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SUMMARY REPORT OF STUDIES CONDUCTED AS A SEARCH FOR PHYSICAL MECHANISMS RELATING SOLAR VARIABILITY AND THE TROPOSPHERE

Edited By S. T. Wu
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Final Report

April 1981

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NASA - George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

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16. ABSTRACT

This document presents results from a study initiated in fiscal year 1979 to assess the status of proposed mechanisms relating solar variability to tropospheric changes. The topics of the study effort were pursued by individual review teams, and the results are reported as individual sections in this report. Included are reports by B. Haurwitz, M. A. Geller, T. D. Wilkerson, et al., and J. D. Klett, prepared under contract NAS8-32482 with the University Space Research Associates; by A. A. Few, Jr., and A. J. Weinheimer, prepared under contract NAS8-33023 with Rice University; and by A. S. Krieger, prepared under contract NAS5-27758 with American Science and Engineering, Inc.

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It is my greatest pleasure to acknowledge the critical suggestions and patience of the COR, Dr. W. G. Johnson, throughout this period of performance of this project (NAS8-33443). It is a fact that without his skillful assistance, it would not have been possible to bring this project to a successful completion.

Furthermore, I wish to express to Dr. Bill Davis my appreciation for his having made available to me copies of reports prepared by members of his study team. In the introduction to his final report to NASA on the USRA study effort, Dr. Davis states: "The overall conclusion of the USRA study is that . . . the reality of an influence on weather or climate remains to be established. . . . There is great scientific interest in settling the question and if a connection were established, this could have important applications, particularly in the improvement of long range forecasts."

The reports by Dr. Haurwitz, Dr. Geller, Drs. Wilkerson, Pitter, Ellingson and Rosenberg, and Dr. Klett were prepared as a part of the USRA study effort.

The report by Dr. Levy, which provides the bridge between my brief discussion of the solar forcing functions and Dr. Geller's discussion of tropospheric dynamical response, was originally prepared and presented by him in the AMS session.

The report by Drs. Few and Weinheimer summarizes briefly results of their extensive investigations of electrical connective mechanisms. It was prepared by them from several more extensive reports which they presented to NASA as their studies progressed.

I take this opportunity to express my sincere appreciation to each of the authors.

Shi Tsan Wu
The University of Alabama in Huntsville
April 1, 1981

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PREFACE

The proposition was advanced long ago that solar variability may modulate conditions in the Earth's troposphere. Many investigators over the years have studied possible correlations between solar and tropospheric changes. The scientific community has received these purported correlations with reservations because the physical mechanisms involved have not been evident. On the other hand, the significance of such correlations and mechanisms is great, if they can be substantiated.

In recent years, more investigators have turned their attention to candidate physical mechanisms by which solar phenomena may rationally influence the Earth's atmosphere. The scientific literature contains a variety of intriguing mechanism concepts presented with more or less clarity and credibility. None of the suggested mechanism chains extending from the Sun to the troposphere seemed in late 1978 to have compelling arguments convincingly presented in their support. Such comprehensive chains are of the greatest importance because of their potential significance to weather and climate, but incomplete chains also offer many scientific challenges.

Before a mechanism chain or links in a chain can be tested by a focused plan of observation or experiments, the proposition must be well formulated. When the Marshall Space Flight Center examined the prospects of using space capabilities to test candidate mechanisms, the need for well-formulated propositions was evident. Therefore, an effort was initiated during Fiscal Year 1979 to assess the status of proposed mechanisms and to strengthen the statement of their propositions. This document is one product of that effort. It contains a critical review of the creditable physical mechanism links and chains.

The review proceeded under several guidelines. The first was a clear emphasis on physical processes rather than statistical correlations. Another was a recognition that perhaps one, possibly none, and remotely more than one of the suggested chains may ultimately be shown to have significance. In this circumstance, progress is made when candidate mechanisms can be eliminated from further contention based on sound analysis of telling deficiencies. Also, it is a positive step forward when a sufficient definition is generated to facilitate tests against observations, existing or new. Likewise, there is value in identifying areas of uncertainty requiring further study or theoretical analysis. Certainly the review proceeded with no expectation that an obvious mode of solar influence on the troposphere would emerge. The expectation was that a careful formulation and review of the proposed mechanisms could be accomplished and that documentation of such would be welcome progress.

The reviews were accomplished by three teams of scientists. Each team had a leader and organized its work into subunits as appropriate. Initially the work of the teams was structured around three principal mechanism classes. One class concerned chains of processes in which the initiating agent is envisioned as variations in the electromagnetic radiation from the Sun. A second class emphasized chains following from differing conditions in the solar wind or resulting in changes in the vorticity indices in the troposphere. The third class concerned solar modulation of the soft cosmic rays reaching the atmosphere and electrification processes in the atmosphere. A scientist from the Space Sciences Laboratory of the Marshall Center was designated to follow and participate in the work of each team.

As the teams progressed with their studies, they found it advantageous to make some redistribution of topics among the teams. They also reached mutual agreement on a division of topics to be covered in a collection of review papers and reports. Whenever appropriate, the teams were encouraged to document their results in a form suitable for submission to standard review journals.

About midway in the efforts of the review teams, a meeting was held in Huntsville at which the teams presented interim results. These findings were critiqued at the meeting by a panel of active workers in the discipline involved. The comments received were reflected in the remaining work of the teams. The midway critical review meeting was hosted by The University of Alabama in Huntsville on April 9-10, 1979, and is described in some detail in Report on a Critical Review of Solar-Terrestrial Physical Connective Chains, by S. T. Wu (1979).

As Fiscal Year 1979 and the work of the review teams approached an end, a public presentation of their results was judged to be desirable. An opportunity for such a presentation arose at the Annual Meeting of the American Meteorological Society in Los Angeles on January 30, 1980. An afternoon session entitled "A Search for Physical Mechanisms Relating Solar Variability and the Troposphere" was organized with seven speakers (Bulletin AAS, 60, 1979, p. 1239). The invited speakers were either participants in the review efforts or individuals whose work the reviewers recognized as pivotal.

Clearly the individual reviews, as finally published, must stand on their own scientific merit, whereas this document is designed to assemble, in one place, the most salient features of the several individual studies and to provide a guide to specific material in them.

It is a pleasure to acknowledge with thanks the contributions of the many participants in this effort: the team leaders, team members, consultants, critical reviewers, and other supporting personnel. I sincerely hope that time will demonstrate that the progress in understanding justified the effort.

Charles A. Lundquist
Director, Space Sciences Laboratory
NASA, Marshall Space Flight Center

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INTRODUCTION

The studies discussed in this report were performed for the purpose of assessing the physical reality of chains of causative mechanisms that have been hypothesized to relate solar variability to the behavior of the Earth's lower atmosphere. Hence, the studies have focused primarily on the physical/chemical processes, per se. Except to the extent that an assessment of the reality or the physical significance of an hypothesized connective link influences the determination of its validity, the studies have not treated any of the numerous Sun-weather correlations reported in the literature.

The studies have attempted (1) to develop physically meaningful descriptions of the individual processes within chains that are hypothesized to relate solar behavior to that of the Earth's atmosphere, (2) to assess the significance and physical realizability of the processes, and (3) to identify experimental investigations required either to provide additional knowledge needed to make possible an adequate assessment or to validate the assessment made in the studies.

The studies were conducted in three parallel, coordinated efforts. The first was led by Dr. Alan S. Krieger of American Science and Engineering, Inc. It identified and characterized those solar variations believed most likely to constitute the forcing functions in an hypothesized solar-terrestrial atmosphere chain.

The second study was led by Dr. Arthur A. Few, Jr., of Rice University. It dealt mainly with changes in the Earth's atmospheric electrical characteristics due to solar variability. Hence, it was an investigation of the major body of transfer functions whereby solar variations have been hypothesized to affect the terrestrial lower atmosphere.

The third study was led by Dr. M. R. (Bill) Davis of the University Space Research Associates, Boulder, Colorado. It focused on some of the observed variations in atmospheric, generally tropospheric, behavior that have been suggested to have been caused by, or strongly influenced by, solar variability. For each, it has attempted to identify, characterize and assess the chain of physical mechanisms, beginning at the observed "effect" and generally moving backwards toward the Sun.

A fourth effort, led by Dr. Shi Tsan Wu of the University of Alabama in Huntsville, provided for an independent critical review of findings as the studies progressed and for dissemination of study results.

The organization of a session entitled "A Search for Physical Mechanics Relating Solar Variability and the Troposphere" for the 60th annual meeting of the American Meteorological Society, Los Angeles, California, January 1980, was accomplished as a part of this effort.

SUMMARY OF STUDY RESULTS

The solar-terrestrial system is complex. From energy considerations, it is highly unlikely that solar activity directly influences tropospheric behavior, i.e., weather (Dessler, 1975, and Willis, 1976). Therefore, it is assumed that an effective connective chain must be one in which the solar variation modulates or amplifies a naturally occurring feature of tropospheric behavior. The single hypothesis of direct connection between solar variability and tropospheric response invokes the influence of a change in the total solar irradiance, the solar constant, on the mean areal temperature at the Earth's surface. The data currently available indicate that the solar constant varies no more than 0.1 percent, the limit of accuracy of the measurements. Numerical simulations of the response of the global atmosphere to variations in total solar energy input indicate that a sustained variation of 1 percent in the energy input results in a sensible change 1°C to 1.5°C, in the mean annual areal temperature. The mechanism might be applicable in explaining long-period climatic changes. Chains proposed to relate shorter-term solar variations to tropospheric behavior must invoke processes occurring in the Earth's upper and middle atmosphere. Figure 1 depicts, in a greatly simplified scheme, the possible chains.

In Figure 1, the variable processes of the Sun are shown in three broad classes: (1) The Electromagnetic Radiation which can change both in total emittance, i.e., the solar constant, and in spectral composition, (2) The Energetic Particles Emission, i.e., Solar Proton events, and (3) The Solar Wind. Processes occurring in the upper and middle atmosphere are classed as either Photochemical or Ionization processes. Those in the lower atmosphere, near and below the tropopause, are considered in four categories: Temperature Effects, Kinematics, Precipitation, and Electrification. Figure 1 does not attempt to depict the multitude of interrelations existing among the classes of mechanisms. Figure 2 shows a few of the interconnections. It, too, in no way portrays the complexity of the real system.

The value of the simplified classification is that it forces one to focus on classes of key processes within causative chains that in reality are so complex as to defy detailed analysis. As an example, consider a simplified chain in which the variation in the spectral composition of the solar emittance is hypothesized as the forcing function influencing the circulation pattern within the troposphere. More specifically, changes in the intensity of the radiation in the spectral region from 2000 angstroms to 3000 angstroms are held to modify the concentration and distribution of ozone and, thereby, the temperature distribution in the stratosphere. The change in temperature distribution changes the flow pattern at altitude, thereby changing the reflection coefficients for planetary waves that originate in the troposphere and propagate energy upward. The change in reflected energy modifies the wave pattern (circulation) within the troposphere. Levy (H. Levy, II, Report III) has reviewed the evidence for solar control of temperature distribution in the stratosphere; Geller (M.A. Geller, Report IV), the tropospheric wave modulation processes. The data now available are not sufficient to validate conclusively the hypothesized chain; however, with the assumptions made in the analyses, the hypothesis concerning wave modulation is shown to be physically realizable. Areas in which additional research is needed are identified.

Modification of the total concentration or distribution of atmospheric ozone at critical altitudes has been frequently invoked as a key mechanism through which solar influence might be exerted on the behavior of the Earth's lower atmosphere. Haurwitz (B. Haurwitz, Report II), Levy (loc. cit.), and Few (Arthur A. Few, Jr., and Andrew J. Weinheimer, Report V) have reviewed the processes involved. The evidence indicates generally that for rapid atmospheric responses, periods of a few days or less, the effects at critical altitudes are probably insufficient to exercise control. Few discusses a mechanism, involving both increased reaction rates and increased concentration due to electric field drift of ion-molecular reactants, that cannot be immediately disregarded. Similarly, there are insufficient data available to assess the extent to which ozone concentration at critical altitudes over long periods, a few years, might be related to solar spectral variability. Both questions require further study.

In those chains that are hypothesized to explain perceived rapid responses of the behavior of the troposphere to that of the Sun, the transfer functions involved are almost invariably electrical in nature. Hence, the key mechanisms to be considered involve changes in the concentration or distribution of ions in the atmosphere together with the immediately local results of such changes. That the Sun influences ion concentration and distribution within the atmosphere is well established. The mechanisms (modulation of galactic cosmic rays entering the Earth's atmosphere, impingement of solar protons into the atmosphere, injection of energetic particles at high latitudes due to disturbances of the magnetosphere induced by changes in the solar wind, and ionization of constituent gases at ionospheric altitudes by solar uv) are all well identified and generally understood. Critical to the assessment of the significance, and validity, of a given proposed connective mechanism are (1) a determination of the magnitude of the solar forcing function on the atmospheric parameter of interest at the site of interest, (2) an estimate of the excursion of the parameter, due to the solar forcing, from its normal value, and (3) a determination of the influence of an excursion of such magnitude on the next immediate processes in the chain. As an example, Few and Weinheimer evaluate the probability that variations in the atmospheric electrical field are sufficient to directly induce sensible changes in atmospheric pressure at tropospheric levels. The pressure due to the clear weather field at tropospheric altitudes is shown to be some 12 orders of magnitude lower than normal atmospheric pressure. At thermospheric altitudes the pressure due to the electric field is about equal to normal atmospheric pressure, but no rational mechanism exists for transmitting differences in these small absolute pressures as a controlling influence to the troposphere. The electric pressure due to the fields developed in thunderstorms is several orders greater than that in the fair weather field but is still insufficient to affect the kinematic behavior of the troposphere directly. Sartor (see Few and Weinheimer and reference therein) has pointed out that in the tropics, where Coriolis forces approach zero, the electrical pressure associated with thunderstorms could be sufficient to produce vorticity.

To affect the meteorological behavior of the atmosphere through solar modulation of the concentration of an ion-molecular species, the ion-molecular species must interact significantly with an atmospheric component that directly influences the meteorological behavior; for example, ozone. Mohnen, and others, (referenced in Few and Weinheimer) had concluded that, even in the greatest reasonable enhanced concentration, the number of ion-molecules available for reaction is orders of magnitude lower than the numbers of ozone and other reactant molecules. Hence, the probability is quite small that solar control of atmospheric behavior could be exercised through ion-chemistry changes. The present study generally confirms these conclusions. However, in the case in which ion concentration is influenced by changes in production rate and drift in the electric field a detectable influence may be possible.

A study of those processes in which ions serve to induce or to enhance nucleation and "particle" growth appears, generally, to support the conclusion that the effects of solar modulation of ion concentration are not sufficient to overcome the randomizing effects inherent in other competitive processes in the atmosphere. However, those cluster processes in which trace gases (for example, H_2SO_4) are involved are not yet fully understood and require additional study before a totally firm conclusion can be reached.

It generally is assumed that the electric field's influence on the coalescence and droplet growth process is important only at field strengths encountered in thunderclouds. However, the Few study reports that an undocumented investigation of the coalescence process in field-free environment had revealed that a field is required for the process to proceed at all. If this is the case (further investigation obviously is needed to confirm this), additional study of the role of the weaker, fair weather, atmospheric electrical fields on the process is indicated. For example, the occurrence and growth rate of cirrus clouds might be influenced by the variation in the fields normally encountered at that altitude (Few and Weinheimer; T. D. Wilkerson, et al., Report VI).

Evidence appears to exist that the rate of electrification of a thundercloud is related to the intensity of the fair weather field and, therefore, might be subject to solar influence through processes that modulate the ionization rate and atmospheric field strength in the lower atmosphere (Few and Weinheimer; J. D. Klett, Report VII). The evidence for direct influences of the level and rate of electrification of thunderclouds on other, more general, lower atmosphere meteorological characteristics is presently quite tenuous. Additionally, the mechanisms whereby solar variations are "mapped down" to influence field strength at the tropospheric level are not completely elucidated. Both areas require additional research.

Solar modulation of high cirrus cloudiness has been invoked as a key mechanism in several chains that have been hypothesized to relate solar variability to the behavior of the Earth's atmosphere. Dickerson, Pitter, Ellington and Rosenberg, as members of the USRA Study Team, have investigated this mechanism. They conclude that sufficient observational data do not now exist for a good test of the hypothesis. They identify the additional data required and suggest the research for obtaining them. In every case that they treat, the data are needed to further understanding of the role of the high cirrus in the meteorological system, generally; the research recommended is important beyond its potential contribution to the determination of the role of the high cirrus as a solar variability-Earth atmosphere connective mechanism.

CONCLUSIONS AND RECOMMENDATIONS

Because of the complexity of the solar-terrestrial system, it would have been surprising had the studies identified conclusively any single chain of physical processes relating solar variability to the behavior of the Earth's lower atmosphere. The studies have identified some areas in which, perhaps, the search for solar-terrestrial coupling mechanisms is most likely to prove fruitful.

In some cases the inability to unequivocably determine the significance of a particular identified process stems from the lack of sufficient data; in some, from the lack of an adequate model from which to assess the consequence, or output, of the process; in some, from both. As an example, the "noise" in currently available general circulation models is at least as great as the uncertainty in the measured values of the solar constant. Should the recently activated program of measuring the solar constant from space reveal persistent small variations, improvements in the model would be required to permit rigorous evaluation of the effects.

From the present study, refinement of models of the type treated by Geller, together with more extensive measurements of temperatures and flow fields in the lower stratosphere, appears warranted. If the predicted correlation between the flow field at altitude and the "phasing" of the tropospheric circulation pattern is verified, an intensive search for the mechanisms controlling the temperature and flow distributions in the lower stratosphere would be a well-justified next step.

The available information appears to indicate that ion-chemistry processes probably are not direct key mechanisms in solar-terrestrial atmospheric behavior chains. Nevertheless, further study (modeling) of solar particle events that include ion transport and ion reactions could be productive. If the models indicate that the concentrations and reaction rates reach levels sufficient to result in significant changes in, for example, ozone concentration, an experiment or program would be justified.

Measurements of clustered ion mobilities in the atmosphere strongly indicate that the atmosphere consistently produces ion clusters larger and more massive than current theory predicts. If this is the case, the probability of producing, in the middle atmosphere, ion clusters sufficiently massive and long-lived to serve as cloud "seeding" nuclei is enchanced. Further research, including in situ measurements, laboratory measurements and theoretical studies, is required.

Modulation of high-altitude cirrus cloudiness has been frequently invoked as a key link in chains hypothesized to relate solar variability to tropospheric behavior and in chains proposed in the examination of possible consequences of the deposition of anthropogenic materials in the stratosphere. Good data on the extent of occurrence of high-altitude cirrus and on its normal fluctuations do not now exist. Measurements to provide these data are urgently needed. Additionally, improvements in the models treating the effects of high cirrus on the thermal and dynamic behavior of the atmosphere in the region of the tropopause are needed.

Although many of the needed measurements arise mainly from uncertainties regarding individual processes, there is strongly implied in the areas just discussed a need and an opportunity for carefully planned joint observational programs in which one observes simultaneously the behavior of a pair of observables that are postulated to be related by rational, physically realizable cause and effect mechanisms. The interdisciplinary investigations making up this study effort have identified a number of such observational programs that are potentially rewarding. Additionally, the study results provide information pertinent to the selection and ordering of such investigations.

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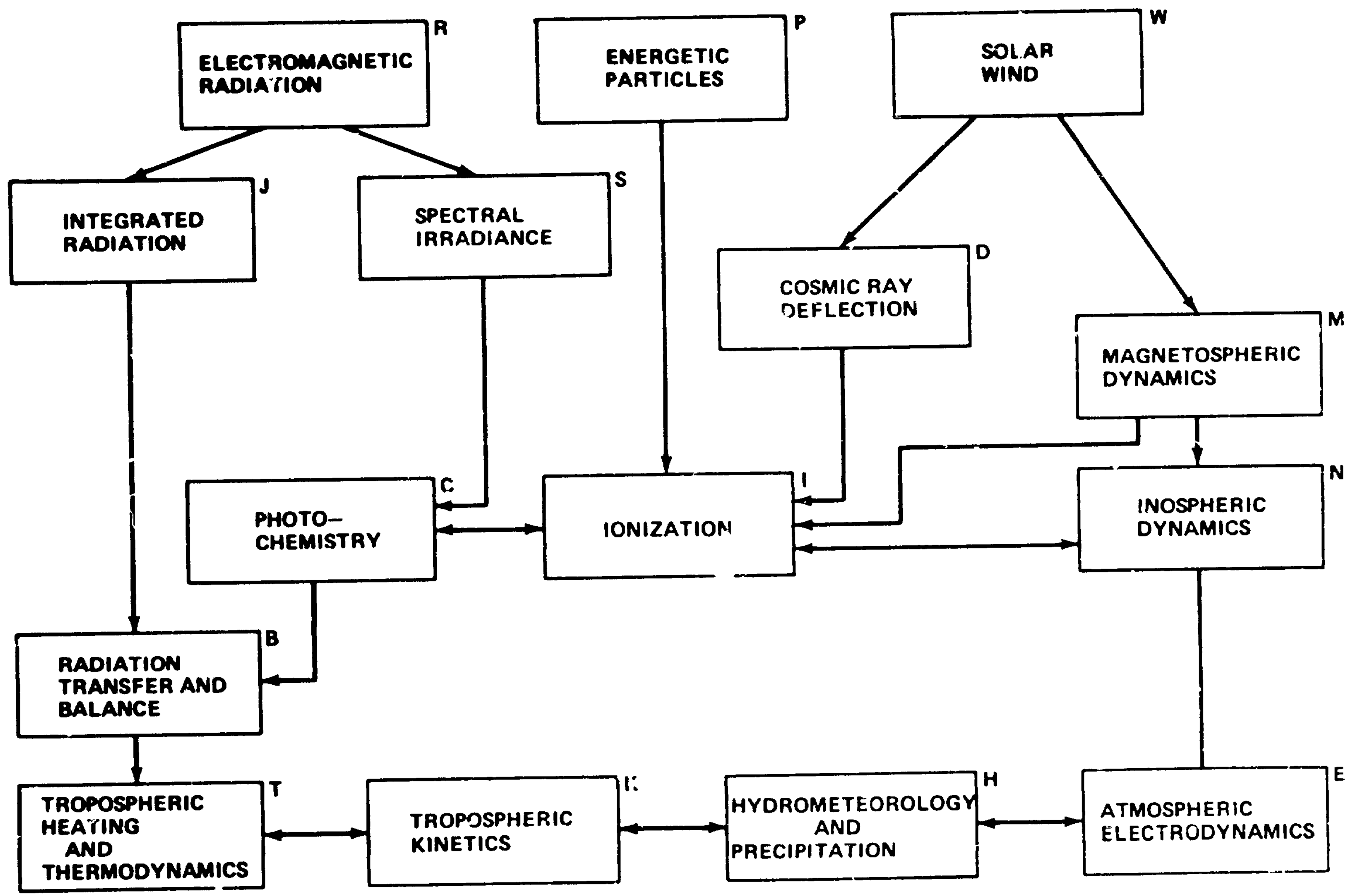

FIGURE 1 SCHEMATIC OF CONNECTIVE CHAINS RELATING SOLAR VARIABILITY TO TROPOSPHERIC BEHAVIOR. SHOWING MAJOR PROCESSES AND CONNECTIVE LINKS.

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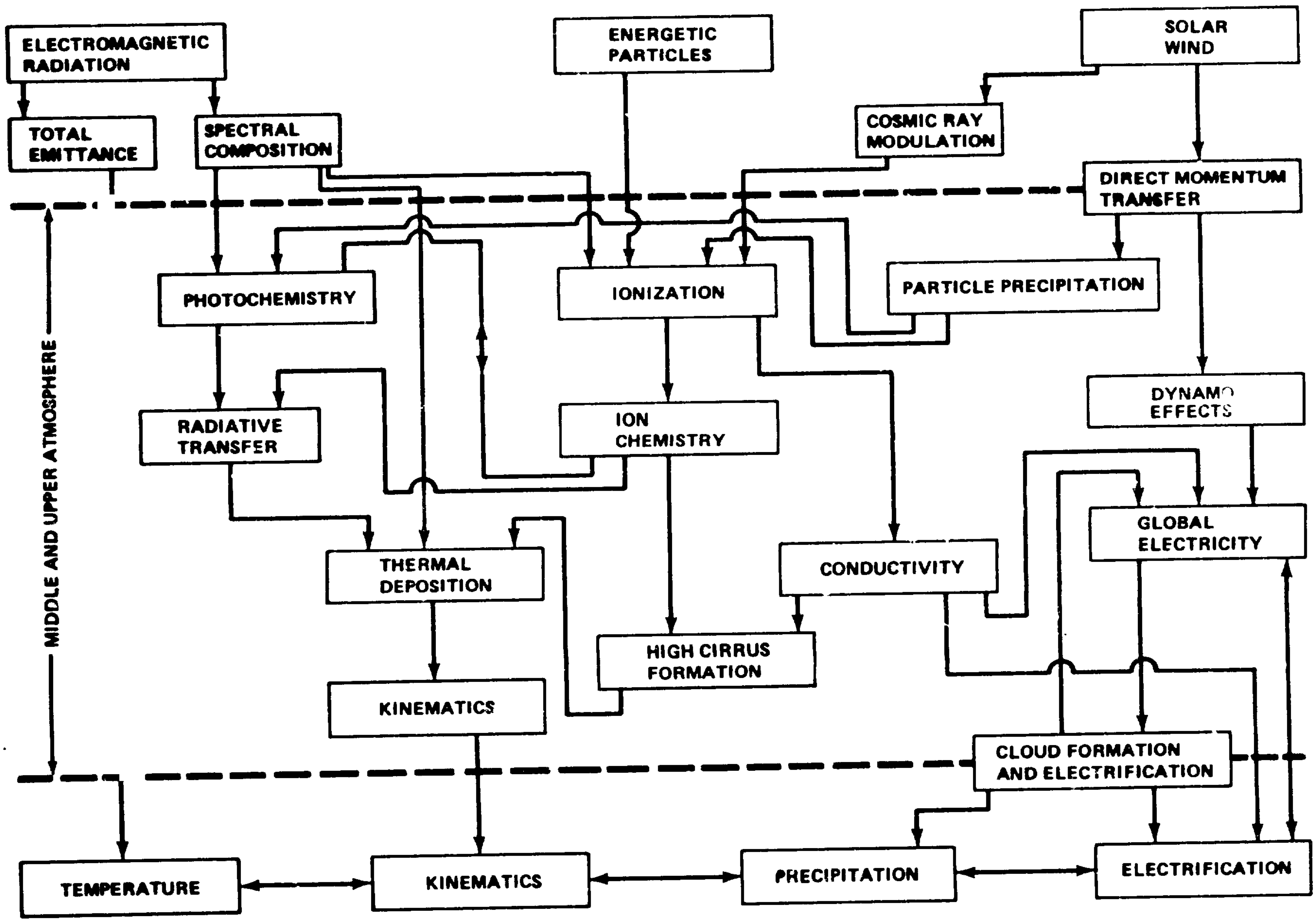

FIGURE 2 SAME AS FIGURE 1 WITH A FEW OF THE INTERMIDIATE PROCESSES AND FEEDBACK LOOPS SHOWN.

