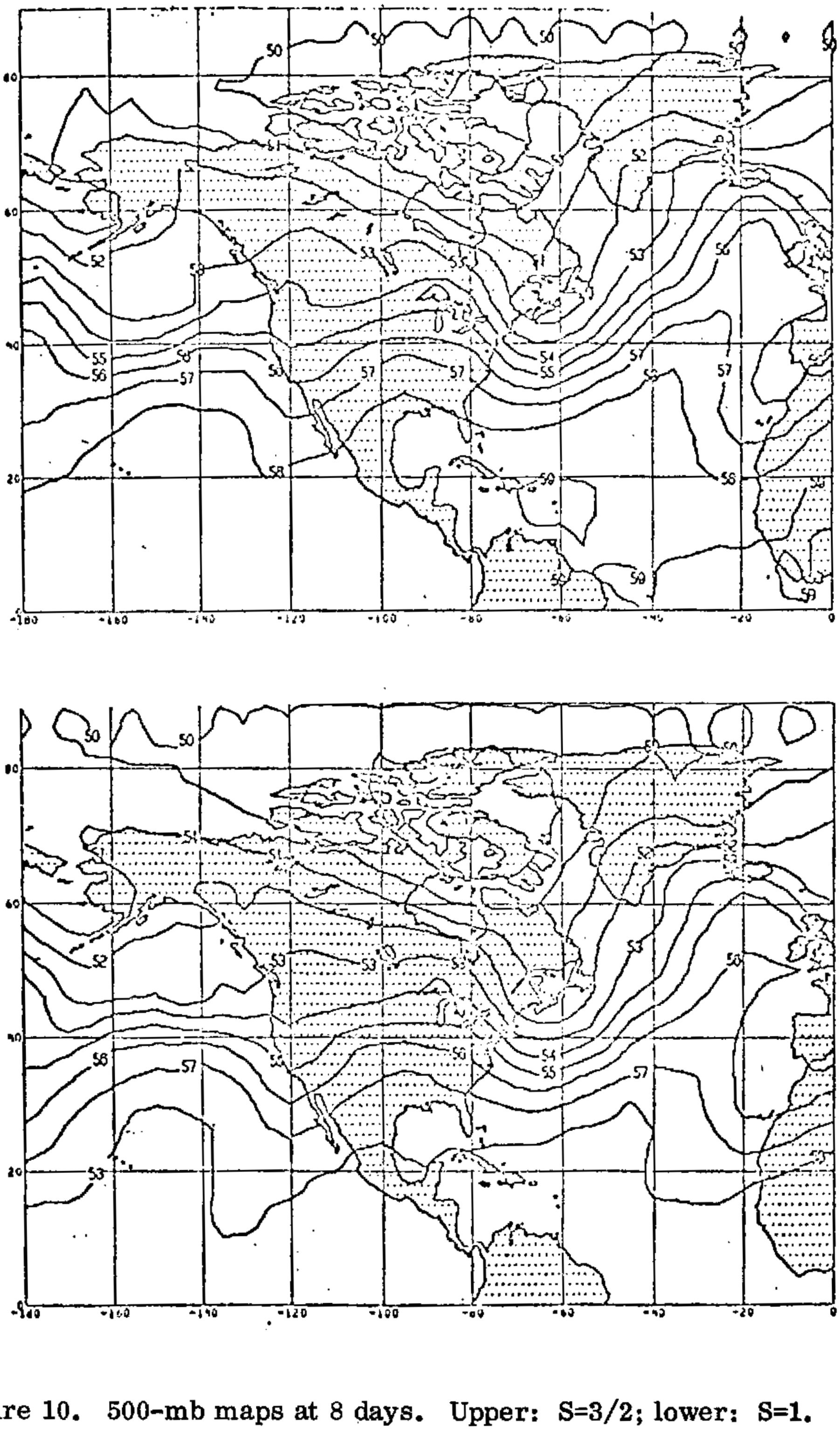

Figure 10. 500-mb maps at 8 days. Upper: S=3/2; lower: S=1.

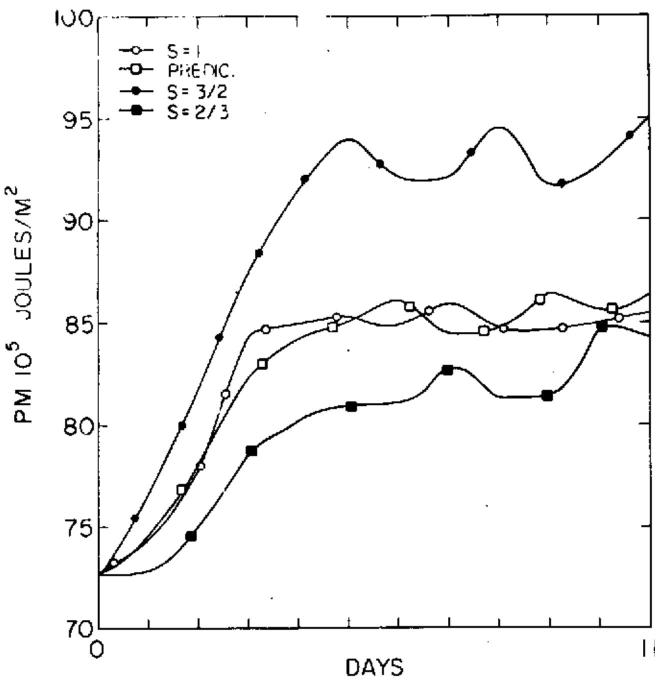

Figure 11. Time evolution of globally-integrated zonal available potential energy (PM) for the solar constant experiments.

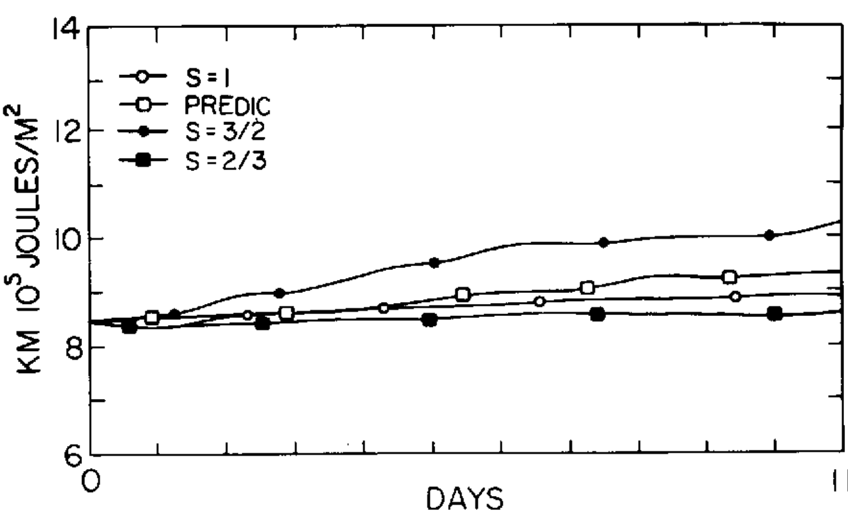

Figure 12. Time evolution of globally-integrated zonal kinetic energy (KM) for the solar constant experiments.

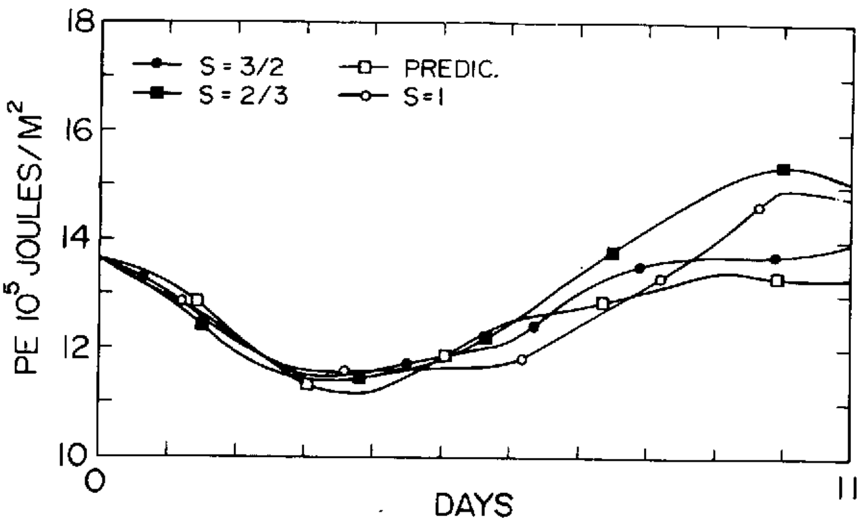

Figure 13. Time evolution of globally-integrated eddy available potential energy (PE) for the solar constant experiments.

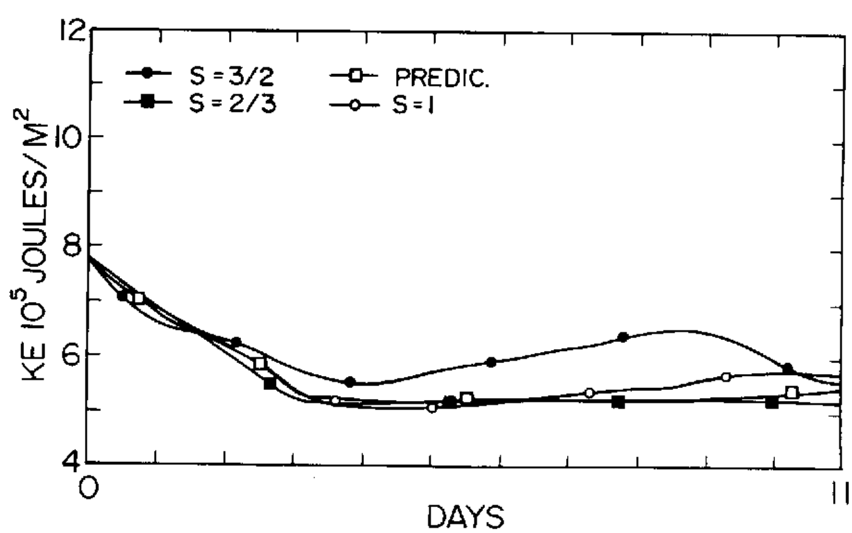

Figure 14. Time evolution of globally-integrated eddy kinetic energy (KE) for the solar constant experiments.

Table 2
Temperatures and Cloud Cover in the Ozone Experiments

Variable	Run	Days 1-3	Days 4-6	Days 7-9	Days 10-12
Mean Global	OZ=1	-26.06	-26.73	-27.23	-27.49
Atmospheric	PREDIC	-26.06	-26.71	-27.21	-27.43
Temperature	OZ=0	-26.17	-27.10	-27.47	-27.78
(°C)	OZ=2	-25.97	-26.54	-26.71	-27.02
Mean Temperature	OZ=1	-58.58	-59.10	-59.26	-59.44
In Highest	PREDIC	-58.61	-59.09	-59.26	-59.51
Model Layer	OZ=0	-60.80	-59.23	-61.91	-62.97
(°C)	OZ=2	-58.08	-57.45	-56.65	-55.95
Mean Temperature	OZ=1	2.82	2.21	1.91	1.63
In Lowest	PREDIC	2.48	2.11	1.81	1.37
Model Layer	OZ=0	2.79	2.14	1.87	1.63
(°C)	OZ=2	2.82	2.20	1.63	1.65
Mean Global	OZ=1	33	46	49	48
Cloud Cover	PREDIC	33	46	49	48
(Percent)	OZ=0	33	46	49	49
	OZ=2	33	46	49	49

gradient. It must be borne in mind, however, that this effect is in response to unrealistically large changes in solar constant. The small effects of these changes on mean atmospheric temperature and cloud cover are shown in Table 3. A search for ground temperature changes at selected grid points produced none that stood out over the noise due to natural variations in weather.

DISCUSSION AND CONCLUSIONS

In interpreting these results, it is useful to note that the planetary blackbody equivalent temperature (BBET) is proportional to the fourth root of the solar constant, so that a change of about 50 percent in solar constant should produce a change of about 10 percent, or about 25 K, in BBET. In our experiments, we would expect much smaller temperature changes, both because the model sea-surface temperature is fixed and because the integrations are short compared to the tropospheric radiative relaxation (e-folding) time of about 50 days (Goody, 1964, Table 9.3). This 50-day time scale cannot be reduced greatly by

Table 3
Temperature and Cloud Cover
in the Solar Constant Experiments

Variable	Run	Days 1-3	Days 4-6	Days 7-9	Days 10-12
Mean Global Atmospheric Temperature (°C)	S=1	-26.06	-26.73	-27.23	-27.49
	PREDIC	-26.06	-26.71	-27.21	-27.43
	S=2/3	-26.46	-27.72	-28.74	-29.02
	S=3/2	-25.65	-25.50	-25.22	-25.13
Mean Global Cloud Cover (Percent)	S=1	33	46	49	48
	PREDIC	33	46	49	48
	S=2/3	34	47	50	51
	S=3/2	33	43	45	45

invoking additional heat transfer mechanisms. Both the approach to radiative-convective equilibrium (Manabe and Wetherald, 1967) and the effects of large-scale eddies (Stone, 1972) involve time scales of about 30 days, a number consistent with the equilibration time scale of general circulation models (for example, Manabe et al., 1965).

This expectation of small temperature changes is in fact borne out by our results (see Tables 2 and 3). The largest changes in global temperature, 2.4 K, occur in the run with increased solar constant, but even here the change is small compared to 25 K and compared to the natural variability of temperatures in typical weather patterns. Thus our negative results are theoretically plausible. We conclude that any causal relationship between solar variability and terrestrial weather on time scales of two weeks or less will have to rely on changes in parameters other than solar constant or ozone amount, or on mechanisms not yet incorporated in our model.

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF R. C. J. SOMERVILLE

QUESTION: If you remove the ozone, what does happen physically — does the UV deposition height go down, or the temperature change, or what happens to the model when you don't have the top layer?

MR. SOMERVILLE: I think what you are essentially changing is the stability — this is speculative — but you are changing the stability near the top of the model atmosphere by simply having a temperature change in the uppermost layer.

MR. MARAN: I think the ozone results are interesting. However, the solar constant variations considered were on time scales on which you don't expect changes of the magnitude considered. It would be very interesting to apply this method to the long time scales that Cameron discussed. When you are changing the solar constant, do you mean that you are changing essentially the visible and near visible light?

MR. SOMERVILLE: Yes, that's right. There is certainly no accounting, as I said earlier, of the particle flux or any other aspect, simply the electromagnetic radiation. And you are quite right, you might not expect large changes of the solar constant on these time scales. On the other hand, there are coupling mechanisms in the model atmosphere that are, in some ways, as complicated and well hidden as those in the earth's atmosphere. So it is nice to have that preconception confirmed. The other point I would like to make is that we do agree that it would be important to look at this on longer time scales, but obviously it is necessary to run for a short time before you run for a long time.

MR. WILCOX: Would it be possible to introduce in your model the following kind of perturbation? They can recognize this curve (Dr. Wilcox sketched on the blackboard a curve from Figure 2 of his paper.) We know that, on the average, the vorticity area index had this kind of behavior averaged over the northern hemisphere so that, say, when you started on December 20, it might be interesting when the next boundary came by to try to introduce this. How would we want to do that? Well, we know that it is kind of a hemispheric effect. It's not particularly localized to any one area, so that you might, for example, in every trough that you have, somehow change conditions so that it went through this behavior. The magnitude is about 10 percent on the average. Would it be feasible to do anything like that?

MR. SOMERVILLE: Yes, you can tinker with model fields any time you want. I am not sure what you are driving at, what you would be learning altering the model?

MR. WILCOX: Well then, you would compare the result of having done that with what is actually observed and see if it has improved over if you didn't do this.

MR. SOMERVILLE: That is certainly possible to do, yes.

MR. WILCOX: That would begin to tie you in to what seems to be a fairly substantial solar influence on the weather, as compared with the solar constant on the ozone, which did not seem to have very much effect.

MR. SOMERVILLE: The feasibility of that, of course, would be tied up with how far the model atmosphere had departed from the real atmosphere, if you were verifying against the real atmosphere, by the time this took place, whether this effect would be lost in the noise of the other effects and model deficiencies and observations which degrade the quality of the forecast.

MR. PRABHAKARA: From the description of the model you gave, there is a decoupling, a deemphasis, of the subgrid scale phenomena compared to the meteorological scales that are built into the models. Namely, increasing the solar constant by 50 percent, or decreasing it by something of that order can influence the subgrid phenomena much more pronouncedly. Then they would have, presumably, feedback into the meteorological scale. And this is inhibited in the model, so if it can be promoted, one might find a direct relationship.

MR. SOMERVILLE: I quite agree. The assumption that you have to make, which is bold but very necessary in constructing a model like this, is that everything that's important that takes place on smaller scales than that explicitly resolved by the model grids (and the gridpoints are separated by something like 400 kilometers in the middle latitude) can be uniquely represented. There is an algorithm which defines the feedback on the large scale of these small-scale processes, given the large-scale values of the fields as explicitly calculated by the models. And this assumption, the parameterizeability hypothesis, is by no means on firm grounds with respect to many small-scale processes. But you have to do that if you are to run the model at all. You can't ignore these processes. You can't possibly compute them explicitly.

MR. BANDEEN: I have a little difficulty when I see charts showing the cloudiness computed by the model. For example, amount of cloudiness is only part of the problem. The height of the clouds and the transmittance at various wavelengths are also important. In one of your graphs, where you showed a considerably lesser amount of cloudiness computed compared to cloudiness observed, and you stated that the clouds in the model were treated as black bodies, it occurred to me that they really were quite equivalent to the greater amount of real cloudiness.

In many cases the transmittance of the clouds in a real atmosphere is considerable, upwelling radiation from lower levels being transmitted through the clouds, inasmuch as they are not at all like black bodies. So it occurred to me that the large discrepancy that was apparent on the graph really was not that large at all, considering the other factors of real clouds.

MR. SOMERVILLE: Yes. I think that may be true. It is also true that in models like these, in which the sea surface temperature is fixed and the lapse rate is strongly constrained by the internal dynamics, such as an adiabatic bound on the lapse rate, that the radiative transfer in the model atmosphere may be much less important than in the real atmosphere for determining thermal structure of the atmosphere.

Once you fix the boundary condition on temperature, and go a long way toward fixing the slope, then you come close to fixing the temperature field. And that kind of empirical lock is going to mask the effect, in many cases, of a deficient radiative transfer treatment, whether it is in the radiative transfer itself or in the input to it such as the cloud field, so that the kind of compensation you mentioned may be present, and even if it weren't, we might not see it. And that is a major problem in extending models like this to computing climates which may be very different from the present climate. It may not show up over the climate scales of weather forecasts or even extended-range weather forecasts involving a synoptic data simulation over a few weeks or months. But if you try to compute a very different climate — and all kinds of very attractive experiments have been proposed to use these models in. For example, geologists know where the continents were a hundred million years ago, and something about the surface conditions then. You could change the boundary conditions corresponding within a model and compute the climate of a hundred million years ago. That is a high risk game right now, because of these kinds of model deficiencies. But I think your point is well taken.

QUESTION: I noticed on some of your energy curves that there was a tendency for them to change during the first four or five days, and then they flattened out. What is the reason for that?

MR. SOMERVILLE: The reason for that is that the equilibrium state of the model differs from the initial state. Whether that is because of observational uncertainties, that we are starting from real meteorological data, which, as you know, over much of the earth are not very reliable, or whether it's because the equilibrium state of the model is truly different from the state of the atmosphere in December of last year, it is hard to say. But you are quite aware there is an adjustment time of a few days before anything happens.

QUESTION: Does that mean that the weather, in a sense, goes away?

MR. SOMERVILLE: In part, that's true, although there is degradation in the aspects of the model that are actually used in forecasting. It is not that fast. And while this mode, and any other such model, in fact, produces useful forecasts only for a few tens of hours after the initial state, nonetheless the model is better than randomly correlated with the real atmosphere for even a week or more. The forecast may not be useful, but there is some resemblance left.

N74-29096

AURORAL EFFECTS IN THE D REGION OF THE IONOSPHERE

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INTRODUCTORY REMARKS

The sun influences the earth's atmosphere in three ways:

(1) Radiations

- (a) UV radiation and X-rays
- (b) Visible radiation
- (c) Infrared radiation

(2) Corpuscles

- (a) Energetic particles
- (b) Plasma

(3) Gravitation (atmospheric tide)

Our main concern here is possible effects of the first two, in particular (1a), (2a), and (2b), on relatively short-term changes in the atmosphere circulation (namely, the development of cellular patterns in the zonal westerly flow, leading to the formation of cyclones) and relatively long-term changes in climate.

Both the solar UV radiation and corpuscles affect the upper atmosphere in essentially the same way, although details of the processes involved are considerably different. They change the chemical composition of the upper atmosphere and heat it. Both the solar UV radiation and X-rays (1a) and solar energetic particles (2a) penetrate directly into the upper atmosphere, while effects of the solar plasma are felt in the upper atmosphere through an intermediate process called the solar wind-magnetosphere interaction. The interplanetary magnetic field is an essential ingredient in this coupling process. This interaction process converts the kinetic energy of solar wind particles into magnetic energy which is stored in the tail portion of the magnetosphere (the magnetotail). This stored energy is intermittently converted into the kinetic energy of auroral particles. In this conversion process, auroral particles are accelerated and penetrate into the upper atmosphere. Thus, it is after this conversion process that the solar plasma can affect the upper atmosphere.

The solar wind-magnetosphere interaction can cause also a large-scale circulation of plasma in the magnetosphere. The "friction" between the plasma and the neutral atmosphere beneath it is responsible for the cause of a concentrated electric current along the auroral oval, called the auroral electrojet, and an intense upwelling of the upper atmosphere is generated by Joule heating. These processes will be described in detail in later sections, and their effects are hereafter, as a whole, called "auroral effects."

As mentioned in the above, the end effects of both the solar UV radiation and solar corpuscles are changes in the chemical composition and heating of the upper atmosphere. Therefore, it is a formidable task to identify their possible effects on weather, unless time variations of the solar UV radiation and X-rays and corpuscles can be identified in meteorological and climatological phenomena. For example, for any 11-year cycle variation in meteorological phenomena, it will be difficult to identify their solar sources, since both the solar UV radiation and corpuscular activity vary roughly in harmony with sunspot number. Further, some long-term changes in climate could be a result of accumulated effects of short-term changes in the atmospheric circulation.

