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POSSIBLE RELATIONSHIPS BETWEEN SOLAR ACTIVITY AND METEOROLOGICAL PHENOMENA

A symposium held at
GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland
November 7–8, 1973

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Edited by
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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, Md.

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 Corp. 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; and 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) and in *EOS, Transactions of the American Geophysical Union* (J. S. Levine et al., May 1974).

S.P.M.
W.R.B.
Greenbelt, Md.

February 15, 1974

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

Chairman: Morris Tepper

Introduction

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 and 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, Nimbus satellites, Television Infrared Observation 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: (1) What is the evidence concerning possible relationships between solar activity and meteorological phenomena? (2) Are there plausible 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 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.

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Symposium Summary

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 cooperation with the University Corp. for Atmospheric Research (UCAR) and the American Meteorological Society. The nearly 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, Japan, 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 100th 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 research, as well as a strong and long-time advocate of the theory that weather is influenced by solar activity. 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 1000 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 meteorological phenomena caused by solar activity is often localized, isolated, and contradictory, and the investigations in this field do not lend themselves to direct comparison because of 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 mechanisms to explain them, and which of these measurements can be accomplished best from space?

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 Soviet 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 United States with sunspots indicated that severe droughts in the High Plains follow the minimum after the minor maximum in the double (22-yr) 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 1 day prior to boundary passage, reached a minimum about 1 day after, and returned to its original value by 4 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 nonboundary 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 Corp. 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 Corp. 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 that 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.

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 that 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 the National Center for Atmospheric Research 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. Because the magnetic field pattern defines the interplanetary sector structure, either two or four 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. Leif 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 regions 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 European Space Research Organization 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 of 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 the NASA Goddard Space Flight Center 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 because of 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 the National Oceanic and Atmospheric Administration (NOAA) reported on plans to monitor energy deposition in the upper atmosphere by future operational satellite systems. Ralph Markson of the State University of New York 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 New York 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 Goddard Space Flight Center presented evidence showing that the direction of ionospheric winds at 200 km could be related to the direction of the interplanetary 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 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 show up around zero days of the geomagnetic dates. In 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.

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 of the 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 of 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} W) or released in a large geomagnetic storm (10^2 TW) compared to the sunlight incident upon 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 because the atmospheric mass above 105 km is only 10^{-12} times 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-yr cycle of precipitation and the 22-yr 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-yr cycle.

Richard Somerville of the 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 coworkers at GISS. They tested effects of changes in atmospheric ozone content and changes in 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 two-thirds and three-halves 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 2 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 of the 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 1 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 the National Center for Atmospheric Research 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 because variations over the solar cycle are small (less than 1 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 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.

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 Goddard Space Flight Center, 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 presatellite 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 in relation to effects observed in the interplanetary magnetic structure.

Several suggestions were made for organized studies to isolate the mechanism that 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: low-latitude middle UV penetration could cause hydroxol formation from water vapor, which would destroy ozone, and 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 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 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. Because C. O. Hines was unable to attend the symposium, no suggestions could be made for its future investigation despite the high interest in his theory.

Dr. Bowen suggested that increased dust input to the atmosphere from extraterrestrial sources might lead to increased storm activity. Dr. Parker commented 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. Somerville 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.

The symposium concluded with some comments on future research by Ichtiaque Rasool of 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 because of 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 stratosphere ozone to such variations.

It was felt by many participants that although we are still without any definite physical mechanisms, this symposium was an important step in stressing the importance of relating meteorological and purely solar parameters. The attendance at the symposium illustrated that this field 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 experienced and new workers from a wide variety of fields.

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Session 1

WHAT IS THE EVIDENCE?

Chairman: Ralph Shapiro

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Relationships Between Solar Activity and Climate Change

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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 an increase in meridional circulation 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.

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 compel the Soviet Union to purchase wheat from Canada and the United States. 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. The impact in India, the sub-Sahara, and elsewhere was far more tragic: 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.

It is therefore not surprising that there is an increased 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, hold 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 that so critically applies to human needs.

One of the many contending theories of climate change involves variations of the solar input to 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, and atmospheric turbidity changes due to manmade 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 of advancing our climate forecasting skills and to devise critical experiments and analyses to determine 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 responds 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 by examining 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 integration with 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 will 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 Prof. 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 (Lamb, 1972; Pokrovskaya, 1970). My purpose, instead, is to discuss critically a few selected findings that 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 1950s, 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 autosuggestion; 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 because then one would have to predict the solar activity to predict the weather, and he thinks we have enough problems without that one.

But the matter will not 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 hangup 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 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, in comparison with that needed to push around the lower atmosphere.

When one is addressing questions of solar activity and climate, still another obstacle must be faced. This is, in brief, the very unsatisfactory state of affairs with 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. 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 provide the securest empirical-statistical evidence 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 km 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 yr to recur with a periodicity of about 20 to 22 yr, and with a reasonably constant phase relationship to the alternate minima of the solar activity cycle.

The easiest representation on which to visualize this cycle 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 20 to 22 yr rather than 10 to 11: The magnetic fields of the leader spots of sunspot pairs are opposite in the opposite hemispheres of the Sun during a given 10-yr 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- to 22-yr 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 to 22 yr. Drawing the sunspot diagram as Thompson has done in figure 1 simply calls attention to this fact.

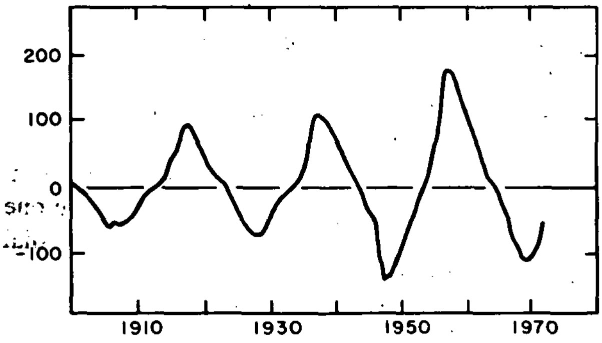

FIGURE 1.—The Hale double sunspot cycle. The alternate maxima in the 10- to 11-yr sunspot cycle are plotted with opposite sign. Plotted below the horizontal zero line are the alternate maxima whose amplitudes have tended to be smaller.

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 10 or 11 yr, 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 international geophysical year, which occurred in 1958, the solar poloidal field was antiparallel to Earth's, having reversed in 1957.

There is, moreover, a tendency in the recent spot cycles for the alternate halves of the 20-yr 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 11-yr 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 maxima 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

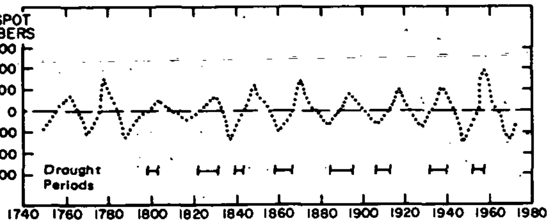

FIGURE 2.—Solar cycle and drought in western Nebraska (Thompson, 1973). Drought periods in Garden County, Nebr., are shown by horizontal bars below the sunspot numbers plotted as in figure 1. All droughts published by Weakly (1962, 1943) are included.

droughts occurred in this region as the major maximum drew to a close.

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-yr solar activity cycle, or are they evidences of a natural terrestrial oscillation of about 20-yr 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 levelel at solar activity versus climate correlation analysis, as Mitchell so cogently points out.

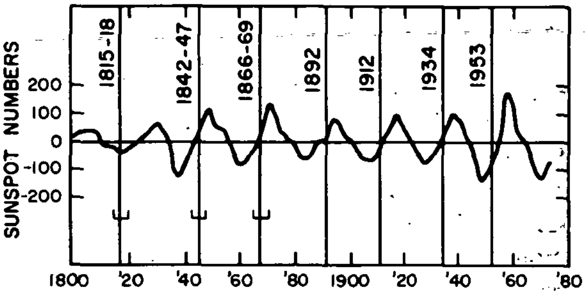

FIGURE 3.—High Plains droughts. This figure is adapted from the Ph.D. thesis of Marshall (1972). The vertical lines correspond to the center dates of all droughts cited by Marshall from rainfall data over the High Plains region. The three earliest droughts are less reliably determined; for them the horizontal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

At my suggestion, Mitchell recently resurrected some drought data for eastern Kansas developed by Wayne C. Palmer, his former colleague in the National Oceanic and Atmospheric Administration (NOAA). He has now plotted severe drought years on two types of harmonic dials: (1) a strict 20-yr recurrence dial and (2) a dial based on the double sunspot cycle (of approximately 20- to 22-yr 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 because I suspect that the extreme years of a given drought period are likely, other things being equal, to come near the end of the

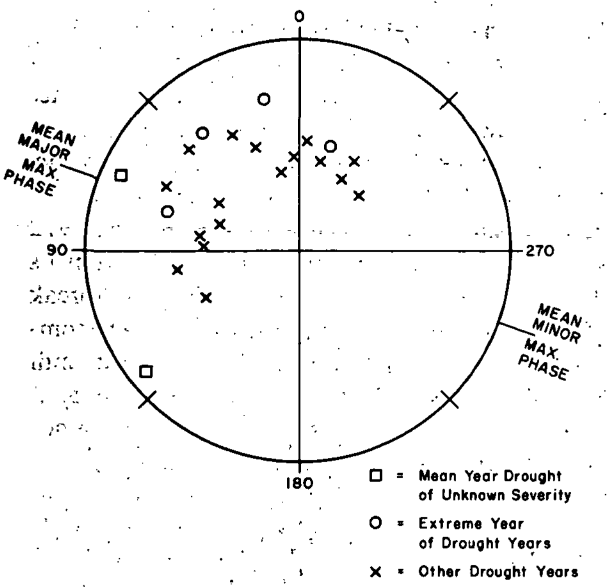

FIGURE 4.—Harmonic dial showing drought dates of differing amplitude for western Kansas as measured by Palmer (Mitchell, 1964). The minimum sunspot phase following the negatively plotted sunspot maximum is designated as phase 0°. Note the clustering of droughts on one-half of the dial around the axis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

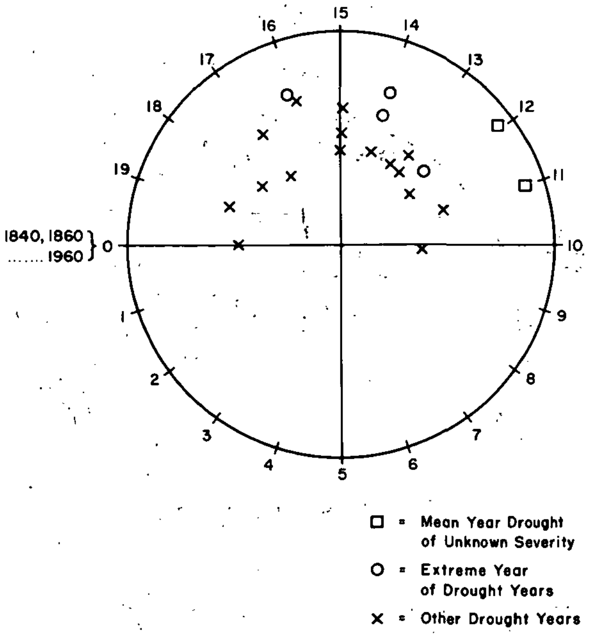

FIGURE 5.—Harmonic dial showing drought dates in figure 4 compared with 20-yr periodicity (Mitchell, 1964). Note absence of droughts in alternating decades 1840 to 1850, 1860 to 1870, . . . , 1960 to 1970. This figure and figure 4 illustrate that western Kansas drought recurrence since 1840 can be explained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

cumulative effect of several successive dry years.

Mitchell next asks whether it is possible, with these same drought data of Palmer, to discriminate between a strict 20-yr 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 in line. One must not forget, however, that in choosing a strict 20-yr 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-yr 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 sunspot 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-yr cycle, although I have not reproduced the 20-yr harmonic dial here. A cycle slightly longer than 20 yr would organize the data just about as well as does the sunspot cycle. So, once again, it is not possible to distinguish with these data between a periodic recurrence of Nebraska droughts with a cycle length of about 22 yr 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

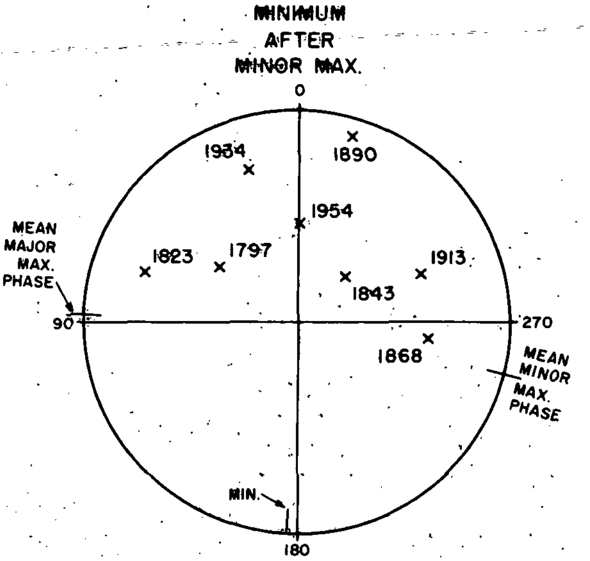

FIGURE 6.—Harmonic dial: western Nebraska droughts reported by Weakly versus double sunspot cycle, 1800 to 1970. Note significant clustering in the upper half of the dial, corresponding to a centering on the minimum following the negatively plotted sunspot cycles. This graph agrees approximately with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

Plains droughts with a 22-yr 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-yr recurrent behavior. For example, Thompson has reproduced July–August temperatures in the "corn belt" of the United States; these data show 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 connections to this drought region though I am sure there are many. What is far more important 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.

I would like to make some additional points before leaving this discussion of 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 yr. A 21-yr 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 (Oct. 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.

Second, 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 yr in duration, is the one latest in phase. Late phase relationships for center dates or long droughts also showed up in the more recent data, as was discussed earlier.

The data do not, however, show that a distinct drought accompanies every 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

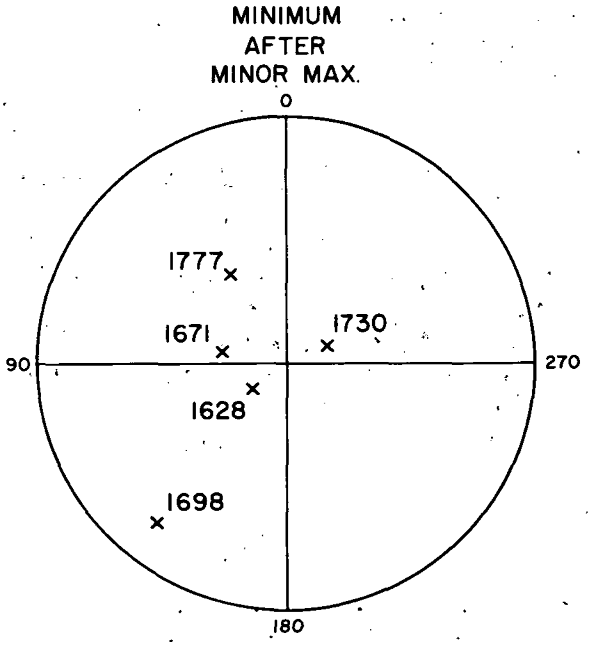

FIGURE 7.—Harmonic dial: western Nebraska droughts reported by Weakly versus double sunspot cycle, 1610 to 1800. Drought data for 1610 to 1800 plotted on same basis as figure 6, but with expanded amplitude scale. The 1698 drought, which is late in phase, was also very long (20 yr), necessitating the 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.

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 would like to comment about what the climatological picture for a High Plains drought might be, in the hope that it will contribute to the search for a mechanism. My concept is perhaps too simple, and therefore I would 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 United States, 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 jetstream westerlies over the Colorado Rockies so that there would 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 eastward. 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 1564, the trees in his test area of western Nebraska were buried in nearly 3 m of windblown soil. Even though long-term wind data are hard to acquire, it may be possible to find jetstream wind and rainfall associations with solar activity that are operative on a short time scale of perhaps week-to-week changes; such findings encourage us to surmise what would happen if the changes were 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 yr to produce differential 300-mb circulation maps for 2-week or 1-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 sunspot cycle because 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, p. 443) 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 percent 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 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-yr period and confirmed an earlier finding of Clayton that high latitudes show higher average pressures at spot maxima than at minima. 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: 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 is much supporting evidence for these conclusions of Willett and Schuurmans; but this will not be discussed in this paper.

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 would 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 downward, 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 Olson and I (Roberts and Olson, 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 per 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 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, Danvillier (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 Earth on the eclipsed Moon that led Vassy to conclude that there is an increase in light-scattering aerosols in 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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DISCUSSION

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 10^6 ergs/cm^2 · s, 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 1000 ergs/cm^2 · s.

It is very difficult—at least, for a nonmeteorologist like me—to calculate the amount of energy that would be required in a brute-force way 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 Earth. But it looks to me as if the energy required to do this in some brute-force way is of the order of 10^4 ergs 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?

ROBERTS: I think I mentioned late winter and spring, for the most part, but I am not sure. In any event, in this region, from the Rockies to about 1000 km 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 by Marshall, for example.

RASOOL: One thing that bothers me in these correlations between solar activity and the phenomena on 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 planetwide, so why not take the measurements from all over the globe?

ROBERTS: First of all, there is very abundant literature on searches for drought in various latitudinal 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.

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. 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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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.

> 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 yr ago. During this interval of 75 yr, well over 1000 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 everyday 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 2 or 3 days after geomagnetic activity; (2) meteorological responses to solar activity tend to be the most pronounced during the winter season; and (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 (Kelvin, 1892):

> 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 s^{-1}], which is about 364 times the total horsepower [3.3×10^{33} ergs s^{-1}] of the solar radiation. Thus, in this 8 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 4 months of his regular heat and light. This result, it seems to me, is *absolutely conclusive* [emphasis added] against the supposition 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.

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 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 (1973*b*), and Svalgaard (1973). A good cross-section of current activity in the field was given by the papers at the International Union of Geodesy and Geophysics symposium entitled "Solar Corpuscular Effects on the Stratosphere and Troposphere" held in Moscow, August 1971. The symposium papers are in press. Fifty reports and communications were presented at the first All-Union conference entitled "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 A.

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 (1973*a*) have studied the development of 300-mb low-pressure trough systems in the North Pacific and North America region. They find that troughs that enter (or are formed in) the Gulf of Alaska 2 to 4 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 is greater than or equal to 20×10^{-5} s^{-1} plus the area greater than or equal to 24×10^{-5} s^{-1}. The study included the winter half years 1964 to 1971. Some results of this investigation are shown in figure 1. During 3 to 5 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 10-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

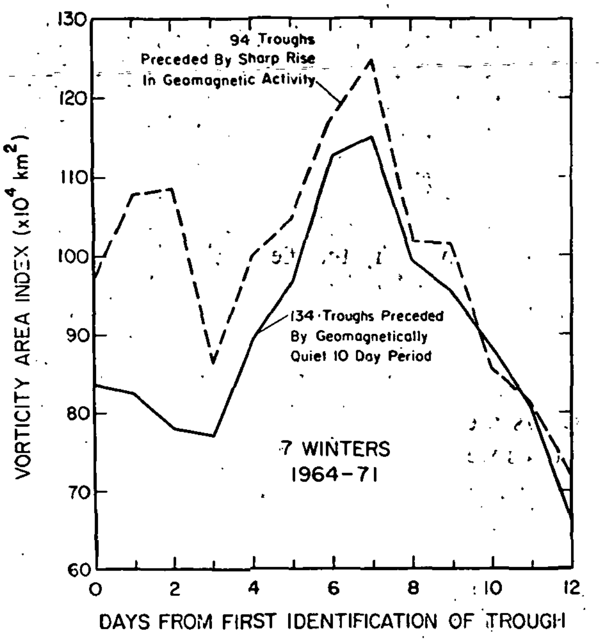


FIGURE 1.—Mean vorticity area index for troughs preceded by sharp geomagnetic activity increases and for troughs preceded by a 10-day geomagnetically quiet period. (For the key troughs add 3 days, on the average, to the lags shown, to ascertain the number of days since the geomagnetic rise that led to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

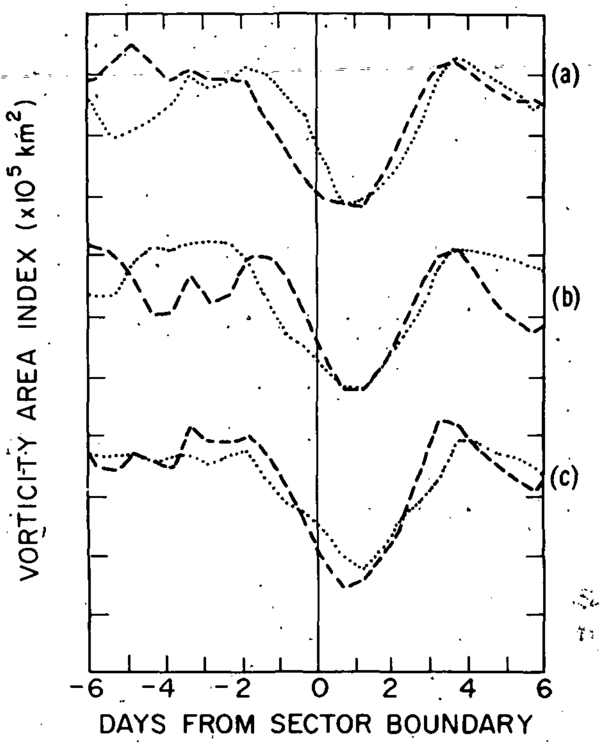


FIGURE 2.—Average response of the vorticity area index to the solar magnetic sector structure. Sestor boundaries were carried past Earth by the solar wind on day 0. The analysis includes 54 boundaries during the winter months of November to March in the years 1964 to 1970. The boundaries were divided 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 in direction from toward the Sun to away from the Sun, and the dashed curve represents 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 represents 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 represents 28 boundaries in the interval 1967 to 1970. The curves have been arbitrarily displayed in the vertical direction, each interval on the ordinate axis being 5×10^5 km^2 (Wilcox et al., 1973*a*, *b*).

(1973*a*) were extended by Wilcox et al. (1973*a*). 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 Earth by the solar wind was used as the 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 will be discussed in more detail. The results of the investigation shown in figure 2 indicate that the vorticity area index reaches a minimum about 1 day after the passing of the sector boundary, followed by an increase in magnitude of approximately 10 percent during the next 2 or 3 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. (1973*b*) 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. Because this meteorological response is related to a well-defined solar structure, it is not subject to the criticism of Hines (1973).

Another prominent investigation during the past decade or longer is the work of E. R. Mustel (1972). 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 3 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 to VI 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

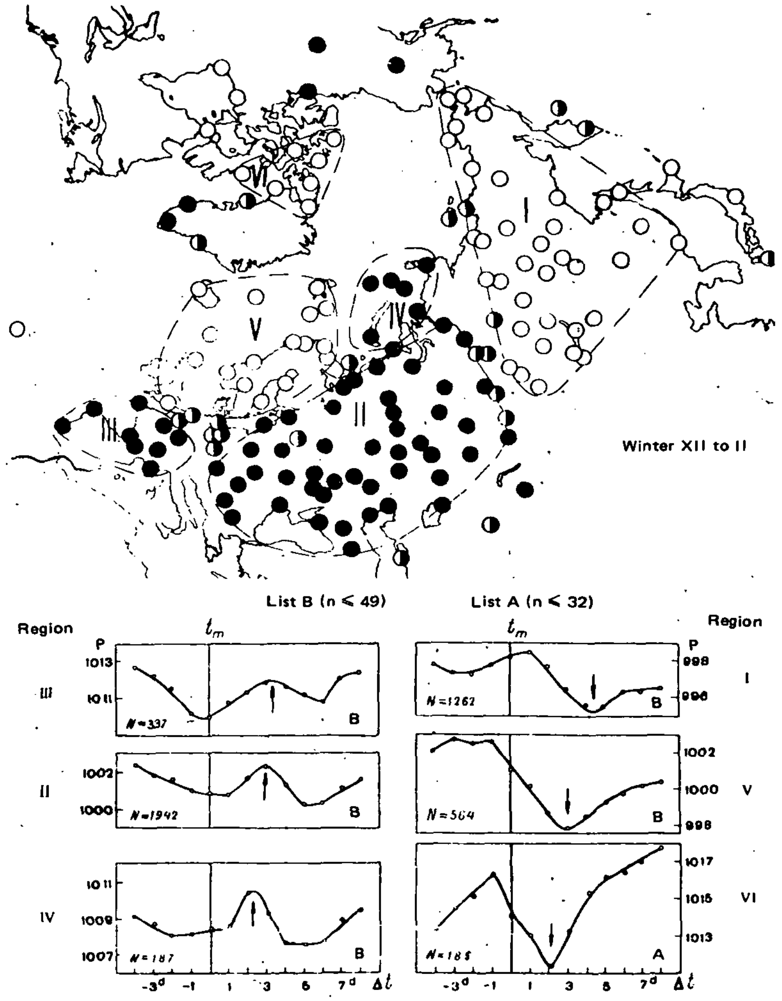


FIGURE 3.—Hemispheric distribution of the change of atmospheric pressure after a geomagnetic storm for the months of December through February and the years 1890 to 1967. The black circles correspond to an increase in pressure and the open circles correspond to a decrease in pressure. At the bottom of the figure the mean statistical curves for the regions I to VI are given (Mustel, 1972). (n=number of stations reporting; t=time in days from 3 days before t_m to 7 days after t_m, t_m=first day when an isolated geomagnetic storm becomes sufficiently strong to be recorded; P=atmospheric pressure in millibars; and N=number of cases in the analysis of data from a particular region.)

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.

TABLE 1.—*Average Atmospheric Pressures Resulting From Variations in Interplanetary Magnetic Field Direction*

Location	Interplanetary field	Pressures, millibars
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 hr 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 midlatitude 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 hr 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.

Shapiro and Stolov (1972) have found significant increases in westerly winds at the 700-mb level in the longitude belt from 90° to 180° W approximately 3 or 4 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 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 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 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 H_α flare, the global thunderstorm activity becomes higher than normal, 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 H_α flares. This is detected through an increased concentration of the radionuclides Be–7 and P–32 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.

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

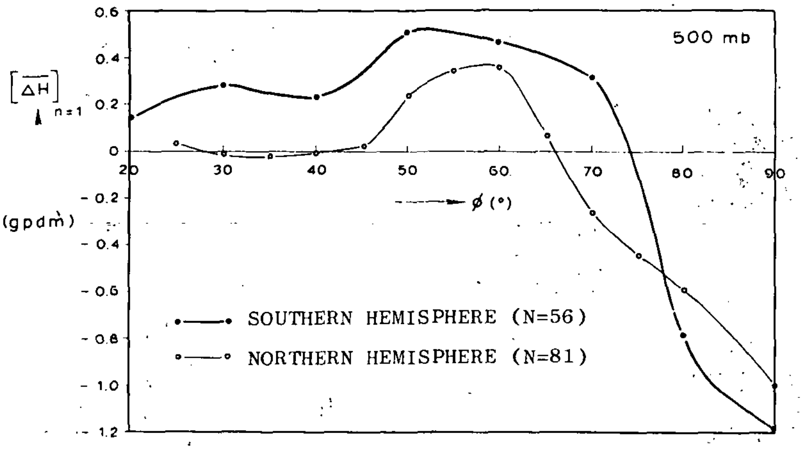


FIGURE 4.—Zonal averages of the difference in height of the 500-mb level between the first aerological observation after a flare and the observation 24 hr earlier as a function of latitude for both hemispheres (Schuurmans, 1969). (gpdm=geopotential dynamic meters; N=number of cases in sample.)

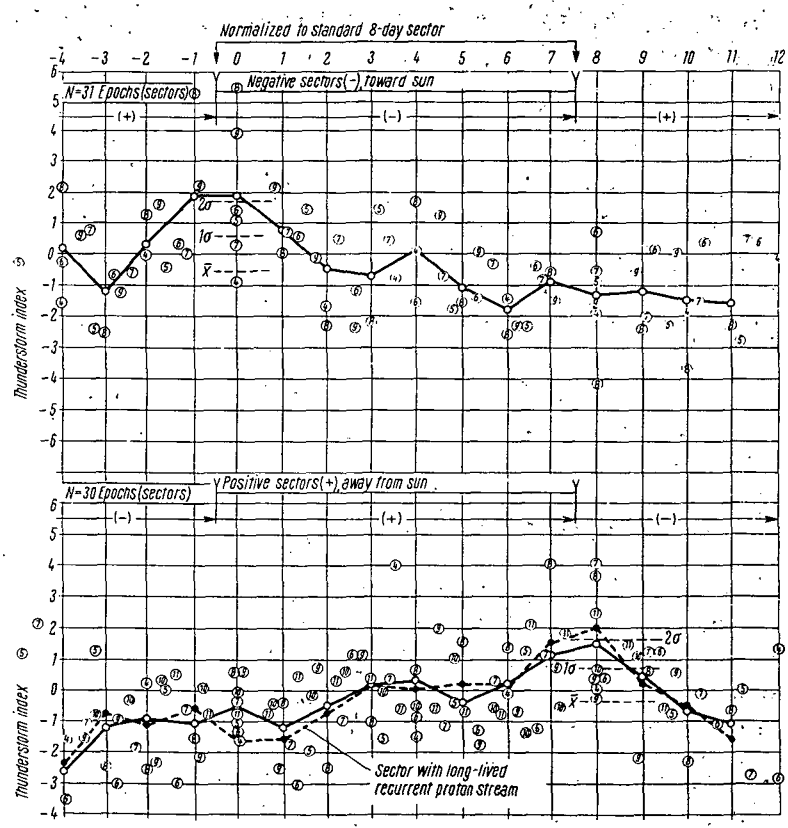


FIGURE 5.—Thunderstorms as a function of Earth's position in a solar sector: negative sectors (*top curve*); positive sectors (*bottom curve*); transitions to adjacent sectors of opposite sign seen at days 0 and 8; all points shown to indicate variance in data; curves drawn through locus of points closest 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).

for physical mechanisms. For example, Berko and Hoffman (1974) have studied high-latitude field-alined 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-alined events observed in the magnetic latitudes from 67.5° to 72.5° and from 1 to 22 hr. Figure 8 shows the probability of this 2.3-keV electron precipitation being field-alined 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.

If other spacecraft experimenters could be

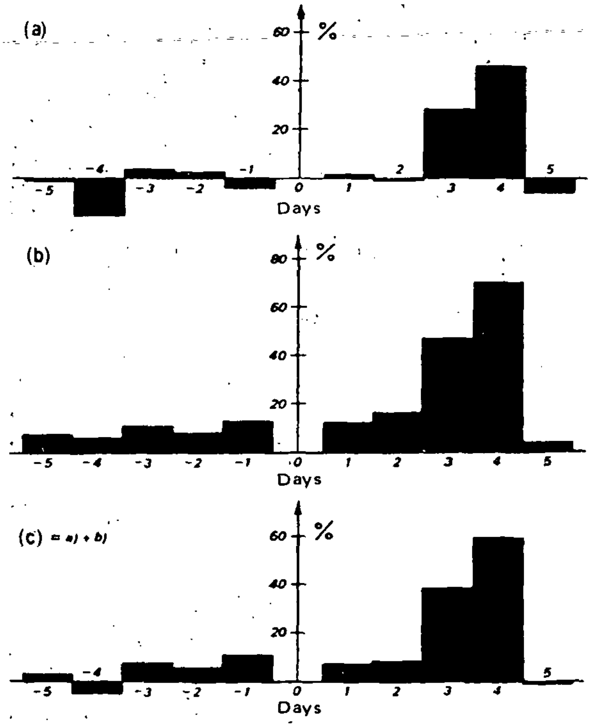


FIGURE 6.—Superposed-epoch analysis of the thunderstorm activity before and after H_α flare day (with H_α flare day as a key day). Data are expressed in terms of percent differences from the value corresponding to the key day (Bossolasco et al., 1972). (*a*) 1961 to 1965. (*b*) 1966 to 1970. (*c*) 1961 to 1970.

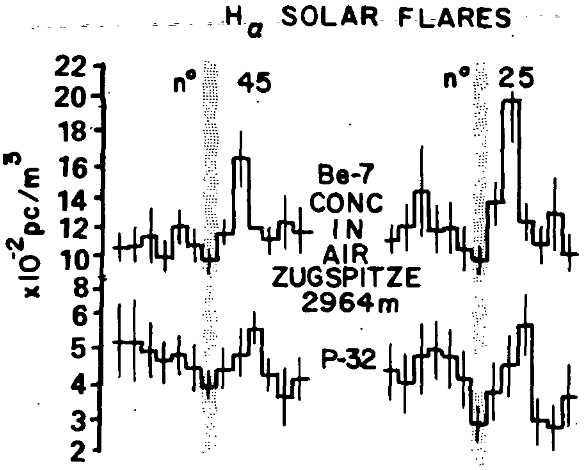


FIGURE 7.—Superposed -epoch analysis of Be–7 and P–32 concentrations in air at 3 km above sea level, and various solar and geophysical data. All solar H_α flares of intensity Z2 plus all flares in the region of the Sun bounded by 20° E, 20° W, 20° N, and 20° S having an intensity Z1 are shown. (n=number of key days; vertical bars: standard deviation (Reiter, 1973).)

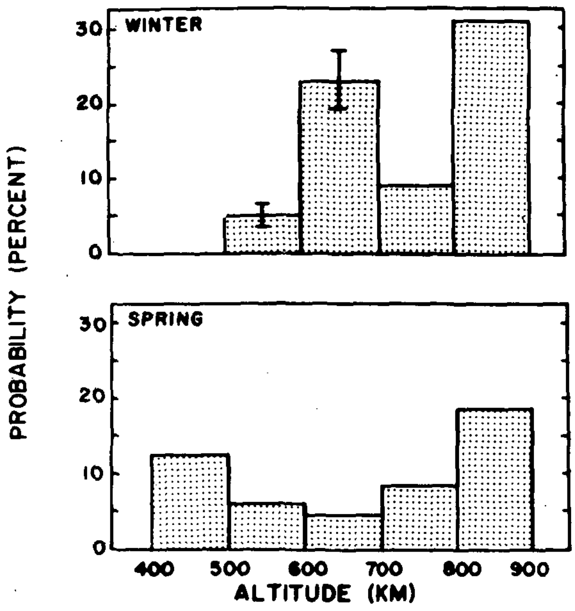
encouraged to analyze their data in terms of the four seasons, it seems possible that valuable clues to the physical mechanisms involved in the effects of solar activity on the weather might result.

The investigations described 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-yr 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 through 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. (1973*b*).

Figure 9 shows spacecraft observations of the polarity (away from or toward the Sun) of the interplanetary magnetic field observed near Earth during 2½ solar rotations. The plus and minus signs at the periphery of the figure represent the field polarity during 3-hour intervals (plus indicates away from the Sun and minus indicates toward the Sun). 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



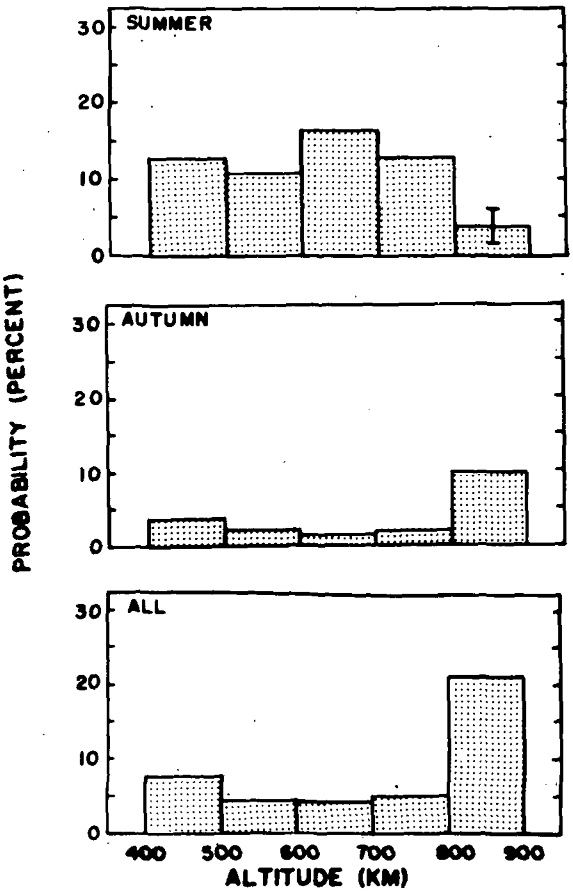


Figure 8.—Probability of 2.3-keV electron precipitation being field alined for the four seasons as a function of altitude in the mean local time interval of 22 hr to 1 hr. The seasons are defined as equal time intervals around the equinoxes and the solstices. During winter at high altitudes the probability is much larger than during the other seasons (Berko and Hoffman, 1974).

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 Earth by the solar wind can therefore often be defined to within a fraction of an hour.

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 Earth with the solar photospheric magnetic field deduced from the longitudinal Zeeman effect measured at the 150-ft 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 west of the boundary has a large-scale field of one polarity and a large-scale region to the east 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, because 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

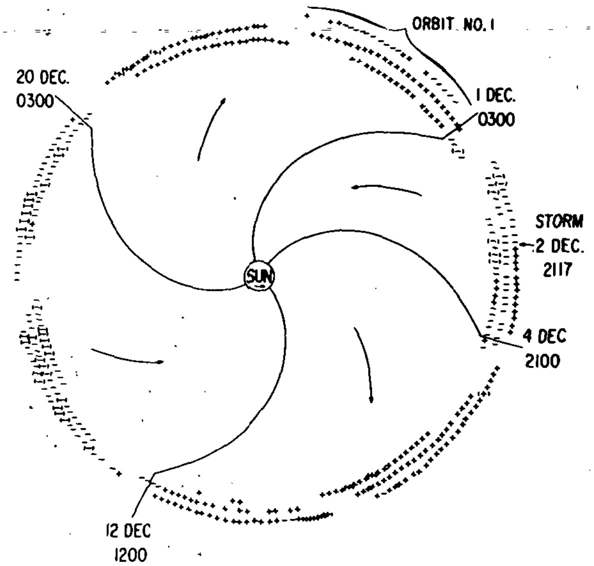


FIGURE 9.—The inner portion of the figure is a schematic representation of a sector structure of the interplanetary magnetic field that is suggested by observations obtained with the IMP 1 spacecraft flight in 1963. The signs at the circumference of the figure indicate the direction of the measured interplanetary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

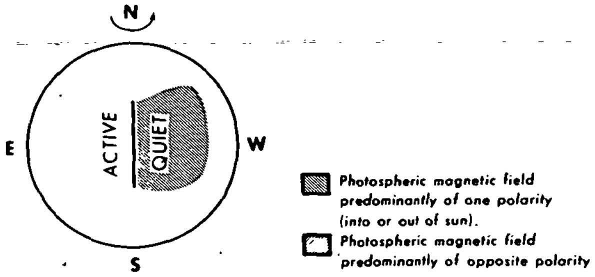


FIGURE 10.—Schematic of an average solar sector boundary. The boundary is approximately in the north-south direction over a wide range of latitudes. The solar region to the west of the boundary is unusually quiet, and the region to the east of the boundary is unusually active (Wilcox, 1971).

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 Earth (Severny et al., 1970). In this comparison, the mean solar field has been displaced by 4½ days to allow for the average transit time from near the Sun to Earth of the solar wind plasma that is transporting the solar field lines past Earth. We see in figure 11 that in polarity and also to a considerable extent in magnitude the interplanetary field carried past Earth is very similar to the mean solar magnetic field. If we use the observed interplanetary field to investigate effects on Earth's weather, we are using a structure that is clearly of solar origin but is observed at precise times near Earth.

In addition to the sharp, well-defined change of polarity at the boundary, the sector structure has a large-scale pattern. During the several days before a boundary is observed to sweep past 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 K_p as sector boundaries sweep past Earth. In the days before a boundary, the average geomagnetic activity has a monotonic decline to a minimum about 1 day before the boundary. Activity then rises to a peak 1 or 2 days 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 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 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 this discussion it appears reasonable to use the solar magnetic sector structure in an investigation of possible effects on Earth's weather. The use of the sector structure for this purpose has several advantages. We are using a funda-

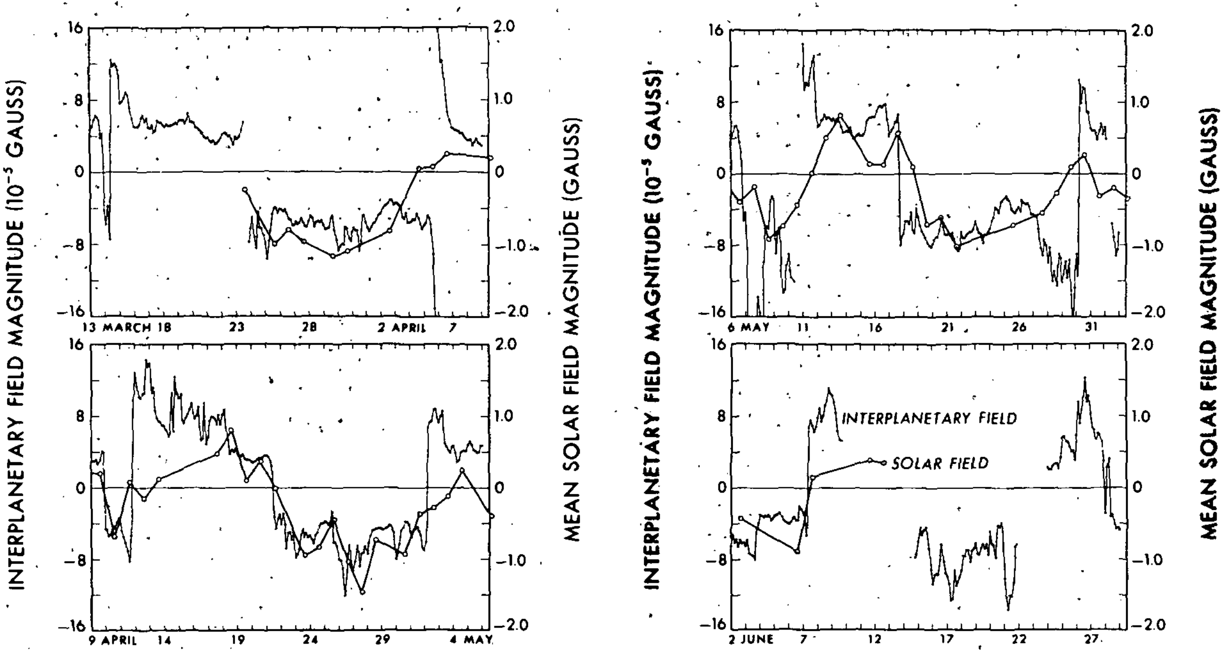


FIGURE 11.—Comparison of the magnitude of the mean solar field and of the interplanetary field. The open circles are the daily observations of the mean solar field, and the dots are 3-hr average values of the interplanetary field magnitude observed near Earth. The solar observations are displaced by 4½ days to allow for the average Sun-Earth transit time. The abscissa is the time of the interplanetary observations (Severny et al., 1970).

mental 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. 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 just discussed, 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 4- or 5-day transit time of the solar wind plasma from the Sun to Earth, we can have, by observing the mean solar magnetic field, a 4- or 5-day forecast of that time at which a sector boundary will sweep past Earth. By improving the solar observation procedure, we may be able to detect a sector boundary 2 or 3 days after it has rotated past the eastern limb of the Sun. This would add an additional 4 or 5 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-yr 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 B. If it were

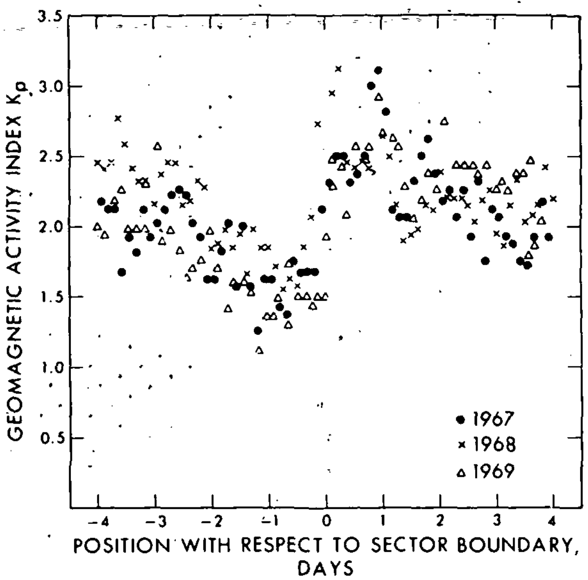


FIGURE 12.—Superposed-epoch analysis of the magnitude of the planetary magnetic 3-hr range indices K_p as a function of position with respect to a sector boundary. The abscissa represents position with respect to a sector boundary, measured in days, as the sector pattern sweeps past Earth (Wilcox and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

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 A—CONFERENCE ON SOLAR-ATMOSPHERIC RELATIONSHIPS IN THE THEORY OF CLIMATE AND WEATHER FORECASTING

The first All-Union conference on the problem "Solar-Atmospheric Relationships in the Theory of Climate and Weather Forecasting" was held recently in Moscow (Lesik, 1972). It was called on the initiative of the Main Administration of the Hydrometeorological Service of the U.S.S.R. Council of Ministers. Scientific specialists from the U.S.S.R. Hydrometeorological Center, the Main Astronomical Observatory of the U.S.S.R. Academy of Sciences, the Institute of Terrestrial Magnetism, the Ionosphere and Radio Wave Propagation Institute of the U.S.S.R. Academy of Sciences, the Main Geophysical Observatory, the Arctic and Antarctic Scientific Research Institute, the Central Aerological Observatory, the Institute of Biology of Internal Waters of the U.S.S.R. Academy of Sciences, the Marine Hydrophysical Institute Academy of Sciences of the Ukranian S.S.R., the Institute of Applied Geophysics, Leningrad and Kazan' State Universities, the Advanced Marine Engineering Institute, the Scientific Research Heliometeorological Station at Gornaya Shoriya, and the Kherson Agrometeorological Station presented different reports at its sessions.

Fifty reports and communications were presented at the conference, which lasted 3 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 performed over a period of several decades in the U.S.S.R. 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 the 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 U.S.S.R. Hydrometeorological Service, the conference nevertheless pointed out serious shortcomings.

For example, in the U.S.S.R. Hydrometeorological Service and in the U.S.S.R. 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 improvement 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 U.S.S.R. 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 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 U.S.S.R. 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 *Fiziak Atmosfery i Okeana*. The U.S.S.R. Hydrometeorological Service, the Main Geophysical Observatory, and the Arctic and Antarctic Scientific Research Institute have been delegated the task of generalizing investigations on this problem and preparing a systematic manual for operational workers in the U.S.S.R. 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 departments of solar/terrestrial relationships at some universities and hydrometeorological institutes. Solar specialists expect great assistance from the institutes of the U.S.S.R. 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 2 or 3 yr, 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 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–Oct. 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 Service of the U.S.S.R. Council of Ministers.

APPENDIX B—OBSERVED AND WELL-DEFINED SECTOR BOUNDARIES[a]

Year	Day of year	Sign[b]	Date	Time[c]
1962	253	+, −	Sept. 10	8–1
	269	−, +	Sept. 26	3–4
	281	+, −	Oct. 8	4–5
	293	−, +	Oct. 20	8–1
1963	336	−, +	Dec. 2	8–1
	346	+, −	Dec. 12	4–3 (gap)
	354	−, +	Dec. 20	1–2
1964	007	+, −	Jan. 7	7–8
	016	−, +	Jan. 16	2–2 (gap)
	023	+, −	Jan. 23	3–4
	035	+, −	Feb. 4	2–3
	284	−, +	Oct. 10	6–7 (1-day gap)
	291	+, −	Oct. 17	7–8
	297	−, +	Oct. 23	6–8 (1-day gap)
	306	+, −	Nov. 1	5–6
	312	−, +	Nov. 7	2–1 (gap)
	320	+, −	Nov. 15	5–6
	325	−, +	Nov. 20	3–2 (gap)
	332	+, −	Nov. 27	7–8
	341	−, +	Dec. 6	4–5
	345	+, −	Dec. 10	8–1
	349	−, +	Dec. 14	8–1
	361	+, −	Dec. 26	1–2
1965	002	−, +	Jan. 2	1–2
	008	+, −	Jan. 8	1–2
	012	−, +	Jan. 12	2–3
	032	+, −	Feb. 1	8–1
	125	+, −	May 5	4–5
	153	+, −	June 2	8–1
	161	−, +	June 10	2–3
	230	−, +	Aug. 18	7–6 (gap)
	235	+, −	Aug. 23	5–7 (gap)
	259	−, +	Sept. 16	2–3
1966	001	+, −	Jan. 1	6–7 (1-day gap)
	032	+, −	Feb. 1	4–5
	043	−, +	Feb. 12	2–3
	062	+, −	Mar. 3	3–4
	067	−, +	Mar. 8	2–3
	089	+, −	Mar. 30	2–3
	099	−, +	Apr. 9	1–2
	127	−, +	May 7	8–1
	249	−, +	Sept. 6	5–6
	257	+, −	Sept. 14	6–7
	276	−, +	Oct. 3	6–7
	285	+, −	Oct. 12	2–3
	303	−, +	Oct. 30	5–6
	312	+, −	Nov. 8	4–5
	331	−, +	Nov. 27	7–8
	338	+, −	Dec. 4	3–4
1967	001	+, −	Jan. 1	7–8
	013	+, −	Jan. 13	3–4
	018	−, +	Jan. 18	2–3 (1-day gap)
	081	−, +	Mar. 22	7–8
	216	−, +	Aug. 4	5–6
	242	−, +	Aug. 30	2–3 (1-day gap)
	249	+, −	Sept. 6	6–7
	270	−, +	Sept. 27	3–4
	276	+, −	Oct. 3	1–2
	297	−, +	Oct. 24	2–3
	324	−, +	Nov. 20	4–5
	338	+, −	Dec. 4	5–6
1968	001	+, −	Jan. 1	6–5 (gap)
	028	+, −	Jan. 28	8–1
	042	−, +	Feb. 11	3–4
	057	+, −	Feb. 26	6–7
	070	−, +	Mar. 10	4–5
	083	+, −	Mar. 23	5–6
	096	−, +	Apr. 5	7–8
	112	+, −	Apr. 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	−, +	Aug. 13	7–8
	234	+, −	Aug. 21	2–3
	263	+, −	Sept. 19	2–3
	290	+, −	Oct. 16	5–6
	318	+, −	Nov. 13	2–3
	334	−, +	Nov. 29	6–8 (gap)
	345	+, −	Dec. 10	2–3
	359	−, +	Dec. 24	6–7
1969	006	+, −	Jan. 6	5–6
	023	−, +	Jan. 23	8–1
	033	+, −	Feb. 2	5–6
	050	−, +	Feb. 19	2–3
	090	+, −	Mar. 31	6–7
	110	−, +	Apr. 20	7–1 (gap)
	119	+, −	Apr. 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	−, +	Aug. 7	6–7
	248	−, +	Sept. 5	3–4

Year	Day of year	Sign[b]	Date	Time[c]
	303	–, +	Oct. 30	8–1
	330	–, +	Nov. 26	5–6
	343	+, –	Dec. 9	1–2
	356	–, +	Dec. 22	7–8
1970	040	–, +	Feb. 9	7–8
	067	–, +	Mar. 8	8–1
	120	–, +	Apr. 30	3–4
	131	+, –	May 11	6–7
	158	+, –	June 7	6–7
	243	+, –	Aug. 31	8–5 (gap)
	309	–, +	Nov. 5	3–4
	328	+, –	Nov. 24	3–4

[a] All sector boundaries listed have at least 4 days of opposite field polarity on each side of the boundary.

[b] Plus indicates away from the Sun; minus indicates toward the Sun.

[c] Time is indicated in 3-hr intervals. The notation 8–1 means that the boundary occurred between the last 3-hr interval of that day and the first 3-hr interval of the next day.

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Magnetometeorology: Relationships Between the Weather and Earth's Magnetic Field

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A comparison of meteorological pressures and the strength of 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° toward the west. Certain features of the "permanent" atmospheric pressure system appear to have moved westward during some decades of the present century, and this movement may be associated with the westward drift of the nondipole component of 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 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-yr 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 1850 A.D. is clearly associated with an epoch of high magnetic

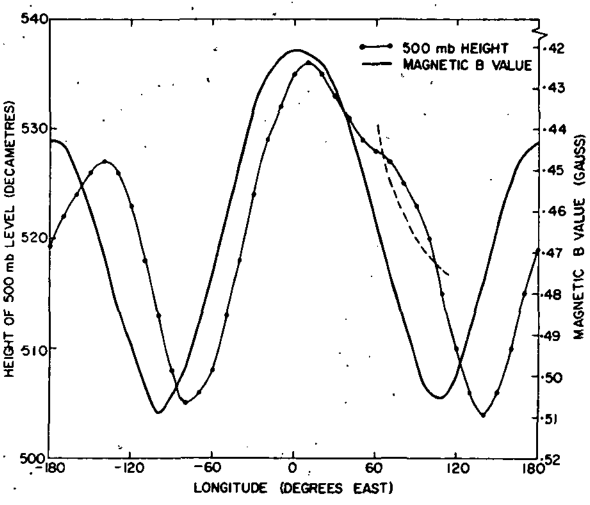

Figure 1.—Curves showing the longitudinal variations at 60° N of the magnetic field strength and the height of the 500-mb level. The short broken curve draws attention to some of the pressure data that may be anomalously high (King, 1974). The magnetic data relate to 1965 and the meteorological data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

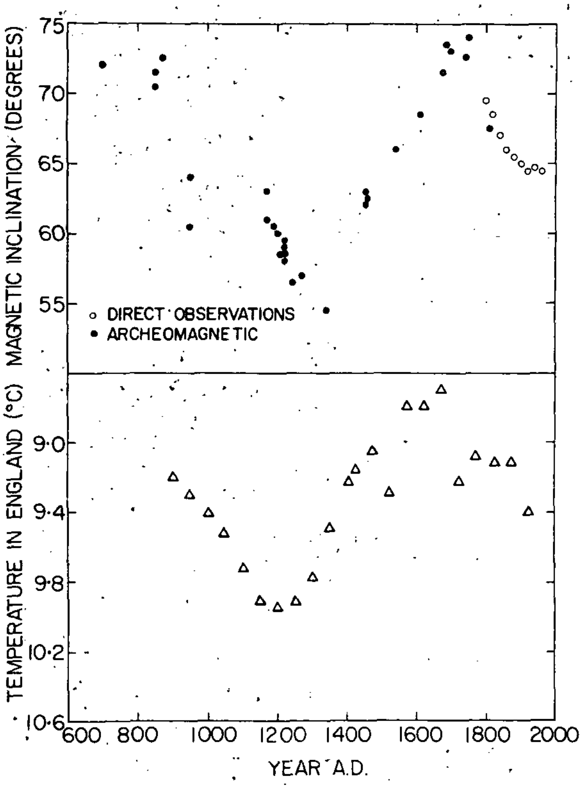

FIGURE 2.—Upper section: magnetic inclination at Paris since 700 A.D. (after Thellier, 1970). Lower section: average temperature in central England since 900 A.D. (after Lamb, 1966).

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 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 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 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 from 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 the 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 10 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 5 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 5-year period. Alternatively, it appears that Earth's magnetic dipole is moving slowly into the northern hemisphere (Nagata, 1965) and the magnetic field is, on the average, gradually increasing there; this behavior may lead, in some unknown way, to the decrease of 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 for climatic changes. We fully appreciate the pitfalls that abound in this area of research and are also cognizant of the speculative nature of the suggestion that spatial and temporal variations of 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.

