Study of the Relationship Between Solar Activity and Terrestrial Weather

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National Aeronautics and Space Administration
Grant NGL 05-020-272

SUIPR Report No. 671

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ABSTRACT

This Committee, set up to advise NASA Headquarters on the above subject, concludes from the existing evidence that there is a *prima facie* case for influence of the sun on terrestrial weather on a time scale of a few days. The Committee recommends further statistical analysis of solar and terrestrial variables to further evaluate the apparent association, to evaluate proposed 11-year and 22-year associations, and to search for possible causal chains. The Committee also recommends theoretical study and computer modeling to evaluate possible mechanisms which may be involved in a chain of mechanisms coupling variations of the sun's atmosphere to variations of the earth's atmosphere.

I. Introduction

This Committee has been formed at the request of Dr. Harold Glaser of NASA Headquarters to assess the existing evidence for a relationship between solar activity and terrestrial weather and to recommend what action, if any, NASA might take in relation to this problem. The composition of the Committee is as follows: Guenter E. Brueckner, Naval Research Laboratory; Robert E. Dickinson, National Center for Atmospheric Research; Norihiko Fukuta, University of Denver; Louis J Lanzerotti, Bell Laboratories; Richard S. Lindzen, Harvard University; Chung G. Park, Stanford University; Peter A. Sturrock, Stanford University, Chairman; and John M. Wilcox, Stanford University. The Committee was fortunate to receive contributions from Joshua W. Knight of Stanford University and Eugene N. Parker of the University of Chicago; these are attached as Appendices B and C, respectively. The Committee had two meetings, the first on February 25 and the second on April 12. The proceedings of these meetings are discussed briefly in Sections II and III, and our recommendations are given in Section IV. Three working papers were prepared by Committee members and are attached as appendices to this report.

Three recent symposia have been devoted to the relationship between solar activity and the earth's atmosphere: a symposium on "Possible Relationships Between Solar Activity and Meteorological Phenomena" held at Goddard Space Flight Center in November, 1973, a conference on "The Solar Constant and the Earth's Atmosphere" held at Big Bear Solar Observatory, California, in May 1975 and a "Solar Output Workshop" held at High Altitude Observatory in April 1976. The proceedings of these conferences and recent review articles are included in the reading list (Appendix A).

A working group on "Solar-Terrestrial Physics — Meteorology" has recently been established by the Special Committee for Solar-Terrestrial Physics (SCOSTEP) of the International Council of Scientific Unions. A group on this subject that is part of the Bilateral Agreement for Protection of the Environment between the U.S.A. and the U.S.S.R. has held recent meetings in Boulder and in Kiev. A report "Solar-Terrestrial Physics and Meteorology: A Working Document" is available from SCOSTEP, c/o National Academy of Sciences, 2101 Constitution Avenue, Washington, D.C. 20418.

II. Current Status

There has in the past decade grown up a *prima facie* case for terrestrial meteorological consequences of solar variability. Recent studies have provided evidence for a correlation between the solar and interplanetary sector structure and the size of low-pressure troughs (cyclones) in the Northern Hemisphere troposphere*.

Over a longer time scale there are the historical world-wide temperature variations which have no physical explanation other than the possibility of a small change in solar luminosity. We may also note the curious fact, pointed out by Eddy**, that the absence of solar activity during the latter half of the Seventeenth Century coincided with a world-wide, century-long period of cold, and that the two previous centuries without solar activity (the Fourteenth and the Fifteenth) also coincided with world-wide cold. Eddy suggests that a slight decrease in solar luminosity was the cause of both the diminished solar activity and the world-wide cold.

None of the causes and connections have been firmly identified, so we must be cautious in accepting the correlations as proving a direct physical relationship, but to believe that there is *no* connection is a position for which there is not even *prima facie* evidence. In view of the scientific and practical significance of any real connection between variability of the sun and meteorological variability on earth, we are not entitled to ignore existing evidence simply because the case is not completely resolved.

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*J.M. Wilcox, Science, 192, 745 (1976) [See Appendix F]
**J.A. Eddy, Science, 192, 1189 (1976)

III. Possible Mechanisms

Although some scientists may be persuaded by the reality of an effect by statistical arguments alone, many scientists will suspend judgement until a valid explanation of the effect is forthcoming. In particular, meteorologists believe that it will be difficult to identify specific physical processes responsible for the proposed relationship, and they are in general quite skeptical of the case as currently presented.

Dickinson reported that a model was run to examine the effect of a 30% change in the solar flux. Remarkably, the calculation yielded no appreciable change in meteorological conditions above the normal noise level in a space of about one week. If the sun-weather relationship proves to be real, it will clearly be necessary to identify subtle processes which are not included in present meteorological models.

The apparent association between atmospheric conditions and sector structure directs attention to the solar wind. However, there are about five orders of magnitude difference in the energy input from the solar flux and from the solar wind.

One possibility is that cloud formation plays a key role in the relationship. Cloud formation depends upon the presence of condensation nuclei and supersaturation, which is a function of both moisture content and temperature. Condensation can exist either in an ice phase or in a non-ice phase. At this time, cloud processes cannot be predicted by thermodynamics alone. The coalescence process depends upon electric fields but at this time we have neither empirical nor theoretical knowledge concerning the effect of electric fields on the amount of rainfall.

The vertical electric field has recently been monitored at Vostock, Antarctica. One interesting result of this study is the existence of a pronounced minimum in electric field approximately one day after sector boundary crossing. We need to obtain more information about atmospheric electric fields and their relationship both to cloud formation and to the interplanetary magnetic field.

As a way of systematizing any search for causal chains relating the sun to terrestrial weather, the Committee drew up a list of measurable and relevant variables at the sun, in the interplanetary medium, in the magnetosphere, in the ionosphere and in the earth's atmosphere. These variables are listed in Table 1.