This difficulty is not reduced for much shorter term phenomena, such as the recent finding by Wilcox et al. (1973) that the solar magnetic sector structure appears to be related to the average area of high positive vorticity centers in the northern hemisphere.

There is only a slight electromagnetic coupling between the sector boundary and the magnetosphere. Figures 1 and 2 show, from the top, the interplanetary magnetic field data (the latitude (THETA), longitude (PHI), and the magnitude (F) of the magnetic field vector), geomagnetic records from several low latitude stations, those from the northern and southern pole stations (Thule, Vostok) and the auroral electrojet indices, AU and AL. A sector boundary passed near the magnetosphere at about 1500 UT, as can be seen in the PHI record. There were several sudden impulses at about that time; they indicate that a sector boundary is often associated with fluctuations in the plasma pressure, which cause compressions and expansions of the magnetosphere. There is, however, little energy transfer from the solar wind to the magnetosphere by so few sudden impulses. There was no appreciable auroral activity during the passage of the sector boundary. Figure 2 shows a little more complicated situation, but it is quite clear that there is no unique phenomena associated with the passage of the sector boundary crossing; an enhanced AE activity is quite common without the passage of sector boundaries.

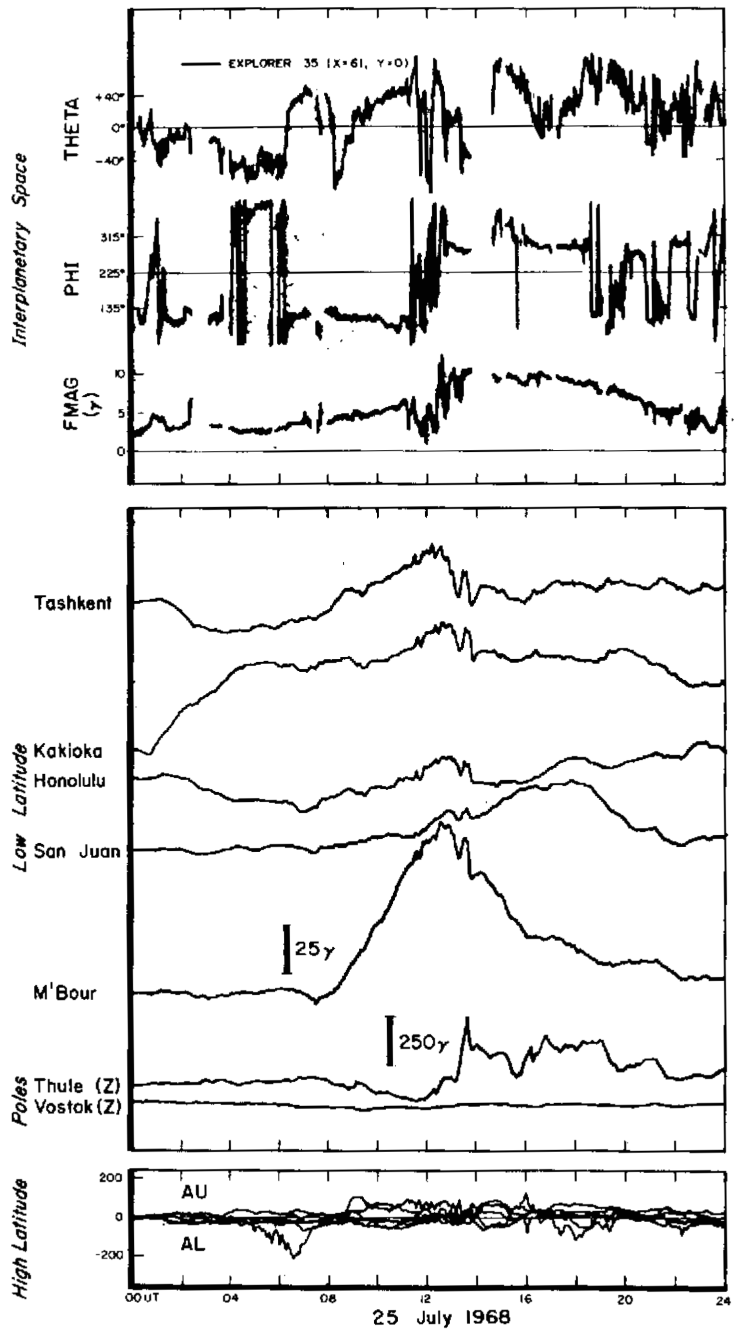

Figure 1. An example of a sector boundary passage on July 25, 1968. From the top, this figure shows the interplanetary magnetic data, ground magnetic records from several low latitude stations and from the northern and southern pole stations, and the AV and AL indices.

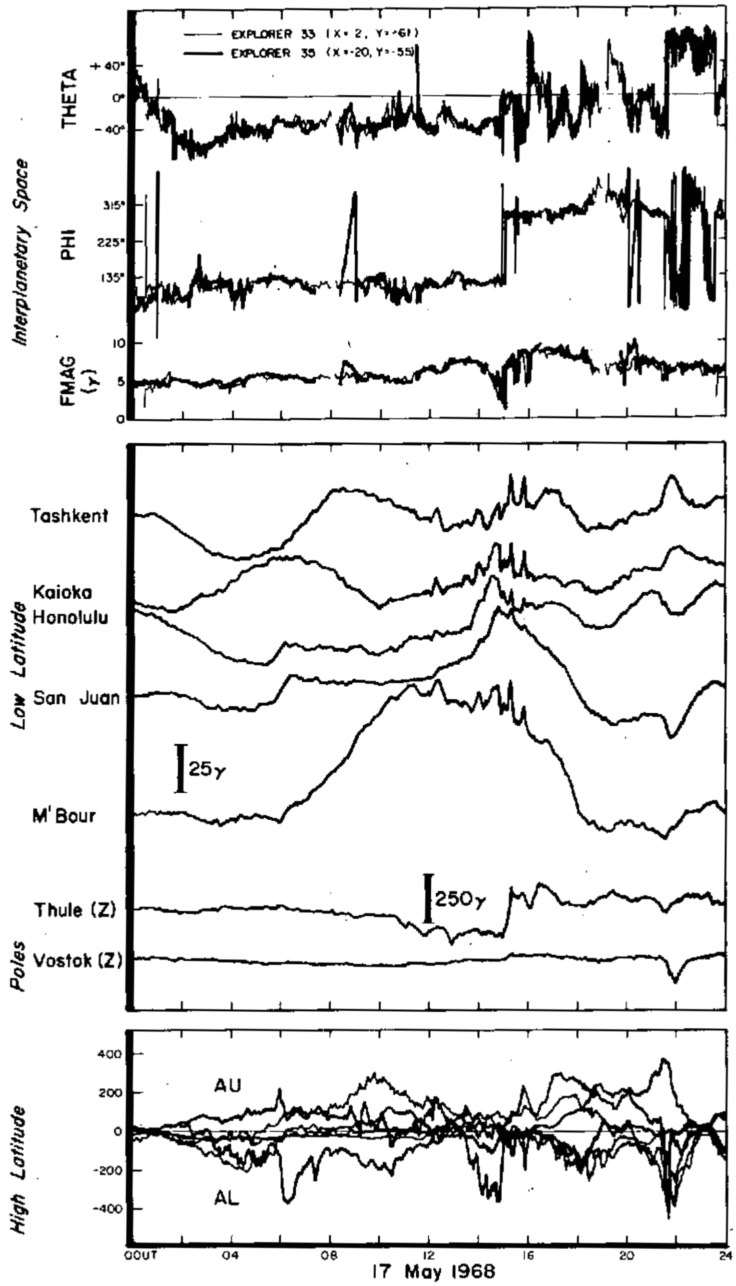

Figure 2. An example of sector boundary passage on May 17, 1968. From the top, this figure shows the interplanetary magnetic data, ground magnetic records from several low latitude stations and from the northern and southern pole stations, and the AV and AL indices.

As noted by Wilcox and Ness (1965) and Wilcox and Colburn (1972), there is a fairly systematic change of the K_p index before and after the passage of the sector boundary. The K_p index increases rather sharply during the first two days (from $K_p = 1.5$ to 3.0) and then slowly decreases. If one interprets that the sharp "recovery" of the vorticity area index (after reaching the minimum value on the plus one day) found by Wilcox et al. (1973) is associated with this sharp increase of the K_p index, one must conclude that the tropospheric circulation responds to auroral phenomena with a time lag of one or two days. This is rather hard to believe. Jastrow, Hanson, Lacis, Quirk, Somerville and Stone (in these Proceedings) showed that some responses of the tropospheric circulation becomes apparent about one week after introducing a particular type of perturbation on it. Indeed, if there were such a simple relationship between auroral phenomena and the development of cyclones, it would have been discovered a long time ago. This is particularly the case because the amount of the increase of K_p after the passage of sector boundaries is not particularly large.

Geomagnetic storms which begin about two days after intense solar flares near the central meridian can cause a far greater increase in K_p. For example, the K_p indices during the great geomagnetic storm of February 11, 1958, were (9_o, 8_+, 9_-, 8_+, 8_o, 5_+, 6_o, 6_o). This may be compared with a typical increase of K_p of about 2 during the sector boundary passage; note that the K_p index is a semilogarithmic index.

Figure 3 shows the magnetic record of Meanook, Canada, which illustrates well a successive occurrence of very intense substorms during the storm of February 11, 1958. The auroral oval descended abnormally equatorward and expanded dramatically several times as the substorms developed and decayed on

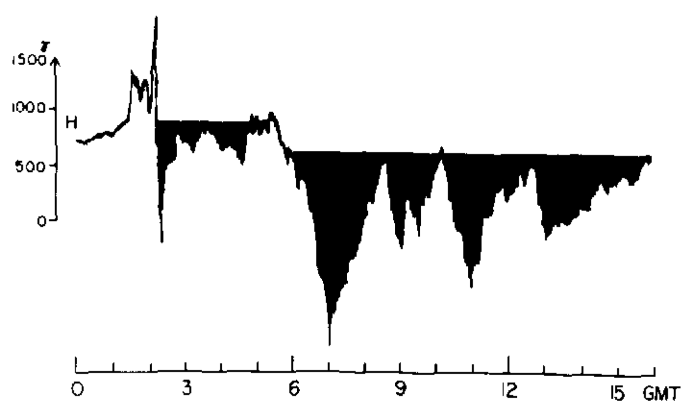

Figure 3. The horizontal (H) component magnetic record from Meanook, Canada, on February 11, 1958. Polar magnetic substorms (manifested on negative bays) are shaded for easy identification.

that day. Figure 4 shows the most violent expansion of the auroral oval during the storm. The upper atmosphere was considerably heated during the storm; its effects were seen as a great enhancement of the 0I 6300 emission over a large portion of the polar upper atmosphere.

Incidentally, the weather during the month of February 1958 was quite anomalous (Klein, 1958; Shellum and Tait, 1958). Klein (1958) noted:

> February 1958 will long be remembered as a month of contrasting weather extremes in many parts of the United States. Many established records of long standing were broken—for cold in the Southeast, warmth in the Northwest, snow along the Gulf and Atlantic coasts, precipitation in the Great Plains and along the west coast, and dryness in the Mid-West. During the last week of the month intense cyclonic activity was responsible for new low barometer readings at many stations in the Central States, as well as for tornadoes, blizzards, and floods over a wide area.
>
> Abnormalities of the weather were produced by corresponding abnormalities in the circulation pattern. Strong blocking ridges over Greenland and Alaska were accompanied by the deepest mean troughs on record along the east coast and in the eastern Pacific. A typically "low index" circulation prevailed throughout the Western Hemisphere as the polar anticyclones intensified and the subtropical anticyclones weakened. This was part of a great index cycle in which the prevailing westerlies of middle latitudes were displaced southward to the subtropics, where they blew with unprecedented speed in the form of an expanded and intensified circumpolar vortex.

However, these abnormal features began from the beginning of January 1958, manifested in a rapid equatorward shift of the main zonal westerlies at 700 mb, reaching a minimum latitude of approximately 31° N, about 8° south of its normal latitude, but there was little change of its location throughout the month of February 1958. Further, an intense cold spell began to cover a large portion of the US from about February 9, at least one day before the beginning of the great storm. In fact, between February 6 and 10, there were two intense blocking highs, one over Davis Straight and the other over northwestern Alaska; the positive height anomaly was 1150 feet and 840 feet, respectively, in 700-mb contours; see Figures 5a and 5b. This anomalous feature was then followed by the period of record high subtropical westerlies which brought the cold spell mentioned in the above.

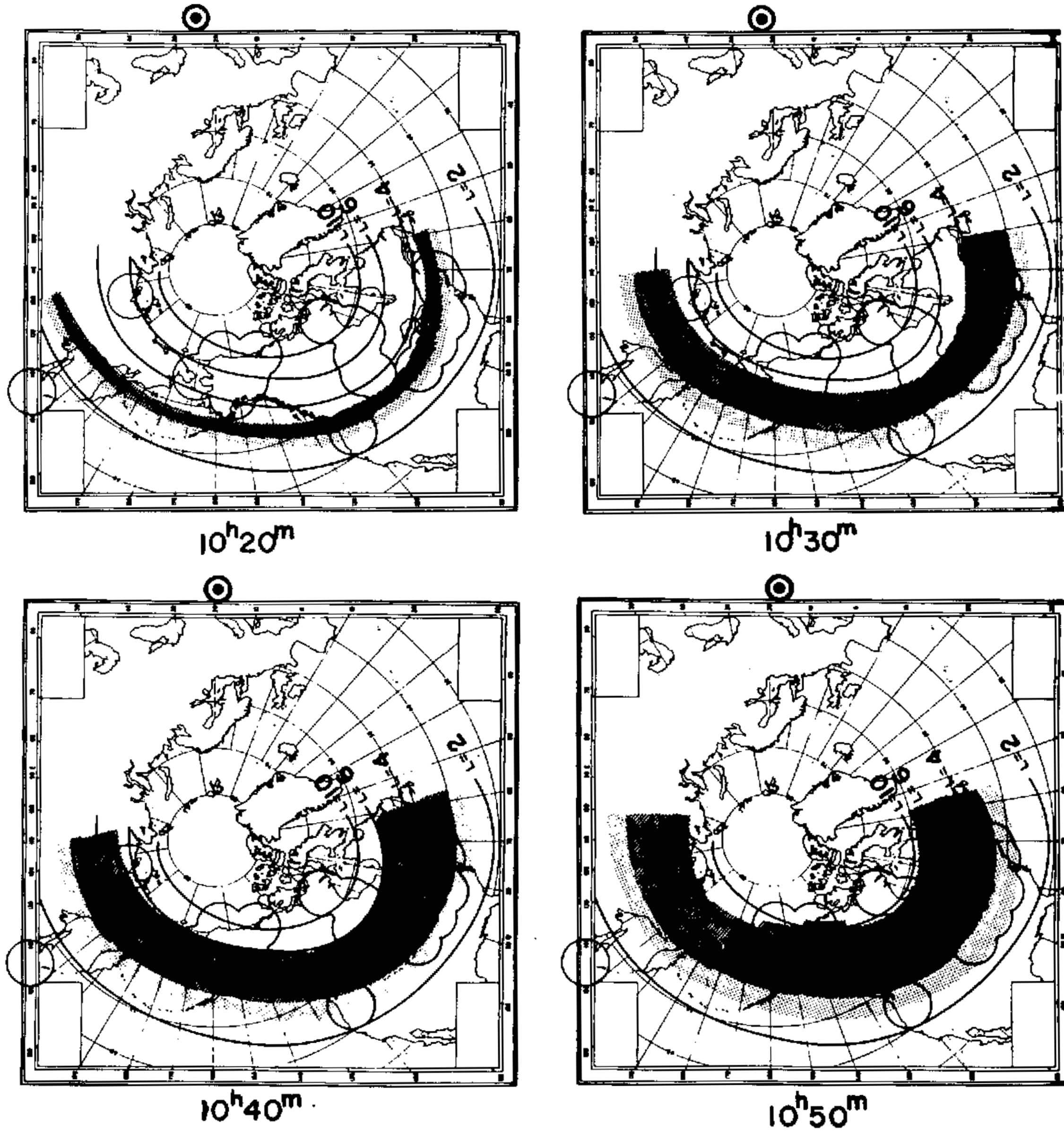

Figure 4. The violent poleward expansion of the auroral oval which occurred near the maximum epoch of the great storm of February 11, 1958.

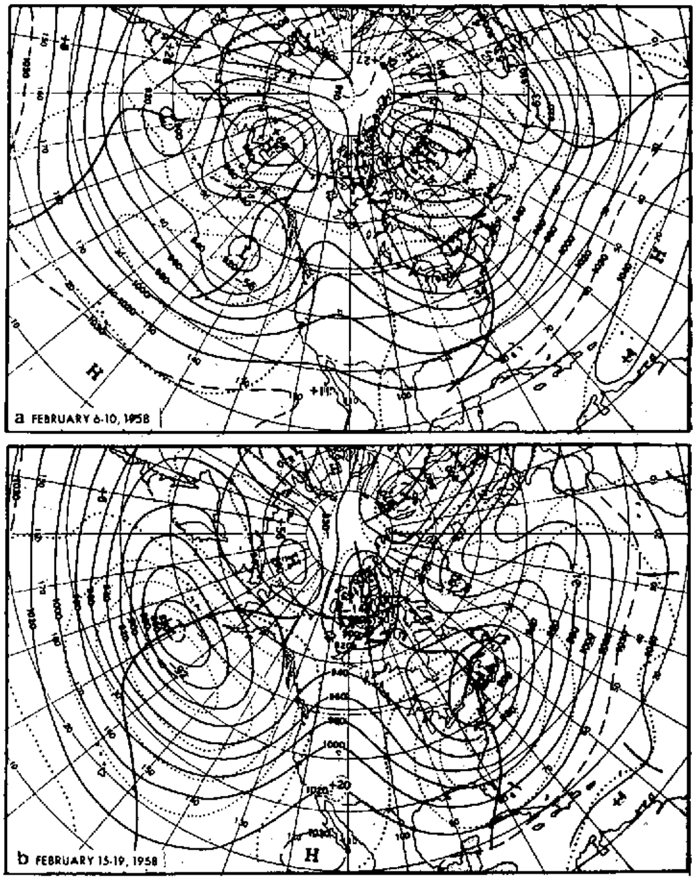

Figure 5. The average weather maps on (a) February 6 to 10, 1958 and (b) February 15 to 19, 1958.

This example is presented here, since it is natural to speculate relationships between the great magnetic storm of February 11, 1958, and the historic cold spell during the third week in the same month. However, the cause of the anomalous weather in February 1958 was apparently present well before the great storm. An interesting study will be to examine whether or not the 700-mb map in Figure 4b can be "predicted" a posteriori by a numerical technique from Figure 4a, without adding any "unknown" factor on February 11. If the contour map in Figure 5a does not lead to that in Figure 5b on the basis of what was known on February 9, it would be of great interest to conduct numerical experiments in an attempt to construct Figure 5b by introducing various perturbations in Figure 5a. If, on the other hand, Figure 5a could lead to Figure 5b without any additional perturbation, it is quite unlikely that auroral effects can significantly alter weather patterns. This is because the storm of February 11, 1958, was one of the most intense geomagnetic storms in history.

Going back to the finding by Wilcox et al. (1973), it is important to understand why the vorticity index begins to decrease about one day before the actual passage of the sector boundary. A more likely possibility is that the "recovery" or "increase" of the vorticity area index two days after a particular sector boundary passage is actually an effect of the one before.

Another possibility is that the "suppression" of the vorticity area index results from solar radiation effects from the vicinity of the "root" or source region of the sector boundary, which are expected to have possible terrestrial effects about four days before the passage of the sector boundary. In such a case, the source may be either (1a) or (2a) or both. For the former, it may be noted that Krieger, Timothy, and Roelof (1973) and Hundhausen (in these Proceedings) showed that there is a marked dark area in an X-ray photograph of the sun on the solar disk; he revived the concept of cone of avoidance which was put forward by Roberts. It may be such a dark region or bright region surrounding the dark region which has an immediate effect in the upper atmosphere; without knowing the time constants of various meteorological phenomena, it is difficult to identify the source region even in this particular case of a high propagation speed from the sun to the earth. Another problem associated with their new finding is that it is not very obvious as to whether or not the sector boundaries had a positive or negative effect on the development of cyclones.

At any rate, if the finding by Wilcox et al. (1973) is a key to the problem of possible effects of solar activity on weather (Wilcox, in these Proceedings), we should make every effort to find causes which have led to their interesting statistical result. It may be noted that for a relatively short-term meteorological phenomena (such as the new finding), it may not be difficult to separate (1a) and (2a) from (2b). There are many intense western limb flares which are associated with both (1a) and (2a), but with little (2b).

STORMS AND SUBSTORMS

As mentioned in the previous section, the magnetic energy stored in the magnetotail is not continuously dissipated. The dissipation occurs rather impulsively, with a time scale of a few hours. This phenomenon is called the magnetospheric substorm, and some of its manifestations are the auroral substorm, polar magnetic substorm, and ionospheric substorm, which we call here as a whole"auroral effects" (Akasofu, 1968). The direct cause of substorms is not understood.

Sometimes intense substorms occur very frequently. Such a period is called the storm. Each substorm is associated with a small amount of injection of protons (of energies of order 50 keV) into the Van Allen belt. When intense injections occur very frequently, an intense belt of protons is formed. Since these protons carry a westward current, the belt is often called the ring current belt. The magnetic field of this (westward) ring current is directed southward near the earth. This field is the cause of what is commonly called the main phase decrease; the horizontal component of the magnetic field is depressed for about a day or so. The Dst index is derived to provide a measure of the intensity of the ring current. The ring current begins to decay as soon as substorm activity declines, first rather rapidly for about 6 hours and then slowly. It may take one week or more for the ring current to substantially decay. Figure 6 shows an example of the relationships between the storm of July 8, 1958, and substorms associated with it. The intensity of the substorms is given in terms of the AE index, and the intensity of the storm is given in terms of the Dst index.