ACKNOWLEDGMENTS

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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 United States. This was published by Kidson (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* as simply the north-to-south range of movement of the anticyclones in any one year. He showed that *R* is

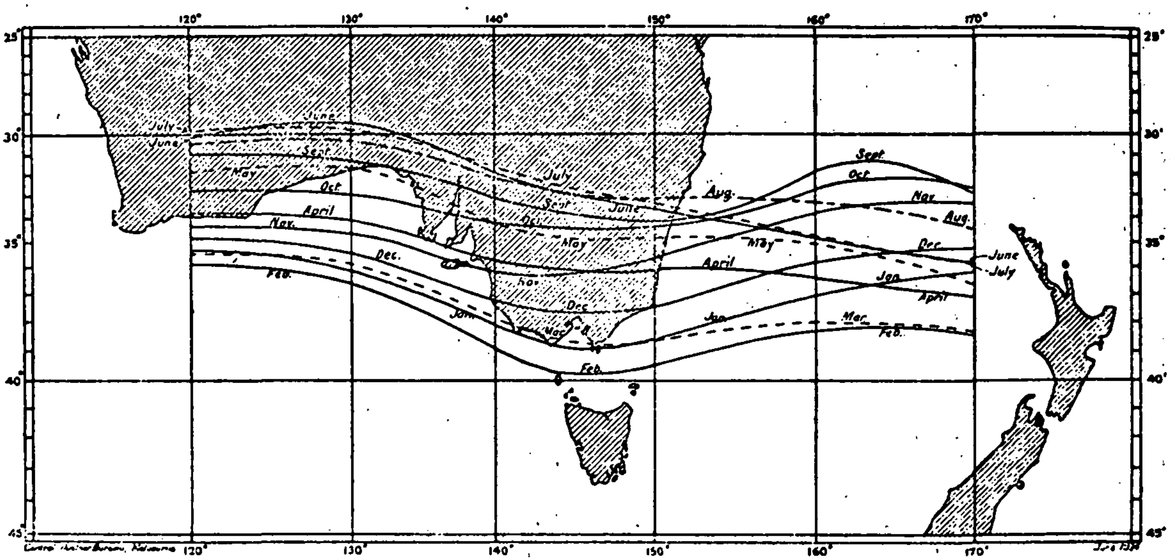

FIGURE 1.—Mean monthly tracks of anticyclones (Kidson, 1925).

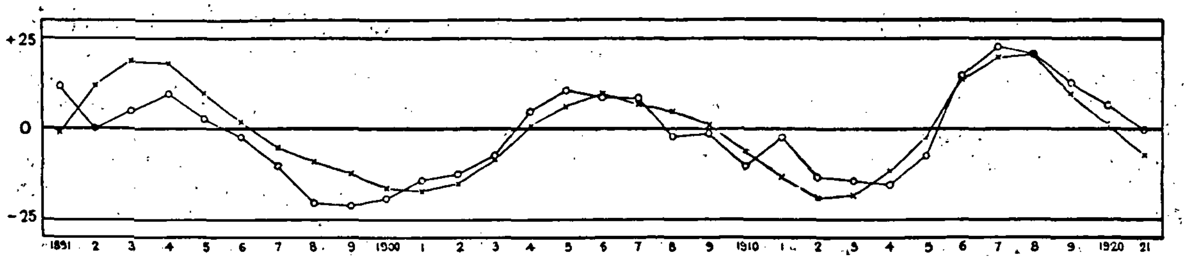

FIGURE 2.—Consecutive means of deviations from normal for 3-yr periods. (X = one-half the Wolf annual sunspot number; O = annual range in latitude in tenths of degrees of anticyclones across the 150° E meridian (normal = 4.0°).)

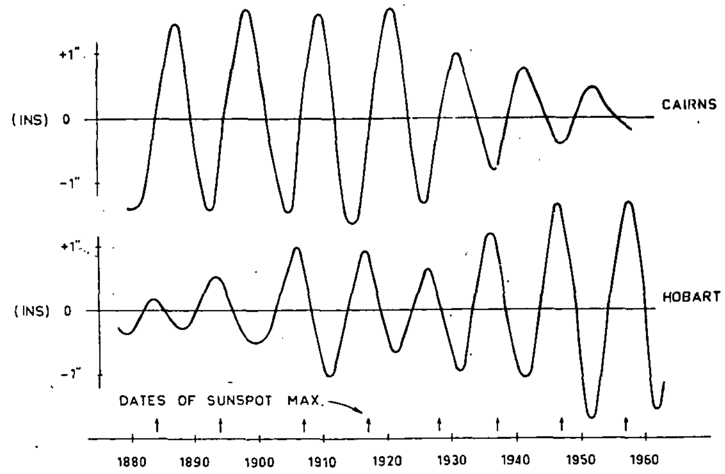

FIGURE 3.—Annual rainfall totals at Cairns and Hobart.

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 30 yr, 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 is clear that if one looks for a 10- or 11-yr 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. 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-yr broadband filter) to the annual rainfall totals, the result shown in figure 3 is obtained.

That is, the 10- and 11-yr 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 the U.S.S.R. 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.

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

DISCUSSION

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

BOWEN: It is essentially a bandpass filter without much flat top. The half values are at 8 and 15 yrs, respectively.

DESSLER: 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-yr 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.

BOWEN: A similar analysis of rainfall data for latitudes intermediate between Hobart and Cairns is indeed confused and might represent noise of low amplitude. However, at the northern and southern latitude extremes, the picture clarifies and two antiphase components stand out.

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Proposed Geomagnetic Control of Semiannual Waves in the Mesospheric Zonal Wind

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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..

Two new distinct polar centers of the semiannual oscillation of the mesospheric zonal wind have recently been identified (Belmont et al., 1974; Groves, 1972). 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 center 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 that, 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.

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.

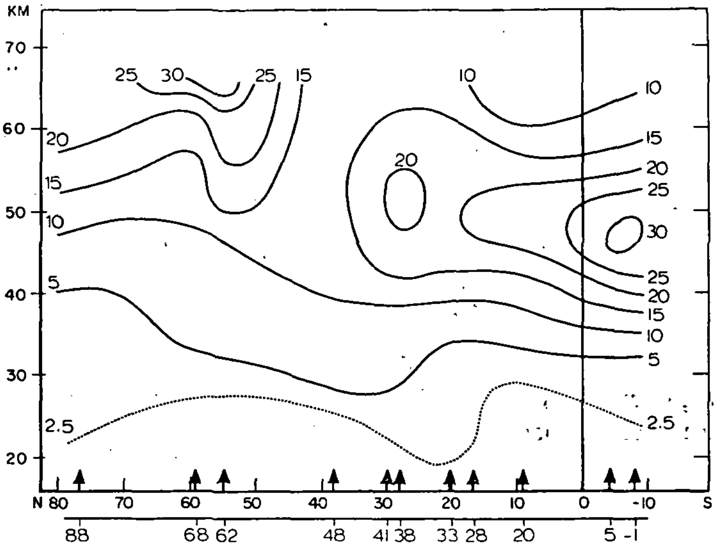

Figure 1.—Amplitude of the semiannual wave in zonal wind (meters per second) for stations near 80° W. Arrows indicate rocket stations. Bottom scale is geomagnetic latitude.

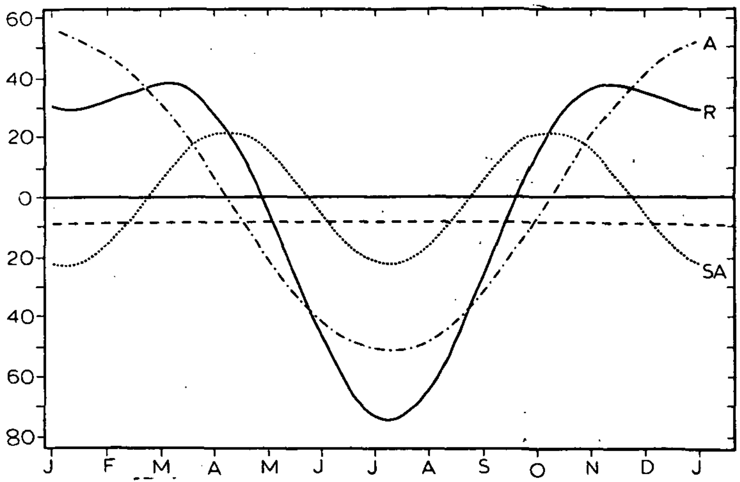

Figure 2.—Yearly wind cycle *R* resulting from addition of annual *A* and semiannual *SA* waves at 60 km at Primrose Lake (55° N). (Ordinate is in units of meters per second; Belmont et al., 1974.)

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. (1974). 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) 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. Because of 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. Therefore, 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 and 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 figures 3 to 6 and the corresponding amplitude of the semiannual wave at 50 km are listed in tables 1 and 2.

Because the maximum of the semiannual wind oscillation coincides with that of the geomagnetic

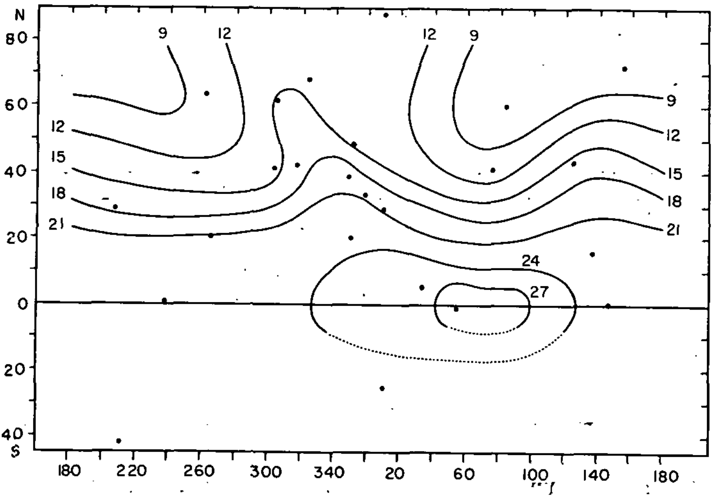

FIGURE 3.—Amplitude (in meters per second) of the semiannual wave at 50 km. Geomagnetic Mercator coordinates are used. The amplitudes of the stations shown by dots are given in tables 1 and 2.

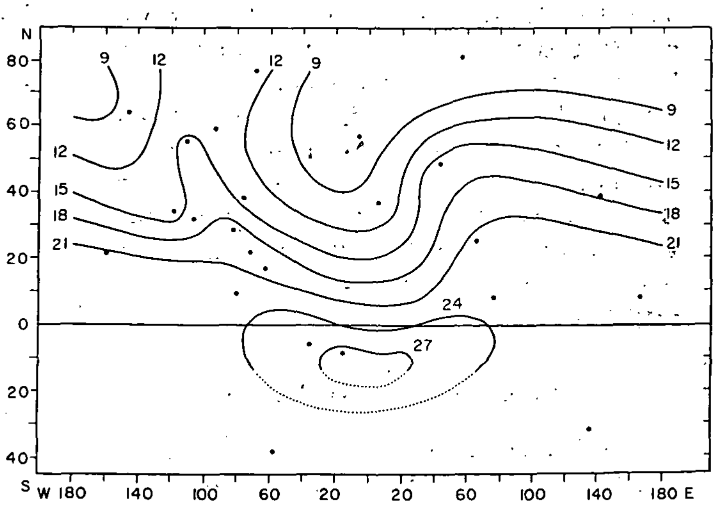

FIGURE 4.—Same as figure 3 in geographic Mercator coordinates.

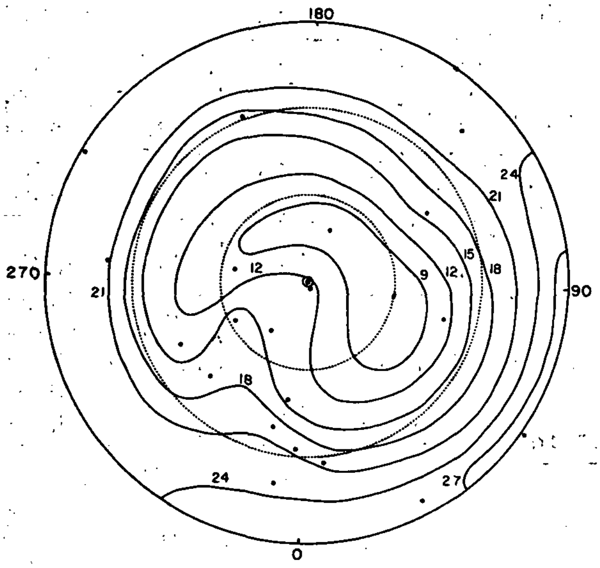

FIGURE 5.—Same as figure 3 in geomagnetic polar coordinates. The dotted lines are 30° and 60° latitudes.

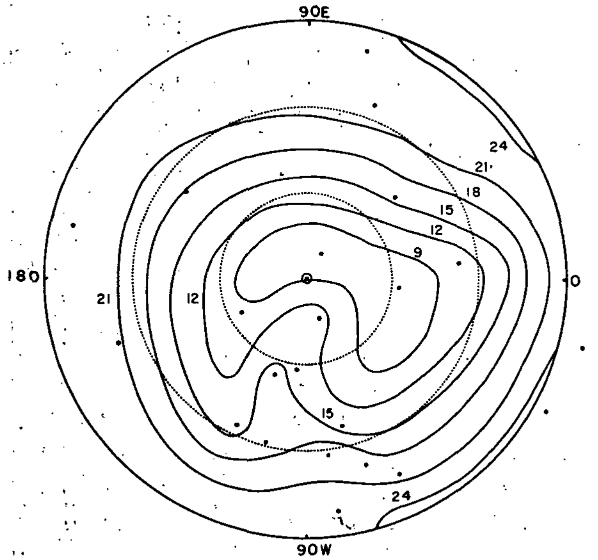

FIGURE 6.—Same as figure 3 in geographic polar coordinates. The dotted lines are 30° and 60° latitudes.

coordinate system, and as the phases of the semiannual wind and magnetic variations are the same, and because the magnetic storm semiannual variation is due to extraterrestrial 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.

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 inter-

TABLE 1.—*Stations Near 80° W*

Station	Latitude	Longitude	Geomagnetic coordinates	Amplitude,[a] 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*

Station	Latitude	Longitude	Geomagnetic coordinates	Amplitude,[a] 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[b]
Volgograd	48° 41′ N	44° 21′ E	43° N 125°	17.1
Ryori	39° 02′ N	141° 50′ E	29° N 207°	17.4[b]
Arenosillo	37° 06′ N	6° 44′ E	41° N 76°	10.9[b]
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[b]
Barking Sands	21° 54′ N	159° 35′ W	21° N 265°	21.1
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
Kwajalein	8° 42′ N	167° 42′ E	1° N 238°	22.8
Thumba	8° 32′ N	76° 52′ E	0° 146°	23.3[b]

[a] From Belmont et al., 1974.

[b] Stations added since Belmont et al. (1973); sources of amplitude data are World Data Center A, Asheville, N.C., and Pakistan Space and Upper Atmosphere Research Committee (1971).

dependent 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 (figs. 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

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.

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.

It is suggested that the *polar* semiannual wind centers are caused by the 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.

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 X' of geomagnetic field at the stations that 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 northern hemisphere X' is greater when Earth is in the positive sector while in the southern hemisphere X' is greater when Earth is in the negative sector (north-south asymmetry). The difference $\Delta X'$ 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 P in the near-Earth layer at the conjugate stations Mould Bay and Dumont d'Urville in 1964.

Resemblance of regularities in the distribution of X' and P is conditioned apparently by a common cause: a zonal magnetospheric convection and related circumpolar ionosphere current vortices that appear first in the southern and then in the northern hemisphere 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, that sometimes get in resonance with oscillation processes in the atmosphere and in the ocean, thus changing the course of the processes that determine the weather and climate.

The existence of a relation between the variations of magnetic field at Earth's surface in near pole regions and the sector structure of the 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 characteristics and physical essence of this relation, the idea about the so-called geomagnetic effect of IMF sector structure, are 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. Both peculiarities are important for understanding 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 that are under the magnetospheric cusps during daytime, at the geomagnetic latitude $\Phi_c = \pm(78° \text{ to } 80°)$, the dependence of Earth's surface magnetic field on the polarity of IMF sectors (under otherwise identical conditions) is expressed by the following inequalities:

$$\left.\begin{array}{ll}\text{Northern hemisphere:} & M\left(X^{1+}_{N}\right) > M\left(X^{1-}_{N}\right)\\ \text{Southern hemisphere:} & M\left(X^{1+}_{S}\right) < M\left(X^{1-}_{S}\right)\end{array}\right\} \qquad (1)$$

where $M\left(X^{1}_{N}\right)$ and $M\left(X^{1}_{S}\right)$ are the time values averaged for a certain interval of the north X^1

component of the geomagnetic field in Hakura's system of coordinates (Hakura, 1965) in the southern S and northern 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 the northern hemisphere when Earth is within the positive sector of IMF and in the southern hemisphere when 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 behavior of $M(X')$ 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 2-month periods keep their levels nearly unchanged during a year, while the magnitudes $M\left(X_N^{1+}\right)$ and $M\left(X_S^{1-}\right)$ obtained in the same way are changing regularly and forming an annual wave with the maximum in local summer. As in the behavior of magnitudes $M(X')$ in the northern and southern hemispheres, similar characteristics are observed at different IMF directions; the peculiarity of the relation between geomagnetic field and IMF 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 the magnetosphere to the solar wind.

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

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

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 mean magnitudes of the geomagnetic field north component X' in gammas for March-April and September-October 1964 for the stations Dumont d'Urville and Mould Bay during two 3-hr groups (morning and afternoon) for the IMF directed away and toward the Sun. Calculations of X' from observations of X and Y (projections of the horizontal component on geographical meridian and parallel) made at the stations are made by

$$X' = 0.87X + 0.49Y$$

for Dumont d'Urville and by

$$X' = 0.69X + 0.72Y$$

for Mould Bay.

Both peculiarities of the relationship of geomagnetic and interplanetary fields are represented in the histograms. The average values $M(X')$ given in table 1 satisfy inequalities (1) and (2).

Control of the significance of the results of analysis by the method of mathematical statistics showed that the distribution of magnitudes X' at positive and negative directions of IMF in 1964 was different with a probability of 99 percent or greater (according to Kholmogorov's and Wilcox's criteria) both for March-April and September-October periods at the Mould Bay station. At the Dumont d'Urville station the distribution of X' was different with the same probability (99 percent or more) only for the period of local spring (September-October). For the period of local autumn (March-April) it was different with the probability of at least 90 percent, according to Kholmogorov's criterion, and at least 94 percent, according to Wilcox's and Pirson's criteria. Thus, one may consider with much confidence that the distributions of X' vary at different directions of IMF. The application of t criteria to estimate the reliability of the difference between the average values X' for these two samples showed that the average values X' in

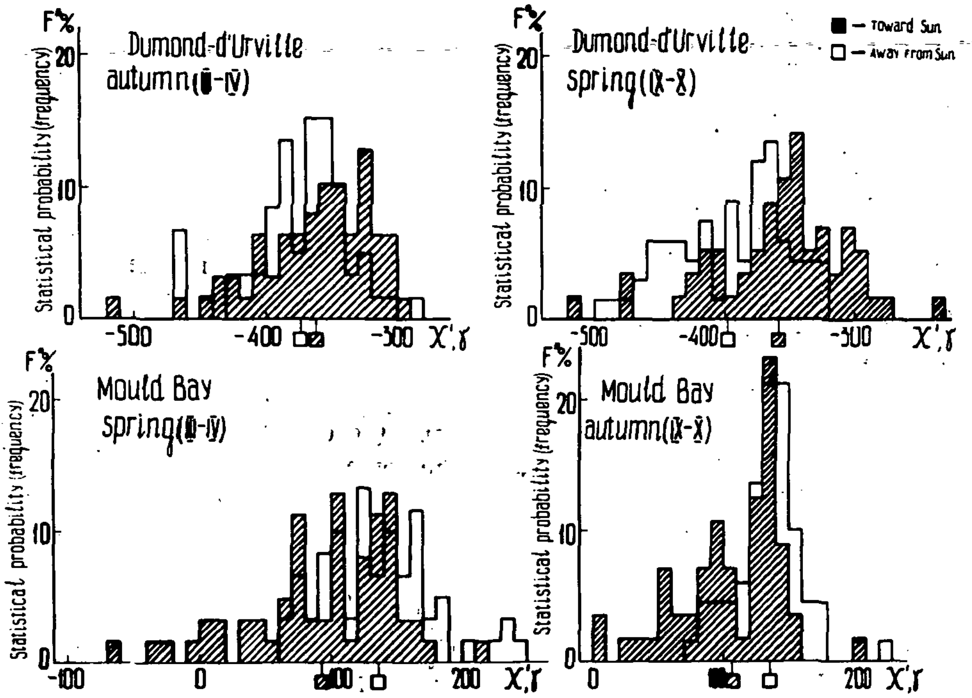

FIGURE 1.—Histograms of the mean magnitudes of the geomagnetic field north component X' in gammas.

local spring at both stations and in local autumn at the Mould Bay station differed with a probability of 99.9 percent. This difference in local autumn at the Dumont d'Urville station is less probable (its probability is about 80 to 90 percent).

In the works by Smirnov (1972), Mansurov et al. (1972), and Wilcox et al. (1973), there are indications of a noticeable influence of IMF sector structure upon near-Earth atmospherical layers and upon the stratosphere. Therefore, the result of analysis of the atmosphere pressure data P in near-Earth layer at the magnetically conjugate Dumont d'Urville and Mould Bay stations (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:

$$\left.\begin{array}{ll}\text{Northern hemisphere:} & M\left(P_N^+\right) < M\left(P_N^-\right)\\ \text{Southern hemisphere:} & M\left(P_S^+\right) > M\left(P_S^-\right)\end{array}\right\} \qquad (3)$$

$$\left.\begin{array}{l}\left[M\left(P_N^-\right) - M\left(P_N^+\right)\right]_{\text{III–IV}} > \left[M\left(P_N^-\right) - M\left(P_N^+\right)\right]_{\text{IX–X}}\\ \left[M\left(P_S^+\right) - M\left(P_S^-\right)\right]_{\text{III–IV}} < \left[M\left(P_S^+\right) - M\left(P_S^-\right)\right]_{\text{IX–X}}\end{array}\right\} \qquad (4)$$

where the $M(P)$ values are the average values of atmospheric pressure for the southern S and northern N hemisphere stations 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 dis-

TABLE 1.—*Values of* M(X′) *and* M(P)

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

Note: Numbers in parentheses indicate sample size.

tribution of atmosphere pressure P values in millibars for March-April and September-October 1964 at the two stations for eight synoptical terms per day with IMF directed toward and away from the Sun. It is seen that both the peculiarities of pressure value distributions depending on IMF structure (north-south and spring-autumn asymmetry) as well as the case of X' distribution (fig. 1) are clearly revealed. The average values of $M(P)$ given in table 1 satisfy the inequalities (3) and (4).

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

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

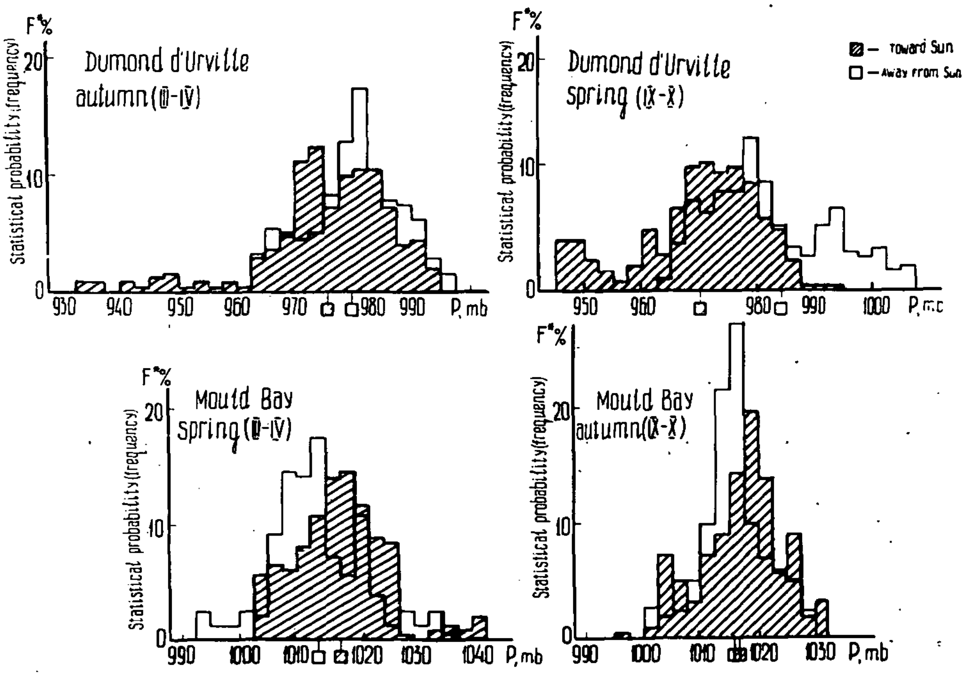

FIGURE 2.—Histograms of the distribution of atmospheric pressure P values in millibars.

The resemblance of the distribution regularity of *X′* and *P* depending on the sign of the 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 that 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 Yoshida et al. (1971), there is a north-south asymmetry in cosmic ray intensity that depends on IMF sector sign. Our results are in agreement with the conception of Sazonov (1972) concerning the cosmic rays effects upon the atmosphere lower layers.

Smirnov (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"

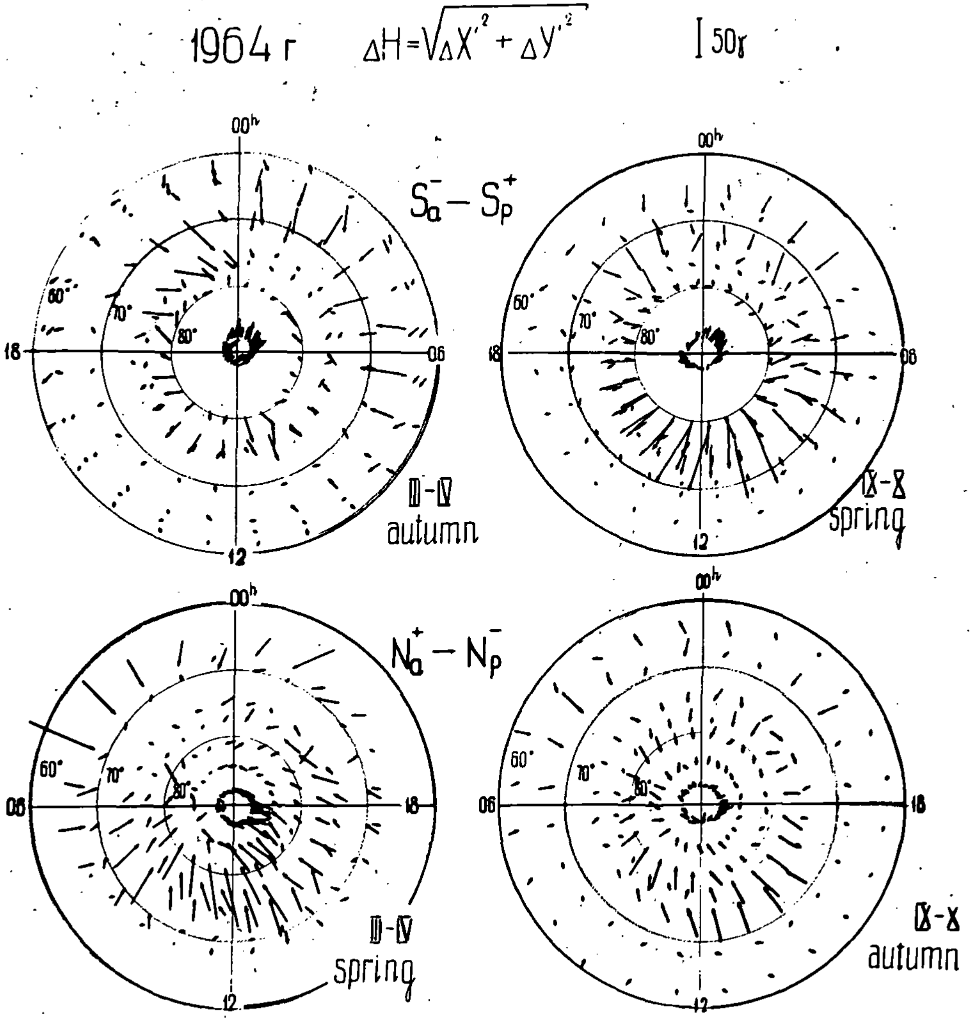

FIGURE 3.—Geomagnetic effect of the sector structure of IMF in horizontal component. The top graphs are of Dumont D'Urville and the bottom graphs are of Mould Bay.

are observed by Sen'ko (1959) and by Mansurov (1958). It means that in the mechanism of relation between upper and lower parts of the 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 (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 that 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 that determine the weather and the climate. Such possibility ensues from the fact that 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 the southern hemisphere and $N_a^+ - N_p^-$ for the northern hemisphere between the mean hour values of the horizontal component of the geomagnetic field, calculated separately for samples at positive (S_p^+ and N_a^+) and negative (S_a^- and N_n^-) directions of IMF for two equinoctial periods of 1964 of 2-month 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.

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On Possible Interactions Between Upper and Lower Atmosphere

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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 millibars increases markedly from 5 to 8 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-millibar cold air pool. This shrinkage commences about 3 days after the stratospheric warming.

Our investigation also indicates that the energy input into the stratosphere that 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.

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-millibar troughs that enter or move into the Gulf of Alaska were amplified several days after 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-millibar level.

Reiter and Macdonald (1973) indicated that fluctuations in the area of the tropospheric cold pool ($T < -30°$ C at 500 millibars) and in the size of the polar vortex at 10 millibars 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-millibar troughs over North America tended to intensify with a lag time from a geomagnetic event to maximum vorticity development of about 5 to 7 days. They define a geomagnetic event as a daily planetary geomagnetic activity index A_p, 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 is 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.

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 yr 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 millibars. 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 gives 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-millibar 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. National Weather Service 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. National Weather Service. Portions of this area that 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-millibar cold pool in arbitrary units.

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 nonkey dates. This eliminates the "preevent" 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

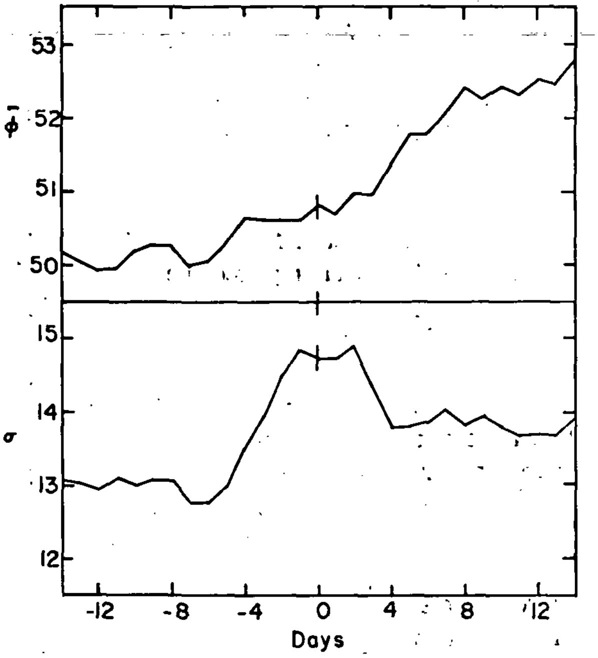

FIGURE 1.—Superposed epoch averages of the daily mean latitude Φ (*top*) and the daily standard deviation σ (*bottom*) of the 30 640-m contour line at 10 millibars surrounding key geomagnetic dates. Data averaged were taken from 98 cases in 9 cold seasons (November through March) for the years 1960–61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

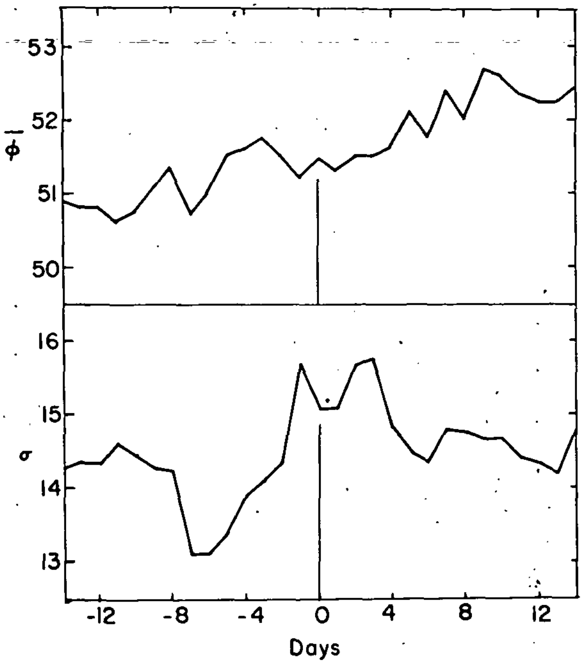

FIGURE 2.—Key geomagnetic dates that were preceded by at least nine nonkey geomagnetic dates (40 cases) in 9 cold seasons (November through March) for the years 1960–61 through 1968–69.

these epochs are show in figure 2. It was noticed, however, that a sudden breakup 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 4- to 5-day shrinkage of the polar vortex follows a key geomagnetic date by about 3 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 prekey event values. Specifically, we used the D_{-10} through D_{-1} mean latitudes for the preevent data, giving a total of 15 values to be compared for each epoch. A simple rank sum test was used to compare 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 preevent 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 these 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 determination are shown in figure 5. Again we selected only those key dates that were preceded by at least 9 nonkey dates, of which there were 14, and the results of the superposed epochs for these events are shown in figure

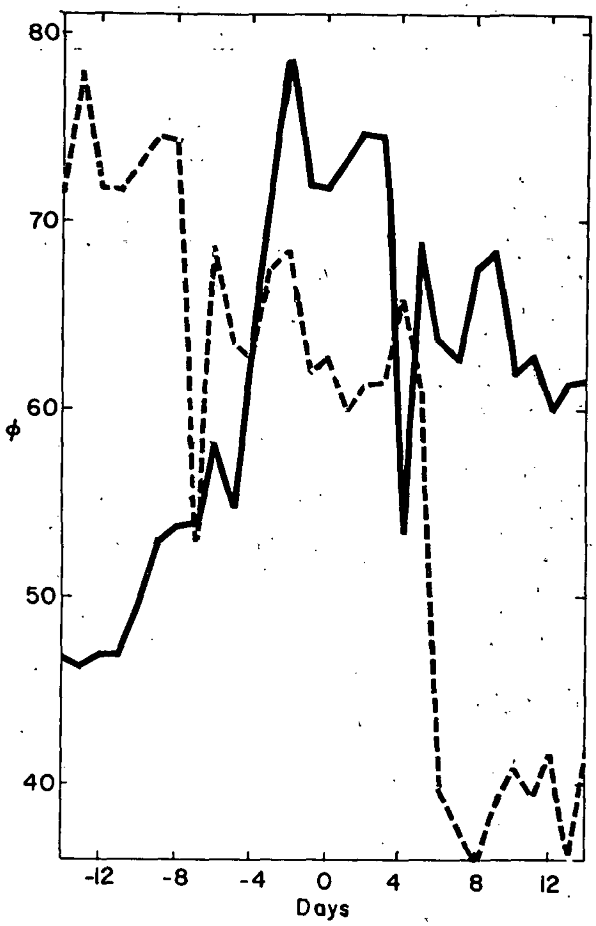

FIGURE 3.—The daily mean latitude values of the 30 640-m contour at 10 millibars surrounding the key geomagnetic dates of January 30, 1963 (solid line), and February 10, 1973 (dashed line).

6. Note a similar trend toward an increase in mean latitude following the geomagnetic event (in this case from 6 to 8 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.

We also tried to determine a mean 500-millibar cold pool response surrounding similar geomagnetic events. Because 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 that were used ran from 1953–54 through 1962–63, and 113 days were selected as key geomagnetic dates from this

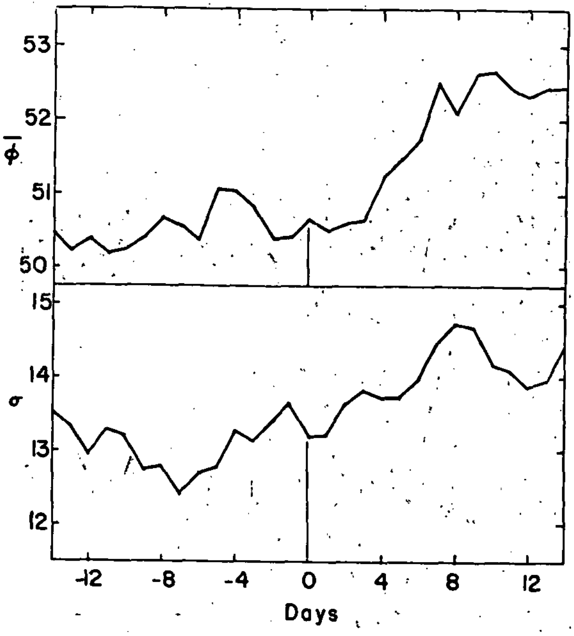

FIGURE 4.—The daily mean latitude values at 10 millibars (38 cases).

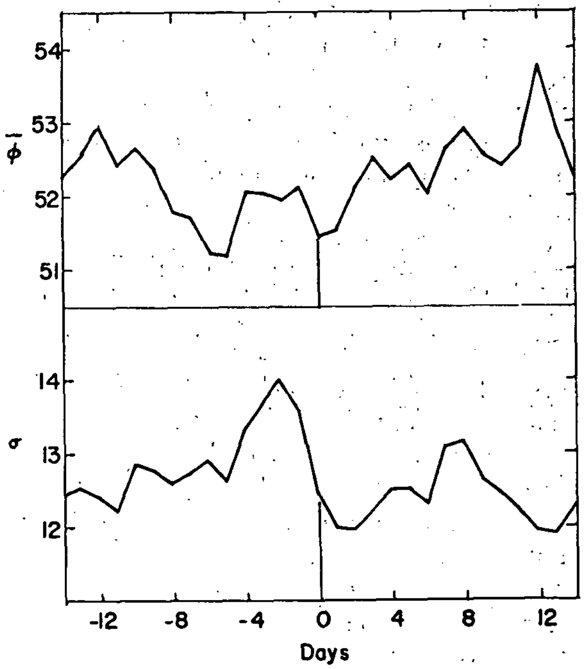

FIGURE 5.—Superposed epoch averages of the daily mean latitude Φ and the daily standard deviation σ of the 30 640-m contour line at 10 millibars surrounding key geomagnetic dates for the 1957–58 through 1959–60 cold seasons (31 epochs).

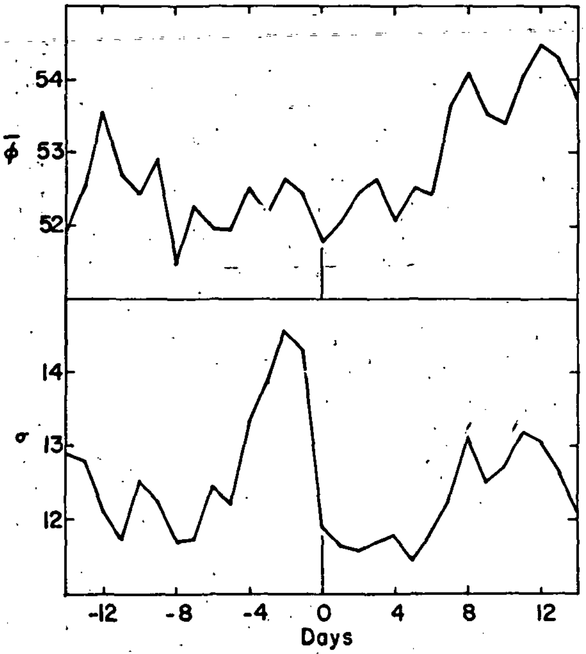

FIGURE 6.—Key geomagnetic dates that are preceded by at least nine nonkey dates for the 1957–58 through 1959–60 cold seasons (14 epochs).

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 these data. Selecting only those key dates that were preceded by at least nine nonkey dates, we noted the mean area variations that are given in figure 7(*b*). Again, no significant variation is apparent.

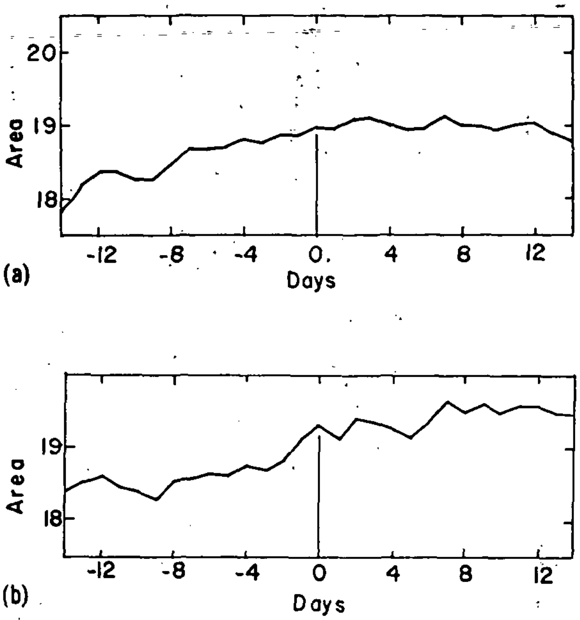

FIGURE 7. (*a*). Superposed epoch averages of the daily area (in arbitrary units) of the cold pool ($T \leqslant -30^\circ$ C) at 500 millibars surrounding key geomagnetic dates. Such dates (113 in all) were selected from November through March in the seasons 1953–54 through 1962–63. (*b*). Superposed epoch averages of the daily area (in arbitrary units) of the cold pool ($T \leqslant -30^\circ$ C) at 500 millibars surrounding key geomagnetic dates. Key dates include only those preceded by at least nine nonkey dates (45 cases) and were selected from November through March in the seasons 1953–54 through 1962–63.

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 1 day following the passage of a sector boundary. No overlap of our tropospheric and sector data was available, but we wanted to determine whether such a switch had an effect on the stratospheric polar vortex at 10 millibars. 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 5 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 prekey 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 prekey date sample above the 95 percent significance level. Thus we could establish no statistically significant trend.

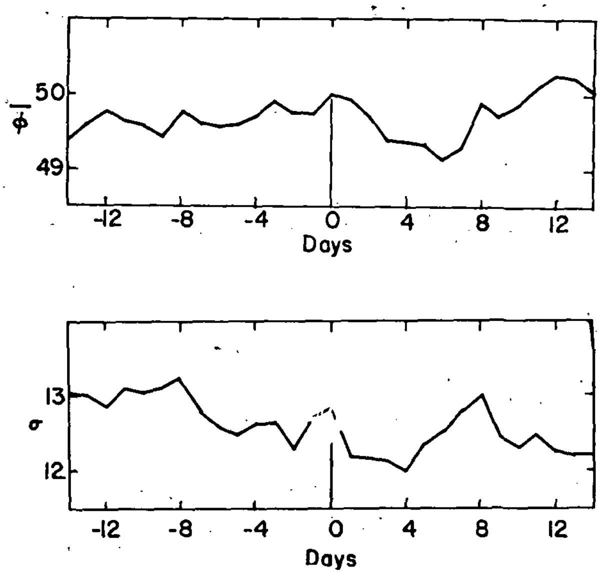

FIGURE 8.—The superposed epoch averages of the daily mean latitude Φ and the daily standard deviation σ of the 30 640-m contour at 10 millibars surrounding sector key dates. Forty-two cases were included from November through March in the seasons 1963–64 through 1968–69.

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 2 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 9-day sequence in each season and separated it into three 3-day sequences. Key stratospheric warming events were determined in the following manner: the 30 640-m contour mean latitude in the second 3-day sequence must be greater than the mean of the first 3-day sequence by 2° of latitude or more, and similarly the mean of the third 3-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 9-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-millibar 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 3 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 warm-

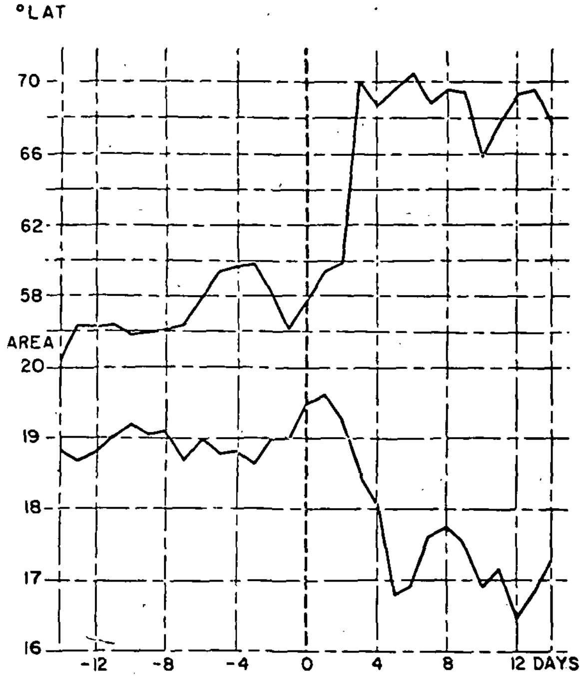

FIGURE 9.—Superposed epoch averages of four cases of stratospheric vortex breakdown measured by an increase in the mean latitude of the 30 640-m contour at 10 millibars (*top*) and the mean area (arbitrary units) of the cold air ($T \leq -30°$ C) at 500 millibars (*bottom*). (From Reiter and Macdonald,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

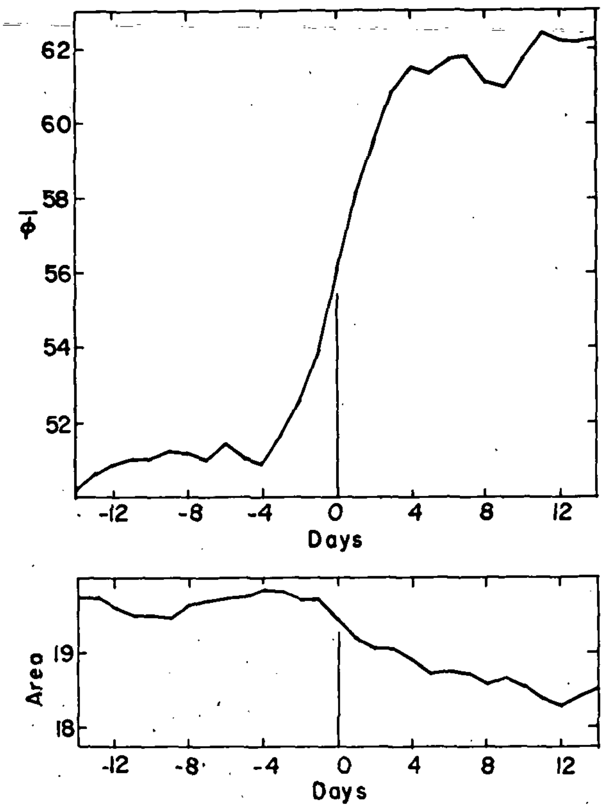

FIGURE 10.—Superposed epoch averages of the 30 640-m contour mean latitude Φ at 10 millibars surrounding an increase in mean latitude of 4° or more in 9 days (*top*), and superposed epoch averages of the area of the cold air ($T \leq -30°$ C) in arbitrary units surrounding such events (*bottom*).

ings that are weaker than those discussed by 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; 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; Reiter and Macdonald, 1973; Teweles, 1958).

POSSIBLE MECHANISMS

Polar Vortex Center

Before determining the mechanism that brings about the shrinkage of the polar vortex discussed in the preceding section, it is important to examine the fluctuations of the vortex center surrounding such warming events. If the center contour at 10 millibars 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

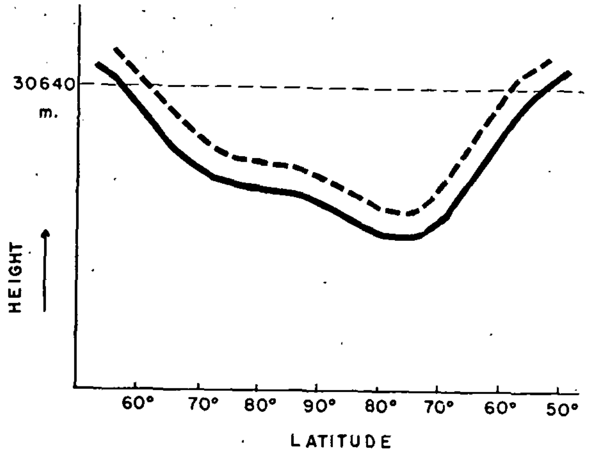

FIGURE 11.—Meridional cross section of the 10-millibar surface surrounding an increase in mean latitude (shrinkage of the polar vortex) of the 30 640-m contour, if it is associated with large-scale warming or subsidence. The solid line represents the 10-millibar heights preceding the shrinkage, and the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

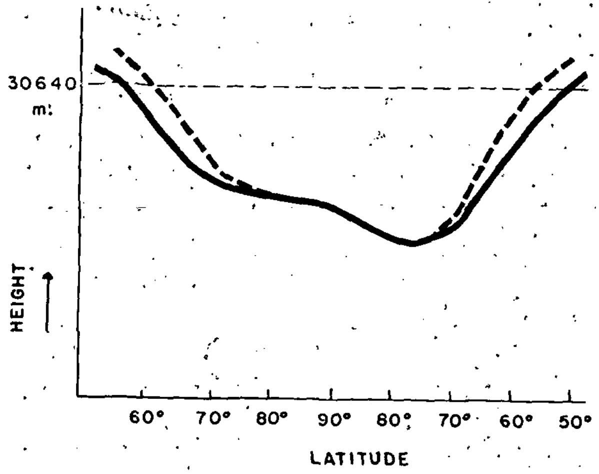

FIGURE 12.—Meridional cross section of the 10-millibar surface surrounding an increase in mean latitude (shrinkage of the polar vortex) of the 30 640-m contour, if it is associated with a steepening of the contour gradient along the vortex edge. The solid line represents the 10-millibar heights preceding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

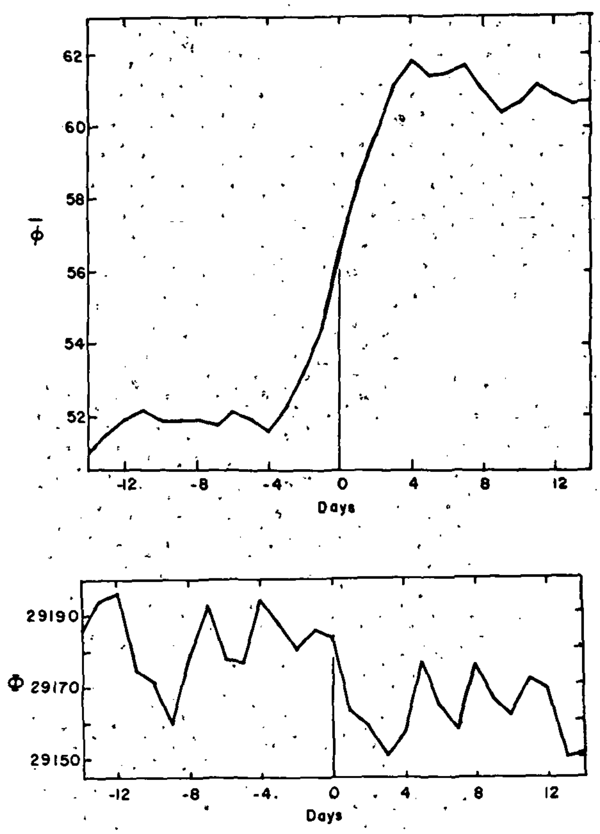

FIGURE 13.—Superposed epoch averages of the 30 640-m contour mean latitude Φ at 10 millibars surrounding an increase in mean latitude of 4° or more in 9 days (*top*) and superposed epoch averages of the value (in meters) of the polar vortex central contour at 10 millibars (*bottom*).

contraction of the vortex edge. As before, we used the criterion in which the mean latitude of the 30 640-m contour at 10 millibars increased by 4° or more in 9 days using the method with the 3-day means described earlier. The superposed epoch method was employed with the key date chosen again to be the middle day of such 9-day sequences. In the 12 seasons for which we have 10-millibar data, seventy-six 9-day sequences met the criterion. The means of the 30 640-m mean latitude values for these events are shown in figure 13. The means of the central contour value at 10 millibars 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 that promotes large-scale subsidence as being responsible for a shrinkage of the polar vortex. We are forced to rely on a mechanism that 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.

One possibility of warming the polar vortex edge at 10 millibars would be through collisional excitation and ionization of the atmospheric molecules during the geomagnetic storm; i.e., through direct absorption of energy. Certainly the fact that auroras occur along a latitude belt 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 resulting from auroral processes during a magnetic storm is about 10^{17} to 10^{18} erg · 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 · s^{-1} are absorbed over one of these bands during a magnetic storm. A cursory examination of the contour gradient at 10 millibars near the polar vortex edge in midwinter yields a mean contour gradient of about −80 m per degree latitude, shown schematically in figure 14. If we assume uniform heating of a 10° latitude band (from 50° 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-millibar surface over this latitude band. If this increase is due totally to heating in the 30- to 10-millibar layer, the calculations shown in appendix A indicate a required mean warming of about 10° C in this layer. Also in appendix A, calculations of the energy required to carry on this heating compared with the 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 millibars 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-millibar layer required to produce such a warming are shown in appendix B. The result (0.14 cm · s^{-1}) is within the realm of variability in vertical motion at 50 millibars reported by Mahlman (1966). He indicates that mean vertical motion during a "stratospheric warming" changed from −0.06 cm · s^{-1} preceding the period to −0.14 cm · s^{-1} during it. The increase in standard deviation of the 30 640-m contour at 10 millibars (see fig. 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.

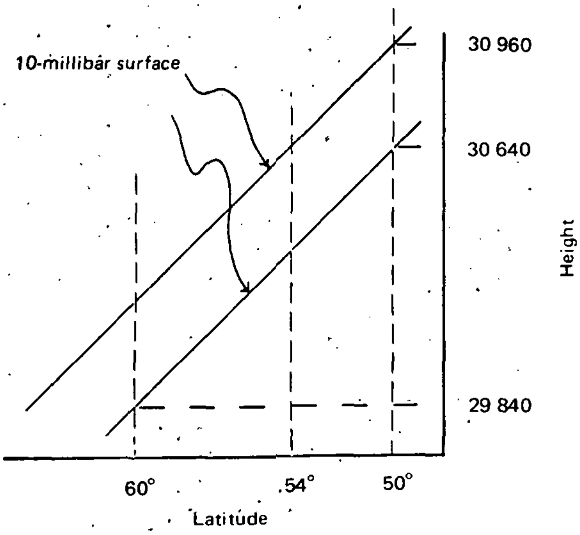

FIGURE 14.—A schematic diagram of 10-millibar surfaces with latitudinal gradient of −80 m per degree latitude.

ACKNOWLEDGMENT

The research reported in this paper was carried out through sponsorship of the U.S. Atomic Energy Commission.

APPENDIX A—CALCULATIONS OF ENERGY REQUIRED FOR STRATOSPHERIC WARMING VERSUS AURORAL ENERGY

(1) Assume a mean temperature of 218 K (−55° C) in the 30- to 10-millibar layer.

(2) Given the formula from the Smithsonian tables:

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

where

$\Delta\Phi$ = thickness of the layer, geopotential meters (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),

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

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

$$t'_{mv} = -45^\circ \text{ C}$$

(5) Therefore, corresponding to an increase of 320 gpm in the 30- to 10-millibar 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 is 5.6×10^{16} cm^2.

(7) The mass of air in the 30- to 10-millibar layer over this band is

$(20\ \mathrm{g} \cdot \mathrm{cm}^{-2})(5.6 \times 10^{16}\ \mathrm{cm}^2) = 1.1 \times 10^{18}\ \mathrm{g}$

(8) The specific heat of air c_p is given as

$$10\ \mathrm{erg} \cdot \mathrm{g}^{-1} \cdot \mathrm{K}^{-1}$$

(9) The energy required to bring about this observed warming is equal to the total mass to be heated multiplied by the specific heat of the mass multiplied by the change in temperature required, from (7), (8), and (5):

Energy required =

$(1.1 \times 10^{18}\ \mathrm{g})(10^6\ \mathrm{erg} \cdot \mathrm{g}^{1-} \cdot \mathrm{K}^{-1})(10\ \mathrm{K})$

$= 1.1 \times 10^{25}\ \mathrm{erg}$

(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 hr or 10^4 sec.

(12) Then the total energy involved in the aurora is

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

(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 B—CALCULATIONS OF SUBSIDENCE REQUIRED FOR STRATOSPHERIC WARMING

Assume a 4° increase in mean latitude of the 30 640-m contour at 10 millibars and assume that this is brought about by the 10 K warming in the 30- to 10-millibar layer noted in appendix A.

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

$$d\theta = dT\left(\frac{1000}{P}\right) - KT\,(1000)^K\,P^{-K-1}\,dP$$

$$dP = 3.1\ \text{millibars}$$

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

Therefore a parcel of air that sinks adiabatically from the 20-millibar level at $T = 223$ 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 9 days (7.78×10^5 s), then the mean vertical motion that accounts for this warming is about -0.14 cm · s^{-1}.

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DISCUSSION

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

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.

SHAPIRO: That is similar to what Roberts has done.