TABLE 1

VARIABLES POSSIBLY RELEVANT TO CAUSAL CHAIN RELATING THE SUN TO TERRESTRIAL WEATHER

SUN	INTERPLANETARY MEDIUM	MAGNETOSPHERE	IONOSPHERE	GROUND LEVEL
ROTATION	SOLAR WIND SPEED, DENSITY, TEMPERATURE, COMPOSITION	TRAPPED PARTICLE DISTRIBUTIONS	SIZE OF AURORAL ELECTROJET (A_e INDEX)	RAINFALL
SUNSPOT NUMBER	MAGNETIC FIELDS		$n_e(h)$	WINDS, GROUND WINDS 500 mb
FLARE ACTIVITY	PARTICLE FLUX (SOLAR, GALACTIC)		TOTAL ELECTRON CONTENT	PRESSURE
LARGE SCALE MAGNETIC FIELDS				THUNDERSTORMS (GLOBAL)
10 cm RADIO EMISSION				ELECTRIC FIELDS
				MAGNETIC FIELDS
				CLOUD COVER
				OZONE CONTENT
				TREE RING HISTORY

By reference to these variables, the Committee identified a number of questions (concerning possible links in the chain) which need investigation by data analysis (D), by theoretical analysis (T) or by computer modeling (M). These are listed, by priority, in Table 2.

TABLE 2

OUTSTANDING QUESTIONS

A PRIORITY

1. RELATION OF IONOSPHERIC AND GROUND-LEVEL ELECTRIC FIELDS (D, T)
2. IONIZATION OF STRATOSPHERE BY GALACTIC COSMIC RAYS (D, T)
3. CHANGE OF CONDUCTIVITY OF ATMOSPHERE BY COSMIC RAY FLUX (D, T)
4. EFFECT OF ULTRAVIOLET AND CHARGED-PARTICLE FLUXES ON OZONE AND NITRIC OXIDE (D, M)
5. EFFECT OF OZONE AND NITRIC OXIDE ON CLIMATE MODELS (T, M)
6. EFFECT OF FAIR-WEATHER ELECTRIC FIELDS ON THUNDERSTORMS AND PRECIPITATION (D, T)

B PRIORITY

7. EFFECT OF SECTOR MAGNETIC FIELD ON SOLAR PARTICLE FLUX (D, T)
8. EFFECT OF STRATOSPHERIC IONIZATION ON FORMATION OF CONDENSATION NUCLEI (D, T)
9. CRITERIA FOR RAINFALL AND INFLUENCE ON METEOROLOGICAL MODELS (T, M)
10. MODULATION OF GALACTIC COSMIC RAYS BY SOLAR MAGNETIC FIELDS (D, T)
11. SOLAR WIND VELOCITY AND DENSITY AS A FUNCTION OF SECTOR STRUCTURE (D, T)
12. COUPLING OF SOLAR MAGNETIC FIELDS TO MAGNETOSPHERE (D, T)
13. CHARGE GENERATION IN THUNDERSTORMS (T)

IV. General Recommendations

At its February 25 meeting, the Committee agreed on the following statements:

1. We have studied the literature and we conclude that there is a *prima facie* case for influence of the sun on terrestrial weather on a time scale of a few days.

2. We advocate a careful and extended statistical study of selected

indicators of solar and terrestrial phenomena with a view to (a) confirming or disproving the present apparent relationship; (b) determining the reality or otherwise of proposed 11-year and 22-year associations; and (c) searching for a causal chain responsible for any such association.

3. We advocate a program of theoretical research with a view to searching for possible causal chains between the sun and the earth's lower atmosphere and examining proposals in terms of physical processes and meteorological models.

This position was reaffirmed and elaborated during the April 12 meeting. Concerning recommendation 2(a) above, it was specifically suggested that there be a study of the morphology of the apparent influence of the solar and interplanetary sector structure on the vorticity area index, tropospheric pressure variations, the zonal index and other meteorological variables. In addition, high priority should be given to completely new studies (hopefully involving different variables and different methods of analysis and possibly different scientists) which may either confirm or negate the results of recent studies.

Concerning item 2(c) above, the Committee recommends searching for correlations between pairs of variables listed in Table 1, as exemplified by the questions listed in Table 2. Some of the questions listed in Table 2 are susceptible also to theoretical analysis and to model analysis, and are therefore specific examples of the general point made in recommendation 3 above.

This work was supported in part by the National Aeronautics and Space Administration under grant NGL 05-020-272.

APPENDIX A

RECENT SYMPOSIA AND SURVEY ARTICLES

"Proceedings of Conference on Solar Variations, Climatic Change, and Related Geophysical Problems", R.W. Fairbridge, ed., Ann. New York Acad. Sci., 95, Art. 1, 1961.

"Proceedings of Conference on Possible Relationships Between Solar Activity and Meteorological Phenomena", W.R. Bandeen and S.P. Maran, eds., NASA SP-366, 1975, Goddard Space Flight Center, Greenbelt, Maryland.

"Proceedings of Conference on the Solar Constant and the Earth's Atmosphere", H. Zirin and J. Walter, eds., BBSO #0149, 1975, Big Bear Solar Observatory, Big Bear City, California.

"The Physical Output of the Sun", O.R. White, J.A. Eddy and D. Heath, eds., University of Colorado Press, 1976 (Proceedings of the Solar Output Workshop held at H.A.O. in April 1976).

"Solar Variability and the Lower Atmosphere", R.E. Dickinson, Bull. of Am. Meteorological Society, 56, 1240, 1975.

"Sun-Weather Relationships", J.W. King, Astronautics and Aeronautics, 13, No. 4, 10, 1975.

"Solar Structure and Terrestrial Weather", J.M. Wilcox, Science, 192, 745, 1976.

APPENDIX B

February 23, 1976

To : Solar Activity-Terrestrial Weather Study Group

From : Joshua W. Knight

Subject: Tests for Solar Influence on Terrestrial Weather

Evidence has been presented in the literature for some connection between weather and solar-related phenomena. We would like to estimate the statistical significance of these apparent connections. From the point of view of the statistician, it would be best to have a long run of data consisting of one number per day for both weather and solar activity. That is we need indices of both solar activity and weather. It is important that the solar index is not contaminated with weather influences. The indices used should have been constructed in a consistent manner and be available in computer-readable form for the entire time span being analyzed. For data runs of the order of a few years or longer, this effectively limits the available indices to those constructed from ground-based observations. For example, records of precipitation might be used to construct a weather index. The vorticity area index used by Wilcox and Roberts and their colleagues is an example of a useful weather index. Geomagnetic activity indices have been used as indicators of solar activity, but these indices suffer the disadvantage that they have annual or semi-annual variations in common with the weather. Other observational data that might be used to construct a solar activity index are (1) sunspot numbers, (2) solar radio maps, (3) PCA data, (4) ionospheric data and (5) neutron monitor data. Some of these indices also have disadvantages. For example, the barometric pressure affects the neutron monitor data. This effect is usually corrected for but it is not clear that all weather contamination is removed by this process.