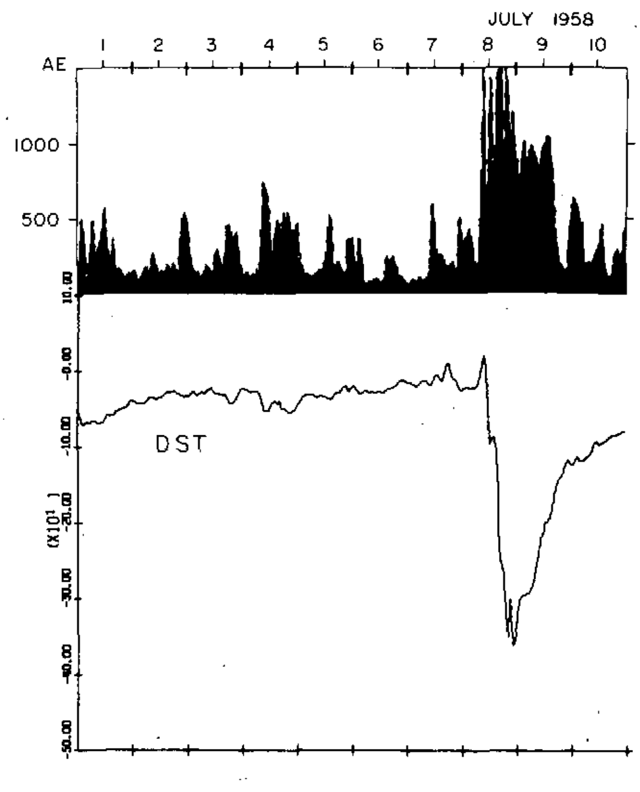

Figure 6. The relationships between the magnetic storm of July 8, 1958 and the associated substorms. The intensity of the former is given in terms of the AI index and that of the latter in terms of the Dst index.

AURORAL EFFECTS

ELECTRON PRECIPITATION

Figures 7a, b, and c show the auroral energy flow chart. Figure 7a shows sequences of processes associated with the precipitation of auroral electrons into the polar upper atmosphere. The most familiar effect is the ionization of atmospheric atoms and molecules and the subsequent chemical processes. The left-hand side of Figure 7b shows how the kinetic energy carried by auroral electrons is transformed into different kinds of energies; the percentages are kindly provided by Rees (private communication and 1973). The total energy input rate, 2×10^7 erg/s, is estimated by taking into account the precipitation of electrons into the region of the diffuse aurora. Although discrete auroras (classical curtain-like form) are caused by a much more intense flux of electrons, their precipitation area is too small to add significantly to the total energy input. Further, it should be noted that the above value of the energy input rate occurs during magnetospheric substorms. The lifetime of a typical substorm is of order 1 ~ hours. On a quiet day, there occur a few substorms. On a moderately disturbed day, several substorms can occur. During geomagnetic storms, several intense substorms can occur in 12 hours (see Figure 6).

It is well known that this energy input rate of 2×10^{10} W is much less than the solar blackbody radiation energy intercepted by the earth, 1.8×10^{17} W (Barry and Chorley, 1970). Further, most of the heat energy is initially deposited in the E region of the ionosphere or above, and will be conducted upward, since thermal conductivity increases rapidly upward (Schunk and Walker, 1970).

There are, however, three processes which should be considered as possible candidates in influencing meteorological phenomena. The first is the ionization by the bremsstrahlung X-rays generated by high energy electrons. Figure 8 shows an example of estimate of ion production rate by the bremsstrahlung effect during an intense auroral activity (Larsen, 1973). Johnson and Imhof (in these Proceedings) showed their estimates of the ion production rate. For the bremsstrahlung effects, see Brown (1964), Rees (1964), and Kamiyama (1966). For a direct measurement of energetic auroral electrons, see Bohn (1972) and references in Larsen (1972). Obviously, the ion pairs produced in this way cannot directly become condensation nuclei, since the mesosphere is far from a state of super saturation. Some "exotic" processes must be found for them to become condensation nuclei (Mohnen, 1971). Another possibility is that the aurora emits UV radiations in a wide wavelength range (Omholt, 1971) and that a part of it can be absorbed by ozone (the Hartley and Huggins bands) in the upper stratosphere. The most interesting possibility is, however, the dissociation of molecular oxygen of auroral electrons and the resulting formation of

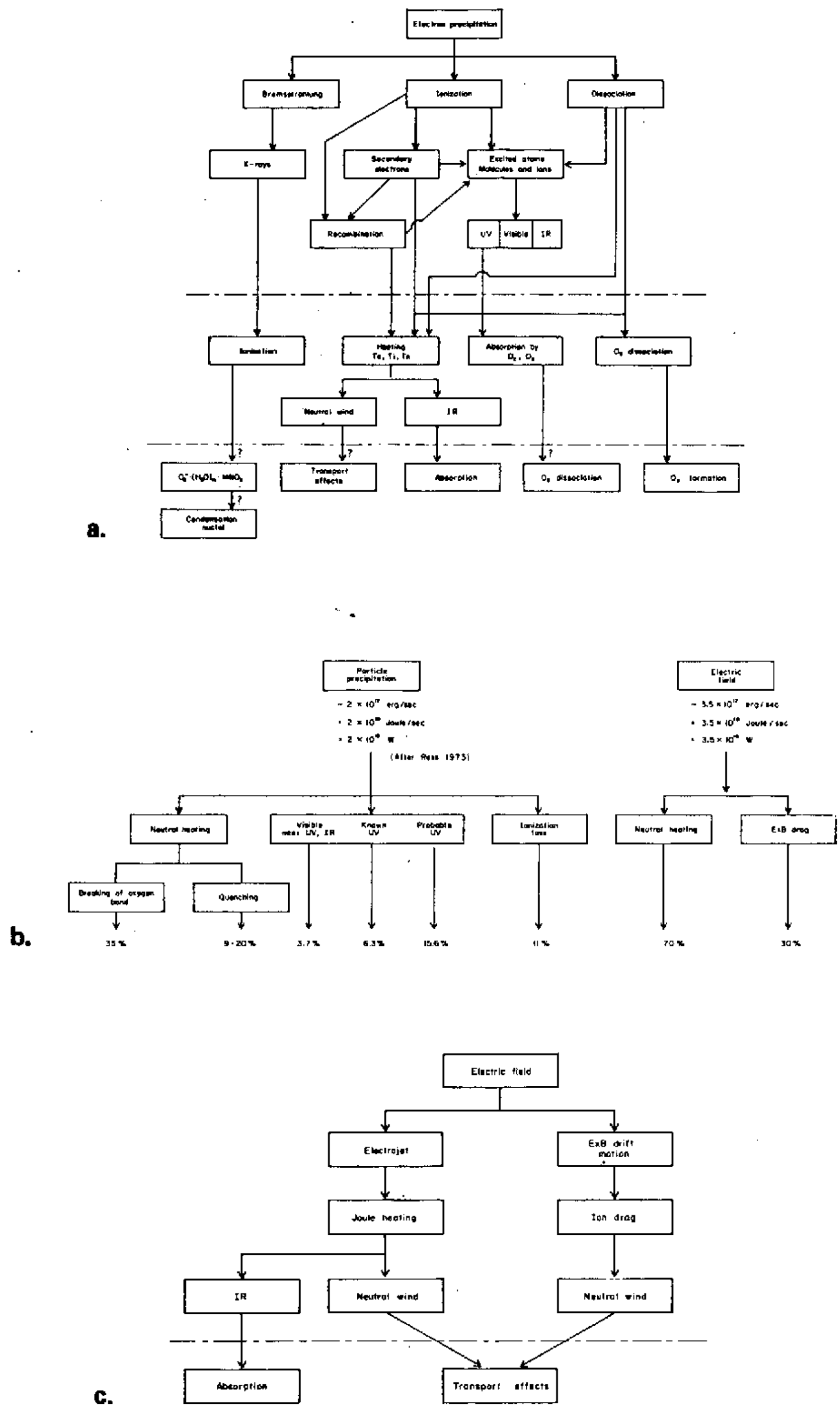

Figure 7. Auroral energy flow chart.

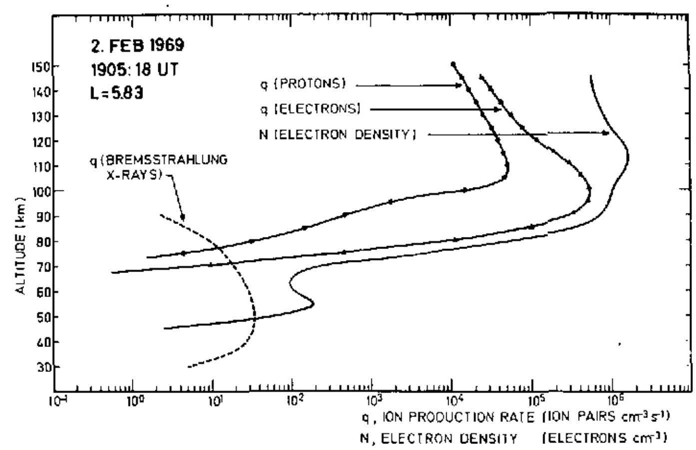

Figure 8. The ion production rates and electron density profile during a substorm of February 2, 1969 (after Larsen, 1973).

ozone. This problem was studied by Maeda and Aikin(1968). They showed that there is little possibility for auroral electrons of energies less than 10 keV to contribute in the formation of ozone, but an intense flux ($\sim 10^{11}/cm^2$ s) of energetic electrons ($\sim$100 keV) could modify considerably the ozone concentration at about the 50- to 65-km level. The proposed flux for this energy range appears to be certainly too high, but this problem should carefully be re-examined.

As mentioned earlier, the solar wind-magnetosphere interaction causes a large-scale convection of plasma in the magnetosphere. The motion is driven by a large-scale electric field in the magnetosphere. This convective motion of plasma interacts with the neutral component of the atmosphere in the E region of the ionosphere. There, a highly concentrated current is generated, if the convection occurs across a narrow belt of high degree of ionization; see Figure 7c. The energy dissipation rate by Joule heating is estimated to be about the same as that of the kinetic energy of auroral particles, 2×10^{10} W. Cole (1971a, b) studied this problem in detail. The upwelling motion of the neutral gas in the ionosphere (by heating of the neutral gas as the combined results of the impact of auroral electrons and of the Joule heating) and the subsequent circulation has been studied by a number of workers. Here, in Figure 9, we show one of such a result by Heaps (1972). For satellite observations, see Devries (1972).

Further, the convective motion of plasma tends to cause motions of the neutral component in the ionosphere. This phenomenon is called the (ExB) drag; see Figure 7c. This particular motion has been identified by observing drift motions of barium ion clouds (Heppner in these Proceedings) and by the incoherent scatter radar at Chatanika, Alaska (Banks, private communication, 1973). The energy input rate in accelerating the neutral gas is estimated to be 1.5×10^{10} W.

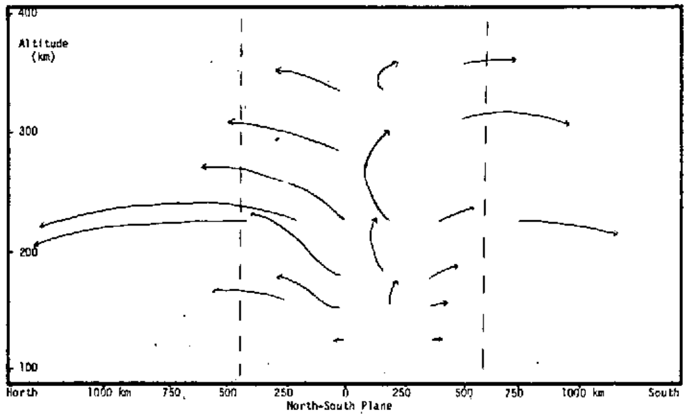

Figure 9. The upwelling of the upper atmospheric gas in meridian plane, generated by the heating by the impact of auroral electrons and Joule heating. The arrows indicate displacements of air parcels for a period of 12 hours (after Heaps, 1972).

There are a number of indications that the upper atmospheric wind is generated in the ionosphere and above during auroral activity. Unfortunately, however, such winds are well confined in the upper atmosphere. There is so far no definite evidence that even the upper mesospheric gas participates in such motions. Hook (private communication, 1973) showed that the wind in the mesosphere is normal even during a high auroral activity; his observation is based on a meteor radar located in Fairbanks. Perhaps chemical releases in the upper mesosphere should be conducted to continue his observations. However, even if winds are generated by auroral activity in the upper mesosphere, there is little hope to dynamically couple the ionosphere with the troposphere by any direct means.

SOLAR PROTON EFFECTS

Solar protons have a profound effect in the polar upper atmosphere (see (2a) in Introductory Remarks) and cause the phenomenon called the polar cap observation (PCA). In terms of the ion production rate in the mesosphere, they can have a greater effect than the bremsstralung X-rays. Further, the precipitation occurs over the entire polar cap, the area encircled by the auroral oval. Figure 10 shows an example of PCA which occurred on February 11, 1958 (Obayashi and Hakura, 1960). Figure 11 shows an example of the estimated ion production rate by Zmuda and Potemra (1972). Complex atomic and molecular

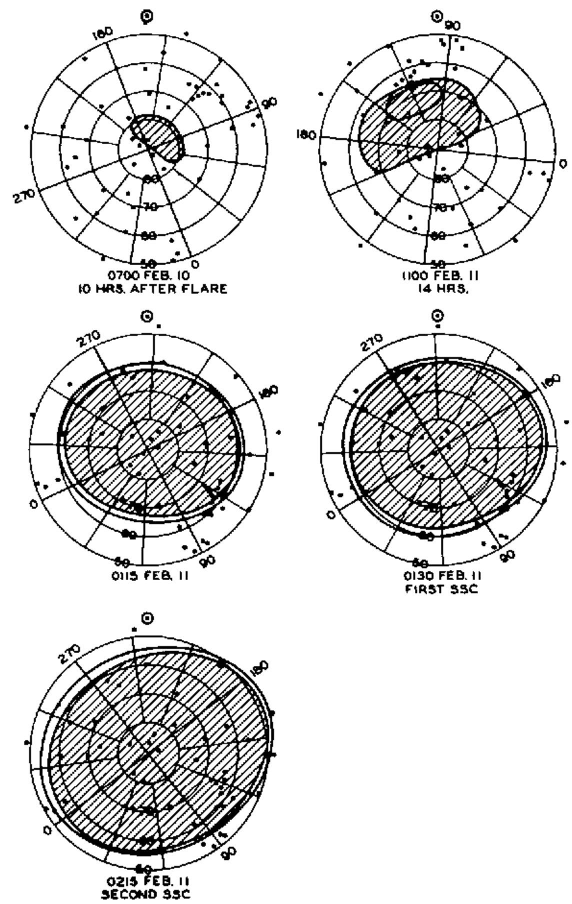

Figure 10. The development of PCA during the geomagnetic storm of February 11, 1958 (after Obayashi and Hakura, 1960).

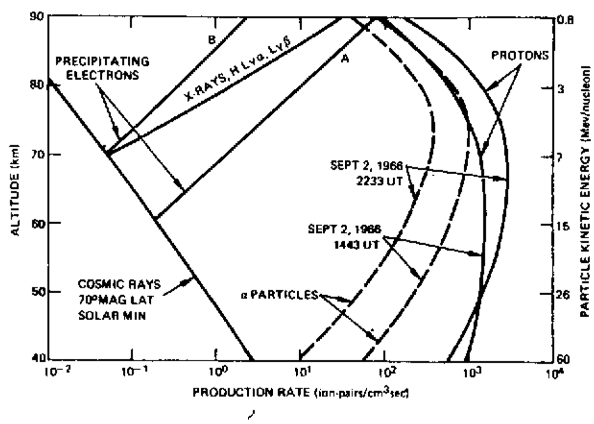

Figure 11. The ion production rate by solar protons during several PCA events (after Zmuda and Potemra, 1972).

processes associated with the ionization in the D region have been studied by a number of workers (Reid, 1971), and it may be of interest to examine whether or not the resulting water-cluster positive ions could become embryos for aerosol particles, as suggested by Mohnen (1971). Unfortunately, intense solar proton events are not frequent, although they may have an accumulated effect during the period of sunspot maximum. Further, it may be difficult to separate between possible effects of solar flares and those of solar protons, since most of the intense solar proton events begin a few hours after an intense flare. One possibility is, however, to use the fact that eastern limb flares do not, in general, produce intense solar proton events.

CONCLUDING REMARKS

It appears obvious that auroral effect cannot directly affect tropospheric phenomena; even violent upper atmospheric winds generated by auroral activity do not seem to directly affect mesospheric winds. On the other hand, it will be interesting to examine mesospheric conditions under auroras by chemical releases. If there is any solar activity-terrestrial weather relationship, it seems that auroral effects go through intermediate processes before affecting weather. For example, if auroral processes can change drastically the ozone concentration, an appreciable change in the radiation transfer may occur in the atmosphere.

Although this possibility may be remote or out of the question to meteorologists, possible auroral effects on the ozone concentration will be an interesting problem to examine from the point of view of aeronomy. Both observational and theoretical studies should be conducted. (In particular, it is of great interest to examine the ozone concentration directly under auroras.)

It is suggested that a detailed numerical experiment should be conducted in reconstructing the weather map in the third week of February 1958 on the basis of the map in the first week of the same month. If the reconstruction fails with all the known parameters, we should examine various perturbations to the circulation pattern during the first week of February 1958. Such an experiment should provide a clue in the search of mechanisms which couple auroral activity and weather.

ACKNOWLEDGMENTS

The author would like to thank Dr. W. O. Roberts and Dr. J. H. Wilcox for their stimulating discussions on the problem. The author is also indebted to H. Cole for his discussion during the preparation of this paper.

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF SYUN-ICHI AKASOFU

MR. STURROCK: What is intriguing about aurora is that there have been reports over many years of sound being produced and the data in the journals seem to be inconclusive. I would like to know your views on the subject.

MR. AKASOFU: Of course, yesterday Dr. Heppner showed Dr. Wilson's data indicating that the infrasonic shock waves are generated by moving aurora, and that is now well documented. Whenever you see the aurora, particularly moving equatorwise, you see the shock waves. Of course those are of very low frequency, so you can't hear them.

As far as the audible range is concerned, even a few weeks ago somebody called me and said he heard the aurora. Nevertheless, with the tremendous progress in electronics and audio techniques, no one had ever detected the sound with modern instruments. And I don't know what is the trouble. I understand that the human ear is much better than any available audio instrument. Is that true? I don't know, but this may be the case. People try all kinds of techniques. For example, they say the dog is very sensitive, so they try a dog. The dog might be upset by the visual aurora, so they put the dog into some dark place, where he can't see it. And during the aurora the dog howls!

(Laughter.)

That's about the state-of-the-art.

MR. BELMONT: You mentioned that the auroral oval expands to the equator, depending on the direction of the IMF. But in the diagram you showed, it looked as if it expanded only on one meridian and not in both. Was it symmetric to the magnetic pole, or does it really expand, in only one direction?

MR. AKASOFU: You know I can't talk about time accuracy of a few minutes, but with half-hour time resolution it expands equatorward, when the interplanetary field turns southward. And, when the interplanetary field turns northward, it contracts toward the pole both on the dayside and nightside.

MR. DELAND: Is there any sign in the auroral structure of the gap between the opposing electric fields that you have in your diagram, that is, the electric current coming towards the atmosphere and going away from it? There must be a transition between these.

MR. AKASOFU: The gap is in terms of fieldline currents, but the fieldline currents come in from the morningside and then flow around the oval. And the midnight region, that is what we call the auroral electrojet. Of course this is my personal view and of course there are so many different systems that people draw; I don't know which is right. But my personal feeling is that what you think the gap is, is the region of the electroiet.

N74-29097

RELATING TERRESTRIAL ATMOSPHERIC CIRCULATION TO SOLAR DISTURBANCES

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Toronto, Ontario

During geomagnetic storms, which are initiated by solar disturbances, two cells of circulatory motion are established in the polar ionosphere. The torques that contribute to either cell might conceivably be as great as 10^{24} dyne cm, and may persist for times of the order 10^5. The angular momentum contributed to a cell may then conceivably be as great as 10^{29} gm cm^2. This is roughly of the order required to account for the changes of vorticity area that are claimed by Wilcox et al. (1973) to be correlated with reversals of solar magnetic sector structure. Transfer of the angular momentum from ionospheric heights to the vicinity of the tropopause might be accomplished either via viscous effects or via planetary waves with delay times of the order of days. A solar-wind source of angular momentum then constitutes one possible mechanism for relating terrestrial atmospheric circulation to solar disturbances.

The vorticity variations studies by Wilcox et al. (1973)* may themselves be analysed in terms of planetary waves. During winter, these waves propagate energy upward into the lower thermosphere. Some reflection may occur there, with the reflected energy returning to the lower altitudes and causing constructive or destructive interference with the initial disturbance. Changes in the reflection process, which might be induced by thermospheric circulation or other effects introduced during geomagnetic storms, would then alter the interference and so alter the observed vorticity. This second mechanism, in contrast to the first, makes active use only of energy derived from the lower atmosphere itself, where energy is in abundant supply. Moreover, in contrast to hypothetical "triggering" processes, the magnitude of the variable energy is a priori matched to the energy of the atmospheric circulation system being studied, albeit via unknown emission, transmission and reflection coefficients.

Mechanisms that require planetary-wave coupling between troposphere and thermosphere, such as the first may and the second must, could not be effective during the summer months because of absorption of the waves at intervening "critical" levels during those months. Such mechanisms would

*J.M. Wilcox, P.H. Scherrer, L. Svalgaard, W.O. Roberts, and R.H. Olson, 1973, "Solar Magnetic Structure: Relation to Circulation of the Earth's Atmosphere," Science, 180, pp. 185-186.

then contain a built-in explanation for the conclusion of Wilcox et al. (1973)* that the correlation they report is available only during winter months.

None of the foregoing should be taken to imply that the present author is convinced that claimed correlations between terrestrial atmospheric circulation and solar disturbances (or sector structure) are in fact established as being physically valid, nor should it be thought that the suggested mechanisms are free from serious difficulties in aspects of the problem that are not discussed here.

ADDENDUM

Circumstances and my own reservations about the mechanisms outlined in the foregoing abstract have combined to prevent my presentation here of an extended development of the abstracted material. The following comments may be of some interest to those who wish to pursue the matter, however.