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

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

MACDONALD: Yes; in fact, it did break up. A breakup occurred near a key date twice, I believe. We excluded such data from these charts to avoid the masking of any other values that we observed from, say, the other 38 key dates; but we only had 12 yr of these data and we could detect no real correlation, with, for example, a massive breakup of the polar vortex following that key date.

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

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

A Spectral Solar/Climatic Model

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Northrop Services, Inc.

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, because of the possibility of man-induced climate changes ("Study of Critical Environmental Problems," 1970; "Study of Man's Impact on Climate," 1971). 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 that 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 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 (1973).

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 sunspot number time series from 1700 to 1970. The mean 11.1-yr sunspot cycle is well known, and the 22-yr 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 sunspot time series has certain important characteristics that will be summarized.

Secular Cycles

The sunspot cycle magnitude appears to increase slowly and fall rapidly with an 80- to 100-yr period. Jose has identified a basic 180-yr period associated with the resonance structure of the planets, and 80- and 100-yr 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 two 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 yr duration, depending on mean cycle magnitude or other characteristic criteria. The most recent intrasecular epoch of potential importance is the interval from about

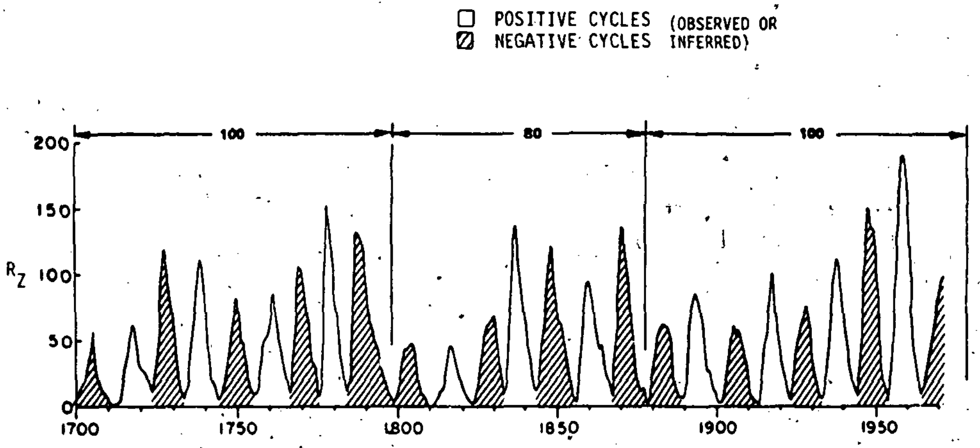

FIGURE 1.—Observed sunspot variations from 1700 to 1970. (R_z = mean sunspot number.)

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 yr. The solar wind structure is related to the Sun's corpuscular emissions, with a corresponding influence on Earth's magnetic field fluctuations (Wilcox, 1968).

Decadal Cycles

The decadal cycles consist of 11-yr 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-yr cycle breaks down every 80 to 100 yr. According to his model, the next 11-yr cycle will be of negative polarity, the same as cycle 20. The Sun's dipole magnetic field may change sign about 3 yr 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-yr solar cycle is a superposition of two or three subcycles closely related to the corpuscular emission from the Sun. These subcycles of 4 to 7 yr duration are further discussed by Sleeper (1972). Differences in subcycle structure may account for differences in the 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 yr 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 yr. 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 will be briefly summarized.

Secular Cycles

Evidence of secular cycles has been found in climate-related variables. Johnsen et al. (1970) studied variations in the O^{16}/O^{18} ratio as a function of depth in a Greenland ice core. From their age calibration, they determined characteristic periods of 78 and 181 yr. They also found periods of 400 and 2400 yr. A period of 180 yr 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 yr. Dzerdeevski (1966) discussed a fluctuation that began about 1922. Troup (1962) pointed out that there was a reasonable correlation between equatorial temperatures and the 11-yr 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 the 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 that may indicate the termination of an intrasecular epoch in both the Sun's and Earth's atmospheres.

Decadal Cycles

Searches have been made for a simple 11-yr 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-yr 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-yr cycle has been found in climate variables in the midlatitudes. Bollinger (1945) found evidence for a 22-yr period in the rainfall in Kansas and Oklahoma. This is related to the 20-yr drought cycle in the great plains. Willett (1965) found a 22-yr cycle in continentality and related it to ozone variations in the atmosphere. Sleptsov-Shevlevich (1972) found a 22-yr period in high-latitude, sea level pressure variations. Spar and Mayer (1973) found a 20.8-yr period in the New York City January temperatures since 1870. They did not recognize that this period corresponds with the mean 20.8-yr solar magnetic cycle forcing function since 1870. A. I. Ol' (1969) has presented other evidence for a 22-yr period in midlatitude climate variables.

Subcycles

In the study of the 22-yr 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 1- or 2-yr 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, manmade CO_2, ocean temperature, and solar activity. While there are undoubtedly effects due to volcanic dust, manmade 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 yr. The fluctuation of the mean world temperature (after Mitchell, 1971) indicates a secular cycle of about 100 yr, 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 until 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 Sun. Willett (1965) showed that the cumulative summer temperature change for representative cities in the southwestern United

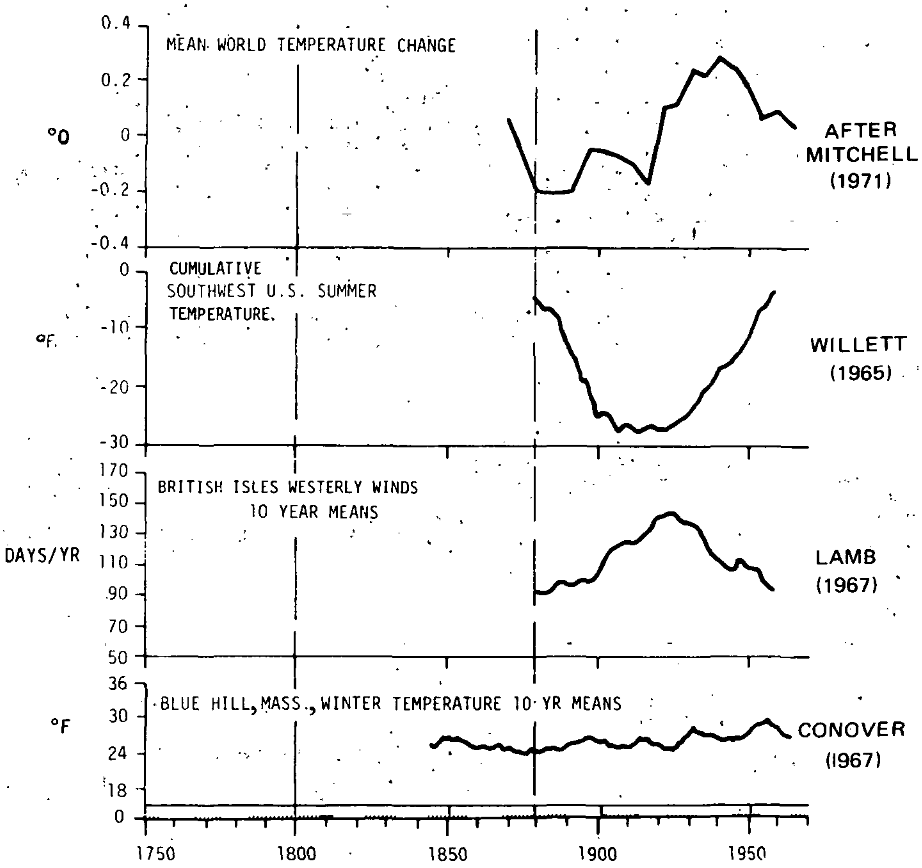

FIGURE 2.—Observed climate variations.

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-yr 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-yr periodicity. This nominal 20-yr periodicity in northeastern U.S. winter temperatures since 1880 has also been studied by Spar and Mayer (1973). The abrupt decadal fluctuations are not apparent in most of these parameters because 10-yr means have been used to display the data.

The sudden decadal changes are more clearly demonstrated in figure 3. Namias (1969, 1970) 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 his 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 a solar dipole field to the opposite sign (Wilcox and Scherrer, 1972); 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-yr solar magnetic cycle. These epochs of uncertain solar wind phase may

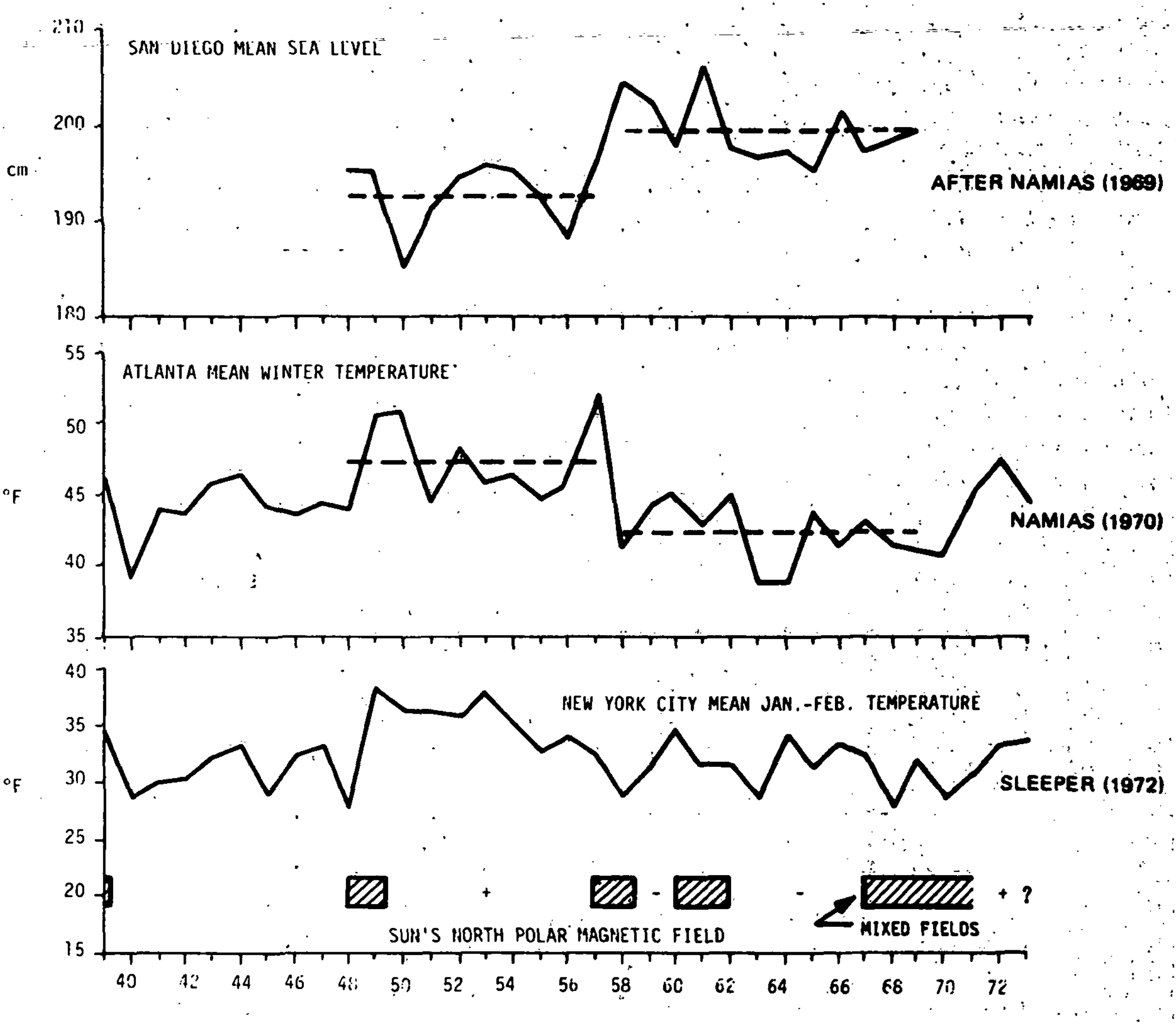

FIGURE 3.—Decadal changes in geophysical variables.

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-yr 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-yr 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) have studied different but related models that suggest that the climate can exist in one of several quasi-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 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

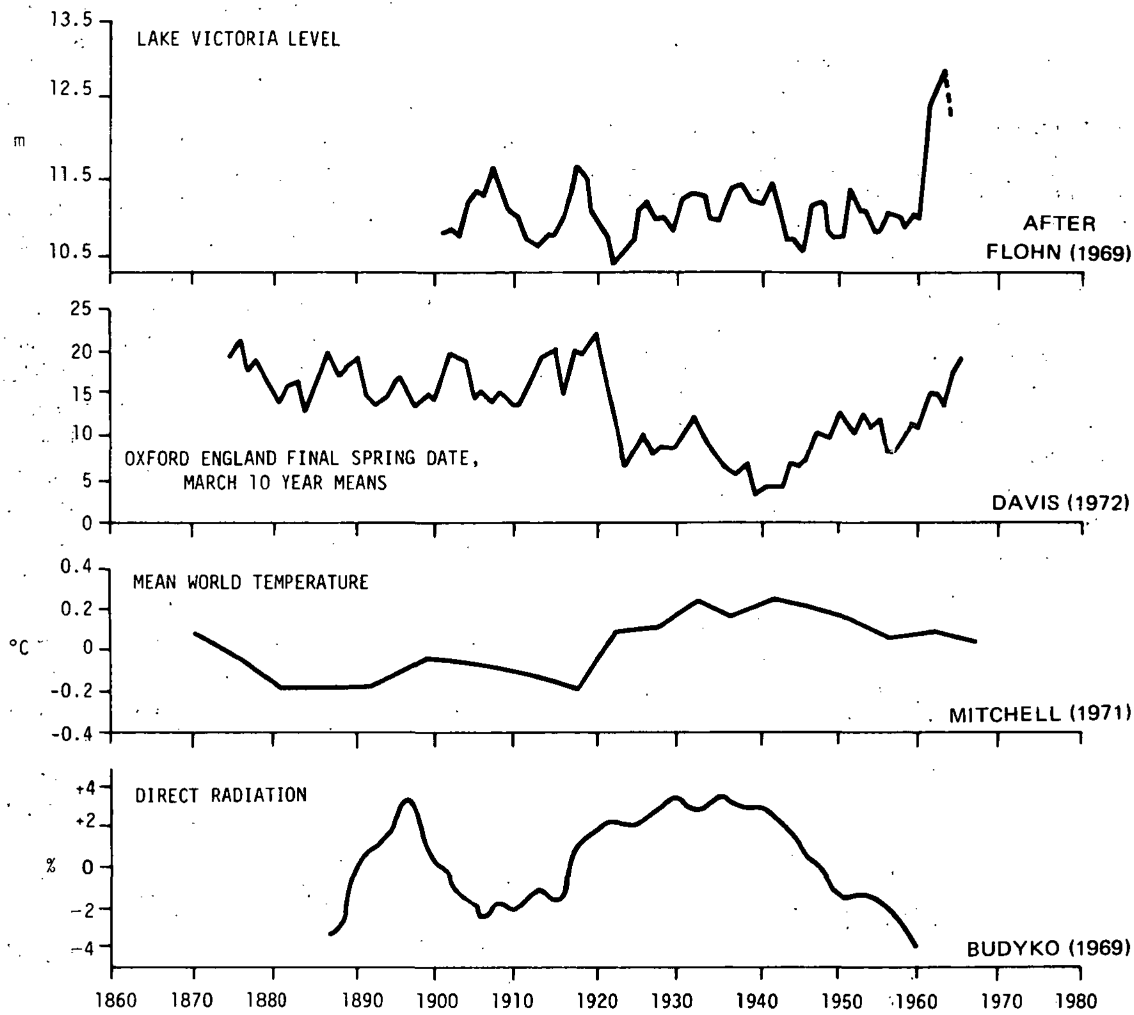

FIGURE 4.—Intrasecular epochs in geophysical variables.

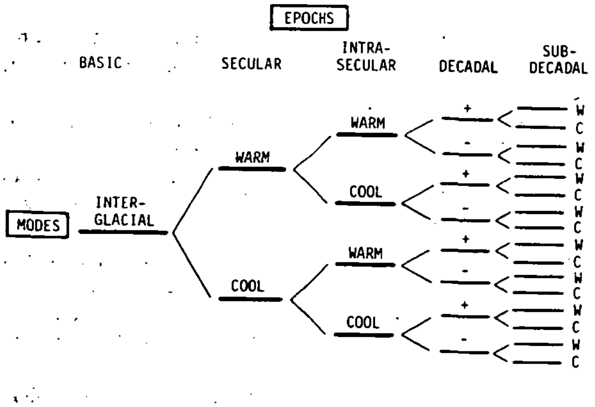

FIGURE 5.—Spectral solar climatic model.

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. The basic assumptions are as follows:

(1) Both the Sun and 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.

(2) 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-yr (secular), 40-yr (intrasecular), 11-yr (decadal), and shorter epochs (subdecadal). In general, two closely related modes are designated warm and cool. The decadal or 11-yr 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 longwave 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 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 that 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 Earth's atmosphere. Mode switches on 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 conclusions:

(1) 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.

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

(3) 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.

(4) 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 the North Pacific Ocean temperature, southern California sea level, and Atlanta winter temperatures.

(5) The current climate anomalies of less than 11 yr in length are such that we may be observing 100- or 180-yr 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.

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

ACKNOWLEDGMENTS

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DISCUSSION

STURROCK: I was very interested to note in your first slide that you state whether the solar cycle is major or minor. How is that determined in the 16th and 17th centuries? I wonder how you infer the sign of the field then.

SLEEPER: Yes, that is a key question. How do we infer magnetic polarity for cycles occurring, say, 100 to 200 yr 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 yr and associating these changes with changes in the 22-yr period of the Sun.

N76 14537

A Possible Correlation Between Maxima of the Far Ultraviolet Solar Irradiance and Central Meridian Passages of Solar Magnetic Sector Boundaries

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and
JOHN M. WILCOX
Stanford University

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 Earth and certain meteorological phenomena. That work with ample references to past work has been reported in detail by Wilcox (1975) elsewhere in the proceedings of this symposium.

It is the purpose of this work to describe the relationship that 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 (1975).

The MUSE experiment has been described in detail by Heath (1973); it consists of five broadband photometers that respond to solar radiation from 115 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 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 that 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 Earth (Wilcox and Colburn, 1972). Because there is a delay of about 4½ 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 Earth (Wilcox, 1968), the sector boundaries shown in figure 2 should be shifted backward by about 4½ 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 judgment on the small difference between away/toward and toward/away boundaries until more observations have been analyzed.

Increases in the solar UV above the minimum during a solar rotation that 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 examining possible physical causes to explain the observed correlations between passages of the solar magnetic sector boundaries past Earth and meteorological phenomena.

In summary, satellite observations of the Sun over almost 5 yr 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 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

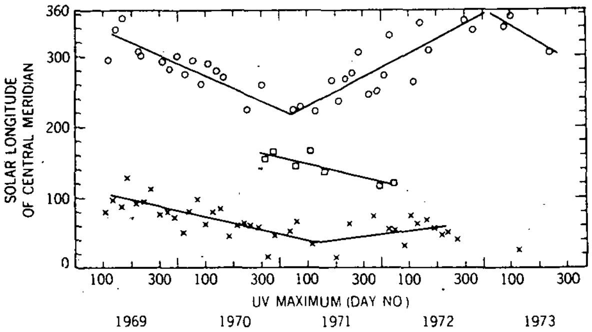

FIGURE 1.—Carrington solar longitude of the central meridian on days of observed UV maximums in irradiance. The different symbols represent regions on the basis of groupings in longitude.

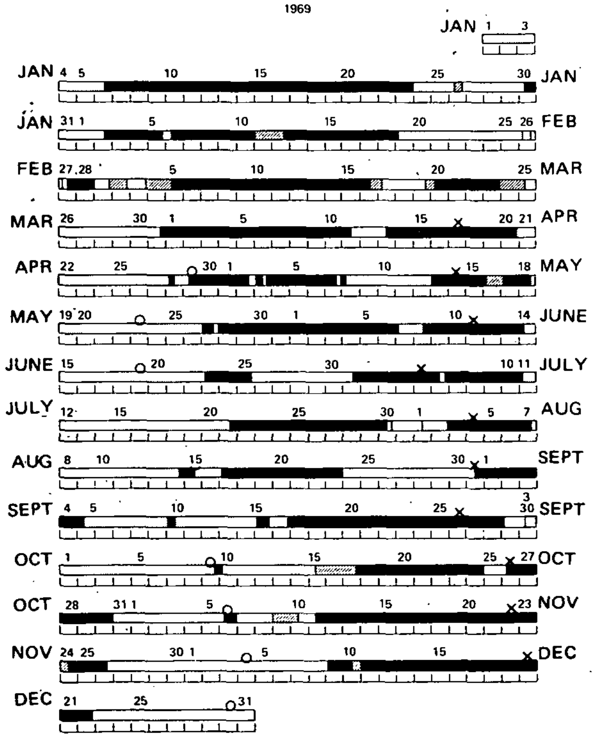

FIGURE 2.—Representation of the sectors of the large-scale photospheric magnetic field carried radially outward by the solar wind as it sweeps by Earth. The shaded regions represent the field directed away from the Sun and the black regions represent the field directed toward the Sun. The times of solar UV enhancements are indicated with the symbols of figure 1. The sector boundaries were near central meridian on the Sun about 4½ days before the times shown in the figure at which the boundaries were observed by spacecraft orbiting Earth.

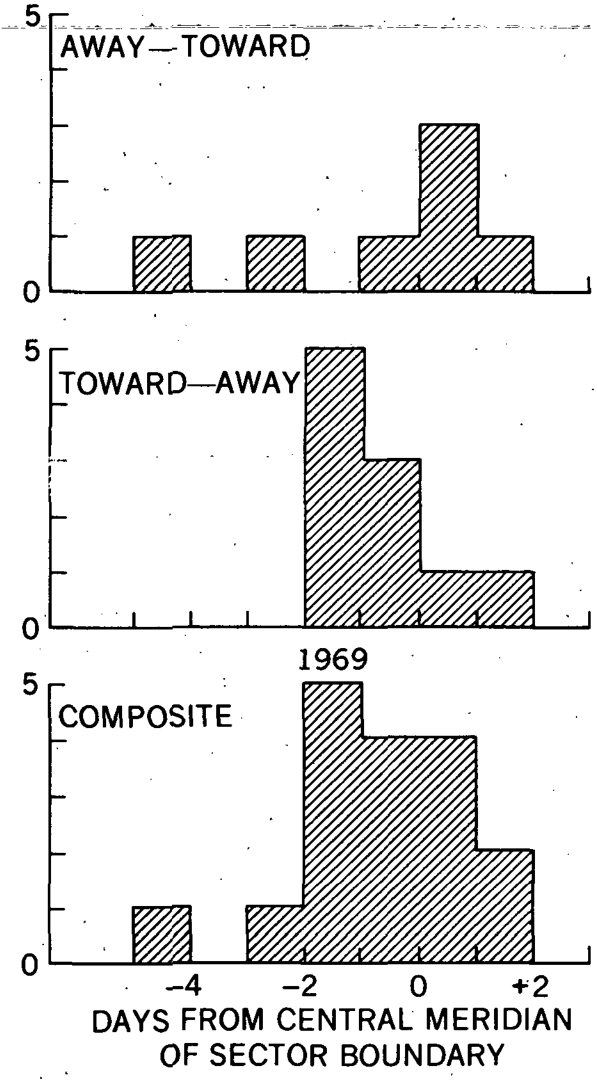

FIGURE 3.—Histogram of the time delay in days between an observed UV solar enhancement (UV max) and a corresponding central meridian passage of the solar magnetic field sector boundary.

nm over a solar rotation is typically at least 230 ergs/cm^2 · s.

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DISCUSSION

LONDON: The Nimbus 3 observations showed, for some of the filtered measurements in the UV, a fairly pronounced solar rotation period in the shorter wave UV. Was there a similar solar rotation period in the Nimbus 4 observations? And, if the UV 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?

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° 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-day, but on the order of 27 days.

HEATH: Two curves in figure 1 represent the two very long-lived active regions, and they are about 180° apart in solar longitude, so there is UV enhancement essentially twice per solar rotation.

RASOOL: What were these enhancements?

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 Å, 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 wavelength, 2900 Å, 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 Å.

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

HEATH: If I use the same sensor that gives these data and I compare the absolute values of the solar radiance 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 Å and also at 1750 Å but not at Lyman-alpha.

N76 14538

The Aurora as a Source of Planetary-Scale Waves in the Middle Atmosphere

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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 220-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 conjectured 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; Dickinson, 1968; Finger et al., 1966; Matsuno, 1970; Newell and Dickinson, 1967). Clearly, a source of Rossby waves in the stratosphere would be 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 such waves 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.

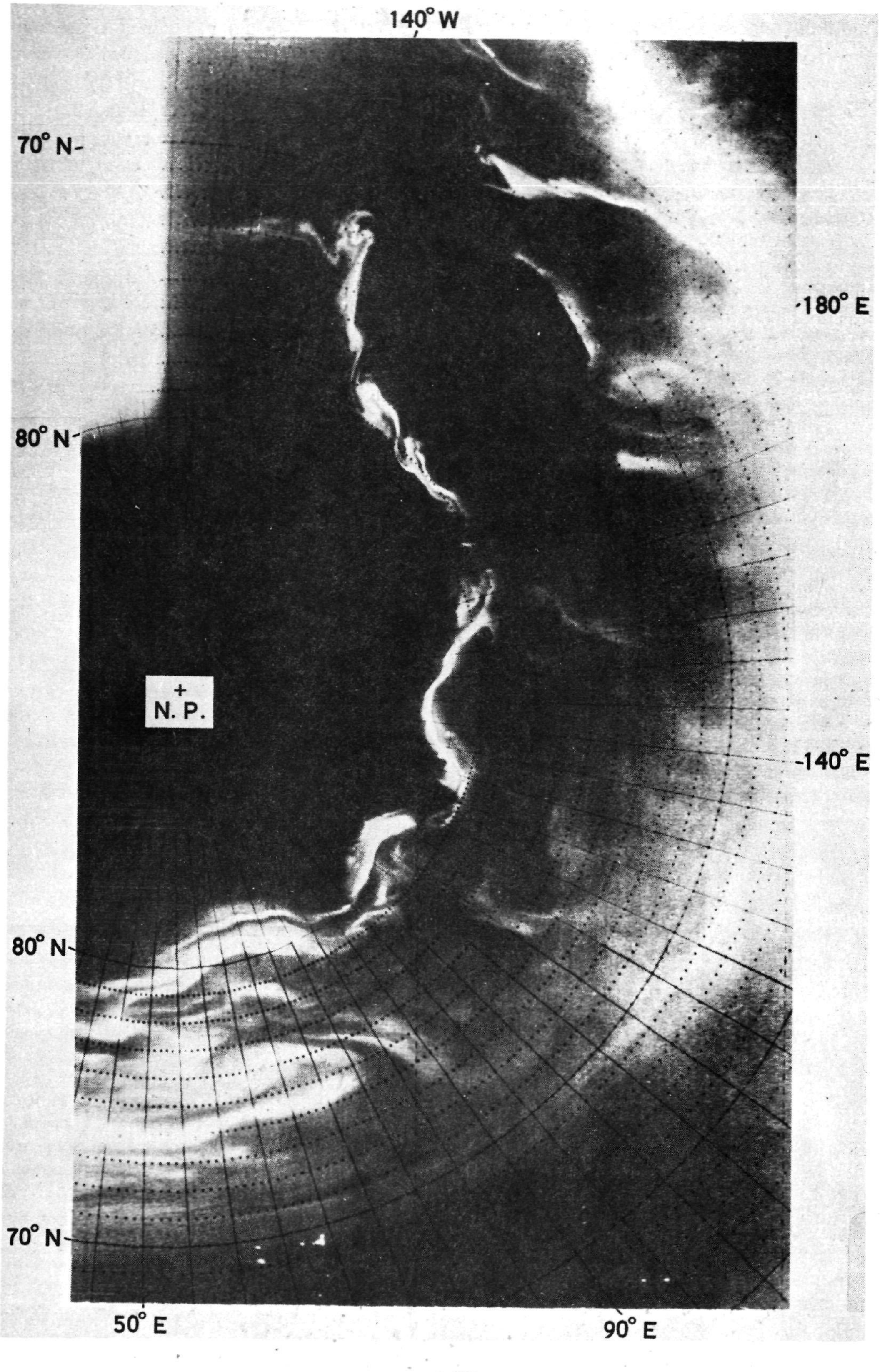
Traveling ionospheric disturbances occurring in the 200- to 800-km altitude region have been observed for many years (Davis and daRosa, 1969; Thome, 1968). Well-correlated ionospheric disturbances of ~ 2000-km horizontal scale and of ~1- to 2-hr periods have been observed to propagate from the auroral zone at speeds of ~500 m/s. These disturbances have been interpreted generically as due to the passage of gravity waves. Because the horizontal scale and wave speed are so large, being reminiscent of longwaves in the ocean, at least two intriguing questions must be raised. First, because auroras 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 auroras 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, whereas 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 of 3 to 6. Because auroral substorms show typical temporal variations of, say, 1 to 2 hr, 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 wavelike 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.

Despite the observation of clearly wavelike variation of planetary scale auroral heating, direct observations of the neutral wind field associated with such wave motion would be desirable 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 crosstrack wind components, deduced from accelerometer and attitude control activity onboard 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, is of particular interest (Feess, 1968). Figure 2 shows data from selected orbits in which well-organized crosstrack wind variations were encountered. Although the major stationary structure near the pole may involve convective overturning 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 exist 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-millibar levels in decameters. Scherhag noted that all four curves show a rapid rise to a peak during the period May 25 to 26, 1967. This becomes somewhat more evident if we take the sum of all four curves so that the random signal

FIGURE 1.—An extensive auroral form observed by scanning radiometers onboard 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 of approximately 3 to 6. The coherent extensiveness of the associated auroral heating is particularly significant. (Courtesy of E. H. Rogers and D. F. Nelson, The Aerospace Corp.)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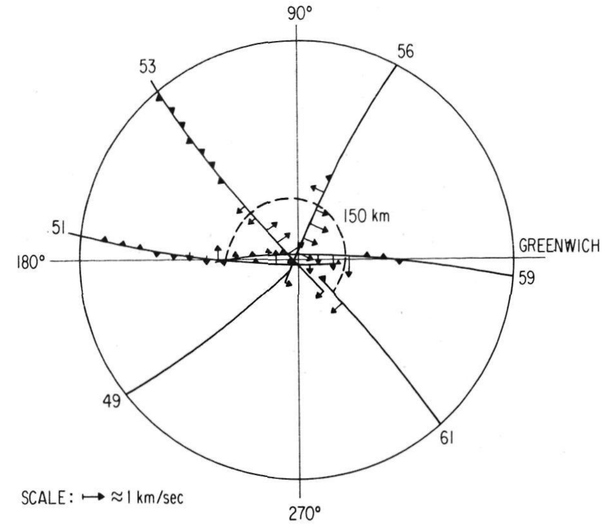

FIGURE 2.—Lower thermospheric winds deduced from accelerometer and attitude control activity onboard the satellite 1967–50B on May 27, 1967, near the north geographic pole, the origin of the figure. The satellite paths are labeled by the orbit numbers (49–61), and the dashed curve indicates the locus 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.)

is reduced. Indeed, the sum shows three clear events (April 24, May 3, and May 26) which interestingly occurred during the most magnetically disturbed days of the period ($\Sigma K_p = 32$, 47, and 51, respectively; K_p is the geomagnetic activity index).

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.

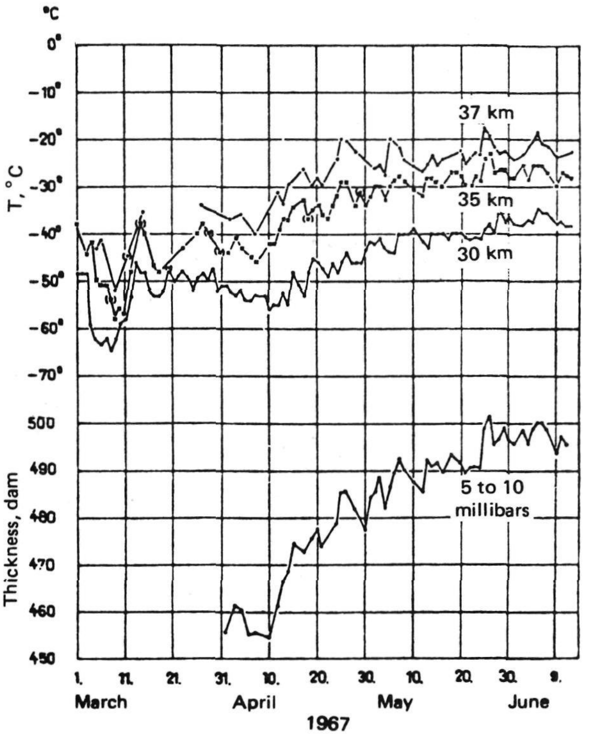

FIGURE 3.—Stratospheric temperatures at 30, 35, and 37 km and the 5- to 10-millibar thickness for the period March to June 1967 (Scherhag, 1967).

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DISCUSSION

AKASOFU: I do not think you can associate that type of picture of the aurora with Rossby waves because in a matter of 10 min, 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; I am sure that Rossby waves are at something like latitude 50.

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 km, even though it changes in a few minutes. If you consider the aurora, or the particle deposition associated with it, as a heating source that 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.

N76 14539

Direct Satellite Observations on Bremsstrahlung Radiation as a Technique to Investigate Its Role in Meteorological Processes

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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-millibar 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 radiation 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 Earth and at frequent intervals. Detailed measurements on the spatial and energy distributions of the bremsstrahlung radiation 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 radiation is a negligible contributor to the ionization near the 300-millibar level.

Recent results on the correlations between interplanetary magnetic sector boundaries and weather patterns (Wilcox et al., 1973) have provided added support for earlier evidence (Roberts and Olson, 1973*a*) of connections between solar activity and weather. The evidence for these connections has recently been reviewed by Roberts and Olson (1973*b*). Although various hypotheses have been advanced for the physical processes connecting the two phenomena, none has 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 et al. (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 5 s and an onboard 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

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the satellite. The collimator is ~20 cm long, providing a relatively sharp cutoff angle and a geometric factor of 27 $cm^2 \cdot s$. Several energetic particle spectrometers provide spectral measurements on the energetic electron and proton fluxes. The details of the instrumentation are provided in other reports (Bakke et al., 1974; Imhof et al., 1973*a*; Nakano 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. Because 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 ellipses 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 2 hr. From the energy distributions of the observed bremsstrahlung, the ion production rates as a function of altitude could then be calculated.

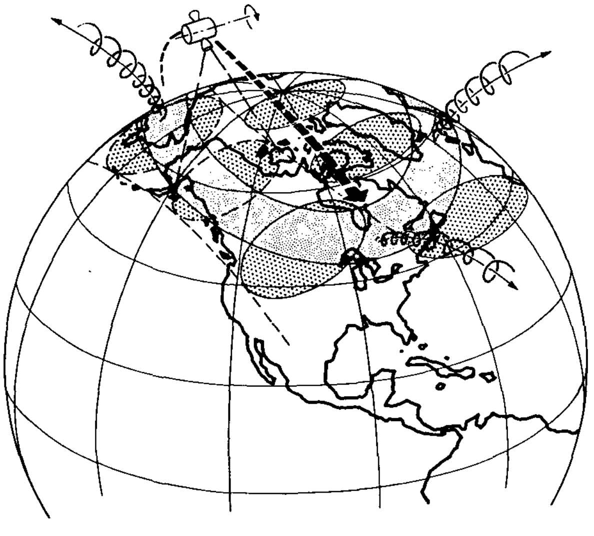

FIGURE 1.—Schematic illustration of the geometry for observing the bremsstrahlung associated with electron precipitation at high latitudes. The shaded ellipses indicate schematically the fields of view of the spectrometers for different positions of the spinning satellite, and the shaded "band" indicates 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 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 taken during a magnetically disturbed period. Normally the levels of bremsstrahlung from the atmosphere are near or below the detectability threshold for the spectrometer. Because the energy threshold of the present gamma ray measurements is higher than that employed in many of the balloon observations and because the electron energy spectra are generally quite soft, the present data, in contrast to the bulk of the balloon measurements, are

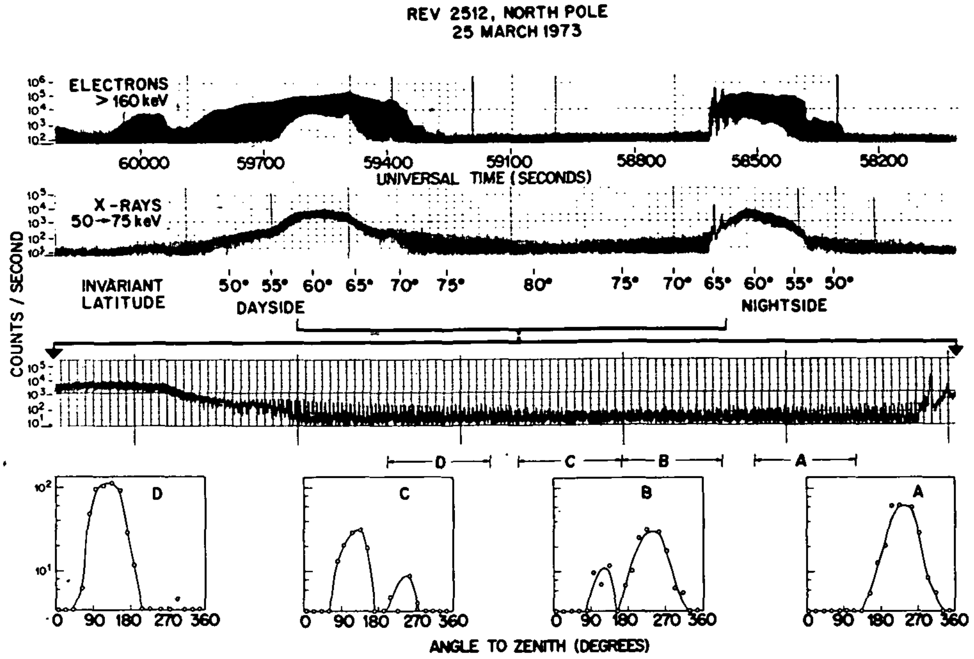

FIGURE 2.—The responses of the electron and gamma ray spectrometers during passage of the satellite over the north polar region at a time of great magnetic disturbance. The counting rates of X-rays in the energy range 50 to 75 keV are also shown for two different expanded time scales. In the bottom row,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

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 dependencies 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 majority of these cases favor coverage in the morning hours. Because 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 that are favorable as a result of the geomagnetic field axis being offset from 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 radiation 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

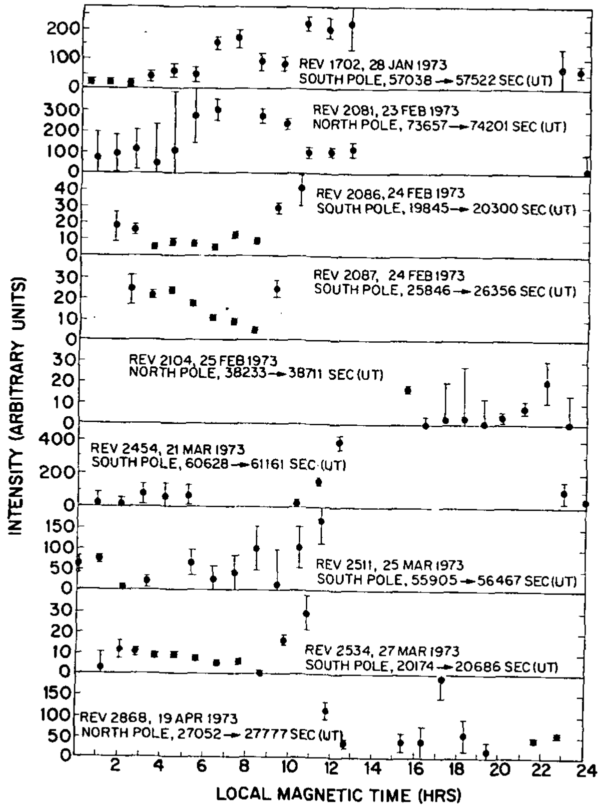

FIGURE 3.—The best fit intensities obtained from the least-squares-fit to the bremsstrahlung data plotted as a function of local magnetic time.

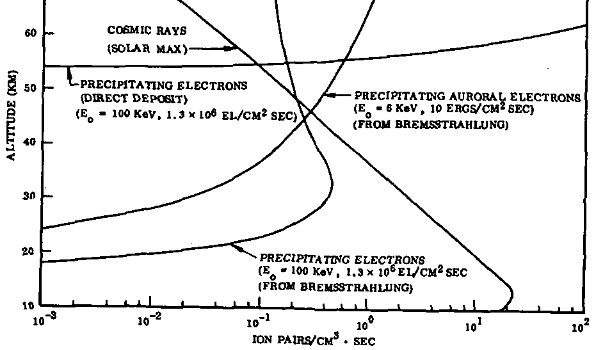

FIGURE 4.—The ion production rate as a function of altitude from the bremsstrahlung radiation and the direct deposit of energy by precipitating electrons with *e*-fold energies of 6 and 100 keV, respectively. The cosmic ray ion production rate at solar maximum is also shown (Webber, 1962).

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 (1973*a*) have suggested that bremsstrahlung radiation associated with strong auroras may cause increased ionization near the 300-millibar 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_0 of 6 keV. The intensity of 10 ergs/cm² · s corresponds to an aurora of moderate intensity and is about a factor of 10 higher than the average nightside auroral particle energy input for the magnetic latitudes of 65° to 70° during a 4-day period that was moderately active magnetically (geomagnetic activity index K_p varied from 0_+ to 8_0) (Sharp, Carr, and Johnson, 1969). The characteristic energy, E_0, 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 the cosmic ray ion production rate at 37 km and the percent decreases rapidly at lower altitudes. The direct ionization from 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_0 equal to 100 keV and a flux of 1.3×10^6 electrons/cm² · 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., 1973*b*; 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 percent decreases rapidly at lower altitudes.

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-millibar level. Thus, we conclude that bremsstrahlung is not an important factor in influencing weather patterns via the formation of cirrus clouds near the 300-millibar level as proposed by Roberts and Olson (1973*a, b*).

It is evident that bremsstrahlung radiation from precipitating electrons can at times significantly increase the ionization in the atmosphere at altitudes above about 25 km. Because this increased ionization will increase the atmospheric conductivity, bremsstrahlung radiation may be important in processes suggested by Markson (1975) 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 2 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 (see Roberts and Olson, 1973*b*), 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; 1971*a, 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).

ACKNOWLEDGMENTS

Thanks are extended to W. E. Francis for his contribution to the calculation of the ion production rates and to Dr. M. Walt for the use of the codes that he developed for the direct electron energy deposition in the atmosphere and for the production and subsequent energy deposition of bremsstrahlung radiation in the atmosphere. The satellite experiments were supported by the Defense Nuclear Agency through the Office of Naval Research. This analysis and review have been supported by the Lockheed Independent Research Program.

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DISCUSSION

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

JOHNSON: It is relatively small. I think it is of the order of 10 or 20 percent. 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; therefore, as soon as the bremsstrahlung contribution drops to a few percent, they would be of comparable magnitudes. If bremsstrahlung radiation is important as a dynamic effect, one would suspect that such importance 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

Chairman: Robert W. Noyes

N76 14540

Solar Flux and Its Variations

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University of Maryland

We present data on the solar irradiance as derived from a number of sources. An attempt was made to bring these data onto a uniform scale. The results are presented in table 5 and figure 6. Summation of fluxes at all wavelengths yields a figure of 1357.826 for the solar constant. Estimates are made of the solar flux variations due to flares, active regions (slowly varying component), 27-day period, and the 11-yr cycle. Solar activity does not produce a significant variation in the value of the solar constant. Nevertheless, variations in the X-ray and EUV portions of the solar flux may be several orders of magnitude during solar activity, especially at times of major flares. It is, of course, well established that these short wavelength flux enhancements cause significant changes in the terrestrial ionosphere.

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 determining values for the solar constant (total electromagnetic energy flux from the Sun incident on 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 shorter than 2 Å and longer than 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 IR wavelengths (10 000 Å to 2 cm), the solar spectrum is essentially a continuum, with the bulk of the emission occurring 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 toward 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. At shorter wavelengths, 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 H(I) 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 the final section we investigate variations, especially in X-ray 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 AU), which can be derived directly from the total solar flux according to the equation

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

where H is the solar irradiance, and r is the radius of the Sun, R is 1 AU, and F is the total solar flux. We use the units W/m² · 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

$$F = \frac{1}{\pi} \int I(0) L(\theta) \cos \theta \, dw$$

where I(0) is the specific intensity at the center of the disk, $L(\theta) = I(\theta)/I(0)$ is the limb darkening, and θ is the angle viewed from the Sun's center between the sub-Earth point and position on the disk.

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 100 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 μW/cm².)

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 these 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^2V star HD 20766. For these reasons, we have adopted the Labs and Neckel data from 3300 to 10 000 Å.

Near Infrared: 10 000 to 24 000 Å

The Labs and Neckel data end at 12 000 Å; for longer wavelengths 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 fig. 1), it became clear that they could be fit with a series of straight lines of the form.

$$\log F = \alpha + \beta \operatorname{long} \lambda$$

where F is the irradiance in W/m²Å, λ is the wavelength in Å, and α and β are listed in table 1.

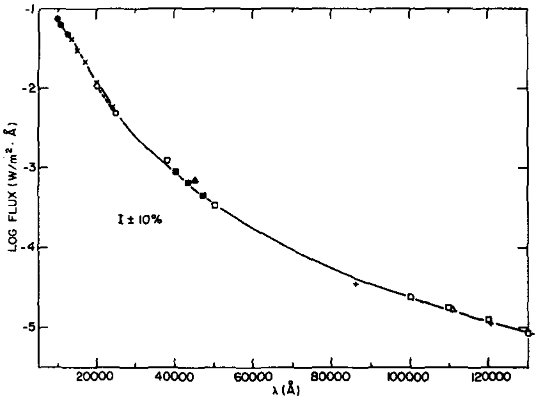

FIGURE 1.—The solar flux in the IR. (Filled circles: Labs and Neckel, 1968; **x**: Arvesen et al., 1969; open circles: Pierce, 1954; open squares: Koutchmy and Peyturaux, 1970; filled squares: Murcray, 1969; filled triangles: Farmer and Todd, 1964; plus signs: Saiedy, 1960; open triangle: Saiedy and Goody, 1959.)

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 datum 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 IR 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

$$H=\frac{8.09\times10^{-21}}{\lambda^{5}(e^{1.44/\lambda T}-1)}$$

where H is the irradiance in W/m² · Å, λ is the wavelength in cm, and T is the brightness temperature in K.

The data are presented in figure 2. Once again, they can be fit with straight line segments.

Near Ultraviolet: 2100 to 3300 Å

For this spectral region we adopt the Broadfoot (1972) rocket data. Unfortunately, his data extend only from 2100 to 3200 Å, with the last 100 Å being rather uncertain. The 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 for wavelengths shorter than 3100 Å, we use Broadfoot's data.

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.

TABLE 1.—*Coefficients for the Linear Relation Between Log Flux and Log Wavelength*

Wavelength range	α	β
10 000 to 12 460 Å	7.670	−2.198
12 460 to 15 000 Å	8.702	−2.450
15 000 to 24 000 Å	13.026	−3.485
24 000 to 40 000 Å	13.820	−3.667
40 000 to 50 000 Å	15.781	−4.093
50 000 to 100 000 Å	14.736	−3.870
100 000 to 200 000 Å	15.534	−4.030
0.02 to 0.238 mm	15.291	−3.984
0.238 to 0.312 mm	15.828	−4.068
0.312 to 1.0 mm	13.510	−3.711
1.0 to 3.0 mm	14.297	−3.824
3.0 to 10.0 mm	13.598	−3.730
10.0 to 20.0 mm	12.991	−2.654

TABLE 2.—*Various Values of the Solar Irradiance in the UV*

Wavelength range, Å	Solar irradiance, W/m² · 100Å	
	Arvesen et al. (1969)[a]	Broadfoot (1972)
3000 to 3100	5.09	5.18
3100 to 3200	6.35	5.82
3200 to 3300	7.81	—

[a] Scaled to the Labs and Neckel data.

Relatively good intensities are available from 1400 to 1900 Å from Bruckner and Nicolas (1973), Rottman (1973) as quoted in Donnelly 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, which agrees with IR 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.

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

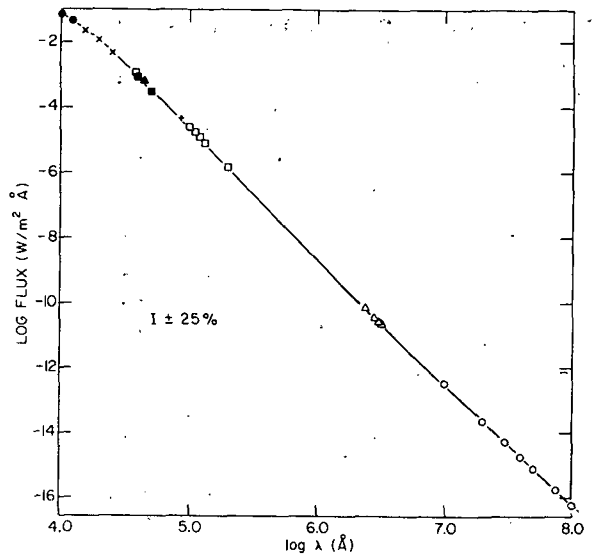

FIGURE 2.—Solar irradiance in the microwave region. The solid line is the adopted fit. (Filled circles: Labs and Neckel, 1968; **x**: Arvesen et al., 1969; open squares: Koutchmy and Peyturaux, 1970; filled squares: Murcray, 1969; filled triangles: Farmer and Todd, 1964; plus signs: Saiedy, 1960; open triangles: Eddy et al., 1969; open circles: Linsky, 1973.)

rise in flux from 2075 to 2100 Å, shown in figure 6, is real. This corresponds to the Al(I) ionization edge and appears clearly in spectra.

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 C(I), H(I), and He(I).

Virtually all available data are 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.

Because 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, 1970*a*, *b*). However, for some high ionization potential lines, there is limb brightening.

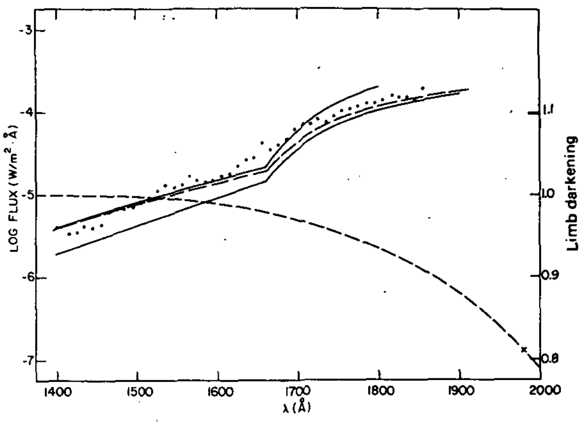

FIGURE 3.—Solar irradiance in the UV. The dash line is the adopted limb darkening. The dots are from Rottman (1973); the upper solid line is from Nicolas (1973); the lower solid line is from Parkinson and Reeves (1969); and the dash line between the two is the adopted limb darkened solar irradiance.

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* is a function of ionization potential (IP) and wavelength. (See table 3.)

Table 4 presents the irradiances for each line. We made allowance for the continua of C(I), H(I), and He(I), as well as a correction to allow for the extended wing of H(I) (wavelength equal to 1216 Å). The data used were from Dupree and Reeves (1971). The H(I) (wavelength equal to 1216 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

TABLE 3.—*Values for Limb Darkening*

Wavelength, Å	*F*/*I*, *eV*
800 to 1400	1.201 + 0.0114IP
600 to 800	1.350 + 0.0068IP
500 to 600	1.069 + 0.0014IP

TABLE 4.—*Ultraviolet Emission Lines and Their Strengths During Moderate Solar Activity*

Wavelength, Å	Ion	Irradiance, W/m^2	Wavelength, Å	Ion	Irradiance, W/m^2
468	—	1.9 (−6)	790	O(IV)	9.9 (−6)
469	Ne(IV)	5.7 (−7)	834	O(II), O(III)	1.7 (−5)
476	—	8.8 (−8)	859	—	1.5 (−6)
482	Ne(V)	6.2 (−7)	904	C(II)	5.2 (−6)
489	Ne(III)	1.4 (−6)	923	N(IV)	6.4 (−6)
499	Si(III)	7.5 (−6)	931	H(I)	4.8 (−6)
507	O(III)	3.7 (−6)	933	S(VI)	2.9 (−6)
515	He(I)	8.8 (−7)	937	H(I)	6.1 (−6)
521	Si(XII)	5.6 (−6)	944	S(VI)	1.8 (−6)
525	O(III)	1.6 (−6)	949	H(I)	9.0 (−6)
537	He(I)	4.1 (−6)	959	—	3.9 (−7)
542	Ne(IV)	7.7 (−7)	973	H(I)	1.8 (−5)
550	Al(XI)	5.1 (−7)	977	C(III)	1.4 (−4)
554	O(IV)	1.0 (−5)	988	—	6.2 (−6)
559	Ne(VI)	9.3 (−7)	991	N(III)	9.2 (−6)
562	Ne(VI)	1.1 (−6)	1010	C(II)	1.8 (−6)
568	Al(XI), Ne(V)	6.3 (−7)	1021	S(III)	1.3 (−6)
572	Ne(V)	6.5 (−7)	1025	H(I)	6.8 (−5)
580	O(II)	7.0 (−7)	1031	O(VI)	4.7 (−5)
584	He(I)	3.2 (−5)	1037	O(VI)[a]	4.2 (−5)
592	—	2.2 (−7)	1045	—	6.6 (−7)
599	O(III)	3.0 (−6)	1063	S(IV)	1.3 (−6)
609	Mg(X)	1.8 (−5)	1068	—	1.6 (−6)
616	O(II)	4.3 (−7)	1077	S(III)	2.6 (−6)
625	Mg(X)	7.7 (−6)	1085	N(II)	7.9 (−6)
629	O(V)	5.3 (−5)	1122	Si(IV)	5.1 (−6)
639	Ca(VII)	3.6 (−7)	1128	Si(IV)	5.1 (−6)
644	O(II)	4.6 (−7)	1134	N(I)	2.7 (−6)
649	—	1.2 (−7)	1139	Al(XI), Ne(VI)	1.2 (−5)
657	S(IV)	4.0 (−7)	1148	—	3.1 (−6)
661	S(IV)	1.1 (−6)	1152	O(I)	3.9 (−6)
671	N(II)	2.3 (−7)	1157	C(II)	4.3 (−6)
681	Na(IX)	1.4 (−6)	1175	C(III)	3.8 (−5)
685	N(III)	2.8 (−6)	1190	Si(II)	2.2 (−6)
692	—	2.5 (−7)	1194	Si(II)	6.9 (−6)
694	Na(IX)	5.4 (−7)	1199	N(I)	1.1 (−5)
703	O(III)	8.1 (−6)	1206	Si(III)	6.9 (−5)
707	—	9.5 (−7)	1215	H(I)	8.5 (−3)
712	S(VI)	2.7 (−7)	1238	N(V)	1.3 (−5)
718	O(II)	16.0 (−6)	1242	N(V)	1.1 (−5)
728	S(III)	1.9 (−7)	1309	Si(II)	1.7 (−5)
736	Mg(IX)	3.2 (−7)	1277	C(I)	4.0 (−6)
744	S(IV)	4.8 (−7)	1302	O(I)	3.1 (−5)
750	S(IV)	8.7 (−7)	1305	O(I)	8.0 (−5)
760	O(V)	3.4 (−6)	1264	Si(II)	7.1 (−6)
764	N(III), N(IV)	8.1 (−6)	1329	C(I)	6.4 (−6)
770	Ne(VIII)	6.2 (−6)	1335	C(II)	1.3 (−4)
775	N(II)	3.0 (−7)	1351	—	8.3 (−6)
780	Ne(VIII)	3.0 (−6)	1356	O(I)	7.3 (−6)
787	O(IV)	8.2 (−6)	1393	S(IV)	3.5 (−5)

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[a] Doublet.

$R \sim 10$ to 40 and no larger 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 longer than 20 Å, we use Freeman and Jones (1970), Argo et al. (1970), Manson (1972), and Malinovski and Heroux (1973). Figure 5 shows the results.

Solar Constant

Table 5 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 6 presents the solar irradiance data in the X-ray and EUV regions for the four conditions indicated in figure 6.