The method of superposed epochs has been used (by Wilcox and his colleagues among others) to look for a connection between solar-related phenomena and weather. There are other methods which might effectively be used in this context. The technique of calculating cross correlation coefficients has the advantage that standard statistical tests for significance are available. However, it suffers from the disadvantage that contamination of one index by another or common trends in both indices can produce spurious high correlation coefficients. We need either a solar index that is free of all terrestrial contamination or a method of verifying that a proposed connection is indeed solar-related. Spectral analysis may be useful in this respect. One can construct power spectra of both indices and look for peaks at or near periods characteristic of solar rotation (for example a paper by Knight and Sturrock using this method was presented at last year's San Diego meeting of the AAS). Since it can be expected that long runs of data will be available, the maximum-likelihood technique of statistical analysis may be useful. This method has properties favorable for the analysis of large samples. It also has the advantage that knowledge of the statistical nature of an index can be used to construct "more powerful" tests. An example of the sort of information that can be incorporated in this technique is the fact that the neutron monitor data can be reasonably well represented by an inhomogeneous Poisson process. Knight and Sturrock have used a maximum-likelihood technique to look for a connection between aircraft accident rates and a geomagnetic activity index. It is also possible to construct tests to evaluate the results of a combination of the cross-correlation and spectral-analysis methods. A simple example is the calculation of confidence estimates for peaks in the power spectrum of the cross correlation of two indices.

There are several possible indicators of both solar activity and weather, and several possible methods for determining if there are statistically significant correlations between these indices. Careful statistical analysis that produces easily interpretable confidence estimates would be a valuable addition to the work that has already been done in the area of solar activity and weather.

JWK:cg

SOLAR AND TERRESTRIAL VARIABILITY

E.N. Parker

There has in the past decade grown up a prima facie case for terrestrial meteorological consequences of solar variability. There is, for instance, the evident correlation between the vorticity index in the north Pacific Ocean and geomagnetic storms and sector boundaries in the solar wind. There is the remarkable coincidence, for some ten cycles, between severe drought in the high prairies and sunspot minimum.

Over a longer time scale there are the historical worldwide temperature variations which have no physical explanation other than the possibility of a small change in solar luminosity. Then we note the curious fact, pointed out by John Eddy in a forthcoming article in Science, that the absence of solar activity during the latter half of the 17th century coincided with a worldwide, century-long period of cold, and that the two previous centuries without solar activity (the 14th and the 15th, based on carbon 14 studies) also coincided with worldwide cold. Eddy suggests that perhaps a slight decrease in solar luminosity was the cause of both the diminished solar activity and the worldwide cold.

None of the causes and connections have been firmly identified, so we must be cautious in accepting the correlations as proving a direct physical relationship. But to believe that there is no connection is a position for which there is not even prima facie evidence. Both the scientific and the practical importance of any existing connection between variability of the sun and the meteorological variability of Earth are enormous. We would be foolish indeed to ignore the existing evidence because the case is not safely complete. It will, of course, take hard work to complete the case.

Consider, then, what should be done to explore the subject. In addition to the current studies of short term meteorological effects and solar activity, it is imperative that there be developed suitable instruments for *absolute* measurements of the solar luminosity to an accuracy of one part in 10^3 and that the measurements be made to search for both short term (1 month to 1 year) and long term (5 years to 20 and 100 years or more) variations of the sun. Of course, there is no need to wait for the sun to vary, in as much as there are hundreds of other G-stars in the sky. The *relative* luminosities of neighboring G-stars should be monitored to one part in 10^3 to see what variations they presently undergo, in anticipation of possible solar variations in other years and decades. Neither the absolute nor the relative measurements will be easy to do, the former necessarily being carried out from spacecraft. The success of the measurements will depend upon one or more *really first rate* experimental physicists undertaking the development of the instrumentation and then maintaining sufficient interest to supervise the observations over the years and decades ahead. The greatest care is needed so that the variations, when they should appear in the observations, can be believed.

In searching for possible causes of variation of the solar luminosity over periods of a century or more, we should note that the recurring centuries of solar inactivity, interspersed with centuries of "normal" activity, suggest at least two distinct modes of circulation in the sun, one producing an active dynamo and enhanced heat transtort, and the other an inactive dynamo with slightly reduced heat transport. The heat transport in the outer solar envelope is predominantly by convection;

the characteristic period of 10^2 years is just the characteristic thermal relaxation time of the outer 3×10^4 km. Therefore, if, as indicated by the magnetic activity, there is a switch from one mode of circulation to another, over depths of the order of $2 - 5 \times 10^4$ km, we expect a small change in luminosity associated with a duration of the order of 10^2 years. The point is that a very serious theoretical effort must be made to advance our presently rudimentary understanding of the difficult problem of convection and heat transport in a stratified atmosphere. It would appear that the sun has a hot, active mode of circulation and a cold, inactive mode, and for some reason the sun cycles back and forth between them over the characteristic time $\sim 10^2$ years.

To: Solar Activity - Terrestrial Weather Study Group

From: G.E. Brueckner

Subject: Response to memo of 24 March 1976 from P.A. Sturrock

If a solar influence on terrestrial weather on a time scale of a few days can be demonstrated beyond doubt, the search for the possible physical mechanism becomes the next most important step. It could be argued also that such a search should be undertaken regardless of the outcome of the statistical relationship study, because in the course of studying the relationship between solar output and terrestrial weather an advanced understanding of the physics of the terrestrial atmosphere can be expected, which in itself may be of much greater value than the understanding of the solar terrestrial relationship. This is even more important, because the search must include countless possible nonlinear physical mechanisms. These nonlinear mechanisms must exist, if any solar influence on the terrestrial weather can be demonstrated. Changes in energy output of the sun reaching the earth cannot explain any connection directly. The detection of such nonlinear processes which may couple the tropopause to the stratosphere or even the ionosphere would be in itself of utter importance, because it may shed more light also on many other climatologic questions, not to forget possible disturbances of the earth climate by man-made influences.

Because of the unknown nature of the physics of any solar-terrestrial relationship, it is necessary to focus the attention on all aspects of the variable solar output. This means that not only those areas of measurements which have established very good values of solar variability must be continued and refined, but also new routes must be explored, where the relative variability of the solar output is much smaller and therefore much more difficult to detect.