Report I

Solar Variability in Relation to Earth Atmosphere

by

S. T. Wu
The University of Alabama in Huntsville

It has long been recognized that the Earth's atmosphere is controlled by the output of the sun (Herman and Goldberg, 1978). Therefore, any fluctuations in the sun's output - radiation, field and particles would be accompanied by a response in the terrestrial atmosphere. The sun's outputs can be classified into three categories:

1. Electromagnetic Radiation
2. Solar Wind and IMF (Interplanetary Magnetic Field)
3. Energetic Particles.

Any of these output forms has shown definite effects on the terrestrial atmosphere. These influences are recognized by the changes of atmospheric chemistry, ionization, and dynamics. In order to further our understanding of the physical chain mechanisms between the source (i.e, solar output) and responses (Earth's atmosphere, including magnetrosphere, ionosphere, and lower atmosphere), it would probably be reasonable to first investigate these sources and then see what possible mechanisms will work to transport energy and momentum to the receiver (i.e., Earth's atmosphere).

Unfortunately, the region between the sources (sun) and receiver (Earth's atmosphere) is an unusually complicated region. Presently, it is impossible to determine a one-to-one type correspondence situation. For example, the atmospheric chemistry can be influenced by electromagnetic radiation and can also be affected by energetic particles. Therefore, we shall only be concerned with variations of sources (i.e., solar outputs) in this section. These sources are presented in the following.

Electromagnetic Radiations

The solar electromagnetic radiation consists of two parts: (a) integrated solar flux and (b) solar spectrum. The spectrum of electromagnetic radiation extends from X-rays with wavelengths of 10 nm or less to radio waves of wavelengths 100 m and more. It has been said that 99% of the energy contained, ranges from 275 - 4960 nm. Even though the solar variability is still controversial, it has been shown there is evidence of the periodical behavior of solar electromagnetic radiation. For instance, the long-term changes of solar electromagnetic radiation associated with the sunspot cycles was reported by Abbott (1958) and the short-term fluctuations over days or weeks was reported by Clayton (1923). However, these changes, whether due to variations of atmospheric transmissivity or the strength of the source, are still debatable. A typical example of these data is shown in Figure 1.

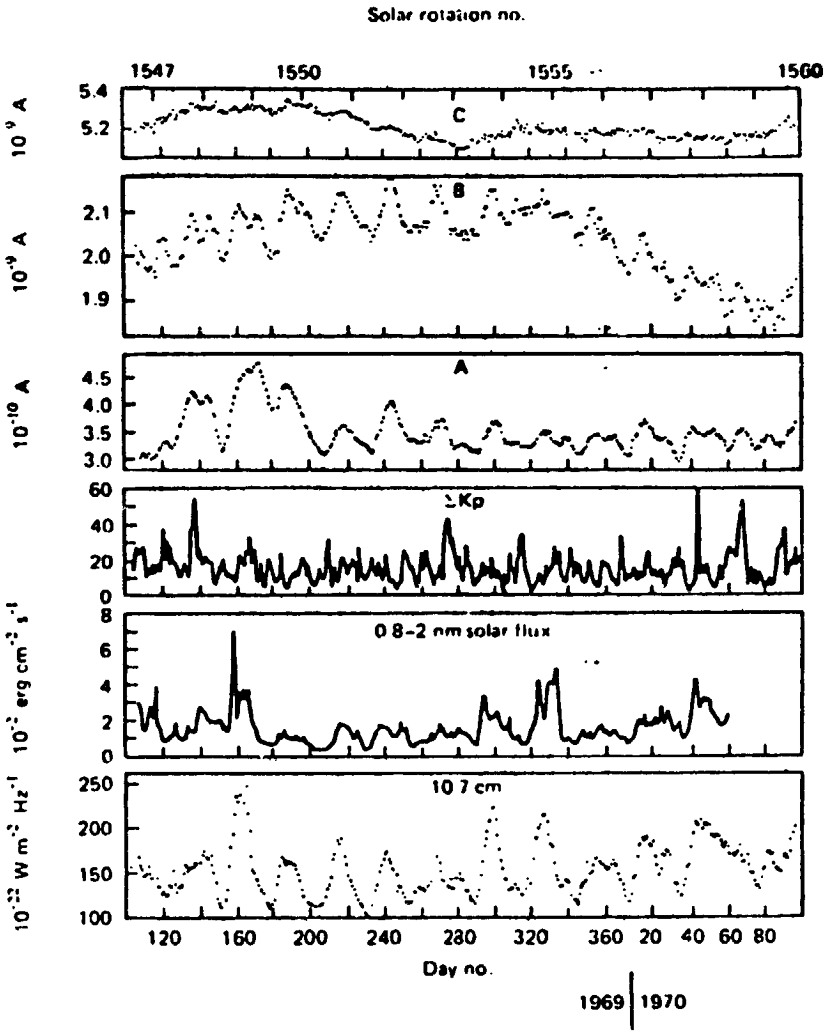

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Fig. 1 Time variation of MUSE sensor currents illustrating 27-day recurrence of UV enhancements, compared to magnetic index (ΣKp), solar X-rays, and 10.7 cm radio flux. The sensors cover the approximate wavelength ranges: A, 110 160 nm; B, 160 200 nm; C 210-320 nm. From Heath (1973) and Heath et al. (1974). (See Herman and Goldberg, 1978.)

Most recently, the ACRIM (Active Cavity Radiometer Irradiance Monitor) experiment on-board Solar Maximum Mission shows a definite variation in solar constant of about a few tenths of one percent (Figure 2, Hudson, 1981). This is the first satellite-based instrument measurement (Wilson and Hudson, 1981) which is capable of resolving solar irradiance fluctuation smaller than $\pm 0.1\%$.

On the other hand, Mitchell (1965), et al. have suggested that a 1% change in solar constant is sufficient to cause profound alterations in atmospheric circulation. Further, Vollant (1977a,b) has shown theoretically that a change of $0.1 \sim 0.3\%$ can produce a measurable change in atmospheric pressure. On the other side, King et al. (1977) have shown similar conclusions based on observations.

Solar Wind and IMF (Interplanetary Magnetic Field)

It has been known that the magnetic field variations observed at the surface of the Earth are produced, in part, by ionospheric and magnetospheric currents associated with the interaction between the solar wind and magnetosphere. Thus, the variation of solar wind and IMF (see White ed.) will be important parameters for searching the physical chain mechanisms between the solar-terrestrial relationships. However, the understanding of these parameters are very much limited. Variations in solar wind bulk flow properties on time scales longer than one day were presented by Goldstein and Sisco (1972). They organized their data into series of high-speed streams and concluded that each solar wind stream is unique, but almost all high-speed streams share common characteristics near 1 AU. From these data, those stream profiles exhibit rapid rise and slow decay of the speed and ion temperatures, the concentration of mass, momentum and energy near the leading edge, and an east-west change in flow direction at the presssure ridge as shown by Sisco (1972). These features are believed to be effective mechanisms in transferring momentum and energy into the terrestrial atmosphere.

The variations in the interplanetary magnetic field strength (IMF) are also categorized by the high-speed streams structure. It has been established by many investigators (Wilcox and Ness; 1965; Neugebauer and Snyder, 1967; Belcher and Davis, 1971) that magnetic field strength maximized simultaneously with the density at the leading edge of streams. This is similar to the bulk flow properties, because characteristics of the magnetic field are caused by the steepening of high-speed solar wind streams in interplanetary space. Furthermore, we realized that the magnetic field tends to point towards or away from the sun along the essential Archimedian spiral for several days at a time. This aspect of the interplanetary field is known as magnetic sector structure as suggested by Wilcox and Ness (1965). There are two to four sectors per solar rotation (Svalgaard and Wilcox, 1975). Magnetic sectors are extremely persistent features of the

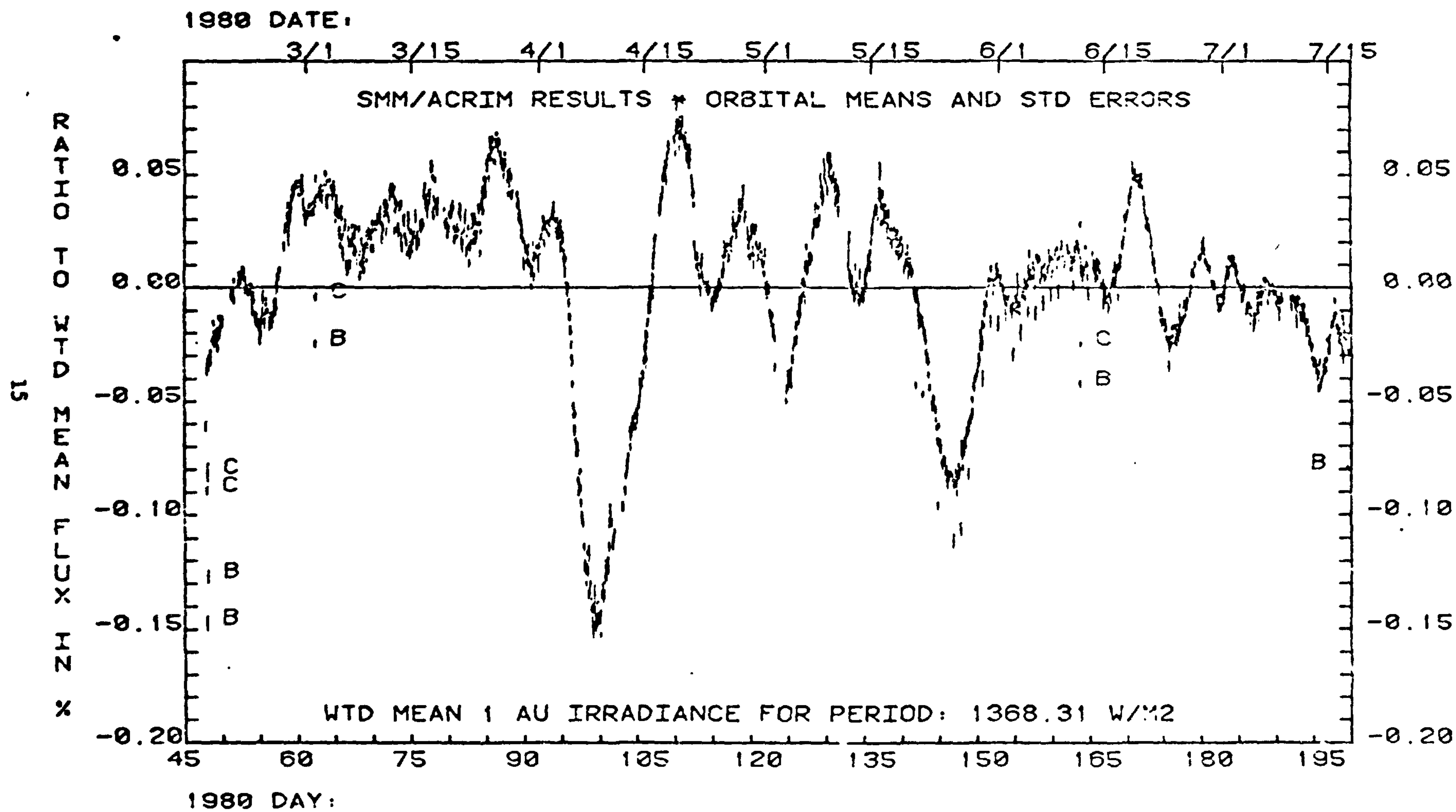

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Figure 2

interplanetary solar wind at 1 AU, and often recur at the same solar longitude for many solar rotations (Svalgaard and Wilcox, 1975). There is a close relation between magnetic structure and solar wind streams. Boundaries between magnetic sectors usually occur in the low-speed gas between streams, and high-speed streams are usually unipolar (Wilcox and Ness, 1965). In addition, high-speed streams are not nearly as stable as the magnetic sectors within which they are imbedded. Many streams do not endure for as long as one solar rotation and those that do often vary significantly in shape, amplitude, and Carrington longitude from one rotation to the next (Gosling et al., 1976). Also, it has been shown that a relationship exists between the high-speed streams and VAI, as well as magnetic sectors and Vortex Area Index (VAI), which may indicate a terrestrial connection.

Energetic Particles

The last, but not least source of influence on terrestrial atmosphere is the energetic particles from the sun which which will affect atmospheric photo-chemistry, ionization, etc., through energy and momentun transfer. In this section, we will briefly discuss the variations of energetic particles of solar origin. To illustrate these variations, Figure 3 shows the percentage increase in the count rate of ground-level instruments for each of the ground-level solar particle events and sunspot number of cycles 18, 19, and 20 as a function of yearly occurrence (Lanzerotti, 1977; Pomerantz and Duggal, 1974). It should be noted that the number of detected ground-level events increased quite drastically after 1954, beginning of the use of the neutron monitors and super neutron monitors (Lanzerotti, 1977). Furthermore, the variations of solar photon fluxes can be obtained from PCA (Polar Cap Absorption) events. Figure 4 shows the variations of solar proton fluxes following the sunspot number.

In summary, we have very briefly discussed the various possible important sources of solar origin which have statistically shown the influences on terrestrial atmosphere. However, the understanding of the physical mechanisms to govern these variations are still vague. For example, the physical mechanisms caused by the solar cycle, acceleration of solar wind, etc. Recently, some progress has been made, but the tasks are still ahead of us. It is felt that in order to understand the physics of whole sequential events of solar-terrestrial relationships, we need to know the physical mechanisms to govern sources which will affect the terrestrial atmosphere.

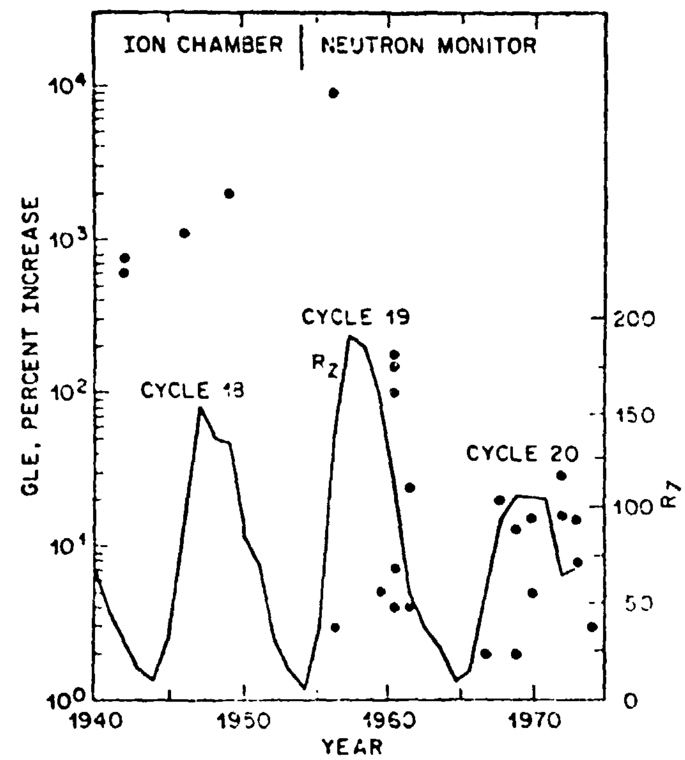

Fig. 3 Magnitudes of ground-level solar cosmic ray events since their discovery in 1942. Also plotted are yearly sunspot numbers. Adapted from Pomerantz and Duggal, 1974a.

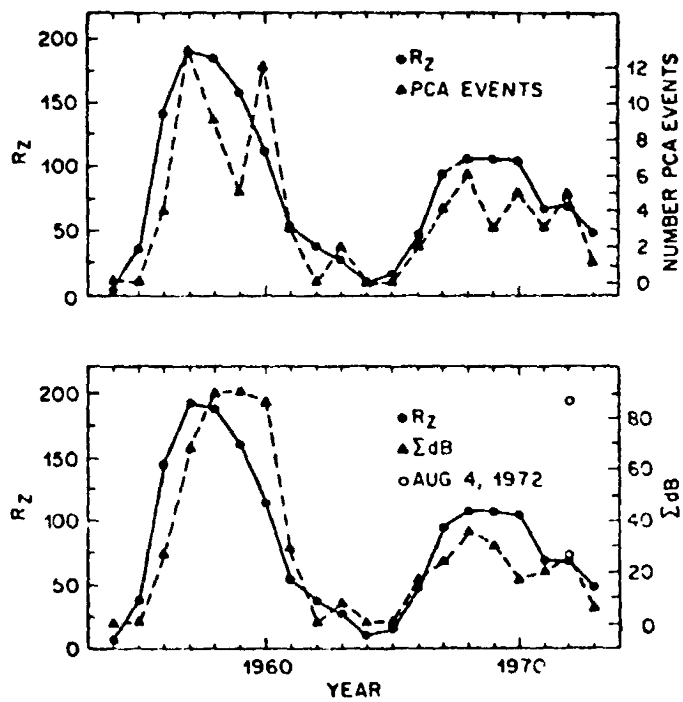

Fig. 4 Top, annual number of PCA events >2.5 dB and annual sunspot numbers during two solar cycles. Botoom, integrated yearly PCA magnitude (Σ dB) and annual sunspot number during two solar cycles. Adapted from Pomerantz and Duggal, 1974a.

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Report II

Physical Mechanisms Linking Solar and Weather Variability

by

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PHYSICAL MECHANISMS LINKING SOLAR AND WEATHER VARIABILITY

by

B. Haurwitz

Preface

This paper describes and discusses briefly some of the physical mechanisms which have been suggested as possible links between solar activity and the weather. Neither the list of mechanisms, nor the references are approaching anything like completeness. I have confined myself to fairly recent proposals and papers, but it is difficult to keep up even with the current literature on the subject.

Neither statistical, nor observational studies have as yet established beyond doubt the existence or physical necessity of a link between solar variability and the weather. In this situation, the development of detailed physical hypotheses might seem premature since there is no specific physical connection to be explained. But it is more and more recognized that the statistical search for relations between solar variability and the lower atmosphere must be preceded by clear, and rational, hypotheses indicating what theoretically suspected link is to be looked for. Much of the theoretical work discussed here is, of course, important for progress in the atmospheric sciences even if no solar connection can be established.

1. Electrical Connection Through Thunderstorms

Effects of solar events on electric properties of the middle and lower atmosphere, especially effects of cosmic ray variations on the conductivity of the atmosphere, appear to be well established by direct measurements. Statistical relations between solar events and thunderstorm occurrence have been claimed (Herman and Goldberg, 1978), but have not been generally confirmed (Pittock, 1978). Nevertheless, the electrical connection seems at present one of the most promising mechanisms to link solar variability and changes in the lower atmosphere.

Markson (1978) has described in some detail such a coupling. He considers the global atmospheric electric circuit between the earth's surface and the "ionosphere", that is the equipotential surface at about 60 km elevation where the conductivity is so large that potential gradients are very small. Global thunderstorm activity maintains the current between the two surfaces by causing positive changes to flow upwards while the return flow to the earth's surface takes place over areas free of thunderstorms. Such conduction currents can exist because the atmosphere, even below the D layers, is slightly ionized, mainly by galactic cosmic radiation.

In the stratosphere, ionization is also caused by solar protons emitted during solar flares and by X-rays from magnetospheric and auroral particle precipitation. Because of their solar origin, these last two sources of stratospheric ionization show a clear correlation with solar events. Further, the flux of galactic cosmic rays as observed in the vicinity of or at the earth shows significant decreases at times of disturbed solar wind caused by solar flares (Forbush decrease). Consequently, the conductivity of the global circuit of atmospheric electricity can be expected to change with solar events.

Specifically, Markson's proposed mechanism for solar modulation of thunderstorm activity focuses on resistance changes in the volume above the thunderstorm. In his scheme of the global circuit, this volume contains most of the global circuit resistance. Thus, it exerts strong control over the current and thereby the ionospheric potential and the fair-weather electric field which would explain its reported enhancement following solar flares, and thus also any correlation between thunderstorm frequency and solar activity.

Herman and Goldberg (1978) suggested a different mechanism for a coupling between solar activity and thunderstorms. They show how solar proton events may lead to excess ionization above about 20 km, hence to increased conductivity and to reduced vertical potential gradient, while below 20 km, the Forbush decrease associated with the same proton event leads to decreased conductivity and, hence to increased vertical potential gradient.

Reference should be made here also to observations by Cobb (1979) who observed, at the South Pole, a strong increase of the air-to-earth current after a solar flare with a gradual return to the normal value. If such variations are found to be a regular feature after solar flares, the global circuit theory might require a modification provided the field enhancement is of local rather than global character.

The influence of the atmospheric electric field on thunderstorm development, cloud-physical processes, and precipitation is still only imperfectly known, although various workers in this field have proposed effects which would provide further links between solar-induced atmospheric electric field changes and increased thunderstorm activity, as well as the additional link with precipitation changes. A convincing physical mechanism linking solar variability and weather through thunderstorm activity would in particular require a more general agreement among cloud physicists on the role of increased field strength in the augmentation of precipitation. Obviously, research to find the answers to such questions would be of fundamental importance to cloud physics in general, not only to the field of solar influences on weather. (Editor's note: These questions are discussed in detail by J.D. Klett in the final chapter of this collection.)

Solar protons arriving near the earth are deflected by the magnetosphere and cannot penetrate into the lower atmosphere at lower geomagnetic latitudes. Galactic cosmic rays reach all latitudes, but are modulated by the solar wind in the magnetosphere, as observed in the Forbush decrease. Thus, it is possible that any relation between the solar cycle and atmospheric electric parameters has opposite phase relationships at high and low geomagnetic latitudes.

One of the attractive features of the suggested linkage mechanism is that it merely requires a change of an atmospheric parameter, electric conductivity, by an extraterrestrial influence, not a solar energy input matching that of the observed atmospheric effect. But it must be repeated that the hypothesis will not be complete until the links from the changes in the atmospheric electric field to thunderstorm development and to such atmospheric phenomena as precipitation and, possibly, kinetic energy and vorticity are established.

2. Cirrus Formation Modulated by Solar Events

Roberts and Olson (1973) have suggested as the physical link between solar activity and the low atmosphere Cirrus formation due to ionization in the vicinity of the 300 mb surface, with the ionization produced by incoming solar particle streams associated with geomagnetic and auroral events. This suggestion was proposed in support of their statistical findings that the vorticity area index at the 300 mb level appears to be closely related to solar activity. The hypothesis has been further discussed in some detail in a paper by Dickinson (1975) who considers a number of the mechanisms which might provide the missing link between solar variability and the earth's lower atmosphere. Before dealing with the solar modulation of Cirrus clouds, Dickinson reviews the effects of clouds in general and of Cirrus in particular on the atmospheric radiation and heat budget. Changes in the height of thick clouds of 0.5 km or in cloud cover of 5 to 10 percent could produce changes in the global mean temperature of the order of 1°K and would thus be comparable to global temperature changes produced by a change in solar constant of one or two percent, at least according to the simple numerical model used for Dickinson's estimates. However, no such changes of cloud height or cloud cover modulated by solar activity have been reported. For the present discussion, the main point is that clouds can substantially influence the atmospheric heat budget.

Because of the hypothesis suggested by Roberts and Olson, we are here interested mainly in the effects of Cirrus clouds. Dickinson quotes the results of calculations by Coakley for a Cirrus deck near the tropopause with 20 percent infrared emissivity under winter conditions: The net solar heating rate changes only slightly, but the cooling rate of the air column below the Cirrus deck is reduced by 0.1K/day between 45° and 60°N, by a bit more at lower latitudes. To appreciate such an effect of a Cirrus layer on the atmosphere, it may be pointed out that a mean temperature gradient of 1°K in mid-latitudes over a distance of 15° in latitude would decrease the mean zonal westerly wind at the tropopause between these latitudes by 2 m s^{-1}.

In order to establish a solar modulation for the occurrence of Cirrus, the effects of cosmic rays on ion and condensation-nuclei production are invoked. As already mentioned in the preceding section, the ionization is mainly due to two components of cosmic radiation, galactic and solar cosmic rays. The solar modulation of the lower-atmosphere ionization has been well established by observation. But it remains to connect this ionization with Cirrus formation, as suggested by Olson and Roberts. Dickinson considers a direct effect of ionization on cloud formation unlikely, even though ions reduce the required supersaturation, because several hundred percent of supersaturation are still required for droplet formation. Such high supersaturation in the lower atmosphere is unlikely because there is always a sufficient number of particles available to ensure nucleation at vapour concentrations of only slightly more than 100 percent.