The total solar constant (quiet Sun) that we derive is 1357.826 W/m^2 at 1 AU (1.947 cal/cm^2 · min). A comparison of this value with previously derived values as presented in NASA Space Vehicle Design Criteria Report SP-8005 (1971) is made in table 7. Note that our value is toward the upper end of the high-altitude results and near the lower end of the ground-based results.

VARIATIONS DUE TO SOLAR ACTIVITY

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-yr cycle reflects the correlation of all solar activity with the sunspot cycle.

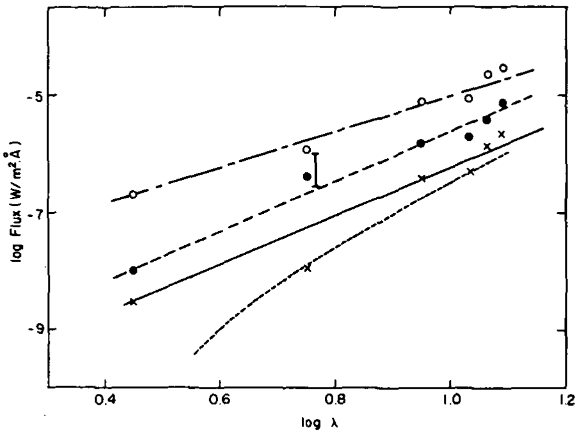

FIGURE 4.—Solar irradiance in the X-ray region. Open circles are Wende's (1972) active Sun, filled circles are his moderate Sun, and x's are his quiet Sun. Lines through the data are the adopted fits. The vertical bar is from Kreplin and Horan (1969) at a time of moderate activity. The dashed line toward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

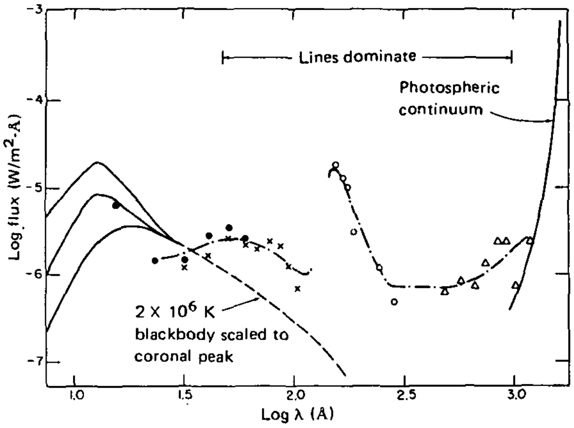

FIGURE 5.—Solar irradiance in the UV and X-ray regions. The solid line to the left is from figure 4; solid line to right is from Nicolas (1973); filled and open circles are from Freeman and Jones (1970); x's are from Manson (1972); and the open triangles are various OSO results. The dash-dotted line is an arbitrary fit.

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 H$_\alpha$ radiation, even though flux increases are frequently proportionally

TABLE 5.—*Summary of the Quiet Sun Solar Irradiance at All Wavelengths*

Wavelength range, Å	Solar irradiance,[a] W/m^2		Percent	Wavelength range, Å	Solar irradiance,[a] W/m^2		Percent
	Per Ångstrom	Sum[b]			Per Ångstrom	Sum[b]	
2 to 3	1.8 (−9)	1.8 (−9)	0.000	2400 to 2500	6.42 (−3)	2.51	0.185
3 to 4	5.6 (−9)	7.4 (−9)	.000	2500 to 2600	9.05 (−3)	3.42	.252
4 to 5	2.0 (−8)	2.7 (−8)	.000	2600 to 2700	2.10 (−2)	5.52	.406
5 to 6	5.0 (−8)	7.7 (−8)	.000	2700 to 2800	2.04 (−2)	7.56	.557
6 to 7	1.0 (−7)	1.8 (−7)	.000	2800 to 2900	2.90 (−2)	1.05 (+1)	.770
7 to 8	1.8 (−7)	3.6 (−7)	.000	2900 to 3000	5.24 (−2)	1.57 (+1)	1.156
8 to 9	3.2 (−7)	6.8 (−7)	.000	3000 to 3100	5.18 (−2)	2.09 (+1)	1.538
9 to 10	5.6 (−7)	1.24 (−6)	.000	3100 to 3200	6.35 (−2)	2.72 (+1)	2.005
10 to 11	8.0 (−7)	2.04 (−6)	.000	3200 to 3300	7.81 (−2)	3.50 (+1)	2.580
11 to 12	1.12 (−6)	3.16 (−6)	.000	3300 to 3400	9.00 (−2)	4.40 (+1)	3.243
12 to 13	1.78 (−6)	4.94 (−6)	.000	3400 to 3500	8.94 (−2)	5.30 (+1)	3.902
13 to 14	2.24 (−6)	7.18 (−6)	.000	3500 to 3600	9.49 (−2)	6.25 (+1)	4.601
14 to 15	2.64 (−6)	9.82 (−6)	.000	3600 to 3700	10.51 (−2)	7.30 (+1)	5.375
15 to 20	9.55 (−6)	5.76 (−5)	.000	3700 to 3800	10.40 (−2)	8.34 (+1)	6.141
20 to 30	4.57 (−6)	1.03 (−4)	.000	3800 to 3900	9.45 (−2)	9.28 (+1)	6.836
30 to 40	3.47 (−6)	1.38 (−4)	.000	3900 to 4000	11.34 (−2)	1.04 (+2)	7.672
40 to 50	3.80 (−6)	1.76 (−4)	.000	4000 to 4100	16.31 (−2)	1.20 (+2)	8.873
50 to 60	4.17 (−6)	2.18 (−4)	.000	4100 to 4200	17.00 (−2)	1.37 (+2)	10.125
60 to 70	3.39 (−6)	2.52 (−4)	.000	4200 to 4300	16.59 (−2)	1.54 (+2)	11.347
70 to 80	2.69 (−6)	2.79 (−4)	.000	4300 to 4400	16.72 (−2)	1.71 (+2)	12.578
80 to 90	3.09 (−6)	3.09 (−4)	.000	4400 to 4500	19.28 (−2)	1.90 (+2)	13.998
90 to 100	2.46 (−6)	3.34 (−4)	.000	4500 to 4600	20.06 (−2)	2.10 (+2)	15.475
100 to 110	1.29 (−6)	3.47 (−4)	.000	4600 to 4700	19.86 (−2)	2.30 (+2)	16.938
110 to 120	7.1 (−7)	3.54 (−4)	.000	4700 to 4800	19.89 (−2)	2.50 (+2)	18.403
120 to 130	Near 0	3.54 (−4)	.000	4800 to 4900	18.88 (−2)	2.69 (+2)	19.793
130 to 140	Near 0	3.54 (−4)	.000	4900 to 5000	19.56 (−2)	2.88 (+2)	21.234
140 to 150	1.41 (−6)	3.68 (−4)	.000	5000 to 5100	19.02 (−2)	3.07 (+2)	22.635
150 to 160	1.70 (−6)	3.85 (−4)	.000	5100 to 5200	18.31 (−2)	3.26 (+2)	23.983
160 to 170	1.41 (−6)	3.99 (−4)	.000	5200 to 5300	18.59 (−2)	3.44 (+2)	25.352
170 to 180	1.82 (−6)	4.17 (−4)	.000	5300 to 5400	19.17 (−2)	3.63 (+2)	26.764
180 to 190	1.29 (−6)	4.30 (−4)	.000	5400 to 5500	18.56 (−2)	3.82 (+2)	28.131
190 to 200	1.00 (−6)	4.40 (−4)	.000	5500 to 5600	18.41 (−2)	4.00 (+2)	29.487
200 to 250	3.16 (−6)	5.98 (−4)	.000	5600 to 5700	18.28 (−2)	4.19 (+2)	30.833
250 to 300	1.26 (−6)	6.61 (−4)	.000	5700 to 5800	18.34 (−2)	4.37 (+2)	32.184
300 to 350	2.00 (−6)	7.61 (−4)	.000	5800 to 5900	18.08 (−2)	4.55 (+2)	33.515
350 to 500	7.9 (−7)	8.80 (−4)	.000	5900 to 6000	17.63 (−2)	4.73 (+2)	34.814
500 to 600	6.9 (−7)	9.49 (−4)	.000	6000 to 6100	17.41 (−2)	4.90 (+2)	36.096
600 to 700	9.1 (−7)	1.04 (−3)	.000	6100 to 6200	17.05 (−2)	5.07 (+2)	37.351
700 to 800	7.8 (−7)	1.12 (−3)	.000	6200 to 6300	16.58 (−2)	5.24 (+2)	38.573
800 to 900	1.53 (−6)	1.27 (−3)	.000	6300 to 6400	16.37 (−2)	5.40 (+2)	39.778
900 to 1000	2.52 (−6)	1.52 (−3)	.000	6400 to 6500	15.99 (−2)	5.56 (+2)	40.956
1000 to 1100	2.82 (−6)	1.80 (−3)	.000	6500 to 6600	15.20 (−2)	5.71 (+2)	42.075
1100 to 1200	1.26 (−6)	1.93 (−3)	.000	6600 to 6700	15.55 (−2)	5.87 (+2)	43.220
1200 to 1300	8.71 (−5)	1.06 (−2)	.001	6700 to 6800	15.16 (−2)	6.02 (+2)	44.337
1300 to 1400	4.47 (−6)	1.11 (−2)	.001	6800 to 6900	14.89 (−2)	6.17 (+2)	45.433
1400 to 1500	5.62 (−6)	1.16 (−2)	.001	6900 to 7000	14.50 (−2)	6.31 (+2)	46.501
1500 to 1600	1.05 (−5)	1.27 (−2)	.001	7000 to 7100	14.16 (−2)	6.46 (+2)	47.544
1600 to 1700	1.78 (−5)	1.45 (−2)	.001	7100 to 7200	13.85 (−2)	6.59 (+2)	48.564
1700 to 1800	7.96 (−5)	2.24 (−2)	.002	7200 to 7300	13.56 (−2)	6.73 (+2)	49.562
1800 to 1900	1.63 (−4)	3.86 (−2)	.003	7300 to 7400	13.16 (−2)	6.86 (+2)	50.532
1900 to 2000	4.00 (−4)	7.86 (−2)	.006	7400 to 7500	12.84 (−2)	6.99 (+2)	51.478
2000 to 2100	1.10 (−3)	1.89 (−1)	.014	7500 to 7600	12.65 (−2)	7.12 (+2)	52.409
2100 to 2200	4.69 (−3)	6.58 (−1)	.048	7600 to 7700	12.36 (−2)	7.24 (+2)	53.320
2200 to 2300	6.41 (−3)	1.30	.096	7700 to 7800	12.07 (−2)	7.36 (+2)	54.209
2300 to 2400	5.72 (−3)	1.87	.138	7800 to 7900	11.83 (−2)	7.48 (+2)	55.080

TABLE 5.—*Summary of the Quiet Sun Solar Irradiance at All Wavelengths*—Continued

Wavelength range, Å	Solar irradiance,[a] W/m^2 Per Ångstrom	Sum[b]	Percent	Wavelength range, Å	Solar irradiance,[a] W/m^2 Per Ångstrom	Sum[b]	Percent
7900 to 8000	11.61 (−2)	7.59 (+2)	55.935	50 to 60 × 10^4	2.73 (−8)	1.36 (+3)	100.000
8000 to 8100	11.36 (−2)	7.71 (+2)	56.771	60 to 70 × 10^4	1.39 (−8)	1.36 (+3)	100.000
8100 to 8200	11.04 (−2)	7.82 (+2)	57.585	70 to 80 × 10^4	7.83 (−9)	1.36 (+3)	100.000
8200 to 8300	10.75 (−2)	7.93 (+2)	58.376	80 to 90 × 10^4	4.74 (−9)	1.36 (+3)	100.000
8300 to 8400	10.51 (−2)	8.03 (+2)	59.150	90 to 100 × 10^4	3.04 (−9)	1.36 (+3)	100.000
8400 to 8500	10.06 (−2)	8.13 (+2)	59.891	10 to 11 × 10^5	2.04 (−9)	1.36 (+3)	100.000
8500 to 8600	9.86 (−2)	8.23 (+2)	60.617	11 to 12 × 10^5	1.42 (−9)	1.36 (+3)	100.000
8600 to 8700	9.68 (−2)	8.33 (+2)	61.330	12 to 13 × 10^5	1.01 (−9)	1.36 (+3)	100.000
8700 to 8800	9.47 (−2)	8.42 (+2)	62.028	13 to 14 × 10^5	7.46 (−10)	1.36 (+3)	100.000
8800 to 8900	9.24 (−2)	8.51 (+2)	62.708	14 to 15 × 10^5	5.61 (−10)	1.36 (+3)	100.000
8900 to 9000	9.20 (−2)	8.61 (+2)	63.386	15 to 16 × 10^5	4.30 (−10)	1.36 (+3)	100.000
9000 to 9100	8.98 (−2)	8.70 (+2)	64.047	16 to 17 × 10^5	3.35 (−10)	1.36 (+3)	100.000
9100 to 9200	8.74 (−2)	8.78 (+2)	64.691	17 to 18 × 10^5	2.65 (−10)	1.36 (+3)	100.000
9200 to 9300	8.57 (−2)	8.87 (+2)	65.322	18 to 19 × 10^5	2.12 (−10)	1.36 (+3)	100.000
9300 to 9400	8.41 (−2)	8.95 (+2)	65.941	19 to 20 × 10^5	1.72 (−10)	1.36 (+3)	100.000
9400 to 9500	8.23 (−2)	9.04 (+2)	66.547	20 to 30 × 10^5	7.28 (−11)	1.36 (+3)	100.000
9500 to 9600	8.06 (−2)	9.12 (+2)	67.141	30 to 40 × 10^5	1.80 (−11)	1.36 (+3)	100.000
9600 to 9700	7.89 (−2)	9.20 (+2)	67.722	40 to 50 × 10^5	6.89 (−12)	1.36 (+3)	100.000
9700 to 9800	7.73 (−2)	9.27 (+2)	68.291	50 to 60 × 10^5	3.23 (−12)	1.36 (+3)	100.000
9800 to 9900	7.56 (−2)	9.35 (+2)	68.848	60 to 70 × 10^5	1.73 (−12)	1.36 (+3)	100.000
9900 to 10 000	7.39 (−2)	9.42 (+2)	69.392	70 to 80 × 10^5	1.01 (−12)	1.36 (+3)	100.000
10 to 11 × 10^3	6.82 (−2)	1.01 (+2)	74.417	80 to 90 × 10^5	6.34 (−13)	1.36 (+3)	100.000
11 to 12 × 10^3	5.58 (−2)	1.07 (+2)	78.530	90 to 100 × 10^5	4.18 (−13)	1.36 (+3)	100.000
12 to 13 × 10^3	4.64 (−2)	1.11 (+2)	81.943	10 to 11 × 10^6	2.84 (−13)	1.36 (+3)	100.000
13 to 14 × 10^3	3.85 (−2)	1.15 (+2)	84.777	11 to 12 × 10^6	2.00 (−13)	1.36 (+3)	100.000
14 to 15 × 10^3	3.23 (−2)	1.18 (+2)	87.154	12 to 13 × 10^6	1.46 (−13)	1.36 (+3)	100.000
15 to 16 × 10^3	2.67 (−2)	1.21 (+2)	89.118	13 to 14 × 10^6	1.08 (−13)	1.36 (+3)	100.000
16 to 17 × 10^3	2.14 (−2)	1.23 (+2)	90.697	14 to 15 × 10^6	8.24 (−14)	1.36 (+3)	100.000
17 to 18 × 10^3	1.75 (−2)	1.25 (+3)	91.983	15 to 16 × 10^6	6.38 (−14)	1.36 (+3)	100.000
18 to 19 × 10^3	1.44 (−2)	1.26 (+3)	93.042	16 to 17 × 10^6	5.02 (−14)	1.36 (+3)	100.000
19 to 20 × 10^3	1.20 (−2)	1.28 (+3)	93.923	17 to 18 × 10^6	4.01 (−14)	1.36 (+3)	100.000
20 to 30 × 10^3	5.53 (−3)	1.33 (+3)	97.998	18 to 19 × 10^6	3.24 (−14)	1.36 (+3)	100.000
30 to 40 × 10^3	1.53 (−3)	1.35 (+3)	99.125	19t o 20 × 10^6	2.65 (−14)	1.36 (+3)	100.000
40 to 50 × 10^3	5.71 (−4)	1.35 (+3)	99.546	20 to 30 × 10^6	1.16 (−14)	1.36 (+3)	100.000
50 to 60 × 10^3	2.54 (−4)	1.35 (+3)	99.733	30 to 40 × 10^6	3.07 (−15)	1.36 (+3)	100.000
60 to 70 × 10^3	1.32 (−4)	1.36 (+3)	99.830	40 to 50 × 10^6	1.17 (−15)	1.36 (+3)	100.000
70 to 80 × 10^3	7.56 (−5)	1.36 (+3)	99.886	50 to 60 × 10^6	5.49 (−16)	1.36 (+3)	100.000
80 to 90 × 10^3	4.64 (−5)	1.36 (+3)	99.920	60 to 70 × 10^6	2.92 (−16)	1.36 (+3)	100.000
90 to 100 × 10^3	3.01 (−5)	1.36 (+3)	99.942	70 to 80 × 10^6	1.71 (−16)	1.36 (+3)	100.000
10 to 11 × 10^4	2.02 (−5)	1.36 (+3)	99.957	80 to 90 × 10^6	1.07 (−16)	1.36 (+3)	100.000
11 to 12 × 10^4	1.40 (−5)	1.36 (+3)	99.967	90 to 100 × 10^6	7.03 (−17)	1.36 (+3)	100.000
12 to 13 × 10^4	9.97 (−6)	1.36 (+3)	99.975	10 to 11 × 10^7	4.86 (−17)	1.36 (+3)	100.000
13 to 14 × 10^4	7.30 (−6)	1.36 (+3)	99.980	11 to 12 × 10^7	3.48 (−17)	1.36 (+3)	100.000
14 to 15 × 10^4	5.47 (−6)	1.36 (+3)	99.984	12 to 13 × 10^7	2.57 (−17)	1.36 (+3)	100.000
15 to 16 × 10^4	4.18 (−6)	1.36 (+3)	99.987	13 to 14 × 10^7	1.94 (−17)	1.36 (+3)	100.000
16 to 17 × 10^4	3.25 (−6)	1.36 (+3)	99.990	14 to 15 × 10^7	1.49 (−17)	1.36 (+3)	100.000
17 to 18 × 10^4	2.56 (−6)	1.36 (+3)	99.992	15 to 16 × 10^7	1.17 (−17)	1.36 (+3)	100.000
18 to 19 × 10^4	2.05 (−6)	1.36 (+3)	99.993	16 to 17 × 10^7	9.29 (−18)	1.36 (+3)	100.000
19 to 20 × 10^4	1.66 (−6)	1.36 (+3)	99.994	17 to 18 × 10^7	7.49 (−18)	1.36 (+3)	100.000
20 to 30 × 10^4	7.03 (−7)	1.36 (+3)	99.999	18 to 19 × 10^7	6.11 (−18)	1.36 (+3)	100.000
30 to 40 × 10^4	1.72 (−7)	1.36 (+3)	99.999	19 to 20 × 10^7	5.04 (−18)	1.36 (+3)	100.000
40 to 50 × 10^4	6.16 (−8)	1.36 (+3)	100.000				

[a] Numbers in parentheses indicate the power of 10 by which the irradiance values given must be multiplied.

[b] Sum of the irradiance at this wavelength interval plus that at all shorter wavelengths.

[c] Sum of the irradiance occurring at this wavelength interval and at shorter wavelengths as a percent of the total irradiance.

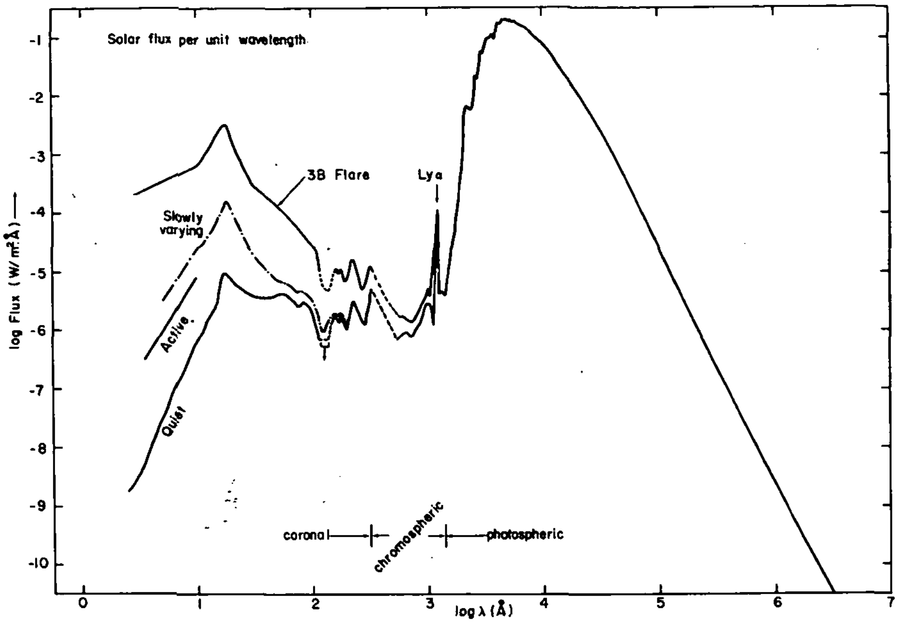

FIGURE 6.—Summary of solar irradiance at all wavelengths.

TABLE 6.—*Summary of Solar 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,[a] W/m^2							
	Quiet Sun		Active Sun		Slowly varying Sun		3B flare	
	Per Ångstrom	Sum[b]	Per Ångstrom	Sum[b]	Per Ångstrom	Sum[b]	Per Ångstrom	Sum[b]
2 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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)
100 to 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 to 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 to 130	Near 0	3.54 (−4)	Near 0	6.64 (−4)	Near 0	1.91 (−3)	Near 0	3.78 (−2)

TABLE 6.—*Summary of Solar Irradiance for the Quiet Sun, a Typical Active Sun, the Maximum Enhancement Due to the Slowly Varying Component, and an Importance 3B Flare*—Continued

Wavelength range, Å	Solar irradiance,[a] W/m^2							
	Quiet Sun		Active Sun		Slowly varying Sun		3B flare	
	Per Ångstrom	Sum[b]	Per Ångstrom	Sum[b]	Per Ångstrom	Sum[b]	Per Ångstrom	Sum[b]
130 to 140	Near 0	3.54 (−4)	Near 0	6.64 (−4)	Near 0	1.91 (−3)	Near 0	3.78 (−2)
140 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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 to 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)

[a] Numbers in parentheses indicate the power of 10 by which the irradiance values given must be multiplied.

[b] Sum of the irradiance at this wavelength interval plus that at all shorter wavelengths.

higher for X-rays and for the far UV. The coincidence of H$_\alpha$ flares with short wavelength radiation enhancements is by no means one to one. While many investigators have found a strong correlation of H$_\alpha$ 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 H$_\alpha$ radiation. Table 8 summarizes this classification system. The frequency of occurrence depends on the phase of the 11-yr 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 2½ hr. 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

TABLE 7.—*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 and Kharitonov, 1969	1418
High-altitude measurements:	
Thekaekara, 1970 (various instruments)	1352
	1349
	1343
	1358
	1338
Murcray, 1969	1338
Kondratyev and Nikolsky, 1970	1353
Drummond and Hickey, 1968	1360
Plamondon, 1969	1353

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 downward, 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).

TABLE 8.—*Definition of Importance Classes Flares*

Importance	Area (solar hemisphere)
S	Less than 10^{-4}
1	1.0 to 2.5 × 10^{-4}
2	2.5 to 6.0 × 10^{-4}
3	6.0 to 12 × 10^{-4}
4	More than 12 × 10^{-4}

TABLE 9.—*Frequency of Occurrence of Flares as a Function of Importance and Phase of the Solar Cycle*

Year (after maximum)	Flares per day			Total
	Importance			
	3	2	1	
0	0.050	1.0	9.0	10
1	.045	.9	8.0	9
2	.035	.7	7.3	8
3	.015	.3	2.7	3
4	.010	.2	1.8	2
5	.005	.1	.9	1
6	.002	.05	.5	.5
7	.001	.01 to .05	.1 to .5	.1 to .5
8	.005	.1	.9	1
9	.025	.5	4.5	5
10	.045	.9	8.0	9

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 than 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. Because 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). The resurgence of activity represented by the August 1972 flares in cycle 20 is quite analogous to the postmaximum 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 occurrence of major flares, it is now apparently accepted that proton flare producing regions are not distributed randomly in solar longitude. (See the section entitled "The 27-Day Period.") The distribution of sunspots, however, does not unambiguously portray such a nonrandom organization.

All these qualifications should be kept in mind when interpreting table 9, which summarizes our knowledge of the frequency of flares over the sunspot cycle. Most of the data used to prepare table 9 come 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 min, and a decay time of 12 min (Drake, 1971). Many bursts have a superimposed short impulsive phase, of 1- or 2-min duration; occurring near the start of the flare. For hard X-rays (~ 1Å or shorter) this phase consists of numbers of even shorter spikes with time scales from under 1 s up to 10 s. 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

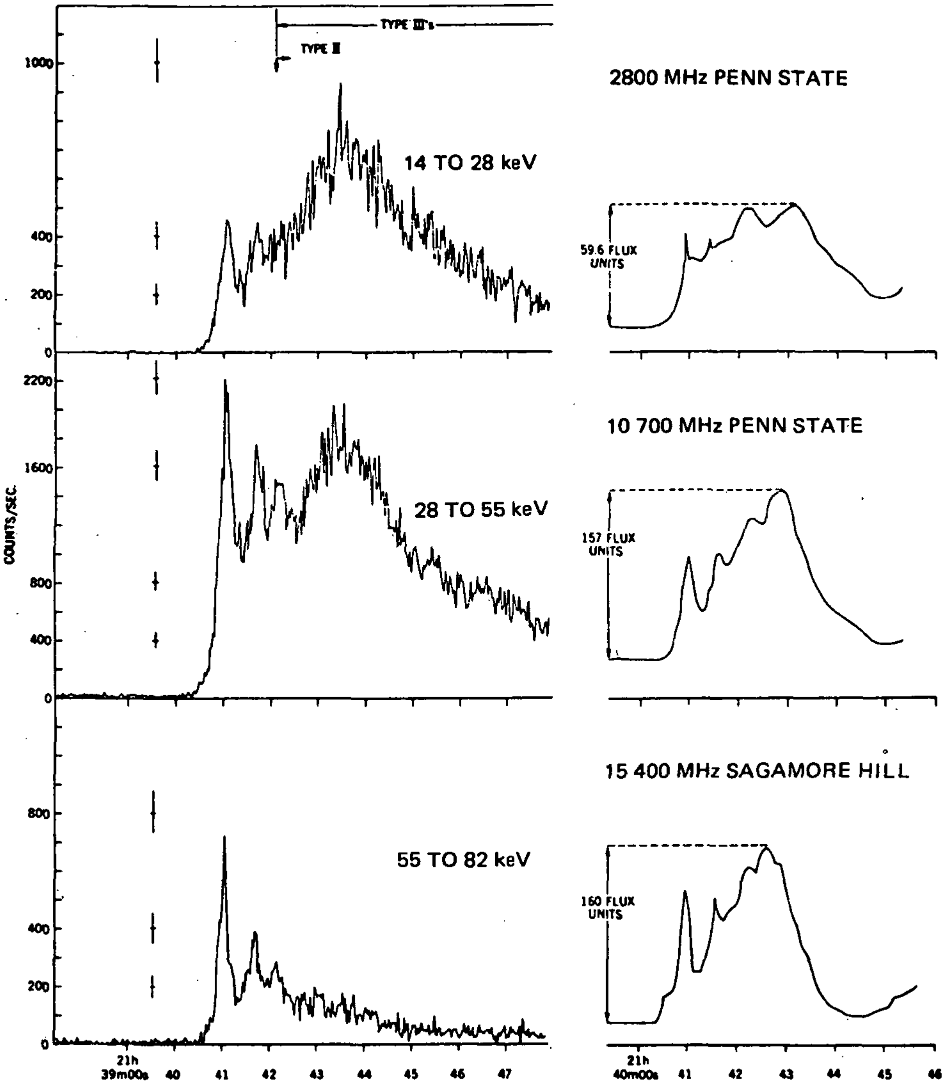

FIGURE 7.—X-ray spectrum of a solar flare at three wavelengths (from Frost, 1969).

the onset of an event. Figure 7 is an example of an X-ray event at several wavelengths.

The relationship between soft X-ray peak flux (2 to 20 Å) and H$_\alpha$ flare importance classification has been ambiguous, for there are large deviations from the mean relation between them. Nevertheless, analyses of significant numbers of flares (Drake, 1971; Hoover, Thomas, and Underwood, 1972) point to the existence of such a relationship, particularly with the brightness of the H$_\alpha$ 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 H$_\alpha$ flares frequently produce large X-ray fluxes. Small flares never produce large X-ray bursts. Conversely, strong X-rays are always accompanied by some H$_\alpha$ 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

TABLE 10.—*Summary of Wende's (1972) Data on X-Ray Flux From Solar Flares*

Flare type	log flux, W/m² – Å Wavelength, Å		
	2.5	6.5	16
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

data also provide useful information on the fluxes of smaller flares. Table 10 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 6 are based on extrapolations, using the enhancement in the X-ray wavelengths, Hall's (1971) measurements of several emission lines, and Heath's (1969) measurements at H(I) Lyman-alpha (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 2 or 3 (Neupert, 1967). Chromospheric lines show considerable enhancement over the flare area (Hall, 1971; Wood and Noyes, 1972), 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 H_α flare areas, namely $E \propto kA^{3/2}$, where A is the H_α flare area and k is a constant of proportionality that ranges from less than 0.4 for H(I), HE(I), and some coronal lines to 2.4 and 2.8 for chromospheric lines like Si(III) ($\lambda = 1206$) and O(VI) ($\lambda = 1032$). 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 in the section on 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 min.

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 1 or 2 min before the X-ray or H_α maximum (Hall, 1971; Wood et al., 1972). Time scales are around 5 to 10 min.

Lyman-alpha radiation of H(I) 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 from Bruner and Rense (1969). Measurements by Heath (1973) and Hall (1971) indicate an overall enhancement from the entire disk in Lyman-alpha 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 H_α 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 kernel covering around 10^{-5} of the solar surface. Using these data, we estimate maximum enhancements in the visual and near IR (4000 to 12 500 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: H_α and the *H* and *K* lines of Ca(II).

Zirin and Tanaka (1973) measured the H_α flux for the August 4 and August 7, 1972, importance 3B flares and found total energies of 2.0 ×

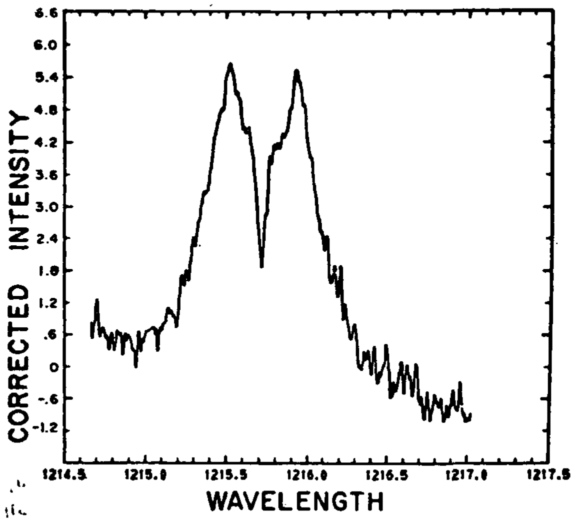

FIGURE 8.—The profile of the Lyman-alpha line (from Bruner and Rense, 1969).

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 H_α emission is concentrated into bright, short-lived kernels and that the excessive line width (12 Å or more) occurs only in these kernels. The energies of Zirin and Tanaka (1973) represent a H_α 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 lines 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 H_α or Ca(II) *K*-line emission. X-rays and UV 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-yr 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 minuscule, amounting to about 0.1 percent; however, it may be as much as 100 percent in certain EUV emission lines and 50 percent at radio frequencies. The major effect of a plage, however, occurs for X-rays. As a rule, the shorter the wavelengths, 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 of 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 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-hr 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, 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. Because 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 (1974) 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 variations 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) ($\lambda=335$ Å) and Fe(XV) ($\lambda=284$ Å) change by a factor of 4 because of the appearance or disappearance of an active region (Neupert, 1967). These lines arise from the high temperature, 2 million degree corona as opposed to the 10 000° to 15 000° chromosphere and chromosphere/corona interface where the lower ionization lines originate.

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 midway between the 3B flare curve and Wende's (1972) "typical active Sun."

In the visual region, the largest fluctuations occur in the *H* and *K* lines of Ca(II). 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 similar to the Ca(II) lines; Fregda (1971) found a correlation coefficient of 0.92 between the intensities of the Mg(II) *K* line ($\lambda=2795$) and the Ca(II) *K* line. The emission cores are far more pronounced in the Mg(II) lines than the

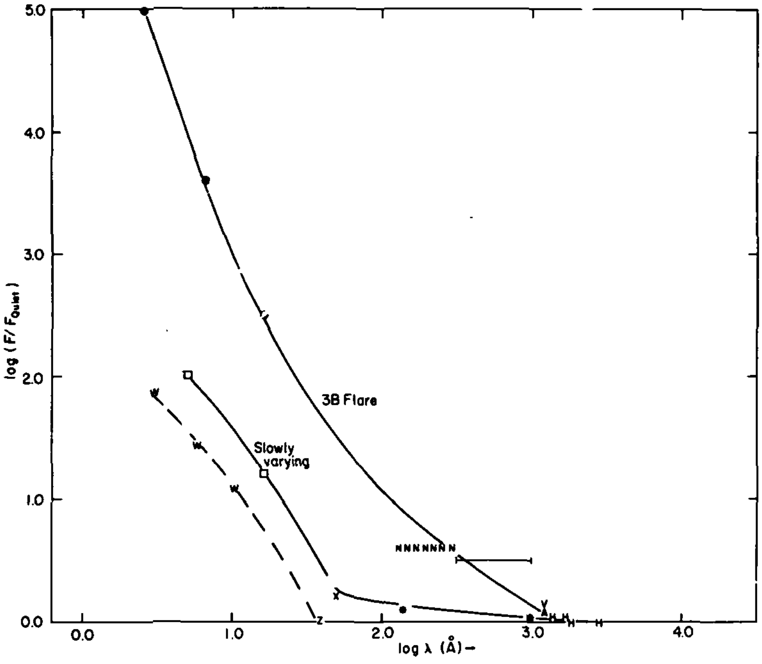

FIGURE 9.—Variations in the solar irradiance as a function of wavelength. (Filled circles: Dere et al., 1973; horizontal bar: Hall, 1971; *V*: Vidal-Madjar et al., 1973; *A*: Heath, 1969, Lyman-alpha; *H*: Heath, 1973; open squares: Kreplin, 1970; *X*: Hall and Hinteregger, 1970; asterisks: Reeves and Parkinson, 1972; *W*: Wende, 1972; *Z*: fig. 5.)

Ca(II) lines, so 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 facula to photosphere intensity of 1.6 at a heliocentric distance of cos θ = 0.2. Even for a large facula that would cover 5 × 10^{-3} of the solar disk when at central meridian, the enhancement is only 0.1 percent.

Variations in any other part of the visible spectrum, including H_α, are dwarfed by those in the *H* and *K* lines, and can safely be ignored. The same is true for the IR. 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 in comparison with the total flux. Radio data are, nevertheless, of great value in diagnosing solar active regions and in estimating the solar flux variations at other wavelengths.

The 27-Day Period

Whereas the slowly varying component is largely due 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.

Because 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 periods of time depends upon the recurrence of major active regions at, or near, the same longitude over extended time scales. 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 go back the longest (over 100 yr), 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 yr.

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*a, b*) 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 entitled "The Slowly Varying Component (Nonperiodic)" because the cause of the periodicity is the appearance and disappearance of active regions around the solar limb.

TABLE 11.—*Factors for the Conversion of Mean Irradiance to Irradiance at Any Given Day*[a]

Day	Factor
Jan. 1	0.9669
Feb. 1	.9710
Mar. 1	.9819
Apr. 1	.9988
May 1	1.0155
June 1	1.0284
July 1	1.0337
Aug. 1	1.0304
Sept. 1	1.0189
Oct. 1	1.0024
Nov. 1	.9851
Dec. 1	.9722

[a] To convert, divide mean irradiance by these numbers.

The 1-Year Period

The varying distance of Earth from the Sun over its orbit is cause for a substantial variation in the solar flux. Table 11 presents appropriate factors by which one should multiply the fluxes to correct to a certain time of year. The following sine curve approximation (day: April 4) for this factor is proportional to the solar distance squared and is accurate to within 0.3 percent at all times:

$$r^2 = 1.0004 + 0.0334 \sin$$

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

The 11-Year Cycle

The 11-yr 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 Tandberg-Hanssen, 1967), which 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-yr" sunspot cycle. There is little reason to believe that the polarity flip affects any other parameter of the 11-yr "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-yr cycles.

Successive solar maximums differ quite considerably. It has been suggested that alternate maxima have higher R values, but this is by no means clear cut. The International Geophysical Year solar maximum of cycle 19 turned out to be unique in that it was exceptionally active. Because this was a well-studied maximum, much of the data obtained there are 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 measurably decreases 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 6×10^{-4} 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 *area* of all the sunspots is of the order of 4×10^{-3} (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 photospheric 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 from 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 H_α plage regions are closely related to the sunspot number. Similarly, the correlations with R number of He(II) ($\lambda = 304$) flux; nonflare X-ray flux at all spectral wavelengths; and radio emission, especially at 10 cm; are very good.

It seems safe to conclude that the 11-yr 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-yr solar sunspot cycle (Kreplin, 1970; Parkinson and Pounds, 1971). 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 in 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.

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-yr 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 behavior. Vidal-Madjar et al. (1973) report an identical result for Lyman-alpha. 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 yr. We conclude that, at wavelengths greater than 1500 Å or so, there is no variation over the 11-yr solar sunspot cycle.

Longer Periods

Periodic variations in the solar flux over time scales greater than 11 yr 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.

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

Numerous analyses of the sunspot number for an 80-yr period have been done. Kopecky (1962) reviews some of these. More recently, Hartmann (1971) has used untreated, unsmoothed *R* values from 1700 to 1950. By plotting alternate cycles as positive and negative, he obtains a convincing portrayal of an 80-yr 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, Henkel, 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 the varying photographic quality of images of the solar disk caused by the atmospheric changes.

The 26 000-Yr Period

The procession of Earth's orbit with a period of 26 000 yr produces a change in the amount of solar energy received at a given terrestrial latitude. Currently, perihelion occurs very near the middle of the northern hemisphere winter; in 13 000 yr 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.

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DISCUSSION

RASOOL: Do we understand the mechanism of the 11-yr cycle?

SMITH: There are some who think they understand it, but I think the answer is no, we do not really understand it.

RASOOL: Is there any reason why there should be a 22-yr cycle?

SMITH: The 22-yr cycle occurs because of the change in the polarity. We have the increase in the number of sunspots every 11 yr, but the polarity of the leading sunspots changes with every 11-yr cycle; and so, on that basis, we have a 22-yr 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.

PRIESTER: Because the radio radiation of the Sun has been left out of this talk, I would like to report some very recent results that have been obtained with the 100-m fully steerable radiotelescope at Bonn, which is located at Effelsberg. The telescope has provided pictures of the Sun measured at a wavelength of 2.8 cm, 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. Within 24 hr, 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 do not find any limb brightening, which should be expected at this wavelength, given the beam size of 1 arcmin. I would like to point out that 30 percent of the observing time with the Bonn radiotelescope has been set aside for foreign guest observers.

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?

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_α line.

MITCHELL: I am 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 percent of the total radiation emitted from the photosphere. Why would it not 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, of individual sunspots? I am referring to some statistics on very large sunspots that occurred around 1946 and maybe some other dates. The total areas of all sunspots on the disk can get up to a fraction of a percent during high sunspot maxima.

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, 1963) the variation in solar constant values that he got over a solar cycle is roughly about two-tenths of a percent, and he did, indeed, also point out that a large sunspot group crossed the central meridian of the Sun, the UV 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 UV flux (in the sense of ground-based observations, 0.35 μm or so) increased. The UV flux increased with increasing sunspot numbers, but as a large spot crossed the central meridian, the UV flux dropped.

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.

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Geomagnetic Responses to the Solar Wind and to Solar Activity

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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 magnetic field lines under the influence of large-scale magnetospheric electric fields is outlined. Ionospheric 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 behind Earth to form the magnetotail so that kinetic energy from the solar wind is converted into magnetic energy in the field lines in the tail. Localized collapses of the crosstail current, which is driven by the large-scale dawn/dusk electric field in the magnetosphere, divert part of this current along geomagnetic field lines 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-yr sunspot cycle from 17 yr 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 goemagnetic 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 Earth's magnetic field recorded at Kew Magnetic Observatory became abruptly disturbed, followed about 18 hr 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. Because 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 Earth to interact with 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 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:

(1) A detectable solar wind was present at all times.

(2) The average solar wind speed was 500 km.

(3) The speed varied between 300 and 860 km and was correlated with geomagnetic activity.

(4) The average proton density was 5/per cm^3.

(5) Several streams of high-speed plasma were found to reoccur at 27-day intervals.

(6) 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 that are large compared with the proton gyroradius (typically 100 km for solar wind plasma near Earth). 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 $B^2/2\mu_0$ (where B denotes the magnetic flux density and μ_0 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 that 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 $B^2/2\mu_0$ 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 that 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 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 normal to the magnetopause b_n vanishes. For an interplanetary field directed along a 45° spiral angle, the calculated geometry and extent of the magnetosphere and magnetosheath regions on the day side of 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.

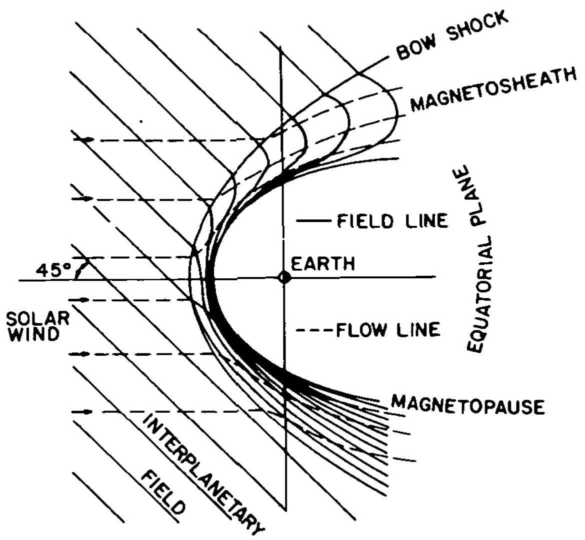


FIGURE 1.—Flow lines of the solar wind around the geomagnetic field confined within the magnetosphere. Interplanetary magnetic field lines corresponding to a spiral of 45° are draped around the magnetopause. The geomagnetic dipole is assumed to be perpendicular to the plane of the figure and to the solar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

The treatment of the solar wind as a cold plasma flow leads to the formation of a magnetosphere that is open in the antisolar direction with its flanks stretching asymptotically to the solar wind flow direction. At great distances from 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 Earth. In this case the magnetosphere is expected to extend in the solar wind flow direction (corrected for the small aberration resulting from the orbital movement of Earth around the Sun) to three or four times the standoff distance on the sunward side of 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 radii 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 kiloelectron volt 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 3(*a*) shows a north-south cut through the magnetotail. Figure 3(*b*) 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 that 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 because 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 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 because of the much higher degree of

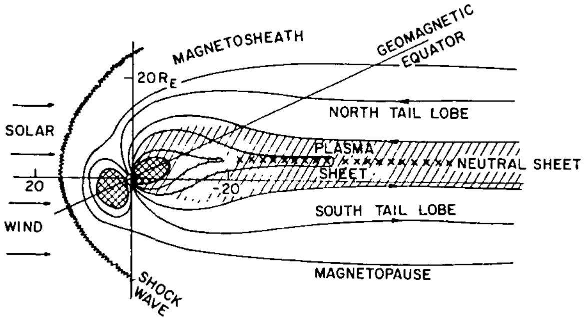


FIGURE 2.—Observed properties of the magnetotail. The distant tail is approximately alined with the solar wind flow direction independent of the inclination of the geomagnetic equator to the ecliptic plane. Field lines in the northern tail lobe are directed toward the Sun, and field lines in the southern tail lobe are directed away from the Sun. 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 Earth, while the rest of the magnetosphere stays roughly fixed in relation to the Sun/Earth line.

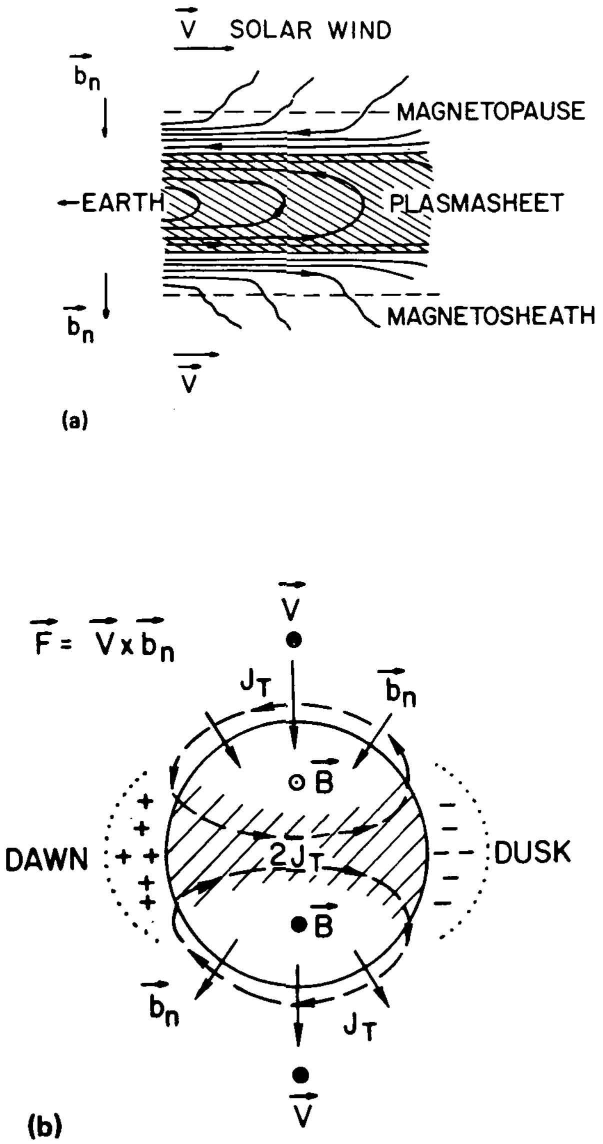


FIGURE 3.—Cross sections of the magnetotail. (a) North-south cut through the magnetotail. Field lines in the central plasma sheet connect with field lines from the other tail lobe. Field lines outside the plasma sheet connect to the interplanetary magnetic field thus providing a field component b_n normal to the magnetopause. (b) Cross section of the magnetotail as viewed from Earth. The plasma sheet is indicated by shading in the middle of the tail. The electromotive force, $V \times b_n$, 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.

isotropy of these particles which do not recognize a magnetopause. In a 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 electric fields, so that

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0 \qquad (1)$$

or, alternatively,

$$\mathbf{v} = \mathbf{E} \times \frac{\mathbf{B}}{B^2} \qquad (2)$$

where **E** is electric field strength, **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 to be a permanent part of the ionospheric and magnetospheric plasma and also to the conducting interior of

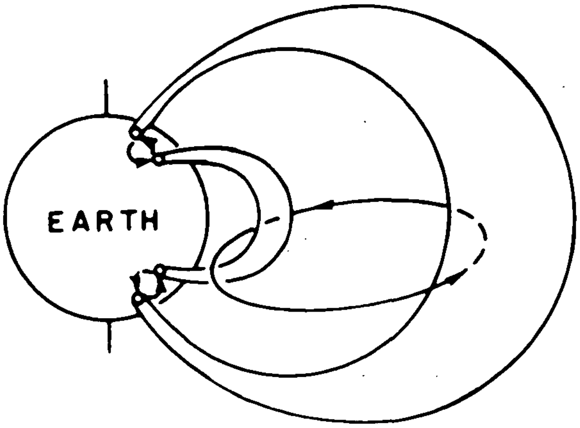


FIGURE 4.—Interchange of tubes of magnetic field lines. The inner tube can be stretched to go into the position of the outer tube, but the outer tube shortens upon moving to the position of the inner tube. In the absence of dissipative forces, no work is done by interchanging flux tubes.

Earth. But this is not true 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 flux tubes amounts to interchanging the plasma in the tubes.

Field lines passing through the ionosphere are embedded in a plasma that 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 because of the plasma lying along any of them, and therefore a potential difference between two points in the ionosphere 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

$$\mathbf{v} = \mathbf{E} \times \frac{\mathbf{B}}{B^2}$$

in order that there be no electric field in the rest frame of the plasma. This drift is called *convection of* permanent 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 $\nu_{\text{electron}} < \omega_{\text{electron}}$ and ω_{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 still 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 approximate direction and (with an estimate of the conductivity) the magnitude of electric fields in the ionosphere, and because 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 to be the result of friction between the charged and the neutral constituents of the atmosphere, is so effective that electric fields in the magnetosphere that are not maintained by some driving mechanisms 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 $\mathbf{b}_n$ of the magnetic field normal to the magnetopause as shown in figure 3(*a*). The electromotive force, $\mathbf{F} = \mathbf{V} \times \mathbf{b}_n$, where $\mathbf{V}$ 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 3(*b*). 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 that 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 antisunward 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 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 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.

These considerations can be summarized by noting that plasma flows down the tail near the tail surface and back again toward 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 permanent 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 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 day side, over the polar caps, and into the night side magnetosphere, wherefrom they return to the day side having their foot-points flowing through the subpolar or auroral zone ionosphere.

Because of viscosity, the neutral atmosphere largely rotates with 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

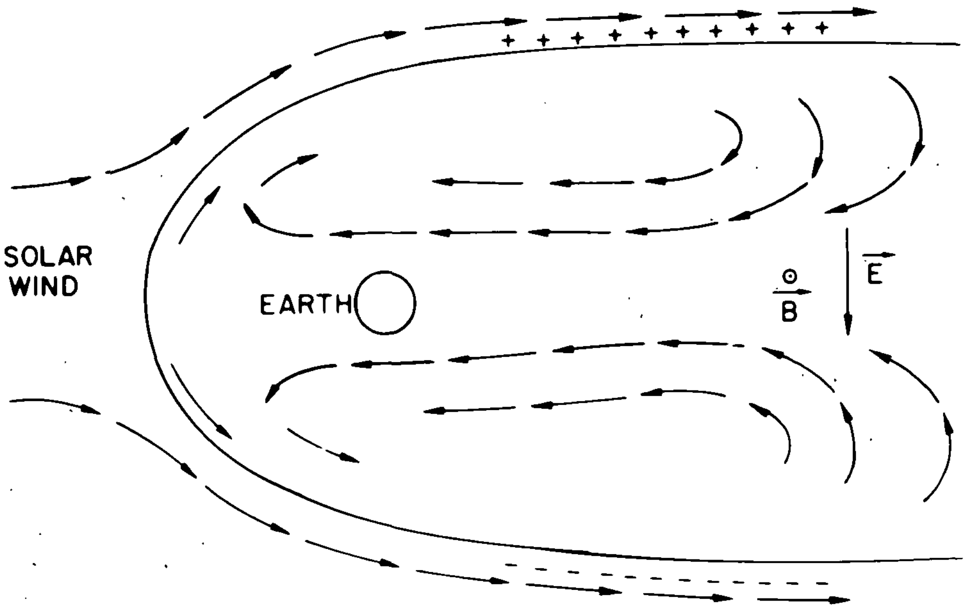


FIGURE 5.—Large-scale magnetospheric circulation of plasma and permanent field lines in the equatorial plane. Solar wind plasma flows down the tail near the magnetopause and toward Earth in the plasma sheet within the tail.

at rest so the electric field is zero. The electric field in a nonrotating frame of reference then becomes

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

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

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

In the approximation that the magnetic field lines are equipotentials, the ionospheric corotational electric field persists along field lines into the magnetosphere causing the inner magnetosphere to corotate with Earth. This inner part of the magnetosphere contains cold ($\sim$1–eV) plasma that has evaporated from the day side ionosphere onto the corotating magnetic field lines.

Even if 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-hr variation because of the diurnal solar heating and ionization 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 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.

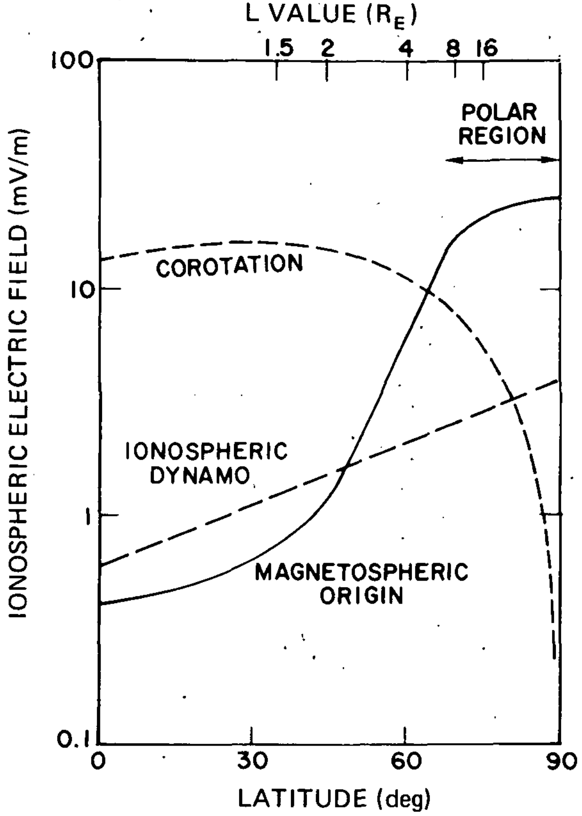


FIGURE 6.—Survey of the relative importance of ionospheric electric fields of different origins as a function of latitude. At low latitudes the corotation and ionospheric dynamo electric fields dominate, while electric fields of magnetospheric origin are most important in the polar regions.

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 $\mathbf{E} \times \mathbf{B}$ drift of the sunlit barium cloud.

Figure 7(*a*) shows the electric field observed on a polar pass of the OGO 6 satellite after subtraction of the $\mathbf{V} \times \mathbf{B}$ fields from both the motion of the satellite and the rotation of Earth. The field seems to be quite uniform across the polar cap directed toward the evening side. Field reversals

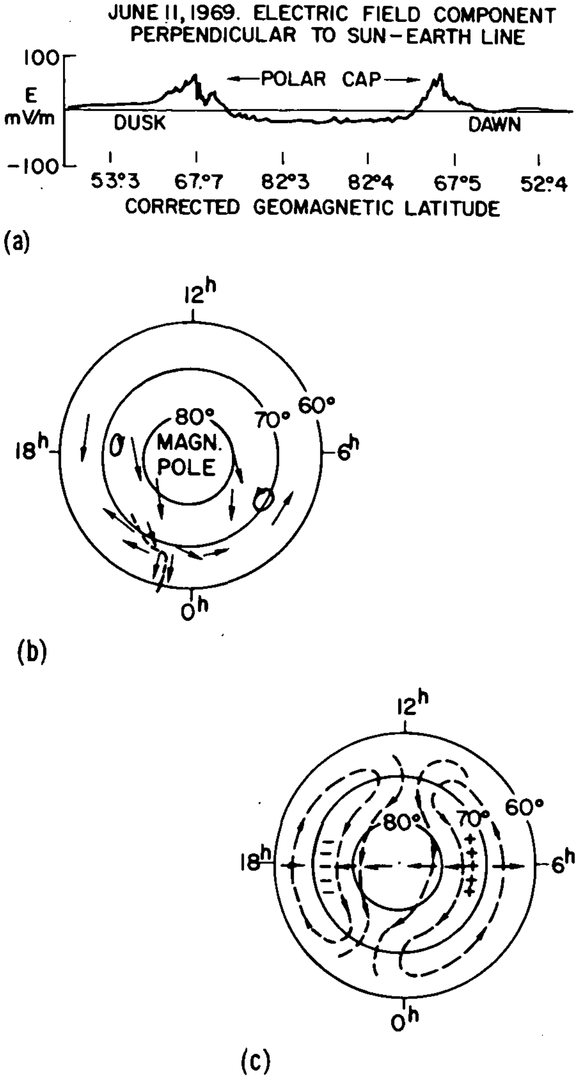


FIGURE 7.—Electric fields and convection. (*a*) Ionospheric electric field dusk-dawn components measured by OGO 6 satellite passing over the north polar region. A rather uniform electric field is found in the polar cap with reversals near the auroral zones. (*b*) Typical drifts of Ba^+ clouds in the F_2 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 (*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 downward over the northern pole.

are seen at the polar cap boundary. Figure 7(*b*) shows typical drifts of Ba^+ clouds released in the F_2 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 7(*c*).