The estimate of maximum potential torque as 10^{24} dyne cm derives from an extension of the analysis by Hirshberg (1972) to take into account the angular momentum of solar plasma prior to capture by the magnetosphere. It allows for the effect of capture of solar plasma on one flank of the magnetosphere at a time, in a process that could give rise to one cell (at a time) of the traditional two-cell magnetospheric circulation pattern (for example, Axford and Hines, 1961). Equal capture on both flanks simultaneously could give rise to a symmetrical two-cell circulation pattern (if various complexities are ignored), with no net transfer of total angular momentum, whereas significant departures from strictly equal capture could give rise to a net transfer of angular momentum of a sense either to speed up or to slow down the rotation of the magnetosphere, the underlying atmosphere, and (to an inappreciable degree) the earth; see Hines (1974a). The statement in the foregoing abstract referred to the torque a single cell at a time, and it would be operative whether or not a second cell were being established simultaneously.

The statement that an angular momentum of 10^{29} gm cm^2 is roughly of the order required to account for reported changes of vorticity area index corresponds to the calculation made by Dessler in these Proceedings, that a change of angular velocity of 2×10^{-5} rad is imposed upon a disk of air whose moment of inertia is 2.9×10^{26} kg m^2, which implies a change of angular momentum of 5.8×10^{21} kg $m^2/s = 5.8 \times 10^{28}$ gm cm^2/s.

Among the difficulties under comtemplation in my abstract for this mechanism was inefficient coupling. My own estimates in the problem of magnetospheric rotation (Hines, 1974a) would indicate an inefficiency marked by a reduction factor of 10^2 at least, and more likely 10^4, based upon observations of maximum wind speeds observed in conjunction with magnetic storms. A quite independent calculation of Dessler in these Proceedings yields a maximum angular acceleration of 10^{-13} rad/s, which, when combined with the moment of inertia cited above, implies a maximum operative torque of 2.9×10^{13} kg $m^2/s = 2.9 \times 10^{20}$ dyne cm and hence an inefficiency of the order 3×10^3 relative to my estimated maximum potential torque. Dessler and I are therefore in reasonable agreement on the degree of unlikelihood of my first mechanism being operative.

I did not reject this mechanism entirely, however, for two reasons: (1) The manner in which the vorticity area index is computed does not in fact demand that the changes of angular momentum should be as great as is indicated above. Indeed, angular momentum might in fact be fully conserved, and the reported variation of vorticity index might simply expose a redistribution of the conserved angular momentum. The question of available torque would then simply not arise; all of the foregoing discussion of torques would be irrelevant. The truth might be thought to be somewhere between the two extremes, somewhere between a required zero torque and a required torque of 10^{24} dyne cm, that is. Just where, I could not possibly say. But to get within two or three orders of magnitude of the maximum torque that might be required seemed to me to be something of an achievement in this general area of study, and therefore an achievement worth reporting, at least orally. (2) In conjunction with my second mechanism, greatly reduced torques might be sufficient. The second mechanism comes into play if the reflection of planetary waves is altered sufficiently at heights well above the 300-mb level, for example at heights of 60 to 80 km. The moment of inertia of the disk of air overlying those levels is reduced by a factor of 10^3-10^4 from the value previously cited, and the torques that are likely to be available then become adequate to effect appreciable changes of circulation and hence, it would seem, adequate to effect appreciable changes of planetary-wave reflection coefficient.

The discussion of the planetary-wave reflection mechanism is pursued a short distance beyond that given in the foregoing abstract in a paper submitted for publication (Hines, 1974b).

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CORRELATIONS AND LINKAGES BETWEEN THE SUN AND THE EARTH'S ATMOSPHERE: NEEDED MEASUREMENTS AND OBSERVATIONS

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INTRODUCTION

The main objective of the solar-weather relationships game, as most people seem to see it, can be stated as follows: To identify the sequence of processes that leads from some change in solar input to the earth to a change in tropospheric circulation and weather.

As a practical matter this game can be played in at least two ways, each entirely legitimate, and these ways are:

(a) To suggest processes that must be related to each other by establishing significant correlations in their behavior.

(b) To explain how one process can be related physically to another through a cause-and-effect linkage.

While the real objective is always the same, as stated above, the two ways of playing the game have different scoring systems, and they are all too often carried out in different arenas. Here, at this Symposium, we are endeavoring to bring them onto the same playing field.

The advantages of combining the two are pretty obvious: (a) suggests where the theoreticians should look for linkages; (b) suggests where to search for new correlations in the real world; and both suggest where we should make efforts to make new observations or rearrange the data from the old ones.

My assignment has been to take advantage of the ideas that have been written up before this Symposium, together with what I have gleaned elsewhere about the subject, to try to summarize what kinds of observations should be emphasized in the future—especially observations from rockets and satellites, but not exclusively. Fortunately, we are not by any means starting from scratch, since a great fund of information already exists; so my task is largely one of sifting out those factors which seem most likely to be important, based on what we have seen in the correlations and what have been suggested as theoretically possible linkages.

Since my paper was to be immediately followed by a panel discussion, it was designed to be a kind of springboard to launch a variety of ideas that need to be looked at critically. It started being revised in a matter of minutes after it was presented.

INPUTS FROM THE SUN, THE SOLAR WIND, AND THE MAGNETOSPHERE

It is clear that both the correlation approach and the identification of linkages must start with some conception about the inputs at the top of the atmosphere, and the variations of these inputs with varying solar activity. A great variety of indices have been used to tell when such variations occur, and part of the confusion in the solar-weather field, as has been pointed out many times, lies in the fact that different indices have been used by different investigators.

Table 1 is an incomplete but hopefully useful summary of such indices, relating to the sun itself, the solar wind, and the magnetosphere. The ionized regions of the ionosphere have been included along with the magnetosphere, since for the purposes of this review it would be fruitless to argue whether, for example, magnetic field changes are caused by processes in the magnetosphere or the ionosphere—they are in both, of course.

It is assumed that this audience is reasonably familiar with each of these indices, or changing features of the upper atmosphere and space, and their general significance. It will be useful, nevertheless, to point to some of the time lags that are associated with such indices, since the scenario that is enacted each time the sun changes its activity or has a flare takes several days to play to the end.

In Table 2 are listed the lags of some of the features that are being used currently by investigators of correlations over a period of days. These are the events that are generally attributable to solar flares, as observed optically or by increases in decimeter radio emission from the sun (the latter being an observation that is not inhibited by clouds). The early atmospheric events, limited to the daylight side of the earth, are caused by enhancement of X-rays and ultraviolet (UV) radiation that travels from the sun with the speed of light, and the later terrestrial events occur when the energetic particles (protons) ejected from the sun reach the magnetosphere and begin to perturb and penetrate it. The particles that reach the ionosphere at high magnetic latitudes (above L = 4), causing changes in electron density and auroral activity, are presumed to be in large part those that came from the sun and were guided by the earth's magnetic field, whereas energetic particles that arrive at lower magnetic latitudes are mostly trapped particles precipitated out of the radiation

Table 1
Available Indices of Changing Inputs to the Atmosphere

Observed from:	Indices that Refer to the: Magnetosphere	Solar Wind	Sun
The Surface	K_p, C_i Auroral activity Ionospheric features Radio wave absorption Ion and electron temperatures	Galactic cosmic rays Magnetic sector boundary crossings from polar magnetograms	Sunspots Solar flares (H_α) Decimeter radio emission Direction of solar magnetic field Plages, faculae, etc.
Satellites	Precipitation of trapped electrons and protons Changing upper atmosphere density and temperature	Solar cosmic rays	Near UV (1800-3000Å) Extreme UV (900-1800Å) Soft X-rays (10-900Å) Hard X-rays (<10Å) Gamma rays (?)
Interplanetary Probes		Interplanetary magnetic sector structure Plasma shock waves	

belts by wave-plasma interactions. (We are excluding here for the moment the very high energy "solar cosmic rays" and true cosmic rays.)

In a different category of solar indices is the solar wind's interplanetary magnetic sector structure, described at this conference in some detail in an earlier paper by John M. Wilcox. (see also Wilcox, 1968: and Wilcox et al., 1973). While the passages of the sector boundaries are associated statistically with a transition from "quiet" to "active" conditions on the sun and back, that does not mean that solar flare activity is necessarily constrained in the same

Table 2
Average Lags (in Days) of Some Terrestrial Ionospheric or Thermospheric Events behind Solar Flares Observed Optically or by Increases in Decimeter Radio Emission

Event	Lag
Enhanced ionization in ionospheric D-region on daylight side (radio wave absorption, fadeout, and such)	< 0.1
Polar cap absorption of radio waves (after major flare event)	0.5-1
Increased density and temperature in upper thermosphere (satellite drag increases, and such)	1
Magnetic storm, main phase	1-2
Ionospheric storm (for example, decrease in f_o F2 at 45° latitude and above)	1-2

Reference: King-Hele, 1962; Matsushita, 1959; Allen, 1948; Vestine, 1960.

way. Furthermore, there is a 4.5-day lag between the passage of the sector boundary across the central meridian of the sun and its passage by the earth, due to the transit time in the solar wind; the average time between sector passages is about 8 days.

Clearly, the transition in thinking from flare-related effects to sector-passage effects will have to be done with care.

A rather different situation prevails when correlations are sought over a period of decades, correlations involving the 11- or 22-year solar activity cycle. There is such good evidence that a variety of upper air phenomena and inputs to the atmosphere change in response to the solar cycle that it is not necessary to review the evidence here.

There is also one input to the atmospheric system that varies with the solar cycle and which reaches directly to the earth's surface, and that is galactic cosmic rays. These are sufficiently energetic to penetrate the earth's magnetic field and its atmosphere, and the solar control of such cosmic rays is now fairly well explained in terms of their deflection in the outer reaches of the solar atmosphere by the magnetic fields embedded in it. (We will return to these cosmic rays later.) So far as we can determine, no similar variations of galactic cosmic rays can be attributed to shorter term solar events such as flares.

INTERNAL LINKAGES TO THE TROPOSPHERE

We must now remind ourselves that we are interested here in transmitting a signal from the sun to the troposphere. Up to now we have dealt with the sun and the obviously solar-connected events in the magnetosphere and upper atmosphere. How can the signal reach the lower atmosphere?

As a general proposition, it seems safe to say that the signal can only get down through the atmosphere with any appreciable strength (at least enough strength to trigger something) by directly penetrating in the form of energetic particles or electromagnetic radiation, or by dynamical interactions between layers of the atmosphere. This seems to cover all the possibilities, but one has a feeling that in this business one is never safe from surprises. At any rate, we will summarize some of the facts in each of these three areas so that the possibilities will be clearer.

DIRECT PENETRATION OF PARTICLES AND BREMSSTRAHLUNG

Particles with energies of from 0.1 to a bit over 100 keV, both electrons and protons, account for the excitation of the aurora at high magnetic latitudes, but the total flux of energy of such charged particles averaged over a few square kilometers must be less than 10 erg/cm^2 s even at solar maximum, though their peak fluxes in the heart of an auroral arc can be more than 100 times larger (Friedman, 1964; Gregory, 1968). These derive their energies from the solar wind, though usually indirectly. There is apparently also a small component of electrons with energies of several tens of keV that are precipitated from the radiation belts in brief pulses due to VLF radio wave interactions with the trapped particles (Helliwell et al., 1973).

Some idea of how far such particles penetrate is given by Table 3, taken from Gregory (1968) and Dessler (this Symposium).

The very energetic particles referred to in Table 3 are solar protons, with particle energies approaching 10^9 eV (1 GeV) but with fluxes that are usually many orders of magnitude less than that of the auroral particles. However, such fluxes may reach 0.1 erg/cm^2 s over the whole polar cap for short periods during a major solar event (Gregory, 1968). Compare these energies with those for solar UV fluxes, given below.

A small fraction of the energy of energetic electrons is converted to radiation as they collide with the molecules of the atmosphere, the energy conversion efficiencies ranging from about 10^{-3} for some visible and near UV excitations to 10^{-5} for X-ray bremsstrahlung radiation. The latter can be detected on

Table 3
Minimum Penetration Altitudes of Incoming Protons and Electrons with a Given Initial Energy

Initial Energy (keV)	Penetration Altitude for	
	Electrons (km)	Protons (km)
1		156
10	98.5	122
100	77.5	105
300	67.0	98
$>10^5$ (or 0.1GeV)	Tropopause	

occasion at balloon altitudes in the auroral zone (Brown, 1966) and is a good indicator of energetic electron precipitation. Nevertheless, the fluxes involved are clearly very small indeed, on the order of 10^{-4} ergs/cm^2 s or less for the X-ray fluxes in the lower stratosphere during solar maximum, and perhaps reaching peak intensities of 10^{-2} to 10^{-1} ergs/cm^2 s (Gregory, 1968, Table 4, assuming 10^{-5} excitation efficiency for bremsstrahlung).

The fluxes of charged particles into the ionosphere at latitudes below the auroral zone are very much less on the average, but during major disturbances of the earth's field these incoming particles appear at lower latitudes, sometimes almost to the equator.

IONIZING RADIATION AND CIRRUS CLOUDS

One of the suggestions for an upper tropospheric link to solar activity depends on the ionizing radiation from auroral particles (or solar protons, perhaps) reaching as far down as the tropopause (300 mb, say) and initiating the formation of cirrus cloudiness before it would otherwise form (Roberts and Olson, 1973). Such cloudiness would change the heat balance of the troposphere, it is argued, and this would have an influence on the development of tropospheric circulation—specifically, the deepening of troughs in winter.

While some traces of ionizing radiation, such as very energetic protons (see Table 3) or bremsstrahlung X-rays from auroral electrons, can indeed get down to such altitudes on occasion (Brown, 1966; Blamont and Pommereau, 1972), the open question is whether they can nucleate clouds. Could such ions appreciably supplement or encourage the action of the condensation and freezing nuclei that are already everywhere in the atmosphere? Are there in fact increases of cirrus cloudiness following the precipitation of energetic particles at high latitudes? We will return to these questions later.

IONIZING RADIATION, THUNDERSTORMS, AND THE EARTH'S ELECTRIC FIELD

There is one other possible effect of ionizing radiation penetrating to the upper troposphere, and that is the increase that it would cause in conductivity of the earth-ionosphere column. An increase in the conductivity would cause more current to flow from the negatively charged earth to the positively charged ionosphere, and this would ("all other things being equal") lower the potential gradient. If the effect occurred over a large area the decrease of potential gradient would be felt worldwide, and might interact with atmospheric electrical processes, especially thunderstorms. This is discussed in a paper by Markson at this Symposium.

There is some evidence that thunderstorm activity is indeed related to solar activity (for example, Reiter, 1964; Bossolasco et al., 1972). Thunderstorms are presumably the generating mechanisms that maintain the fair weather potential gradient, and in turn they depend on the fair weather electric field to initiate the charge separation that increases the rate of coalescence of droplets (rate of rainfall), and that also, of course, leads to lightning (Sartor, 1969). A simple-minded line of reasoning, based on the above, would suggest that increased ionization from cosmic rays, solar protons, or bremsstrahlung would decrease thunderstorm activity due to the decrease in electric field (see Figure 1, Ney, 1959); but Bossolasco et al. (1972) have found exactly the reverse in their superposed epoch analysis of thunderstorm frequencies following an $H\alpha$ flare.

We seem to have uncovered another case where apparent facts and simple theory are in contradiction—too bad we have to be bothered with facts! Yet the conclusion is inescapable that if we are to unravel this possible set of linkages we need more and better data on thunderstorm frequency and global-scale electric fields.

To make matters still more confusing, attempts to determine whether thunderstorm activity was correlated on a longer term with the solar cycle have so far been negative (Ney, 1959; Figure 2, Sparrow and Ney, 1971), in spite of the established fact (Figure 3, Forbush, 1957) that cosmic ray fluxes and their resulting ionization have a distinct solar cycle dependence.

Nevertheless, to carry the thunderstorm argument one step further, a possible link between changes in the worldwide potential gradient and global heat

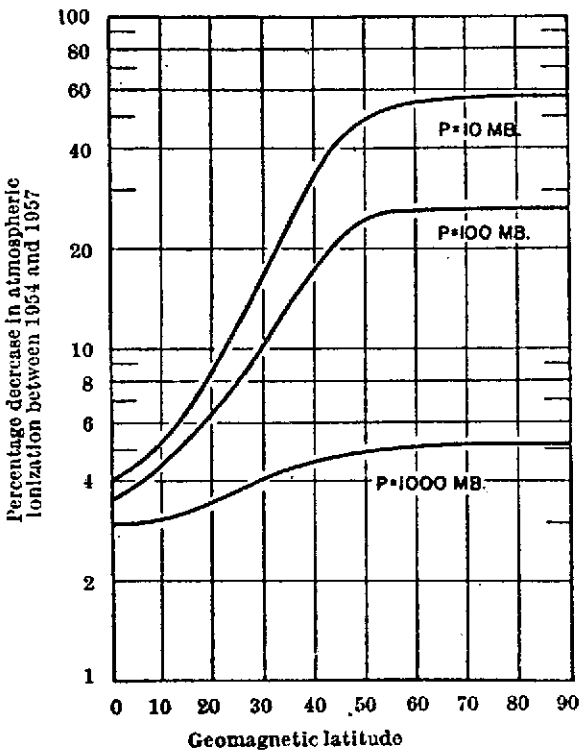

Figure 1. Percentage reduction in atmospheric ionization during the last solar cycle. The percentage change is calculated with respect to the value of the ionization at sunspot minimum in 1954. (Ney, 1959)

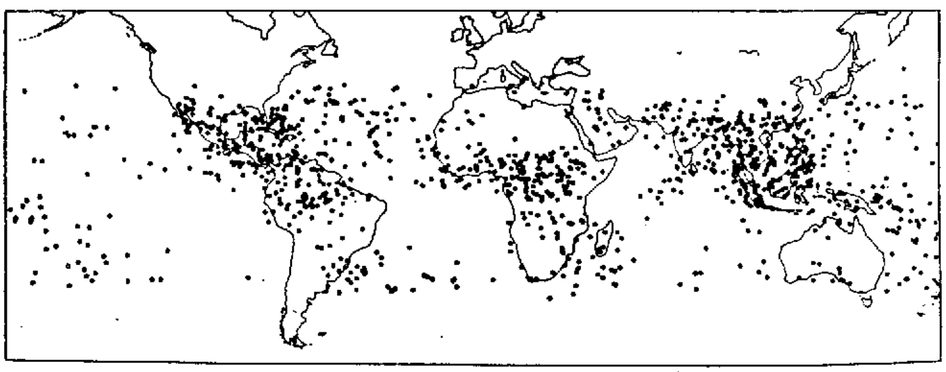

Figure 2. Distribution of nighttime lightning storm complexes observed by photometers on board satellite OSO-5. (Sparrow and Ney, 1971)

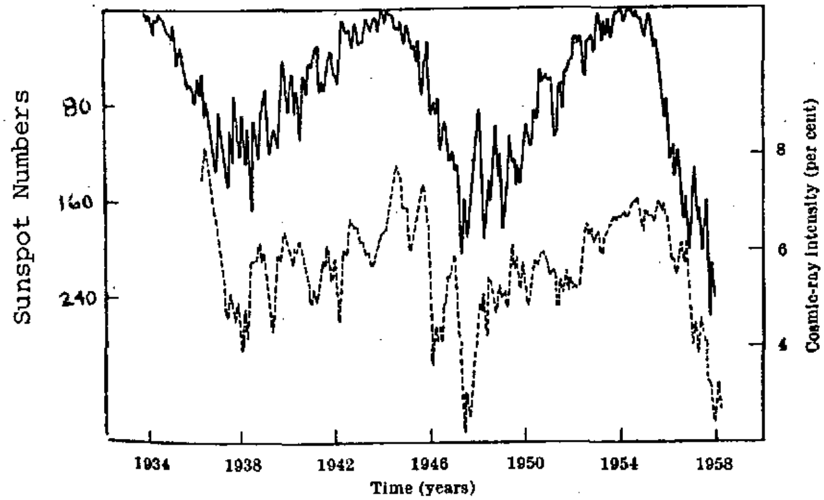

Figure 3. Illustrating the "Forbush effect," the inverse correlation of cosmic ray flux and solar activity. Solid line is sunspot number; dashed line is relative cosmic ray intensity. (Forbush, 1957)

balance can be hypothesized due to the effects of the increased cirrus cloudiness with increased thunderstorm activity (Ney, 1959), and also the greater convective vertical transport of heat and moisture (Byers, 1965). The former would tend to cool the upper troposphere while the latter would tend to warm it, but not at the same places. This hypothesis can hardly be considered as past the handwaving stage.

DIRECT PENETRATION OF ULTRAVIOLET AND X-RAYS

The sun's total output, the so-called "solar constant," does not vary by as much as 1 percent, which is the limit of our ability to measure its absolute value. Some solar physicists estimate a variation of less than 0.001 percent (Elske Smith, paper presented at this Symposium). However, it has been known since the pioneering rocket flights of the NRL and AFCRL groups in the 1950's that X-ray fluxes change very markedly with solar activity, and UV fluxes also change but much less dramatically. All of these radiations must be measured above the atmosphere, since below about 3000 Å they do not reach the surface.

An early summary of these variations of solar emission in the X-ray region is shown in Figure 4 and the depths of penetration into the atmosphere for various wavelengths are shown in Figure 5, both taken from Friedman (1964).