An important, so far neglected area is the relative variability of the solar output in the 1200 to 3000 Å region. Here it is necessary to develop measuring methods which have a repeatability of 0.1% over a few days and 1% over a solar cycle to establish definite values of the relative variability. This wavelength region is of particular interest because of the absorption in lower layers of the earth atmosphere.

The XUV region 100-1000 Å must be explored further, specifically to establish more accurate solar fluxes and their variability. Because of the influence on the ionosphere this region of the spectrum may be crucial, and it is so far the only ultraviolet radiation of which a definite cause-effect relationship between the sun and the terrestrial atmosphere has been established.

X-rays from 0.1 Å to 10 Å are absorbed between 40 and 120 km. Their influence on the ionosphere is well known, but the calibration of flux levels may be uncertain within ± 40%. An improvement may be necessary.

Of equal importance are detailed studies of the absorption of UV, EUV, XUV and X-ray radiation in the terrestrial atmosphere.

Absorption between 2100 and 3000 Å seems to be well understood, but only a few measurements exist. On the other hand, no variability larger than 10^{-3} of the solar radiation will be expected on time scales of a few days, and nothing larger than 5×10^{-3} on a time scale of a solar cycle.

Solar radiation at wavelength $\lambda < 2100$ Å is variable. From active regions we expect a 3 - 5% variability between 1400 - 2100 Å. Nothing is known about the absorption of Schuman Runge bands in this spectral region. Particular attention should be focussed on high resolution absorption spectroscopy between 40 and 100 km in the 1700 - 2100 Å region.

It is also of importance to develop a comprehensive program to measure the properties of the earth atmosphere under disturbed conditions. This may be the only way to recognize the physical coupling mechanism. Such a program must be carried out from a satellite. It will require the measurement of terrestrial absorption with very high spectral and altitude resolution over a wide spectral range (X-ray into the ultraviolet). Sounding rockets and balloons will never be able to collect the necessary data for the disturbed atmosphere. Most experiments presently flown on satellites are not capable of the necessary spectral and altitude resolution.

These absorption studies of the disturbed atmosphere must be accompanied by in situ probing of ions, atoms and molecules. The development of very high-flying balloons capable of staying in the atmosphere over several weeks is necessary.

It should also be recommended to develop a new class of satellites which can be flown at very low altitudes, even if their lifetime is short. Studying the disturbed atmosphere requires the coverage of the 60 to 120 km region with long-term in situ measurements.

Solar particle flux measurements are in much better shape. But in a coordinated program to study the disturbed terrestrial atmosphere, it must be ascertained that the whole energy spectrum of solar particles is covered by appropriate satellite measurements.

The connection between earth magnetic field disturbances and high-speed solar wind streamers requires extensive studies to understand the mechanism causing the unsettling of the geomagnetic field. Missing are *in situ* measurements of particle penetration depths at the earth polar regions.

A powerful tool complimenting absorption measurements and *in situ* probing would be high spatial and time resolution images of the earth in the UV (e.g., O I triplet at 1300 Å, continuum backscattering at different wavelengths, backscattering in Schuman-Runge bands, etc.) from a geostationary satellite. Such pictures with their potential altitude probing would reveal the global interaction of different layers of the earth's atmosphere under disturbed conditions.

Last but not least, imaging of the sun remains an important task. It was this aspect of solar UV and X-ray spectroscopy which finally revealed the connection between the corona and geomagnetic disturbances.

To : Solar Activity - Terrestrial Weather Study Group

From : L.J. Lanzerotti

Subject: Solar Activity and Terrestrial Weather: Cosmic Rays and Magnetosphere Particles

The subject of energetic particles incident on the earth's upper atmosphere is a multi-faceted problem. Working from outside the magnetosphere inward, the initial particles of interest are solar cosmic rays and galactic cosmic rays. The number of solar cosmic ray events depend upon solar cycle and the occurrence of solar flares, and is a topic discussed in some length in my paper "Measures of energetic particles from the sun" for the Solar Output Workshop*. The galactic cosmic ray intensities vary as well with the solar cycle, with the percent variation dependent upon particle energy. Galactic cosmic rays measured at any one longitude have a diurnal dependence which varies from day to day and from longitude to longitude, depending upon interplanetary magnetic field conditions; this diurnal dependence is typically only a few tenths percent of the galactic cosmic ray flux.

Both the galactic and solar cosmic rays must have access to the magnetosphere in order to propagate to the upper atmosphere. Only cosmic ray protons with a rigidity above about 10GV can reach the upper atmosphere near the equator, whereas in the auroral regions ($\sim 60^\circ - 65^\circ$ geomagnetic latitude) cosmic rays of about 1GV rigidity can reach the upper atmosphere. The results of the cosmic ray interactions with the upper atmosphere are generally measured on the ground by neutron monitors. Solar cosmic rays with energies as low as a few MeV can reach the upper atmosphere only in the polar regions above $\sim 75^\circ$ geomagnetic latitude.

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*Proceedings published as "The Physical Output of the Sun"; see Appendix A.

After solar flare events these particles are of sufficient number density to produce severe ionosphere disturbances as measured by various ionosphere propagation techniques.

In addition to cosmic rays incident on the upper atmosphere, electrons and protons are precipitated from the radiation belts and ring current. During certain magnetic storm conditions electrons of energy ⩾ 1 MeV are precipitated into the upper atmosphere producing ionization at the 60 to 70 km level in the auroral zone. Even at mid-latitudes some airglow effects and VLF propagation effects have been observed which are attributed to the more or less steady precipitation of radiation belt particles into the upper atmosphere.

There are hemispherical asymmetries in the precipitation of radiation belt particles, but the magnitudes of the asymmetries are not well quantified at this time. The asymmetries arise principally from the offset tilt of the geomagnetic dipole axis with respect to the geographical dipole axis. Thus, there is evidence for somewhat more intense aurora and more intense particle precipitation in the Alaskan sector than in the New Zealand/Australia sector. The opposite situation holds for the south Atlantic/Antarctic sector and the Northern Hemisphere/Greenland sector.