The convection pattern can be described as consisting of two vortices, one in the morning and one in the evening. Because usually it is the electrons and not the atmospheric ions that 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. Because the electric field is strongest at auroral latitudes surrounding the polar cap (see fig. 7(*a*)) and because 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 8(*a*) shows a schematic of the two-celled current system with the electrojets indicated by heavy arrows, while figure 8(*b*) 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 antisunward flow over the polar cap.

FIELD LINE MERGING

There is an increasing understanding that most geomagnetic and related activity results from nonbalance of the convection rates on time scales less than typical reaction times of various parts of the coupled magnetosphere-ionosphere system. Understanding the processes that govern the convection rates in different regions within the magnetosphere is therefore extremely important but is largely lacking or at best phenomenological 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

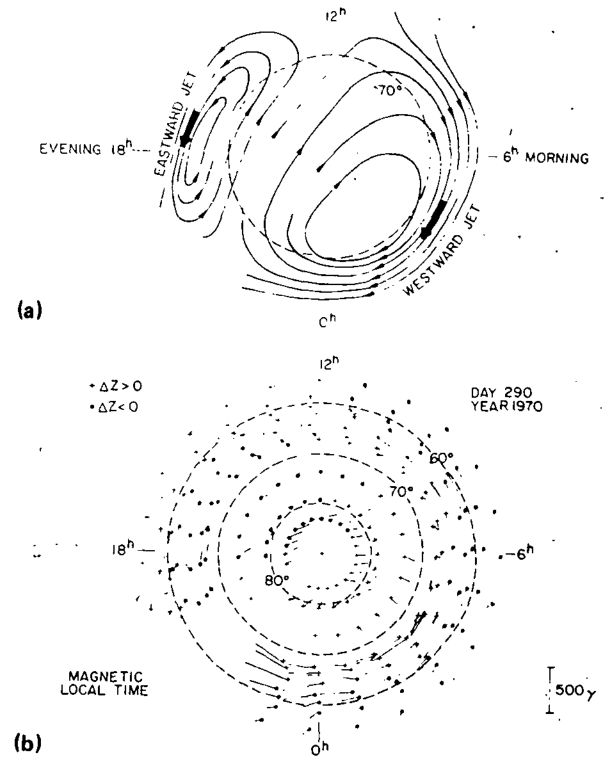


FIGURE 8.—Currents. (*a*) Schematic overhead equivalent currents flowing in the polar ionosphere. Equivalent currents are not necessarily real currents but simply model currents at constant altitude that could produce the observed magnetic variations on the ground. The current system is plotted as a function of corrected geomagnetic latitude and local magnetic time and is constructed assuming that the current pattern is fixed in space and time with 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 plotted 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 plus 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.

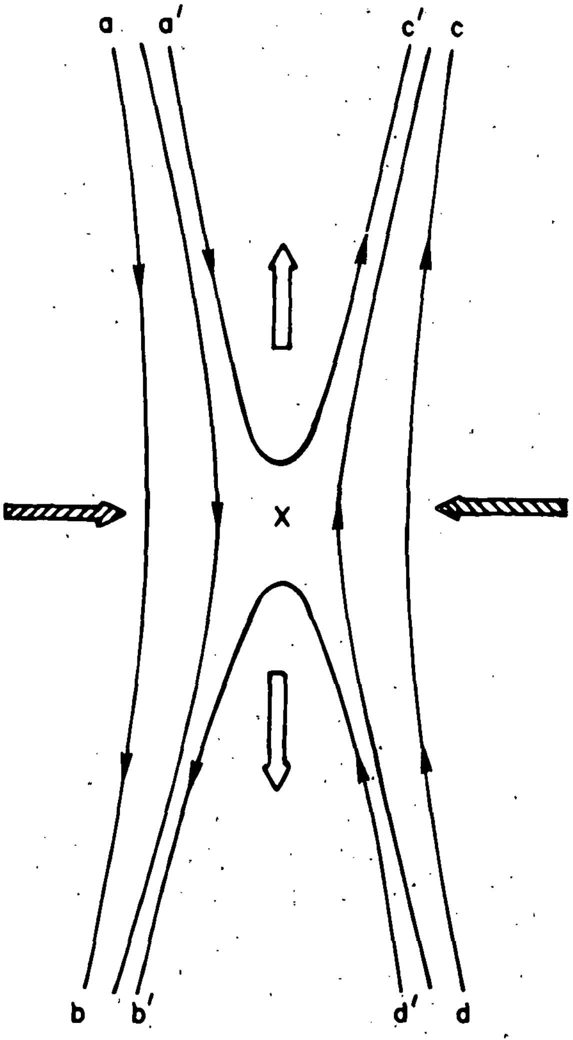


FIGURE 9.—Reconnection of oppositely directed magnetic field lines embedded in a plasma. If the plasma is compressed (shaded arrows) field lines merge at the X-type neutral point and plasma flows away (open arrows) from the reconnection region carrying the connected field lines. Field lines *ab* and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

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 day side magnetopause is that of an X-type neutral point as indicated in figure 10(*a*). The interplanetary field lines and the geomagnetic field lines merge at *A*, and the magnetosheath plasma flow carries the field lines in the antisolar direction. The numbers 1 to 7 in figure 10(*a*) 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. Merging of field lines has the effect that we must distinguish three classes of magnetic field lines near Earth: interplanetary field lines, such as *AA′* in figure 10(*b*), which are unlinked with the geomagnetic field lines; open field lines, such as *BB′*, which link the two fields; and closed terrestrial field lines, such as *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 property of the field line. On open field lines, solar wind particles and electric fields have direct access to 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 crosshatching on figure 2 and coincides roughly with the outer part of the plasmasphere.

When interplanetary field lines have just merged on the day side 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

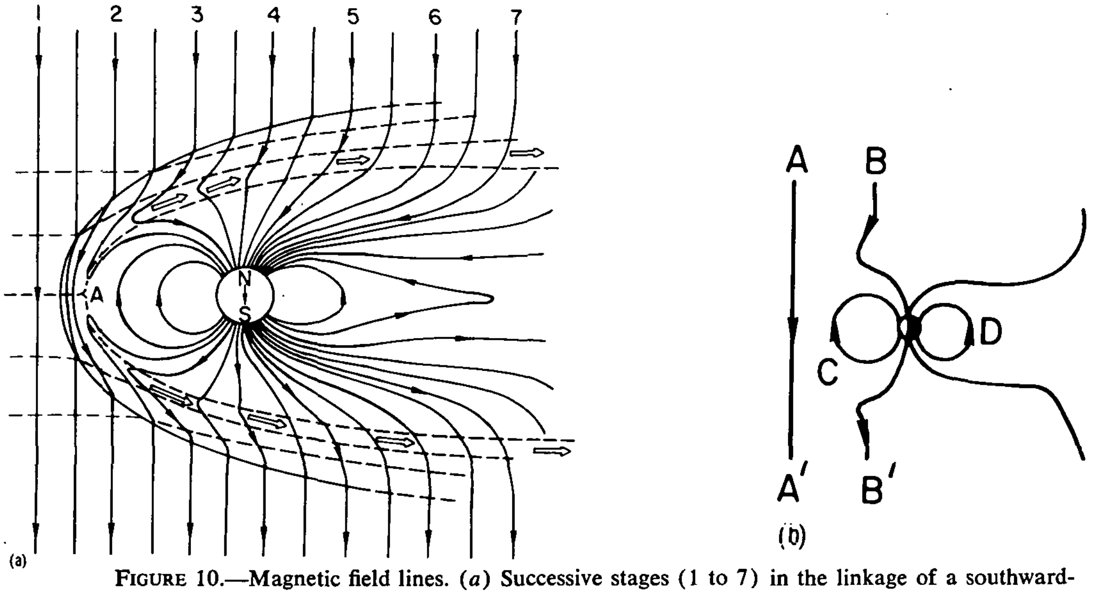


FIGURE 10.—Magnetic field lines. (*a*) Successive stages (1 to 7) in the linkage of a southward-directed interplanetary magnetic field line with the terrestrial field as the linked lines are carried past Earth by the magnetosheath flow (open arrows). (*b*) Classes of magnetic field lines with different 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.

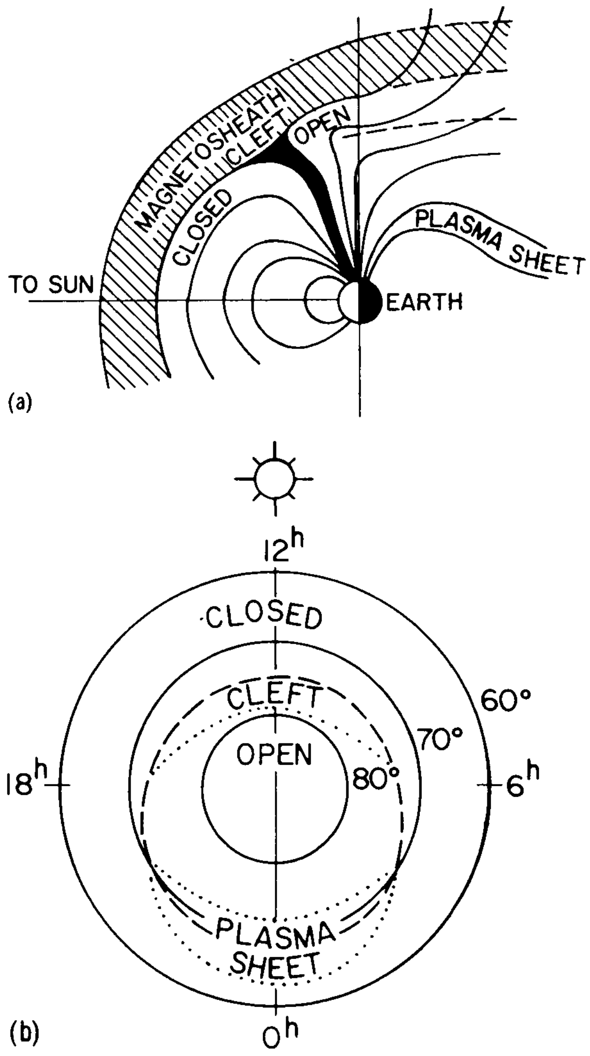


FIGURE 11.—Magnetospheric cleft. (*a*) The postion of the magnetospheric cleft in a north-south section of the magnetosphere. Various magnetospheric regions are indicated. The cleft is shown as the heavy black funnel-shaped region at the boundary between open and closed day side field lines. (*b*) The 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 day side than on the night side. The plasma sheet maps down to the night side oval tapering out as we approach the day side.

day side 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 11(*a*) as a funnel-shaped connection between the magnetosheath and Earth. As indicated on Figure 11(*b*) the cleft has a large longitudinal extent adjacent to most of the day-side polar cap boundary. The field lines extending into the plasma sheet are in a similar manner located near the night side 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 day side is closely related to B_z: particle observations of position of the cleft show that a persistent 6γ southward B_z for 45 min is enough to move the cleft 5° equatorward. 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 magnetosphere.

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 (fig. 3(*b*)). 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 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 Earth because of the northward component across the neutral sheet. During this convective motion, the field lines resume a more dipolar configuration, as they approach 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 Earth cause auroral displays along an oval-shaped belt, the auroral oval, around the magnetic pole. Figure 12 (*a*) 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 12(*b*). 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.

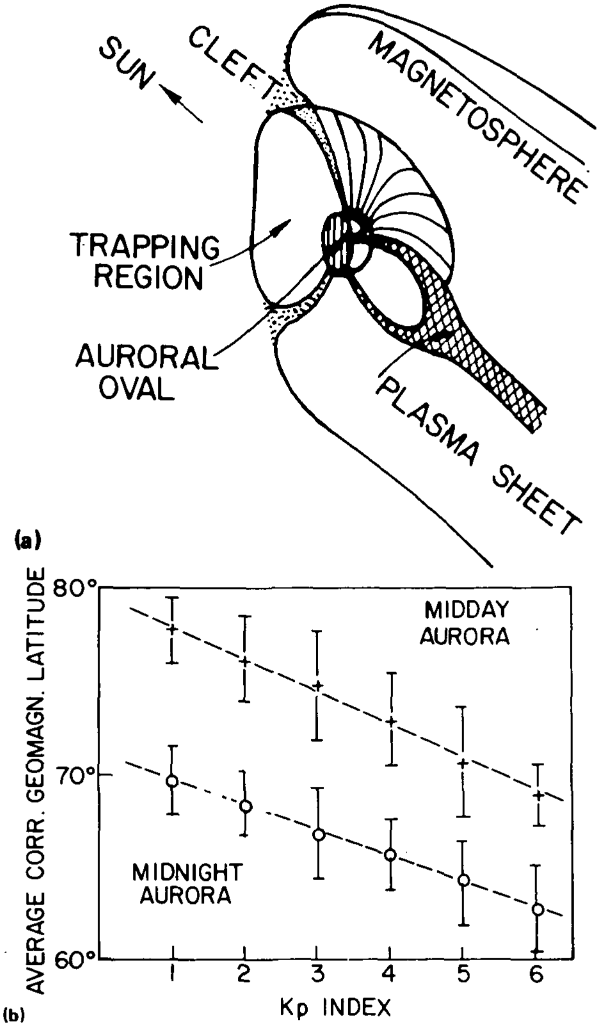


FIGURE 12.—Auroras. (*a*) Noon-midnight cross section of the magnetosphere showing the auroral oval as the region where the cleft and the plasma sheet intersect the ionosphere. (*b*) Average corrected geomagnetic latitude of auroras in the midday and midnight parts of the auroral oval as function of geomagnetic activity as given by the K_p index. Both parts of the oval move toward lower latitude as the activity increases.

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 13(*a*). There seems to be about 30 min 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 13(*b*) 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 (fig. 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 poleward while new bright auroral forms were forming behind it. This is the onset of an auroral substorm. 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 mag-

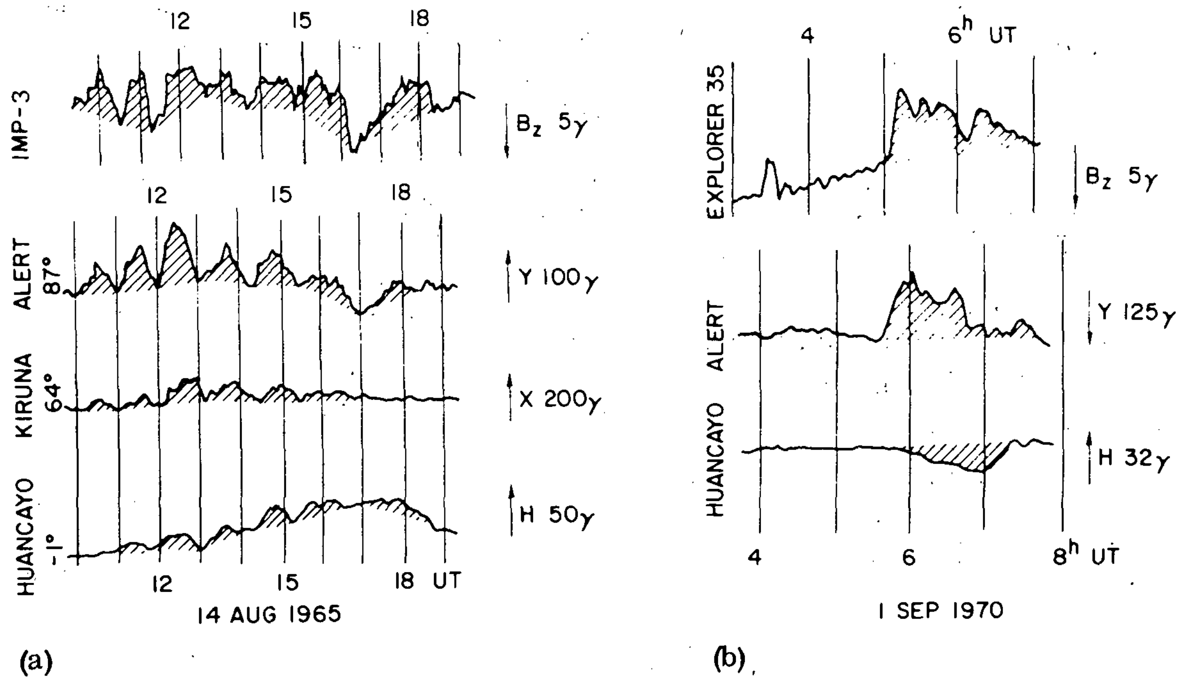


FIGURE 13. (*a*) Coherent fluctuations in the north-south component of the interplanetary magnetic field (as viewed from IMP 3) and in the horizontal component of the geomagnetic field at Alert near the pole (87° corrected geomagnetic latitude), at Kiruna in the auroral zone (64°) and at Huancayo near the equator (−1°). The fluctuations on the ground seem to be delayed approximately 45 min. (This day (August 14, 1965) is also shown in the bottom panel of figure 21(*b*), 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 approximately 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 (*a*) because of the different time of day (about 9^h).

netic pressure in the tail, increases the reconnection rate drastically with resulting increased plasma flow both toward 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 "taillike" state. The plasma moving rapidly toward 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 dawn side tail to the dawn side auroral oval along the geomagnetic field lines, flows then in the ionosphere to the dusk side oval and finally up to the dusk side 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-alined currents to a current circuit located at great distance beyond 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-alined 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 con-

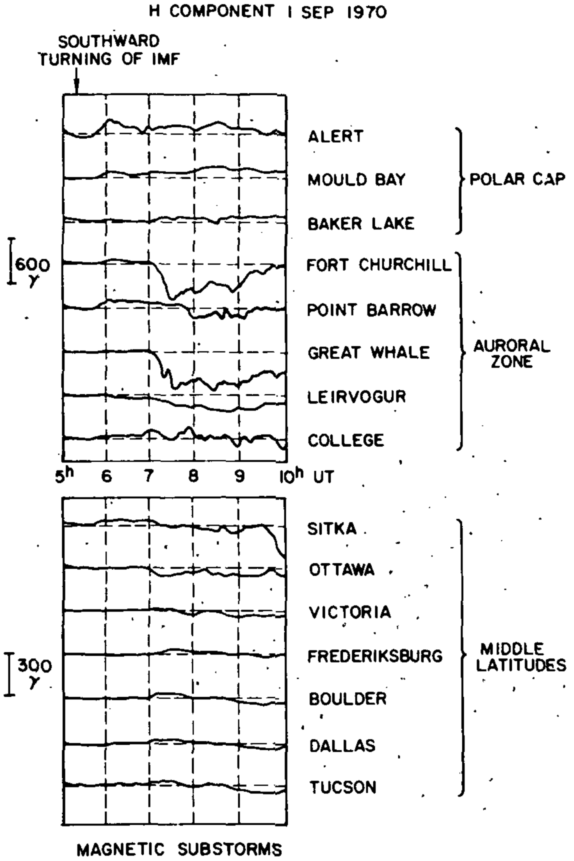


FIGURE 14.—Horizontal component magnetograms from several observatories for the interval following the southward turning of the interplanetary magnetic field shown in figure 13(*b*). In the polar cap the horizontal component in the direction of the corrected geomagnetic pole is increased after the event. 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.

verting magnetic energy in the tail to heating and ionization of the upper atmosphere. Often the tail collapse progresses in a stepwise fashion as if several localized disruptions take place successively; the whole process can exhibit extraordinary complexity and diversity with a series of rapidly moving and very bright looplike auroral displays. The rapid earthward movement of the plasma leads to jetlike 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 Earth because of gradient and curvature of the magnetic field. The drift direction depends on the charge of the particles, and electrons tend to move toward the morning side, while protons are drifting toward the evening side as sketched in figure 16(*a*). The drifting particles constitute a net westward ring current. The magnetic field produced by this current is opposite to the dipole field (see fig. 16(*b*)) 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 toward 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 magnetically complex active region. Intense X-ray, UV, radio, H_a, 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 Earth, the geomagnetic field

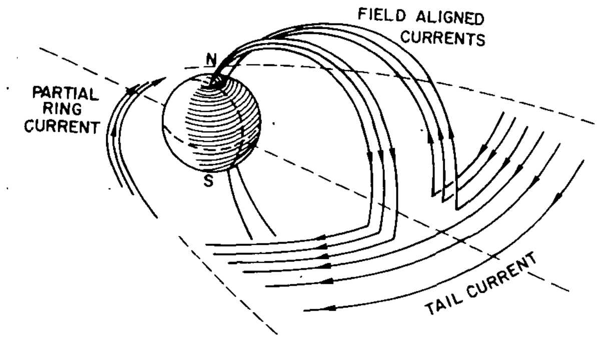


FIGURE 15.—Currents within the magnetosphere during a magnetospheric substorm. The magnetotail current is disrupted and the magnetospheric currents establish a new circuit down the field lines to the ionosphere and back again to the tail. The intensity of the ring current becomes enhanced. There are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

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 almost simultaneously over the globe. Figure 17(*a*) 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 hr. 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 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 17(*b*).

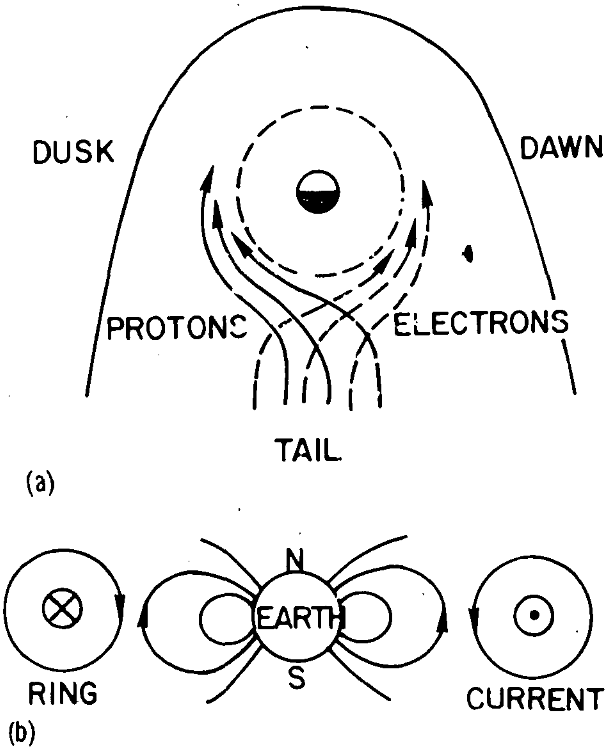
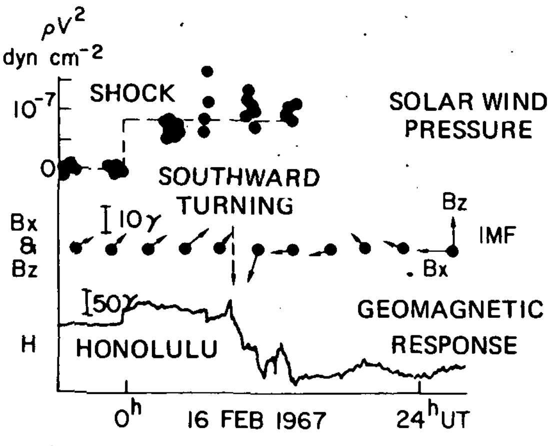
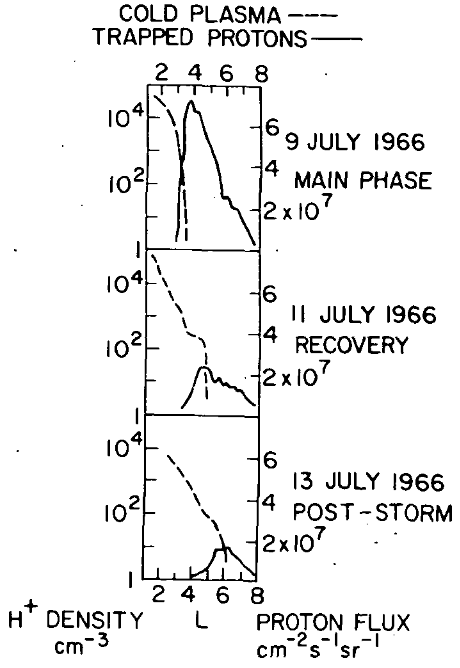


FIGURE 16. (*a*) Injection of plasma from the tail into the trapping region. The protons tend to drift westward, while the electrons tend to move eastward. The net result is a westward ring current as shown in panel. (*b*) The ring current and its magnetic effect, which is opposite the dipole near Earth.

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 seems to determine the overall structure of



(a)



(b)

FIGURE 17.—Results of a geomagnetic storm. (*a*) A geomagnetic storm on February 16, 1967, following an interplanetary shock. The solar wind pressure increased eightfold, 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 (dashed line) 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 poststorm 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 $L = 6$.

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 sudden commencement, 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 sudden storm commencement, 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

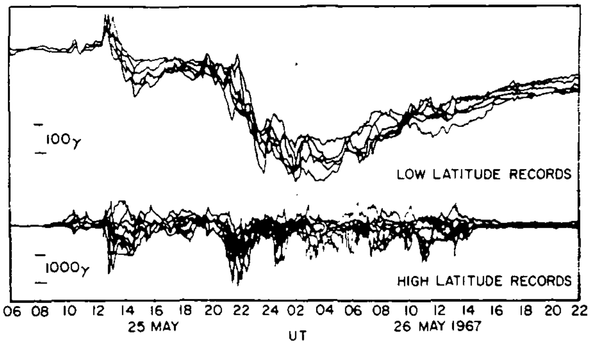


FIGURE 18.—Horizontal component magnetograms for a magnetic storm on May 25 and 26, 1967. The traces are superposed for a number of low-latitude stations and for a number of auroral zone stations separately. The quiet level before the storm has been used as a common zero level. The difference between 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.

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 semiannual variations. Even if the interplanetary field had a constant B_z perpendicular to the solar equatorial plane, there would still be a varying component that was antiparallel to the geomagnetic dipole so that diurnal and semiannual modulations of the field line merging efficiently would be expected. On the other hand, the radially outflowing solar wind forming the magnetosphere alined with the Sun-Earth line would tend to diminish these modulations. It is at present not clear what the relative importance of all these effects is, but semiannual and diurnal modulation of geomagnetic activity are, in fact, observed.

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.

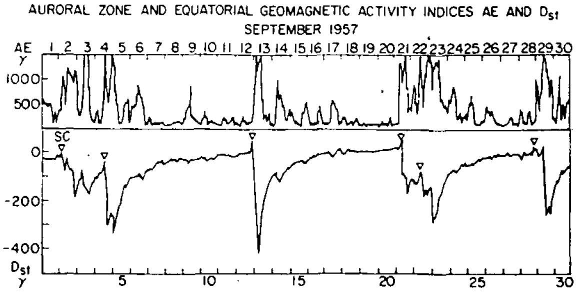


FIGURE 19.—Variations of the AE and D_{st} index during the very disturbed month of September 1957. Sudden storm commencements (SC) are marked by open triangles.

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 that may sweep by Earth in a few minutes. The sector structure implies that the solar wind within each magnetic sector emanated from a coronal region of similarity 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 1 or 2 days after the boundary, and then declining toward 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 increase the energy input to the magnetosphere, hence we would expect geomagnetic activity to be organized in a similar manner within a sector. Figure

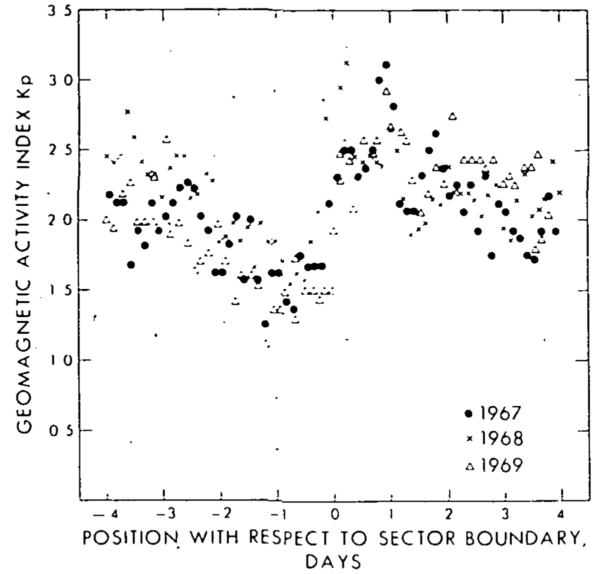


FIGURE 20.—Average response of the geomagnetic activity index K_p to passage of an interplanetary sector boundary. The response is shown separately for three different years as the response averaged for all sector boundaries occurring in each year.

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 1 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 21(*a*) shows the average variation 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 are 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. Because 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 toward Earth, we can summarize the effect by noting that central polar cap Z perturbations are predominantly directed away from Earth during sectors with polarity away from the Sun, and toward Earth during sectors with magnetic polarity directed toward the Sun. From Figure 21(*b*) 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 min or less during the interval 10^{h} to 22^{h} UT.

A note about coordinate systems: The x-axis points toward 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 right-handed 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 min 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 counterclockwise for positive B_y. Passage of a sector boundary thus causes an abrupt reversal of the current.

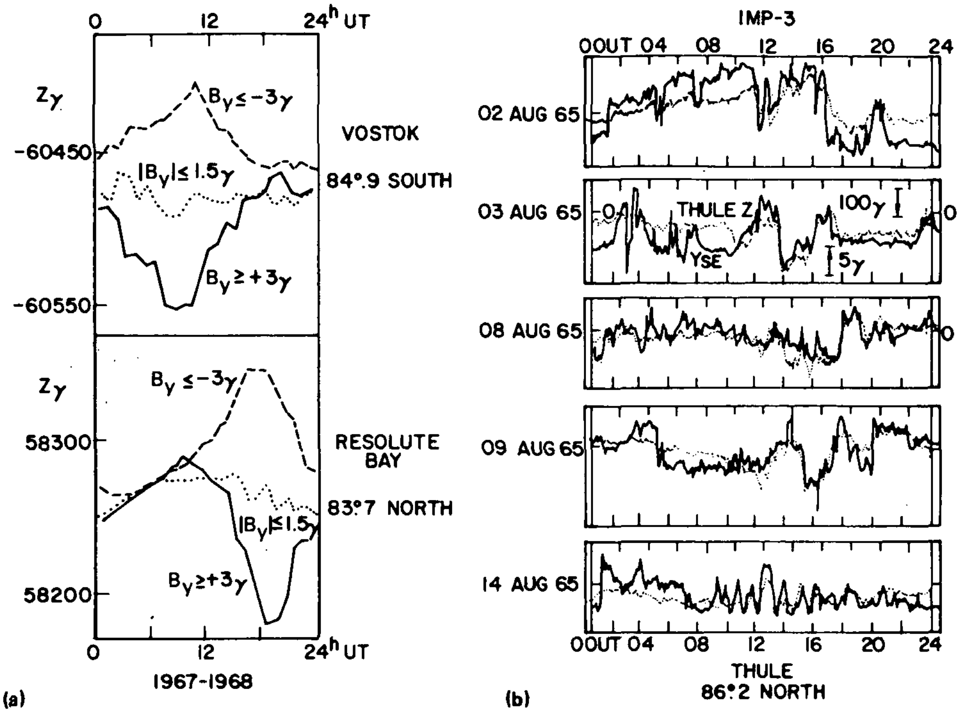


Figure 21. (*a*) Diurnal variation of the vertical component Z at Vostok and Resolute Bay during 1967 and 1968. All hours where the hourly average of the interplanetary east-west component (solar magnetospheric coordinates) B_y was less than -3γ were averaged for each UT hourly interval to yield the dashed curves. When B_y is greater than $+3\gamma$, the solid curves result, while the dotted curves were computed for times where B_y was near zero ($|B_y| \leqslant 1.5\gamma$). (*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.

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 realined and the concept of the magnetospheric substorm constitutes a basic framework for our understanding of the major disturbances within the magnetosphere.

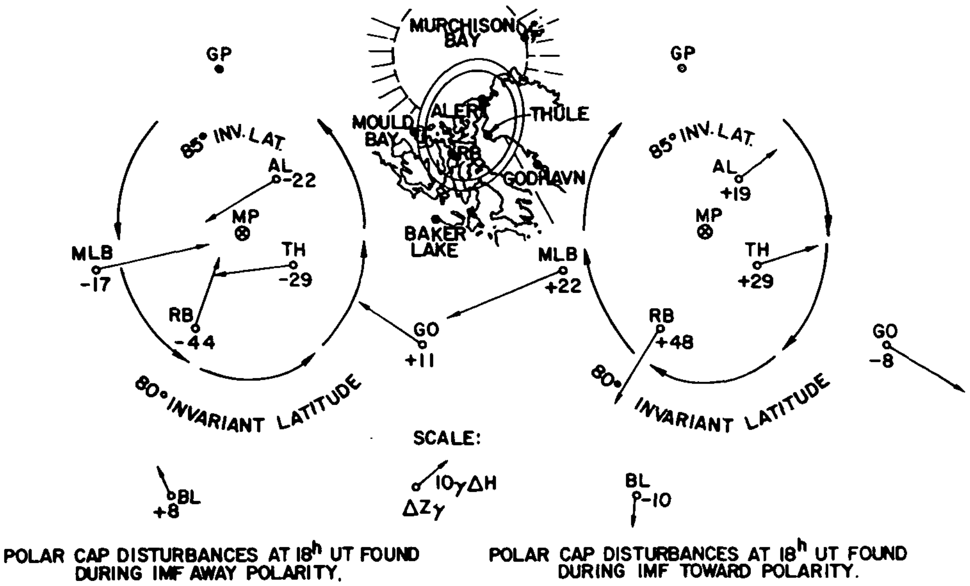


FIGURE 22.—Typical polar cap magnetic disturbances observed for the two opposite polarities of the east-west component B_y of the interplanetary magnetic field. Two synoptic maps are shown with disturbance vectors corresponding to positive B_y (normally within the "away" sector) at the left and to negative 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 that could produce the magnetic variations are sketched. The perturbations (and the current) reverse when B_y reverses sign.

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 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, $\varepsilon \sim \mathbf{w} \times \mathbf{b}_n$, supplied by the solar wind to the magnetospheric dynamo is of the order

$$\varepsilon = wb_n$$

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

$$A_T \doteq \pi R_T S_T$$

where R_T is the radius of the tail. Hence,

$$\begin{aligned} b_n &= \frac{M_P}{A_T} \\ &= \frac{r_P^2 B_P}{R_T S_T} \end{aligned}$$

With $r_P = 15° = 1.7 \times 10^6$ m, $B_P = 55\,000\gamma = 00.55 \times 10^{-4}$ Wb/m², $R_T = 20R_E = 1.3 \times 10^8$ m, and $S_T = 500R_E = 3.2 \times 10^9$ m, we get $b_n = 3.7 \times 10^{-10}$ Wb/m² $= 0.37\gamma$. 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

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

The total potential difference across the tail then becomes

$$\begin{aligned} \Phi &= \varepsilon \pi R_T \\ &= 6.4 \times 10^4 \quad \text{V} \\ &= 64 \text{ kV} \end{aligned}$$

and the electric field in the polar cap is

$$\begin{aligned} E_i &= \frac{\Phi}{2 r_P} \\ &= 20 \times 10^{-3} \quad \text{V/m} \\ &= 20 \quad \text{mV/m} \end{aligned}$$

We can also write

$$\begin{aligned} \Phi &= w b_n \pi R_T \\ &= \frac{w M_P \pi R_T}{A_T} \\ &= \frac{w M_P}{S_T} \end{aligned}$$

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

$$\begin{aligned} B_T &= \frac{M_P}{\frac{1}{2}\pi R_T^2} \\ &= 2B_P \frac{r_P^2}{R_T^2} \\ &= 19 \times 10^{-9} \quad \text{Wb/m}^2 \\ &= 19 \quad \gamma \end{aligned}$$

The typical quiet time convection velocity over the polar cap can be obtained from

$$\mathbf{v}_c = \mathbf{E} \times \frac{\mathbf{B}}{B^2}$$

as

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

The time to convect the footpoints of the tail field lines across the polar cap is now

$$\begin{aligned} t_c &= \frac{2r_P}{v_c} \\ &= 9250 \text{ s} \\ &= 2.6 \text{ hr} \end{aligned}$$

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:

$$\begin{aligned} S_T &= wt_c \\ &= \frac{w^2 r_P B_P}{E_i} \\ &= 3.8 \times 10^9 \quad \text{m} \\ &= 600R_E \end{aligned}$$

For a line current (auroral electrojet) at height h over the ground to give a magnetic substorm effect of $B_A = 1000\gamma = 10^6$ Wb/m², the current strength must be of the order

$$i_A = \frac{2\pi h B_A}{\mu_0}$$

Taking $h = 110$ km $= 1.1 \times 10^5$ m, we get $i_A = 550\,000$ A. If n_T is the current density of the tail current estimated by treating each half of the tail as a solenoid: $n_T = B_T/\mu_0$, we find that the extent of the tail current disruption is of the order of

$$\begin{aligned} k_d &= \frac{i_A}{n_T} \\ &= 3.7 \times 10^7 \quad \text{m} \sim 6R_E \end{aligned}$$

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

$$\begin{aligned} U_d &= \frac{B_T^2}{2\mu_0}(\text{volume}) \\ &= \frac{B_T^2}{2\mu_0}\frac{\pi R_T^2}{2}k_d \\ &= \frac{B_T \pi R_T^2 i_A}{4} \end{aligned}$$

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

$$L = \mu_0 \frac{B_T}{B_A} \frac{R_T}{4h} = 890\ \mathrm{H}$$

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

$$\begin{aligned} t &= \frac{L}{R} \\ &= 7.4 \times 10^3 \quad \mathrm{s} \\ &\simeq 2\ \mathrm{hr} \end{aligned}$$

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

$$\begin{aligned} P &= i_A \Phi \\ &= 3.5 \times 10^{10}\ \mathrm{W} \end{aligned}$$

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} W. If the substorm lasts for 1 hr, the total amount of energy dissipated in the currents is then about 3×10^{14} J. 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} J 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 fig. 3(*b*)). Hence the average current density:

$$\begin{aligned} n_T &= \tfrac{1}{2} n_T \\ &= \frac{B_T}{2\,\mu_0}, \end{aligned}$$

so that

$$\begin{aligned} J_T &= J_{\mathrm{northern}} + J_{\mathrm{southern}} \\ &= 2 S_T n_T \\ &= \frac{S_T B_T}{\mu_0} \\ &= 5 \times 10^7\ \mathrm{A}. \end{aligned}$$

The total amount of energy drawn from the solar wind by the current J_T over a potential difference Φ is then

$$\begin{aligned} P_S &= J_T \Phi \\ &= 3 \times 10^{12}\ \mathrm{W} \end{aligned}$$

The energy deposited in a substorm corresponds to about 2 min 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 $= 5 \times 10^6$ m^{-3} is the number density. We find $K = 1.6 \times 10^{13}$ W, 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.

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DISCUSSION

SCHMERLING: I am having some difficulty bridging the sharp discontinuity between one speaker and another, and I wonder if somebody can help me by providing a 1 AU 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 Earth out of the ecliptic plane, is north-south or south-north. More specifically, I can look at that picture 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.

SVALGAARD: Part of the answer is that the important thing is the fluctuation of the field. A field line is not really like a straight line; it is wiggling all around. And so, as seen from 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, because of 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.

MANKA: It seems to me that you discussed a lot of mechanisms that 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 that will be related to the magnetic field strength and the flow velocity. When it gets to Earth, if the interplanetary electric field creates polarization and crosstail 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?

SVALGAARD: That is a difficult question to answer straightaway, 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 that has the effect on Earth. There is very little solar plasma that 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 Earth, but then it is the tail that 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.

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.

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 yr or so there will be a conference on lunar influences on the weather!

N76 14542

Solar Models in Relation to Terrestrial Climatic Variations

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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 that may or may not be accompanied by relatively small changes in the state of Earth's atmosphere. The present paper deals with the possibility of occasional larger changes in the state of the Sun, lasting for some millions of years, that might be responsible for producing more drastic changes in 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 that 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 is separated and any radioactive argon atoms are 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's 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 (SNU). When the experiment was first designed, model calculations had predicted that Davis should obtain a signal equivalent to about 30 or 40 SNU. 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 1 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 7 SNU. It is this discrepancy that has led to an intense search for aspects of nuclear astrophysics, stellar physics, or neutrino physics that 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 toward the normal condition.

There have been a number of discussions in the last 2 yr 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" that 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: $^1H(p, \beta^+ \nu)^2D$. 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 at the center of the Sun. This reaction is immediately followed by another: $^2D(p, \gamma)^3He$. The deuterium formed in the first reaction is almost instantaneously removed and converted to ^3He by this reaction. The ^3He builds up until there is enough of it present for it to react with itself: $^3He\ (^3He, 2p)^4He$. This reaction has a much higher temperature sensitivity, something like the 20th 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 that has been postulated.

It is necessary to emphasize that we do not know of a suitable mixing mechanism that 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 the 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 2 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 4 million years. The total time involved in the core expansion was thus 6 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 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 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 example. A more realistic calculation would probably bring the minimum down only comparable with Davis's 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 one exception that will be discussed.

Therefore, it is important that the geologic record does not seem to give clearcut 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 3 or 4 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 the order of 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 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 6 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 Davis's 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, because the temperature and luminosity of the Sun change in such a way as to drive the Sun straight 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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DISCUSSION

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?

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 or 50 percent, of that order, a gradual increase. If you believe in time variation of *G,* 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. If not, then the solar luminosity has increased by an order of 40 or 50 percent since the time the Sun was formed.

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 is not a lot of chlorine or some other neutrino absorber somewhere in the Sun, since not very much is known about its constitution?

CAMERON: There is nothing special about chlorine except that it 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 100,000 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 than 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 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, however, I would like to lay to rest: that is that when the sun changes in this way, the distribution of stars (which are also doing this) on the main sequence that one can measure for a cluster or something like that is broadened.

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?

CAMERON: The time scale for a luminosity decrease occurred in just a little less than 1 million years, and most of the recovery occurred in about a 2-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 if you just perturbed it in some way? What would be the lower limit for changing solar luminosity due to maybe other forces? How fast can a big thing like that change?

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 5 or 6 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 is not going to help you.

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, would not 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?

CAMERON: That is correct. If you turned off all the nuclear reactions in the Sun, the Sun would keep shining, 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.

ARKING: So why do you need a 30-percent change in luminosity?

CAMERON: 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. 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 that decreases the luminosity.

QUESTION: Would a strong magnetic field of the order of millions of gauss, in the interior of the Sun have any effect?

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.

DAVIS: I am curious as to where you got your 20 million year figure for the Antarctic Icecap because, as

I recall, the ice at the bottom of the core at Byrd Station has a radiocarbon date of about 40 000 to 50 000 yr, which would probably fit your theory better.

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 have not seen it in the literature, all I have seen it in is a popular report; therefore, 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 do not know how good those numbers are. If one can say that the duration is longer than about 6 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 will not cure the neutrino problem. Maybe there is some other explanation for the neutrino problem, and the Sun still behaves this way, but we still do not know of a driving mechanism that would make it behave this way, another very fundamental weakness of this theory.

Possible Relationships Between Solar Activity and Atmospheric Constituents

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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.

In 1902 a series of observations was begun at the Smithsonian Institution's Astrophysical Observatory, generally called the APO. The purpose for these observations 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 Earth's atmosphere at over 40 places in the solar spectrum covering a wavelength range from about 0.35 to 2.5 μm. 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 the northern and southern hemispheres.

The techniques used and results obtained are extensively documented in the *Annals of the Astrophysical Observatory* (Abbot, 1908, 1913; Abbot, Aldrich, and Fowle, 1932; Abbot, Fowle, and Aldrich, 1922; 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 performed 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 will be of value in answering many of the questions raised at this symposium.

It is not our intention here to rediscuss 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. Elsewhere in these proceedings Dr. Roberts discusses predictions of such a drought made in the last few years. Dr. Abbot's prediction was first published in the year 1938.

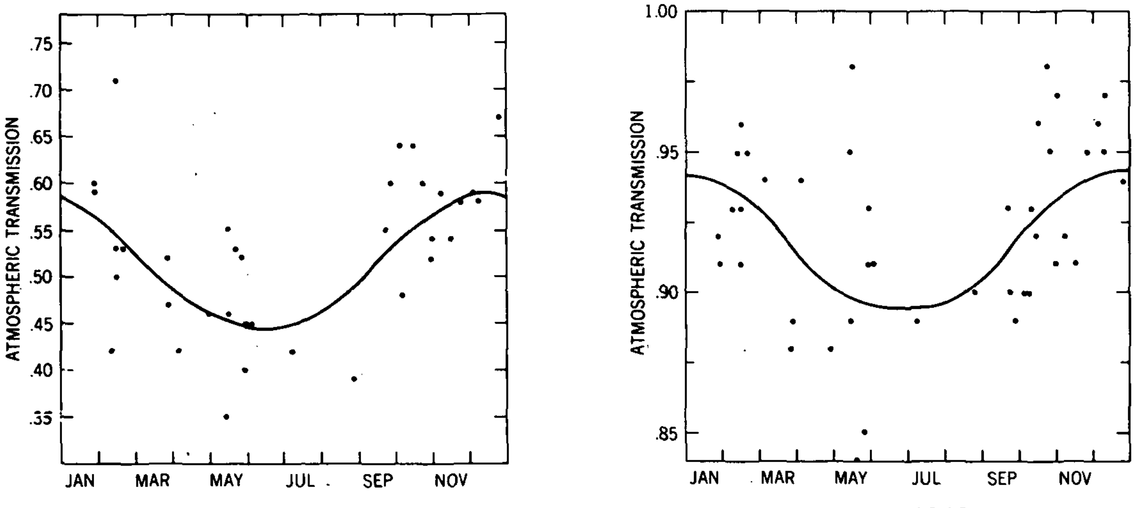
SHORT-TERM VARIATIONS IN ATMOSPHERIC CONSTITUENTS

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 because these results are from solar observations, all of the work reported 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 μm as measured at the APO in Washington, D.C., during the period from 1902 to 1907. Because 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), wind-blown dust, sea spray, volcanoes, and forest fires (Hidy and Brock, 1971). To these we can add manmade effects such as smoke from slash-and-



1902-1907
.40μm

1902-1907
1.60μm

FIGURE 1.—Observations of atmospheric transmission at Washington, D.C.

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 the 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.

CORRELATION WITH SOLAR ACTIVITY

In large part the previous remarks were meant to give an idea of the caution that we feel in approaching our subject. We spent more than 3 yr writing our paper that merely describes some of the variations in atmospheric constituents (Roosen, Angione, and Klemcke, 1973). In contrast we have spent only 6 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

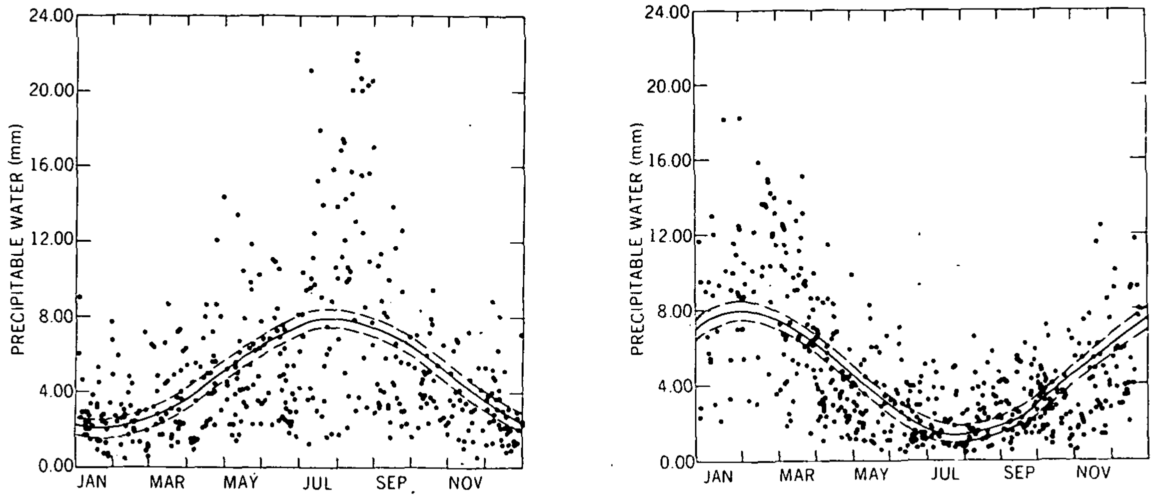


TABLE MOUNTAIN, CALIFORNIA
1925-1930
PRECIPITABLE WATER

MOUNT MONTEZUMA, CHILE
1920-1930
PRECIPITABLE WATER

FIGURE 2.—Observations of atmospheric precipitable water vapor at the two main APO sites.

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 0.02, which we will call zero for short. The correlation at Mount Montezuma is apparent to the eye; the computer says that it is −0.20.

Figure 4 is a plot of sunspot numbers versus observations at Mount Montezuma, Chile, of solar brightness at an altitude of 30° corrected to mean solar distance. The correlation coefficient between these two quantities is 0.56. The observed brightness certainly seems to increase with increasing solar activity. Because the observed solar brightness depends directly on the amount and size of aerosols in 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 triangle in the lower left-hand corner of the graph. This point represents the year 1932, during which at least five separate volcanoes erupted in the Chilean Andes. We believe this to be the only year in this study that is significantly affected by volcanic dust.

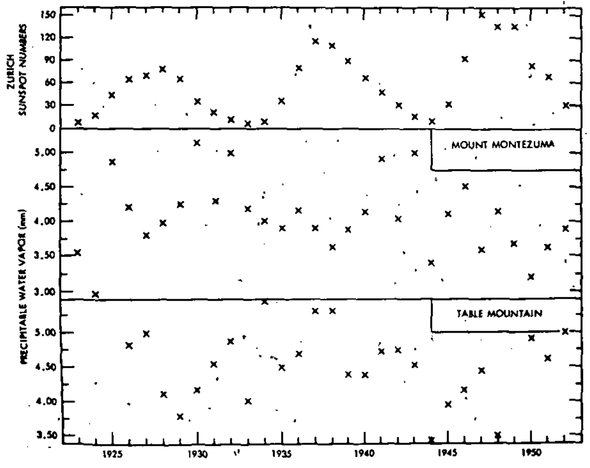


FIGURE 3.—Annual means of precipitable water vapor and sunspot numbers.

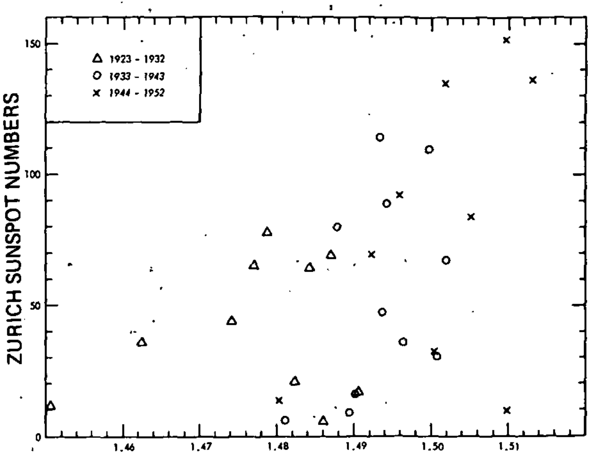


FIGURE 4.—The relation between annual means of direct solar brightness at 30° altitude corrected to mean solar distance and sunspot numbers at Mount Montezuma.

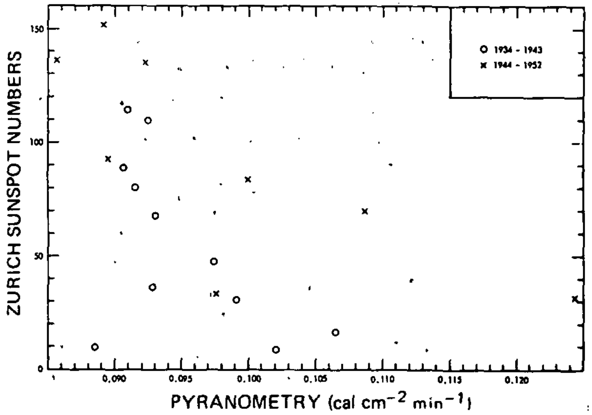


FIGURE 5.—The relation between annual means of scattered light near the Sun at 30° altitude and sunspot numbers at Mount Montezuma.

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 −0.51. This figure tells us that scattered light near the Sun decreases with increasing solar activity. The 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

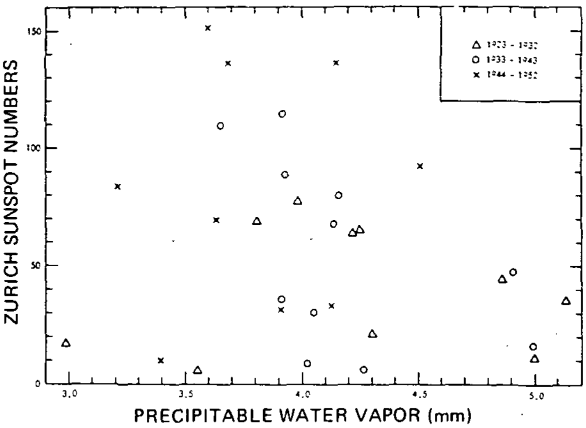


FIGURE 6.—The relation between atmospheric precipitable water vapor and sunspot numbers at Mount Montezuma.

vapor versus sunspot numbers for Mount Montezuma. Remember that the correlation coefficient is −0.20 and that increasing solar activity is associated with decreasing amounts of precipitable water.

Figure 7 shows plots of precipitable water vapor versus the astronomical extinction coefficient, which is an indicator of the amount of light removed from the direct solar beam by atmospheric constituents (Roosen, Angione, and Klemcke, 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 Mountain, 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 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.

CONCLUSION

We have found evidence that (as seen from a high-altitude desert site) increased solar activity is associated with a decrease in attenuation because of 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: 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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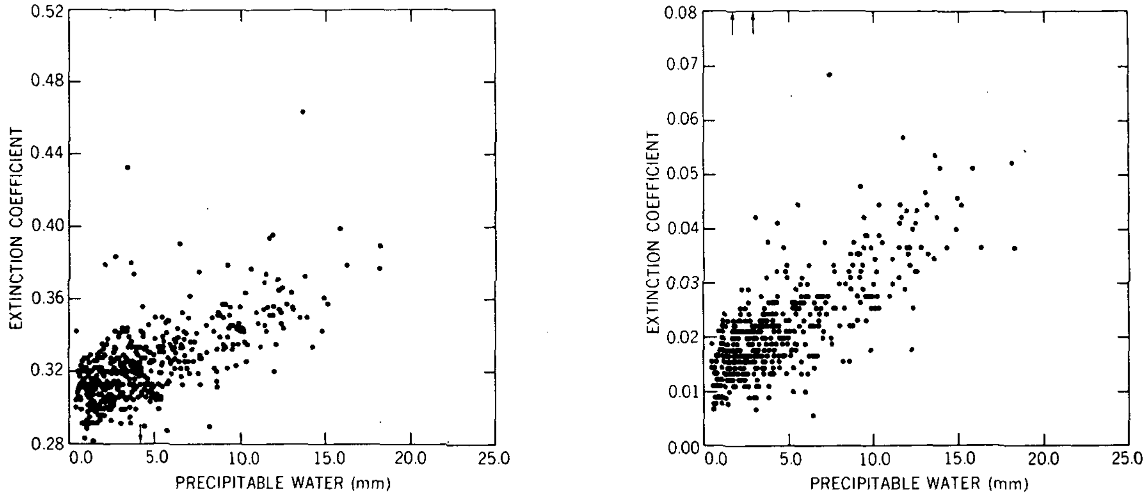

1920-1930
.395 μm

1920-1930
1.214 μm

FIGURE 7.—The relation between atmospheric extinction and atmospheric precipitable water vapor at Mount Montezuma. The extinction coefficient

$$k(\lambda) = -2.5 \log T(\lambda)$$

where $T(\lambda)$ is the atmospheric transmission.

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DISCUSSION

LONDON: It is good to hear of the care that was taken in reviewing the Abbot measurements. I wonder if you have an estimate of the probable error of those measurements, and whether you have an estimate of any change in probable error with time as a result of the improvement of the instruments.

ROOSEN: That is one of the reasons that we took 3 yr 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 1 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 eliminate. In terms of the probable error of the individual solar constant observations, I do not 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. I wish that I could do one-tenth as well as he did.