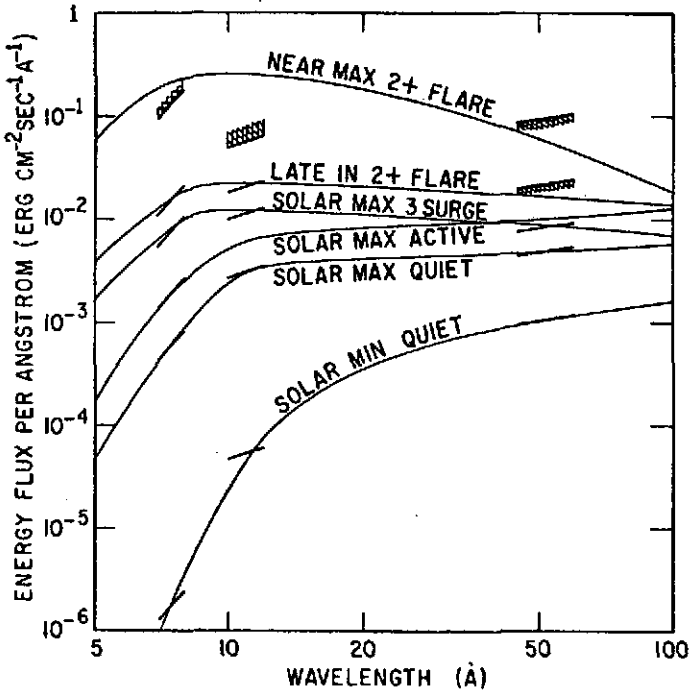

Figure 4. Solar X-ray emission for various solar conditions. The curves indicate the approximate energy distributions for sunspot minimum, sunspot maximum, and solar flare conditions. The curves are drawn on the basis of measurements made in three wavelength bands, as indicated by heavy bar segments. The slopes of the bar segments are the slopes of the assumed X-ray emission functions used to reduce the photometer responses to the energy fluxes plotted on the chart. Energy fluxes refer to values observed just outside the earth's absorbing atmosphere. (Friedman, 1964)

The situation regarding fluxes in the near and extreme UV is still not clear, since the authorities do not agree on the interpretation of the existing measurements and the measurements do not agree with theory (Breig, 1973; Roble and Dickinson, 1973). However, for these purposes it is probably enough that the integrated energy of solar flux below 1310 Å, excluding Lα, is about 3 ergs/cm^2 s, and the Lα flux around 1210 Å is 3 to 6 ergs/cm^2 s. In the Schumann-Runge continuum between about 1310 and 2100 Å, the flux is about 240 ergs/cm^2 s.

The penetration heights of these UV radiations are shown in Figures 6 and 7, after Friedman (1960) and Watanabe and Hinteregger (1962).

Between 2100 and 3000 Å, the solar radiation is absorbed by the Hartley bands of ozone, mostly in the stratosphere (Figure 6), and the total flux involved when the sun is directly overhead is about 17 W/m^2, or 1.2 percent of the

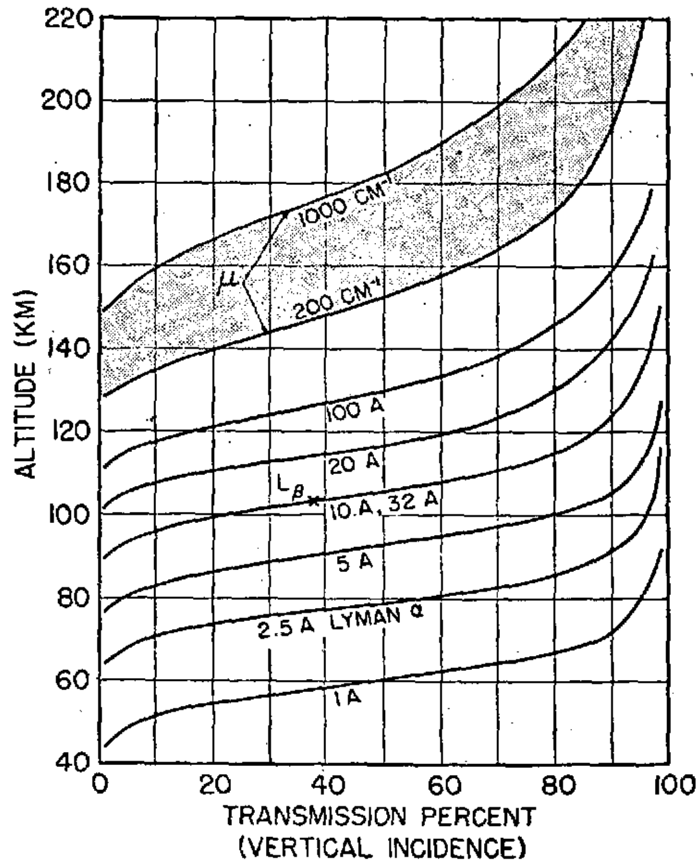

Figure 5. Penetration of the atmosphere by solar X-rays and UV radiation. The shaded portion includes the broad range of wavelengths from 100 to 850 Å for which the linear absorption coefficients lie between 200 and $1000/cm^{-1}$. (Friedman, 1964)

1400 W/m^2 solar constant (1 $W/m^2 = 10^3$ $ergs/cm^2$ s). This is an appreciable flux, and its absorption accounts for the warm stratosphere. There is, again, conflicting evidence concerning the variation of this near UV flux with solar activity. It could vary by a small amount—perhaps a percent or so (Heath, paper presented at this Symposium). However, even a 1 percent change of the 2100- percent to 3000-Å radiation would amount to 170 $ergs/cm^2$ s, and this is over 0.01 percent of the solar constant and a factor of 10 times more than the solar physicists expect (Smith, paper at this Symposium).

In view of the fact that this near UV part of the solar radiation flux does reach the stratosphere and troposphere directly, it is clearly a prime contender for attention as a possible solar-atmosphere link, and it is unfortunate that we cannot say more about its variations.

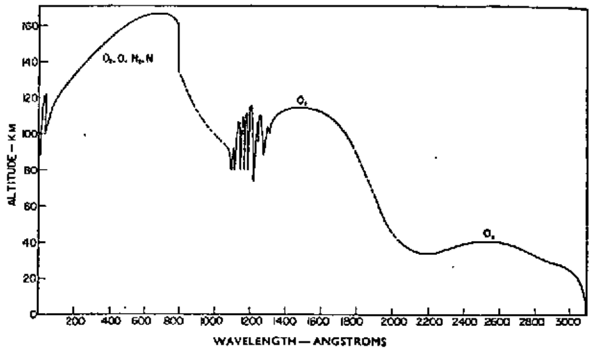

Figure 6. Penetration of solar radiation into the atmosphere. The curve indicates the level at which the intensity is reduced to e^{-1}. Absorption above 2000 Å is principally due to ozone, between 850 and 2000 Å to molecular oxygen, and below 850 Å to all constituents. (Friedman, 1960)

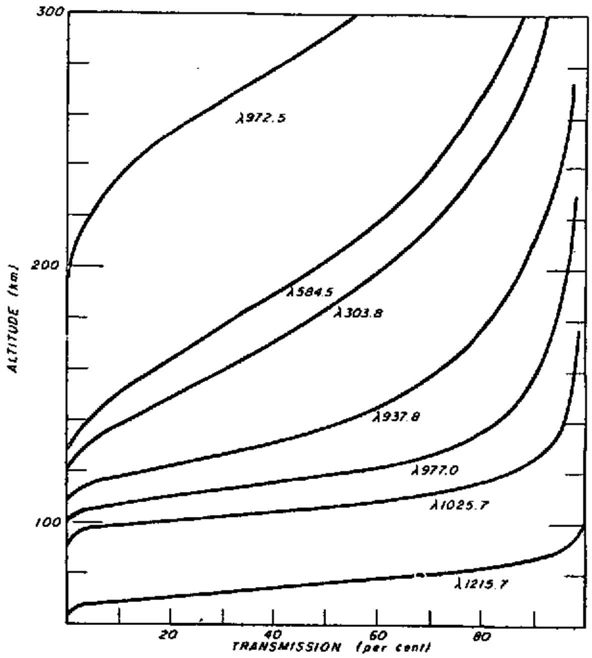

Figure 7. Penetration of the atmosphere by solar UV radiation. (Watanabe and Hinteregger, 1962)

PROPAGATION OF GRAVITY AND PLANETARY-SCALE WAVES

The fact that gravity waves (with horizontal scales of a few hundred kilometers) and planetary waves (with horizontal scales of a few thousand kilometers) can both propagate vertically and transport energy and momentum makes them a promising link between troposphere and mesophere or thermosphere. However, because of the fact that density falls off exponentially with height, the transport of energy or momentum downward has a trivial effect on the lower atmosphere; transport of energy and momentum upward, on the other hand, can and does have a very marked influence on the winds and temperatures of the upper atmosphere (Hines, 1960; Dickinson, 1968; Lindzen, 1969).

This has led Hines to argue that at least a part of the correlations that have been uncovered between tropospheric and ionospheric events are actually due to the tropospheric control of the ionosphere, and therefore are not related to solar activity. In order to get around this argument several investigators have resorted to the Wilcox solar wind magnetic sector passages instead of geomagnetic storms as indicators of solar input changes, since no one can argue that the troposphere has an influence on the solar magnetic field.

A new thought has been brought forth by Colin O. Hines at this Symposium, a variation on the gravity wave theme. The idea is that gravity waves and the related planetary waves can be reflected in the upper atmosphere, the conditions for reflection depending on the wind shears and temperature structure there. Changing solar activity does influence circulations and temperatures in the thermosphere, as we know; so why might not such changes cause the reflecting characteristics of the upper atmosphere to return the energy of the troposphere-generated gravity waves on some occasions and not on others, depending on solar activity? The energy involved in these reflected waves, given some constructive or destructive interference with the initial disturbance, could presumably be enough to change things in the troposphere, since the troposphere generated the waves in the first place.

While the suggestion is most ingenious, it appears that Hines has not yet been able to show in any detail how such a mechanism would actually work in the real atmosphere. We can predict, however, that this concept will attract others to pursue it as well, since until it is either demonstrated as correct or laid to rest as another bad idea it will serve as a source of frustration to all those seeking linkages in the solar-weather game.

CONCLUSIONS

Having tried to set down some of the main factors in the complex question of how solar changes could cause changes in tropospheric weather, we are more than ever impressed by the fact that relatively little progress has been made in finding completely believable links that could account for the apparent correlations that exist. Out of all the ideas and suggestions, however, a few seem to still hold some promise of providing the answer (or part of it), and these are the ones that should obviously be pursued.

Some observations that would help us to establish whether such linkage mechanisms make sense are as follows—and we realize that some of these observations have been or are about to be made:

- Continuous monitoring (by geosynchronous and polar orbiting satellites) of the energy and pitch angle distribution of geomagnetically trapped electrons and protons in order to determine when they are precipitated into the lower ionosphere. (The recent work of Helliwell et al. on wave-plasma interactions in the auroral zone will add fuel to this fire.) The most interesting information probably pertains to the auroral particles trapped at around L = 4, but attention should also be given to the particles that can be precipitated at lower latitudes.

- Monitoring from balloons in the region of the tropopause (10 to 15 km) the incidence of ionizing radiation and any accompanying changes of temperature, conductivity, ozone amount or ultraviolet flux, and so on. (This would be an extension of Blamont and Pommereau's experiment.)

- Continuous monitoring from a satellite of absolute solar flux in the near UV, between 2100 and 3000 Å. This should be done in several broad spectral bands, in order to establish any changes that would influence energy deposition (heating rate) and ozone formation in the stratosphere. (D. Heath of GSFC has tried to do this already in Nimbus-3, -4, and -5.)

- Monitoring ozone distribution in the region above 30 km, which can be done globally from satellites by techniques such as the Backscattered Ultraviolet (BUV) experiment on Nimbus-3, would also throw light on solar UV changes in the 2100- to 3000-Å region.

- Observations of wind systems in the mesosphere and lower thermosphere are possible by a variety of ground based (for example, radio meteor drifts) and rocket (for example, grenades, smoke trails) techniques, and should be tied to the proposition of Hines concerning the possible reflection of gravity and planetary waves under changing solar inputs. The theoretical work has apparently not yet pinpointed where one should look, however.

In a somewhat different category are the atmospheric features that may be closely related to changing solar inputs—perhaps even directly related. Any change in the circulation patterns and weather must be the result of a change in the heating and cooling of the atmosphere, so we should look for evidence concerning these energy-controlling mechanisms. In addition to the possible control of stratospheric temperature through the UV-ozone interaction (already covered above) there are two others that deserve our attention:

- Cirrus formation of high latitudes due to the nucleating effects of ionizing particles could be detected from satellites through optical techniques or through the effect of a cirrus deck on the upward infrared radiation in the atmospheric window. Cirrus is difficult to detect in the visible or near infrared, so the second alternative may be more promising. W.O. Roberts and his colleagues are attempting to do this.

- Thunderstorm activity, as pointed out, may be related to solar activity, and since thunderstorms transport heat and water vapor from the lower troposphere to the upper troposphere at low and middle latitudes, and also influence the amount of cirrus cloudiness, they play a role in the overall heat balance. There are both optical and radio techniques that could be used to monitor thunderstorm activity globally with the help of satellites (Jean, 1973; Sparrow and Ney, 1971).

- The frequency of occurrence of thunderstorms probably depends on the global fair-weather electric field, and this field must be, in turn, maintained by thunderstorms. To monitor the fair-weather electric field at representative sites, avoiding local interference as much as possible, is one of the aims of the proposed Atmospheric Electricity Ten-Year Program (Dolezalek, 1972). (See also Cobb, 1967.)

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QUESTIONS AND ANSWERS FOLLOWING THE PRESENTATION OF WILLIAM W. KELLOGG

MR. HAURWITZ: I don't think I understood this business about the gravity waves. Now, if I followed you correctly, the gravity waves, which propagate upward from the ground—there is really very little energy compared to the energy of the motion at the ground anyway—would under certain conditions be reflected from above. So, little energy comes back to the ground, and this should not produce a noticeable effect on the ground.

So I really don't see how the thing would work. I realize it is unfair really to ask, because you are not Colin Hines, and you have only read his abstract, but I thought I would just mention that.

MR. KELLOGG: I can only point out one thing. One of the difficulties the general circulation modelers have if they don't handle the upper boundary right is that the energy of the system really is changed by the reflection of gravity waves in the model. Now, the models, of course, sometimes generate more gravity waves than the real atmosphere, particularly during their initial startup, when you perturb them. Nevertheless, they do represent an appreciable factor in the overall energy of the atmosphere.

MR. HAURWITZ: The models which reflect all the energy really don't compare to what I think we are talking about here. We would, in any case, really just get a small fraction of the upward moving energy reflected and I simply don't believe that that is very much so that it could have any effect.

It might be interesting to see and also if possible to make some observations of whether gravity waves at say, 100 or 150 kilometers, are more in evidence at certain times of solar activity than at other times. That would be an additional suggestion for things that possibly could be studied.

MR. NOYES: The disagreement attributed to Don Heath and Elske Smith is only apparent because they are talking about somewhat different spectral regions. Dr. Smith is talking about the visible, where if you look at the sun it looks like a pretty homogeneous ball with a few sunspots that occupy only infinitesimal area. And her figure of a very small percentage modulation due to sunspots is due mostly to that. In the visible, you cannot see the active regions or plages, except at the limb with very, very small contrast. However, in the far ultraviolet these plages occupy a much larger fraction of the surface area and they cause a larger modulation.

I can't quote figures for the modulation in the region around 2,000 angstroms, but in the extreme ultraviolet, Lyman alpha, for example, typical fluctuations of 10 percent are certainly reasonable. I don't believe we can rule out fluctuations of several percent in the 2,000-angstrom region, where in fact you are beginning to see these plages as rather strongly emitting above the continuum quiet sun.

MR. KELLOGG: What is the change that you might imagine in the solar constant, which of course includes everything, the UV, visible, and IR.

MR. NOYES: I think I would argue strongly you could not see a change in the solar constant of the integrated luminosity of the sun of anything like a percent. It is going to be a small fraction of a percent. But certainly in the near ultraviolet, you could see much larger modulations.

MR. HEATH: From what I have seen over a part of the solar cycle, the change in the solar constant would be of the order of a tenth of a percent or less. I talked to Elske Smith and there really is no contradiction, we were talking about different things.

And I would like to make one other statement, and that is that Dr. Kellogg was talking about the ozone data. We now have completely reduced one year of the total ozone data for every day of the year from plus 80 degrees to minus 80 degrees. We are now going into the high level distribution, and one of the first things we are going to look for is different types of periodic phenomena, and see if we can find any, find what meteorological system or any other exterior system that they may be correlated with.

We do see that in the wintertime, especially in the southern hemisphere, that there are very strong fluctuations in the total ozone. These fluctuations have periods of the order of 7 to 10 or 12 days. These are zonal means. As far as this analysis goes, we have averaged the ozone around the world in 10-degree bands of latitude on a daily basis. And there are really very large fluctuations in the southern hemisphere in the wintertime, and there are fluctuations in the northern hemisphere in the wintertime but they are not nearly as pronounced. And the equatorial regions are extremely constant. I hope that these data will become available very shortly.

MR. KELLOGG: You see how fast this field progresses. Here I am suggesting an observation be made that has been made. I will look forward very much to seeing the data, though.

MR. MARKSON: Since you devoted quite a bit of your talk to thunderstorms, I would like to make a few comments. You assumed that all thunderstorm theories depended on environmental conditions. I would like to point out that the majority of thunderstorm theories do not; they involve, for example, temperature gradients, splintering, splitting of crystals, and riming-icing theories, all the things that have to do with particles.

Secondly, you implied that a change in conductivity, per se, would affect the electric field through the atmosphere, while recognizing that this conductivity variation would be in the upper atmosphere. Well, the columnar resistance above 10 kilometers is about 10 percent of the total columnar resistance, and at 20 kilometers it is about 2 percent. This is why my conclusion was that, even if you make a complete conductor out of the atmosphere above these heights, you have not changed the electric field in the lower region. Therefore, look toward changes in the current, possibly from thunderstorms, as your mechanism.

Third, another thing about thunderstorms, if they were changed, is that you have a nice source of cirrus clouds, which could affect your radiation budget.

And also, finally, a comment on the idea that the thunderstorm variation over the world could be measured from places like the Zugspitse or Mauna Loa with ground measurements. It takes a week's data under the most favorable conditions, at the best possible stations including the Arctic and ships at sea, to see the diurnal variation. But I think we have proven now that from airplanes flying well above the mixing layer, out over the ocean in maritime air, you can see it immediately.

Robert Anderson of the Naval Research Laboratory and I made measurements simultaneously, 7,000 kilometers apart, and our data correlated at the 99-percent significance level. And I think this points to the fact that now we have a way to look at worldwide thunderstorm activity, which then could be compared to the solar variation.

MR. KELLOGG: I would just like to make one comment on that. You are saying, in effect, that we ought to measure the potential gradients on a worldwide basis, and thereby monitor thunderstorms. But this does not answer the question of what made the thunderstorm activity change, or what changed the potential field. That is, if it is solar-related, then we still have to find that trigger, that handle, that the sun has on the lower atmosphere. It isn't enough to say that thunderstorms change. I agree with you, thunderstorms change. Fine, but what made them change?

MR. MARKSON: Well, if you are sitting over a thunderstorm, and concurrent with the arrival of particles which change the production rate, which change the conductivity, and see that the current goes up from that thunderstorm, I think you have a handle on what might be causing the effect.

SESSION 4

PANEL DISCUSSION—WHAT FUTURE CRITICAL MEASUREMENTS, EXPERIMENTS, AND THEORETICAL WORK ARE NEEDED, AND WHICH OF THESE CAN BE ACCOMPLISHED BEST FROM SPACE?

Morris Tepper, Chairman
National Aeronautics and Space Administration

PANEL DISCUSSION
WHAT FUTURE CRITICAL MEASUREMENTS, EXPERIMENTS, AND THEORETICAL WORK ARE NEEDED, AND WHICH OF THESE CAN BE ACCOMPLISHED BEST FROM SPACE

MR. TEPPER: In opening the conference yesterday, Mr. Hearth mentioned that we would address three problems, or three aspects of this problem. The first is a review of the status of our knowledge, and this we did yesterday. The second would be that we would explore and search for possible mechanisms, and we did that this morning. And the third part would be to investigate future critical measurements, experiments, and theoretical work that are needed, and which of these can best be accomplished from space. This is the subject of this afternoon's panel discussion, which was really introduced after lunch by Will Kellogg in his opening remarks.

In my letter to the panel discussants, I asked them to prepare a few remarks to open this discussion, and to address themselves essentially to these three questions, but emphasizing the third one in their view: what are the necessary observations and measurements? And, from the point of view of one of the host organizations, which of these can be accomplished best in space? Of course this would be very valuable to us in future planning of space program activities.

I thought it would be most appropriate to call on those members of the panel, first, that have not had an opportunity to make formal presentations. Starting from my right, I would like to ask Professor London to begin the discussion.

MR. LONDON: So much has been said in the last two days, and in a sense some of this so well summarized in the suggestions of Will Kellogg, that it leaves us very little to add. Unless we add spectacular things that, perhaps, have no or very little relevance. Or, as Kelvin suggested, are impossible simply because we don't know what is possible. I don't know what is possible or impossible. I will simply stick to a few ideas, or emphasize a few ideas that have already been made in terms of trying to focus attention on what I consider is perhaps the most fruitful line of investigation in terms of the future.

These are, I must add, personal views that have no commitment at all by any of my sponsors. My own personal feeling about a possible solar-weather relation was, perhaps, given a little push by the discussion of Somerville this morning, a realization that the atmosphere has a tremendous amount of inertia, a normal relaxation time of the order of 30 days. Therefore, it is my own feeling that—and this is now in terms of weather, and not in terms of the ionosphere—looking for relationships that are relatively short of the order of minutes, hours, or even days would not prove fruitful.

On the other hand, we are in the very, very unfortunate position—and I can say this because I have been following this work since 1955—that every time Walt Roberts tries to take some more data to disprove what he has done, the statistical certainty gets a little bit closer.

And I think that Walt is very, very unlucky. I know that Bernhard Haurwitz will pardon me for recounting a bit of fortune that he and I had once very soon after we first came in contact with Walt. Bernhard had a long history of looking for possible solar weather effects, and has a few suggestions in the literature. One time after a conference in Boulder it occurred to me—we discussed this—that if there were a direct heating of the stratosphere, as a result of solar flare activity or other activity, this would give a temperature rise in the stratosphere. And since the semidiurnal tidal oscillations are fairly well tuned to the temperature in the stratosphere, one should find an amplification of one of the semidiurnal tidal components, the lunar tidal component.

As a result, when we got back to the quiet academic atmosphere that used to be New York University, we looked at the correlation between the amplitude of the semidiurnal lunar oscillation and sunspots. For the amount of data that we had available, some 45 years if I remember correctly, we ran the correlation coefficient, and unfortunately it was 0.2, and for the number of data points was significant at about between a 1 and 5 percent level. And we were disturbed. Fortunately, Bernhard had an old friend who is an astronomer, and who had published a list, in a book, of sunspot activity that went way back. At that time he went back to the library, picked up an additional five years of sunspots, for which he had five years of data from Batavia on the lunar semidiurnal tide, put the extra five data points in, and we were very fortunate. The correlation coefficient went to zero!

(Laughter.)