The precipitation of the energetic particles into the upper atmosphere in the auroral zone changes by a substantial amount the ionization density and conductivity of the upper atmosphere-ionosphere. During these larger geomagnetic storms intense electric currents flow in the auroral zone; this upper atmosphere heating seems to produce gravity waves which may propagate to lower latitudes.

From my point of view as a magnetospheric/cosmic ray physicist the major couplings that seem to occur between the ionosphere and the lower atmosphere (as well as the surface of the earth) are produced by the electric and magnetic fields. Magnetic field changes observed on the surface of the earth are related to ionization changes in the ionosphere and plasma and wave changes in the magnetosphere. (In fact, magnetic field measurements made on the surface of the earth are very important for studying the spatial extent of magnetospheric and ionospheric current and wave phenomena.) The subject of electric field coupling from the surface of the earth to the ionosphere has been one of controversy and skepticism for a substantial amount of time. However, it appears to me as if there is some small but growing evidence that small-scale changes in the fair weather field on the surface of the earth can be attributed to changes in the electric field in the ionosphere. In addition, thunderstorm electric fields above thunderclouds must map in some way into at least the lower ionosphere. Thus, it might be reasonable to expect that changes in the conductivity of the ionosphere must produce changes in the electric and magnetic fields that reach the lower atmosphere and the earth. The magnitude of the electric coupling is not easy to calculate and is an area where substantial more measurements are needed.

An example of the type of speculative measurement that one might propose concerns the seeding of rain clouds with the overlying ionosphere conductivity as a variable. That is, is cloud seeding more or less effective when the conductivity of the overlying ionosphere is substantially enhanced? Another aspect of this area of research concerns the global coverage or extent of the fair weather electric field. The amount of monitoring for scientific purposes that has been done is not exceedingly large and the relationships of the changes in the fair weather field to precipitating particle fluxes is almost totally unknown. The people who work in atmospheric electricity do not communicate extensively with magnetospheric physicists and common ideas are often not explored.

In summary, it would appear that an area that needs substantial further investigation both with old data as well as with new, well thought-out measurements, involves the area of particle modification of atmospheric and ionospheric conductivity. Possible couplings of these conductivity changes to the lower atmosphere via electric and magnetic fields may well occur and influence weather conditions.

APPENDIX F

21 May 1976, Volume 192, Number 4241 SCIENCE

Solar Structure and Terrestrial Weather

After more than a century of controversy this subject may be moving toward scientific respectability.

John M. Wilcox

Claims for a connection between the variable sun and the earth's weather can be found in a literature of well over 1000 published papers during the past century. The subject has been discussed by such illustrious authors as Herschel, Gauss, Sabine, Faraday, Wolf, Stewart, Schuster, and Airy. Nevertheless, the subject has tended to remain on the fringes of respectable science.

Observations of the changing sun are not now employed in routine weather forecasting. Many scientists are reluctant to admit the possibility of such an influence. Perhaps the main stumbling block involves energy considerations. The variation of the amount of energy received at the earth in connection with the variable sun is rather small compared to the energy in the general circulation of the earth's atmosphere. By the variable sun I mean any changes on a time scale of a few days in the sun as viewed from the earth. Lacking a knowledge of the physical mechanism(s) that may be involved, I cannot be more specific.

Such concern with energy is undoubtedly valid, but may not be conclusive. It may be instructive to consider the situation at the turn of the century. It had been noted that geomagnetic activity often increased after a large solar flare. Furthermore, days with enhanced geomagnetic activity sometimes recurred at intervals of 27 days, the solar rotation period. This led to suggestions that geomagnetic activity was caused by the sun.

In his famous presidential address in 1892 to the Royal Society, Lord Kelvin (*1*) made a stiff dismissal of such claims. He calculated the energy associated with 8 hours of a not very severe geomagnetic disturbance, and concluded that in order to supply this energy to the geomagnetic field "as much work must have been done by the Sun in sending magnetic waves out in all directions through space as he actually does in four months of his regular heat and light." Lord Kelvin's calculations were quite correct within the framework of his knowledge. He did not know about the solar wind, which extends the solar magnetic field away from the sun in all directions and completely changes the energetic considerations. We may wonder if an unknown process comparable in importance to the solar wind may be part of a causal chain between the variable sun and the earth's weather.

It seems possible that sun-weather investigations are finally beginning to move to a position of scientific respectability. The most firm conclusion that I would draw is not related to any specific claim, but rather is that this subject has reached a state in which it merits the consideration of serious scientists (*2*). Such consideration is indeed increasing as witnessed by several symposia on the subject, the most recent of which was held in 1975 at the 16th General Assembly of the International Union of Geodesy and Geophysics in Grenoble. It is encouraging that such symposia have been attended by solar physicists and meteorologists, who are thus beginning to bridge the interdisciplinary gap.

Some Recent Work

I will now describe some recent work involving the cooperative efforts of several scientists at several institutions. For a decade or more W. O. Roberts at the National Center for Atmospheric Research and the University of Colorado in Boulder has been a leading American worker on the subject of sun-weather interactions. Some recent work by Roberts and Olson (*3*) studied days on which geomagnetic activity had a sizable increase, which was assumed to have a solar cause. They also studied the history of low-pressure troughs (cyclones) from the Gulf of Alaska as they moved across the continental United States, and found that troughs associated with geomagnetic activity were significantly larger on the average than troughs associated with intervals of quiet geomagnetic conditions. The vorticity area index, a measure of the size of low-pressure troughs devised by Roberts and Olson, has been used in several subsequent investigations.

A low-pressure trough is a large rotary wind system, having a diameter of a few thousand kilometers, that is usually associated with clouds, rain, or snow. Although the formation and structure of low-pressure troughs have been studied in some detail, it is not possible in general to predict the time and place at which a trough will form. This is one reason why the skill in short-range weather prediction becomes small (that is, little better than a prediction of average properties) within 2 or 3 days (*4*). The vorticity area index devised by Roberts and Olson can be computed from maps of the height of constant-pressure (300-mbar) surfaces by using the geostrophic wind approximation. These maps are prepared twice a day, at 0 and at 12 universal time (U.T.), by the National Weather Service. The circulation of the air mass in a trough is defined as the line integral of the velocity of the air around a closed path. Vorticity is defined as the circulation per unit area. In our use of the vorticity area index, it is computed for the portion of the Northern Hemisphere north of 20°N. The index is

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now defined as the sum of all areas in which the vorticity exceeds a certain threshold, which is chosen so that all well-formed troughs are included. Once the threshold level (20×10^{-6} sec^{-1} in our work) has been chosen, the computation of the vorticity area index is completely objective.