Therefore Dickinson suggests another role of the ionizing process by solar protons than that visualized by Roberts and Olson, namely the formation of stratospheric aerosol, predominantly a mixture of sulfuric acid and water. Such nuclei require only low supersaturation for droplet growth. To put the hypothesis on a firmer basis, it will be necessary to show that the sulfuric-acid aerosol formed near the tropopause has properties which vary with the fluctuations in ion concentration, and that this aerosol is, in fact, the predominating nucleating agent of the clouds at these levels.

Apart from their relevance for solar-weather coupling, the processes considered in these discussions are clearly of general importance for cloud and precipitation physics. Their further investigation would be of general interest to meteorology, not merely for a decision whether or not they constitute a viable mechanism to link solar and atmospheric variability. (Editor's note: A comprehensive analysis of the Cirrus mechanism appears in Part II of the USRA Final Report: "Consideration of Cirrus Clouds as a Possible Sun-Weather Link," by Wilkerson, et al.)

3. Ozone Variability in the Middle Atmosphere

Atmospheric ozone is produced by UV radiation at wave lengths less than 242nm, and the atmospheric ozone layer absorbs UV radiation completely in the Hartley band (about 300 to 200nm) giving rise to the high temperatures of the upper stratosphere. There is some indication that the ultraviolet solar energy flux, including that part of the spectrum responsible for the production of ozone and the high temperature of the upper stratosphere, varies with solar phenomena. But observations of such variations of the solar flux which are important for atmospheric ozone formation have, of course, only become possible since the advent of satellites so that not enough observational data about the variability of the relevant part of the ultraviolet solar spectrum have been accumulated until now.

As far as the total ozone content is concerned, no connection with solar variability has been established yet, although some claims (and counterclaims) have been made. If there are variations of the ozone with solar variability, they would in any event be most readily recognized at higher levels, rather than in the levels around 23 km where the ozone density has its maximum. At these altitudes and up to about 30 km, the ozone density and its time variations are largely determined by mass transport, not by photochemistry, and the residence time of ozone is here about 2 years. On the other hand, above 50 km altitude, the photochemical equilibrium values of ozone are quickly reestablished, that is in a matter of hours, if there has been a disturbance. Thus, any sun-induced variations of the ozone density, and of the air temperature, would be expected to occur in the upper part of the ozone layer, not in the lower part which contains most of the total ozone. There have been some reports in the literature (see Herman and Goldberg, 1978) of such variations in ozone content in connection with solar flares, but much more observational evidence would be needed to make a convincing case.

Apart from UV radiation, NO produced by cosmic rays in the atmosphere also affects the amount of ozone, as is indicated by observations during solar proton events. Based on such observations and theoretical considerations, Zerefos and Crutzen (1975) have considered the effect of NO generation in the middle atmosphere. Since NO below 45 km reduces the amount of atmospheric ozone, and since most of the NO production by solar proton events takes place above 30 km, it is hypothesized that the ozone decrease at about 30 km will lead to a lowering of upper-stratospheric temperatures, but will permit UV radiation to penetrate deeper into the lower stratosphere and result here in higher temperatures and ozone concentrations. Cooling and heating rates due to such changes are presented for the large solar proton event of August 1972. The time scale for the approach to a new equilibrium is probably measured in weeks, but its estimate is difficult because the transport processes in the upper stratosphere are only imperfectly known.

An observational check of these calculations is hampered by the scarcity of temperature data; but a few measurements at high-latitude Canadian stations indicate at least that the temperature deviation from the average is in the right direction. Zerefos and Crutzen present also some curves showing that monthly stratospheric mean temperatures and thicknesses vary with the solar cycle. However, the time series are too short to make the parallelism convincing. The same is true for the apparent relation between solar activity and total ozone referred to on the basis of a paper by Angell and Karshover (1973). In fact, these two authors themselves are very reluctant to accept such a relation on the basis of their results.

In this context, reference should also be made to a paper by Reid (1977) who discusses the production of oxides of nitrogen by ionizing radiation from extraterrestrial sources and considers in particular the production of NO_2 and the possible climatic effects caused by its increased concentrations in the stratosphere. He concludes that it is doubtful that the NO_2 mechanism can account for a sun-weather relationship, but he conjectures that supernovae in the proximity of the solar system might produce dramatic results. It is worthwhile to quote from his paper that "we do not yet fully understand the various chemical and dynamic influences in the stratophere." In this situation, we should be careful in accepting, or rejecting, mechanisms linking solar and atmospheric variability too quickly. Instead, especially under these conditions, any physical hypothesis should be confirmed by an appropriate observation program.

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Although the role of atmospheric ozone as a coupling mechanism between solar and weather variability is doubtful, it seems worthwhile to investigate its potential role further both theoretically and by means of observational data.

The possible effects on atmospheric motions of differential atmospheric heating because of changes in the ozone distribution will be discussed in section 5.

4. Variations of Solar Electromagnetic Radiation and Generation of Atmospheric Waves

Speculations about the mechanism linking solar variability on all time scales and weather and climate changes have included the possibility of variations of solar constant. Unfortunately, reliable measurements of the solar constant, unaffected by the transparency of the earth's temperature, could not have been made before the advent of satellite observations. Even now, such data are not available on a systematic and continuing basis. From the available data, it is generally concluded that the solar constant, if it is variable at all, does not change by more than a few tenths of one percent.

Foukal et al (1977) have studied the observations from Mariner 6 and 7. These measurements indicate that direct changes of the solar constant of more than 0.03 percent can be ruled out, at least for the period of observations in 1969, even though during this time solar magnetic activity reached a peak. On the other hand, the data obtained by the Smithsonian Astrophysical Observatory suggest an increase of the solar constant up to 0.1%, apparently related to an increase in the facular areas, although this result is at the limit of statistical significance. The authors suggest that this increase may be caused by an actual change in atmospheric transparency within the visible spectrum, not by the reduction procedure used by the Smithsonian

Observatory to obtain the solar constant. They speculate that the change in atmospheric transparency may be due to ultraviolet radiation from the faculae and associated coronal plages which might change the ozone content of the atmosphere. However, it must be kept in mind that such atmospheric ozone changes correlated with solar variability are hypothetical, and observational and theoretical demonstration of such relations would be necessary to make this chain of hypotheses appear more probable.

Nevertheless, it is interesting to speculate on possible effects of such a variation of 0.1 percent of the solar flux reaching the lower atmosphere. Thus, Volland (1977) assumed that the solar flux reaching the earth's surface has a period of 27 days, corresponding to the sun's synodic period of rotation, and estimated that the resulting pressure change would be of the order of 0.1 mb. He discussed this estimate in the light of some results by King et al (1977) which seem to indicate oscillations with periods of 27 days of the 500 mb level, although the statistical evidence presented for these oscillations is not very satisfactory. In fact, in a more recent note, Volland and Schaefer (1979) reexamine these results by King and his coworkers and conclude that no causal relation exists between these waves and solar activity.

Despite this negative conclusion by Volland and Schaefer, further investigations of the possible forcing of atmospheric oscillations by solar events might be useful. Even if it is found to be impossible to excite atmospheric oscillations by solar activity, such a study might make interesting contributions to the dynamics of the middle and lower atmosphere.

5. Modulation of Reflective Index of Planetary Waves*

The energy produced by solar events in the vicinity of the earth is very much smaller than that of the changes in the lower stratosphere and troposphere which are suspected to be statistically correlated. As a way out of this difficulty, Hines (1974) has suggested a mechanism in which the mismatch between atmospheric and extraterrestrial energy becomes irrelevant. The mechanism was specifically proposed to provide a hypothesis for an explanation of the relation between magnetic sector boundary passages and the VAI found by Wilcox et al (1974), but might also suggest the search for other correlations if theoretical studies prove its feasibility. The VAI variations may be regarded as manifestations of long planetary scale atmospheric waves. These waves propagate upward into the high atmosphere where they may possibly be reflected. Thus, their energy may, at least in part, be returned to the lower atmosphere and produce there constructive or destructive interference with the original wave system. Whether or to what extent such reflection takes place depends on the state of the atmosphere at these high levels, largely on the temperature and wind distribution. It appears not impossible that the changes in solar emission connected with solar variability may be strong enough to produce the required changes in the reflective indices. The energy required for such changes in the tenuous high levels would be much smaller than that involved in the observed changes in the troposphere and low stratosphere. Thus the difficulty is avoided which arises out of the discrepancy between the energy supplied by the solar activity and the much more energetic changes in the lower atmosphere, without invoking any unspecified trigger action.

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* Editor's Note: This hypothesis is discussed in depth in the chapter by M.A. Geller.

There are, as Hines points out, various possible difficulties which may make the proposed hypothesis unacceptable. Among these are dissipation by Newtonian cooling, and by damping increasing with altitude due to viscosity and thermal conduction both of which become more effective with decreasing air density. Some indications whether or not the proposed mechanism is feasible may be found in the existing literature on wave propagation through the atmosphere. As in the case of other proposed physical mechanisms even a demonstration that the mechanism does not work, a possibility which Hines (1974) by no means excludes, would be valuable, not only because of its intrinsic value for the understanding of solar-terrestrial relations, but also since such theoretical research would further our knowledge of atmospheric wave behavior per se.

It will be necessary to show theoretically that solar emission, electromagnetic or corpuscular, can modify the structure of the atmosphere so that hypothesized reflection of atmospheric waves can occur. The reflection coefficient is determined by the spatial distribution of the mean wind and to a smaller degree, by the mean temperature field. Since the mean wind is to a good degree of approximation geostrophic, its vertical shear is largely a function of the horizontal temperature gradient. Thus, for a modification of the reflection coefficient, the solar emissions will have to produce temperature changes of different magnitude dependent on latitude. Such differences are to be expected, in the case of electromagnetic radiation because of the earth's spherical shape; in the case of charged particle emission because of the geomagnetic field, although it is not *a priori* clear that the changes will be in the right direction.

Solar-induced ozone and temperature changes in the stratosphere and mesosphere have been derived by numerous authors under different assumptions, for instance by Callis and Nealy (1978). Schoeberl and Strobel (1978) computed variations in the mean, zonal, atmospheric circulation due to ozone and solar flux changes, with realistic assumptions about these changes based on observed events. All calculations show very little effect of the assumed variations on the zonal circulation, even though in one model calculation the ozone reduction reached about 20 percent locally in the polar region. These results do not support the hypothesis suggested by Hines to account for possible solar-weather connections. But because of our incomplete knowledge of the state of the upper atmosphere, its photochemistry and its trace substances, together with difficulties involved in studying wave motions in the real atmosphere with mean winds and temperatures changing in all three directions and in time, the conclusion can hardly be regarded as final and further research is desirable.

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Report III

Influence of Solar Variability On Atmospheric Chemistry and Heating/Cooling

by

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INFLUENCE OF SOLAR VARIABILITY ON ATMOSPHERIC CHEMISTRY AND HEATING/COOLING

by

Hiram Levy, II

1. Introduction

The addition of Heating/Cooling to the original title completes the link between the preceding paper on solar variability and the following one on possible dynamical couplings between the stratosphere and troposphere. There is no question that both atmospheric chemistry and heating/cooling are driven by the sun and that U.V. solar variability, if it exists, would lead to fluctuations in both the atmospheric composition and temperature. The major uncertainties are the size and location of these fluctuations and their influence, if any, on the troposphere. Possible forcing mechanisms range from the direct radiative heating of the troposphere, to modifications of the stratospheric heating/cooling, to modification of trace gas concentrations which in turn control the concentrations of the major short and long wave absorbers in the stratosphere. The latter two are indirect mechanisms which introduce a complex coupling among temperature, chemical composition, heating/cooling rates, and dynamics. They may force fluctuations in the troposphere through either modifications in both short and long wave heating or through dynamical coupling, the latter to be discussed in detail by the next speaker.

2. Direct Mechanisms

An excellent example of the direct effect of solar variability is the possible fluctuation in the solar constant (the total flux from the solar disk). The solar forcing mechanism is quite simple. The actual response in the troposphere is a very complex interaction of clouds, sea ice and snow cover, ocean heat transport, hydrology and atmospheric transport of heat and water. The first simple model of these effects was developed by Budyko. A more detailed calculation was reported a few years ago by Wetherald and Manabe who found that a 2% change in the solar constant produced a 3°C change in the annual mean area average surface temperature. Current best estimates of fluctuations in the "solar constant" are $< 0.1\%$ which is the current limit for measurement accuracy. The tropospheric response to a solar constant variation of the order of 0.1% might be observable on a climatic time scale. It should not show up on the short time scale of weather where the normal fluctuations in the effective solar constant due to variations in cloud cover, atmospheric dust, and surface albedo are much larger.

3. Indirect Mechanisms

It would appear that we need a subtler mechanism than fluctuations in the total solar flux. We will now take a more detailed look at the solar flux as shown in Figure 1. In this figure we have a plot of unit optical depth as a function of wave length. It is clear that very little solar flux with wave lengths < 1800 Å penetrates into the middle stratosphere. Variations in temperature and atmospheric composition above 40 km are not thought to have any radiative effects (direct or indirect) on the troposphere. The question of dynamical coupling will be discussed by Dr. Geller.

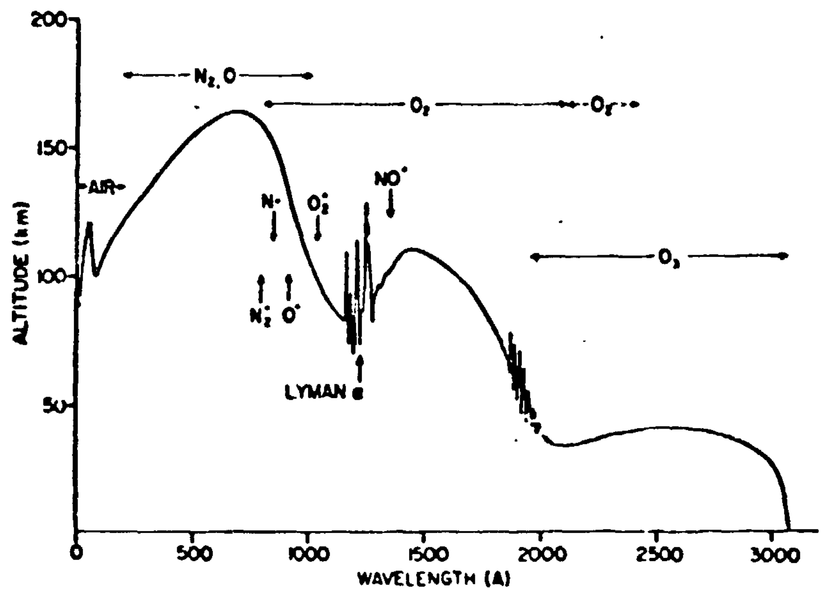

Fig. 2.2 Altitude at which the intensity of solar radiation drops to $1/e$ of its value outside the earth's atmosphere, for vertical incidence. (Based on Nawrocki, Watanabe, and Smith [7].)

Figure 1

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3.1 Indirect Radiative

The least complex of possible forcing mechanisms involves solar variability in the wave length region of solar heating (O_3 absorption) of the atmosphere.

Let us consider the example of a decrease in solar flux of $\lambda \sim 2500Å$.

1) Solar heating decreases which decreases T, then Solar Heating being proportional to U.V. flux from O_3;
2) decreased T decreases long wave cooling;
3) decreased T decreases O_3 destruction which increases O_3 and increases solar heating;
4) decreased solar heating amounts to a decrease in O (atomic oxygen) which causes a further decrease in O_3 destruction and increase in O_3 and solar heating.

The net effect is still a decrease in stratospheric T. The actual value of the decrease requires a detailed calculation which includes all the feedbacks. This change in stratospheric temperature may, through radiative effects or dynamical coupling, affect the troposphere. Such an effect, if it existed, would, because of the short photochemical time scale of O_3, have the possibility of causing tropospheric responses on short time scales (i.e., weather).

3.2 Indirect Photochemical-Radiative

a) A more complex mechanism would involve solar variability around 2200Å. This wave length is not that important to solar heating of the stratosphere but does effect the destruction of long-lived, IR active compounds such as CFM's and N_2O.

We again consider the specific example of a reduction in solar flux at 2200Å.

1) The reduced flux causes an increased lifetime and concentration of the IR active gases.

2) The increased concentration causes an increased long wave cooling of the stratosphere and heating of the troposphere.

3) All the previous temperature dependent feedbacks would again be in operation.

4) The net effect would be a lower stratospheric temperature through the magnitude of the reduction depends on the negative feedbacks as well as the concentration of the IR active gases, their % concentration change, and their particular IR spectra.

Again the effect on the troposphere might be either dynamic or radiative. In this case, since the lifetimes of the gases are determined by stratospheric destruction, they are long-lived (photochemically slow) and would produce effects, if any, on climate time scales only.

b) The 3rd and most complex mechanism I will discuss involves an indirect modification of stratospheric ozone which then indirectly affects the troposphere. An excellent example is the mechanism proposed by Crutzen, Isaksen, and Reid, a solar proton event.

As a result of a large influx of solar protons at high latitudes, NO production in that region greatly exceeds the normal level. This then causes O_3 to decrease in that region of the stratosphere. Such an event has been observed in August 1972. The decrease in stratospheric O_3 should cause a decrease in solar heating and result in a lower stratospheric temperature. Tropospheric responses to this were not observed although they have been postulated. It should be pointed out that this particular phenomenon is quite unusual and its effects are, for the most part, limited to high latitudes.

4. Model Results

I would now like to switch from the hypothetical to the concrete and present some results of a recent GFDL GCM. This model has 40 vertical levels up to 80 km, a coarse 9° grid and was developed by Mahlman and Sinclair. They, together with Fels and Schwarzkoph, ran two annual mean integrations, one with the normal climatic and temperature consistent O_3 and one with a uniform 1/2 O_3. In this experiment one assumes some mechanism exists for uniformly reducing O_3 to 1/2 its former concentration and examines the difference in equilibrium states for the two cases, both assuming annual mean radiation.

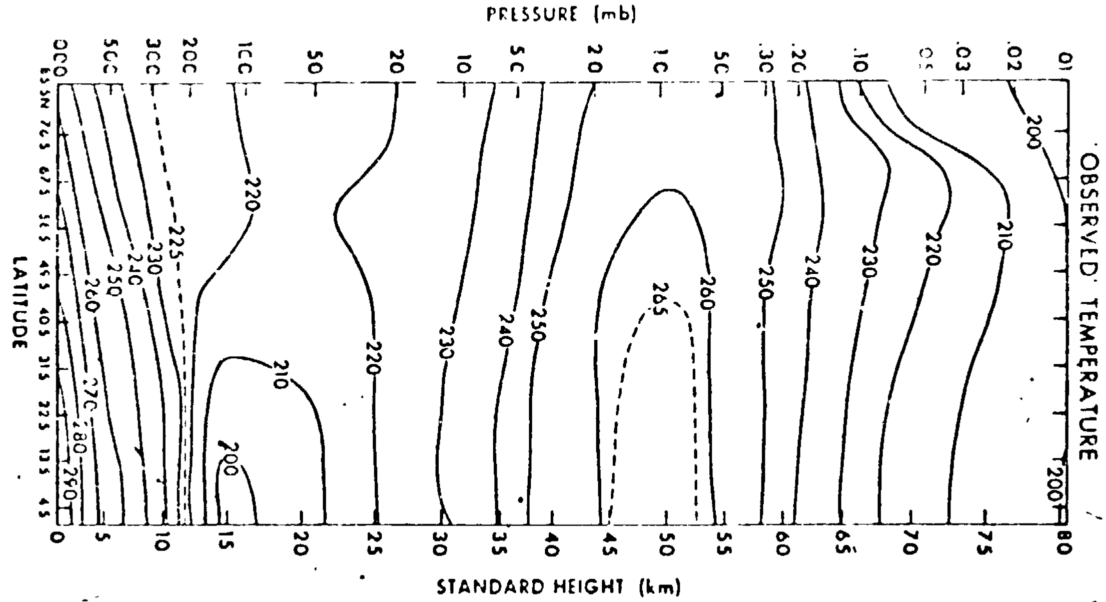
Figure 2 shows the control T field. The simulation is not bad through certainly not perfect.

Figure 3 shows the difference in T field for the 2 experiments. There is a sizeable reduction in stratospheric T, particularly in the tropics, but little change in the troposphere. It must be noted that the sea surface temperature was held fixed which would certainly have considerable influence on the lower troposphere. Without an air-sea model it is hard to do otherwise. It is also interesting to note that, while there was a significant change in tropical mesopheric circulation and lower stratospheric dynamical heating, no tropospheric effects were observable, given the normal statistical noise of the system. A final point of interest - while a series of latitude depend radiative-convective models were very poor in reproducing the GCM's results, these same models with a fixed dynamical heating based on the GCM did an excellent job in most regions of the atmosphere. Their work is presented in detail in a paper submitted to JAS.

5. Conclusion

It is clear that stratospheric O_3 has dominated this presentation. Its major role in solar (short wave) heating of the stratosphere, its susceptibility to photochemical modification, and its ability to radiate at 9.6 μ which is a CO_2 window, make it a very strong candidate. Neither CO_2 or H_2O would appear to have any possibility for short time scale control by solar variability. Personally, I do not believe that any of the specific examples I have outlined have been shown to, in fact, provide a chemical-radiative link between solar variability and the troposphere. I do think they are representative, however, of the class of possibilities.

I would strongly recommend detailed monitoring of solar U.V. and stratospheric O_3 to see if some form of cyclic variation does exist.



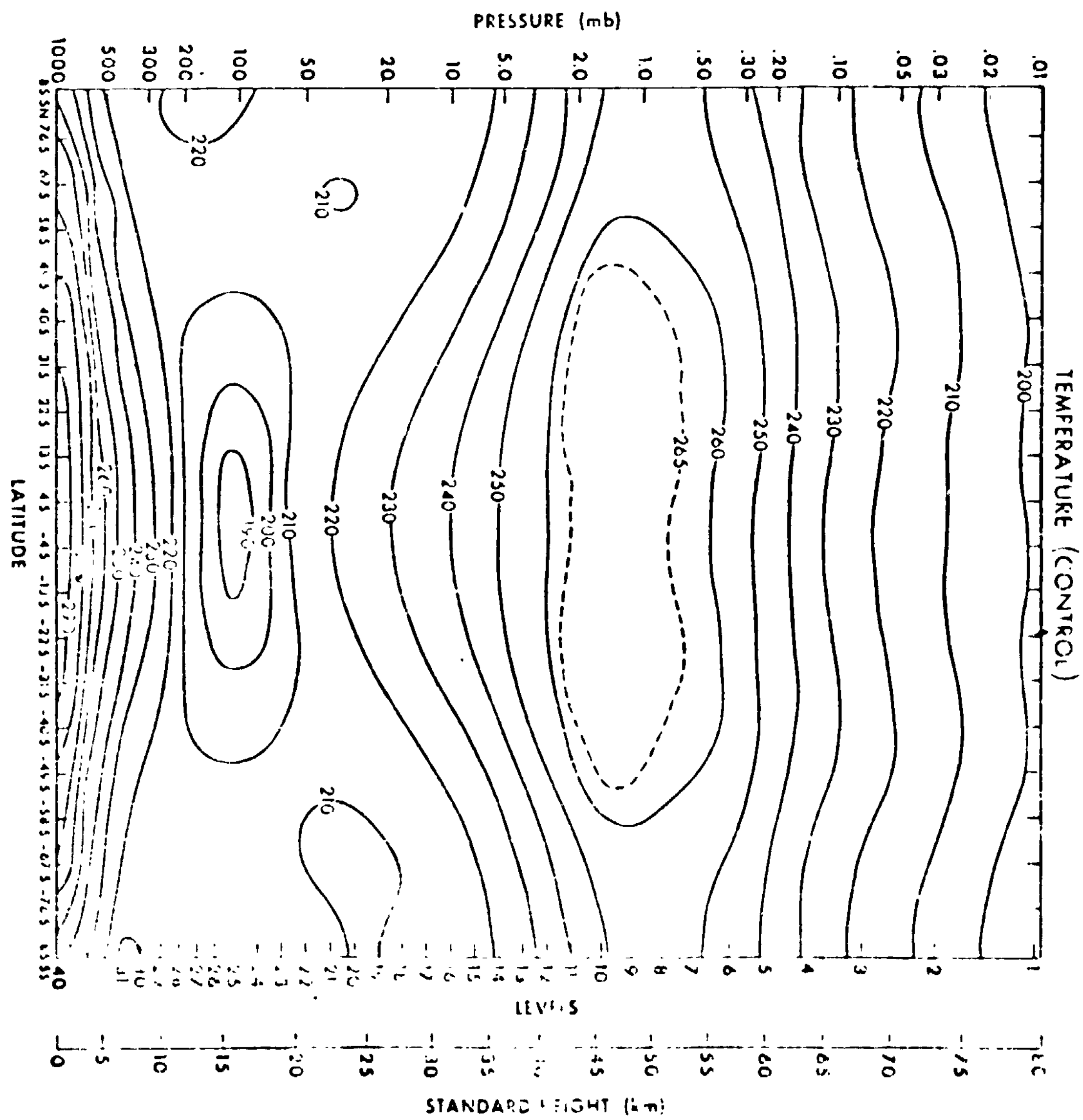


Figure 2

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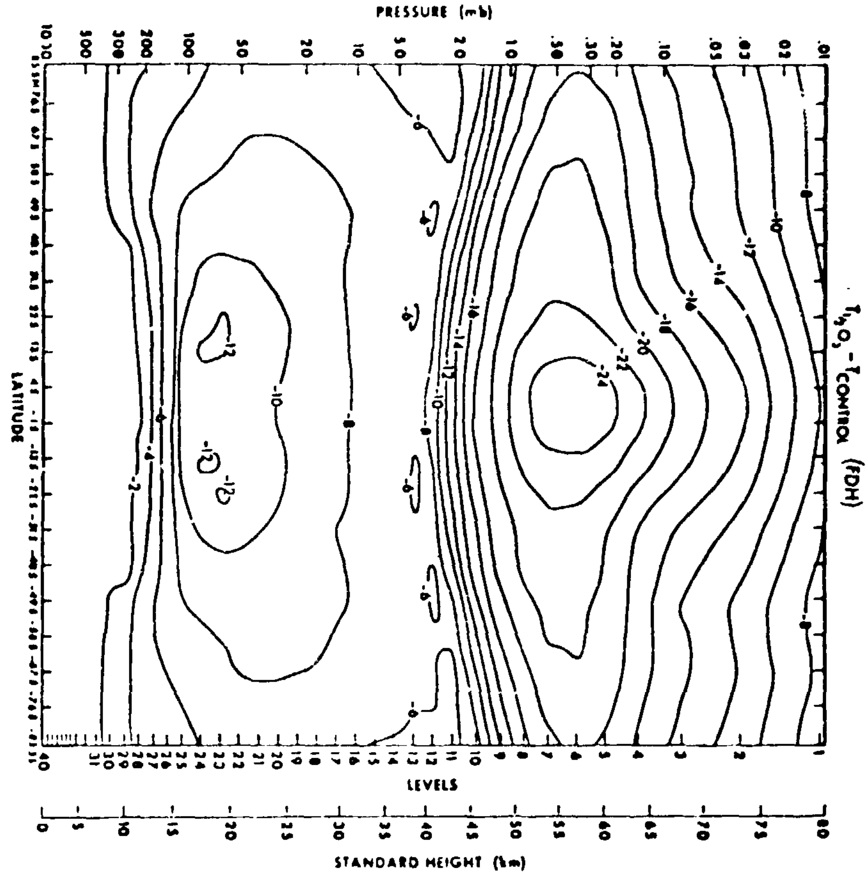
$T_{½O_3} - T_{CONTROL}$ (FDH)
PRESSURE (mb)
LEVELS
STANDARD HEIGHT (km)
LATITUDE