This, incidentally, we published in the JGR. We had thought of publishing it in the Journal for Unsuccessful Research, but we thought that negative results in this case were important. Let me indicate—I don't think we should stop looking for a short-term variation just because my gut feeling says that we won't find one. Let me point, however, to some physical types of relationship that one can expect, and perhaps should look for, and these can modulate the atmosphere over perhaps a long period of time.

It seems to me that one of the most direct sets of observations that should be made is observation now from satellites of the absolute magnitude and the time-period variation of the solar constant, if any. I think it is almost criminal that it has not been designed so far. And in terms of the entire atmosphere and scientific community it is an observation that simply has to be made. One has to, once and for all, determine whether or not there is any kind of variation. Now, this does not mean that there won't be variation from some parts of the spectrum. We have already had ample discussion of this today, and I think that the type of observation that Don Heath is making should be made, incidentally, by other people; that is, there should be another independent verification of the Nimbus system of observation. Not that we doubt Don at all, but we need some independent verification, because I feel that the results that he has shown are so important in their implication of, if not at the ground, at least an atmospheric effect that could be felt at 60 or 70 kilometers. Let me indicate the line of reasoning that undoubtedly would be important in looking at the kind of variations that Don looked at.

We can skip the near ultraviolet for a moment, around 2900 angstroms. And if one goes down to the observed variation in the middle ultraviolet from Lyman alpha all along, we know that the Lyman alpha variation can directly affect the dissociation of water vapor that is found at 60 or 70 kilometers. And there is a very nice molecular oxygen window in this region, and there can be penetration by Lyman alpha down to levels of 60 or 70 kilometers. Lyman alpha will dissociate water vapor.

Water vapor being dissociated in this way forms a hydroxyl which will have at this level deleterious effects on ozone. There is ample evidence in terms of laboratory measurements that this is true. The relaxation time for ozone and water vapor is relatively short at these levels. This will be an effect that will be found principally in equatorial regions rather than in polar or auroral regions. Therefore, this is an effect that would be distinctly different from that of particle radiation, which is focused directly into the polar regions, which would have a similar kind of influence except in the opposite sense.

Protons or particles that precipitate into the polar regions have within their own energy spectrum the ability to dissociate molecular oxygen. The dissociation of molecular oxygen, now, has an opposite effect to that of hydrogen. That is, we get atomic oxygen which then reforms into ozone, and we will get, therefore, an increased amount of ozone as the result of particle precipitation. The point here is that now the relaxation time, however, is long if it is in the dark side, because there is no proton dissociation present. So we would get a completely different effect as the result of both of these.

I would urge that we make efforts to repeat Don Heath's type of experiment, giving him support. This is an unpaid announcement. But also to devise another complementary system to observe the same thing.

There are two other kinds of observations that I think are important. It is always easy, at least for me, to argue with Colin Hines. However, I think that in his discussion of the problem of trapped energy, in terms of dynamics and wave motions in the atmosphere, there is a point to looking at this particular problem.

There are many types of trapping phenomenon that take place in the atmosphere. One, for instance, takes place at the base of the stratosphere as well in the thermosphere. This is a kind of trapped energy that is at least thought by some people to be responsible for the quasi-biennial oscillation. Therefore, changes in the energetics in the radiation budget in the composition of the atmosphere at levels in the lower stratosphere, levels of about, let's say, 18 to 25 kilometers, could have some type of resonant effect or reflecting effect, which will be important, not for short period variations but for long period variations.

I think you had one example of how the atmosphere reacts in this kind of thing. The current theory accepted by many people, as to the origin of the quasi-biennial oscillation, is an energy source that comes in the tropical troposphere as a result of convection that makes itself felt in the form of Kelvin waves in the base of the stratosphere. These have periods characteristically of the order of about 15 days or so. The quasi-biennial oscillation is an oscillation of the order of 24 to 30 or 33 months. So that if one has a forcing function, there can be within the atmosphere some type of response such as that. It is because the atmosphere acts this way that I think one should concentrate on observations that affect the stratosphere for some kind of an indirect effect.

The last set of observations, I would suggest, therefore, is one that directly affects or could affect the stratosphere, where one also needs some additional observations. The trace constituent in the atmosphere that is most responsible for the thermal structure, and therefore with a latitudinal variation for some of the dynamics of the stratosphere, is of course the ozone concentration.

I would suggest that we make, as a result of balloon observations, all attempts at getting a measure of the ionization rate in the energy deposition in the stratosphere, particularly in this case in polar regions, to find out what possible changes there could be to the constituents at this level. Now, as I have indicated here, too, there are two opposite theories as to what might happen as a result of increased ionization. One could have, with increased ionization, a change in the nitric oxide content, which when recombining with ozone will destroy ozone. This is the present SST type of problem. But there is another mechanism, and one that would ionize oxygen, which would again produce some atomic oxygen particles and tend to increase the ozone content. Both of these, however, would require sufficient ionization at these levels to be able to produce some type of an effect. Now, if these effects, however, are going to be felt in terms of ozone variation, it would seem to me the most important thing to do is measure the ozone at this level.

And here, again, I would like to endorse the kinds of work that Don Heath and others are doing, and ask NASA not only to support them but to continue this for an additional very, very important reason. That is, continue the observations of not only the vertical distribution of ozone from satellites, but also of the total ozone amount from satellites. And the reason why observation of the total amount from satellites is particularly important is because we have a long history of total ozone observations from the ground, dating back to about 1930—1925, 26, 1930.

Therefore, if we can find something in present observations, which observational period necessarily will be short, then we can possibly extrapolate that fact in time. So I would suggest that the observations of both total ozone and of the vertical distribution of ozone are quite important to determine some type of possible solar weather effect.

MR. TEPPER: Thank you very much. Before we begin an interactive discussion among the eight members of the panel and the audience, I think we will proceed with the rest of the opening statements by the panel members.

I would like to call on Dr. Parker now.

MR. PARKER: Well, I have sat here yesterday and today and listened with great fascination to the various facts and ideas that people have presented. And there are several things that come to my mind.

Speaking as an amateur—I guess a lot of us are amateurs in this field though many people have some professional knowledge of various parts of it. First of all, I am impressed with the subtlety of some of the large effects that appear. Maybe it sounds a little contradictory. I think an example of what Walt Roberts did is a good model for what I have in mind, namely drought in the high prairie. It is a large effect if you happen to live in the high prairie. It is sort of a difference between rain and no rain for a period of several years. On the other hand, it is a subtle effect, because it appears only along a fairly narrow band of land which lies in a particularly special place. And in listening to the effects that other people talked about, I have a feeling that all of the effects are of that nature, not always large.

Sometimes though, they are strikingly large. They are always very subtle and difficult to get at, but nonetheless important in some way in the climate and the weather of this planet. Regarding the possible explanations and mechanisms for these solar activity effects in our weather, I think the evidence is fairly strong that there is a real connection. But so far as the explanations and the mechanisms go, the possibilities that people have mentioned here seem to fall into two categories.

On the one hand, there is the category in which you find some instability or resonance in the earth's atmosphere. The earth's atmosphere is quite unstable. It not only fluctuates from day to day, but there are various patterns, and it seems able sometimes to flip-flop between these patterns, implying some kind of an instability. And several people have mentioned resonances of various kinds. These are simply properties of the system where a small push of one kind or another can make a big change in the weather.

On the other hand, there are the mechanisms which are best represented by the ideas, I guess first suggested by Walt Roberts, that perhaps extra ionization in the atmosphere leads to nucleation formation of high cirrus clouds. And so, with a very small expenditure of energy you have built in a feature which then brings on the greenhouse effect, and the sun does the rest. People have mentioned—Julie London was just talking about ozone, and I have heard other people mention oxides of nitrogen, and so forth. These would all be examples where a very small investment in energy of some special and efficient form sets up the atmosphere in a way that the atmosphere then reacts quite differently to the tremendous power being forced in by the sun every day.

I suspect there are contributions from each of these two categories. I certainly think we are up against a complicated phenomenon that probably is made up of anywhere from ten to an infinite number of effects, and I think we should certainly pursue all of these. I continually am impressed with the possible long-range importance of this particular connection of solar activity with terrestrial weather. Perhaps my feeling of urgency is exaggerated or beyond what is reasonable, but perhaps I am recoiling from the present feeling in this country that if you can't make a buck on it in the next 12 months, the hell with it. I think that here is a case where the payoff is tremendous. It is going to involve a lot of exploration before we can even talk intelligibly about it, and before we can focus in on more than one or two exploratory programs.

But let me come back to a favorite topic of mine which some of you have heard me talk about before. There are indications in the historical records of the last couple of centuries that the level of solar activity sometimes varies far more than anything we know of in the last century. We have certainly seen some fluctuations in solar activity. Perhaps the best documented of these early variations is the period 1645 A.D. to 1715 A.D., a period of about

70 years. Telescopes were available during this time. I remember that Galileo invented the thing about 1500. Sunspots were known and records were kept. I am not a historian, but my impression from reading articles about it is that they were kept fairly systematically. People observed eclipses. Professionals observed eclipses. And of course, you know an eclipse is a very awesome sight with the solar coronas beaming out light behind the dark side of the moon, and so forth. During this 70-year period, starting in 1645, the sunspot cycle was there, the general 11-year half-cycle was apparent, but the number of sunspots which appeared were extremely small. And they appeared only in one hemisphere—enough sunspots to identify the cycle, but instead of thousands, it was just a few hundred. At the same time, it is recorded that the eclipse observers failed to see the solar corona. Inasmuch as people who have been to eclipses tell me this is a spectacular aspect of the eclipse, it is hard to understand how they could fail to see it, if it was there. It makes one wonder how low the level of convection and activity in the sun might have fallen during that period of time.

It is also claimed that during these years there were only one or two auroral events per decade, instead, of course, the fairly large number that you see now. And remember that in the Scandinavian countries, which were active in scientific matters in those days, auroras are a very common occurrence. So that, if they recorded very few auroras, then, the indications are there were very few. Well, I have no way of verifying these reports. The papers which comment on them are very vague about their references. They merely say, "the records show," but it seems that, unless something really has gone wrong here, the sun was extremely inactive during that period of time. Just how inactive is, of course, a little hard to assess now.

There are some clues as to the weather, though the weather records are, of course, very poor from those times. There were apparently some worldwide changes in mean temperature, which people have wondered might be connected with that very low level of activity.

I think the thought that I would like to leave you with is that if the sun can play games once, it certainly can play games with us a second time, perhaps not anything like the first time around. It is conceivable that the sun might become extremely active. And inasmuch as we humans are foolishly pressing on both the mineral and food reserves of this world by continually increasing our population, so that we have less and less spare in reserve for worldwide changes, I think this problem of the solar connection to weather and trying to anticipate what enormous changes in solar activity might take place in the future, is, let me say, urgent in the long-range sense. That is, I think it is something we really must follow, if we want to be able to foresee and plan intelligently for our future.

MR. TEPPER: Thank you very much, Dr. Parker. I would like to call on Dr. Nordberg now for his remarks.

MR. NORDBERG: I was going to start this with an historic announcement. I was going to say that for the last day and a half I have been pondering what I should say here this afternoon, and after all this pondering I came to the conclusion I had nothing to say. But this has changed. I was listening to Will Kellogg at the beginning of the afternoon, and I found that what he had to say agreed, in large part, with my thoughts. And therefore, I could say a lot by just repeating those parts of what Will Kellogg said that I agreed with. So I will start.

I want to get a few definitions straight, and I thought I would address myself in some variation of the title of the Symposium, to the interactions between extraterrestrial phenomena and processes and the weather. That would not necessarily confine itself to the sun, because it is really interplanetary space when we talk about extraterrestrial phenomenon processes. However, it would leave out the very enthusiastically discussed subject of gravity wave propagation or propagation from the ground on up, and maybe mysteriously coming back down again. It leaves it out conveniently, because I really do agree with Bernhard Haurwitz's introductory remarks to this question that it is unfair to address it amongst each other, if Colin Hines, the proponent of that idea, is not here. So I conveniently leave it out by definition.

Then, having made that definition, I believe that whatever one has to say on this subject must be subjective. Because wherever you go from this point will tend either in the direction of trying to prove a relationship or disprove it. And depending on whether you believe in it or not, it will go in one direction or another. And my conviction is really very much based on the evidence that you have heard expressed by Walter Roberts and many others. I do believe in the evidence.

There is, I think, very convincing evidence that there is some relationship, even though it is only statistical. However, it is easier to believe in a physical process, because that is obvious. It is all part of the same physics. So there should conceivably be processes that relate what happens out there to what happens within the troposphere. Now, having said that I believe in the evidence, I am trying to pursue how we can answer some of these questions that were raised to the panelists.

I would like to follow the formalism that I know you, Morris, and I, and those of us involved in the meteorological program have discussed a lot, namely, these three elements or milestones of observation, understanding, and prediction. And how far along are we, how far along should we go in assessing the status of our knowledge in observation, understanding, and prediction?

Concerning prediction—we can forget about this. The only thing that I would predict here today, in relation to the interaction between extraterrestrial phenomena processes and the weather, is that probably 15 years from now there will be another panel discussing it. That is as far as I would go in prediction.

So we are dealing mainly with the proceeding from observation to understanding, and then with the mutual interactions between those two milestones. And it is always an iterative process. You make some observations of phenomena. You are trying to understand the processes involved, from which you get a better idea of what you really should observe, and specify better your observational parameters. You go back to the observations, and eventually a model will result from this upon which you make some predictions. Now, as was already alluded to in the discussions this morning, both the observation and the understanding cover a very wide range of spectra. And each of these spectra starts, I suppose, with a very uneducated guess at one end, and at the other end has in the observational area a complete quantitative and topological description of all the parameters involved.

In the understanding area, you go from better and better educated guesses to very rigorous analytical models, which encompass the entire domain. That is an important point. I think the Lord Kelvin reference was a good example. I think Kelvin had a very good understanding of what was going on, but in a rather limited domain. And he overlooked the fact that whatever was being discussed transgressed the boundaries of that domain. At the extreme end of that spectrum you could either have a very good understanding of a rather limited domain, or some poor understanding of a larger domain.

Now, where do we stand on our subject in both the observational spectrum and the spectrum of understanding? Well, if you narrow the domain for a minute—I don't want to belabor the point, but I think it is a significant thought which is worth repeating—if you limit the domain, say, to either the interplanetary structure phenomenal processes or tropospheric phenomenal processes, mainly weather, we are fairly far along in both of them.

I have been, in the last few years of my career, much more exposed to the latter, to the understanding of tropospheric processes, than to the interplanetary, magnetic field structures and particle physics. And I was very impressed when I listened to some of the talks, how much has happened, particularly since IGY, but perhaps even more so in the last five or six years.

So we are very far along in each of them, both in the observational area and in the understanding. I think in the meteorological area in the observational spectrum, we are very close to having a complete, quantitative, topological, if you wish to call it that, description of the weather field. And, after all, that is what we are after with the Goddard group, and if the Goddard program is anywhere near being successful, that is what we should be getting out of it in the late '70s.

A similar situation is in the understanding area. The models you have heard of, and you have got a small glimpse of them from the Jastrow group this morning, are quite far along. I am sure analogously similar things can be said by people who are better qualified about the field, particles, and radiation area. I am also sure that everybody will agree with me that the link between the two is very greatly lacking, and that in that link, which is, after all, what we are talking about when we are talking about interaction, we are very much at the beginning of the spectrum, both in the observational category as well as in the category of understanding. And here I am becoming very subjective, because I am filtering what Bill Nordberg liked to hear or thought he heard in these various presentations, when I come to defining where I think we stand. And please, in the ensuing discussion don't spend much time proving that I was wrong or that I misunderstood. I will agree with you perhaps. So rather, if you think that I am wrong, please give me your understanding of what you think, and how you think it differs from mine.

In the observational area, I think we have demonstrated very much the existence of some relationship, of some interaction, between the extraterrestrial phenomena and weather, although these demonstrations are purely statistical and phenomenological. They are not quantitative. They are not even good, complete pictures in a qualitative way, but simply statistical relationships which I believe are significant. And what we want to do, of course, is to push them forward to the next step. And I think the next step from that is to have some qualitative picture, from which then will result a better understanding, which will lead to specifications of very selective quantitative measurements, down then to the complete quantitative picture.

In the area of understanding, I think I have got out of the many relationships that were mentioned and the many areas of understanding that were alluded to a fairly educated guess and a relationship that goes something like this.

It starts with the particles and perhaps electromagnetic radiation, but I would rather like to believe and concentrate on the particles, which somehow are guided down into the stratosphere and perhaps upper troposphere by a magnetic field structure, or by a field structure, or processes in a field, and which cause ionization and perhaps chemical processes in the stratosphere and perhaps upper troposphere. These then lead to condensation and to modifications of the radiative transfer in that part of the atmosphere, and that, in turn, relates to tropospheric dynamics.

That is the process, or the educated guess of a process that I would like to concentrate on, and I would like to pursue out of the many that were discussed. I guess you alluded to between half a dozen and a dozen. But if you want me to say what ought to be observed, and how difficult it would be to observe something, and what should be investigated, I would like to take one of the items, and that is the one that I have mentioned—the models and analysis area, which is synonymous to the understanding part of the activity—and I would rather start with that in a deductive way. I would rather say, all right, what do we have to do next to understand better these processes and phenomena, and that leads back to the observation system, almost arbitrary where you start the cycle.

In the area of understanding then of models and analysis, I would like to see a much more concerted effort and an organized effort to investigate the feasibility quantitatively, investigate the feasibility of producing ionization and chemical processes in the stratosphere and perhaps in the upper troposphere. This, I believe, has not been done really highly quantitatively, if what Will Kellogg presented this morning was any measure of the status in this area. I don't think it certainly has been done with specific regard to showing a relationship of the radiative flux divergence to the condensation of cirrus clouds, and so on. Certainly not a lot of effort has been put in, in a quantitative and mathematical way.

Next, of course, and in parallel perhaps, we want to describe the possible relationship between tropospheric dynamics and radiative energy transfer, as modified by the variations in the state of the stratosphere and the troposphere, namely, the occurrence of various types of cirrus clouds, the occurrence of selective areas of condensation, which of course then are, in turn, introduced by the extraterrestrial phenomena.

Now, when you go to the parallel requirements for observations, then, in the first area of understanding that I had mentioned, namely investigation of the feasibility of producing these ionizations and chemical processes, we want to observe the occurrence of that. And that would also lead to quantitative measurements of the parameters—of the parameters relating to these condensation processes and to related flux divergences—on a geographic, temporal, and height variation scale. In other words, we really would like to explore and describe the stratosphere, the structure of the stratosphere, and the upper troposphere much better than we have done up to now.

And really, as far as I know, the only thing that has been done in that area quantitatively on that kind of scale were the ozone measurements that Julius London referred to, by Don Heath. Of course others have done ozone measurements too, but I think the Nimbus-4 set of measurements by Don Heath was probably the most complete, and certainly the largest data set on a temporal, global scale.

We have data now for about four years of the ozone structure. But the ozone structure is just a small part of it, and further, there haven't been any measurements of the chemical structure of the stratosphere made on that kind of scale that come close to the ozone measurements. They are difficult to make, of course. Perhaps what is being planned with Nimbus-G is a step in the right direction, but it is not a very extensive step, and I am sure it does not go far enough to fulfill that requirement that I am talking about.

The second set of observations would be concentrated on the long-term variability of cloudiness and radiative flux divergence, and on tropospheric dynamics. Tropospheric dynamics can be easily dispensed with, because you can just take the daily weather maps which result from a large number of observations, some of which are satellite-based. The cloudiness and the flux divergences are much more difficult.

I don't really know how we could get a good, complete, long-term set of global observations of radiative flux divergences together. We have struggled with this ever since the first meteorological satellite was conceived. Bill Bandeen is one who knows that very well, and the entire platoon of Julius London's students had been put to work from the early '60s on to help us derive some flux diverbence measurements from the TIROS radiation observations.

Of course, it is difficult. So this is going to be some combination of both geostationary and polar orbiting satellite operation, very strongly complemented by ground-based and probably balloon observations.

And finally, on the cloudiness variations, some of you may be disappointed that I am pessimistic about it, or that I am saying we really haven't obtained any global cloudiness observations, because after all that is what we observed with TIROS-1. But those of you who heard Bill Bandeen's remarks this morning, I believe in statement of a question, will remember that the observation is much more complicated than that of just the occurrence of clouds. For the processes that we want to understand, it is really required that we know the radiative characteristics of the clouds and their composition, at least to some extent, in terms of particle sizes, particle distribution, whether ice or water, thicknesses, et cetera. And this has not been observed in any way from a satellite so far. It is only being inferred in secondary and tertiary ways.

You have heard that Walt Roberts had attempted to analyze this very phenomenon on the basis of a data set compiled with Nimbus-4. And aside from the difficulties of just mechanically extracting that information out of the Nimbus-4 observation, there are also serious scientific difficulties in extracting information in terms of cloud thickness and cloud properties.

The Nimbus series of satellites, including Nimbus-5, which is flying now, and Nimbus-6, which will be flying soon next year, are not designed to observe cloud structure. They only are designed to observe cloud cover and the circulation features associated with it. Further, Nimbus-G does not have a cloud-observing tool on board. And the earliest time that we here at Goddard, and I think that speaks for the entire NASA meteorology program, are thinking of a cloud physics type of observation from a satellite, is somewhere down in the early '80s on something that is called the Earth Observatory Satellite Number 2. In the realm of the geosynchronous satellite, it would have to await measurement from a sounder, which is also some years downstream; or perhaps even better, from what we call the SEOS, the Synchronous Earth Observatory Satellite, which is, again, down into the 1980's.

And finally, I would like to recommend the observation of something that I alluded to this morning in my comments when I talked about resonances and forcing functions, and the relationship between the sector boundary passages and the planetary waves. Here I am not smart enough to specify the observation to be made. But in essence, we should be thinking about perhaps nothing in terms of an instrument, rather more in terms of what approach to take, and that is to expand or concentrate our statistical analysis on that forcing function-resonance relationship, namely, a resonance between the spectra. And I emphasize now the spectra: the frequency spectrum of magnetic sector boundary passages and the spectrum of tropospheric cyclogenesis.

MR. TEPPER: Thank you very much, Bill. I think that concludes the three speakers that haven't had an opportunity to have formal statements. And I would like to call now on the rest of the panel members for additional remarks over and above those that they made formerly, and specifically directed to the subject of panel discussion.

I would like to start with the other end of the panel. Dr. Akasofu, please.