The results of the investigations to be described in this article will be presented in terms of graphs in which the meteorological input to the investigation is plotted on the ordinate and the solar input is plotted on the abscissa. The meteorological input is the vorticity area index just described. Now we must consider what the solar input will be.

Roberts and Olson (*3*) assumed that the increases in geomagnetic activity used in their analysis were caused by the changing sun. This assumption was challenged by Hines (*5*), who suggested that some geomagnetic activity may be caused by current systems induced by motions of the lower atmosphere. To the extent that this assumption is correct, the assumed chain "sun → geomagnetic increase → weather change" would be replaced by a closed circle "weather change → geomagnetic activity → weather change." In my opinion such an influence on the investigations of Roberts and Olson (*3*) can probably be neglected. Nevertheless, it is clearly an advantage in this situation if a structure that is clearly of solar origin can be used for the solar input in the investigation.

For this purpose we consider the solar sector structure, which is a fundamental large-scale property of the sun. A description of several solar, interplanetary, and terrestrial properties of this structure is available (*6*). The structure is readily perceived in observations by spacecraft magnetometers of the interplanetary magnetic field that is swept past the earth by the solar wind. For several consecutive days this interplanetary field will be observed to have a polarity directed away from the sun. For the next several days it will be observed to have a polarity directed toward the sun. These two sectors are separated by a thin boundary that typically is swept past the earth during an interval measured in tens of minutes.

In the investigations described here, the time at which a sector boundary is observed to sweep past the earth is used as a zero phase reference. This sharply defined time is very convenient for the analysis, but it must be emphasized that the sector boundary itself is probably not an important influence on the weather. Furthermore, the large-scale sector pattern of the interplanetary magnetic field (and associated structures in the solar wind) is not necessarily a physical influence on the weather. The solar influence (if there is one) described in this article could be related to variations in the solar ultraviolet emission, in the solar "constant," in some manifestation of the changing solar magnetic field such as energetic particle emission, in an influence of the extended solar magnetic field on galactic cosmic rays incident at the earth, or in some other unknown factor. In any event, the extended solar sector structure as observed with spacecraft in the interplanetary magnetic field near the earth is clearly a solar structure that is not influenced by terrestrial weather. We now consider further the possibility that some aspect of the solar structure may influence the weather.

Extension of Earlier Investigations

Our group at Stanford joined forces with Roberts and Olson to extend their original investigations. The first results (*7*) of this collaboration are shown in Fig. 1, where the average change in the vorticity area index is plotted against days from sector boundary as the sector structure is swept past the earth by the solar wind. Day zero represents the time at which a sector boundary passed the earth. We see in Fig. 1 that on the average the vorticity area index reaches a minimum approximately 1 day after the boundary passage. The amplitude of the effect from the minimum to the adjacent

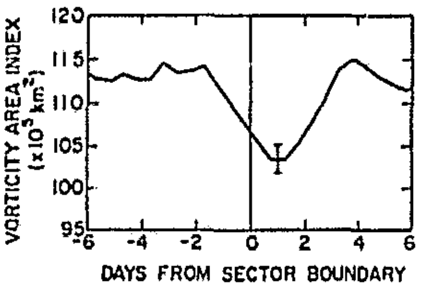

Fig. 1 (left). Average response of the vorticity area index (the area of all the low-pressure troughs in the Northern Hemisphere) about times when solar magnetic sector boundaries were carried past the earth by the solar wind. Sector boundaries were carried past the earth on day 0. The analysis includes 53 boundaries during the winter months November to March in the years 1964 to 1970. The standard error of the mean (error bar) was calculated after subtracting a 27-day mean centered on each sector boundary, to remove long-term trends. The deviations corresponding to the individual boundaries are consistent with a normal distribution about the mean.

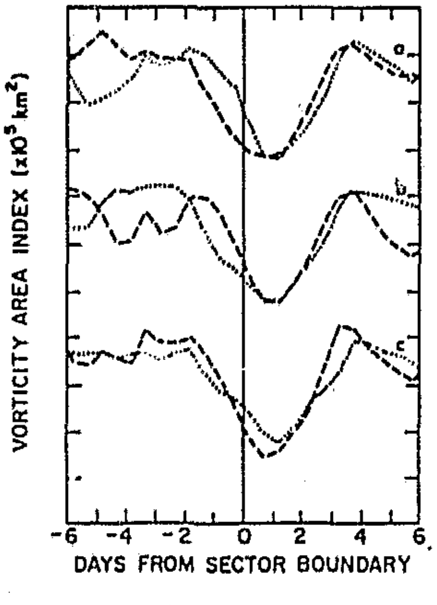

Fig. 2 (middle). Same format as Fig. 1. The list of boundaries used in Fig. 1 was divided into two parts according to (a) the magnetic polarity change at the boundary, (b) the first or last half of the winter, and (c) the yearly intervals 1964 to 1966 and 1967 to 1970. (a) The dotted curve represents 24 boundaries in which the interplanetary magnetic field polarity changed from toward the sun to away from the sun, and the dashed curve 29 boundaries in which the polarity changed from away to toward. (b) The dotted curve represents 31 boundaries in the interval 1 November to 15 January, and the dashed curve 22 boundaries in the interval 16 January to 31 March. (c) The dotted curve represents 26 boundaries in the interval 1964 to 1966, and the dashed curve 27 boundaries in the interval 1967 to 1970. The curves have been arbitrarily displaced in the vertical direction, but the scale of the ordinate is the same as in Fig. 1; that is, each interval is 5×10^5 km^2.

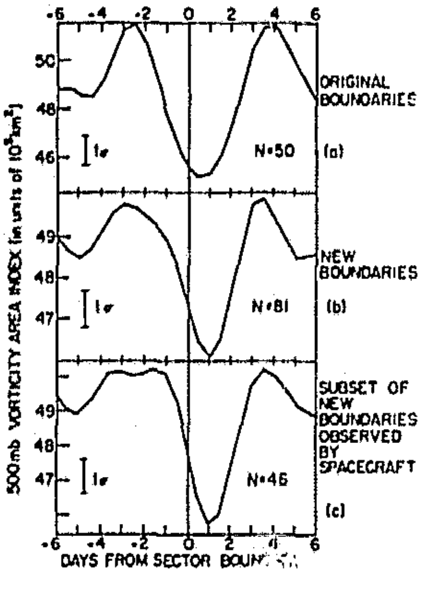

Fig. 3 (right). Same format as Fig. 1 for (a) 50 of the boundaries used in the original work, (b) 81 new boundary passages not included in the original analysis, and (c) a subset of (b) in which the times of 46 boundary passages were determined from spacecraft observations.