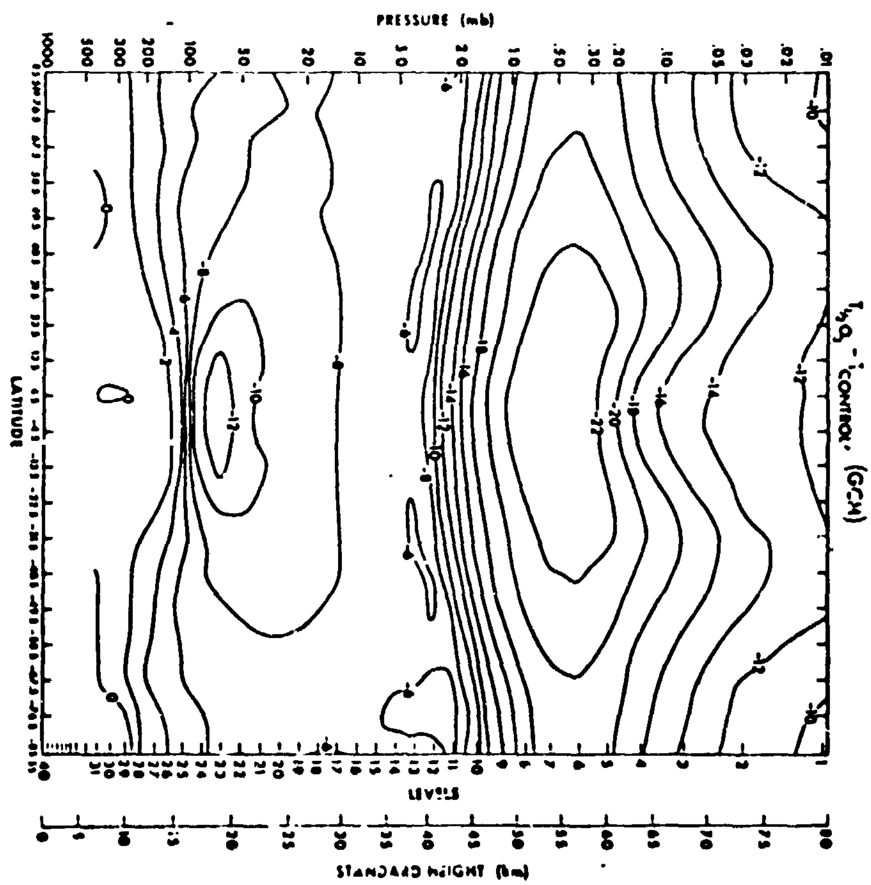
$T_{½O_3} - T_{CONTROL}$ (GCM)
PRESSURE (mb)
LEVELS
STANDARD HEIGHT (km)
LATITUDE

Figure 3

Report IV

Planetary Wave Coupling Between the Troposphere and the Middle Atmosphere as a Possible Sun-Weather Mechanism

by

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PLANETARY WAVE COUPLING BETWEEN THE TROPOSPHERE AND THE MIDDLE ATMOSPHERE AS A POSSIBLE SUN-WEATHER MECHANISM

by

M. A. Geller*

Abstract

The possibility of planetary wave coupling between the troposphere and solar-induced alterations in the upper atmosphere providing a viable mechanism for giving rise to sun-weather relationships is investigated. Some of the observational evidence for solar activity induced effects on levels of the upper atmosphere that range from the thermosphere down to the lower stratosphere are reviewed. It is concluded that there is evidence for such effects extending down to the middle stratosphere and below. Evidence is also reviewed that these effects are due to changes in solar ultraviolet emission during disturbed solar conditions. A theoretical planetary wave model is then used to see at what levels changes in the mean zonal state of the upper atmosphere would result in tropospheric changes. It is concluded that changes in the mean zonal flow of about 20% at levels in the vicinity of 35 km or below would give rise to changes in the tropospheric planetary wave pattern that are on the same order as the observed interannual variability in the tropospheric wave pattern. Thus, planetary wave coupling between the troposphere and the upper atmosphere appears to be a plausible mechanism to give a tropospheric response to solar activity. This mechanism does not appear to be viable for short period changes such as the suggested solar sector boundary vorticity index relation, but

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rather is applicable to changes of longer period such as the 11-year solar cycle.

1. Introduction

Few subjects in the atmospheric sciences have been the subject of more controversy than has the subject of sun-weather relationships. Recently, the arguments of a "believer" in these relationships have been nicely presented in the review paper of King (1975) while the arguments of a "skeptic" have been nicely presented by Pittock (1978). The purpose of this paper is not to present arguments for or against sun-weather relationships, but instead to discuss a physical mechanism whereby solar disturbance effects in the troposphere may occur by virtue of dynamical coupling to those higher levels in the atmosphere which are known to be affected by solar activity. In this discussion, the evidence, both observational and theoretical, will be reviewed for solar effects on the thermosphere, mesosphere, and stratosphere. Then the evidence, mostly theoretical, will be presented for sufficient dynamical coupling existing between the troposphere and upper levels so that these solar disturbance effects may significantly affect the troposphere.

2. Solar Disturbance Effects on the Upper Atmosphere

It is well known that the thermospheric temperature varies greatly with both day to day and long-term changes in solar activity. Satellite drag measurements indicate this (Jacchia, 1969), as do incoherent scatter radar measurements (Evans et al. 1979). Volland (1970) has suggested that increasing thermospheric temperatures with increasing solar activity are produced by increases in the solar EUV emission occurring during disturbed conditions. Hicks and Justus (1970) have statistically analyzed 52 rocket vapor trail wind measurements and found that while the winds both above and below 110 km are correlated with geomagnetic variations, the lag correlations of K_p with the winds above this altitude act differently than those with the winds below. This led them to conclude that the solar activity (that initiates geomagnetic disturbances) forces wind changes above 110 km while the wind changes below this altitude themselves may be giving rise to a fraction of the observed geomagnetic changes. It is noncontroversial that the disturbed sun emits increased EUV radiation that significantly affects thermospheric temperatures and winds, leading to the observed association between solar activity and changes in thermospheric parameters.

More controversial are solar disturbance effects on the mesosphere. Ramakrishna and Seshamani (1973) have analyzed the correlation between mesospheric temperatures, as measured by sounding rockets at Thumba, India, which is located 8° north of the equator, and solar activity as indicated by the $F_{10.7}$ index. They conclude that there is a very significant correlation (at the 99% confidence level) between solar activity and mesospheric temperature at Thumba with a time lag of less than one day, but that the magnitude of the mesospheric temperature response is one order of magnitude less than it is in the thermosphere. It is interesting that Ramakrishna and Seshamani (1973) hypothesize that this association exists by virtue of increased EUV emission during periods of solar disturbance, but in a later paper (Ramakrishna and Seshamani, 1976), when they found a significant lag correlation between K_p and mesospheric temperature during daytime hours at Fort Churchill (in the auroral zone), they hypothesized that this was due to auroral electrojet enhancements during disturbed conditions. For the mesosphere, there have been studies where a connection between solar and geomagnetic disturbance conditions with mesospheric temperature has been found and physical links have been hypothesized. At the moment, however, our understanding of what physical mechanisms might give rise to such solar control is minimal.

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More work has been done on the extent of solar activity effects on the stratosphere than has been done on the mesosphere. There have been observational studies, theoretical simulation studies, and some observations of the variability of the relevant part of the solar spectrum with solar activity. For example, Schwentek (1971) has indicated that winter stratospheric temperatures over Berlin vary with solar activity but that no clear variation is seen in the summer temperatures. Figure 1, from Schwentek (1971), illustrates this. It also illustrates, curiously enough, that while an apparent increase in stratospheric temperature with sunspot activity is seen for sunspot numbers below 160, the opposite tendency is seen for higher sunspot numbers. Arranging this same data differently, Schwentek (1971) found that the winter stratospheric temperature was minimum during solar minimum (1964) and maximum during solar maximum (1969), but that the summer stratosphere did not show this behavior. This is shown in Figure 2. Note that the effect seen by Schwentek is a sizeable one amounting to about 20°C at 35 km, 10°C at 30 km, and no more than 5°C at 25 km. Of course, Schwentek's study only includes radiosonde data from a single station, Berlin. Recently, Angell and Korshover (1978) have collected the western hemisphere rocketsonde data for the years 1965-1976 for the height layers 26-35, 36-45, and 46-55 km. They segmented this data both by latitude band and by season. Figure 3 shows Angell and Korshover's (1978) results for the north polar rocketsonde stations in the western hemisphere (Fort Greeley - Poker Flats and Fort Churchill), the north subtropical stations (Wallops Island, Cape Kennedy, White Sands, Point Mugu, and Barking Sands), and for the equatorial stations (Ascension Island, Fort Sherman, and Kwajalein). Note that the temperatures in the 26-35 and 36-45 km layers in the polar region were observed to be maximum at the time of solar maximum in qualitative agreement with the results obtained by Zerefos and Mantis (1977) from high level (24-31 km) radiosonde data; however, this is not seen so clearly in the 46-55 km layer. A similar situation is seen in the subtropical data. In the equatorial region, however, the main feature seen in the data is a general temperature decrease during the period of observation with some indications of a weak temperature rise during the solar maximum. When the data are segmented by season (see Figure 4), one sees that there is a general temperature decrease in the layer 46-55 km with temperature maxima in the two layers below at the time of solar maximum during all the seasons. An indication is seen, however, that the winter effect may be strongest.

Quiroz (1979) has just published the results of a study that was conducted independently from, but is quite similar to, that of Angell and Korshoever (1978). Quiroz (1979) examined summer rocketsonde temperature measurements for the time period 1965-1977 at several sites which ranged in latitude from 8 S to 64 N. Summer data was chosen since one might expect to be able to identify a statistically significant signal more easily in a summer data set with less meteorological noise than is present during other seasons. Another difference between Angell and Korshover's study and Quiroz's is that Quiroz applies known correction factors to the rocketsonde temperature measurements. Quiroz's results, while being in general agreement with those of Angell and Korshover, indicate a stronger relation between stratospheric temperature and solar activity taking place at 35 km altitude than at 50 km altitude. This is shown in Figure 5 and Table 1 from Quiroz (1979) where the 35 km and 50 km temperature trends and sunspot numbers are displayed as are the correlation coefficients. Note that Quiroz finds bigger solar activity related trends and correlation coefficients at 35 km than at 50 km. This is at variance with Angell and Korshover's results, but Quiroz attributes this difference to the fact that he used instrumental temperature correction factors that were sizeable at 50 km whereas Angell and Korshover did not make such corrections.

Summarizing the stratospheric temperature observations then, it does appear that the western hemisphere stratosphere between the altitudes of 26 and 50 km in the northern hemisphere was warmest in the polar and subtropical regions when the sun was in its most active state during the past twelve years. No such clear variation was observed below these altitudes or in the equatorial zone.

There have also been published reports of high coherencies between the 10.7 cm flux of solar radiation and the 10 mb circulation by Ebel and Batz (1977) and between the 10.7 cm solar flux and stratospheric winds over the altitude range of 25-65 km by Nastrom and Belmont (1978). These coherency studies indicate that there exists more of a connection between the 10.7 cm solar flux and the stratospheric flow than if there were independent fluctuations in these parameters with the same period (as Volland and Schaefer (1979) claim is the case for the observed 27-day variability in tropospheric planetary waves and solar activity).

On the theoretical side, there are at least three mechanisms by which solar disturbances may affect stratospheric structure. One of these was originally suggested by Crutzen et al. (1975) who illustrated that solar proton events should lead to a vastly increased production of NO_x compounds in the stratosphere. Since solar proton events occur more frequently during disturbed solar conditions, one would expect more NO_x under such conditions with a resulting increase in the catalytic destruction of ozone which would, in turn, alter the radiative balance of that portion of the atmosphere affected. Such a depletion of ozone during a solar proton event has been observed to take place by Heath et al. (1977); however, Schoeberl and Strobel (1978a) have illustrated that sizeable as this effect is locally, its geographical extent is too limited to appreciably affect global stratosphere dynamics. Ruderman and Chamberlain (1975) and Chamberlain (1977) have hypothesized that the known modulation of cosmic rays by solar activity leads to a modulation in stratospheric NO_x which results in a modulation of ozone. It should be mentioned that it is far from being settled whether ozone, in fact, is observed to vary with solar activity. A third mechanism by which solar activity may affect the structure of the stratosphere was motivated by some observations by Heath et al. (1973), in which they claim that the solar output of ultraviolet radiation in the wavelength range of $0.175 \leq \lambda \leq 0.310\mu$ varies by some tens of percent. It should be remarked that these observatinos are somewhat controversial (see Smith and Gottlieb, 1974). Photochemical models by Callis and Nealy (1978) and Penner and Chang (1978) show that sizeable temperature changes would result from variable solar ultraviolet radiation as observed by Heath et al. (1973), with the Callis and Nealy (1978) results appearing to indicate much larger stratospheric temperature changes with solar activity than were observed by Angell and Korshover (1978). The Penner and Chang (1978) results show some qualitative agreement with the observations, but there are also areas of significant disagreement between these observations and their theory.

3. Dynamical Coupling Between the Troposphere and the Upper Atmosphere

The most difficult obstacle to overcome in constructing a theory for how solar activity may give rise to significant tropospheric changes is the requirement to explain how extremely small changes in solar energy output bring about changes in tropospheric energetics that are orders of magnitude larger (see Willis, 1976). For instance, according to Livingston (1978) the solar constant does not vary by more than 0.1% on the short term, and Volland (1977) has demonstrated that if the solar output did vary by 0.1% with its 27-day rotation cycle that this would generate tropospheric planetary waves with amplitudes of no more than one geopotential meter.

Hines (1974) has suggested a possible mechanism that might be operative despite this energy mismatch between solar input and tropospheric energetics. The basis of this mechanism is that the

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surface air-flow over topography and the global distribution of diabetic heating in the troposphere force planetary scale disturbances that propagate their energy upward. Stratospheric and mesospheric winds play a dominant role in determining the "refractive index" for these waves (see Charney and Drazin, 1961; Matsuno, 1970; and Schoeberl and Geller, 1976, for example) which will, in turn, determine the transmission-reflection properties of these waves. Thus, changes in the middle atmosphere flow might lead to changes in the tropospheric amplitudes and phases of planetary waves that propagate to this level. The energetics of these changes are such that relatively small amounts of energy may give rise to significant effects in the upper atmosphere where the density is low, and these upper atmosphere effects merely act to modulate the effect of fixed energy sources in the troposphere. Some of the relevant dynamical model studies that relate to the viability of this mechanism, that was suggested by Hines (1974), are those of Bates (1977), Schoeberl and Strobel (1978a) and Mahlman et al, (1978). Since the results of these studies show significant differences, the relevant results from each one will be briefly reviewed here.

Bates (1977) developed a set of scaled equations for steady state planetary wave motions assuming that both the wave variables and the basic state parameters have zonal and meridional length scales at middle latitudes, that are at least on the order of the earth's radius and that the vertical scale of variation in log-pressure coordinates is at least of order one (implying that the vertical length scale is at least on the order of a scale height). Taking the relative angular velocity of the mean zonal winds to be much less than the angular velocity of the earth, he was able to decouple the horizontal structure of these waves from the vertical structure, i.e., he found that the vertical structure of these waves was governed by an ordinary differential equation in the altitude variable. A somewhat curious result of Bates' (1977) formulation is that his cut-off westerly wind velocity for energy propagation is independent of wavenumber. This is different from the earlier results of Charney and Drazin (1961) and Dickinson (1968a). The key result of Bates' (1977) paper, in the present context, is that the amplitude and phase of the tropospheric planetary waves as well as the resulting meridional heat flux were found to vary significantly when the tropospheric forcing remained fixed but the stratospheric wind and/or static stability fields were altered. As Bates (1977) points out, a number of simplifying assumptions were made to allow him to obtain an analytic solution to this problem, and one must be careful to apply his formulation only to geophysical situations where these assumptions are satisfied over a range of latitudes, if in fact such situations exist.

Schoeberl and Strobel (1978a) have used a numerical quasi-geostropic model to look at the effect of ozone reductions on the zonally averaged circulation of the middle atmosphere. They calculated the response to the August 1972 solar proton event; to halocarbon pollution; to uniform ozone density reductions; and to changes in the solar constant. They also calculated the resulting effects of the changes they obtained in the zonal mean state on stationary planetary waves using essentially the planetary wave model of Schoeberl and Geller (1977). They found that no significant effect on the planetary wave structure should accompany an event of the nature of the August 1972 solar proton event. They also calculated the alteration in middle atmosphere planetary wave structure to halocarbon pollution and found changes near the 50 km level that were no more than those of normal winter variability.

Mahlman et al (1978) used a primitive equation general circulation model with 40 vertical levels between the earth's surface and 80 km altitude for their studies. They performed an experiment in which they ran a "control" case and compared it with a case in which ozone amounts were halved. This led to temperature decreases in excess of 20°C at the tropical stratopause and in excess of 10°C at the tropical tropopause. The winds were seen to decrease by about 10 - 15 ms^{-1} in the region of the middle atmospheric jet decreasing downward to generally less than 5 ms^{-1} at about 40 km. No striking difference was seen between the two modelled tropospheres.

In assessing the confidence to be placed in these and other studies of dynamical coupling between the troposphere and the upper atmosphere, it is very important to take into account the role of both radiative and mechanical dissipation properly. Obviously, the planetary wave energy must be able to penetrate upward to the level where the refraction-transmission properties are altered as well as to return down to the region of forcing after reflection in order for the Hines (1974) mechanism to be viable. The three main dissipation mechanisms operative in the stratosphere and mesosphere are radiative damping acting through carbon dioxide and ozone; mechanical dissipation which is presumed to act through the turbulent mixing that results from the "breaking" of waves and tides; and the possible absorption of wave momentum at critical levels. We will remark on each of these processes in the following.

Dickinson (1973) has developed a Newtonian cooling approximation to the infrared cooling due to CO_2 and O_3 using the temperature structure of the 1962 U.S. Standard Atmosphere. Dickinson's formulation has been used by such investigators as Schoeberl and Strobel, (1978b) and Holton and Wehrbein (1979). Dickinson (1973) found the minimum dissipation time scale due to infrared processes to be about five days in the stratopause region. Blake and Lindzen (1973) have developed a Newtonian cooling approximation for infrared cooling plus photochemical acceleration (the apparent cooling that arises from the photochemical destruction of ozone that takes place as the ambient temperature increases). They found the minimum dissipative time scale to be about two days at the stratopause region. Schoeberl and Strobel (1978b) have indicated that they believe the Blake and Lindzen (1973) values to be inapplicable to global large vertical scale motion, however for reasons given in their paper. Ramanathan and Grose (1978) have indicated that although the Newtonian cooling approximation cannot be used for detailed simulation of stratospheric climate, it is probably sufficient for mechanistic studies of the type being discussed here.

The situation is not nearly so well understood for mechanical dissipation, however. Both Schoeberl and Strobel (1978b) and Holton and Wehrbein (1979) have found it necessary to introduce a parameterization for a marked increase in mechanical damping above the stratopause to achieve reasonable looking simulations of the zonal mean state of the middle atmosphere. Mahlman et al, (1978) have also included a parameterization for enhanced mechanical dissipation in their general circulation model. Comparing the Schoeberl and Strobel (1978b) and the Holton and Wehrbein (1979) parameterizations for mechanical dissipation, it appears that they both have dissipation time scales of about 10 days at 65 km with smaller values below (Schoeber and Strobel's values being larger there) and larger values above (Holton and Wehrbein's values being larger there).

Finally, we come to the role of critical levels as a dissipation process for planetary wave energy. Until recently, based on the work of Dickinson (1968b, 1970) it was believed that stationary planetary waves were absorbed at locations of zero mean zonal wind. This concept was used in the design of a number of mechanistic planetary wave models (Matsuno, 1970, and Schoeberl and Geller, 1977, for example). Tung (1979) has recently argued that nonlinearities probably dominate over dissipation in the vicinity of critical levels, and has shown that most of the planetary wave energy is reflected rather than absorbed there if this is the case. This becomes important in the context of dynamical coupling between the troposphere and the upper atmosphere since if the singular wind lines reflect rather than absorb planetary waves, the only dissipation mechanisms are radiative damping, mechanical dissipation in the free atmosphere, and Ekman friction in the planetary boundary layer. Since the first two of these mechanisms grow with altitude, significant tropospheric changes due to variations in the upper atmosphere are more likely to occur if such changes occur at lower levels in the upper atmosphere. For instance, Tung and Lindzen (1979) argue that the troposphere will be affected much more greatly if the middle atmosphere jet is lowered below the middle stratosphere, than if its structure is changed at higher levels.

4. Model Calculations

The model we will use in this section is a quasi-geostrophic model of stationary planetary waves that extends in the vertical from the ground to 100 km. This model is essentially the same as that used by Schoeberl and Geller (1977) except it has been altered by S.K. Avery, M.A. Geller, and J.C. Alpert to include tropospheric forcing by the surface airflow over the appropriate zonal harmonic of the northern hemisphere topography (as given by Berkofsky and Bertoni, 1955) and planetary wave forcing by diabatic heating (by using the appropriate zonal harmonic of the lower tropospheric diabatic heating that was calculated for the northern hemisphere by Geller and Avery, 1978).

The model equations are as follows:

$$\frac{\sin^2\theta}{\cos\theta}\frac{\partial}{\partial\theta}\left(\frac{\cos\theta}{\sin^2\theta}\frac{\partial\psi_m}{\partial\theta}\right) + Q_m\psi_m + \left(\frac{\bar{u}m - ia_o}{\bar{u}m - i\delta_R}\right)\frac{\sin^2\theta}{S}\frac{\partial^2\psi_m}{\partial z^2}$$

$$- \frac{i\sin^2\theta}{\bar{u}m - i\delta_R}\frac{\partial a_o}{\partial z}\frac{1}{S}\frac{\partial\psi_m}{\partial z} = - iG_m \qquad (1)$$

where

$$Q_m = \frac{m \frac{\partial \bar{q}}{\partial \theta}}{(\tilde{u}m - i\beta_R)\cos\theta} + \frac{\tilde{u}m - ia_o}{\tilde{u}m - i\beta_R} \frac{\sin^2\theta}{S} T$$

$$- \frac{i \sin^2\theta}{(\tilde{u}m - i\beta_R)} \frac{\partial a_o}{\partial z} \left[\frac{1}{2S} \left(1 + \frac{1}{S} \frac{\partial S}{\partial z} \right)\right] \quad (2)$$

$$\frac{\partial \bar{q}}{\partial \theta} = \cos\theta \left[2(\Omega + \tilde{u}) + 3\tan\theta \frac{\partial \tilde{u}}{\partial \theta} - \frac{\partial^2 \tilde{u}}{\partial \theta^2}\right.$$

$$\left. - \sin^2\theta \, e^z \frac{\partial}{\partial z} \left(\frac{e^{-z}}{S} \frac{\partial \tilde{u}}{\partial z}\right)\right] \quad (3)$$

$$G_m = \frac{\sin^2\theta}{\sqrt{S}\,(\tilde{u}m - i\beta_R)} e^{z/2} \frac{\partial}{\partial z} \left(\frac{e^{-z}}{S} R J_m\right) \quad (4)$$

and

$$T = -\frac{3}{4} \frac{1}{S^2} \left(\frac{\partial S}{\partial z}\right)^2 - \frac{1}{2S} \left(\frac{\partial S}{\partial z} - \frac{\partial^2 S}{\partial z^2}\right) - \frac{1}{4} \quad (5)$$

In writing equations (1) through (5), the stationary planetary wave geopotential, with zonal wavenumber equal to m, is given by $\phi = e^{z/2} \sqrt{S} \; \psi_m \; e^{im\lambda}$, where λ is longitude; $\tilde{u} = \frac{\bar{u}}{a\cos\theta}$ where $\bar{u}$ is the mean zonal wind, a is the earth's mean radius, and

θ is latitude; a_o is the Newtonian cooling coefficient;

$$S = \frac{R}{(2\Omega a)^2} \left[\frac{RT_o}{c_p} + \frac{\partial T_o}{\partial z} \right]$$

where R is the gas constant for dry air, Ω is the earth's rotation rate, T_o is the globally averaged temperature profile, c_p is the specific heat of dry air at constant pressure and $z = \ln(p_o/p)$, p being pressure, and p_o is the surface pressure (taken to be 1000 mb). β_R is the Rayleigh friction coefficient. J_m is the mth Fourier coefficient of the diabatic heating, i.e., $J = \Sigma\, j_m\, e^{im\lambda}$, where $i = \sqrt{-1}$.