LONDON: Our experience suggests that as the accuracy of the instrument increased, observed variation of the solar constant decreased.

ROOSEN: I would be very pleased to discuss that with you later.

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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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The National Oceanic and Atmospheric Administration has been performing routine monitoring of 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 Earth's charged particle environment. We describe briefly the charged particle observations proposed for the new low-altitude weather satellite 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 developments. Estimates are given to assess the potential importance of this type of energy deposition. Discussion and examples are presented illustrating the importance of distinguishing between solar and geomagnetic activity as possible causative sources. Such differentiation is necessary because of 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 that 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 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 distri-

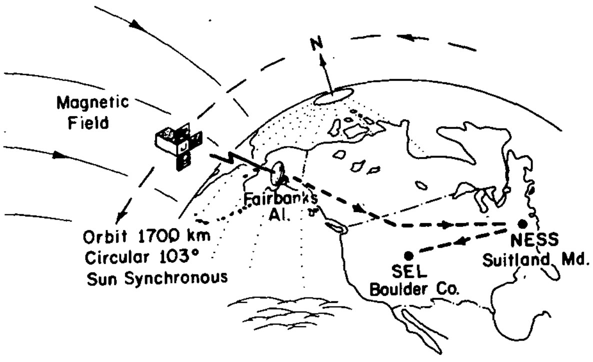

FIGURE 1.—TIROS N spacecraft orbit. It will be launched in mid 1977. Followup operational spacecraft will be launched at 1- to 2-yr intervals. (NESS = National Environmental Satellite Service; SEL = Space Environment Laboratory.)

bution 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 upward nearly along the field line, thereby measuring particles whose local pitch angles are very small. It is these latter particles that 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 to greater than 10^9 eV. A variety of detectors (thin scintillators, solid-state detectors, and Cerenkov detectors) will be used to cover this energy range and will be sized to measure energy inputs greater than or equal to 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, Colo.

Because 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 Data Acquisition and Processing Program (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. The aurora also can be seen over the polar cap alined in the noon-midnight direction.

The area of the photograph is approximately 1.4×10^7 km^2, with approximately 20 percent of the area covered with auroral glow. A modest energy influx during an aurora is approximately 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

$$\Sigma\sigma \sim 20 \text{ mhos/m}$$

and a nominal potential difference of about 0.015 V/m, a power dissipation of approximately 4.5×10^{-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 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 con-

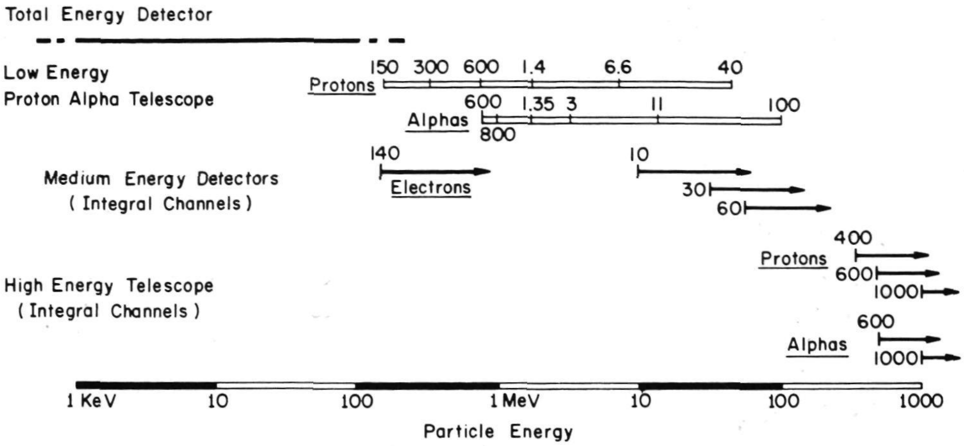

FIGURE 2.—Energy coverage of proposed TIROS N space environment monitor.

trast with auroral particle precipitation, which is confined to a relatively narrow latitude band (⩽10°) and may last for hours, particles released from a solar flare impinge on 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 exents, a peak energy dissipation rate into the polar cap of approximately 2 ergs/cm^2 · s occrured for a ½-hr period. For the remaining several days of this solar activity, the energy dissipation rate due to flare-associated particles was less than approximately 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 ½-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.

We see evidence for significant energy deposi-

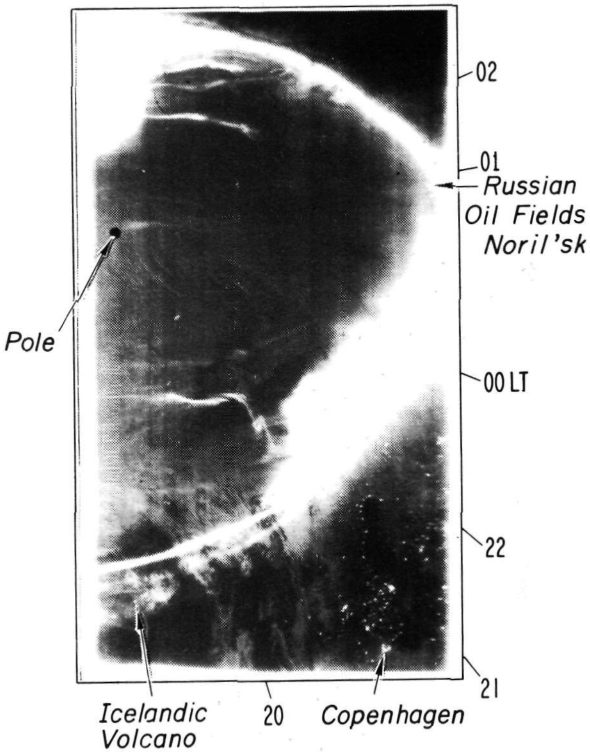

FIGURE 3.—Aurora obtained from the Data Acquisition and Processing Program (DAPP) satellite on January 11, 1973. The estimated area of the aurora in the satellite picture is approximately 2.8×10^6 km^2. For a commonly occurring "moderate" aurora, which will last for several hours, the particle energy deposition is approximately 4.0 ergs/cm^2 . s, or a total power input of approximately 1.1×10^{10} W. The ohmic losses due to the Pedersen currents flowing at 110 to 120 km may be approximately 1×10^{10} W. If these processes heat the neutral atmosphere at 115 km, the resultant heating rate would be greater than 1000 K/day.

tion in 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 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 yr (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, and radio energy) produces a global variation throughout Earth's sunlit hemisphere. Consequently, slight

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[a]	Potential atmospheric effects
Solar: Overall change in electromagnetic emission from the Sun (includes possible changes in solar constant)	Millennia(?)	Global, direct	Long-term worldwide climatic changes. Glacial advances and recessions.
Overall change in emitted solar wind	Millennia(?)	Global, indirect	Long-term worldwide climatic changes. Glacial advances and recessions.
Number of sunspots[b]	Solar cycle 11 to 22 yr	Global, direct, indirect	Shorter term climatic changes, for example, the 20- to 22-yr cycle of U.S. High Plains droughts. Motion of atmospheric jet stream.
Solar flare particle emission	Days	Polar regions, direct	Atmospheric storm system development. Isolated, unique atmospheric phenomena.
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 $(\leqslant 10^\circ)$ at high latitudes. Night side. Direct.	Atmospheric storm system development. Isolated, unique atmospheric phenomena.
Magnetic storms	Days	Wide latitude band at midlatitudes. Global. Direct.	Atmospheric storm system development. Isolated, unique atmospheric phenomena.

[a] Direct = energy from given phenomena applied directly to the atmosphere. Indirect = energy from given phenomena applied indirectly to the atmosphere; for example, solar wind energy applied through magnetospheric coupling to the atmosphere.

[b] As indication of overall solar activity.

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 types of solar and geomagnetic activity.

Finally, in attempting to understand many of the correlations being presented, it is necessary to examine all possible mechanisms that may conceivably provide a connection between the lower atmosphere (⩽10 km) and solar and geomagnetic activity. For example, it has been long known that atmospheric turbulence is capable of producing upward-traveling acoustic gravity waves that 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 upward/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 this 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 Earth's weather and climate be established.

ACKNOWLEDGMENTS

We would like to acknowledge the U.S. Air Force, Air Weather Service, and the World Data Center A, National Oceanic and Atmospheric Administration, Boulder, Colo., for providing the DAPP satellite photo in figure 3.

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On Climatic Changes Related to the 22-Year Solar Cycle

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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 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 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.)

Nobody may have thought of the 22-yr 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 Earth, mainly because the charged-particle radiation of the Sun is involved in this cycle.

Some investigations have already been made to show that the 22-yr 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-yr periodicity. In view of this, 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 table 1, 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.)

It may be concluded from table 1 that each second cycle has more circulation types with Scandinavian lows in winter than its predecessor. The mean frequency of occurrence of circulation types with lows near Iceland (Grosswetterlagen Wz and SWz) is largest in the winters of the other four cycles, as is to be expected. However, the number of days with circulation types having high-pressure centers over the Icelandic area

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TABLE 1.—*Low-Pressure Center in Scandinavian Area*

Year	Percent of time
1888 to 1900	8.1
1901 to 1912	10.8
1913 to 1922	5.5
1923 to 1932	8.4
1933 to 1943	8.7
1944 to 1953	14.8
1954 to 1963	8.9
1964 to 1973	13.4

(Grosswetterlagen HNa, HNz, HNFa, HNFz, NEa, NEz, and TM: circulation types that usually cause very severe winter conditions over Western Europe) is also largest in the same winters having the most low-pressure centers over Iceland: the average number of days per winter season (December, January, and February) being 12 for these years and 8 for the other years. 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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Apparent Relationship Between Solar Sector Boundaries and 300-Millibar Vorticity: Possible Explanation in Terms of Upward Propagation of Planetary-Scale Waves

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It appears to be well established that large-scale variations of pressure fields in the troposphere are propagated up to ionospheric levels, to at least the *E*-region (Brown and Williams, 1971; Deland and Cavalieri, 1973). 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 the geomagnetic activity index 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 is 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 for removing such influences is suggested.

WELL-DEFINED BOUNDARIES AND THE BOW SHOCK

In their comparison of solar sectors and 300-millibar 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.

Autocorrelations for the magnetic field polarity obesrved 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

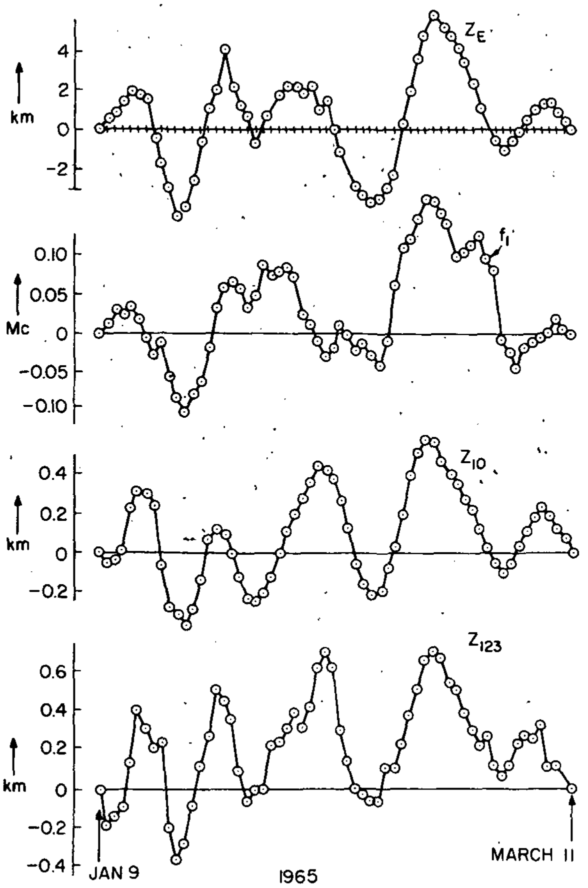

FIGURE 1.—Simultaneous variations of ionospheric and stratospheric variables over Aberystwyth from January 9 to March 11, 1965, taken from Deland and Cavalieri (1973): Z_E is the height of a constant electron density surface in the E-region (Brown and Williams, 1971); f_1 represents smoothed variations of f-min; Z_{10} is the height of the 10-millibar surface over Aberystwyth (Brown and Williams, 1971); and Z_{123} is the smoothed variation of 10-millibar height corresponding to the first three zonal wave numbers.

($2P - 1$), 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 Earth's bow shock and a satellite orbit such as that of IMP 3 is shown. Because the figure is schematic, it is not meant to be realistic. In the figure, *2* and *3* denote points just outside the bow shock that fall within 4 days after passing **X**. Let us assume that there is a (−, +) crossing at **X**; therefore, there is positive polarity at *1* and 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 polarity at *1*, because 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 because this will determine the time lags between point *1* and 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). It follows 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 to Earth, and fewer for a relatively disturbed "pushed out" magnetosphere. If the latter occurs in part

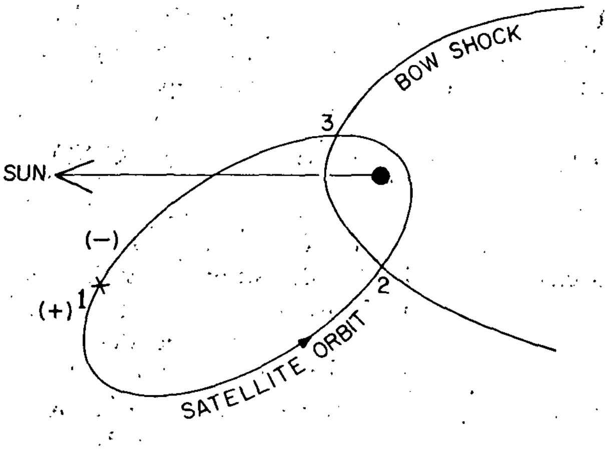

FIGURE 2.—Schematic diagram of a satellite orbit and the bow shock, showing the possibly well-defined boundary of a magnetic sector at **X**. Point *1* is just after the sector boundary, and points *2* and *3* are just before and just after, respectively, the satellite encounters the bow shock.

because of 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 should be undertaken with special care to avoid the problems discussed in this paper. One method would be 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 insure that the selection is not affected by the bow shock or magnetosphere.

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DISCUSSION

WILCOX: We thank Dr. Deland for his interest in our work, but I do not believe that the remarks are relevant to it. The sector pattern is well defined almost all the time, being either two or four sectors per solar rotation as seen on spacecraft going out to Venus, for example, where one will have continuous observations for several months. 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.

I just do not 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 10 yr 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 that would have had a considerably longer time to go down to zero. It seems to me, however, that the basic point is just that spacecraft observations away from Earth establish very clearly that one has either a two- or a four-sector pattern with a very sharp boundary.

If there is a suggestion of a selection effect, it would seem that the clearest way to remove that possibility is to have no selection at all. We worked with 54 boundaries that were well observed by spacecraft. The interplanetary field for 4 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. We, therefore, repeated the analysis, using all 74 boundaries, in which case I do not think there could be any selection effect. It seems to me that if you have 54 out of 74 you are not dealing with a problem of selection.

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. I still stick to my point, that if you really want to be sure of having no problem, you should essentially stay clear of Earth and any possible statistical contamination.

High-Latitude Ionospheric Winds Related to Solar-Interplanetary Conditions

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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. 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. 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 meterological 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 that 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 Earth's surface in the form of infrasonic waves.

Above 110 km at magnetic latitudes greater than 60°, it has become apparent that the integrated 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

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B}$$

where $\mathbf{v}$ is the plasma velocity and $\mathbf{B}$ is the magnetic field. For example, joule heating that arises from ionospheric current flow transverse to $\mathbf{v}$, tending to short out the field $\mathbf{E}$, 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 $\mathbf{E}$ (that is, the potential drop) commonly varies by a factor of 5 (Heppner, 1973). The coupling of ion and neutral motion 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. Papers such as those of Walbridge (1967), Cole (1971), and Fedder and Banks (1972) should be consulted. Their numbers for the energy dissipation, and the range 1 to 100 ergs/cm^2 · s given previously, 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 observations that demonstrate that the spatial distribution of **E** is related to the sector structure and neutral wind observations that demonstrate that mass motions of the high-latitude thermosphere are primarily a response to collisions with the convecting plasma (that is, ion drag).

Observations relating the spatial distribution of **E** to the sector structure are 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, 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 ($90° < \Phi < 180°$), respectively. 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 **E** pattern provide a physical explanation for the Svalgaard-Mansurov findings relating sector structure to polar magnetic variations.

The neutral wind observations are 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 at altitudes between 180 and 310 km from 27 rockets. Seven of these rockets also released trimethyl aluminum/triethyl aluminum neutral trails extending from 180 km down to 80 km. Observations of the simultaneous motions of ion and neutral clouds provide a powerful tool

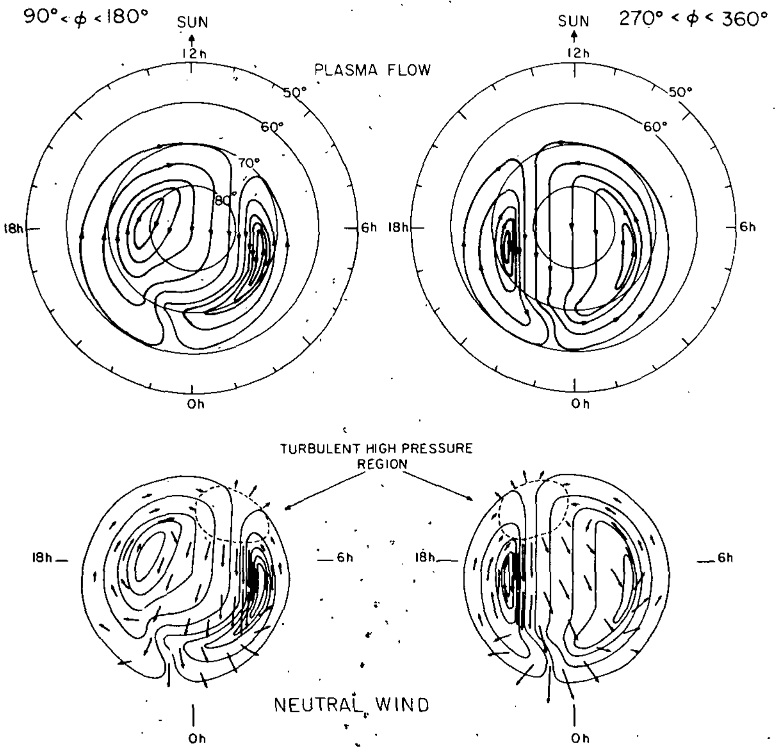

FIGURE 1.—(*Top*) Idealized polar patterns of the convective plasma flow for "away" and "toward" sectors of the interplanetary magnetic field. Streamlines, the direction of **v**, are lines of constant electric potential; thus the spacing between lines is inversely proportional to the magnitude of E 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.

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 above 180 km fit very well with motions expected from ion drag forces. Apparent discrepancies, in the form of neutral wind vectors not alined with the ion flow, appear consistently in the postmidnight 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 where 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 day side. (See fig. 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 fig. 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 neutral masses to respond to changes in ion drag increases (that is, the neutral mass motion is more sluggish). The ratio of ion to neutral mass 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 that 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° so that they point in the direction

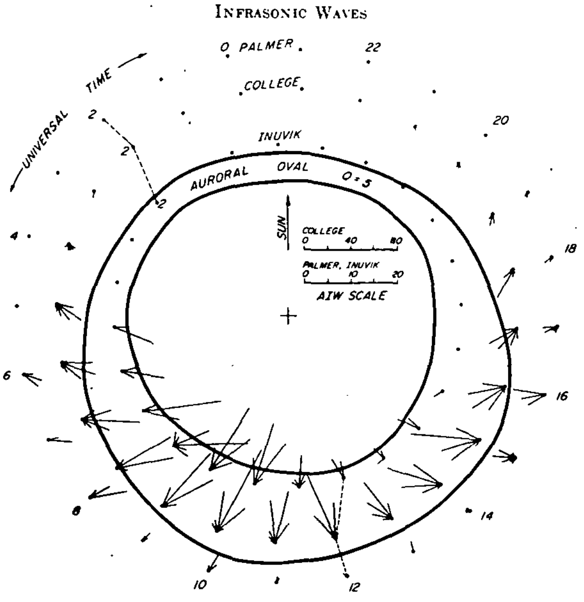

FIGURE 2.—Wilson's (1972) illustration of the frequency of occurrence of auroral infrasonic waves. Vectors point toward the directions from which the waves came. (Q is a geomagnetic index; AIW = auroral infrasonic wave.)

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) a high velocity, antisolar wind blowing into the midnight auroral belt from the polar cap and (2) a sudden increase in the auroral ionization such that the antisolar wind hits a new wall of dense plasma.

If an infrasonic shock is produced by the above conditions, it raises a more general question; that is, whether a similar momentum transfer is taking place all the time but is not identifiable 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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There have been numerous reports indicating that solar activity somehow modulates 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.

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:

(1) 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.

(2) 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 A 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 Earth under thunderstorms due to corona discharge and cloud-to-ground lightning. It is trans-

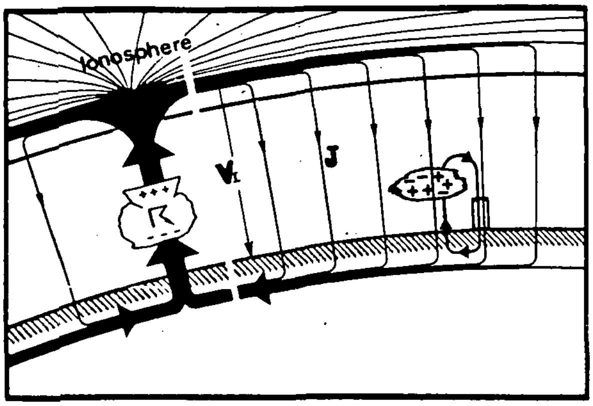

FIGURE 1.—The basic elements of the atmospheric electrical global circuit; thunderstorms, the ionopheric potential, and the fair weather conduction current. (After Mühleisen and Fischer, 1967.)

ported 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 Earth. In nonthunderstorm regions, over 99 percent of 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 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 to altitudes in the 10- to 20-km height range. 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 cloudbase at 2 km and top at 12 km will be used. The resistance between the top and the upper atmosphere is 2×10^7 Ω. This gives 10^4 Ω for 2000 storms (parallel) constituting the global generator. Under a thunderstorm the estimated resistance is 3×10^5 Ω, or 150 Ω for the global generator. This value was derived by increasing the normal fair weather conductivity 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 Earth is 160 Ω.

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 1.5×10^5 Ω, or 750 Ω 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, because 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 because 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; Sartor, 1965; Vonnegut, 1955; Wilson, 1929) 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

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). 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).

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. Although 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). Because 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.

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 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 Earth's surface.

An inverse relationship between ionospheric potential and long-term solar activity is suggested by figure 2. These data from Mühleisen (1969) depict 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). Because galactic cosmic radiation is inversely correlated with solar activity, and because 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.

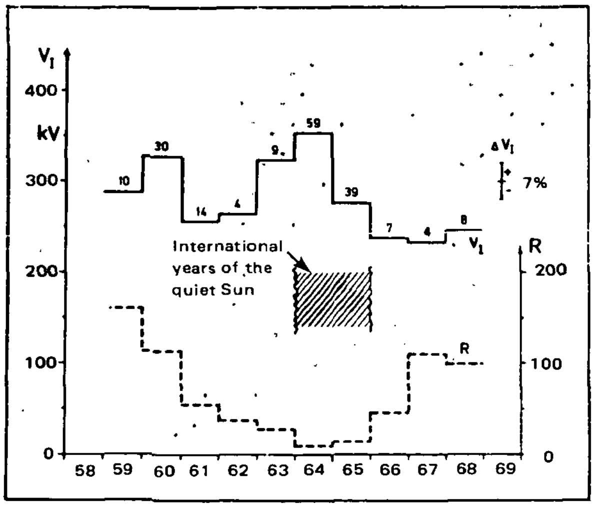

FIGURE 2.—The variation of ionospheric potential through a solar cycle; numbers on the line are total balloon soundings for the year. (After Mühleisen, 1969.)

Additional support for this conclusion is seen in Lethbridge's (1969) comparison of galactic cosmic radiation, as monitored by neutron counts at Chicago, with U.S. 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 3 and 4 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 PREVIOUSLY 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. Because 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 because 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 polar 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 billion-electron-volt energy range contacts air molecules. Some of the charge carried by the primary cosmic radiation 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 million-electron-volt 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 (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 that 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) that 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-km high mountain indicates that even under the most ideal circumstances, it is very difficult with electrical data taken at Earth's surface. Kasemir (1972) reports that with measurements made on a ship in mid-ocean (the cleanest air possible), at least 1 week's data were necessary for statistical averaging to detect the well-known diurnal variation that 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 min.

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 1 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 min.

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 polar cap absorption 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 because 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 Earth's position in a solar magnetic sector. Markson (1971) suggested because the sector structure of the solar magnetic field controls extraterrestrial particles, the analysis of extraterrestrial effects on weather should consider 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 Earth's solar sector position. Solar and galactic cosmic radiation reaching Earth is a function of 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 maximums versus solar minimum would be of considerable 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 that 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 cirruslike cloud shields that 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 Earth's weather.

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DISCUSSION

DESSLER: Would the fair weather electric field at the surface of 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?

MARKSON: The ionospheric potential?

DESSLER: Relative to Earth, is the minimum at sunspot maximum?

MARKSON: That is correct.

DESSLER: What is the fair weather electric field in volts per meter at Earth's surface?

MARKSON: This is also essentially proportional to ionospheric potential.

DESSLER: This would not necessarily be true. If you are lowering the effective height of the ionosphere, which I understand you are doing, then it could go the other way.

MARKSON: Assuming I maintain the same kind of conductivity distribution in both cases (solar maximum and minimum), the potential gradient near Earth would be less when the ionospheric potential is less.

DESSLER: I thought you were changing the conductivity distribution.

MARKSON: No. The point is that the big variations occur in the 10- to 20-km region. This increases the current. If you have a thunderstorm model in which enhanced current in the external circuit does not drain the thunderstorm generator and if you can maintain its potential, the lowering of resistance above the thunderstorm would increase current flow to the upper atmosphere and thus raise the ionospheric potential and potential gradient in the lower atmosphere. According to several thunderstorm theories, an increase in fair weather potential gradient would enhance thunderstorm activity.

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Solar Luminosity Variations and the Climate of Mars

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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 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 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 at present (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 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 atmosphere pressure is below the triple point of water. This makes it impossible to have permanent bodies of liquid water on presentday Mars and suggests a higher atmospheric pressure in past epochs.

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 longterm solar luminosity variations than Earth's. Figure 2 shows the results of solving a simple heat balance equation that contains these ideas


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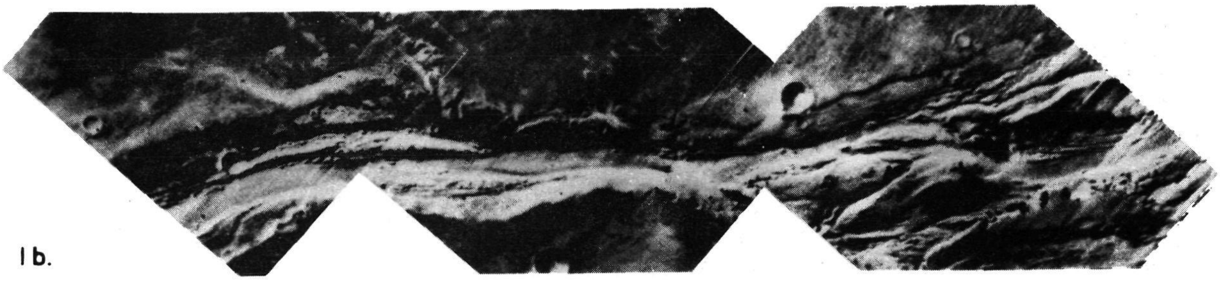
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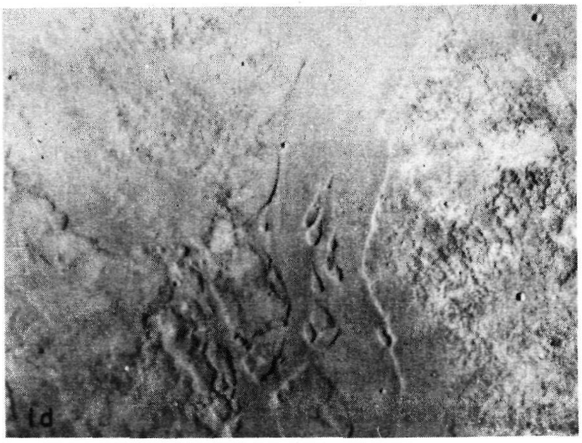
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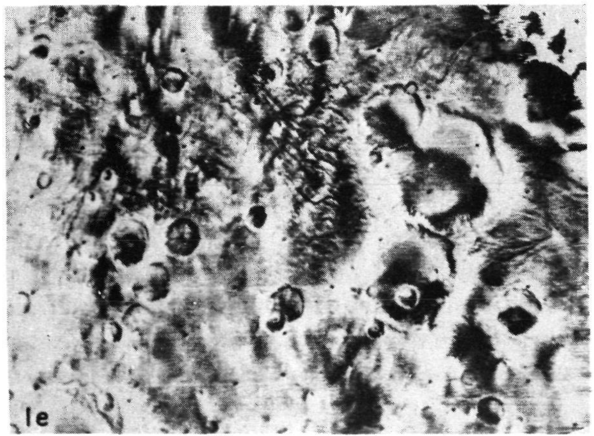
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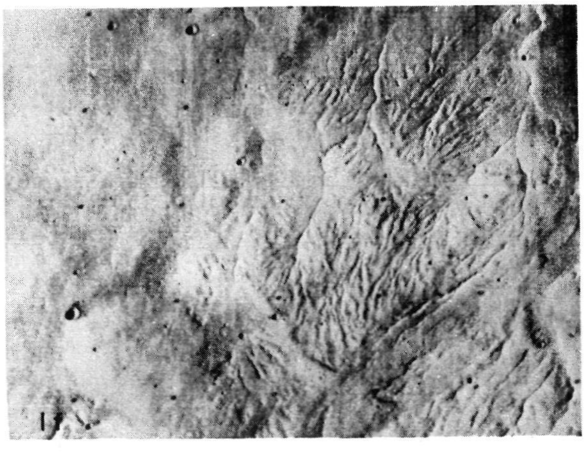
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FIGURE 1.—Mariner 9 photographs indicative of running water on Mars. The details of flow—for example, whether produced by rainfall or underground rivers—differ from case to case. (*a*) Mosaic of sinuous dendritic channel system in Mare Erythraeum 29° 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 (MTVS) 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 because of deflation of bright overlying dust by winds coursing down the channel. (*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).

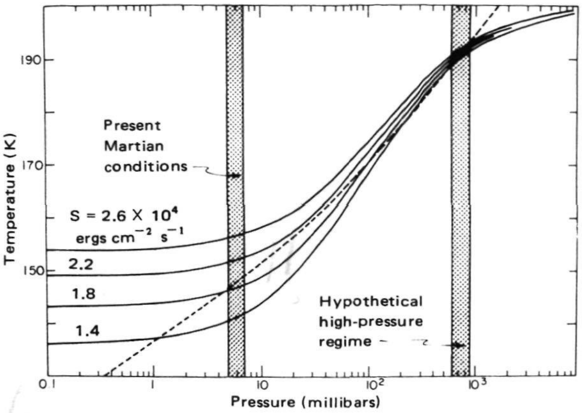

FIGURE 2.—A solution of a simple climatological model of Mars. The dashed line is the vapor pressure curve of CO_2. The solid line is a solution of a simple energy balance model that includes parameterizations of heat transport from atmosphere to polar ground by conduction and radiation, and heat transport 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 $S \cong 1.8$; 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, σ 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).

(Gierasch and Toon, 1973). One discovers that the annual average solar heating at the poles

$$S = \frac{S_0(1-A)\sin\sigma}{\pi a^2(1-e^2)^{1/2}}$$

is critical. The semimajor axis of Mars a and the eccentricity of the orbit e do not change enough to affect S. However, obliquity σ 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 duststorms. Duststorms in turn may be favored by times when perhelion isolation 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 (±10°) 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 Earth, is a hundred times greater than the period of albedo or obliquity oscillations. There may be features on Mars that reflect very-long-term oscillations in contrast with the shorter ones. Figure 3 shows a small part of an interest-

C. 3

FIGURE 3.—A view of the polar laminas. These features are found in both polar regions. The finest dark bands are thought to be about 30 m thick. The distance across the layered region is about 5 km at the widest part. The laminas 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.)

ing set of features, known as the polar laminas, that are found in both north and south polar regions. Unfortunately, how these features were formed, what they are made of, and how 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 laminas 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 that are arranged one on top of the other. Future studies of the laminas and plates may provide us with a climatic history of Mars.

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

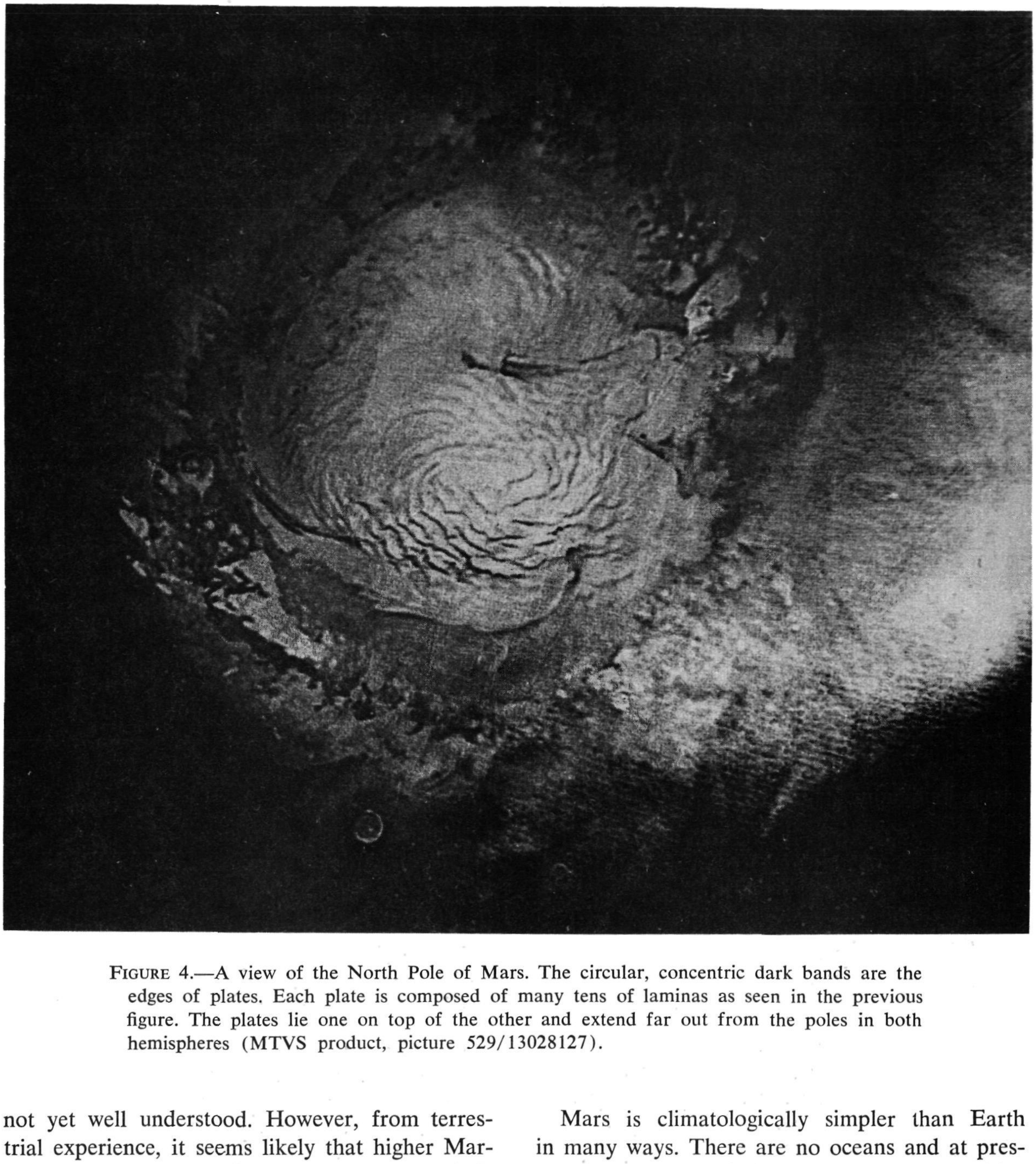

FIGURE 4.—A view of the North Pole of Mars. The circular, concentric dark bands are the edges of plates. Each plate is composed of many tens of laminas as seen in the previous figure. The plates lie one on top of the other and extend far out from the poles in both hemispheres (MTVS product, picture 529/13028127).

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 and Toon, 1973). If this is not the case, then solar luminosity variations will become attractive because they both raise the planetary mean temperature and lead to increased pressures through the instability we have described.

Mars is climatologically simpler than 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. We have now entered an era when studies of the planet may be of real use in understanding 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 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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DISCUSSION

QUESTION: Can the finer divisions be annual variations?

TOON: I think it is very unlikely that there are annual variations. The thickness of the finer layers is about 30 m. It is pretty hard to think of anything annual that would make a 30-m thick layer of dust. The layers are very uniform in thickness, remarkably uniform one layer compared to the next.

Session 3

IN SEARCH OF PHYSICAL MECHANISMS

Chairman: Eugene N. Parker

N76 14549

Some Problems in Coupling Solar Activity to Meteorological Phenomena

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Rice University

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-yr cycle, and meteorological phenomena undergo either no closely correlated variation, an 11-yr variation, or a 22-yr variation.

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 fig. 1) as a "mere coincidence." The concept that this correlation exists, survived, however, because the result could be reproduced cycle after cycle.

After the discovery of the correlation between sunspot numbers and geomagnetic activity, there were attempts to establish a relationship between sunspot number and a variety of items, such as the occurrence of the aurora, animal and plant growth, stock market prices, the temperature of the thermosphere, the frequency of volcanic outbursts (see fig. 2), cosmic radiation, suicide rates, variations in the solar constant, and, of course, the subject of this conference—the weather. Of these items, 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.

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

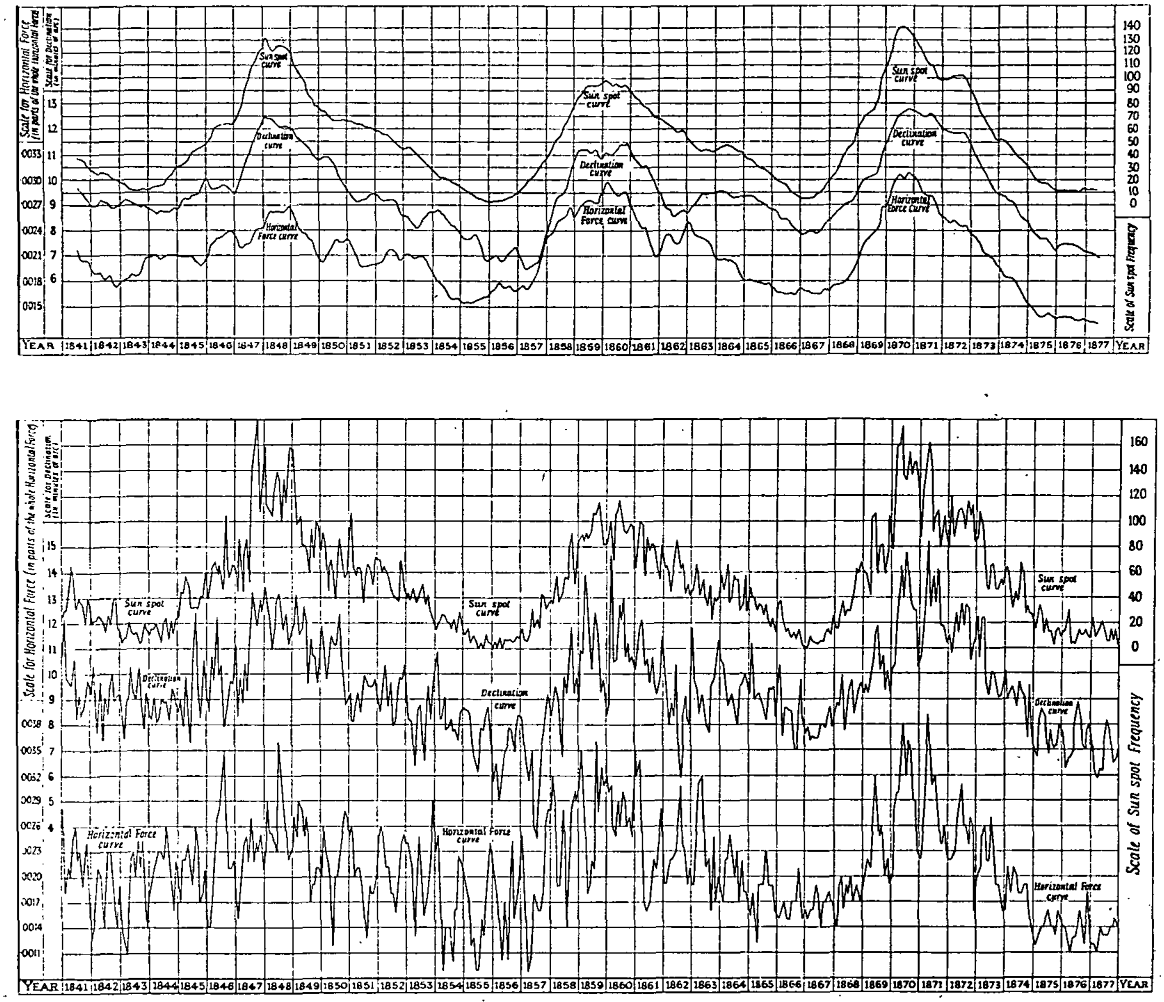

FIGURE 1.—Sunspot number and geomagnetic activity plotted for the time period between the years 1841 to 1877 (after Chapman and Bartels, 1940). The correlation between solar and geomagnetic activity is obvious.

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 yr to establish the 11-yr 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 Kepler's work that resulted in his laws of planetary motion. Kepler had the data that Tycho Brahe had gathered with painstaking observations over his lifetime. 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, although Kelvin was often wrong in his prolific criticisms, he was

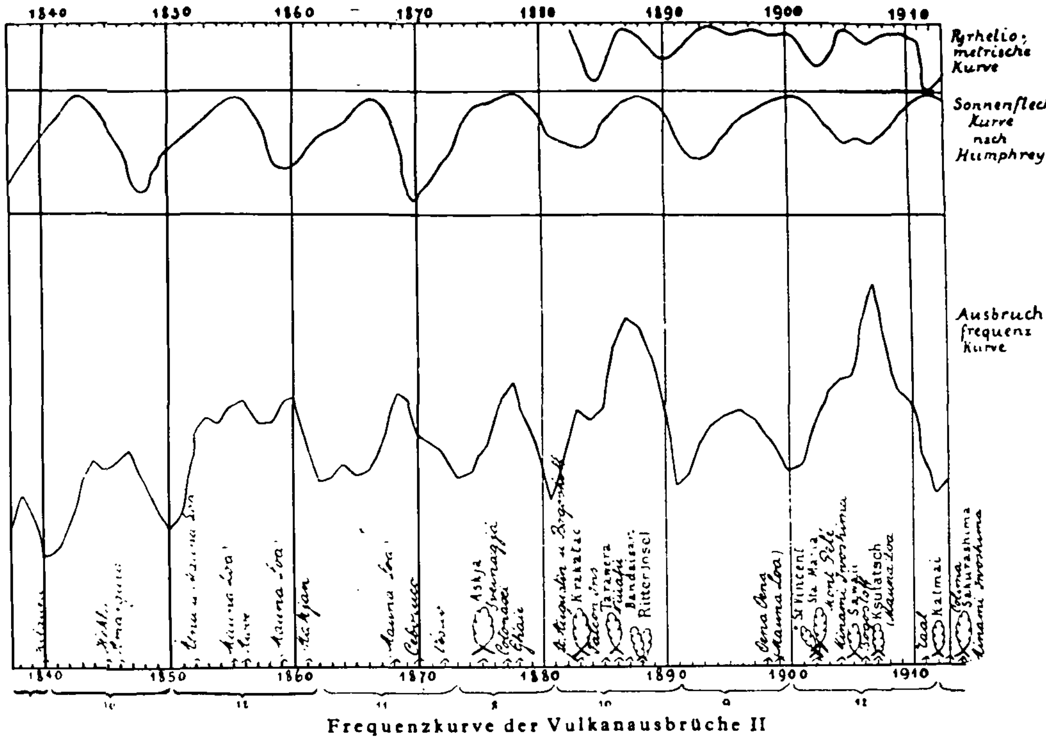

FIGURE 2.—Sunspot number and frequency of volcanic outbursts plotted for the time period between the years 1838 to 1914. The correlation between solar and volcanic activity, while not as obvious as the correlation of figure 1, is "not bad."

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 present viable theory that proposes a coupling between solar activity and some meteorological phenomenon. However, there is much good, relevant data 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 by the Earth's surface. This energy flux is $U_{\mathrm{EM}} = \pi r_E^2 F(1-A)$, where r_E is the radius of 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 $U_{\mathrm{EM}} = 8.9 \times 10^{16}$ 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, where

$$U_s = \pi r_M{}^2 \left(\frac{1}{2}\rho V_s{}^2 + \frac{B^2}{2\mu_0}\right) V_s$$

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. μ_0 is the magnetic permeability of free space. Calculations made using various space and ground based observations indicate that less than one 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/sec, and $B = 10$ nT (that is, 10 γ), we find that $U_c = 5 \times 10^{-2}$ TW, and the ratio $U_c/U_{\mathrm{EM}} = 6 \times 10^{-7}$, where U_{EM} is the solar electromagnetic energy flux. Thus the available energy flux of the solar wind and interplanetary magnetic field is less than one millionth 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, $U_{\mathrm{EM(min)}}$ 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} J 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 $U_{c(\mathrm{max})} = 10^2$ TW. This leaves us with

$$\frac{U_{c(\mathrm{max})}}{U_{EM(\mathrm{min})}} = 1.7 \times 10^{-2}$$

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 approach 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 (1973*a*) 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 (1973*a*).

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/sec to 6×10^{-5} rad/sec. (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, $\rho = 3 \times 10^3$ kg/m^2. Substituting these values we obtain $I = 2.9 \times 10^{26}$ kg m^2. The energy of the rotating system is $E = \frac{1}{2} I\omega^2 = 5.3 \times 10^{17}$ J for $\omega = 6 \times 10^{-5}$ rad/sec. This energy is comparable to the energy of a magnetic storm. The power input U_r required to increase ω from 4×10^{-5} rad/sec to 6×10^{-5} rad/sec in 24 hr is

$$U_r = \frac{dE}{dt} = I\omega\frac{d\omega}{dt} = 2.7\ \mathrm{TW}$$

The increase in energy of rotation is 2.3×10^{17} J. This power value is to be compared with $U_{c(\mathrm{max})} = 10^2$ TW, derived earlier, 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 because 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, Jacchia et al., 1967; Newton et al., 1965). 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, such as infrared radiation and infrasonic noise, is converted to forms that can penetrate through these temperature minima to the troposphere. 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 component would provide a significant 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.

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 $J = 10^6$ A as an upper limit, exert a force $\mathbf{J} \times \mathbf{B}$ per meter of length on the neutral atmosphere. For the polar value of $B = 6 \times 10^{-5}$ T,

$$\mathbf{J} \times \mathbf{B} = 60 \text{ N/m}$$

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

$$\frac{d\omega}{dt} = \frac{2JBR^2}{I} = 10^{-13} \text{ rad/sec}^2$$

is the result. This acceleration is to be compared with the acceleration of 2×10^{-10} rad/sec^2 that is necessary to make the process fit the phenomena reported by Roberts and Olson (1973*a*). 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 hopeful view of the serious nature of this 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 in a higher region?) 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 lack of theoretical groundwork 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 would 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 a bistable atmosphere of the type described, or even if we need one. 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-yr cycle in the weather. Reports of either no sunspot correlation or a 22-yr 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-yr cyclic pattern. There is presently a claim that 3 rings show an 11-yr pattern. If this is true, the 11-yr, rather than a 22-yr, 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 (1973*b*).

There is perhaps a clue to a possible mechanism arising from this work. If there is no 11-yr cycle in the meteorological phenomena they are testing, perhaps there is a special type of geomagnetic storm that should be sought that also does not have an 11-yr 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-yr variation in his meteorological data, elimination of the geomagnetic data from sunspot maximum would tend to eliminate the 11-yr cycle in geomagnetic activity. This point has been taken up by Hines (1973*b*) 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 Shapiro, 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 (1973*a*) for pressure troughs in the northern hemisphere. The number of sector boundary crossings per year should show an 11-yr cycle. Does the vorticity index show a similar 11-yr 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 (1973*b*) 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-yr 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.

ACKNOWLEDGMENTS

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DISCUSSION

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 does not 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.

LONDON: In the magnetosphere observations, is there any way that you can recognize one cycle from another except for changes in polarity, supposing you were given a long trend and asked to identify them?

DESSLER: That is a good point, because in geomagnetic activity, auroral activity, and things like that, there is no trace of the 22-yr 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 have not 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 did not 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 do not 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-yr cycle, not a 22-yr cycle.

QUESTION: Can you describe in a few words what actually happens when the boundary sector passes the Earth, from the standpoint of physics?

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.

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-yr and not the 22-yr cyclic phenomenon.

ROSNER: You are quite correct. There is no 22-yr variation in the sector.

PARKER: How is it known, insofar as the polarity is concerned, though?

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-yr cycle.

DESSLER: Again, I do not believe the sector structure's peak will occur coincident with the solar cycle's peak. I think there will be a 4-yr displacement, because they are the source of recurrent storms, and recurrent storms peak 4 yr later.

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 4 sectors, and so it is 4 divided into 27?

DESSLER: Either 2 or 4, yes, and it would be 2 into 27 or 4 into 27. Now, at times it gets more complex when the solar structure gets complex. During some intermediate stages, as new sectors are being created, you may not have such a simple division, but generally, that is right, either 2 or 4 divided into 27.

NORDBERG: In that case, since you raised the question of what to look for in 22 yr, 11 yr, 3 days, or what not, I have a wild idea here. If it turns out 4 into 27, then it just falls right that you have about 6- or 7-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 condition 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 does not work where you have a mismatch.

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.

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?

DESSLER: I am afraid I do not 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. Did you not like that result?

HEPPNER: I think you may have confused our nonmagnetospheric physicists 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 do not know of any theories that relate sector structure to rate of reconnection. I think you called that the party line.

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.

ROBERTS: This is on your comments about, for example, *trying to distinguish between an 11-yr cycle and a 22-yr 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-yr 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-yr cycle could be driven by an 11-yr forcing function.

QUESTION: You brought in one pseudocorrelation 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 km. So this is a good relationship and I would like to hear your comment.

DESSLER: I was very brief in discussing the cosmic-ray variations in the soft component for cosmic-ray energies of a few billion electron volts. And it comes into the polar cap where its ionization peak is at about 22 km altitude. The tropopause in the polar cap is at 10 km, and at this altitude there is just no change. There is almost nothing reaching there now.

If you have an effect where you can use production of ions or maybe some gas chemistry 10 km 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 do not see any good way to get around this fact.

PARKER: 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.

DESSLER: Now, those unusual events will just do everything, but they are once every 5 yr. They are a funny kind of flare that, in my opinion, show no relationship to the solar cycle. They just appear once every 3, 4, 5, 6 yr. 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.

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-yr cycle? How often do they occur? How violent are they? Or are they associated with the 20-yr cycle?

DESSLER: I think that clearly these changes are associated with an 11-yr cycle.

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 10 yr in which just very regularly the boundaries sweep past the earth.

VOICE: Why?

WILCOX: Based on the work of Leif 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 do not know.

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 phenomena. 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.

DESSLER: That is why I wanted to see what happens with the nonsector 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.

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.

LONDON: Since we are talking about mechanisms, it might be important here to mention an idea that has been advanced by Ruderman and 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 km, and there exciting nitrogen and thus lead to the local formation of nitric oxide. We know that nitric oxide can be deleterious to the ozone concentration at these altitudes.

At 20 to 30 km, 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 km, this effect 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 very easily tested by numerical models.

However, a countermechanism 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.

So we have two counterprocesses. One can put both of these into a numerical scheme, knowing what the relaxation times or kinetic rates are for these reactions, and get some kind of approximate solution.

DESSLER: This procedure would take a long time to carry out. It would not be a geomagnetic storm effect.

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-yr period.

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 km. I think some numbers that would answer an earlier question about looking into this are that at 10 km the variation from solar minimum to solar maximum, between 1954 and 1958, was 30 percent. At 15 km 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.

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 km. 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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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 sets of 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.

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 energy variations associated with solar variability are small compared to the total output of solar energy, 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 the weather by numerical experiments with a large general circulation model of the atmosphere. 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, mountains, 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. Its calculations of energy transfer by solar and terrestrial radiation make use of model-generated fields of cloud and water vapor. Parameters used in the parameterization of the solar radiation (Lacis and Hansen, 1974) include ozone absorption, the diurnal variation of solar zenith angle, and the diurnal and seasonal variation of solar flux. The amount and vertical distribution of ozone in the model are based on results summarized by Manabe and Möller (1961). These quantities vary latitudinally and seasonally.

This model has produced a realistic simulation of tropospheric, January climate (Somerville et al., 1974) and has demonstrated a 2-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 2 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 typically occur on time scales which are long compared to those which characterize the previously cited statistical relationships between solar or geomagnetic variables and meteorological ones.

EXPERIMENTAL PROCEDURE

In view of the capabilities and limitations of the model, we have employed the following procedure to determine the sensitivity of the evolution of the atmosphere as predicted by the model to changes in solar constant and ozone amount: First, we perform a control run by integrating the variables given by 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 perform the integrations for 12 days. Next, we carry out a second set of integrations to measure the natural variability of the model atmosphere. This set of integrations differs from that of the control run only in that the initial state is created by modifying that of the control run by random perturbations with RMS amplitubes of 1 K in temperature and 3 m/sec in wind at all grid points, and 3 mb in pressure at all surface grid points. Because such pairs of sets of integrations can be used to estimate the effect of observational uncertainty on atmospheric predictability, we denote this second set of integrations as the predictability run.