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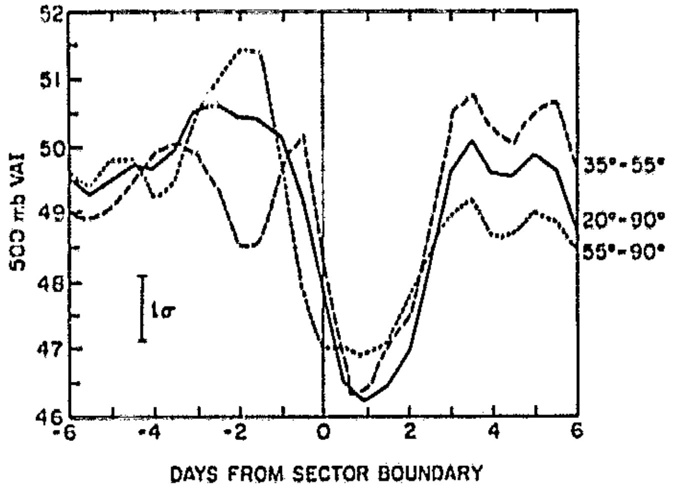


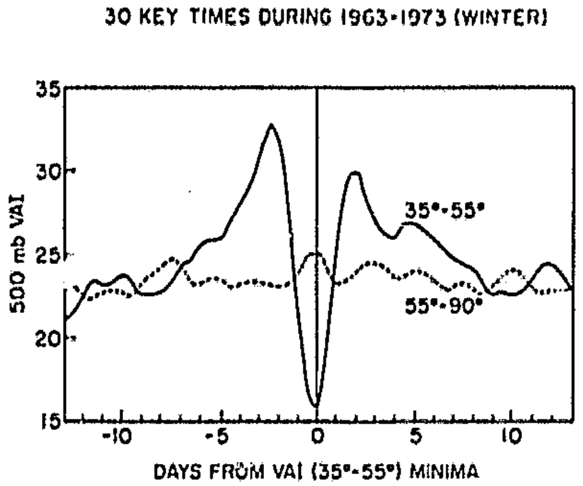


Fig. 4 (left). Similar to Fig. 3, except that the results are shown separately for the latitude zones 35°N to 55°N and 55°N to 90°N, and for the entire Northern Hemisphere north of 20°N. The form of the minimum at 1 day after the boundary passage is rather similar in all of these latitude zones. Fig. 5 (right). Same as Fig. 4, except that the key days are 30 minima in the latitude zone 35°N to 55°N that are not near sector boundaries (see text). The solid curve shows the results for the zone 35°N to 55°N, and the dashed curve shows the results for the zone 55°N to 90°N. The deep minimum in the lower zone does not appear in the upper zone. Abbreviation: *VAI*, vorticity area index.

maxima is about 10 percent. When we consider that weather usually consists of relatively small changes about climate (the average properties), this represents a sizable and important change. I repeat the warning that the sector boundary passage, although very convenient as a precise timing mark, almost surely does not have an important physical influence on the weather. The large-scale sector structure in the interplanetary magnetic field also may not have a direct causal influence on the weather, but may merely delineate some solar structure that does. Figure 1 is computed for 300 mbar, but similar results are found for 200, 500, and 700 mbar.

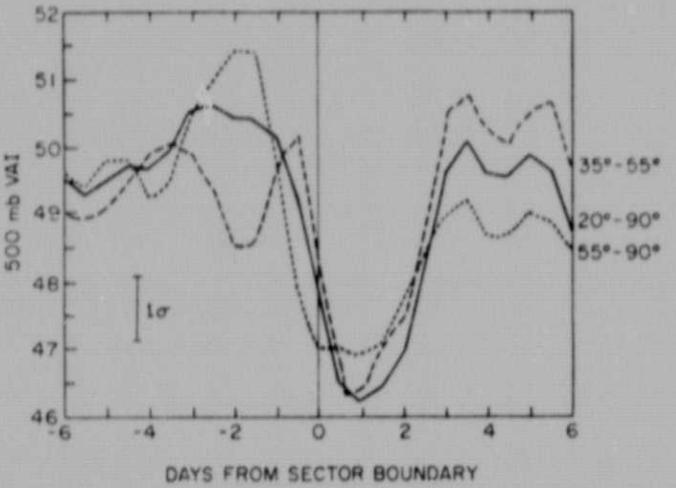
The result shown in Fig. 1 is prominent only during the winter months (*8*). This may be related to the fact that this is the season in which the equator-to-pole temperature differences are the largest, producing the largest stresses on the earth's atmospheric circulation.

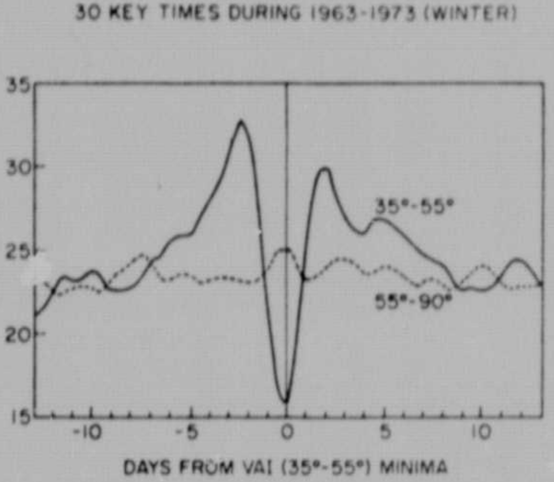
In view of the checkered history of sun-weather influences, the new claim shown in Fig. 1 must be subjected to the most careful scrutiny. The first test is to compute the standard error of the mean, which is shown by the error bar in Fig. 1. This is satisfyingly small, and on formal grounds one might conclude that the minimum near the sector boundary in Fig. 1 is significant. However, the textbook instructions for computing an error bar are always subject to assumptions and boundary conditions that are never completely fulfilled in any analysis of real observations. We therefore proceed to further tests. Figure 2 is in the same format as Fig. 1, but in this case the list of times of boundary passages has been divided into two parts, and the same analysis has been performed on each half separately. The extent to which the analysis of parts of the data is similar to the analysis of the entire data set is a further test of significance. In Fig. 2 the data have been divided into two parts in three different ways, as explained in detail in the figure legend. We see that the effect persists in all of these divisions of the data set.