The vertical velocity that results from surface airflow over the mth zonal harmonic of the surface topography is used as the lower boundary condition, and we use a radiation boundary condition to assure upward energy flux at the upper boundary of our computations (z = 14 or about 100 km). For lateral boundary conditions, we take ψ_m to vanish at both the pole and equator (see Schoeberl and Geller, 1977, for details). The Newtonian cooling coefficient is based on the computations of Dickinson (1973), and the Rayleigh friction is taken to have a small background value of $5 \times 10^{-7}\ s^{-1}$, which implies a dissipation time scale of about 23 days, with larger values at zero wind lines to provide for critical level absorption (see Schoeberl and Geller, 1977). This point will be returned to later in light of the discussions of the previous section. The static stability profile, S(z), is that which was calculated for January by Geller (1970). The effect of dissipation in the planetary boundary layer is included in our computations through an Ekman pumping component to the surface vertical velocity.

Now, given the evidence for solar disturbance effects altering the state of the thermosphere, the mesosphere, and the stratosphere, in this section we inquire to what extent, if any, the planetary waves in the troposphere will respond to changes in the mean zonal state at various levels of the upper atmosphere.

Since Schoeberl and Geller (1977) have shown that the structure of planetary waves appears to be much more sensitive to changes in the zonal wind structure, $\bar{u}$, than to changes in S, the static stability profile, we will be restricting ourselves to examining the response to changing the mean zonal wind state. Our "control" mean zonal wind state was derived from the January mean zonal wind state in Oort and Rasmussen (1971) below 50 mb and by utilizing the CIRA (1972) atmosphere above. This is shown in Figure 6. Our planetary wave model is then run for the "control" case as well as for cases where the "control" case mean zonal winds are decreased by 20% at various levels ranging from $z_o = 12$ ($\approx$ 85 km) to $z_o = 2$ ($\approx$ 17 km). In each case the mean zonal wind values are essentially unchanged from their "control" values over the height interval $z_o - 1 > z > z + 1$. For instance, Figure 7 shows the basic wind state when $z_o = 6$ ($\approx$ 42 km) and Figure 8 shows the mean zonal wind values that are given when the wind values in Figure 7 are subtracted from the wind state that is shown in Figure 6.

What is generally seen in these computations is that when the mean zonal flow is changed at a given level in the atmosphere by 20% over a restricted altitude range as previously indicated, the effects of these changes on the planetary wave structure are seen at all levels above the level where the wind change has taken place; however, only those levels higher than about $z_o - 3$ show any measurable change in planetary wave structure. Several test comparisons will be shown to illustrate these points. Figure 9 shows a comparison of the amplitude and phase structure for the computed planetary wave with zonal wavenumber one between the "control" and the $z_o = 10$ ($\approx$ 73 km) mean zonal wind structures for the latitudes of 30 N, 50 N, and 65 N. Note that no perceptible change in either the phase or the amplitude of wavenumber one is seen below $z = 7$ ($\approx$ 50 km) at any of the latitudes. There is also an indication that the change penetrates furthest downward at the highest latitude. Similar calculations for planetary waves two and three for these two wind states give qualitatively similar results for the change in wave structure due to mean zonal flow alterations around $z_o = 10$ although, of course, the wave structures for the different wavenumbers are quite different.

When the wind structure is changed below the middle stratosphere, however, significant changes in the tropospheric planetary wave structure became evident. For instance, Figure 10 shows a comparison of the amplitude and phase structure for the computed planetary wave with zonal wavenumber one between the "control" and the $z_o = 5$ ($\approx$ 35 km) mean zonal wind structures for the latitudes of 30 N, 50 N and 65 N. Note that while no perceptible change in either the phase or the amplitude is seen below $z = 2$ ($\approx$ 17 km) at the two lower latitudes, significant changes in the amplitude and phase of wavenumber one are seen in the phase at 65 N that penetrate all the way down to the Earth's surface.

Changes in the wind structure at levels lower than 35 km give alterations in the planetary wave structure that penetrate both further down into the troposphere and to lower latitudes. For instance, Figure 11 shows the comparison of the amplitude and phase structure for the computed planetary wave with zonal wavenumber one between the "control" and the $z_o = 2$ ($\approx$ 17 km) mean zonal wind structures for the latitudes 30 N, 50 N, and 65 N.

In order to give a better idea of the magnitude of the changes in tropospheric circulation that occur as a result of altering the middle atmospheric transmission-reflection properties for stationary planetary waves, Figure 12 shows a comparison of the 500 mb planetary wave patterns that result from our model with the "control" mean zonal winds and with the 20% reduction case at $z = 4$ ($\approx$ 30 km). These patterns are generated by adding our modeled January wavenumbers one, two, and three together for both of the wind state cases. Our choice of including wavenumbers one, two, and three was made on the basis of van Loon, et al's (1973) finding that these wavenumbers account for 96.2% of the deviations from the zonal mean values of geopotential and temperature at 50 N in January at 500 mb. Also shown in this figure is the planetary wave pattern obtained by adding the January wavenumbers one, two, and three at 500 mb from van Loon et al, (1973) together. In order to get an idea of the level of relevance of our model to the actual atmosphere, we compared the observed pattern (from van Loon et al's analysis) to our "control" case results. A ridging of about 10 dm is seen over the British Isles in the observations. This is compared to the modeled ridging of about 18 dm in roughly the same location. Over northeastern North America a troughing of about 10 dm is seen in the observations. A similar magnitude troughing is seen in the model results but shifted somewhat to the northwest. A ridging is seen along the western coast of North America reaching a maximum of about 10 dm over Alaska. The model results show a general area of ridging centered in the Pacific Ocean off the west coast of the North America of roughly the same magnitude. The observations show a large troughing area centered in the vicinity of Japan with a magnitude of about 20 dm. The model results show a large troughing area centered about 30^{o} to the west of Japan with a magnitude of about 11 dm. We only compare our model results to observations at middle latitudes since good comparison between the observations and the model at very high and very low latitudes, if it occurred, would be considered fortuitous given the limitations of both the observations and the model. Given that the observational results from van Loon et al (1973) are for a seven year average and that a substantial year to year variability is noted by these authors (see Figure 13), we believe that our model agrees well with the observations. In order to compare the "control" case with the 20% reduction case at z_o = 4 most easily, Figure 14 shows the z_o = 4 pattern subtracted from the "control" pattern. This figure shows that in addition to the differences in the magnitude of the ridging and troughing that were seen in Figure 12 (for instance, a difference of .4 dm to the west of the British Isles), there are larger differences produced at higher latitudes due to phase differences. For instance, in response to the changes in the zonal winds around $z_o = 4$, the 500 mb heights over northeastern Asia have increased by about 1.9 dm; the 500 mb heights over northeastern Europe have decreased by about 1.4 dm; the 500 mb heights off the northeastern coast of North America have increased by about 1.3 dm; and the 500 mb heights over north central Canada have decreased by about 1.5 dm. These changes are put into perspective by comparing them with the observed interannual variability as shown in Figure 13. The difference field in Figure 14 amounts to a substantial fraction of the observed interannual variability. We have also pointed out previously that larger changes in the mean zonal flow at lower levels would produce larger effects. What we have shown then is that changes in the mean winter 500 mb height field of about 20 m in response to solar disturbance effects are quite possible on theoretical grounds and that these changes are not negligible when compared to observations of the interannual variability in the mean January planetary wave field.

Thus, the upper atmosphere appears to vary in response to solar activity down to sufficiently low altitudes that changes in tropospheric planetary wave structure can occur as a result of the altered planetary wave propagation through the middle atmosphere. One candidate mechanism for giving rise to changes in the temperature structure at these stratospheric levels is changes in the sun's ultraviolet emission with changing solar activity. Therefore, it appears that in light of our best present knowledge dynamical coupling of the troposphere to those regions of the upper atmosphere that seem to be directly affected by solar activity is a viable mechanism for solar activity to make itself felt on the tropospheric circulation. This mechanism is, however, incapable of explaining any near instantaneous tropospheric response to solar activity such as that reported by Wilcox et al (1974). This is because of the finite time that it takes for planetary waves to propagate their energy upwards to reflection levels, to be reflected, and return back down to the forcing region as is required for this mechanism to be operative.

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Muench (1965) has observed that periodic amplifications of planetary waves with zonal wavenumbers one and two appear to propagate upwards at a rate of about 6 km/day. Taking this to be an indication of the planetary wave group velocity implies a two-way transit time between the troposphere and 35 km of about 10 days. So, there should be at least a time lag of this order between a solar disturbance affecting the atmosphere at this altitude and its effect being felt on the tropospheric planetary wave structure. In fact, this planetary wave reflection mechanism is probably most applicable to climatic time scales (on the order of a solar cycle, say) rather than on the scales appropriate to changes in the weather (a few days).

It should be mentioned once again, however, in view of the importance of dissipation effects for the planetary wave transmission-reflection problem, which such effects are included in this model. Dickinson's (1973) values for Newtonian cooling were used. A small background value for Rayleigh friction, 5×10^{-7} s^{-1}, was used with enhanced values for the Rayleigh friction being used in the vicinity of zero wind lines in an effort to totally absorb planetary waves there. No enhanced mechanical dissipation was used at high altitudes which almost certainly accounts for the continuous growth of the wavenumber one planetary wave above about 60 km, a phenomenon which is not observed. Investigations into the effects of altered dissipation in our model are under way with particular emphasis on the treatment of singular wind lines.

5. Discussion

We have seen in previous sections that observational evidence indicates that the atmosphere from the thermosphere on down to an altitude of about 25 km varies in a manner that is consistent with a response to solar activity. Of course, since in most cases observations are only available for one eleven year solar cycle, no firm statistical inference of such an effect can be made (Pittock, 1978). The results of our modeling study indicate that changes in the mean zonal flow at levels of about 35 km and below should alter the propagation of stationary planetary waves such that the winter tropospheric circulation is significantly affected in the manner that was hypothesized by Hines (1974). Changes in the mean zonal flow above this level as well as changes in the mean zonal flow during the summer and equinox seasons (this point remains to be checked rigorously) would not appear to affect the tropospheric circulation to such an extent. Our modeling study also shows that such alterations in the tropospheric flow should take place mainly at high latitudes.

6. Possible Observational Studies

There are several observational studies that could be carried out to either establish or to disprove the viability of the mechanisms discussed here. First, more observational studies should be undertaken to look for correlations between upper atmospheric parameters and solar activity parameters on both long and short time scales. While studies that look at the variation of meteorological parameters at a single location have some use, an effort should be made to look at zonally averaged and spectrally analyzed meteorological parameters so as to establish the geographical scale of the dynamics being affected. There should also be investigations undertaken to relate the ozone variability at various stratospheric levels to solar activity using newly available satellite data. Joint studies of planetary wave fluxes of energy and momentum should be undertaken using conventional and satellite data in the troposphere and satellite data in the stratosphere. These studies should be carried out in a manner to facilitate comparisons with theoretical predictions of the effects on tropospheric planetary waves of changes in upper atmospheric parameters. Also, observational studies should be carried out that would either confirm or refute the existence of changes in the sun's ultraviolet emission during disturbed solar conditions of the type that were reported by Heath et al (1973). Other solar disturbance energy inputs that may affect the stratosphere should also be studied.

Finally, there are some observational studies that should be undertaken to clarify the role of dissipation on planetary waves. Studies to clarify the mechanical dissipation resulting from "breaking" gravity waves should be done. The newly emerging technology of VHF Doppler radar should be most useful for this. Also, observational studies to clarify the role of singular wind lines on planetary waves should be made.

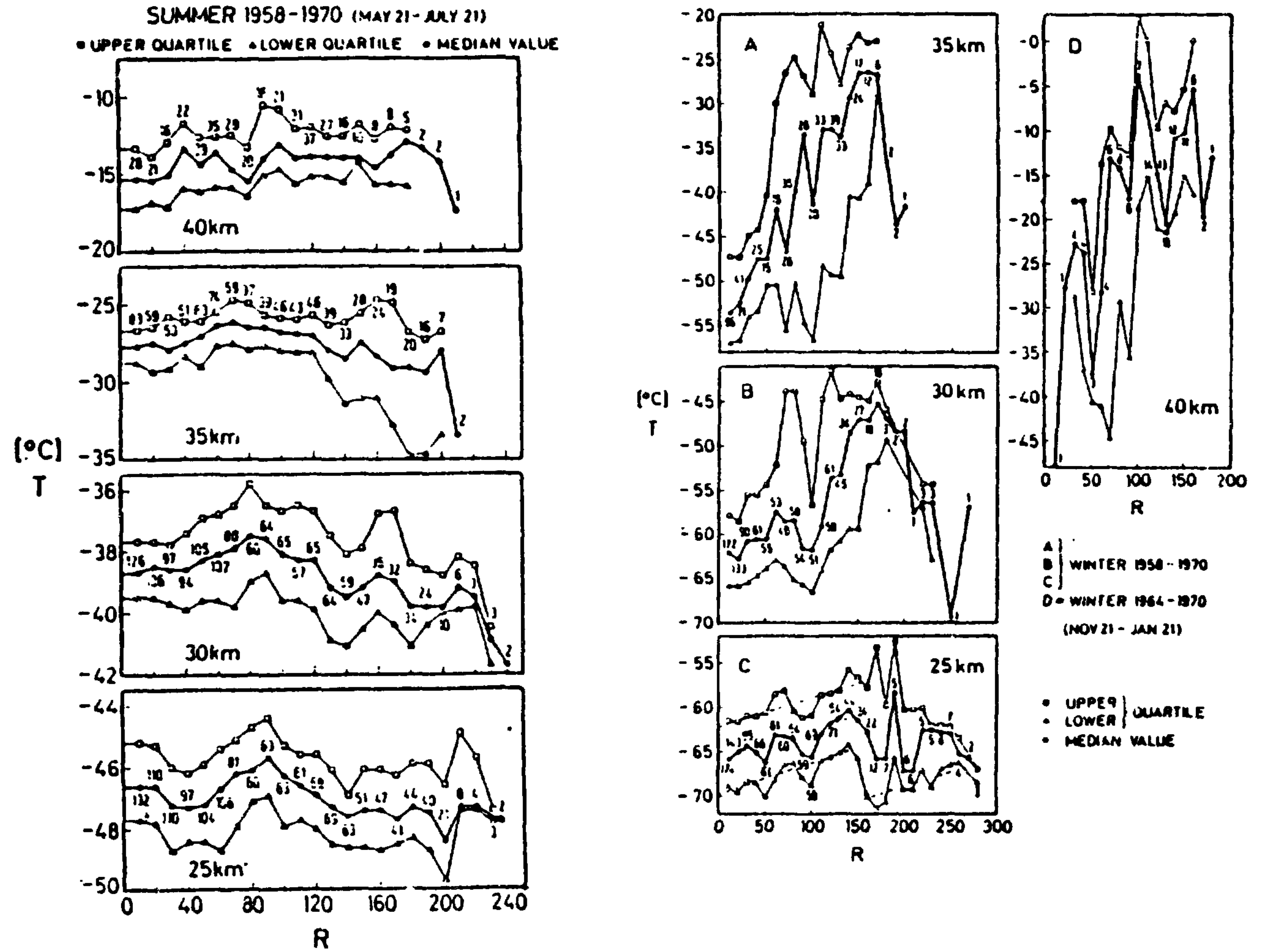

Figure 1: Median values of stratospheric temperature T at four different heights obtained from daily measurements by means of radiosonde launchings at Berlin plotted vs. Zurich sunspot number R. For definite groups of sunspot number, that is R = 0-20, 10-30, 20-40 and so on, the median values of T have been determined, separated for summer and winter, (from Schwentek, 1971).

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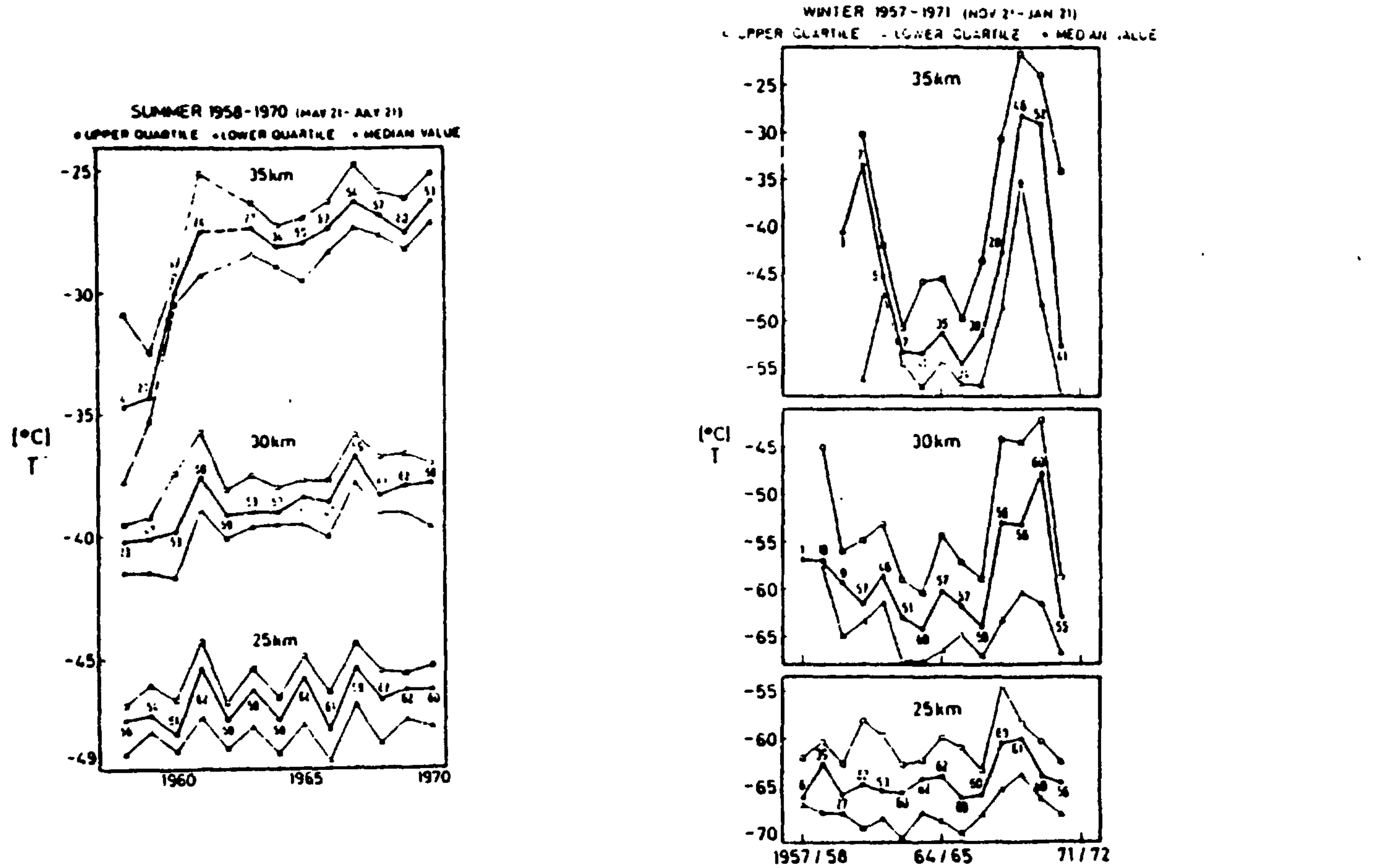

Figure 2: Median and quartile values of temperature in the stratosphere at 25,30 and 35 km in summer and winter for the sunspot cycle 1958-1970 determined from radiosonde launchings at the Free University at Berlin; sunspot minimum was in June 1964. Note the biennial (26-month?) period in summer at 25 km; change of phase in 1970/71? (from Schwentek, 1971).

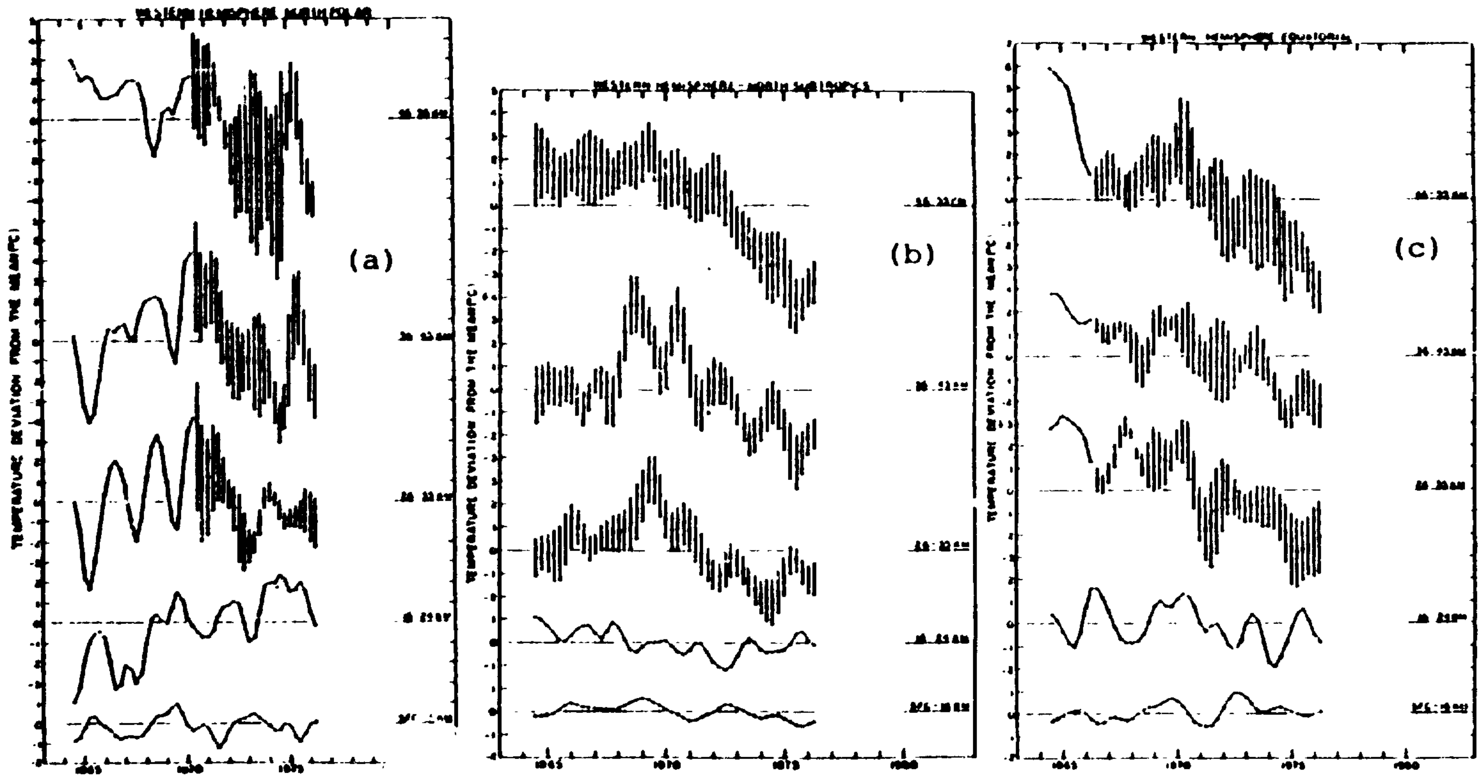

Figure 3: (a) Temperature variation (^{o}C) within given height layers (the top three based on rocketsonde data, the bottom two on radiosonde data) for north polar regions of the western hemisphere. A 1-2-1 smoothing has been applied twice to successive seasonal values (1-1 at beginning and end of record) after removal of the annual oscillation. When more than one station is available, the vertical bars on the rocketsonde data (smoothed as above) extend two standard deviations of the mean either side of the mean. The vertical arrows signify the time of quasi-biennial west wind maximum at 50 mb (20 km) in the tropics, and the tick marks are in summer of the given year.

(b) As in (a) except for the north subtropics of the western hemisphere.

(c) As in (a) except for the equatorial zone, basically, of the western hemisphere. (from Angell and Korshover, 1978).