Since we anticipate that realistic changes in the solar constant and the amount of ozone would cause effects too weak to be detected except by a Monte Carlo procedure involving many sets of integrations of the model's variables (Leith, 1973), we artificially increase the signal-to-noise ratio by performing several sets of 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 sets of integrations can be carried out with smaller input changes; but 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 sets of integrations which differ from the control run only in the value of solar constant or amount of ozone. The values of solar constant employed are 2/3 and 3/2 the normal value, and the values of amount of ozone 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. OZ is the ratio of the amount of ozone to the standard amount. It is clear that the map least resembling the control run is that of the predictability run. The changes in the amount of ozone 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 amount of ozone
Control (also called $S=1$ or OZ=1)	Standard (0000z GMT 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 changes in the amount of ozone 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 changes in the amount of ozone 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. S is the ratio of the solar constant to the standard value. 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 (fig. 11), essentially a measure of the pole-equator temperature 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 tempera-

TABLE 2.—*Temperatures and Cloud Cover in the Ozone Experiments*

Variable	Run	Days 1 to 3	Days 4 to 6	Days 7 to 9	Days 10 to 12
Mean global atmospheric temperature, °C	OZ=1	−26.06	−26.73	−27.23	−27.49
	PREDIC	−26.06	−26.71	−27.21	−27.43
	OZ=0	−26.17	−27.10	−27.47	−27.78
	OZ=2	−25.97	−26.54	−26.71	−27.02
Mean temperature in highest model layer, °C	OZ=1	−58.58	−59.10	−59.26	−59.44
	PREDIC	−58.61	−59.09	−59.26	−59.51
	OZ=0	−60.80	−59.23	−61.91	−62.97
	OZ=2	−58.08	−57.45	−56.65	−55.95
Mean temperature in lowest model layer, °C	OZ=1	2.82	2.21	1.91	1.63
	PREDIC	2.48	2.11	1.81	1.37
	OZ=0	2.79	2.14	1.87	1.63
	OZ=2	2.82	2.20	1.63	1.65
Mean global cloud cover, percent	OZ=1	33	46	49	48
	PREDIC	33	46	49	48
	OZ=0	33	46	49	48
	OZ=2	33	46	49	48

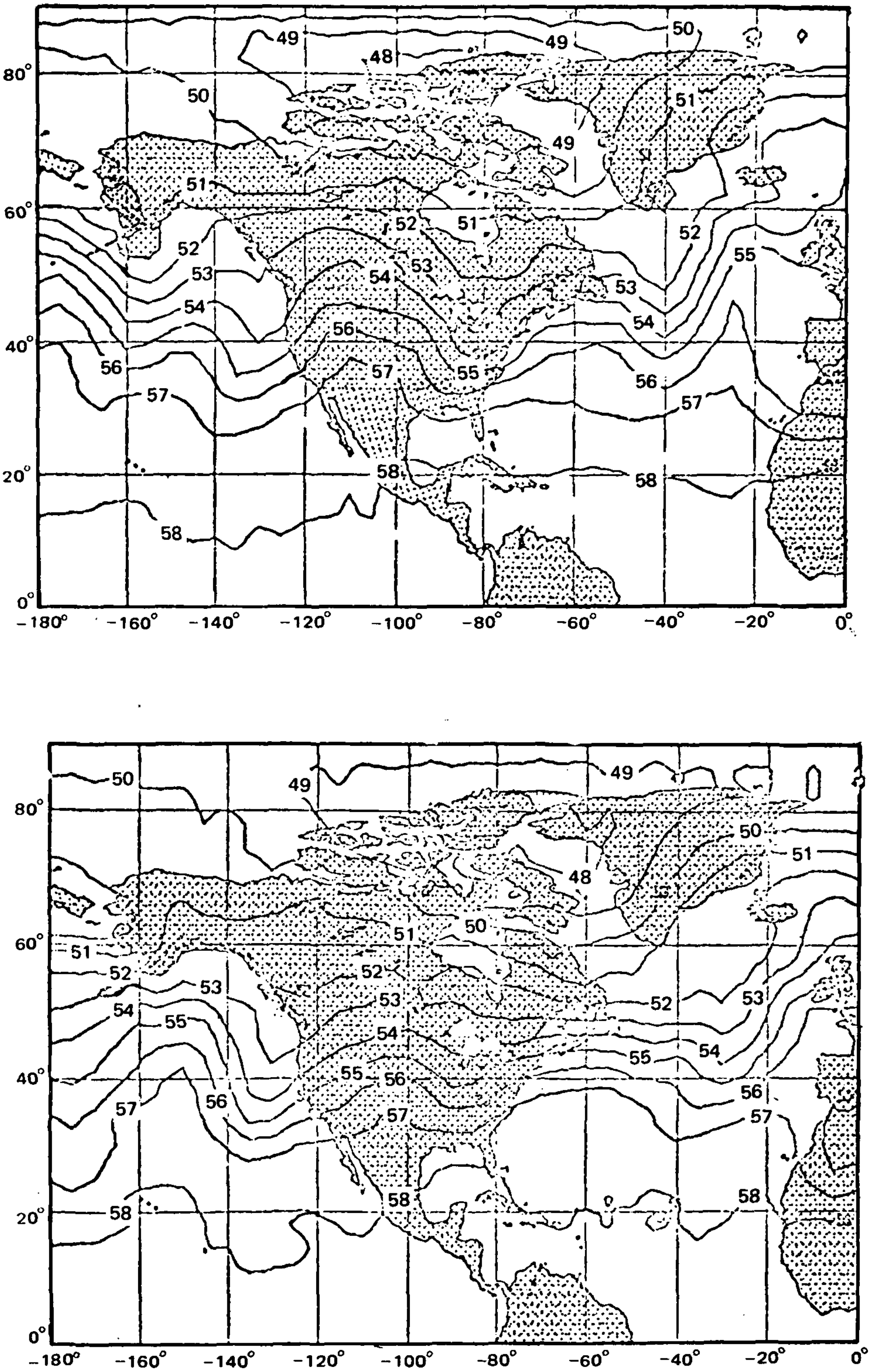
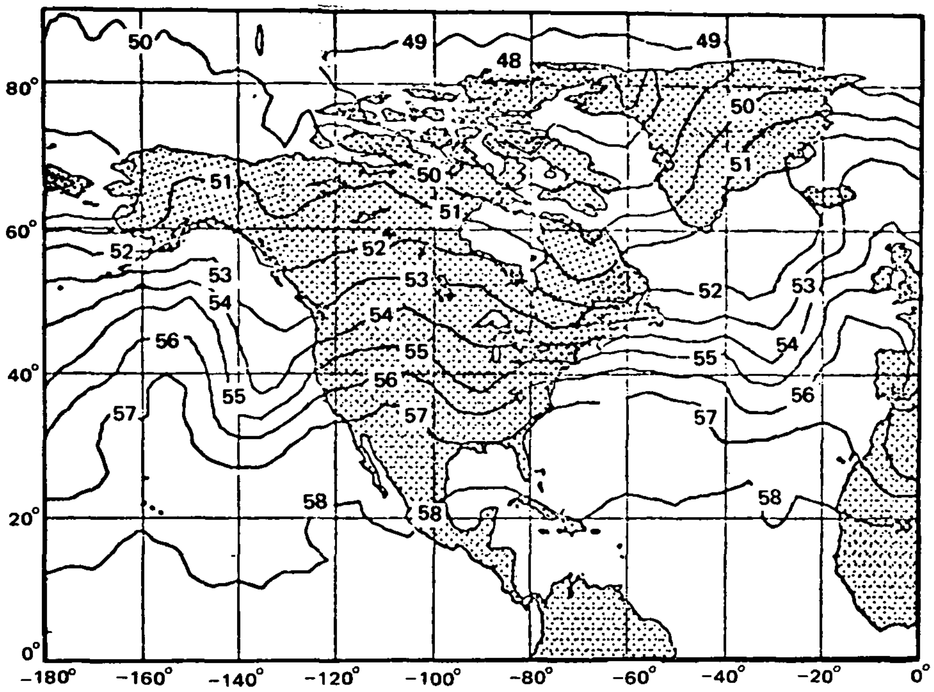


FIGURE 1.—500-millibar maps at 11.5 days. Numbers on map in figures 1 to 3 and 8 to 10 represent height of 500-millibar level in 100 m. *Upper:* PREDIC; *lower:* control (OZ=1).



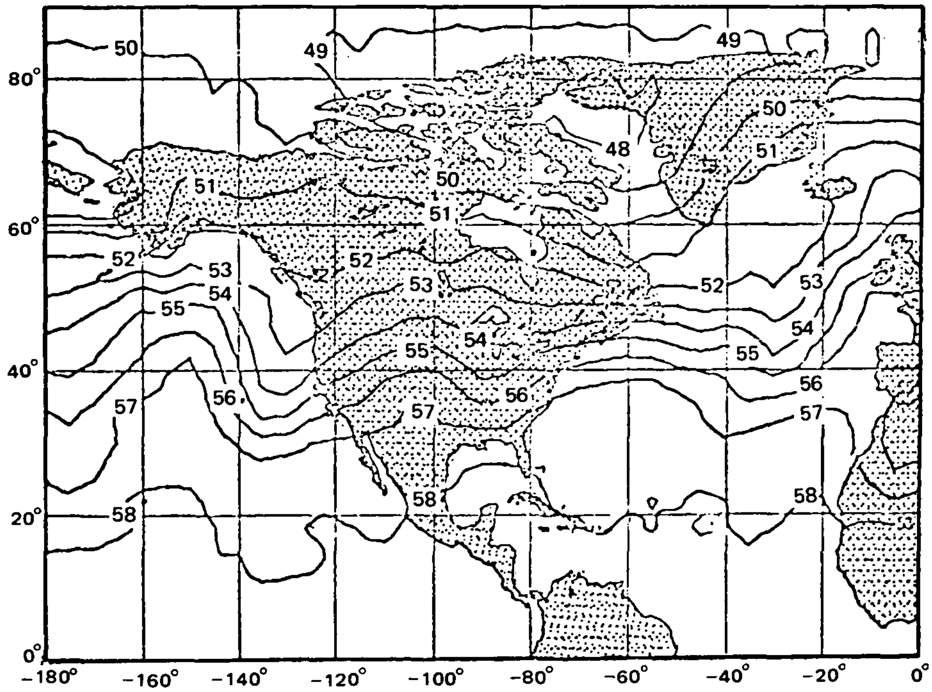


FIGURE 2.—500-millibar maps at 11.5 days. *Upper:* OZ=0; *lower:* OZ=1.

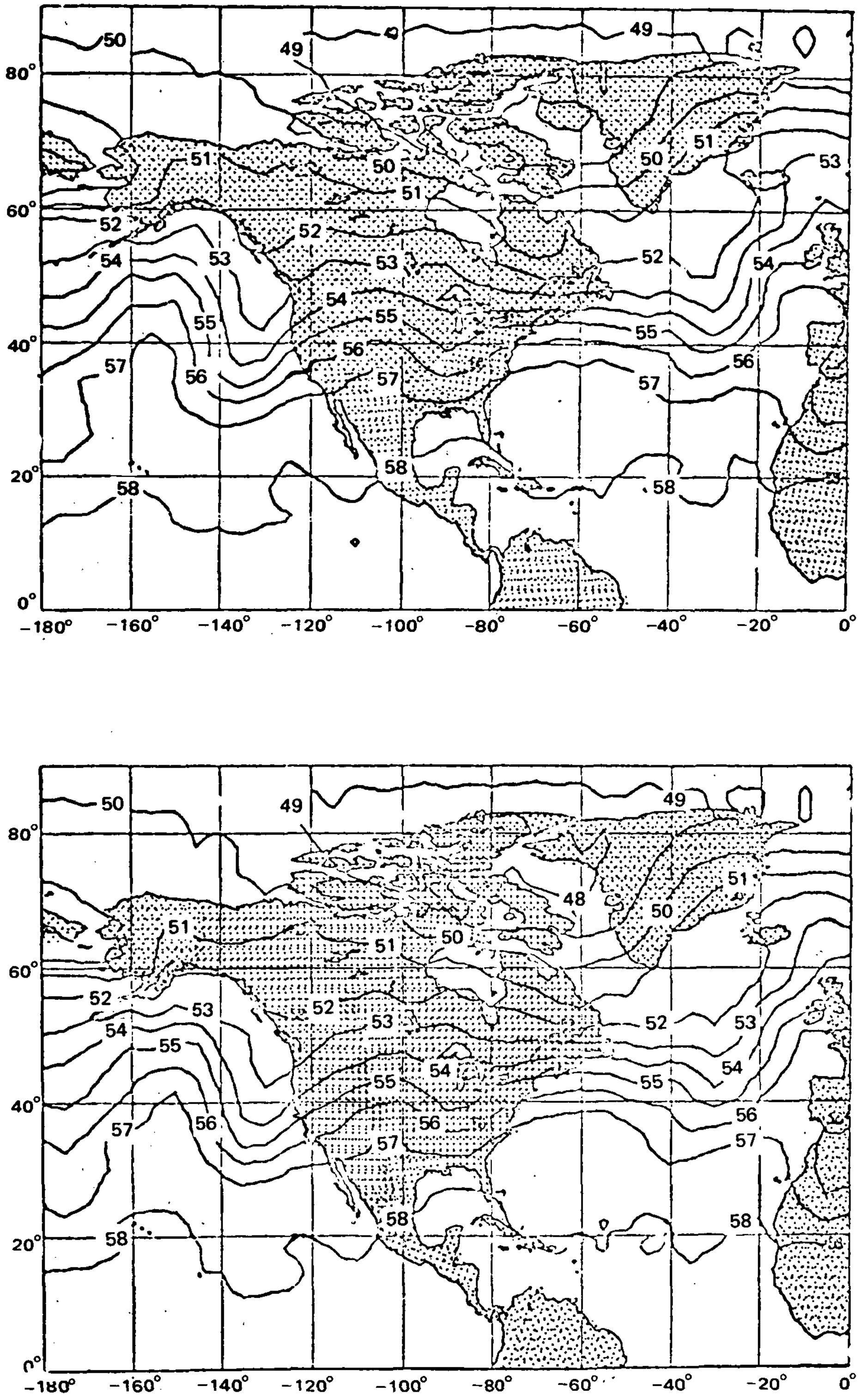


FIGURE 3.—500-millibar maps at 11.5 days. *Upper:* OZ=2; *lower:* OZ=1.

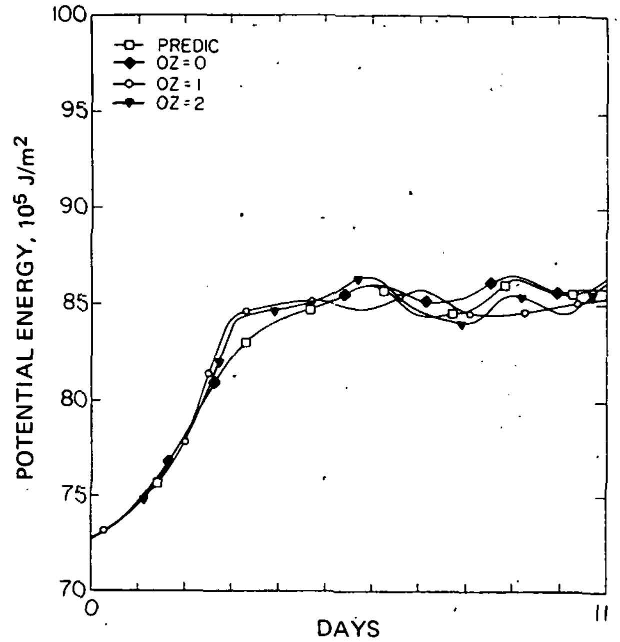


FIGURE 4.—Time evolution of globally integrated, zonal, available potential energy (PM) for the ozone experiments.

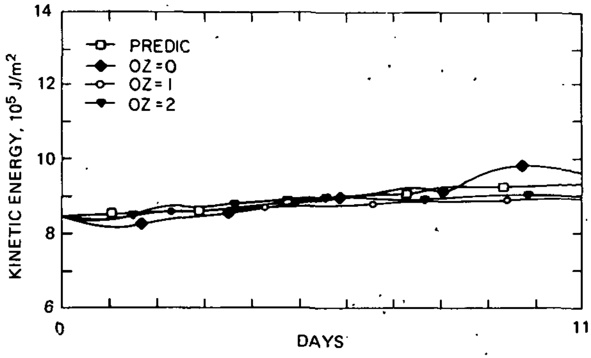


FIGURE 5.—Time evolution of globally integrated, zonal, kinetic energy (KM) for the ozone experiments.

ture (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's 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).

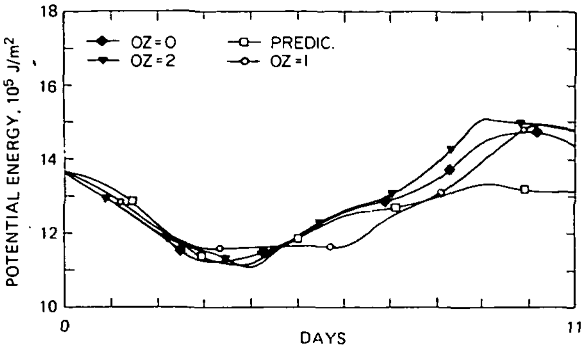


FIGURE 6.—Time evolution of globally integrated, eddy, available potential energy (PE) for the ozone experiments.

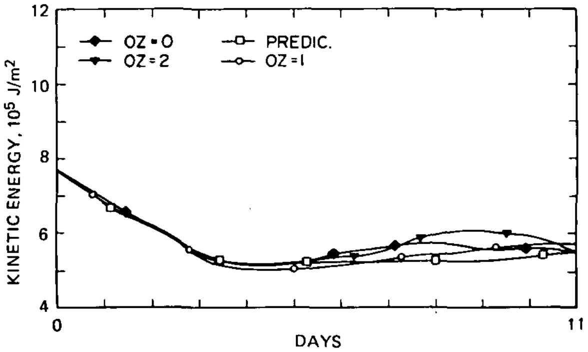


FIGURE 7.—Time evolution of globally integrated, eddy, kinetic energy (KE) for the ozone experiments.

This 50-day time scale cannot be greatly reduced by 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

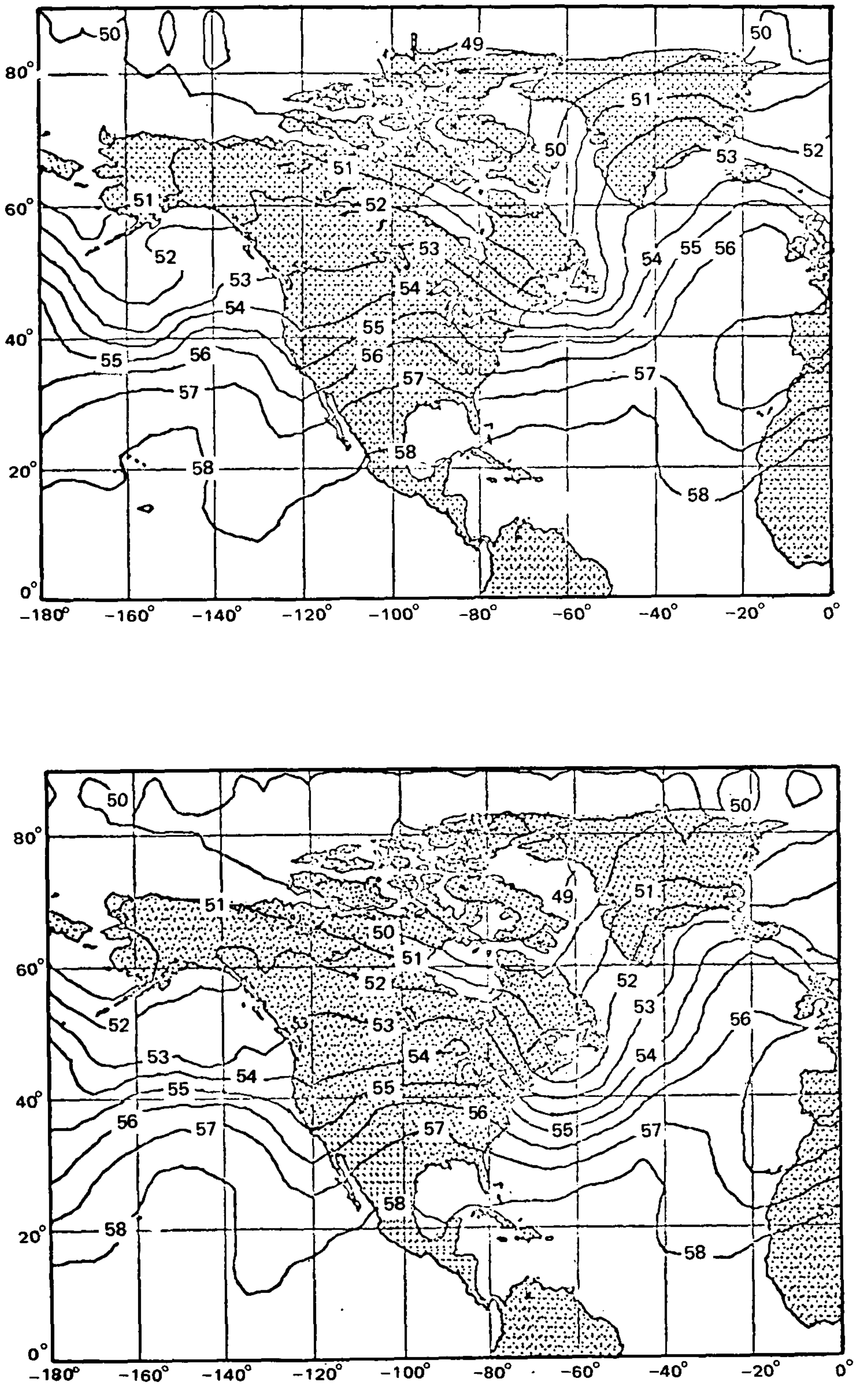


FIGURE 8.—500-millibar maps at 8 days. *Upper:* PREDIC; *lower:* (S=1).

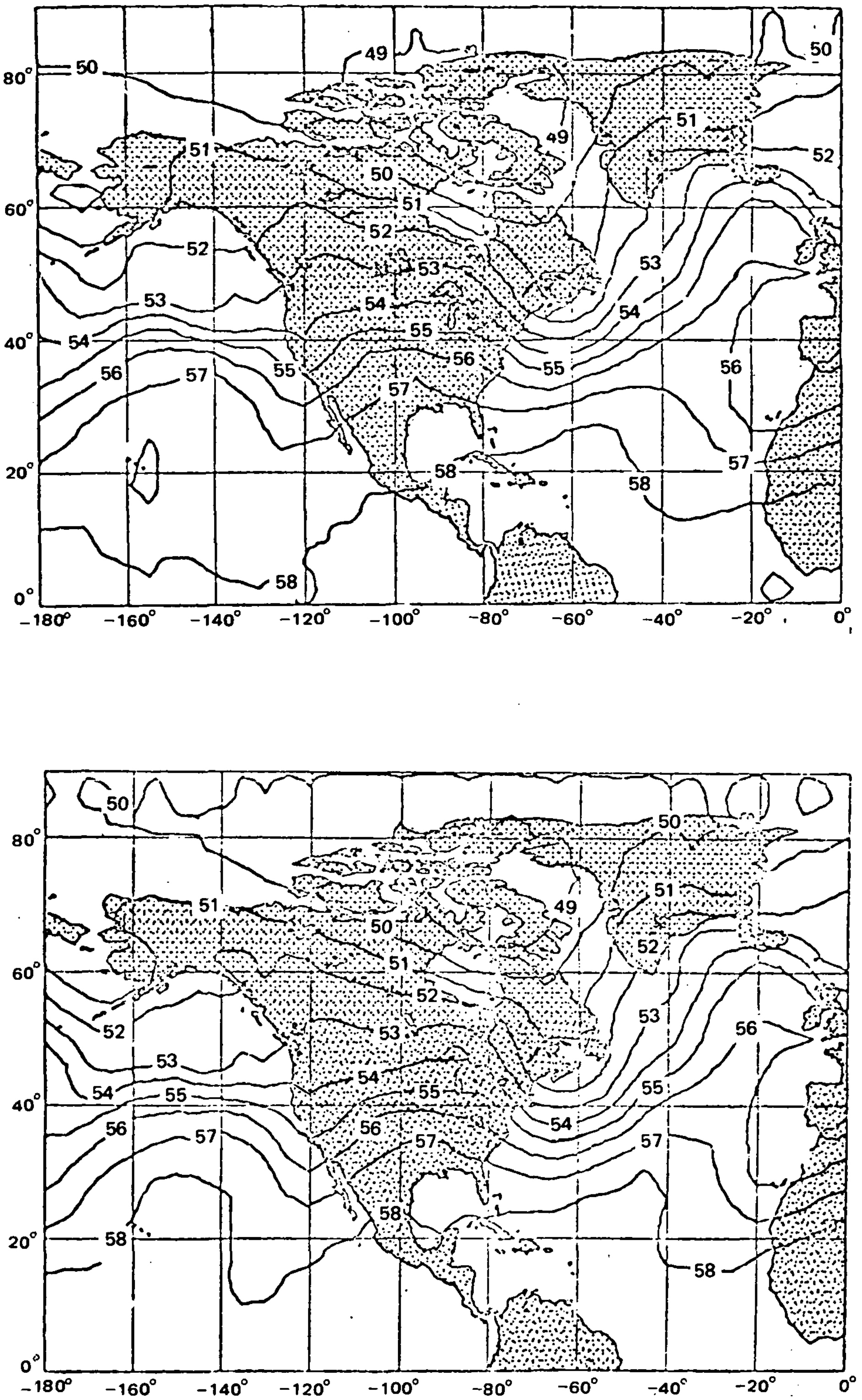


FIGURE 9.—500-millibar maps at 8 days. *Upper:* S=2/3; *lower:* S=1.

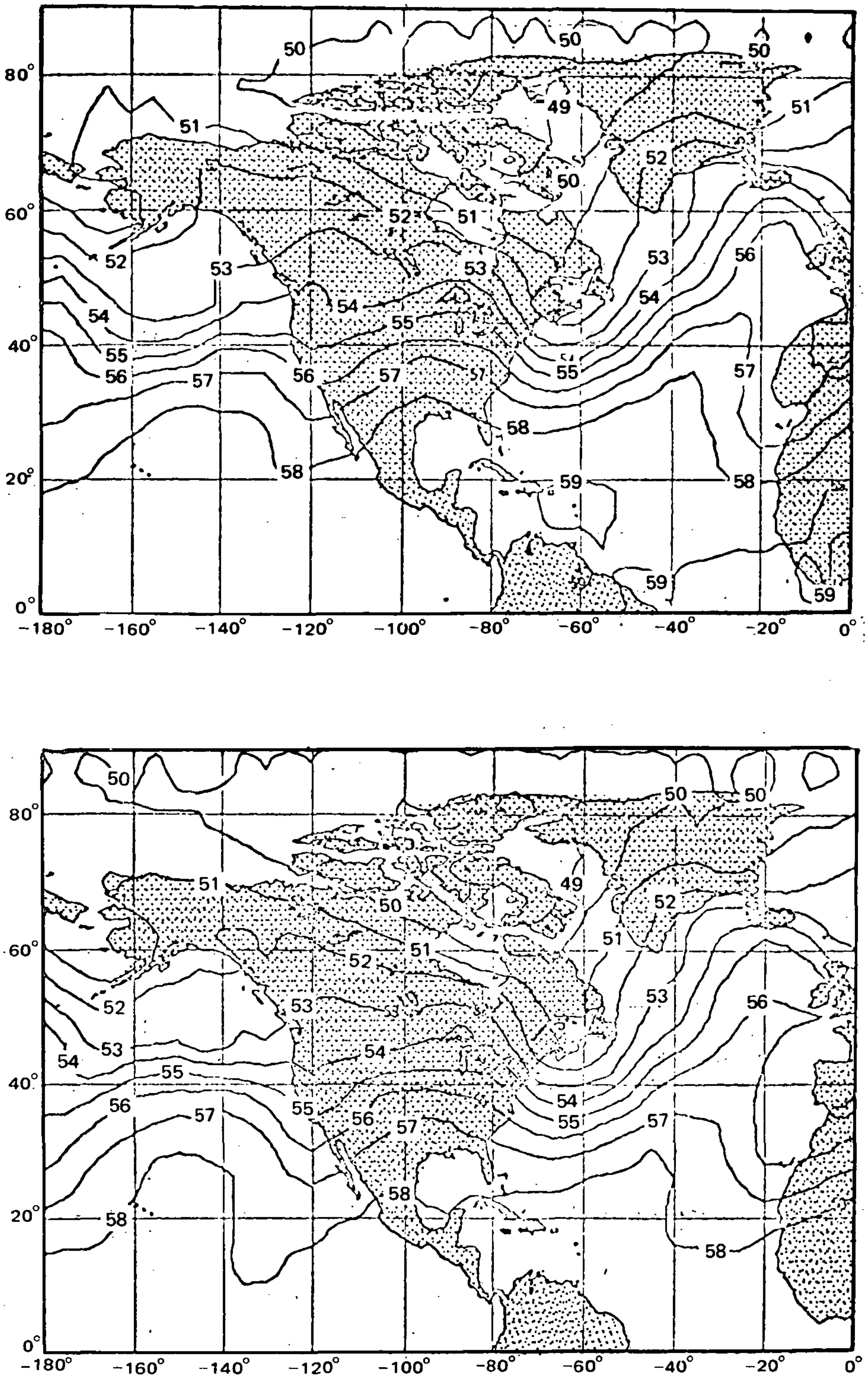


FIGURE 10.—50-millibar maps at 8 days. *Upper:* S=3/2; *lower:* S=1.

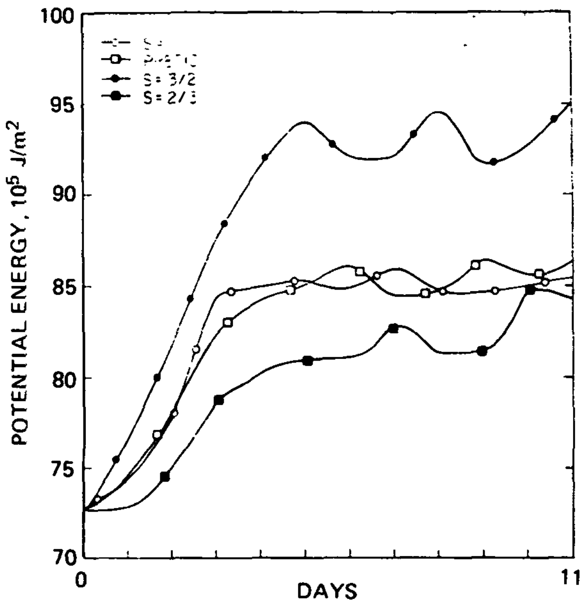


FIGURE 11.—Time evolution of globally integrated, zonal, available potential energy (PM) for the solar constant experiments.

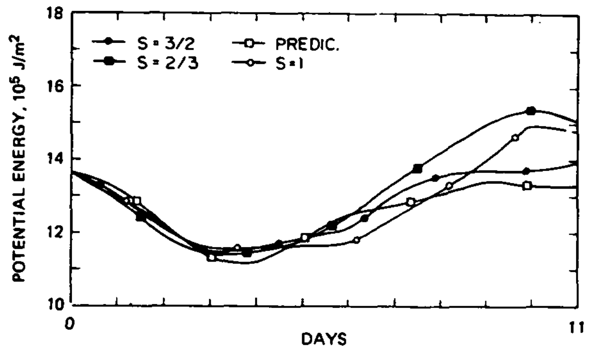


FIGURE 13.—Time evolution of globally integrated, eddy, available potential energy (PE) for the solar constant experiments.

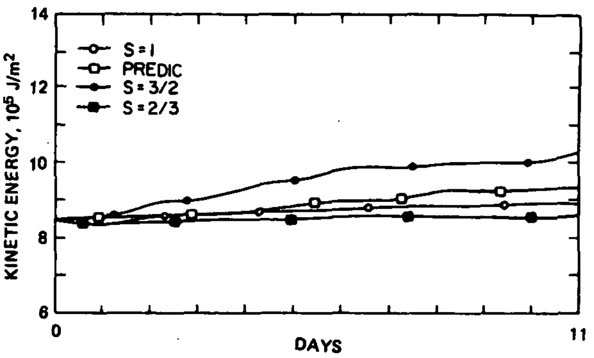


FIGURE 12.—Time evolution of globally integrated, zonal, kinetic energy (KM) for the solar constant experiments.

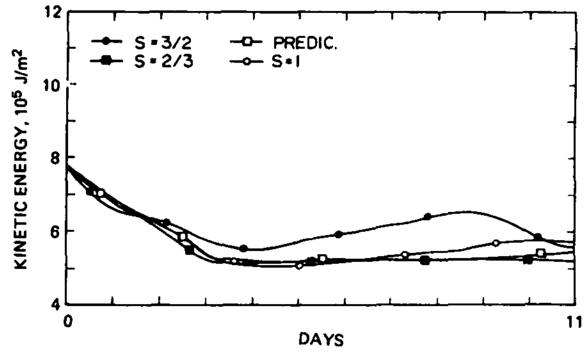


FIGURE 14.—Time evolution of globally integrated, eddy, kinetic energy (KE) for the solar constant experiments.

TABLE 3.—*Temperature and Cloud Cover in the Solar Constant Experiments*

Variable	Run	Days 1 to 3	Days 4 to 6	Days 7 to 9	Days 10 to 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	46	49	48
	$S=3/2$	33	46	49	48

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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DISCUSSION

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 do not have the top layer?

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.

MARAN: I think the ozone results are interesting. However, the solar constant variations considered were on time scales on which you do not 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 essentially changing the visible and near visible light?

SOMERVILLE: Yes. There is certainly no simple accounting, as I said earlier, of the particle flux or any other aspect, of the electromagnetic radiation. And you are quite right, you would 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 make those observations using longer time scales, but obviously it is necessary to run for a short time before you run for a long time.

WILCOX: Would it be possible to introduce the following kind of perturbation into your model? 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 to try to introduce this perturbation when the next boundary came by. How would we want to do that? We know that it is kind of a hemispheric effect. It is not particularly localized to any one area, so that you might change conditions somehow, for example in every trough that you have, so that it went through this behavior. The magnitude is about 10 percent on the average. Would it be feasible to make an alteration like that?

SOMERVILLE: Yes, you can tinker with model fields any time you want. I am not sure what your goal is, what you would be learning by altering the model?

WILCOX: You would compare the result of that alteration with the behavior that is actually observed and see if this result has improved over the results you obtain when you do not make the alteration.

SOMERVILLE: That comparison is certainly possible to make.

WILCOX: That procedure would begin to give you some clearer insights into what seems to be a fairly substantial solar influence on the weather, as compared with the influence of the solar constant on the ozone, which did not seem to have very much effect.

SOMERVILLE: The feasibility of the procedure, of course, would depend on the deviation with which the model atmosphere had departed from the real atmosphere, if you were verifying it with respect to the real atmosphere, by the time the effect occurred. Possibly this effect would be lost in the noise of the other effects, model deficiencies, and poor observations which degrade the quality of the forecast.

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 in a much more pronounced manner. Then they would have, presumably, feedback into the meteorological scale. And this feedback is inhibited in the model. If it can be promoted, one might find a direct relationship.

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 is important that takes place on smaller scales than those explicitly resolved by the model grid (and the gridpoints are separated by something like 400 km in middle latitudes) can be uniquely represented. There is an algorithm that defines the feedback of these small-scale processes on the large scale, given the large-scale values of the fields as explicitly calculated by the model. And that assumption, the parameterizability hypothesis, is by no means on firm ground with respect to many small-scale processes. But you have to make it if you are to run the model at all. You cannot ignore these processes; you cannot possibly compute them explicitly.

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 considerable 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 considerably, 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.

SOMERVILLE: Yes. I think your statement might be correct. 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, the radiative transfer in the model atmosphere may be much less important than in the real atmosphere for determining the 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. Even if it were not, we might not notice it. This deficiency is a major problem in extending models like this to computing climates which may be very different from the present climate. The effect may not show up over the time scales of weather forecasts or even extended-range weather forecasts involving a synoptic data simulation over a few weeks. But it may be crucial 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 correspondingly within a model and compute the climate of a hundred million years ago. Carrying out this kind of calculation is a high risk game right now, because of the kinds of model deficiencies that we have been discussing. 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 4 or 5 days, and then they flattened out. What is the reason for that kind of behavior?

SOMERVILLE: The reason is that the equilibrium state of the model differs from the initial state. Whether the difference is because of observational uncertainties—we are starting from real meteorological data, which, as you know, over much of the Earth are not very reliable—or whether it is 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 correct that there is an adjustment time of a few days.

QUESTION: Does that mean that the weather, in a sense, goes away?

SOMERVILLE: In part, it does go away. Although there is degradation in the aspects of the model that are actually used in forecasting, it is not that fast. And although this model, and any other such model, in fact, produces useful forecasts only for a few tens of hours after the initial state, the model is nonetheless 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.

Auroral Effects in the D Region of the Ionosphere

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Geophysical Institute, University of Alaska

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 (1(a)), (2(a)), and (2(b)), on relatively short-term changes in the circulation of the atmosphere (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 (1(a)) and solar energetic particles (2(a)) 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 the 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. 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-yr 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 aver-

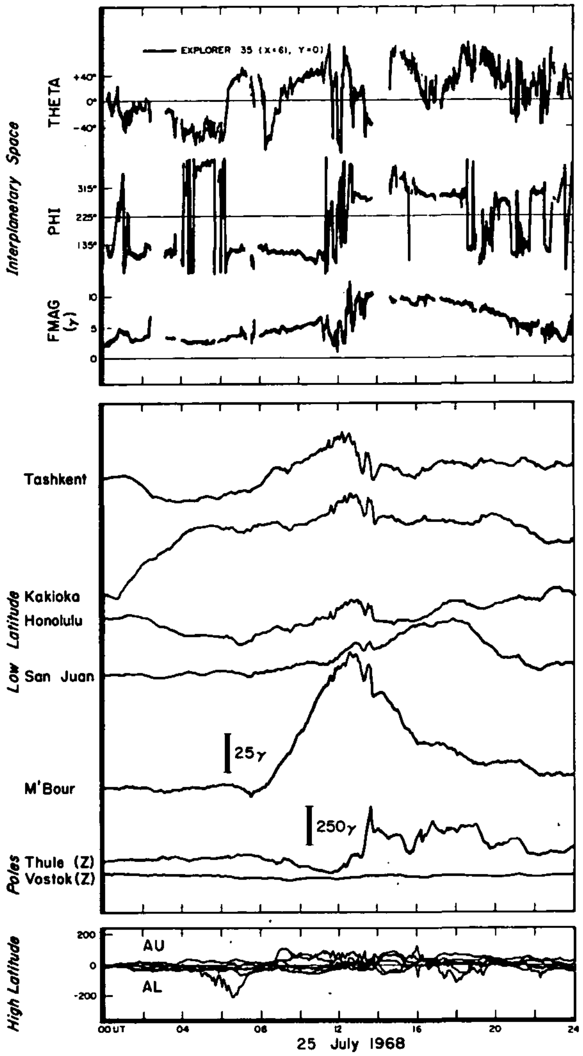

FIGURE 1.—An example of a sector boundary passage on July 25, 1968. From the top, this figure shows the interplanetary magnetic data, ground records of Earth's magnetic field strength from several low-latitude stations and from the northern and southern pole stations, and the AU and AL indices. $1\gamma = 10^{-9}$T. THETA, PHI, and FMAG are, respectively, the latitude, the longitude, and the magnitude of the magnetic field sector.

age 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 (FMAG) of the magnetic field vector), geomagnetic records of the field strength of the Earth's magnetic field 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 mag-

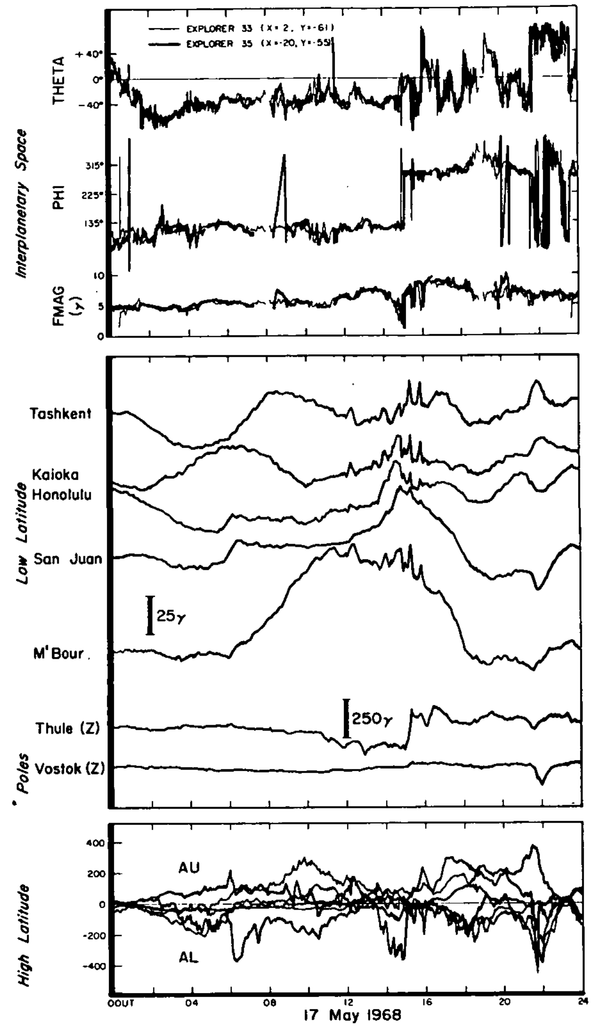

FIGURE 2.—An example of sector boundary passage on May 17, 1968. From the top, this figure shows the interplanetary magnetic data, ground records of Earth's magnetic field strength from several low-latitude stations and from the northern and southern pole stations, and the AU and AL indices.

netosphere. 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 index value for auroral electrojet (AE) activity is quite common without the passage of sector boundaries.

As noted by Wilcox and Ness (1965) and Wilcox and Colburn (1972), there is a fairly systematic change of the geomagnetic activity index K_p 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 conclusion is rather hard to believe. Jastrow, Hansen, 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_0, 8_+, 9_-, 8_+, 8_0, 5_+, 6_0, 6_0). 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 well illustrates 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 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 O(I) (λ=6300 Å) mission over a large portion of the polar upper atmosphere.

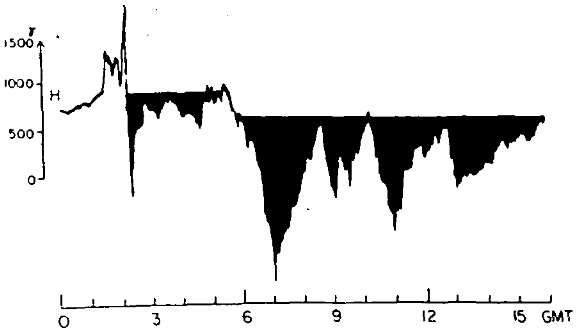

FIGURE 3.—The record of the horizontal component H of Earth's magnetic field at Meanook, Canada, on February 11, 1958. Polar magnetic substorms (manifested on negative bays) are shaded for easy identification.

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 sub-

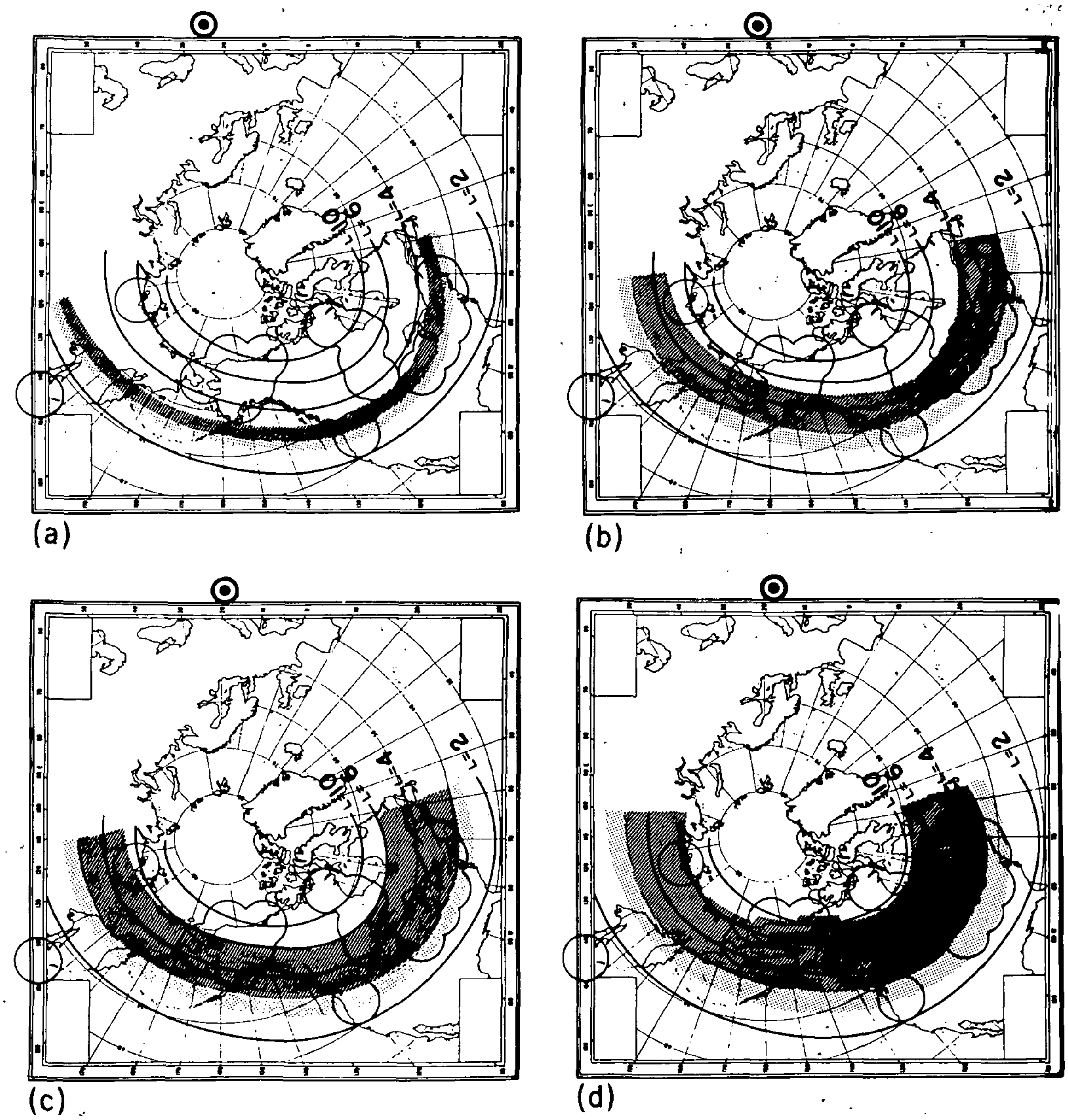

FIGURE 4.—The violent poleward expansion of the auroral oval which occurred near the maximum epoch of the great storm of February 11, 1958. Shading is the extent of the auroral oval in the region. (*a*) $10^{h} 20^{m}$; (*b*) $10^{h} 30^{m}$. (*c*) $10^{h} 40^{m}$. (*d*) $10^{h} 50^{m}$.

tropics, 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 the 700 mb level of the atmosphere, reaching a minimum latitude of approximately 31° N, about 8° S 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 block-

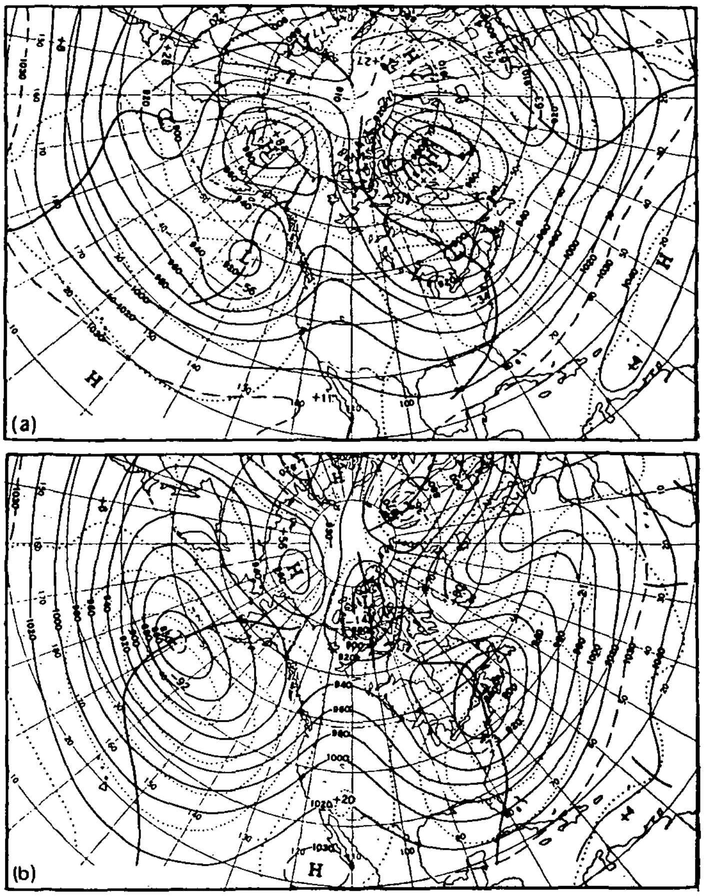

FIGURE 5.—Average weather maps. (*a*) February 6 to 10, 1958. (*b*) February 15 to 19, 1958. (Contour heights are in feet.)

ing highs, one over Davis Straight and the other over northwestern Alaska; the positive height anomaly was 1150 ft and 840 ft, respectively, in 700-mb contours. (See figs. 5(*a*) and 5(*b*).) This anomalous feature was then followed by the period of record high subtropical westerlies which brought the cold spell mentioned.

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 4(*b*) can be "predicted" a posteriori by a numerical technique from figure 4(*a*), without adding any "unknown" factor on February 11. If the contour map in figure 5(*a*) does not lead to that in figure 5(*b*) 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 5(*b*) by introducing various perturbations in figure 5(*a*). If, on the other hand, figure 5(*a*) could lead to figure 5(*b*) 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.

Let us go 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 (1(a)) or (2(a)), listed at the beginning of this article, 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; they 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 that 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 (1(a)) and (2(a)), listed at the beginning of the article, from (2(b)). There are many intense western limb flares which are associated with both (1(a)) and (2(a)), but little with (2(b)).

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." 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 of 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 hr 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 index of intensitv of ring current Dst.

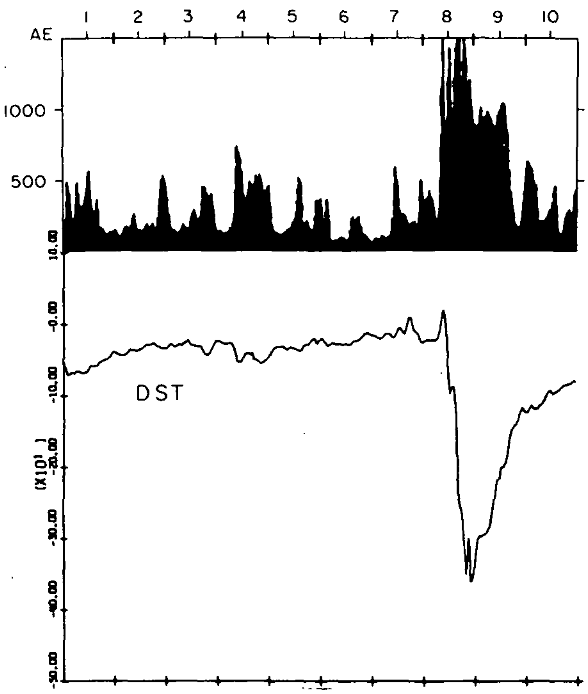

FIGURE 6.—The relationships between the magnetic storm of July 8, 1958, and the associated substorms. The intensity of the former is given in terms of the AE index and that of the latter in terms of the Dst index.

AURORAL EFFECTS

Figures 7(*a*), (*b*), and (*c*) show the auroral energy flow chart. Figure 7(*a*) 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 7(*b*) 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 Rees, 1973). The total energy input rate, 2×10^{10} W, 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 the order of 1 hr. 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 hr. (See fig. 6.)

It is well known that the energy input rate of 2×10^{10} W from auroral electrons is much less than the solar blackbody radiation energy intercepted by 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 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 (of the order of 10^{11} cm^{-2} sec^{-1}) of energetic electrons (of the order of 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 reexamined.

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 convection motion of plasma interacts with the neutral component of the atmosphere in the *E* region of the ionosphere. There, if the convection occurs across a narrow belt of high degree of ionization, a highly concentrated current is generated. (See fig. 7(*c*).) 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 (1971*a*, *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

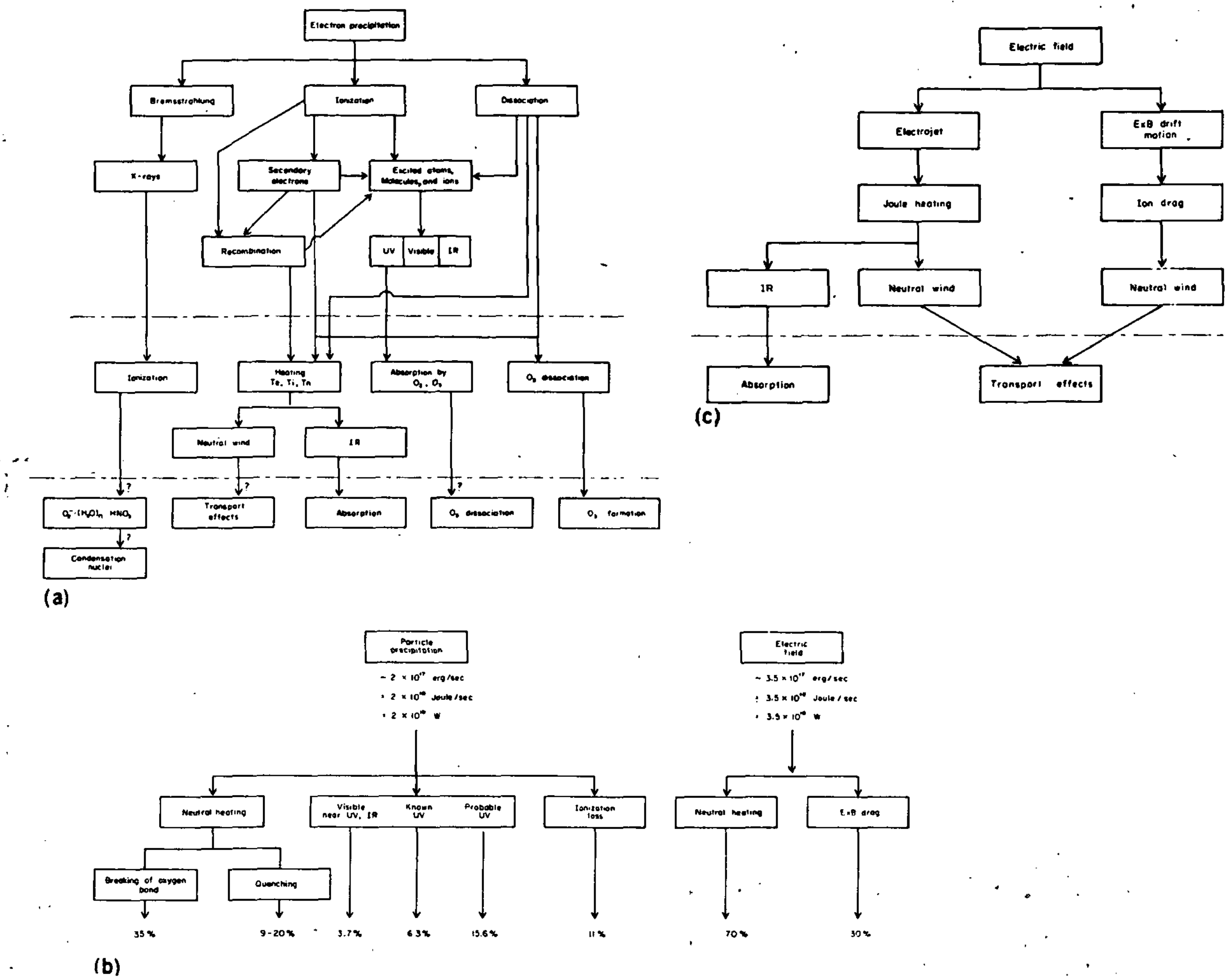

FIGURE 7.—Auroral energy flow chart (Rees, 1973). (*a*) Processes associated with the precipitation of auroral electrons into the polar upper atmosphere. (*b*) Transformation of kinetic energy carried by auroral electrons. (c) Transformations resulting from convective motions of plasma in the magnetosphere.

the ionosphere. This phenomenon is called the (**E** × **B**) drag. (See fig. 7(*c*).) 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.

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 2(*a*)) and cause the

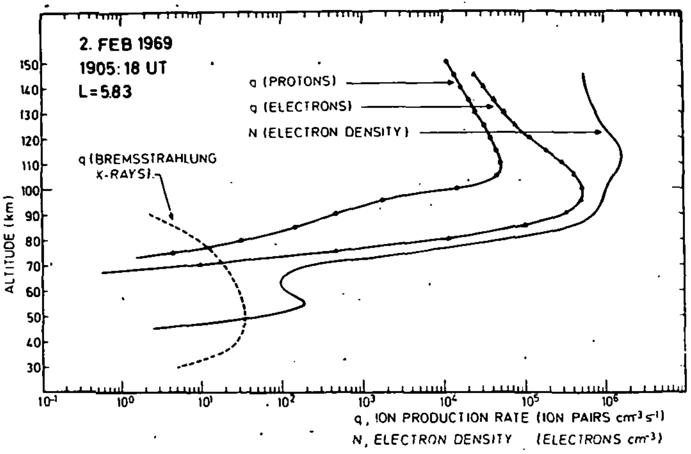

FIGURE 8.—The ion production rates and electron density profile during a substorm of February 2, 1969 (after Larsen, 1973). The ion production rate ζ is in ion pairs cm^{-3} s^{-1} and the electron density N is in electrons cm^{-3}.