MR. AKASOFU: I have several remarks here. I don't do statistics myself, but I have a list of people who do statistics in this particular field. I think we are in a stage to try to eliminate various possibilities and try to narrow down the possibilities and eliminate the very obvious, you know, the things that are going to occur. And I hope in this way that you don't eliminate everything. I think the Kp seemed to correlate everything. This is the beginning of the trouble.

First of all, I would like to see Dr. Roberts' drought case. He indicated a 22-year period, and Kp is obviously 11 years. In this case, we have two ways of going: one is improve the statistics, or try to find some other parameter which can say it is not due to Kp or something else. That is to say, the solar interaction we can think of in two ways: One is a radiation coupling, the other is an electromagnetic coupling. We should try to find some means to eliminate the various obvious possibilities and narrow down the parameters which are really affecting the weather.

Then I would like to go to the experiment on future studies. I will just pick up two of them. To me, as Dr. Dessler said, it is so difficult to couple the top of the atmosphere and the troposphere. I feel that perhaps I am an amateur; as I stated earlier, I would like to pick up ozone as one example, and I feel that every effort should be made to study it in such a way that by the next meeting, if any, we can say that ozone is important or is not important. We should have good observations by infrared methods or rockets, also theoretical studies like Dr. Maeda did. So I would like to know as soon as possible, say, if ozone changes after aurora activity, or does not change.

Another thing, I think I would like to see if there were any drastic changes of chemical composition in the agents of the atmosphere. And people are finding all kinds of complex molecules and ions these days, for example HNO_3 and $H_3O^+ \cdot (H_2O)_n$, and I find it a very, very interesting subject. I would like to see if those complex molecules drastically change before and after solar events.

Perhaps we could again use rockets. What type of laser beam could we use? Anyway, this is a region people call "ignorosphere." So this is a good time to study it.

Just a final comment. Of course, I am doing the aurora business, and I like to see that what I am doing has something to do with society. I have the men do something good for society. So I would like to see that the aurora does affect the weather, but we can't just jump into the weather study. We have to understand the "aurorasphere." We can't just jump across this and worry about the weather alone. I think we have progressed tremendously during the last five years in understanding thunderstorms and all that, but still there is a lot to be done, and we cannot, we should not jump across that. Otherwise we have to go back and do the same thing again. Thank you.

MR. TEPPER: Thank you very much.

Mr. Kellogg, you have spoken to us extensively about your views on this subject. However, I see it is at least an hour since you concluded your last remarks. I was wondering if you have any modifications you would like to make at this time.

MR. KELLOGG: I do feel a bit talked out, but there are two things which have come up which I would like to address myself to very briefly.

Somebody, Alex Dessler, I guess, asked the flux of gravity wave energy. Al Miller from the Air Resources Lab of NOAA, who I don't spot here still, came up during the intermission and said that he had a number, for which I am grateful. And it is 300 of these units, 300 ergs per square centimeter per second. If he is still here, he may wish to explain that number, if anybody wants to go further with it.

Now, Bill, on connection with the matter of looking at cirrus clouds from s satellites, you may be familiar with the work that Gary Hunt is doing with the British scanning Selective Chopper Radiometer, the far IR channel, which hopefully will get at specifically the matter of cirrus, looking for and trying to identify ice. I think if it works that is going to be a step forward in this particular field, and I should have thanked you that you brought it up again. It is obviously important.

And then one final small remark in connection with Gene Parker's interest in the possibility of solar anomaly in the 1645 to 1715 A.D. period, I think he said. Actually, one can attribute the Middle Ice Age in Europe to that period, unfortunately. The cooling began well before that period. That doesn't mean that the sun didn't change for that period, too, but the last ship to Greenland from Iceland, for instance, was in 1410, as the Atlantic ice came down and cut it off. So the massive cooling started at least 200 years before the period that you are referring to. That's all, those are just little footnotes.

MR. TEPPER: Thank you, Will.

Dr. Wilcox, please?

MR. WILCOX: Well, I also would like to see the kind of observations that Don Heath is making continued, as they seem very significant. Our group at Stanford has been fortunate to start a collaboration with him, and I would like to see that continue.

Well, just to put the matter of the solar and interplanetary sector structure in maybe a slightly different approach for a moment, we might think about the traditional black box that the electrical engineers like to have, where they have an input terminal and an output terminal and the enormously complicated system in between.

So, for the black box I would propose the earth's atmosphere and its magnetosphere; for the output—for the measuring device—some quantitative meteorological parameter such as the vorticity area index of Roberts and Olson. And then for the input to the driving function, the few days on each side of an interplanetary sector boundary. Now, the point is that we have a repeating organized structure coming up to the earth in the solar wind and interplanetary field, which can be timed or phased accurately with regard to the time in the sector boundary. But for a few days before the boundary, for example, we have a declining solar wind velocity and interplanetary field magnitude. And for a few days after the boundary, we have increases in these quantities, and all in all it tends to repeat fairly well. So we are hitting this black box again and again with a driving function, which is fairly reproducible. Now, of course the black box has a big variety of initial conditions, probably for each sector boundary, so the output signal also varies around. But maybe if we keep doing this 50 or 100 or 1000 times we can eliminate these other variable causes and begin to get more ideas of what the physical mechanism might be that is related to this.

So it follows then that we would seem to need more effective proof on spacecraft observations of the interplanetary magnetic field, solar wind, and so on. I think that as far as analysis goes, people doing the various investigations represented in the literature in this field could be induced as just one part, maybe one small part, of the investigation to use the interplanetary sector boundaries as an organizing influence. This might help very much in regard to this matter of the scatter and diversity and unrelatedness of the present literature. It would be, it seems to me, much easier to compare the results of Author A with B and C, and so on, if they all have this common organizing influence.

The fact that it takes four and a half days for the solar wind to transport the interplanetary field and, therefore, these patterns, and so on, from the sun to the earth, would seem to allow some good possibility for forecasting, as we begin to understand better the results of the sector structure.

And for this purpose, and also to aid our fundamental understanding, it would seem that we should encourage the appropriate solar observation. I can't fail to mention that an observatory and telescope at Stanford are going to be dedicated to observing the large-scale solar field related to the sector structure.

A similar telescope will be dedicated at the Crimean Astrophysical Observatory under Professor Severny. Since these are 11 hours apart in time, one will have almost continuous solar observations.

With regard to the 20-year interval report on sunspots, it relies on this nice effect discovered by Svalgaard and Mansurov, whereby using polar geomagnetic observations, one can infer the polarity of the interplanetary field and, therefore, the polarity of the mean solar magnetic field.

And since these geomagnetic observations go back without interruption to 1926 at the station of the Danish Meteorological Institute in Godhaven, this gives one five sunpot cycles to work with and makes it possible to start having a little more realistic look at things like that 22-year cycle.

MR. TEPPER: Thank you very much.

With apologies to Walt, I would like to skip over to Al Dessler. Dr. Dessler?

MR. DESSLER: It is still not worth recording, but I am beaten into submission. There is one thing I was going to mention, and this reminded me. This morning Julie showed me a review paper he had written 20 years ago, and it reads very, very well today. It is in the Transactions of the New York Academy of Sciences. It covers quite a bit of the arguments of energy and boundary conditions, and I recommend writing for a reprint.

Let's see, just going on, picking up a point that Wilcox made, the experiments do appear to be conflicting, sometimes mutually contradictory, special cases. You wonder what the relationship is. I would like to see the experimenters begin referring to other experiments when they write a paper, and saying this contradicts or this supports the experiment of so and so. Perhaps the 11 and the 22-year variations go together very well, and perhaps the winter effect of vorticity fits very well with the spring and summer activity. I think this would help a lot in defining the question, what is the question that you wish solved, or what mechanism is supposed to be brought forth to explain what is going on.

One comment on experiments Nordberg suggested, about putting something in the stratosphere to see how it implements the stuff, I come back to my favorite—volcanoes. Volcanoes do this. True, it is not a programmed basis, but when you get one going, it might be a good experiment to see what kind of quantitative meteorological effect follows from injection of all sorts of stuff. I am sure a volcano would put in anything you have in mind.

Another thought I had was to read the final paragraph of Colin Hines' abstract. It is really a pity he is not here, and it is quite sad his boy was injured. But at least it would be worthwhile showing why we have these ideas. He ends up by saying: "None of the foregoing should be taken to imply that the present author, Colin Hines, is convinced that clear correlations between terrestrial atmospheric circulation and solar disturbances of such a structure are in fact established as being physically valid.

"Nor should it be thought that the suggested mechanisms are free from serious difficulties and aspects of the problem that are not discussed there." Well, he suggested that it was very tentative.

Another thought I had, and just to add to the difficulties experimenters face, while little correlations pop up here and there, there was one who presented the growing season. The length of the growing season had an 11-year variation, temperature variation, rainfall variation, different kinds. The experiment struck me as perhaps like the spectroscopies of 50 years ago before the invention of quantum mechanics. I mean you have to say there were correlations of sorts with very nice arrays of lines, some cases beautifully regular, but with others bewildering, absolutely bewildering. And as soon as the idea of quantum mechanics came in, why most of them fell immediately into place, and then it was just refinement and getting into the more and more complex cases. We might very well have a breakthrough of a theoretical idea that pulls all the experimental evidence very neatly into a package so we can begin to refine it and go after the details.

One more question or suggestion for an experiment. On that list it had "What about nonsector boundary storms, are the storms different in their behavior," because magnetically speaking, there are slight differences in the storms.

Meteorologically speaking, are magnetic storms different? Another thing is the suggestion that cosmic rays coming down in the atmosphere might affect the conductivity of altitudes like 20 to 30 kilometers. There is a possibility there. Perhaps meteorological phenomena could be keyed on PCA phenomena, polar cap absorption events. Polar cap absorption events are the rival of solar flare cosmic rays in the polar cap. These are normally 30 MeV particles, maybe 100 MeV, and occasionally once or twice a solar cycle they will come right down to the top of the troposphere, but normally they are much higher. They stop at altitudes like 30 kilometers. However, there are quite a few of these events, a dozen a year, maybe 15 a year at sunspot maximum. They show a nice sunspot cycle variation. Let's key in on those which show some kind of an effect. Another suggestion.

Then finally, I thought I should end on an optimistic note. I am impressed by the wide-ranging representation at the meetings, a good turnout of people who are obviously interested. They are looking for something, a lot of ideas—certainly a lot of optimism and hope represented here, and I think it is a healthy sign for the field.

MR. TEPPER: Thank you very much, and I think it is appropriate that we wind up the opening statements by the panel members. We will now hear from Dr. Roberts.

MR. ROBERTS: Thank you, Morrie. I want to speak about three observations that I would like very much to see carried out, and try to put them in priority order, at least as far as my own personal interests are concerned. And two, pieces of work that I think need to be done that don't involve new observations. Before I do that, I want to make just a very, very brief comment preparatory to it.

I think the problem of climate, whatever the causes of change are, including the possibility of a solar influence on climate, is perhaps the most important problem facing us in terms of payoff, but in many ways the most difficult for us to approach. And if we try to go at it directly and frontally, in terms of the droughts in the Great Plains area or anything like that, it is going to take us a half century to get the data and do the analysis in any direct fashion.

So I would like to take up from something Ralph Shapiro said yesterday and emphasize that it seems to me that we must try to look for the solar influence and climate by looking for short-term responses of the atmosphere to solar activity impulses.

And secondly, it seems to me that no matter how naive they may be, we ought to work wherever possible from some kind of working hypothesis. So I am tremendously gratified by the number of ideas that have been thrown out here that I think could be framed into good working hypotheses that will render themselves susceptible of test observationally, which seems to me should be the name of the game, from here on.

Now the observations. Bill Nordberg referred to the one that is nearest to my heart, that I would like to see, above all else, in the near future, and I don't want to wait till 1980, Bill. I would like to see infrared data for two winter seasons. I don't care about having enormously high resolution. I would like to have coverage of certain critical geographical areas particularly, and especially, if it would be possible to get, say, Northern Hemisphere maps of the infrared radiation flux from the earth to space in two wavelengths: one in the water vapor window and one down around six microns. It would be a tremendous step forward in trying to establish whether some kind of solar modulation of the infrared flux is causing lower atmosphere responses. And for the last two years, in spite of the most valiant efforts of NOAA and NASA, Roger Olson and I have been unable to get our hands on six months of data for the winter of '71. And I must say it is terribly frustrating, because I thought it would be one of the easiest things in the world to get out of the space program. So I would like to see that done and I would like to see if the infrared results are positive, insuring a connection between solar activity, one or another indices that I will speak of in a minute. I would like to see some laboratory work done on the possible mechanisms by means of which freezing nuclei can be generated in the atmosphere through chemical or other processes.

A second observation, I think it is terribly important to try to get homogeneous and reliable thunderstorm frequency data, especially if they can be tied to specific geographical regions and if they can be freed of bias. And I don't know enough about this to know—and I should ask Markson—if they can be completely free of bias that has to do with the collection, for example, spherics due to changes in ionospheric reflectivity or something like that. In other words, thunderstorm frequency data that are independent of solar activity themselves—I mean the observation of which is independent of solar activity that refer in specific to the frequency of occurrence of the thunderstorms themselves.

And I would be very much interested if Akasofu or someone else wants to comment on it, find out whether it would be possible to observe, from a DAPP satellite or from some other satellite, thunderstorm frequency by day as well as by night. I don't know if this is possible. If it isn't, it seems to me that some land-based or space technique, or some technique for giving us reliable thunderstorm frequencies by day and by night, one observation for some uniform period of time per day, is very highly important.

Thirdly, I would like to see some observations made that might be extremely simple ones to verify and extend the time series, the observations by Blamont and Pomerantz, who flew two geiger counters at 100 millibars altitude, and apparently found increases of ionization of about a factor of three, lasting for about a day or a day and a half, widespread over the earth in the Southern Hemisphere. I would like to see those observations either verified or put to rest. It seems to me that if sudden increases of ionization of this sort occur at 16 kilometers altitude, it is tremendously important for us to have homogeneous coverage of this sort of thing. I don't know whether it could be done from satellite, but I think it is a terribly important observation.

Now two pieces of work. It seems to me enormously important for us to do some additional kinds of synoptic map studies, and my favorite level is 300 millibars, but I would do it wherever you can get adequate data, 500 millibars if necessary. Synoptic maps of either vorticity, you know the area where the vorticity is above a certain value, or some other useful parameter like the change of pressure from one day to the next, or something like that. And have these maps added together so that you get superimposed epic map building related to various key dates, and I think the key dates that ought to be looked at should be the sector boundaries that John Wilcox has pointed out forcefully.

I think we should also look at magnetic storms, both of the type that are associated with sector boundaries and all other magnetic storms. And I think if possible, if the data are homogeneous enough, again Akasofu might be able to tell us, I think we should try to use as key dates some kind of direct observation of magnetospheric dumping or auroras or something like that, that may be indirectly related to geomagnetic activity, but nonetheless should be looked at independently.

By the way, I think these synoptic maps ought to be for certain special geographical areas, if it is not possible to do it for the Northern Hemisphere, and I think it is particularly important to do it in the area of the Gulf of Alaska and the Alaska Peninsula, also the area of North America farther east from the one I have just mentioned, and also in the region of Iceland to Scandinavia. I am pleased that Ralph Shapiro is doing some new work in this. I hope that prospers, and I am also very enormously encouraged that Schuurmans is working on that subject at the present time.

The second piece of work that I feel is really important to be carried forward is the kind of thing Dick Somerville was telling us about: numerical modeling experiments. I think these hold enormous promise for us in testing working hypotheses in the future. I can't overemphasize the importance, and I can't overemphasize my discouragement about how the models work so far. I am terribly disappointed, for example, that my own modeling experiments in the entire computer in which, with Ralph Shapiro's and Roger Olson's help, we introduced an auroral zone heat source, and also introduced a heat source that was slightly more sophisticated than that in an effort to see if we could generate very large increases of vorticity, nothing whatsoever happened. Of course this shows that the models are no good, and so I hope that, Dick, you and your colleagues and our gang at NCAR and Yale Mintz and Joe Smag, and everybody else, gets busy and makes good enough models to model these effects.

MR. TEPPER: Thank you very much.

I would like to spend a few minutes now on some interactive discussions, if any, among the panel members themselves, to ask each other questions or answer any comments or anything of that sort. I will recognize anybody by a show of hand, a wink of the eyelash, or anything else.

MR. ROBERTS: I already asked Akasofu a question about thunderstorms.

MR. TEPPER: Dr. Akasofu, would you care to respond?

MR. AKASOFU: I don't remember now precisely, but the photographs are very distinct, sharp, and could be used for that.

MR. KELLOGG: The DAPP is extremely high resolution. That means it also scans very fast, and so it is only looking at one element for a microsecond or something.

MR. ROBERTS: I was talking with Glenn Jean about this a few days ago, and it was his impression that there might be suitable means for observing from satellites thunderstorm flashes by daylight. And if this is so, I would like to know, is this the best way to get this kind of data. Maybe there are much cheaper and much simpler ways to get uniform thunderstorm coverage. What is the best way?

MR. NORBERG: Walt, I agree with Lou Kellogg's answer that, from the kind of instruments that you have on DAPP, which would be scanning instruments, you couldn't possibly expect to get that. That doesn't mean it can't be done. I am quite sure it can be done. Lou Battan, I believe it was, proposed years ago an H-alpha experiment, measuring the emission that's in that line, and it was shown on paper at least to be feasible.

MR. TEPPER: A few members in the audience have been mentioned by name during the panel discussion. I wonder if they would like to amplify on any reference made to them.

Question from the audience about the vertical propagation of energy by gravity waves.

MR. DESSLER: The major question, of course, is how important are these waves, and that is the point I guess everyone wants to be addressed to. If I might refer to the work of Dr. Somerville, and for those who have photographic memories, of the slide he presented, you find out that any kinetic energy in the atmosphere is really reacting to the small difference between several large terms. You have the baroclinic energy coming in of the order of several thousand ergs per centimeter squared per second. This is essentially balanced by frictional factors. You have the baroclinic energy conversion of about several hundred ergs per centimeter squared per second. So that, in net effect, I would say that this vertical energy flux can be as important, and how important on this particular point I wouldn't want to question Dr. Hines.

MR. TEPPER: Thank you very much.

Mr. Svalgaard, your name was mentioned. Do you want to make any remarks?

MR. SVALGAARD: Well, there is one special plea I would like to make. This work that we have been doing is helpful to us in understanding the model better, too, and my job and the job of people who work with me is to provide the best model we can for the number of applications. And if people have candidate physical mechanisms, whether or not they are currently representable by the model, then I think you should encourage your neighborhood modeler to incorporate them in his program.

If you have a mechanism, volcanism for example, if you have a clearcut way in which you think solar effect might be manifest through volcanism, then if it is clearcut and well defined enough to be expressible in algorithmic form, then you ought to put out the method yourself, I think, to see that it is tested out. I really am full of faith in the ultimate possibilities of the modeling approach, and in fact that is where the payoff is going to be.

I think, in connection with what Dr. Wilcox was saying about having sector boundary crossings as a standard input to the black box, that we ought to agree also on some standard output.

And for example, vorticity indices are useful research measures, but the public won't pay for a forecast of vorticity area indices. And I would like to see correlations made of solar indices with practical, meteorologically practical important phenomena.

It may be that, as far as the short-range is concerned, that the only kind of thing you will be able to establish with weak statistical correlations is something that will end up with the forecaster saying, instead of 20 percent chance of rain, 20.02 percent, and that won't be useful. I hope that that kind of correlation can be pinned down further as well.

MR. TEPPER: Thank you very much.

We now open it up to the comments by the audience, either in the form of short comments of their own, or questions to the panel members. I remind you we try to adhere to a rigid schedule, and the quicker you make your comments, the more time we will have for other people. I see we have somebody with a microphone already.

MR. NOYES: Okay, this is Bob Noyes from Harvard. I want to take off on comments of John Wilcox, referring to the input and output of the black box. I think it is certainly true that the inputs are not completely constant. There is a lot of substructure in the solar wind around the sector boundaries, and the point is that we ought to be very encouraged, I think, that we can now get to the point where we understand the substructure of this input.

I am personally very encouraged, as was brought up by the talk by Hundhausen yesterday, that we are now virtually at the point where he can identify the solar source of the solar wind, and perhaps the solar sources of the high velocity and low velocity streams. I am referring in this case to the so-called corona holes, which I personally believe are very ripe candidates for being the source of at least the high velocity component of the winds. Art and I were talking yesterday, and I was expressing the possibility that the holes might be the source of the wind in toto, and the substructure in these holes might in fact relate to the substructure of the wind.

Now the reason that I bring this up is that this is a very important subject for space observation and suggests an experiment. One can measure the structure of the coronal holes from space and get some idea of the energetics of the low corona that may be driving the wind in its various components. I feel that a very ripe field for investigation is a thorough understanding of the structure of the holes in relation to the wind. Dr. Norberg mentioned earlier the natural progression from observation to understanding to prediction, and again, I would reinforce Wilcox's comments that if we can identify the photosphere source of the coronal wind variation, we have a good predictive indicator at last, because we can identify the holes shortly after they come over the east rim which is four days travel time plus perhaps five days worth of rotation before the effect actually strikes the earth.

I really think that we are on the threshold now of beginning to understand the phenomenon we observed, and I think with a little more effort we will be in a position to predict the input to the black box.

MR. TEPPER: Thank you very much. We have a question here. I would like the microphone to be brought down here for the next question, after this one.

MR. POLK: University of Rhode Island. Dr. Roberts pointed out the importance of measuring lightning activity. A few years ago, it was suggested that Schumann resonances—I must categorize them below about 100 cycles, below 50 cycles—can be used to establish worldwide lightning activity, and that has now been done in part. Some of the necessary calibration was recently published in the IEEE Transactions on Antennas and Propagation, and I have with me data for the period September 1970 to May 1971. While they somewhat disagree with other published studies, they don't disagree very badly and actually the data are very, very encouraging. I am mentioning this, because that is obviously a very cheap ground-based method for measuring lightning activity, and it would be useful to compare the results of that method with what one obtains from the other ways of getting lightning activity.