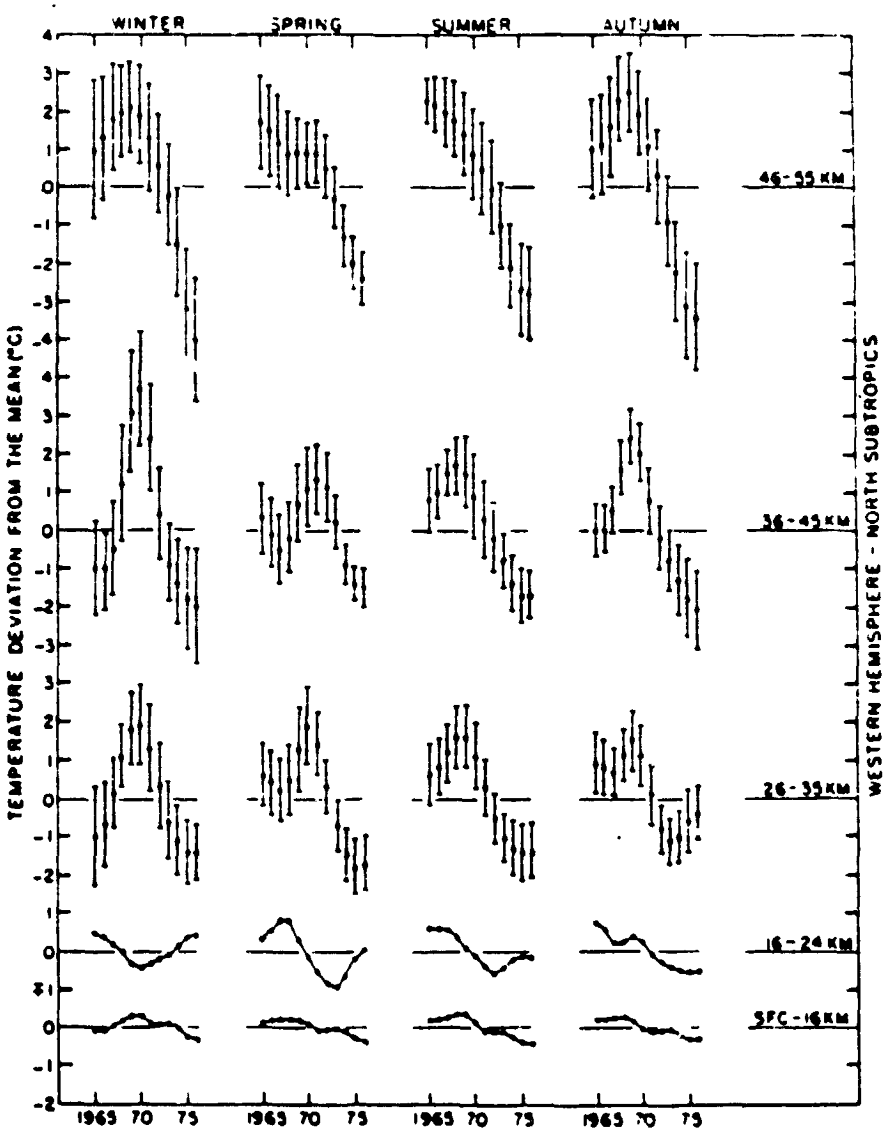

Figure 4: Temperature trend by season in the north subtropics of the western hemisphere. A 1-2-1 smoothing (1-1 beginning and end of record) has been applied twice to successive yearly values of the temperature, and the vertical bars (smoothed as above) again extend two standard deviations of the mean either side of the mean (from Angell and Korshover, 1978).

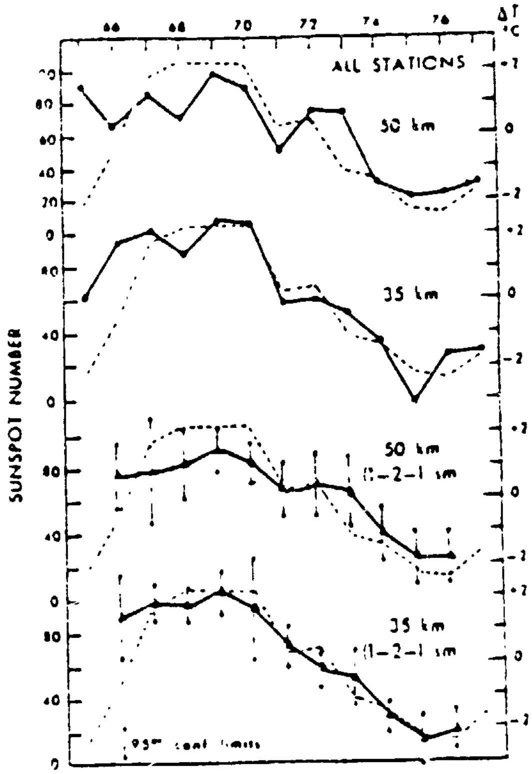

Figure 5: Mean temperature departure from long-period mean, smoothed (lower curves) and unsmoothed (upper curves), compared with mean annual sunspot number (dashed lines), (from Quiroz, 1979).

Station	Longitude	35 km A†	35 km B‡	50 km A†	50 km B‡
Poker Flat	64°N	0.82	0.93	0.14	0.24
Churchill	59°N	0.55	0.83	0.63	0.89
Point Mugu	34°N	0.71	0.89	0.79	0.94
White Sands	32°N	0.76	0.89	0.49	0.84
Cape Kennedy	28°N	0.73	0.83	0.66	0.89
Kwajalein	9°N	0.75	0.90	0.75	0.87
Ascension Island	8°S	0.47	0.72	0.17	0.32
All Stations		0.77	0.89	0.67	0.89

Period measured at Kwajalein is 1970–1977.
†Based on unsmoothed yearly data.
‡Based on 3-year running means (1-2-1 smoothing) of temperature data, 1966–1976.

Table 1: Coefficients of Correlation Between Summer-time Temperature Departure from Long-Period Mean and Mean Annual Sunspot Number, 1965 - 1977 (from Quiroz, 1979).

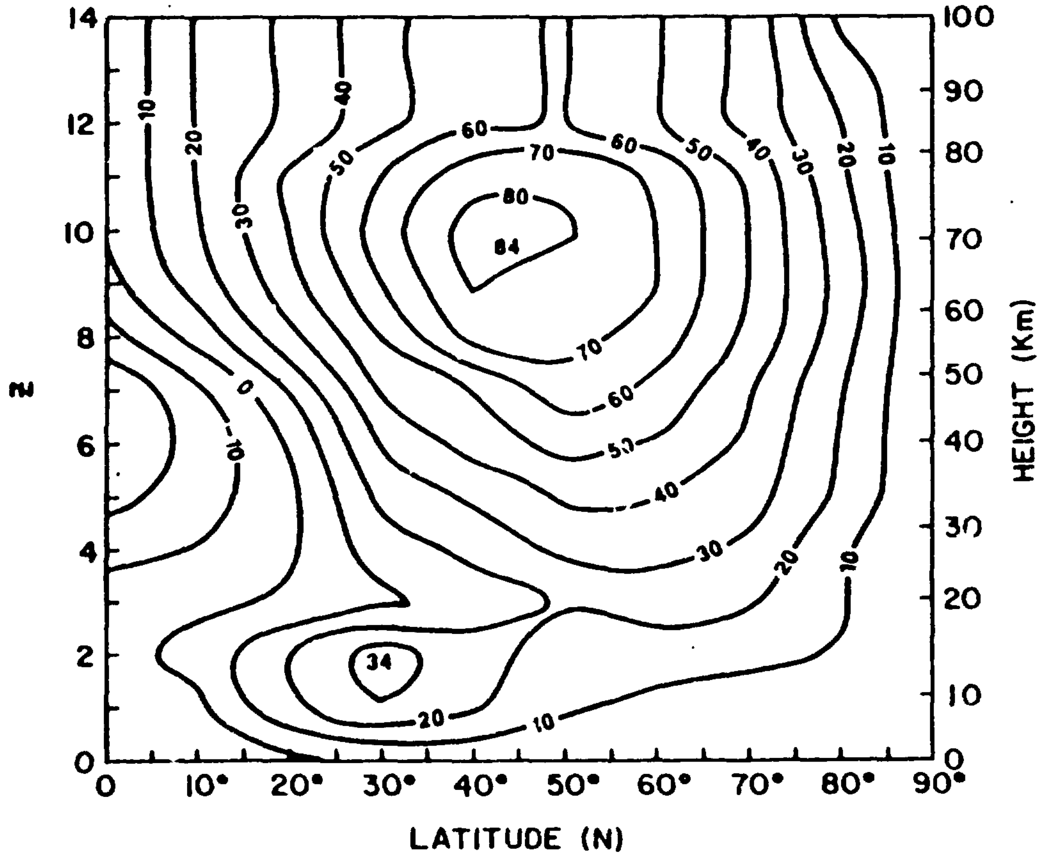

Figure 6: "Control" case mean zonal wind state in units of m s^{-1}. Positive values indicate westerly flow and negative values indicate easterly flow.

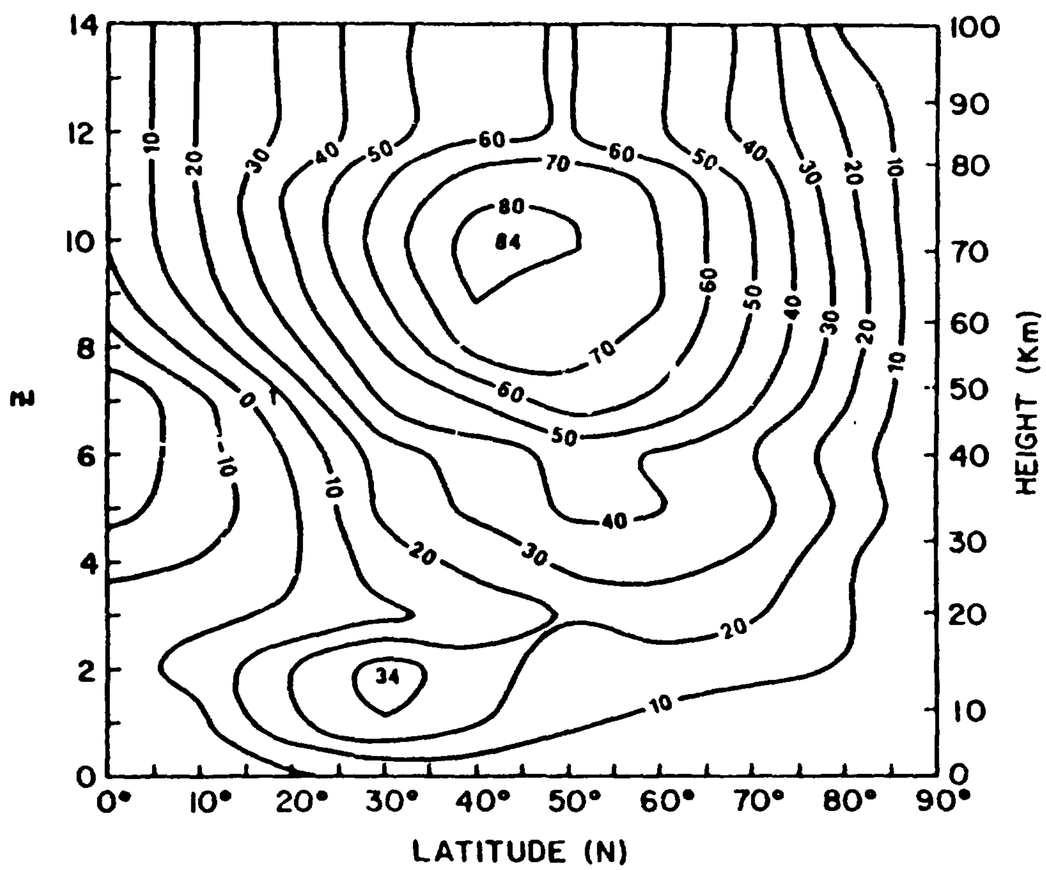

Figure 7: Mean zonal wind state when the wind magnitudes in the vicinity of $z = 6$ are reduced by 20%.

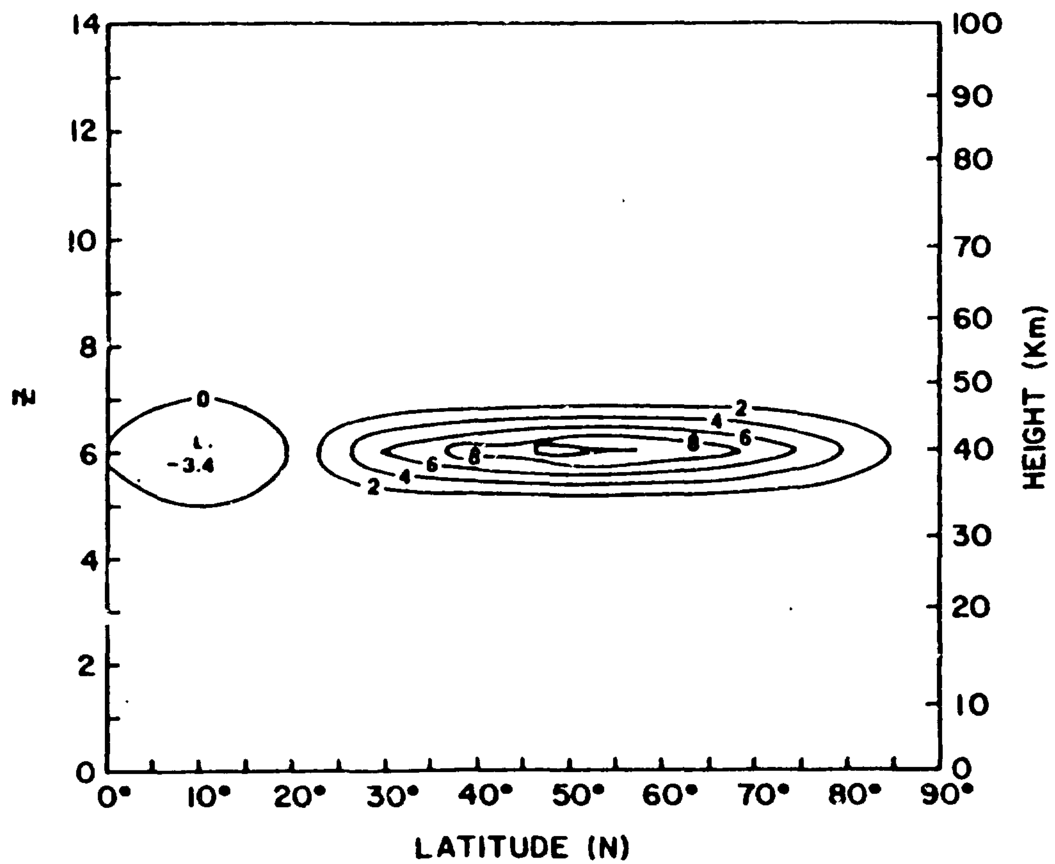

Figure 8: Difference given by subtracting the mean zonal wind state shown in Figure 7 from that shown in Figure 6.

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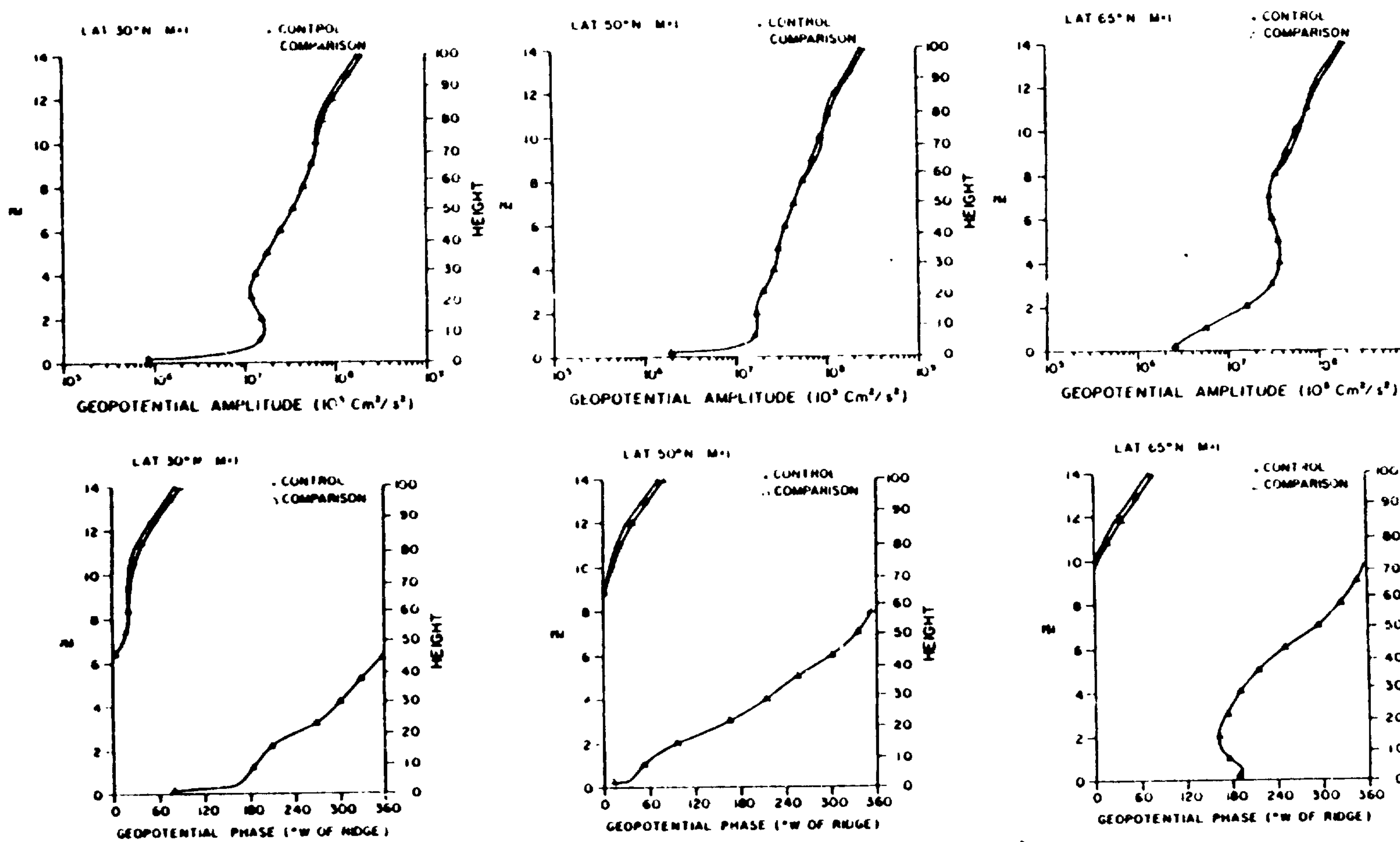


Figure 9: Comparison between the modelled planetary wave with zonal wavenumber one for the "control" mean zonal wind state and that when the wind magnitudes are decreased by 20% in the vicinity of z = 10. Left-top: Amplitude in units of cm^2s^{-2} (1 dm in geopotential height corresponds to approximately 10^6 cm^2 s^{-2}). Left bottom: West longitude of ridge. Middle: Same at 50 N; Right: Same at 65 N.

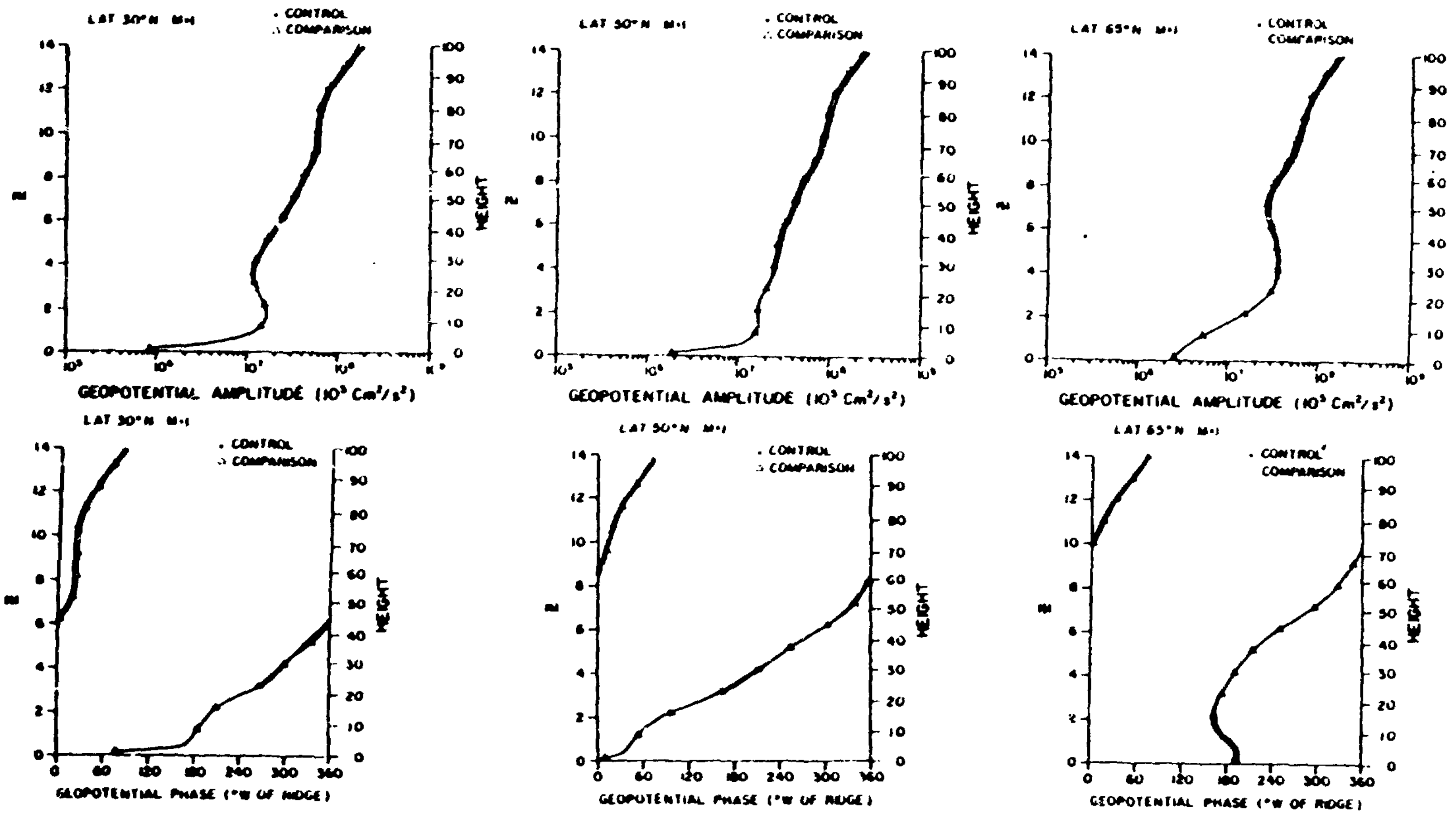


Figure 10: Same comparison as in Figure 9 except when 20% reduction is made at z = 5.