A further test of significance is to inquire if the effect persists in new observations (*9*). Figure 3a shows our original analysis, while Fig. 3b shows the same analysis performed with a list of 81 new boundary passage times, none of which are included in the analysis of Fig 3a. The new boundary passage times used in Fig. 3b were obtained by increasing the interval examined to 1963 to 1973, and by supplementing spacecraft observations of the interplanetary magnetic field polarity with inferred polarities of the interplanetary field obtained from analysis of polar geomagnetic variations (*10*). In response to the suggestion (*5*) that some geomagnetic activity could be caused by variations in the weather, we performed the analysis shown in Fig. 3c, using a subset of 46 of the 81 boundary passage times used in Fig. 3b. In the analysis of Fig. 3c we used only boundary passages in which the time was fixed by spacecraft observations. It can be seen from Fig. 3 that the effect clearly persists in the new observations.

The last test of significance (*9*) to be described in this article is shown in Figs. 4 and 5. Figure 4 shows the same analysis performed in the latitude zones 35°N to 55°N, 55°N to 90°N, and 20°N to 90°N. We see that the effect is quite similar in these three zones. The possibility might still remain that due to conventional meteorological processes, whenever the vorticity area index has a minimum in the zone 35°N to 55°N it also has a similar minimum in the zone 55°N to 90°N. This possibility has been investigated in the following way. From a plot of the vorticity area index in the zone 35°N to 55°N during the time interval of interest, all those times not near a sector boundary passage at which the index had a minimum resembling the average minimum in Fig. 3 were tabulated. Figure 5 shows the same analysis performed with the resulting list. The result for the zone 35°N to 55°N shows a deep minimum, since each individual case was selected to have such a minimum. By contrast the result for the zone 55°N to 90°N is essentially a null result. No trace of a corresponding minimum is to be seen. It thus appears that at times that are not near sector boundary passages, minima in the two latitude zones occur independently, whereas some solar influence causes both zones to show similar minima 1 day after the passage of a sector boundary. If we accept the reality of this result, we can turn the argument around and say that the unknown solar influence causes similar results in the two latitude zones.

The most important test of the significance of the results claimed in Fig. 1 was made by Hines and Halevy (*11*), who stated, "Reports of short-term Sun-weather correlations have been greeted with skepticism by many." They subjected the data used in preparing Fig. 1 to a variety of statistical tests and requested the analysis of new data shown in Fig. 3. They concluded that "We find ourselves obliged, however, to accept the





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What does one conclude from all of the above? The results of the past century suggest that a certain caution would be very appropriate. The one statement that I would make with complete conviction is that this appears to be an interesting subject that should be vigorously pursued.

Summary

If there is indeed an effect of the variable sun on the weather, the physical cause for it remains quite elusive (*12*). We should keep in mind the possibility that there may be several causes and several effects. The situation may change through the 11-year sunspot cycle and the 22-year solar magnetic cycle, as well as on longer time scales.

Work is proceeding at a lively pace at the institutions mentioned in this article and at many others around the world. The Soviet Union has long had considerably more workers interested in this field than has any other country. A bilateral agreement between the Soviet Union and the United States has considerably increased the interactions between workers interested in this subject, including an exchange of extended visits between the two countries.

A detailed knowledge of solar causes of geomagnetic activity is only now beginning to emerge after many years of scientific efforts. This suggests that a possible successful solution to the sun-weather problem will require a similar magnitude of effort. We look forward with interest and optimism to the results of the next few years.

References and Notes

1. Lord Kelvin, *Nature (London)* 47, 106 (1892).
2. For recent reviews on this subject see J. M. Wilcox, *J. Atmos. Terr. Phys.* 37, 237 (1975); L. Svalgaard, in *Correlated Interplanetary and Magnetospheric Observations*, D. E. Page, Ed. (Reidel, Dordrecht, 1974), pp. 627–639; J. W. King, *Astronaut. Aeronaut.* 13, 10 (1975); "Proceedings of the symposium on possible relationships between solar activity and meteorological phenomena, NASA Goddard Space Flight Center, Greenbelt, Md., 7 to 8 November 1973," *NASA Spec. Publ.*, in press.
3. W. O. Roberts and R. H. Olson, *J. Atmos. Sci.* 30, 135 (1973); *Rev. Geophys. Space Phys.* 11, 731 (1973).
4. C. E. Leith, *Rev. Geophys. Space Phys.* 13, 681 (1975).
5. C. O. Hines, *J. Atmos. Sci.* 30, 739 (1973).
6. J. M. Wilcox, *Space Sci. Rev.* 8, 258 (1968).
7. ———, P. H. Scherrer, L. Svalgaard, W. O. Roberts, R. H. Olson, *Science* 180, 185 (1973); ———, R. L. Jenne, *J. Atmos. Sci.* 31, 581 (1974).
8. J. M. Wilcox, L. Svalgaard, P. H. Scherrer, *Nature (London)* 255, 539 (1975).
9. ———, *J. Atmos. Sci.*, in press.
10. L. Svalgaard, *J. Geophys. Res.* 77, 4027 (1972); *ibid.* 78, 2064 (1973); *ibid.* 80, 2717 (1975); J. M. Wilcox, *Rev. Geophys. Space Phys.* 10, 1003 (1972).
11. C. O. Hines and I. Halevy, *Nature (London)* 258, 313 (1975).
12. A. J. Dessler, in "Proceedings of the symposium on possible relationships between solar activity and meteorological phenomena, NASA Goddard Space Flight Center, Greenbelt, Md., 7 to 8 November 1973," *NASA Spec. Publ.*, in press.
13. This work was supported in part by the National Aeronautics and Space Administration under grants NSG 5024 and NGR 05-020-559, by the Atmospheric Sciences Section of the National Science Foundation under grants ATM74-19007 and DES75-15664, and by the Office of Naval Research under contract N00014-76-C-0207.