Now the other thing is a different subject, but it is a little bit related to that. Schumann's resonances, if treated differently, treated analytically differently, can also be used to obtain information about the average electrical conductivity of the altitude range between ground level and 40 kilometers. You don't get a profile, you just get an average value for the conductivity, which of course depends upon ionization. And we did this for a fair amount of data, and we get consistently a conductivity which is about three times the value which one would get from a Cole-Pierce model, which indicates there is something above 20 kilometers where you don't really know the ionization very well, which seems to be higher, greater ion density than what would be predicted by the Cole-Pierce model.

MR. TEPPER: Thank you very much. Dr. Bowen.

MR. BOWEN: If I may begin with a personal remark, this is a subject from which I have been absent for three to five years, and I am very pleased indeed to see such an enlightened discussion as we have had in the last couple of days. However, judging by one or two things which have not been said, it looks as if I have been making my absence felt. So if I may just repair that omission, gentlemen, as briefly as I can.

It is perfectly clear from the remarks that I made earlier that I am impressed, but there are, indeed, very close relations between solar activity and certain weather phenomena. At the same time, I would be the first to agree with many of our speakers that the mechanism eludes us at this time. It does appear from all of our discussion that we are still looking for that handle which cranks this particular machine.

We have gone all the way from solar particles to magnetic activity, soft X-rays, gamma rays, cosmic rays, these and others, but there is one conspicuous subject which has hardly been mentioned. Now, what we are looking for is something that exists in the environment around the earth—let's forget the sun for the moment—something which is capable of coming down through the earth's atmosphere in a very definite way, and something which, when it arrives in the lower atmosphere, is capable of triggering large amounts of energy. Well, you've got it; there is dust, plenty of dust around the earth.

This falls into the atmosphere, and I am talking about particles now big enough to fall on the gravitational field. They will fall down through the atmosphere, nothing is going to stop them. They will have minor influences while they fall down. They will then fall into the troposphere, and I am again the first to agree that if you have a blue sky situation the dust will fall to the ground and the ocean, and it won't do a thing. On the other hand, if you have a nice tropical storm built up, which is not going to go of its own volition and the dust drops into it, then you will get enormous releases of latent heat with the water which is dropped out of that storm.

I have forgotten my figures in kilowatts or megatons or what have you, but it does amount to the release of several atom bombs worth of energy into that system. Well, I have not yet now referred this back to the sun, but surely we are going through a field of dust in the planetary field itself which is variable in intensity, spotted, of course. Surely the sun is having some effect on that interplanetary dust. Thank you.

MR. TEPPER: Thank you very much. I believe that Dr. Wilcox wants to reply.

MR. WILCOX: Yes, I would like to respond briefly to Bob Noyes' comment. I agree very much with him that we may well be on the threshold of obtaining fundamental understanding of the solar structure that relates to the origin of the solar wind and to the various things we talked about. A lot of progress has lately come toward that goal from the Skylab observation, and as far as what we need in the future, it seems very important to follow up on this exciting possibility, either with that kind of continued observations, or with the orbiting solar observatory observations.

And also, on the interplanetary part we have in two or three years a big improvement scheduled in something called International Magnetospheric Explorer, a collaborative project with NASA and European States Research Organization. One spacecraft of that is called Heliocentric, and it is orbiting the sun, but it remains very close to the earth. It remains on the earth-sun line about one one-hundredths of the way into the sun, so that it is continuously observing the solar wind in interplanetary field. And particularly, as Bob says, if we are really trying to get some fundamental understanding of the solar structure as extended out into the solar wind, we need this kind of continuous, uninterrupted, interplanetary field observation.

The final point is that it is planned on the Heliocentric to have almost real time reduction availability of the observation. And if we have progressed to the point at which it may be of some utility in meteorological context, that is clearly going to be very useful, too.

MR. TEPPER: Thank you very much. Are there other comments by panel members at this time?

MR. WILCOX: Yes, I would just like to emphasize to Dr. Bowen that when I spoke earlier of my working hypotheses and spoke of particles, I purposely did not say electrons or protons particles and did not exclude the dust. I apologize to Dr. Bowen that I did not look in his direction when I made the remarks. I would say that he did make his presence felt with me.

MR. TEPPER: Thank you.

MR. ROBERTS: I wanted to say just a word to Taffy Bowen also. I noticed very carefully that he did not use the word "meteor" in speaking of interplanetary dust. And, of course, if Curt Hemenway were here he would talk about dust of a different origin, dust from the sun. But that is another story.

MR. DESSLER: I just wanted to ask, what is the status of that now? I remember reading about it, oh, it was 15 years ago, and it looked like it was a good theory, and it had experimental evidence to back it up. What is the current status of that work?

MR. BOWEN: I'd rather you didn't use the word meteor dust, because that raises hackles in certain directions. But the answer to the question what is the status of the theory, I think I must be the only person in the world who still sincerely believes that there is an effect. And certainly, all the meteorological professors of this world disagree, but that doesn't bother me.

MR. DESSLER: Why is that? Because they couldn't reproduce the results?

MR. BOWEN: I will give you the answer in private.

(Laughter.)

MR. LONDON: I think it is fair to say that the evidence is contradictory. It is evidence of studies that have been made on New York dust and rainfall that show some different things. Would you agree with that?

MR. TEPPER: Shall we say inconclusive.

MR. MARKSON: (Inaudible) . . . quantitative field for the variation of worldwide thunderstorm activities. (Inaudible.) But getting this program going is proving to be very difficult, and I really think that it is going to be very difficult counting spherics to get a field for worldwide thunderstorm activity.

Now, one thing that most workers in atmospheric electricity agree on is that thunderstorm activity in general over the world maintains the ionospheric potential: the integrated summation of the energy of all the storms. And therefore, it seemed to me the parameter to measure would be the ionospheric potential continuously, as it varies in time, and I think this can be done with several techniques.

We should also try to get this spheric state and see how it correlates, and this is the experiment that we are trying to do in the ten-year program in atmospheric electricity. And this is a check on the whole global circuit picture, and if this is an accurate picture, the spherical condenser model. Thank you.

MR. TEPPER: Thank you very much.

MR. HUNDHAUSEN: I would like to make one final comment here about what I see as the emergency of an overly sectarian view of the solar interplanetary input function.

One question yesterday pointed out something very interesting, and in fact, the sector boundary is a nice standard. But the vorticity index that Roberts and Olson have studied dipped before the sector arrival at the earth. This would seem, in all probability, to rule it out as a physical cause. So now when we pick standards for input signals, let us not pick them so as to rule out the probable physical causes. In fact, a very interesting study that I think must be carried out, and has not been looked at by solar physicists for a good many years, is to correlate our wealth of new plasma and cosmic ray and energetic particle data with those sector boundaries to find out what does happen several days before the convenient marker, but perhaps not the physical cause, arrives at the earth.

And for amusement this noon, I walked over to see some friends here and looked at an old issue of JGR, or a paper that was published by Norman Ness and myself, in which we looked at seven of the well-defined sector boundaries for which we had plasma data. Granting the poor statistics, three of these were preceded within a day by a shockwave, so that the separation between sector and nonsector events is not at all clear. And we will have to look carefully for this kind of coincidence before we take all of them labeled sector and consider them to be of one single class.

MR. WILCOX: Well, I think Art and I are in somewhat violent agreement, as occasionally happens. It is partly a matter of words. We think of the sector structure as being the whole bag, the change is everything back to the sun, the EUV maybe, the coronal holes appear to be related to it. And then out into the solar wind in terms of the high velocity in the sector structure—to quote Art yesterday. So we certainly include all of this. Now it is true that the boundary itself is a very convenient timing marker, as Syun Akasofu showed. The boundary itself seems to just produce some small wiggles in the geomagnetic field, which presumably are not very important in themselves.

MR. TEPPER: I regret that, due to the lateness of the hour and the fact that we have exceeded our time for the panel discussion from the audience, we'll have to close. However, I do want to ask the panel discussants if they want to make a final remark before we terminate this.

MR. LONDON: Just one remark. You can't ask for a study to be made, and then after the study is made, get results, say well, no, I don't believe that, Walt. If we are going to look at model results, we have to do this seriously and be careful and then look at what they tell us and learn something from what they tell us.

I think this is important. I might, incidentally, add something that we all know, and that is, as Pascal pointed out—this was before he joined the abbey—although he didn't strongly believe in a Deity on the basis of evidence on the basis of possibility he had to because the return was infinite.

(Laughter.)

MR. NORDBERG: I want to come back very briefly to the discussion of thunderstorms and the relationship with extraterrestrial events. I am not sure if I am not a little bit confused in my own mind, and there is probably some confusion in the audience's mind.

The thunderstorm activity was brought up a number of times, at least by implication, in the context of rainfall. And after hearing Walter talk yesterday on the 22-year cycle, I think that, if I had my choice between the alternate mechanisms of interplanetary events to ionization to condensation and the forming of cirrus clouds and then cyclogenesis on the one hand, and ionization and electric fields and thunderstorms on the other hand, and then both relating in some way to rainfall or drought, I would, without hesitation, but still of course on the basis of intuition, pick the first one. There have been a large number of competent meteorological analyses of recent history drought. By recent history I mean 20 to 30 years. And, as far as I know, they were all invariably tied to changes and perturbations in global circulation, and not necessarily to any thunderstorm events. So of course if thunderstorms are tied in a secondary way to droughts or to the occurrence of these changes in general circulation, then they play a role. But just thunderstorms related to rainfall and/or the lack of rainfall, I am a little hesitant, and I would think that the mechanism of ionization to electric field to thunderstorm is probably a more interesting scientific thing to pursue, and should be pursued for that purpose.

As a practical thing—"Do I get a buck out of it in the next year?"—I certainly would want to pursue the general circulation aspect.

MR. TEPPER: I would ask the panel members to stay where they are. The Steering Committee in its great wisdom in organizing this Symposium realized that many of you would have other responsibilities during the two days, other than sitting here and listening to every paper.

So, while some of you were doing these other responsibilities, things were going on here, and we had chained to one of the seats a member of NASA whose duty was to record religiously everything that took place, and to capsulize it for us. So those of us who either were not paying attention or had a lapse of one thing or another, can get the full benefit of the Symposium simply by listening to the next 20 minutes or so.

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SUMMARY OF HIGHLIGHTS OF THE SYMPOSIUM

S.I. Rasool
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SUMMARY OF HIGHLIGHTS OF THE SYMPOSIUM

MR. RASOOL: I heard a remark that you have heard summaries and summaries and summaries all afternoon. I thought Will Kellogg summarized very nicely this afternoon, and then we heard summaries of many of the things I would have wanted to say by Julie and other people on the panel. But I would like to give you some impressions that I acquired through the last two days, and at times my remarks may be a little critical, and I guess that is the purpose of this presentation.

I want to start— yesterday everybody was starting out with quotations and historical references—I want to start out with my own. On the risk of being pretentious, I will start out with my own quotation.

My scientific year has a span of one and a half solar cycles. I look old, but I am not so old. It is one and a half solar cycles I have been doing science, and it corresponds to about 200 solar rotations. And out of these, only about four or five I have spent thinking about the topic of the day, which is the solar activity and the weather. This produced a paper, and this was during 1960. I have a copy of it. It is in French, that is why it didn't get much circulation.

But I have two viewgraphs. The first one shows a chart; the abscissa is the sunspot number, you see from near zero to 200, and the ordinate is the height of the tropopause. These are the tropopause heights for a full solar cycle for different regions on the meridian, zero degree longitude, from Paris all the way down to the equator. And the conclusion here was that the tropopause height increases more at the equator than at the middle latitude.

That is an isolated case of solar activity with a meteorological parameter. The second parameter in the same paper is the ozone, and the average ozone value at the top three stations. This is not an annual variation. It is a delta in ozone. That means you take ozone, you take a 40-year average, and find out the difference between the actual that you have minus the average. We take out the seasonal effect. And below that is a solar activity index. To me, the conclusions were very interesting, and I got carried away and made a puzzle which is in French at the top, and it says that one way of explaining this is that the solar activity heats the atmosphere, ozone is increased, and the temperature changes. And because the temperature changes, stratospheric circulation changes, and that affects the lower atmosphere.

This presentation was made in Helsinki, and Bob Jastrow was sitting in the audience, and despite my accent he understood what I was saying. He instantly invited me to New York on a fellowship and said, "Use my computer and work out the mechanism." That brought me to this country about one full solar cycle ago, and still now I don't have the answer. I am wondering why Jastrow didn't fire me. But the reason I will say is that I have been worrying about Mars and Venus and Saturn, and so on, and lately I have been sitting in meetings at Headquarters.

But the point is that the information contained in these two charts, and a third chart that I didn't show, which is also distinguished, shows the relationship with the solar activity in the next few days with the geostrophic index of the circulation of the atmosphere, and it looks very much like what we have been hearing about over the last two days.

So with this background, I must come back today to my chore of the afternoon, to summarize or give some comments on what we have learned in the last two days, and I start out with the evidence. Now, I will say most of the evidence I have heard is probably better than what I had. And one important thing which I have learned, and what I should have done if I was in business is to make this whole field more credible.

We are correlating the solar activity, or the changes in solar radiation over the planet earth. We should not—I think, to be more credible—look at isolated cases of one parameter or one local region. After all, there are changes in the sun. We have been talking about a 27-day cycle effect that lasts for several days maximum. We should be looking at the whole world if it is an effect coming from the interplanetary medium.

So, in those days we didn't have data. We could say then that we didn't have data, but for the last ten years we have been in space, and in the next five years we will be looking at the whole earth in the Global Atmosphere Research Program. So my appeal to the people who are going to do such studies is to at least look at the parameters over a large scale of the planet. That is one thing.

And then don't look at the parameters. For example, if you are looking at ozone, then the next step is to look at the temperature of the stratosphere where that is affected, because we know that ozone affects the temperature. So where the temperature varies and when two things say the same things, then send the paper to publication. That is one thing. I have learned what is going on in the field only being editor of the Journal of the Atmospheric Sciences. From time to time I read papers that come to me in this field, and what I have learned in the last two days is that the important thing that is missing still is the interpretation of parameters, and a global scale of the effect.

The third thing in this same field is that, if the effect is coming from the top near the surface of the earth, if the source of energy is outside the earth it is coming from the upper atmosphere to lower atmosphere, then we should, of course, be looking at different levels in the atmosphere to see whether the effect propagates downward.

I will have more to say about it in a minute. Now, to summarize the evidence part. I think that we should consolidate our efforts in looking at the parameters, which should be affected by the sun or by particle flux coming down in the atmosphere, but do it in a more general way.

The second thing is the source. Here is the sun, and you have little sorts of flares in here, prominances and sunspots. There are two types of variations we learned about yesterday. The first is the short-term variation of the order of one second to ten to the seventh seconds. And here the delta E in energy was quoted yesterday from one erg to about ten to the thirty-third ergs. And when I heard this after ten years, I was horrified that, after ten years in space, we don't know what is the variation in the near ultraviolet or the solar constant. And I found out the solar constant is not known within one-tenth percent. And to paraphrase what Julie said, it is almost criminal not to know this.

So that is the most important thing that was missing in the progress so far; they should know what is the solar constant. And it is extremely important to know whether the variation is in the ultraviolet, because in the chart this is the earth, this is the troposphere, and this is the upper atmosphere, and this is the magnetosphere, let's say. The radiation coming down from the sun and the visible part is going all the way to the surface. The near UV is going to the stratosphere. The extreme ultraviolet is going to the upper atmosphere, and the IR is going to lower levels.

Now, if you are looking at a mechanism of the solar changes in weather here, to me it seems very logical to start out—in order to economize on the number of hypotheses—at the region closest to the troposphere. And this is the radiation which contains approximately a thousand ergs, and ozone is primatary. Ozone exists in this region. So if this is gray and if it is near UV, then you have the source close to the top of the troposphere. So you don't have to go very far, in work on these mechanisms, if you are bringing protons or cosmic rays into this region.

So I think the first duty of Don Heath and his group is to give us the right number of near-ultraviolet radiation variations. In the last year or two, what is it?—one, one-tenth, or ten percent?

The quotation yesterday was could the solar cycle variation from minimum to maximum be of an order of magnitude, and if it is true, it is very important.

You saw beautiful temperature profiles by Priester yesterday, but if you increase this by a factor of one thousand you may be getting the same temperature for five years because the density is different by a factor of a thousand.

So there is one thing which I think is mandatory to get very soon. I think the problem of the solar observations is that we have been concentrating quite a bit on the sun and the stars, but have not centered the source of energy to the earth, in the research in the solar physics.

Now this much about the source. Now in solar wind, we find that these numbers are a little better. We have been out in space very often, and we get about one erg, approximately one to five ergs, but there the problem is much more complicated, because you have to go through this boundary layer. But the electromagnetic radiation is great, because it comes right in here, and if you find this it is the simplest way you can explain. But here you have to go through the high energy protons. You stop here, you know that you stop here, then you have to find another mechanism going here.

Now, there is a long-term change of the order of ten to the seventh, to ten to the seventeenth seconds. Cameron was talking about that, and even Cameron doesn't know what is happening in the interior of the sun. So here these present entire different dimensions because his changes are of the order of 30 percent of the total solar flux, and so the wind apparently has changed by a factor of ten to the seventh in the early history of the earth.

That is a very important problem also, but one that is related mainly to the long term of the order of millions of years, or thousands of years, the problem of ice ages, and the problem of evolution of different planets.

And here the presentation by the Cornell group was very interesting, that you can now have two planets on which the same sun is acting. And on Mars maybe you have witnessed the changes in the history of the atmosphere of Mars by looking at the polar caps. They have their own ice age problem, and putting the two together with the source, we can do much better than just with the Earth.

So there is a different problem. I don't want to mention this, but here the questions are very clear what we ought to ask.

I will come to most of the other things discussed in the panel. My problem with this entire Symposium was one of a gaping hole, I thought, in the whole discussion, namely that there was no discussion of the stratosphere in the meeting itself except for this panel discussion this afternoon. And the stratosphere is the region where either the source is put in or the energy is transferred through, so you have to study it, unless, on the other hand, you have a solar constant variation in the visible so you have a change here and then you propagate it upward. But I can't tell, because I don't have the solar constant measurement as yet, unfortunately.

So the stratosphere discussion was lacking. I don't agree with Bill Nordberg that in a few years we should be looking at the stratospheric measurements and we get this and we get that. If you have four years of measurements by Nimbus, then today if we had in our Symposium from four years of data, a one-year data set of ozone and the stratospheric temperatures, then we would have made great progress at least. So my point is that instead of preparing for the measurements in the next few years , we should look at the data we have, try to understand it, and put it in this problem. As long as I am here, I can say what I want to say.

Now, coming to the mechanisms, unfortunately another gaping hole there was the absence of Colin Hines, who is the only one who had proposed the mechanism, or two mechanisms, which relate to this part of the atmosphere, to this part of the energy source. And I cannot discuss the content of the paper, because it was only in abstract form, and it was presented by another person other than the author himself.

So it is not fair to discuss it. We don't understand very much about it. But the important thing I would like to mention is that with these measurements in hand, if we know this, then I think it should be fairly straightforward, with the present computations or models that exist of the atmosphere and the stratosphere, to show if this amount of change does anything to the stratospheric dynamics.

We had an example of what it does to the lower atmosphere, but I am sorry to say it was the wrong example, because what it told us, and what Julie said earlier at lunchtime, is that if you turn off the sun completely, the earth's troposphere will have still circulation for another 15 days, because relaxation time of the atmosphere is 15 or 30 days. So if you turn off the sun completely, you would still have the patterns. What you are looking for is one-tenth percent effect of the sun, so you can't possibly find it. But where you can find it is here, and I know that NCAR and others have models of the stratosphere, and they do dynamics in the stratosphere, so why can't they put in the variations and show us what happens? That's a very good part of what was missing.

Now a few comments on what type of meeting we should have in the future in order to get the answers to these questions. And I don't think a meeting of these five-minute presentations and questions in the microphone would make great progress towards the understanding of the problem which needed a workship—a working meeting of a week. And I was thinking if you put groups of scientists, like Don Heath and Elske Smith, again, and other solar physicists who have made measurements on OSO and Nimbus, and who know the physics of the sun, for a week together in the classroom and have a computer at their disposal, it is possible that they will come back in two or three days and give us these numbers after analyzing the data. Another group of circulation people in the lower atmosphere would do the circulation part. And then we would meet as a group and discuss around the table, or across the table, as a workshop.

And I was wondering—last summer I was at a workshop like this, making the model of the atmosphere of Titan, which is a satellite of Saturn. We got together, the few measurements, there were nine people with different theories on Titan, and we sat together for three days, and we have a model of the atmosphere of Titan.

It was very interesting. Why can't we do the same thing here? And so, my suggestion is that next time we get together we really have a working meeting, and we owe it not only to Walt Roberts but to the scientific community to give a yes or no answer where there is a relation, and if there is a relation, how does the relation work.

CONCLUDING REMARKS

Morris Tepper
NASA Headquarters

CONCLUDING REMARKS

MR. TEPPER: Ladies and gentlemen, it is with a great deal of satisfaction that I draw this Symposium to a close. Before doing that, however, I would like to recognize the various people that made it a success. And really, I feel that the people who have made this a success today have been the audience. We have had an interdisciplinary group of the kind that I have never associated with in one room before, and your participation has been magnificent.

I apologize for those of you who did not have an opportunity to make your remarks, but perhaps you will have that opportunity either in that closed room with Elske and Don Heath or in some other workshop or perhaps at our next get-together.

In addition to that, I would like to recognize the efforts and the excellent papers given by our various speakers. We never dreamt that the quality would be as good or as comprehensive as it turned out to be, and I have had nothing but compliments on the choice and the presentation of all the speakers.

The chairmen of our session did a magnificent job in maintaining the time schedule which was totally impossible, and yet they maintained it, and we are finishing practically on time.

I would like also to recognize my colleagues on the Steering Committee, whose names appear in the program, who put all this together. Now after you are all going home, they are going to be left with all the information that has been accumulated here.

Six young men, rapporteurs who have been sitting here, also chained to their seats, in the next 24 hours or so will be putting out a summary of this Symposium, which will then be submitted to journals for immediate publication, so that the events that have taken place here will be known to the scientific community. Following that, and depending on how soon the various speakers will get their papers to the editors, we will issue a full proceedings of the two days.

So again, I ask for the cooperation of the various speakers. What about the future? Well, one thing is that we should maintain contact with one another and maintain our interest.

With that, I adjourn this meeting until the next time, the next place, somewher

LIST OF ATTENDEES

APPENDIX

LIST OF ATTENDEES

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