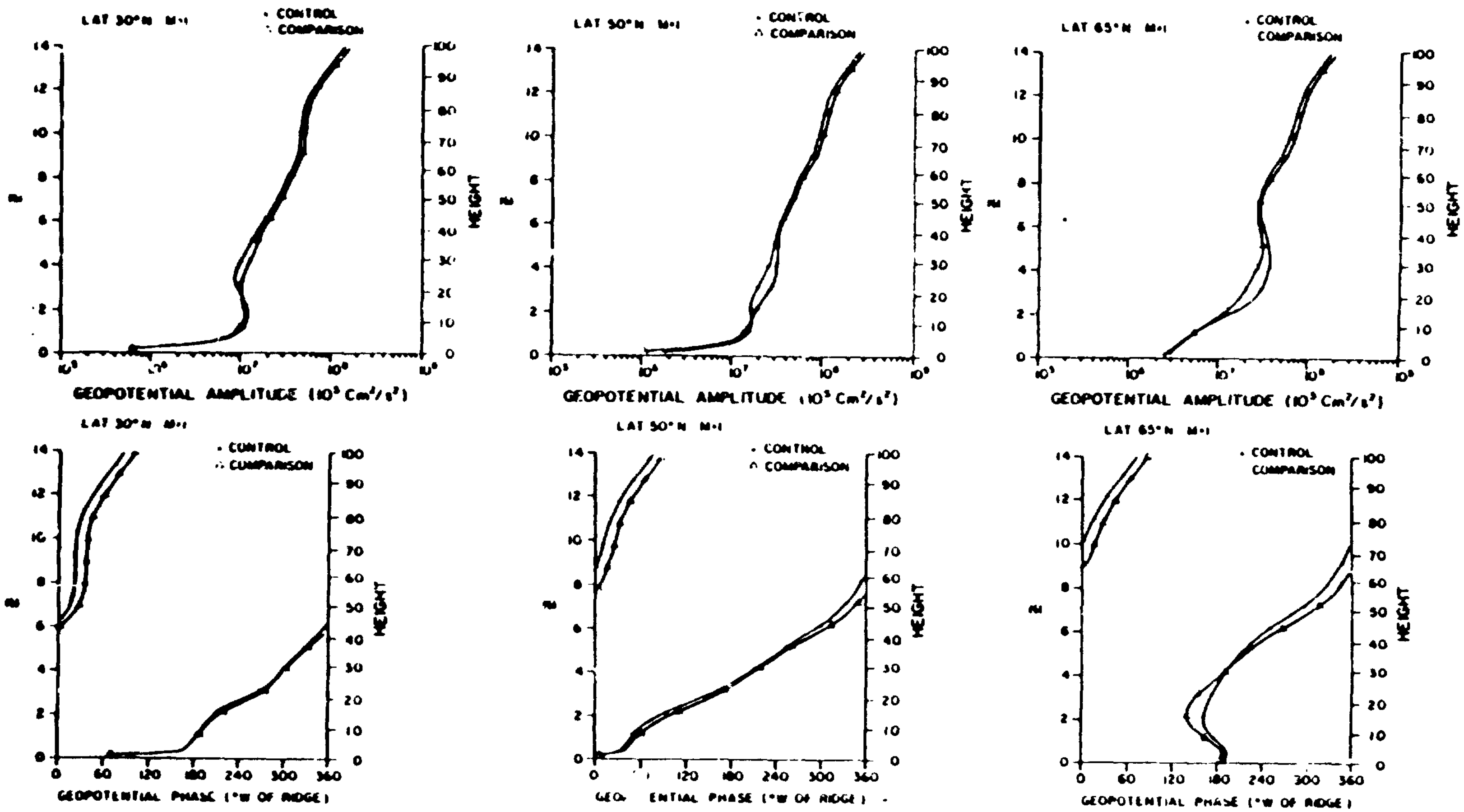
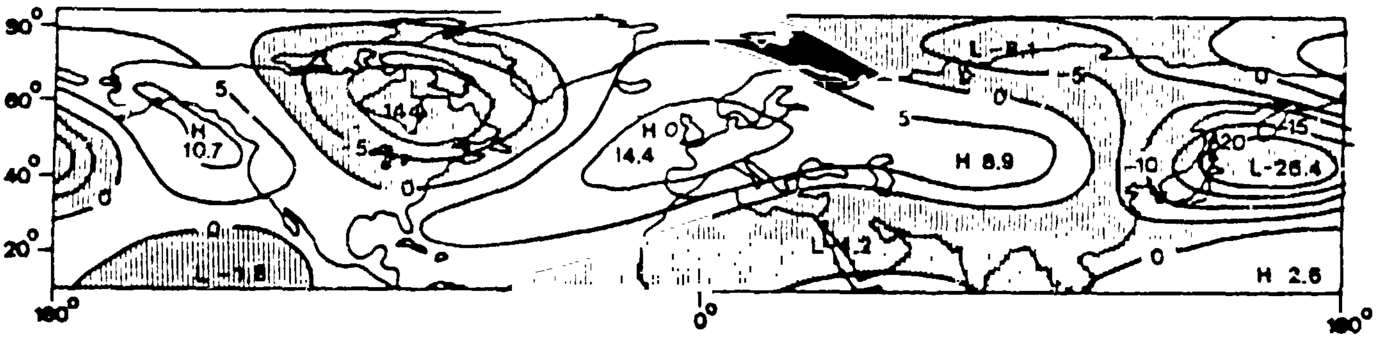
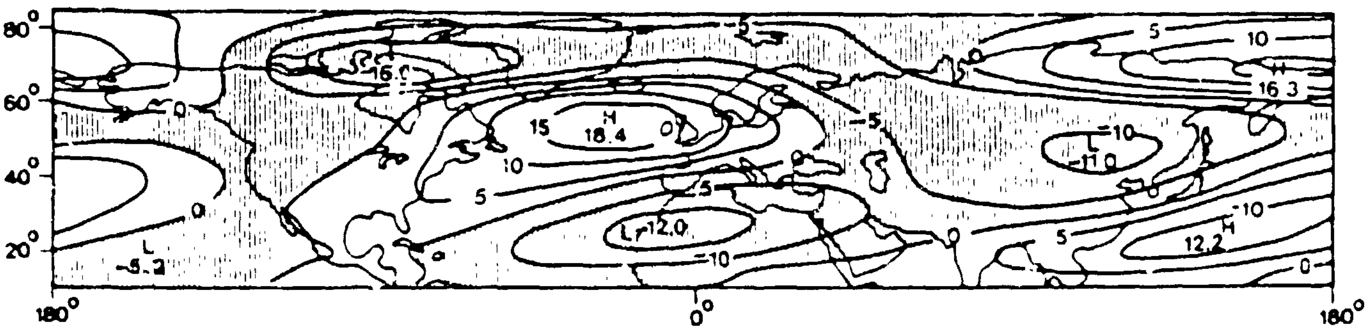


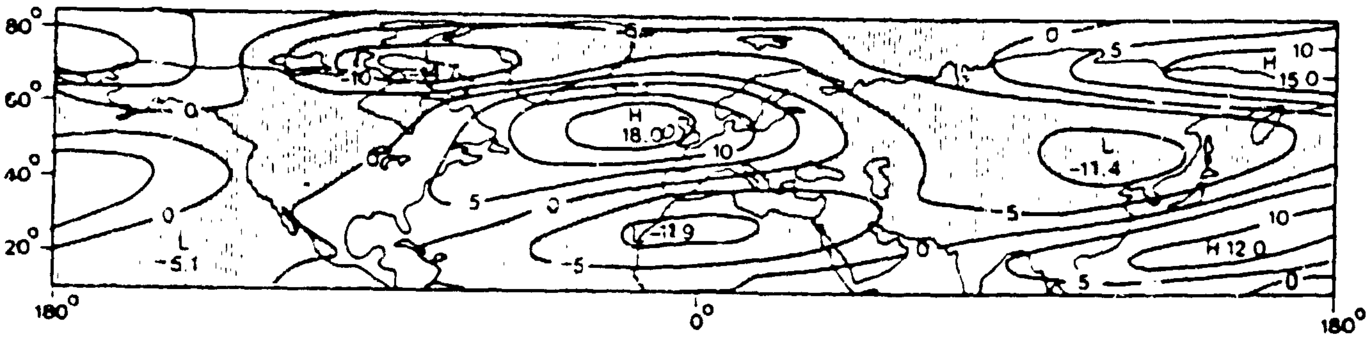
Figure 11: Same comparison as in Figure 9 except when 20% reduction is made at z = 2.



(a)



(b)



(c)

Figure 12: (a) Observed mean northern hemisphere January 500 mb planetary wave height pattern due to zonal harmonics one, two, and three in dm using the results of van Loon et al, (1973).

(b) Modelled northern hemisphere January 500 mb planetary wave height pattern due to zonal harmonics one, two, and three in dm using "control" mean zonal wind state.

(c) Same as (b) except for 20% reduction of the mean zonal winds in the vicinity of $z_0 = 4$.

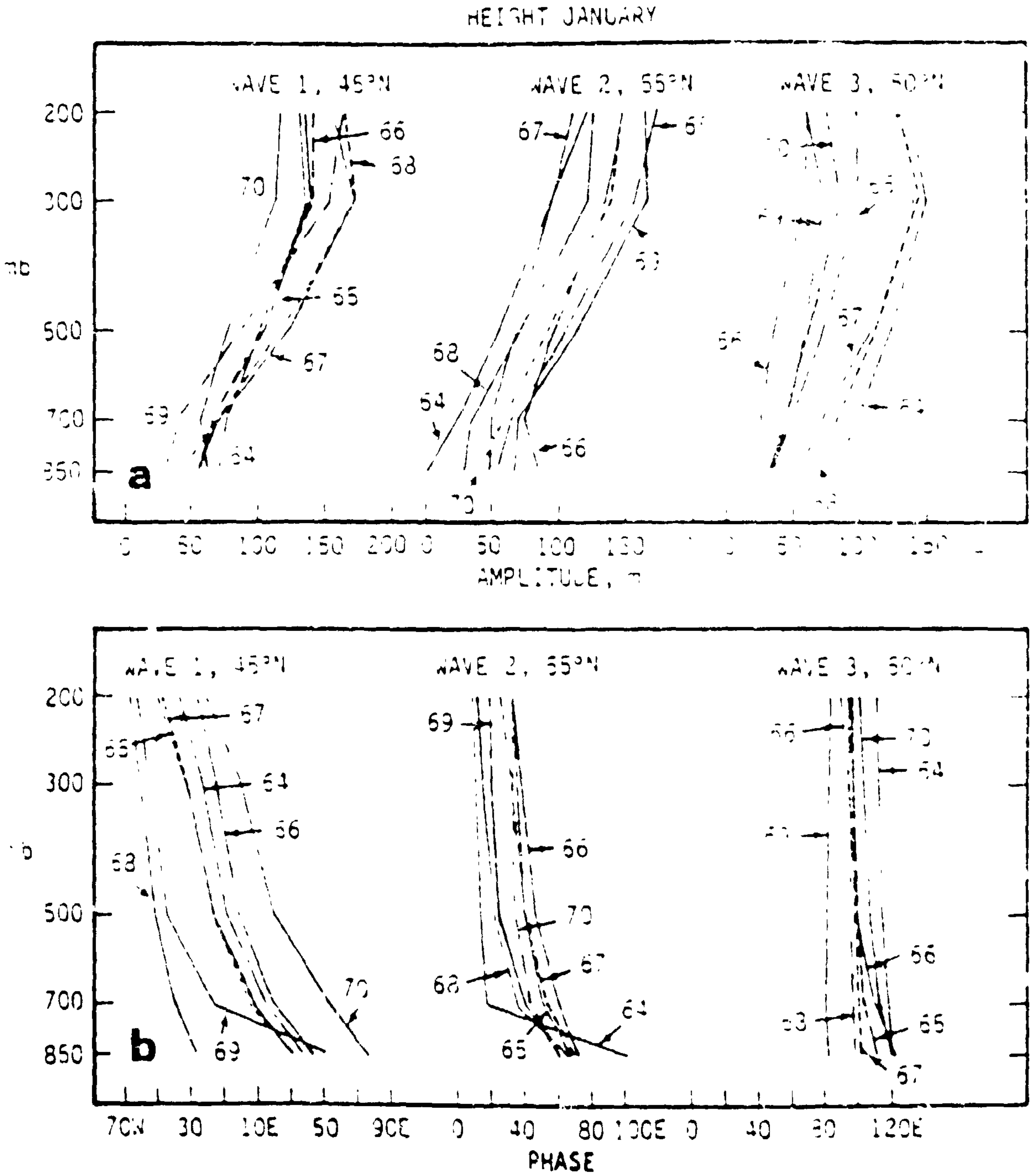


Figure 13: Monthly mean wave structure of zonal harmonics one, two, and three at a constant latitude during January for five different years from 850 mb to 200 mb (from van Loon et al, 1973).

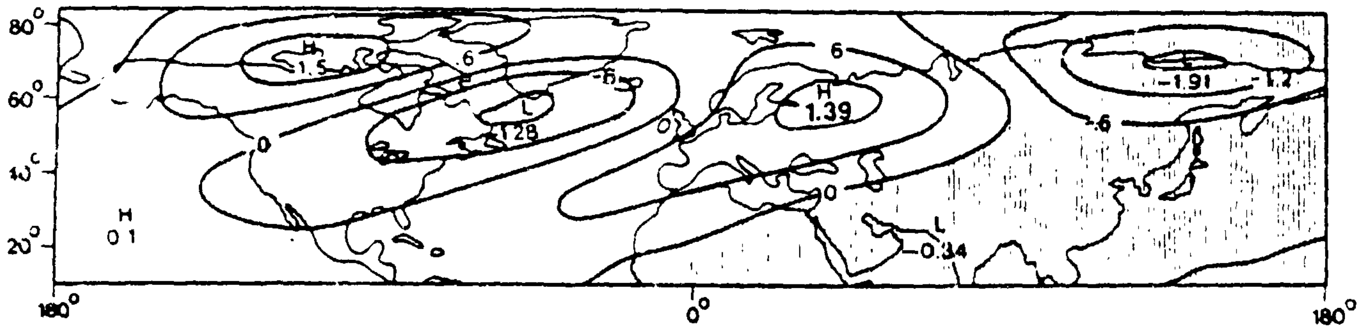


Figure 14: Difference field given by Figure 12b minus Figure 12c.

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Report V

Results of a General Survey on the Possibility of Atmospheric Electric Links Between Solar Events and Terrestrial Weather

by

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Abstract

We have completed a systematic assessment of coupling mechanisms between solar activity and weather that include, as key links in the coupling chain, atmospheric electrical processes. We find many mechanisms whereby solar activity can influence or alter the electrical state of the atmosphere. Our research has identified a wide variety of mechanisms in which atmospheric electrical parameters interact with meteorological systems. The difficult aspect in completing the coupling chain is in finding a meteorological connection that is significant. At this time connections involving thunderstorm electrification appear to be the most viable. Because of the lack of understanding of the electrical generating processes in thunderstorms and their consequences for thunderstorm development, we are not able to quantify this causative chain.

Introduction

In most meteorological systems we have found that there are other naturally occurring processes competing with the electrical influences. In all but the very rare cases the electrical interaction is weak. Because the strengths of these competing influences are typically proportional to concentration or energy density, these interactions generally decrease in strength with altitude. This observation, added to the fact that the solar-activity-influenced atmospheric electrical perturbations (the forcing functions) increase with altitude, leads us to hypothesize that the probability of finding a solar-activity-related meteorological effect (the responding functions) will increase with altitude. This hypothesis is certainly consistent with observations of solar-activity-related effects in the ionosphere and thermosphere.

From energy considerations we do not expect a direct solar-activity produced influence on the tropospheric weather (Dessler, 1975; Willis, 1976). The energy content of the solar activity is insignificant compared to tropospheric processes. We seek instead a "meteorological amplifier" wherein atmospheric electricity modulates the amplifier performance and the amplifier supplies the energy to alter the tropospheric weather. The "amplifier power" with respect to tropospheric weather modification is a function that decreases with altitude owing to the decrease with altitude of atmosphere energy density and to the displacement of the system from the troposphere with altitude.

We expect then that the probability function of finding a connecting mechanism will be characterized by the product of the "responding functions" and the meteorological amplifier functions This resulting probability distribution function will have a peak near the middle atmosphere for the same basic reason that the "Chapman Layers" form peaks in the atmosphere. The position of a probability peak will be determined by the particular mechanism being considered, just as each of the photoionizing and photochemical reactions produces a peak at a particular altitude.

In the following sections we will examine a series of potential mechanisms involving electrical connections. We are looking in particular at the lower links of the chain, the processes that couple the influence to the meteorological processes, because these processes are the pivotal processes in the causative chain. We will start with the molecular scale systems and advance to the larger systems.

In this research we have had the benefit of many valuable consultations with experts in the particular specialties discussed here. These participants are listed in the acknowledgments.

Electrical Interactions on the Molecular Scale

1. Direct Electrically Driven Motions

Atmospheric ions of all sizes drift in the presence of the atmospheric electric field, $\vec{E}$. The average motion of the ion (or charged particle) is the constant velocity at which the electrical force on the ion is balanced by the drag force exerted by the atmosphere. The drag on the atmosphere by the motions of the ions and charged particles can be treated as an electrical pressure, P_E, on the atmosphere. For a simple horizontally stratified atmospheric model we find that

$$P_E = \epsilon_0 E^2/2$$

At the earth's surface under fair weather conditions ($E \sim 150$ V/m)

$$P_E \approx 10^{-7} \text{Pa}$$

which should be compared to the atmospheric pressure P_A;

$$P_A \approx 10^5 \text{Pa}.$$

The difference is 12 orders of magnitude; whereas, meteorologically significant pressures can be as low as 3 to 4 orders of magnitude below atmospheric pressure. As we go to higher altitudes, the pressure and electric field strength both decrease roughly exponentially; hence, the fair-weather electric field never has an opportunity to be competitive.

There are two atmospheric regions where these electrical processes have increased importance. One is in the thermosphere, where, owing to anisotropic conductivities, the electric field becomes relatively large and the atmospheric pressure is very low. The thermosphere is so remote from the troposphere that these electrical effects cannot be invoked as a mechanism for modifying tropospheric weather without introducing another complete set of coupling mechanisms.

The second region requiring special consideration is in and around very active thunderstorms where the electric field becomes very large. Assuming $F \sim 10^5$ V/m in the anvil of a thunderstorm where $P_A \sim 10^4$ Pa; $P_E \sim 5 \times 10^{-2}$ Pa. The above equation for P_E is not rigorously applicable to the thundercloud field geometry, but it is adequate for order-of-magnitude calculations. Even with this very high field we find that the electrical pressure is 5 orders of magnitude below atmospheric. There is no reason to expect that there will be a direct dynamical effect of electrical pressure on thunderstorms. Sartor (1979 and personal communication) has pointed out, however, that these thunderstorm electrical forces might be important producers of vorticity in the tropics where the Coriolis parameter approaches zero. We will return to the question of thunderstorms later.

2. Ion Chemistry Connections

There are two electrical responses in the area of ion chemistry that we have considered, increased ion production rate and electric field drift of ion species.

There are well-documented studies of polar cap absorption (PCA) events that have produced very large increases in the ion-pair production rates in the middle atmosphere. The largest PCA event studied thus far occurred August 4, 1972, and is shown (number 4) in Figure 1 from Herman and Goldberg (1978, p. 60). At 50 km altitude there was a 5-6 order-of-magnitude increase in ion-pair production rate; however, the same event produced no appreciable change below 20 km. There are other PCA's that are much less dramatic at the higher altitudes but contain harder components that penetrate deeper into the atmosphere and thus may be of greater significance meteorologically. PCA events labeled 2 and 5 in Figure 1 both produced increased effects below 20 km. These increased ion-pair production rates affect, locally, every stage of the ion chemistry reaction chain and the resulting concentrations of reactants. Thus during a PCA event orders-of-magnitude changes can occur locally. Before completing this analysis we look at a second possible process.

The second process considered involves the electric-field drift of ions, which by ion chemical reactions have become selectively attached to specific molecular species in the atmosphere. Though this process is not as dramatic as the PCA events, it is a persistent process which over a long time may

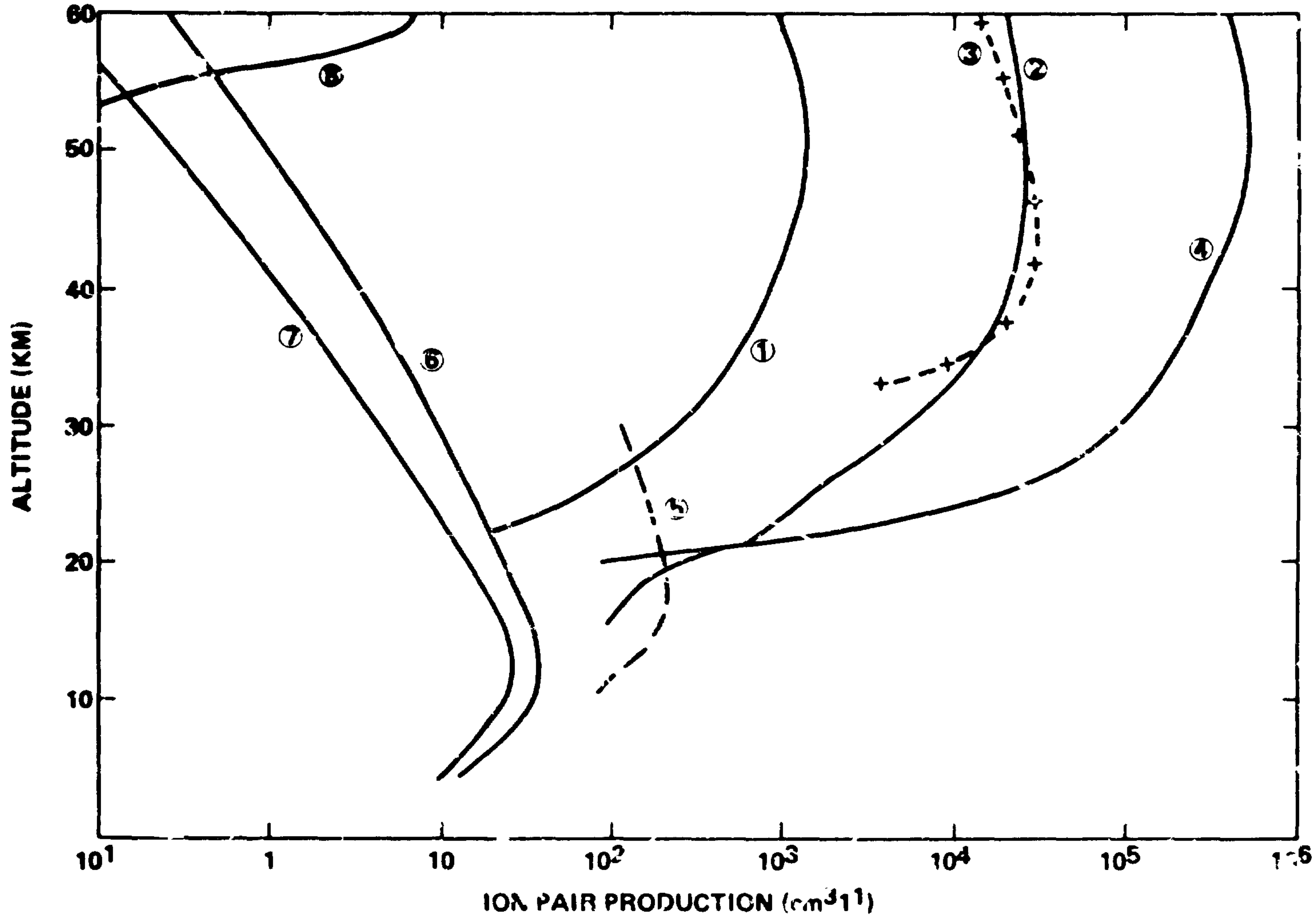

FIGURE 1
ION PAIR PRODUCTION RATES DUE TO SOLAR PROTONS: 1 PCA, 11/2/69; 2–PCA, 8/4/72, 1500–1600 UT, 3–PCA, 8/4/72, 1508 UT; 4PCA, 8/4/72, 2200 UT; 5–PCA 9/29/61; SUN SPOT MINIMUM GALACTIC COSMIC RAYS; 7–SSMAX (SUN SPOT MAXIMUM) GALACTIC COSMIC RAYS; 8–PRECIPITATING ELECTRONS IN A HARD AURORA (HERMAN AND GOLDBERG, 1978).

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provide an important net transport of reactants.

Hence we compare three transport processes: molecular diffusion, eddy diffusion, and electric field drift. In the expressions below n is the concentration of the species of interest, which is assumed to be ions in the electrical computation; N is the total molecular concentration making n/N the species mixing ratio. For the species of interest the fluxes by molecular diffusion J_D, eddy diffusion J_K, and electric drift J_E are given by:

$$J_D = -DN \frac{\partial}{\partial z}\left(\frac{n}{N}\right) = -D\left(\frac{\partial n}{\partial z} + \frac{n}{H}\right)$$

$$J_K = -KN \frac{\partial}{\partial z}\left(\frac{n}{N}\right) = -K\left(\frac{\partial n}{\partial z} + \frac{n}{H}\right)$$

$$J_E = n\mu E$$

In these equations D and K are the molecular and eddy coefficients of diffusion respectively, and μ is the ion mobility. When evaluated at the peak in the concentration $\left(\frac{\partial n}{\partial z} = 0\right)$ these simplify to:

$$|J_D| = \left(\frac{D}{H}\right)n$$

$$|J_K| = \left(\frac{K}{H}\right)n$$

$$|J_E| = |\mu E|n$$

At twenty kilometers altitude typical values for the parameters in these equations are: $H \sim 7$ km; $|E| \sim 1$ V/m; $K \sim 1$ m^2/s; $\mu \sim 10^{-3}$ m^2/V-s; $D \sim 2 \times 10^{-4}$m^2/s. This produces the following estimates for the fluxes:

$$|J_D| \sim (10^{-8}\ \text{m/s})n$$

$$|J_K| \sim (10^{-4}\ \text{m/s})n$$

$$|J_E| \sim (10^{-3}\ \text{m/s})n$$

We find that the electrical drift produces a flux that is larger than the eddy diffusion flux, which is larger than the molecular diffusion flux.

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Both of the above processes, enhanced ion production rate and electric drift, can produce local increases in the concentration of some ion-molecular component in the atmosphere. For this increase to be meteorologically significant, the perturbed component must interact with some meteorological system of influence. In the middle atmosphere regions, ozone is the atmospheric constituent that drives the thermal and dynamical processes. The local ozone concentration depends upon a number of variables including transport mechanisms, but the principle process by which ozone is usually destroyed involves its reaction with NO_x. (A non-electrical mechanism involving this process may occur during PCA events where the production rate of NO_x by solar protons is greatly increased).