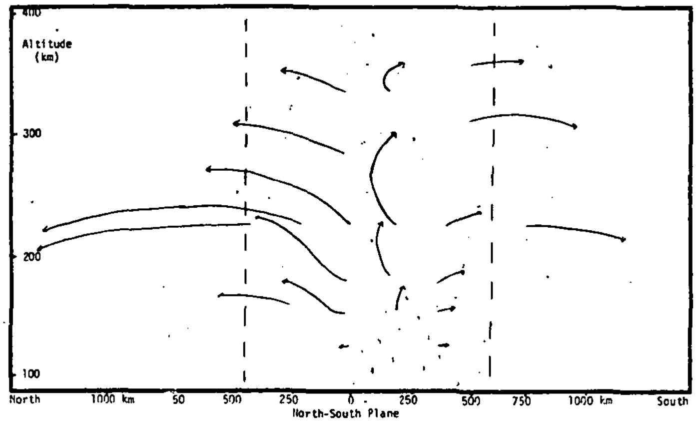

FIGURE 9.—The upwelling of the upper atmospheric gas in the meridian plane, generated by the heating by the impact of auroral electrons and joule heating. The arrows indicate displacements of the air parcels for a period of 12 hr (after Heaps, 1972).

phenomenon called the polar cap absorption (PCA). In terms of the ion production rate in the mesosphere, they can have a greater effect than the bremsstrahlung 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 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.

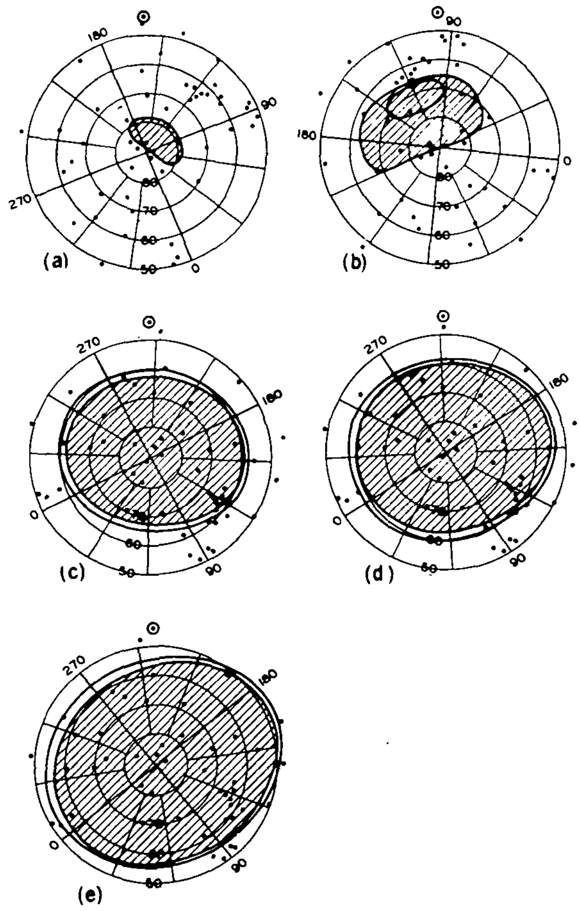

FIGURE 10.—The development of PCA during the geomagnetic storm of February 11, 1958 (after Obayashi and Hakura, 1960). (*a*) 0700, February 10, 10 hr after flare. (*b*) 1100, February 11, 14 hr later. (*c*) 0115, February 11. (*d*) 0130, February 11. First sudden storm commencement. (*e*) 0215, February 11. Second sudden storm commencement.

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

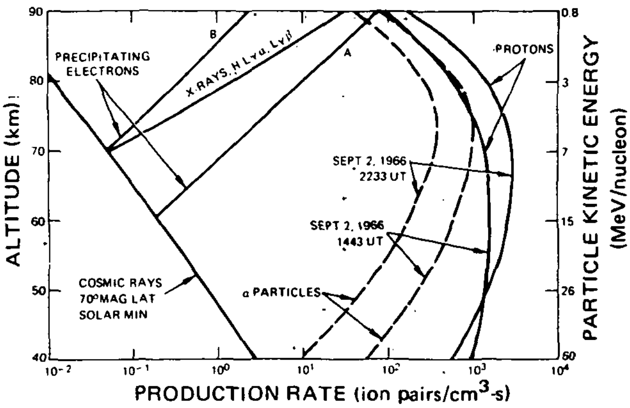

FIGURE 11.—The ion production rate by solar protons during several PCA events (after Amuda and Potemra, 1972).

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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DISCUSSION

STURROCK: What is intriguing about auroras is that there have been reports over many years of sound being produced and the data in the journals seems to be inconclusive. I would like to ask you to express your views on the subject.

AKASOFU: 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 an aurora, particularly moving equatorwise, you see the shock waves. Of course those are of very low frequency, so you cannot hear them.

As far as the audible range is concerned, even a few weeks ago somebody called me and said he heard an aurora. Nevertheless, with the tremendous progress in electronics and audio techniques, no one had ever detected the sound with modern instruments. And I do not know what the trouble is. I understand that the human ear is much better than any available audio instrument. Is that true? I do not 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 cannot see it. And during the aurora the dog howls! That is about the state of the art.

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?

AKASOFU: You know I cannot 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 day side and the night side.

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, is the electric current coming toward the atmosphere and going away from it? I believe there must be a transition between these two cases.

AKASOFU: The gap is in terms of fieldline currents, but the fieldline currents come in from the morning side and then flow around the oval and the midnight region, the auroral electrojet. Of course, this is my personal view; there are so many different systems that people draw; I do not know which is right. But my personal feeling is that what you think the gap is, is the region of the electrojet.

N76 14552

Two Possible Mechanisms for Relating Terrestrial Atmospheric Circulation to Solar Disturbances

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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 sec. The angular momentum contributed to a cell may then conceivably be as great as 10^{29} g cm^2/sec. 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 by viscous effects or by 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 studied by Wilcox et al. (1973) may themselves be analyzed 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 by unknown emission, transmission and reflection coefficients.

Mechanisms that require planetary-wave coupling between troposphere and thermosphere, such as the first may require and the second must require, could not be effective during the summer months because of absorption of the waves at intervening "critical" levels during those months. Such mechanisms would 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.

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, 1974*a.*) The statement in the foregoing abstract referred to the torque acting on 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} g cm^2/sec 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/sec 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/sec $=$ 5.8×10^{28} g cm^2/sec.

Among the difficulties under contemplation in my abstract for this mechanism was inefficient coupling. My own estimates in the problem of magnetospheric rotation (Hines, 1974*a*) 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/sec^2, which, when combined with the moment of inertia cited above, implies a maximum operative torque of 2.9×10^{13} kg m^2/sec^2 $= 2.9 \times 10^{20}$ 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 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 to 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 (Hines, 1974*b*).

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N76 14553

Correlations and Linkages Between the Sun and the Earth's Atmosphere: Needed Measurements and Observations

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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 lead 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:

(1) To suggest processes that must be related to each other by establishing significant *correlations* in their behavior.
(2) 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: (1) suggests where the theoreticians should look for linkages; (2) 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, because a great fund of information already exists. 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

TABLE 1.—*Available Indices of Changing Inputs to the Atmosphere*

Point of observation	Indices		
	Magnetosphere	Solar wind	Sun
Surface of the Earth	K_p, C_i ([a]) Auroral activity Ionospheric features Radio wave absorption Ion and electron temperatures	Galactic cosmic rays Magnetic sector boundary crossings from polar magnetograms	Sunspots Solar flares (observed from H_α emission) 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 to 3000 Å) Extreme UV (900 to 1800 Å) Soft X-rays (10 to 900 Å) Hard X-rays (<10 Å) Gamma rays (?)
Interplanetary probes		Interplanetary magnetic sector structure Plasma shock waves	

[a] C_i = arithmetic mean of the subjective classification by observatories of each day's magnetic activity.

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 travel from the Sun at 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 belts by wave-plasma interactions. (We are excluding here for the moment the very high energy "solar cosmic rays" and true cosmic rays.)

TABLE 2.—*Average Lags of Events in Upper Atmosphere Occurring After Solar Flares*

[References: King-Hele (1962); Matsushita (1959); Allen (1948); Vestine (1960)]

Event	Lag, days
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 to 1
Increased density and temperature in upper thermosphere (satellite drag increases, and such)	1
Magnetic storm, main phase	1 to 2
Ionospheric storm (for example, decrease in f_0 F2 at 45° latitude and above)	1 to 2

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.) Although the passages of the sector boundaries are statistically associated 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 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-yr 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 directly reaches the Earth's surface, and that is galactic cosmic rays. They 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 here we are interested 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 it in the form of energetic particles or electromagnetic radiation, or by dynamical interactions between layers of the atmosphere. These processes seem 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 keV 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 sec 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 particles derive their energies from the solar wind, though usually indirectly. Apparently there is 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 very low frequency (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 sec 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

TABLE 3.—*Minimum Penetration Altitudes of Incoming Protons and Electrons*

Initial energy, keV	Penetration altitude	
	Electrons, km	Protons, km
1		156
10	98.5	122
100	77.5	105
300	67.0	98
$>10^5$ (or 0.1 GeV)	Tropopause	

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 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 sec 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 sec (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 (the 300-mb level, say) and initiating the formation of cirrus clouds before they would otherwise form (Roberts and Olson, 1973). The resulting cloudiness would change the heat balance of the troposphere, it is argued, and that 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 from ionizing radiation penetrating to the upper troposphere, and that is the increase that it would cause in the 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 condition 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 effect 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 fig. 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

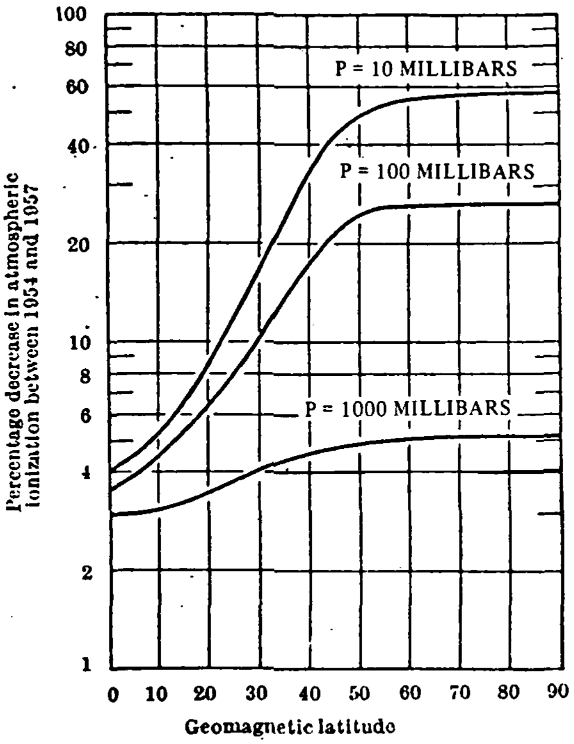

FIGURE 1.—Percent of reduction in atmospheric ionization during the last solar cycle. The percent of change is calculated with respect to the value of the ionization at sunspot minimum in 1954 (Ney, 1959). *P* is atmospheric pressure.

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; fig. 2, Sparrow and Ney, 1971), in spite of the established fact (fig. 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 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 groups of Naval Research Laboratory (NRL) and Air Force Cambridge Research Laboratories (AFCRL) 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, because with wavelengths less than 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).

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 Lyman alpha radiation (L_a), is about 3 ergs/cm^2 sec, and the L_a flux around 1210 Å is 3 to 6 ergs/cm^2 sec. In the Schumann-Runge continuum between about 1310 and 2100 Å, the flux is about 240 ergs/cm^2 sec.

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 (fig. 6), and the total flux involved when the Sun is directly overhead is about 17 W/m^2, or 1.2 percent of the 1400 W/m^2 solar constant (1 W/m^2 = 10^3 ergs/cm^2 sec).

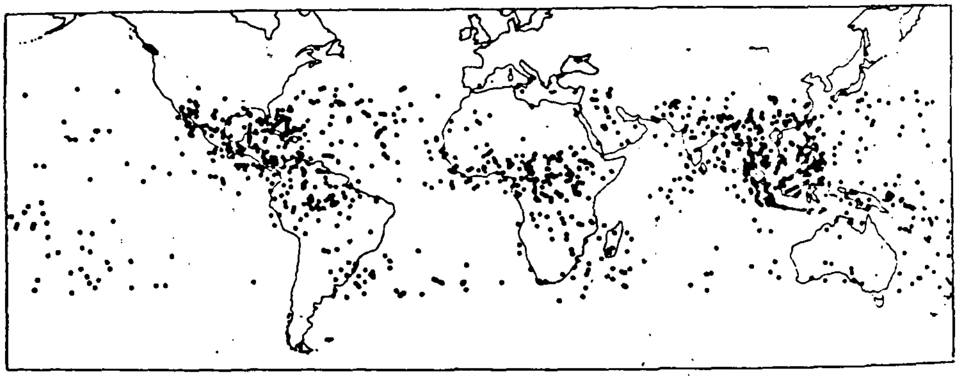

FIGURE 2.—Distribution of nighttime lightning storm complexes observed by photometers on board satellite OSO 5 (Sparrow and Ney, 1971).

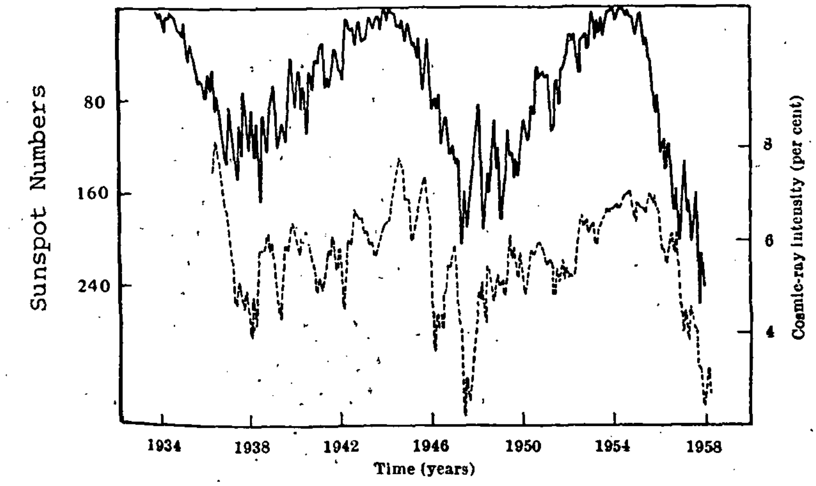

FIGURE. 3.—Illustrating the "Forbush effect," the inverse correlation of cosmic ray flux and solar activity. Solid line is sunspot number; dashed line is relative cosmic ray intensity (Forbush, 1957).

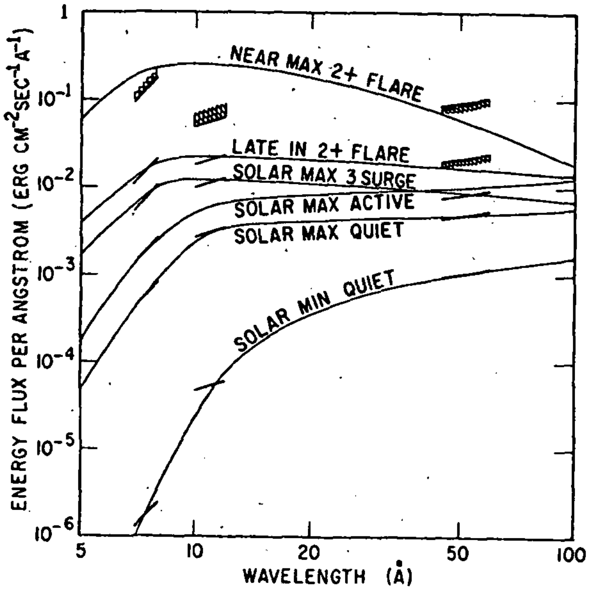

FIGURE 4.—Solar X-ray emission for various solar conditions. The curves indicate the approximate energy distributions for sunspot minimum, sunspot maximum, and solar flare conditions. The curves are drawn on the basis of measurements made in three wavelength bands, as indicated by the heavy bar segments. 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 Earth's absorbing atmosphere (Friedman, 1964).

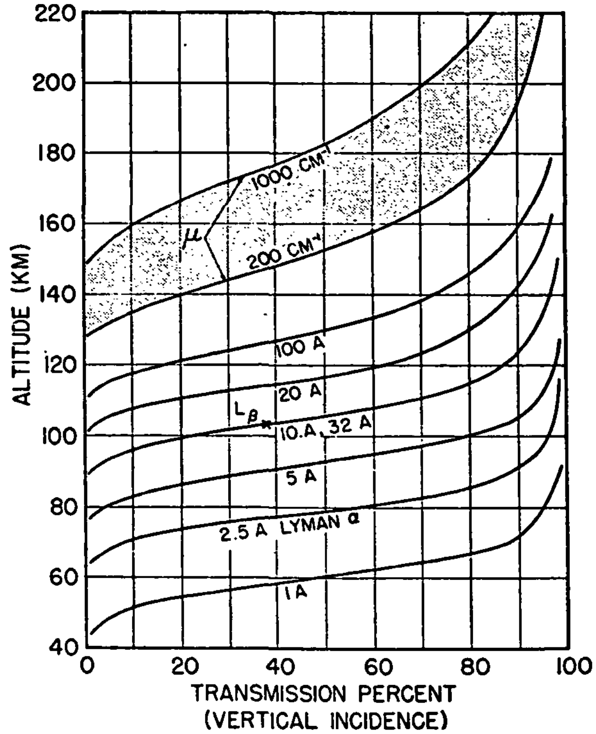

FIGURE 5.—Penetration of the atmosphere by solar X-rays and UV radiation. The shaded portion includes the broad range of wavelengths from 100 to 850 Å for which the linear absorption coefficients μ lies between 200 and 1000 cm^{-1} (Friedman, 1964).

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- to 3000-Å radiation would amount to 170 ergs/cm^2 sec, 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.

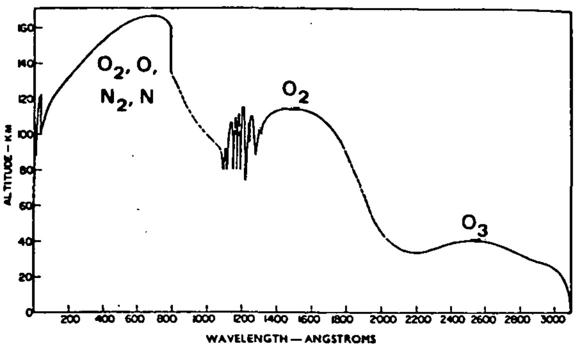

FIGURE 6.—Penetration of solar radiation into the atmosphere. The curve indicates the level at which the intensity is reduced to e^{-1}. Absorption for wavelengths greater than 2000 Å is principally due to ozone, for those between 850 and 2000 Å, to molecular oxygen, and for those less than 850 Å, to all constituents (Friedman, 1960).

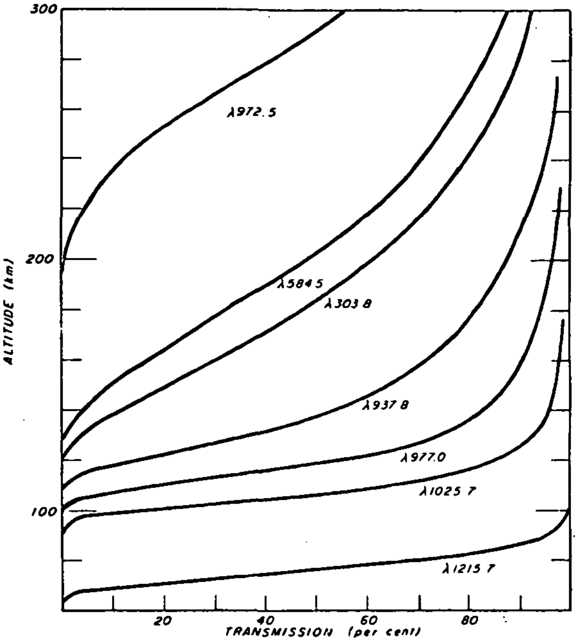

FIGURE 7.—Penetration of the atmosphere by solar UV radiation (Watanabe and Hinteregger, 1962).

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 mesosphere or thermosphere. However, because the 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 preferred direction of transport of energy and momentum 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.

Here are some observations that would help us to establish whether such linkage mechanisms make sense—and we realize that some of these observations have been or are about to be made:

(1) 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.

(2) 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's and Pommereau's experiment (Blamont and Pommereau, 1972).)

(3) 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.)

(4) 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.

(5) 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:

(1) Cirrus formation at 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 make observations of cirrus formation by the second alternative.

(2) 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).

(3) 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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DISCUSSION

HAURWITZ: I do not think I understood the role played by gravity waves. Now, if I followed you correctly, 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 situation should not produce a noticeable effect on the ground.

So I really do not understand how the effect would work. I realize it is really unfair to ask, because you are not Colin Hines and you have only read his abstract, but I thought I would just mention my objection.

KELLOGG: I can only point out one fact. One of the difficulties the general circulation modelers have if they do not 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.

HAURWITZ: The models which reflect all the energy really do not compare to what I think we are talking about here. We would, in any case, only get a small fraction of the upward-moving energy reflected. I simply do not believe that this energy is very much and that it could have any effect.

It might be interesting to see and, if possible, to make some observations of whether gravity waves at say, 100 or 150 km, 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.

HINES (subsequent correspondence): Some of the strongest ionospheric gravity waves do indeed occur as a consequence of auroral electrojets or related phenomena, and in some cases the aurorally associated gravity waves appear to have been detected at ground level. My proposed mechanism did not call upon gravity waves, however, whether generated at low or at high altitudes. I do not favor them as a Sun-weather coupling mechanism for much the same reason as that given by Dr. Haurwitz, though I would point out that their relevance should be judged by way of their energy flux, integrated over a period of time, rather than by way of their energy density. My proposed mechanism called only upon planetary waves, which do have adequate energy since it is they themselves that are to be modified. It is perfectly possible that their upward energy flux and their reflection coefficients on high are of inadequate strength to result in much modification at the tropopause under varying solar conditions; but the observations they are being called upon to explain are revealed (if at all) only statistically and so have no right to demand of a mechanism much power of modification.

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 region of the spectrum 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 cannot quote figures for the modulation in the region around 2000 Å, but in the extreme ultraviolet, Lyman-alpha, for example, typical fluctuations of 10 percent are certainly reasonable. I do not believe we can rule out fluctuations of several percent in the 2000-Å region, where, in fact, you are beginning to see these plages as rather strongly emitting above the continuum quiet Sun.

KELLOGG: What is the change that you might imagine in the solar constant, which of course includes everything, the UV, visible, and IR?

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.

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 1 yr of the total ozone data for every day of the year from 80° to −80°. 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 external system that they may be correlated with.

We do see that in the wintertime, especially in the southern hemisphere, 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° 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.

KELLOGG: You see how fast this field progresses. Here I am suggesting an observation be made that has been made. I will very much look forward to seeing the data, though.

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. The columnar resistance above 10 km is about 10 percent the total columnar resistance, and at 20 km 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 finally, a comment on the idea that the thunderstorm variation over the world could be measured from places like the Zugspitze 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 the diurnal variation immediately.

Robert Anderson of the Naval Research Laboratory and I made measurements simultaneously, 7000 km apart, and our data correlated at the 99-percent significance level. And I think this agreement 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.

KELLOGG: I would just like to make one comment on what you said. 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 is not enough to say that thunderstorms change. I agree with you, thunderstorms change, but what made them change?

MARKSON: If you are sitting over a thunderstorm, and concurrent with the arrival of particles that change the production rate, which change the conductivity, and see that the current goes up from that thunderstorm, I think you have a clue to what might be causing the effect.

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Session 4

PANEL DISCUSSION – WHAT FUTURE CRITICAL MEASUREMENTS, EXPERIMENTS, AND THEORETICAL WORK ARE NEEDED, AND WHICH OF THESE CAN BE ACCOMPLISHED BEST FROM SPACE?

Chairman: Morris Tepper

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. The second would be explore and search for possible mechanisms. The third part would be to investigate what future critical measurements, experiments, and theoretical work are needed, and which of these can best be accomplished from space. This is the subject of this panel discussion.

LONDON: So much has been said in the last 2 days, and in a sense some of this was so well summarized in the suggestions of Kellogg that it leaves us very little to add. I will simply 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.

My own personal feeling about a possible solar/weather relationship was emphasized by the discussion of Somerville: The atmosphere has a tremendous inertia, a normal relaxation time of the order of 30 days; therefore—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 that every time Roberts tries to take some more data to disprove what he has done, the statistical certainty gets a little bit higher.

I think that Roberts is very lucky. Haurwitz has 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 that if there were a direct heating of the stratosphere, as a result of solar flare or other solar activity, this would produce a temperature rise in the stratosphere, and because 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 yr if I remember correctly, we ran the correlation coefficient, and unfortunately it was 0.2, which for the number of data points was significant between a 1- and 5-percent level. We were disturbed. Fortunately, Haurwitz had an old friend, an astronomer, who had published a list of sunspot activity that went way back. At that time he sunspot data, for which he had 5 yr of data from went to the library, picked up an additional 5 yr of Batavia on the lunar semidiurnal tide, put the extra five data points in, and we were very fortunate. The correlation coefficient went to zero. This, incidentally, we published in the *Journal of Geophysical Research.* Let me point to some physical relationships that one can expect, and perhaps should look for, that 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 observations from satellites of the absolute magnitude and the time period variation of the solar constant, if any. I think it is almost criminal that this has not been done so far. It is an observation that simply has to be made. One has to, once and for all, determine whether there is any kind of variation. Now, this does not mean that there will be no variation from some parts of the spectrum. We have already had ample discussion of this, and I think that the type of observation Don Heath is making should be made by other people; that is, there should be independent verification of the Nimbus system of observations. We need some independent verification because the results that he has shown are so important in their implication of at least an atmospheric effect that could be felt at 60 or 70 km.

We know that Lyman-alpha radiation can directly affect the dissociation of water vapor that is found at 60 or 70 km. There is a molecular oxygen window in this region, and there can be penetration by Lyman-alpha down to levels of 60 or 70 km. Water vapor being dissociated in this way forms hydroxyl molecules that will have, at this level, deleterious effects on ozone. 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. 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 has an opposite effect to that of hydrogen. That is, we get atomic oxygen, which then recombines with molecular oxygen to form ozone; and we could get, therefore, an increased amount of ozone as the result of particle precipitation. The point here is that now the relaxation time is long if it is on the dark side because there is no photodissociation present. So we would get completely different effects as the result of both of these mechanisms.

There are two other kinds of observations that I think are important.

There are many types of trapping phenomenon that take place in the atmosphere. One, for instance, takes place at the base of the stratosphere. This is a kind of trapped energy that is at least thought by some to be indirectly responsible for the quasi-biennial oscillation. Therefore, changes in the energetics, in the radiation budget, in the composition of the atmosphere at levels of about 18 ot 25 km could have some type of resonant or reflecting effect that will be important, not for the short period, but for long-period variations.

The quasi-biennial oscillation is of the order of 24 to 30 or 33 months. If one has a suitable forcing function, there can be within the stratosphere some type of resonant response.

A set of observations, I would suggest, therefore, is one that directly affects the stratosphere. 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 also suggest that we make all attempts at getting a measure of the ionization rate and 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. As I have indicated, there are two opposite ideas 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, 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 ionization at these levels to be able to produce some type of an effect. If these are going to be felt in terms of ozone variations, it would seem to me that the most important thing to do is measure the ozone and ionization rate simultaneously at this level.

I would like to endorse the efforts of Heath and his colleagues in NASA in continuing the observations of the vertical distribution of ozone and the total ozone amount from satellites. 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 1925. Therefore, if we can find something in present observations, by necessity a short observational period, then we can possibly extrapolate backward 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.

PARKER: Speaking as an amateur—I guess a lot of us are amateurs in this field although 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 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 that 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.

However, sometimes, they are strikingly large. They are always very subtle and difficult to get at, but nonetheless important in some way to 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. As 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 Earth's atmosphere. 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 move back and forth between these patterns, implying some kind of an instability. Several people have mentioned resonances of various kinds. These are simply properties of the system in which a small push of one kind or another can make a big change in the weather.

On the other hand, there are the mechanisms that are best represented by the idea, I guess first suggested by Roberts, that perhaps extra ionization in the atmosphere leads to nucleation formation of high cirrus clouds. Therefore, with a very small expenditure of energy you have built in a feature that then brings on the greenhouse effect, and the Sun does the rest. 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 10 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 I think that here is a case where the payoff will be tremendous. It is going to involve a lot of exploration before we can even talk intelligibly about it and before we can concentrate on more than one or two exploratory programs.

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 from 1645 to 1715, a period of about 70 yr. Telescopes were available during this time. (I remember Galileo invented the telescope in about 1500.) Sunspots were known, and records were kept. I am not a historian, but my impression from reading articles is that records 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-yr period, starting in 1645, the sunspot cycle was there, the general 11-yr half-cycle was apparent, but the number of sunspots that appeared were extremely small and they appeared only in one hemisphere. There were 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 rather than the fairly large number that you see now. Remember that in the Scandinavian countries, which were active in scientific matters in those days, auroras are a very common occurrence. Therefore, if they recorded very few auroras, then, the indications are there were very few. I have no way of verifying these reports. The papers that comment on them are very vague about their references. They merely say, "The records show." It seems that, however, unless something really has gone wrong here, the Sun was extremely inactive during that period of time. Now it is a little hard to assess just how inactive it was.

There are some clues as to the weather, although the weather records are, of course, very poor from those times. There were apparently some worldwide changes in mean temperature, which have caused people to wonder whether they 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. Because we humans are foolishly pressing on both the mineral and food reserves of this world by continually increasing our population, leaving less and less in reserve in event of 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 urgent in the long-range sense. That is, it is something we must follow if we want to foresee and plan intelligently for our future.

NORDBERG: What Kellogg said agreed, in large part, with my thoughts. 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 processes and the weather. That would not necessarily confine itself to the Sun, because it is really interplanetary space when we talk about extraterrestrial phenomena processes. However, it would leave out the very enthusiastically discussed subject of gravity wave propagation or propagation from the ground up and maybe mysteriously coming down again. It leaves it out conveniently, because I really do agree with Haurwitz's introductory remarks to this question that it is unfair to address it amongst each other when Hines, the proponent of that idea, is absent. 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. Depending on whether you believe in it or not, it will go in one direction or the other. My conviction is really very much based on the evidence that you have heard expressed by 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 Tepper 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. 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 foregt 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 yr from now there will be another panel discussing it. That is as far as I would go in prediction.

Therefore, we are dealing mainly with the process of moving 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 enables you to specify better your observational parameters. You go back to the observation. Eventually a model will result from this upon which you make some predictions. Now, as was already alluded to in previous discussions, both the observation and the understanding cover a very wide range of spectra. 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? If you limit the domain, say, to either the interplanetary structural 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 interplanetary, magnetic field structures and particle physics. I was very impressed when I listened to some of the talks by how much has happened, particularly since the International Geophysical Year, but perhaps even more so in the last 5 or 6 yr. 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. 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 '70's.

A similar situation exists in the understanding area. The models you heard about and caught a glimpse of 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 lacking, and in forming 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. I am becoming very subjective; I am filtering what I liked to hear or thought I heard in these various presentations when I come to defining where I think we stand. Therefore, do not spend much time proving that I was wrong or that I misunderstood—I will agree with you perhaps. Instead, 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 demontrated 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 that I believe are significant. What we want to do, of course, is to push them forward to the next step. I think the next step is to have some qualitative picture from which then will result in a better understanding, which will lead to specifications for very selective quantitative measurements, and then to the complete quantitative picture.

In the area of understanding, 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 would be something as follows. 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. This is the process, or the educated guess of a process, that I would like to concentrate on and 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, 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 start with that in a deductive way. I would rather discuss what has to be done next to understand better these processes and phenomena, and that leads back to the observation system.

In the area of understanding of models and analysis, I would like to see a much more concerted and organized effort to investigate the feasibility quantitatively 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 Kellogg presented this morning was any measure of the status in this area. I do not think it 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 expended 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 we go to the parallel requirements for observations in the first area of understanding that I mentioned, investigation of the feasibility of producing these ionizations and chemical processes, we want to observe the occurrence of these processes. Such observations would also lead to quantitative measurements 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. As far as I know, the only thing that has been done in that area quantitatively on that kind of scale was the ozone measurements that London referred to by Heath. Of course, others have done ozone measurements too, but I think the Nimbus 4 set of measurements by Heath was probably the most complete, and certainly the largest data set on a temporal global scale.

We have data now for about 4 yr of the ozone structure. But the ozone structure is just a small part of the problem, and, in addition, there have been no measurements of the chemical structure of the stratosphere made on the kind of scale that comes 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 the 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 do not really know how we could get a good, complete, long-term set of global observations of radiative flux divergences. We have struggled with this ever since the first meteorological satellite was conceived. Bandeen is one who knows that very well, and the entire platoon of London's students has been put to work from the early '60's to help us derive some flux divergence 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.

Finally, on the cloudiness variations, some of you may be disappointed that I am pessimistic about it, or that I am saying we really have not obtained any global cloudiness observations, because after all that is what we observed with TIROS 1. But those of you who heard Bandeen 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, ice or water content, and thicknesses. These characteristics have not been observed in any way from a satellite so far. It is only being inferred in secondary and tertiary ways. Roberts attempted to analyze this very phenomenon on the basis of a data set compiled with Nimbus 4. 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 F, which will be flying 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 sometime in the early '80's 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 longer, from measurement on what we call the Synchronous Earth Observatory Satellite (SEOS), which is not scheduled until the 1980's.

I would like to recommend the observation of something that I alluded to when I talked about resonances and forcing functions and the relationship between the sector boundary passages and the planetary waves. Although I am not able to specify the observation to be made, in essence, we should be thinking about what approach to take, rather than what instrument, and this approach would be to expand or concentrate our statistical analysis on that forcing function-resonance relationship; namely, a resonance between the spectra. I emphasize now the spectra: the frequency spectrum of magnetic sector boundary passages and the spectrum of tropospheric cyclogenesis.

AKASOFU: I do not do statistics myself, but I have a list of people who do statistics in this particular field. I think we are in a stage of trying to eliminate various possibilities and trying to reduce the possibilities and eliminate the very obvious. And I hope in this way that you do not eliminate everything. I think the geomagnetic activity index K_p seemed to correlate everything. This is the beginning of the trouble.

First of all, I would like to see Roberts' drought case. He indicated a 22-yr period, and K_p is obviously

11 yr. 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 K_p or something else. We can think of the solar interaction in two ways: one is a radiation coupling and the other is an electromagnetic coupling. We should try to find some means to eliminate the various obvious possibilities and reduce the parameters that 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 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 IR methods or rockets, also theoretical studies like Maeda did. I would like to know if ozone changes or does not change after aurora activity.

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 $H_3O^+ \cdot (H_2O)_n$. I fiind it a 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.

I am studying the aurora, and I like to see that what I am doing has something to do with society. I would like to see that the aurora does affect the weather, but we cannot just jump into the weather study. We have to understand the "aurorasphere." I think we have progressed tremendously during the last 5 yr in understanding thunderstorms, but still there is a lot to be done, and we cannot, we should not, skip that to concentrate on weather alone. If we do, we have to go back and do the same thing again.

KELLOGG: Somebody asked about the flux of gravity wave energy. Miller from the Air Resources Lab of the National Oceanic and Atmospheric Administration (NOAA) said he had a number, for which I am grateful, and it is 300 ergs/cm^2 · s.

In connection with the matter of looking at cirrus clouds from satellites, Hunt is doing work with the British scanning selective chopper radiometer, in 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 it is going to be a step forward in this particular field. It is obviously important.

One final small remark in connection with Parker's interest in the possibility of solar anomaly in the 1645 to 1715 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 does not mean that the Sun did not 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 yr before the period that you are referring to.

WILCOX: I also would like to see the kind of observations that 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.

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. For the black box I would propose 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. 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 Earth in the solar wind and interplanetary field, which can be timed or phased accurately with regard to the time in the sector boundary. For a few days before the boundary, for example, we have a declining solar wind velocity and interplanetary field magnitude; for a few days after the boundary, we have increases in these quantities, and all in all it tends to repeat fairly well. We are hitting this black box again and aegain 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. 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.

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 4½ days for the solar wind to transport the interplanetary field and, therefore, these patterns from the Sun to Earth would seem to allow some good possibility for forecasting, as we begin to understand better the results of the sector structure.

For this purpose, and also to aid our fundamental understanding, it would seem that we should encourage the appropriate solar observation. I cannot 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 Prof. Severny. Because these are 11 hr apart in time, one will have almost continuous solar observations.

With regard to the 20-yr 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. Because these geomagnetic observations go back without interruption to 1926 at the station of the Danish Meteorological Institute in Godhaven, this gives one five sunspot cycles to work with and makes it possible to start having a little more realistic look at things like that 22-yr cycle.

DESSLER: London showed me a review paper he had written 20 yr ago, and it reads 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.

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-yr 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 greatly in defining the question that you wish solved and the mechanism to explain what is going on.

One comment on the experiments Nordberg suggested, about putting something in the stratosphere to see the effects, I come back to my favorite—volcanoes. Volcanoes do this. True, they do not work on a programed 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.

There was one who presented the growing season. The length of the growing season had an 11-yr variation: temperature, rainfall, and others. The experiment struck me as perhaps like the spectroscopies of 50 yr 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.

I have one more question or suggestion for an experiment. Meteorologically speaking, are magnetic storms different in their behavior? Another thing is the suggestion that cosmic rays coming down in the atmosphere might affect the conductivity of altitudes of 20 to 30 km. There is a possibility there. Perhaps meteorological phenomena could be keyed on 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 of about 30 km. 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. We should investigate some kind of an effect.

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 is represented here, and I think it is a healthy sign for the field.

ROBERTS: I want to speak about three observations that I would like very much to see made 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 do not involve new observations. Before I do that, I want to make a 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. 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 Shapiro said yesterday and emphasize that it seems to me that we must try to look for the solar influence on climate by looking for short-term responses of the atmosphere to solar activity impulses. Second, it seems to me that we ought to work wherever possible from some kind of working hypothesis no matter how naive it may be. I am tremendously gratified by the number of ideas that have been submitted here that I think could be forged into good working hypotheses that will render themselves susceptible of observational test, which seems to me should be the name of the game from here on.

Nordberg referred to the one that is nearest to my heart, which I would like to see, above all else, in the near future, and I do not want to wait until 1980. I would like to see IR data for two winter seasons. I do not 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 IR radiation flux from Earth to space in two wavelengths: one in the water vapor window and one down around 6 μm. It would be a tremendous step forward in trying to establish whether some kind of solar modulation of the IR flux is causing lower atmosphere responses. And for the last 2 yr, in spite of the most valiant efforts of NOAA and NASA, Olson and I have been unable to get our hands on 6 months of data for the winter of 1971. 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. I would like to see that done and I would like to see if the IR results are positive, insuring a connection between solar activity and 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 would like to make is that 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. I do not know enough about this to know—I should ask Markson—if they can be completely free of bias that has to do with the collection; for example, sferics due to changes in ionospheric reflectivity or something like that. In other words, the thunderstorm frequency data needed should be independent of solar activity related to the frequency of occurrence of the thunderstorms themselves.

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 Data Acquisition and Processing Program (DAPP) satellite or from some other satellite, thunderstorm frequency by day as well as by night. I do not know if this is possible. If it is not, 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 important.

Third, I would like to see some observations made that might be extremely simple. These observations would be to verify and to extend the time series of the observations by Blamont and Pomerantz who flew two geiger counters at 100-millibar altitude and apparently found widespread over Earth in the Southern Hemisphere increases of ionization of about a factor of 3, lasting for about a day or a day and a half. 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-km altitude, it is tremendously important for us to have homogeneous coverage of this sort of thing. I do not know whether it could be done from satellite, but I think it is a terribly important observation.

Now I will discuss two pieces of work to be done. 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 or some other useful parameter like the change of pressure from one day to the next can be added together so that you get superimposed epic map building related to various key dates. I think the key dates that ought to be looked at should be the sector boundaries that Wilcox has pointed out forcefully.

I think we should also look at magnetic storms, both the type that are associated with sector boundaries and all other magnetic storms. 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 examined 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 entire Northern Hemisphere. I think it is particularly important to do it in the area of the Gulf of Alaska and the Alaska Peninsula, the area of North America east of this, and also in the region from Iceland to Scandinavia. I am pleased that Shapiro is doing some new work in this. I hope that work prospers, and I am also very 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 Somerville was telling us about: numerical modeling experiments. I think these hold enormous promise for us in testing working hypotheses in the future. I cannot overemphasize the importance, and I cannot overemphasize my discouragement about how the models work so far. I am terribly disappointed, for example, that in my own modeling experiments in which, with Shapiro's and Olson's help, we introduced an auroral zone heat source and a heat source that was slightly more sophisticated 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 Somerville and his colleagues, our group at the National Center for Atmospheric Research, Mintz, Smag, and everybody else involved get busy and make good enough models to simulate these effects.

ROBERTS: I asked Akasofu a question about thunderstorms.

AKASOFU: I do not remember now precisely, but the photographs are very distinct, sharp, and could be used for that purpose.

KELLOGG: The DAPP has extremely high resolution. That means it also scans very fast, and so it is only looking at one element for about a microsecond.

ROBERTS: I was talking with Jean a few days ago, and it was his impression that there might be suitable means for observing from satellites thunderstorm flashes by daylight. If this is so, I would like to know if this is the best way to get this kind of data. Maybe there are much cheaper and simpler ways to get uniform thunderstorm coverage. What is the best way?

NORBERG: I agree with Kellogg's answer. From the kind of instruments you have on DAPP, which would be scanning instruments, you could not possibly expect to get such data. That does not mean it is impossible, I am quite sure it can be done. Battan, I believe it was, proposed years ago an H_α experiment to measure the emission in that line, and it was shown on paper at least to be feasible.

DESSLER: The major question about vertical propagation of energy by waves, of course, is how important are these waves. That is the point I guess everyone wants discussed. Somerville determined that any kinetic energy in the atmosphere is really reacting to the small difference between several large terms. Incoming baroclinic energy is of the order of several thousand ergs per square centimeter per second. This is essentially balanced by frictional factors. Baroclinic energy conversion is about several hundred ergs per square centimeter per second. In net effect, I would say that this vertical energy flux can be as important, and how important on this particular point I would not want to question Hines.

SVALGAARD: 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. If people have candidate physical mechanisms, whether or not they are currently representable by the model, then I think you should encourage your modeler to incorporate them in his program.

If you have a mechanism (volcanism, for example), if you have a clear-cut way in which you think solar effect might be manifest through volcanism, and if it is clear cut 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. 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 Wilcox was saying about having sector boundary crossings as a standard input to the black box, we ought to agree also on some standard output.

For example, vorticity indices are useful research measures, but the public will not pay for a forecast of vorticity area indices. I would like to see correlations made of solar indices with meteorologically practical important phenomena.

It may be that, as far as the short range is concerned, 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 will not be useful. I hope that that kind of correlation can be made more accurate as well.

NOYES: I want to expand on the comments of 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 in the talk by Hundhausen, 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. Hundhausen and I were talking yesterday, and I was expressing the possibility that the holes might be the source of the wind, 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. Nordberg 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 4 days traveltime plus perhaps 5 days worth of rotation before the effect actually strikes Earth.

I really think that we are on the threshold 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.

POLK: Roberts pointed out the importance of measuring lightning activity. A few years ago it was suggested that Schumann resonances—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. Although they somewhat disagree with other published studies, they do not disagree very badly, and, actually, the data are 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.

Schumann's resonances, if treated analytically differently, can also be useful to obtain information about the average electrical conductivity of the altitude range between ground level and 40 km. You do not get a profile, you just get an average value for the conductivity, which, of course, depends upon ionization. We did this for a fair amount of data, and we get consistently a conductivity about three times the value one would get from a Cole-Pierce model, which indicates there is something above 20 km where you do not really know the ionization very well, which seems to be higher, greater ion density than what would be predicted by the Cole-Pierce model.

BOWEN: This is a subject I have not been involved with for 3 to 5 yr, and I am very pleased indeed to see such an enlightened discussion as we have had in the last couple of days. However, I believe I can add one or two things to this discussion.

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 discussions that we are still looking for the 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, and others, but there is one conspicuous subject that has hardly been mentioned. Now, what we are looking for is something that exists in the environment around Earth—let's forget the Sun for the moment—something capable of coming down through Earth's atmosphere in a very definite way, and something that, when it arrives in the lower atmosphere, is capable of triggering large amounts of energy. The answer is dust, there is plenty of dust around Earth. It falls into the atmosphere. I am talking about particles big enough to fall on the gravitational field. They will fall 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 will not do a thing. On the other hand, if you have a nice tropical storm built up, which is not going to disappear of its own volition, and the dust drops into it, then you will get enormous releases of latent heat with the water that is dropped out of that storm.

I have forgotten my figures, but the energy is equivalent to that of the release of several atom bombs into that system. I have not yet referred this to the Sun, but surely we are going through a field of dust in the planetary field itself that is variable in intensity, spotted, of course. Surely the Sun is having some effect on that interplanetary dust.

WILCOX: I would like to respond briefly to 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 observations, 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.

Also, on the interplanetary part, we have in 2 or 3 yr a big improvement scheduled in something called the International Magnetospheric Explorer, a collaborative project with NASA and the European States Research Organization. One of its spacecraft is called Heliocentric, and it is orbiting the Sun, but it remains very close to 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 the interplanetary field. Particularly, as Noyes 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.

My 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.

WILCOX: I would just like to emphasize to 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 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.

ROBERTS: I wanted to say just a word to Bowen also. I noticed very carefully that he did not use the word "meteor" in speaking of interplanetary dust; and, of course, if Hemenway were here he would talk about dust of a different origin, dust from the Sun. But that is another story.

DESSLER: I just wanted to ask, what is the status of that theory now? I remember reading about it 15 yr ago. 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?

BOWEN: I would rather you did not use the word meteor dust because that raises hackles in certain directions, but in answer to the question about 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. Certainly all the meteorological professors of this world disagree, but that does not bother me.

DESSLER: Why is that? Because they could not reproduce the results?

BOWEN: I will give you the answer in private.

MARKSON: Roberts wanted some comments on monitoring worldwide thunderstorm activity, and I think he was particularly interested in the possibilities of doing so from satellites. Currently work is proceeding at three or four ground stations in different parts of the world using the Berlin sferics analyzer. This network covers a large portion of Earth, and the plan is to eventually have worldwide coverage. So far, one might say this instrumentation gives a qualitative feel for the variation of worldwide thunderstorm activity. But problems have come up getting this program going and I think it will be difficult to measure global thunderstorm activity this way. Satellite instrumentation has been used to count lightning flashes as mentioned in Kellogg's talk. But these observations only count visible lightning external to or near the outer boundary of a thunderstorm cloud. Most of the flashes are within the cloud and may be missed. The percentage not recorded would increase with the size of the cloud because, assuming a spherical cloud, surface area is proportional to radius squared while volume is proportional to radius cubed. This could weight the data so that the largest thunderstorms near the equator appear to be weaker than they really are. Another problem with obtaining an index of worldwide thunderstorm activity by optical observation from satellites is that at a given time only measurements on the nightside of Earth can be obtained. To help define possible solar/meteorological mechanisms, it is desirable to have a continuous measure of total worldwide thunderstorm activity. It could be used for comparison with the arrival at Earth of particular solar particles and variations of geophysical parameters as well as variation of ionospheric potential.

HUNDHAUSEN: I would like to make one final comment about what I see as the emergence of an overly sectarian view of the solar interplanetary input function.

One question yesterday illustrated 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 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 performed and has not been looked at by solar physicists for a good many years is to correlate our wealth of new plasma, 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 Earth.

I looked at an old paper that was published by Norman Ness and me 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 shock wave, so that the separation between sector and nonsector events is not at all clear. We will have to look carefully for this kind of coincidence before we take all the data labeled sector and consider all of such data to be of one single class.

WILCOX: Well, I think Hundhausen and I are in agreement. We think of the sector structure as being the answer, the change is everything from the Sun, the EUV maybe, the coronal holes appear to be related to it, and the solar wind in terms of the high velocity in the sector structure. So we certainly include all of this. Now it is true that the boundary itself is a very convenient timing marker, as Akasofu showed. The boundary itself seems to just produce some small wiggles in the geomagnetic field, which presumably are not very important in themselves.

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. After hearing Roberts talk yesterday on the 22-yr 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 yr. As far as I know, they were all invariably tied to changes and perturbations in global circulation, 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 of the theory of 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 idea to pursue, and should be pursued for that purpose.

Summary of Highlights of the Symposium

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The symposium has already been very well summarized by Kellogg and other members of the panel. I will therefore confine myself to some comments on the total approach to the understanding of the problem, some critically needed measurements, and the organization of future symposia.

I would like to start out with two figures that are taken from a paper I wrote in 1960. Figure 1 is an attempt to show the existence of a possible relationship between the solar activity and the height of the tropopause. The stations chosen are all situated on approximately the zero meridian, and the spread in latitude is from 49° N to the equator. It appears that the tropopause height increases with solar activity and this *increase* is more substantial at the equator than at middle latitudes.

Figure 2 shows a relationship between an index of geomagnetic activity and departures from average in the total ozone amounts measured at three stations in Europe. We concluded that there is a relationship and also made a hand-waving type suggestion for a mechanism that had the following line of thought: Increased solar activity means increased UV radiation, which heats the upper stratosphere forming more ozone, and more IR radiation, involving changes in temperature gradients and consequently changes in circulation patterns, which propagated the effects downward to the tropopause.

This was 13 yr ago. Although what I have heard on the "evidence" at this symposium is probably a little better than what I had, it is still not quite credible. We are still correlating changes in solar activity with isolated parameters at localized regions. Long-term changes in solar radiation should affect the entire planet Earth. It could have some latitudinal or longitudinal differences, depending upon what type of radiation we are talking about, but it could certainly not be localized, for instance, in Kansas or Garden County, Nebraska. In 1960 at least I had the excuse of not having global data on many of the meteorological parameters, but today with weather satellites and the Global Atmospheric Research program underway, we should be able to do much better. My second plea to the people who present the evidence is not to confine themselves to a single meteorological parameter. Suppose it looks like ozone has a correlation with the solar activity, then the next thing to look at is whether the temperature in the upper stratosphere, which should be correlated with the ozone at that level, also shows a correlation. Only after such a cross check should one send the paper to be published. Today, as the editor of the *Journal of the Atmospheric Sciences,* I can say that I probably would not accept my 1960 paper for publication.

The second topic I would like to comment on is the "source." We talked about two types of variations in the solar energy that could effect the weather and climate. First, let us talk about the short-term variation in the time period of 1 to 10^7 sec (~ 1 yr). Here the numbers quoted were from 1 to 10^3 ergs/cm^2 · sec. When I heard this I was horrified that after more than a decade in space we do not know the time variations in the solar constant any better than 0.1 percent

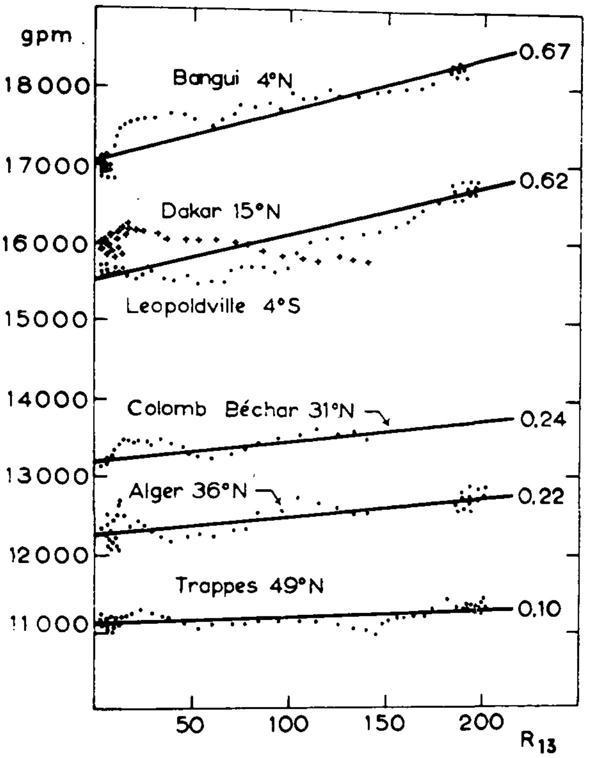

FIGURE 1.—Variation of the height of the tropopause with sunspot number. (gpm = geopotential meters.)

and we do not know the spectral dependence of these changes. As you know, the near UV radiation from the Sun is absorbed in the stratosphere and is directly responsible for the heating and dynamics of that region of the atmosphere. This energy is of the order of 10^3 ergs/cm^2 · sec. Now if the changes in the solar energy that we are talking about and which are also of the order of 10^2 to 10^3 ergs are all in the near UV, then it makes quite a bit of impact on the energy balance of the stratosphere. On the other hand, if they are in the visible and near IR, then although the fractional change is less, it is closer to home; namely, in the lower atmosphere and the surface. To paraphase Dr. London, it is almost criminal not to know these parameters any better than what we do.

Talking about the long-term changes for periods ranging from 10^7 to 10^{17} sec (from one to a billion years). Al Cameron told us how the luminosity of the Sun could have changed by as much as 30 percent and the solar wind flux by a factor of 10^7 since the early history of the Sun. This is an important question and is directly related to the problem of long-term climatic changes, ice ages, and evolution of the atmosphere of different planets. Here the Cornell presentation was very interesting because it looks like we have evidence of long-term climatic changes on Mars. Now, if the cause of these changes on both Mars and Earth is the same, namely the variations in the solar flux, then the problem suddenly becomes much simpler. We now have two planets rather than one on which we can cross check cause and effect theories. This is quite important progress, and I hope modelists begin to capitalize on this advantage.

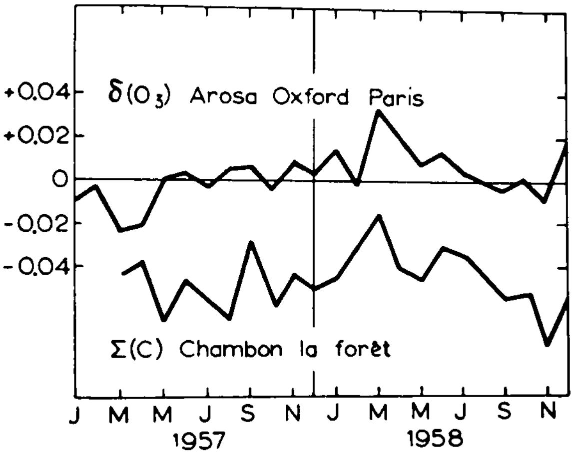

FIGURE 2.—Variations in ozone and geomagnetic activity. C = geomagnetic activity index.

As far as the symposium as a whole is concerned, I found two major deficiencies. First, there was almost no discussion on the stratosphere except during the panel deliberations. It appears to me that this is the region to look for evidence bceause it is probably here that large variations in solar energy input take place. I do not agree with Nordberg that we should wait and make more measurements in the stratosphere. I am sure that enough data have already been acquired, during the last decade, by TIROS, Nimbus, and other satellites. If we had taken time to analyze and understand those measurements that already exist, we would have made much more progress in this symposium today. Also, the numerical modeling exercises that are now going on at a number of places tend to ignore the stratosphere. We heard a presentation on what small changes in solar radiation do to the circulation in the troposphere. Unfortunately, it was a wrong example. We know that the relaxation time of the lower atmosphere is so long and the heat capacity of the ocean is so large that if the Sun disappeared, the atmospheric circulation patterns would *persist for at least 10 to 15 days.* What we are looking for is the effect of one-tenth of a percent of change in solar energy; obviously it does not make any difference to the tropospheric circulation pattern. It is the people who are modeling the stratospheric dynamics who should be doing such calculations. Let them show what a factor of 2 change in the solar near UV input does to the stratospheric circulation.

The other serious deficiency was the absence of Colin Hines, who was the only one scheduled to talk about possible mechanisms.

My last comment is about the nature of the conference we need to get answers to many of these questions. What we do not want is a symposium where there are 5-min presentations and where one cannot ask a question without a microphone. What we really need is a 1- or 2-week working meeting or workshops where, for example, people like Don Heath and Elske Smith can have long discussions and finally develop *one number* on the extent of the variability of the solar radiation. Simultaneously, atmospheric dynamicists can compare their models and parameters in long private sessions. Finally, we can all get together and make actual research assignments to be completed before the next "workshop." We had a working meeting like this last year on the atmosphere of Titan, in which the diversity of opinion was great. However, at the end of 3 days, we eliminated all but two models. In addition, we made suggestions of diagnostic measurements that will allow us to choose between the two models. We should begin to do the same thing here. We really owe, not only to Roberts, but to the entire scientific community, an answer to the question of whether there is a relationship between the solar activity and the meteorological phenomenon. If the answer is "Yes," we should explain why.

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[1] Because of circumstances beyond his control, Dr. Hines was unable to attend as planned; however, an abstract of his paper is included.

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