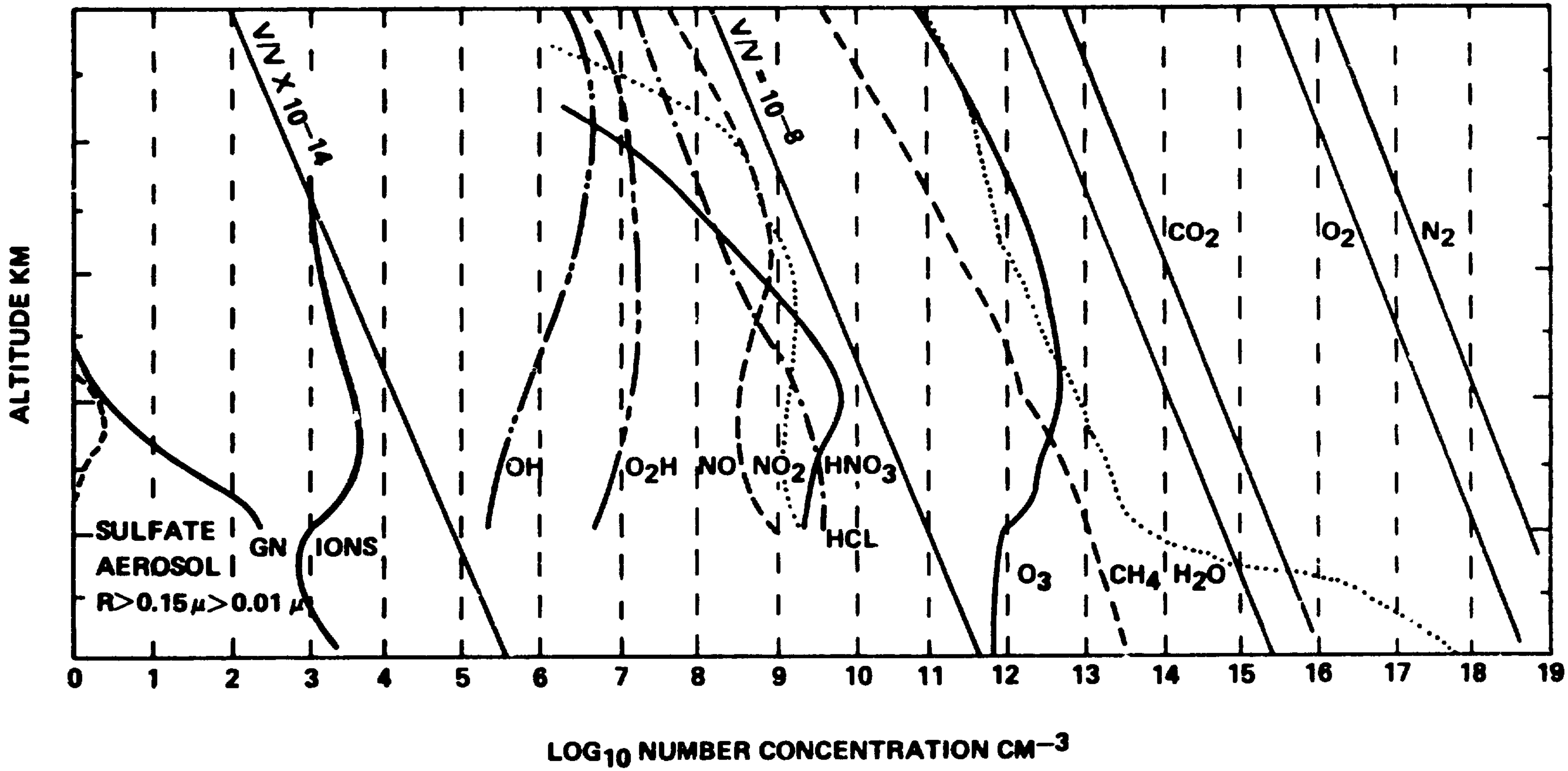
Ion-molecule reactions have been postulated to cause ozone destruction with reaction rate constants 3 to 4 orders of magnitude greater than the non-ionized pathways (Ruderman et al., 1976). [The terminal ions that are thought to be produced within ~1 sec of the ion pair production are:

$$H_3O^+(H_2O)_n \quad \text{and} \quad NO_3^-(H_2O)_m$$

An ozone molecule and an oxygenated nitrogen molecule (probably HNO_3) have been incorporated in the negative ion during the reactions. Upon ion recombination one gets HNO_3 and H_2O, thus losing the ozone but preserving the HNO_3, with which the ion has performed the function of a catalyst].

The problem faced by all of the ion-chemistry-ozone mechanisms is one of numbers. Figure 2 graphically demonstrates that the normal concentration of ions is 9 orders of magnitude less than ozone and 5 orders of magnitude less than NO, NO_2, and HNO_3. Thus the ion chemistry reactions are unimportant even with rate constants 10^4 times larger than the non-ion reactions.

In situations of greatly enhanced ion concentration, such as may occur with PCA's, we must seriously examine the viability of the ion chemistry-ozone mechanism. For example, increasing the ion concentration by several orders of magnitude and utilizing a 10^4 factor higher ion rate constant produces an ion chemical reaction chain for the destruction of ozone that exceeds the neutral species rates. (However, the neutral species concentration may also increase during PCA's).



FROM MOHNEN, V.A., IN PROCEEDINGS OF THE FOURTH CONFERENCE ON THE CLIMATIC IMPACT ASSESSMENT PROGRAM, FEB. 4–7, 1975, ED. BY THOMAS HARD AND ANTHONY BRODERICK, PP. 478–491.

FIGURE 2.

The above discussion is an oversimplification of a very complex process that requires detailed modeling; the type of consideration given here is sufficient only to indicate the situations that can yield promising results.

We believe that the modeling of solar particle events that include the ion reactions and ion transport can be a productive area of research, and we recommend its pursuit.

3. Ion Cluster Infrared Radiation

Alex Dessler (private communication) had suggested that the clustering of water molecules about ions might produce a system capable of radiating through infrared windows, hence allowing a more rapid local cooling. This concept faces the same numbers problem exhibited in Figure 2; namely, that the clustered water molecules are in concentrations 10^9 below that of the neutral water molecules and cannot, therefore, contribute a significant radiative component to the thermal balance.

In summary of the molecular scale processes we conclude that competing processes by neutral species will dominate the significant meteorological processes owing to the low concentrations of the ions. In special situations in which ion concentrations are greatly enhanced (e.g., PCA's) ion-chemical reactions that catalytically destroy ozone may become important; this is based upon the assumption that these ion reaction rates are themselves 10^3 to 10^4 greater than their neutral counterparts.

Electrical Interactions on the Aerosol and Particulate Scales

1. Ion Induced Nucleations

The process by which water molecules cluster about atmospheric ions is reasonably well understood. Under very special conditions these clustered ions continue to grow to form water droplets; this is the basic process by which the Wilson cloud chamber works. Calculations show that these stable clustered ions will not grow far beyond a cluster state of 5 to 7 water molecules unless the relative humidity is near 400% (Mohnen and Kiang, 1978). Because of other omnipresent nuclei in the atmosphere, this requisite condition will not occur.

2. Ion Assisted Gas to Particle Conversion

This process differs from one described above in that an additional gaseous constituent (H_2SO_4) is added to the mix of vapors from which ion nuclei embryos are produced. (The source of the H_2SO_4 is thought to be atmospheric SO_2, which gets oxidized in the atmosphere.) The presence of H_2SO_4 in the system lowers the vapor pressures over the embryonic droplets allowing them to grow faster than in the pure water system. By initiating the growth process on an ion, it is possible to start the growth process at H_2SO_4 concentrations a factor of 10 below those required for the non-ion processes.

The problem with this ion-assisted process is competition from other, more efficient processes, as we have seen in other cases. The presence of background nuclei provides preferred sites for the growth of embryos over the ion.

Another scheme involving the molecules of HNO_3 along with H_2SO_4 produces, in theory, embryos that grow even faster yet. In short, ions are important as initiators of embryos only if the usual competing processes are absent.

Lidar, a recently developed tool for atmospheric research, offers great promise for yielding new and better information on the variations of background nuclei in the middle atmosphere. We recommend additional research into sources and availability of middle atmosphere nuclei.

3. Exotic ion-assisted gas to particle conversion

One is free to hypothesize any number of different possible reactions involving other trace gas constituents in the atmosphere so long as the concentration of the constituents is sufficient to react with the ions in their lifetimes of approximately 200s to 1000s at ~ 20 km (Mohnen and Kiang, preprint). But again these special cases must compete with the natural background processes that appear to be rather efficient in their own right.

A somewhat unsettling feature of all of the theoretical and modeling research is that the predicted mobility of the clustered ions is ~ 1.75 $cm^2V^{-1}s^{-1}$ whereas the measured mobility spectrum peaks around 1.2 $cm^2V^{-1}s^{-1}$. The atmosphere, if we believe the theory and measurements, is consistently constructing ion clusters larger and more massive than is predicted by theory. This is an area where the need for continued research is indicated.

Although the average ion lifetime is ~ 1000 seconds, there are ions that will exist for much longer periods; these ions have an opportunity to interact or react with many components of the atmosphere that have not yet been considered. Since measurements indicate that ion growth continues beyond the predicted size, these as yet unidentified reactions very likely are taking place. We need to know if continued ion growth in the middle atmosphere is occurring. Because if it is, then we may have a viable mechanism for "seeding" cloud development with ions. This will require in situ measurements, laboratory measurements, and theoretical research.

4. Multiple Ion Clusters

"Zwitter" ions also belong to this classification of exotic ion processes. Sodium hydroxide (NaOH) and other chemicals with high electron or proton affinities form such strong bonds when clustering in the atmosphere that when recombination occurs with an ion of the opposite sign a stable dipole cluster is formed rather than neutralization (Arnold, 1980). This dipole cluster may continue to grow or later acquire other ions forming multiple ion clusters. These multiple ion clusters are very stable and form semipermanent atmospheric constituents; odd multiple ion cluster could account for the differences between observed and predicted mobilities of atmospheric ions. The ultimate fate of the multiple ion clusters would be to form aerosols and to precipitate. Arnold (1980) has made an estimate of the concentration of aerosol produced by multiple ion clusters for comparison with observed aerosol concentrations in the stratospheric aerosol layer; his result is that this process is insufficient to explain the observed aerosol concentration.

This process is, however, a new research area and requires extensive investigation before all of the pathways and parameters can be quantitatively understood.

5. Electric-Field-Assisted Coalescence and Coagulation of Aerosols and Particles

The mechanism envisioned here is simply that the electric field changes the relative motions of an existing population of charged aerosols and enhances the collision probability. A second element in the coalescence consideration is that the presence of the electric field (enhanced in the space between close aerosols) assists in breaking the surface tension, allowing more coalescence and fewer bouncing collisions. These two factors could lead to larger aerosols and faster growth.

A population of aerosols that has evolved under steady conditions will locally have a rather narrow size distribution and hence small relative velocities. When the medium is ionized, we know that the aerosols also become charged and the local electric field will produce an electric drift velocity that is added to the gravitational drift. The presence of the steady electric field when aerosols are undergoing charge change, or a sudden change in the electric field itself, will cause a change in the relative motions of the aerosols. Such changes affect the collision probabilities of the aerosol population. This mechanism has not been analyzed in detail theoretically, nor has it been verified experimentally to our knowledge. Although, it has been noted both by Mohnen (1971) and by Pruppacher and Klett (1978, p. 584) that electric drift velocities for aerosols of radius .1μ and larger are typically small in comparison with sedimentation velocities. For these larger particles then, coagulation rates are not likely to be affected by changes in electric drift velocities. However, for aerosols smaller than .1μ, Mohnen (1971) indicates that electric drift velocities may be significantly larger than sedimentation velocities. So, coagulation rates for these smaller, more electrically mobile aerosols may be affected by changes in the electrical state of the atmosphere. This mechanism has the property that any change from a previously "steady" condition will cause an increase in collision probability.

John Latham (personal communication) has told us of an experiment of a third party in which the coalescence of small droplets was greatly decreased when all electric fields were excluded from the laboratory test chamber. The interpretation was that in the absence of electric fields, the collisions between small droplets were predominantly of the bouncing type and that when electric fields were present, the coalescence probability increased dramatically. This interpretation needs verification both experimentally and theoretically because it is of significance both to this research and to cloud physics and cloud modification research.

We found in our discussions with the cloud physics scientists and with the particle and aerosol scientists that most believed that strong (thunderstorm) electric fields would affect the coalescence and coagulation processes. The extent to which smaller electric fields could be effective in these processes was thought to be limited or simply unknown. This area of research should produce definitive answers in both the experimental and theoretical research directions over a relatively short period with relatively small investment in research funds.

High Altitude Ice Clouds

The basic problem that we are addressing in this section is this: given the existence of a high altitude ice cloud, can changes in the electrical environment alter in any significant way the development of the cloud? For example, enhanced growth of the ice particles could increase settling velocities and produce seeding nuclei for lower atmospheric layers. Alterations of the normal condition of the ice particles can alter both the radiation behavior of the cloud and the microphysics and dynamics of the particles. Either of the above may destabilize the cloud and hasten its disappearance.

The existence of a layer cloud offers one additional electrical property that we have not considered in our previous mechanisms; the electric field is enhanced inside the cloud providing us with somewhat larger electric fields. This enhancement comes about as a result of ion attachment to the cloud particles which significantly reduces the conductivity of the air within the cloud. The cloud appears to be an insulator relative to the more conducting atmosphere; the atmospheric electrical current places surface charges on the cloud boundary increasing the internal electric field to the point that the internal electric field E_c is enhanced by a factor equal to the ratio of the conductivities outside and inside the cloud:

$$E_c = E(\lambda/\lambda_c)$$

The internal conductivity has been computed (Pruppacher and Klett, 1978, p. 589) and measured (Allee and Phillips, 1959) for non- or weakly electrified clouds, and the conductivity within such clouds is reduced by factors of 1/3 to 1/40. A factor of 10 may then be used as a representative value for the field enhancement. Since many of the electrical effects scale as E^2, we may typically expect a factor of 100 increase in potential electrical effects for a process inside such clouds.

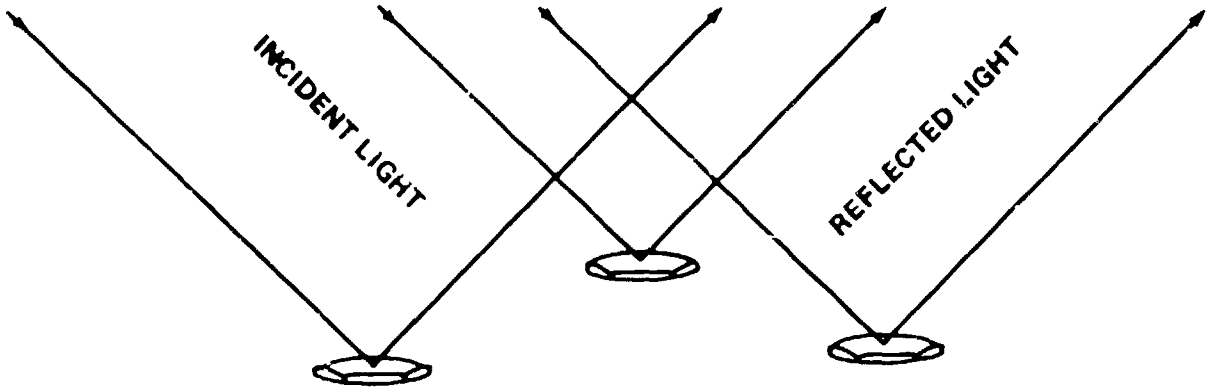
In regard to the electrical effects on coalescence and coagulation, we are here in the same situation as discussed with regard to the aerosol problem. The effects are known to occur for strong electric fields. There is unconfirmed evidence that effects are also present in weak electric fields. This area is "ripe" for both theoretical and experimental research.

We have spent considerable effort on the problem of the electric field alignment of ice crystals, because, if the process occurs, it would have a rapid response to changing atmospheric electric fields. The potential meteorological effect employing this process involves changes in the radiative properties of cirrus clouds as a result of changes in crystal orientations. Aerodynamic torques generated by the falling motion of the crystals tend to align the crystals with their long dimensions horizontal, while the vertical fair weather electric field tends to align the crystals' long dimensions (and their induced dipole moments) with the vertical. We have called this potential influence of electric fields on crystal orientations the "Venetian blind" effect. If it occurs, the possibility exists that the radiation balance of the atmosphere could be modulated by the fair weather electric field. Our Figure 3 (from Vonnegut, 1965) illustrates the effect on platelike ice crystals. Columnar crystals respond similarly. The electric field alignment of ice crystals unquestionably occurs in strong electrical fields and has been observed at visual wavelengths (Vonnegut, 1965) and with radio techniques (Hendry and McCormick, 1976; Watson et al., 1979).

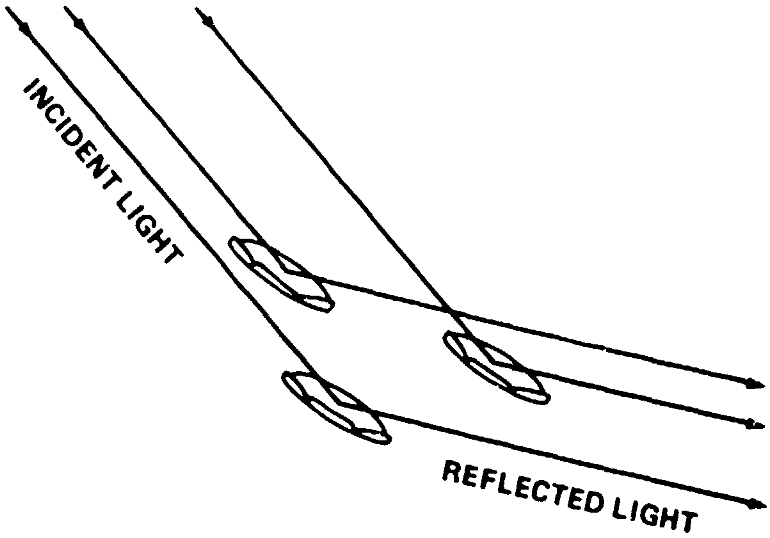
Over the range of crystal sizes occurring in the atmosphere, several dynamical regimes are encountered. On the small end of the spectrum (< 1 μm) Brownian motions cause the crystals to randomly change their orientations. Somewhat larger crystals fall (slowly) in a low Reynolds number regime (Stokes flow) where the hydrodynamic torques are small (Happel and Brenner, 1965, p. 187). In the laboratory these crystals assume no preferred orientation as they fall; they maintain their initial orientation (Willmarth et al., 1964; Jayaweera and Mason,, 1965). The larger crystals fall with higher Reynolds numbers and experience significant aerodynamic torques (approximated by potential flow); laboratory and in situ observations show that these crystals fall with their shortest axis oriented in the direction of fall (Willmarth et al., 1964; Jayaweera and Mason, 1965; Platt, 1978; Platt et al., 1978).

We can estimate the relative importance of these torques by approximating ice crystals with spheroids; we use oblate spheroids for plate crystals and prolate spheroids for the columnar crystals. The electric torque, T_E, in an electric field, E, is

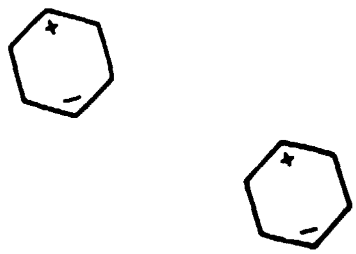
$$T_E = 4\pi\varepsilon_0 E^2 a^3 \cos\theta \sin\theta \, f(k,\varepsilon_r)$$



ICE–CRYSTAL PLATELETS FALL WITH THEIR PRINCIPAL AXES VERTICAL AND THEY REFLECT LIGHT LIKE LITTLE HORIZONTAL MIRRORS



UNDER THE INFLUENCE OF AN ELECTRIC FIELD THE ICE CRYSTALS ASSUME A NEW ORIENTATION AND REFLECT LIGHT IN A DIFFERENT DIRECTION



UNDER THE INFLUENCE OF AN ELECTRIC FIELD INDUCED DIPOLES CAN FORM IN CRYSTALS THAT CAN CAUSE ALIGNMENT OF THE HEXAGONAL STRUCTURES

FROM VONNEGUT, B., ORIENTATION OF ICE CRYSTALS IN THE ELECTRIC FIELD OF A THUNDERSTORM, WEATHER, 20, 310, 1965.

FIGURE 3.

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where a is the equatorial radius of the spheroid, θ is the angle between the electric field and the spheroid's axis of rotation, and $f(k, \epsilon_r)$ is a function of the spheroid axis ratio, k, and the permitivity of ice ϵ_r.

The aerodynamic torque, T_p, can be estimated from potential flow, which actually gives an overestimate of the torque (Weinheimer, 1980)

$$T_p = M' U^2 \cos\chi \sin\chi \, h(k)$$

where M' is the mass of air displaced, U is the fall velocity, χ is the angle between the axis of rotation and vertical, and h is a function of the axis ratio, k. [Two papers on this particular research effort by Weinheimer and Few are currently being written. Weinheimer's Ph.D. thesis (1980) is devoted to this subject.] When we apply this system of torques to the wide range of crystal sizes and atmospheric electric fields, we find, as expected, a wide range of solutions. For a strong thunderstorm field (3×10^5 V/m), and for a crystal with an axis ratio of 2, there is some degree of electrical alignment for crystals as small as 1μ and up to as large as 1mm. The actual behavior changes from (1) an overdamped aligning of the 1 μm crystals to, (2) underdamped oscillations of the 10 μm and 100 μm crystals to (3) alignment within the horizontal plane only, for particles larger than 1mm. When we examine the behavior at electric fields that we might expect to find in high altitude clouds (~ 100 V/m at most) these electrical effects vanish owing to the E^2 dependence of the electrical torque.

As a specific example, we include Figure 4, which delineates the different dynamical regimes described above, for an oblate spheroidal ice crystal with a semi-minor axis that is one-half its semi-major axis.

Our research has convinced us that there will not be significant electrical alignment of ice crystals in clouds unless the electric field strength is at least 10^3 V/m, and perhaps even greater.

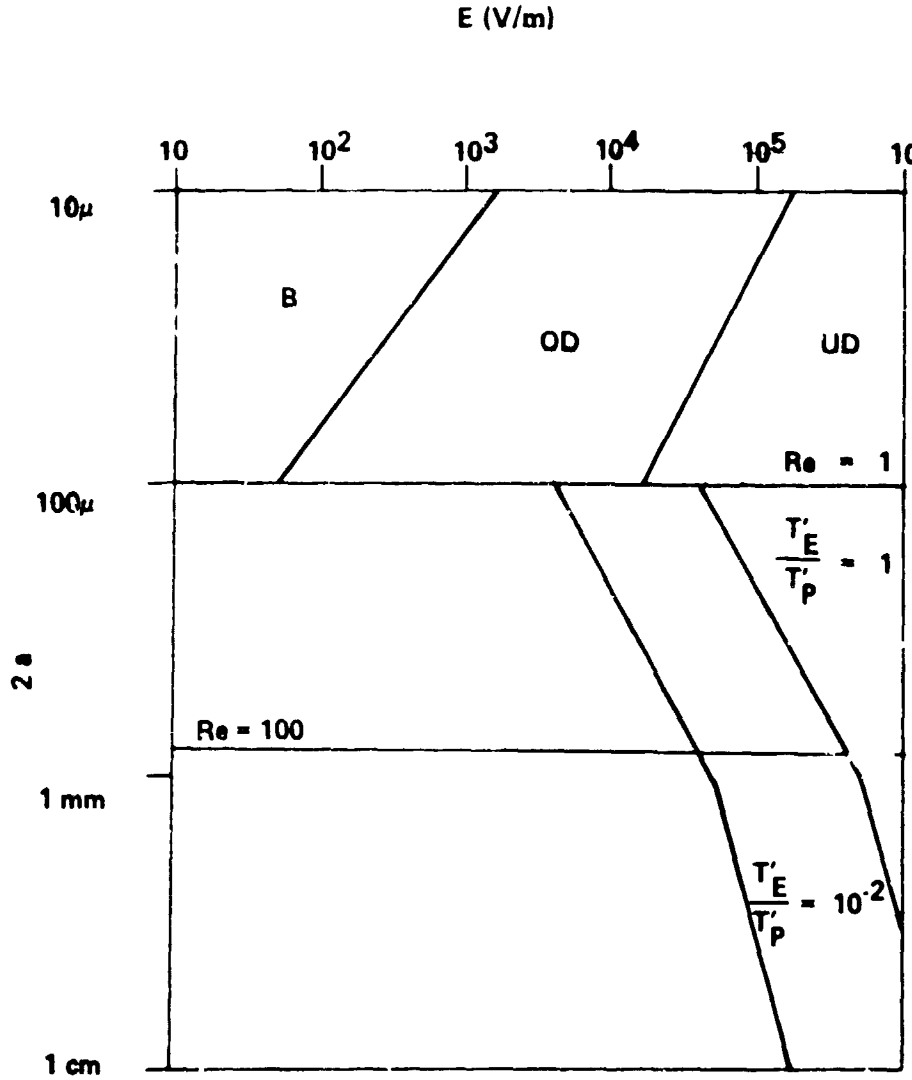

FIGURE 4. DELINEATES DIFFERENT DYNAMICAL REGIMES FOR AXIS RATIO k = 2. THE MOTION IS ANALYZED FOR RANGES OF ELECTRIC FIELDS AND CRYSTAL SIZES. "B" DENOTES BROWNIAN MOTION, "OD" DENOTES OVERDAMPED AND "UD" DENOTES UNDERDAMPED. Re DENOTES THE REYNOLD'S NUMBER APPROPRIATE TO THE SIZES SHOWN.

Convective Cloud Mechanisms

The basic scheme proposed here is as follows: the atmospheric electrical environment interacts with the electrical charging mechanism of the thunderstorm; the electrical properties of the thunderstorm then interact with microphysical processes and modify the precipitation or cloud water budget of the storm; the total energy depends upon the water budget; and the mesoscale interactions are related to the thunderstorm energetics. This mechanism has some definite advantages: (1) The energy source (thunderstorm) is large and is known to have habitual electrical characteristics. (2) Certain microphysical and cloud physical processes are basically unstable systems that when triggered greatly multiply the triggering effects. (3) In some climatic regions most of the precipitation originates in electrified clouds. (4) Because thunderstorms are responsible for the global electric field a local effect can have worldwide manifestations.

In addition to electrical influences on cloud microphysics which in turn influences dynamics, there may also be more direct electrical effects on atmospheric dynamics, such as vorticity production, as mentioned briefly in an earlier section.

1. Convective Charging--A mechanism that bootstraps on the environmental electrical properties.

The following discussion is based upon a theory described by Vonnegut (1955). The precloud atmospheric electrical structure has an electic field that decreases exponentially with height; corresponding to this is a net positive space charge density that also decreases with height. In this model a warm convective bubble of air rises from the surface, forms a cloud upon reaching the lifting condensation level, and continues to rise. The space charge within the bubble will (to first approximation) be conserved as it rises, but the bubble itself will expand adiabatically with altitude. (The bubble also expands owing to entrainment but this effect is not included in this discussion). The electric field due to the space charge within the bubble is directed outward. As the bubble, now a cloud, rises higher in the atmosphere, the electric field due to the cloud becomes comparable to the decreasing electric field of the environmental air. Negative ions in the air will be attracted by this field to the sides of the clouds where they become attached to boundary cloud droplets. Because of the eddy drag on the cloud boundary, the inner positively charged part of the cloud rises more rapidly than the negatively charged boundary regions. If the cloud top rises high enough to reverse the direction of the electric field above the cloud, then the convective charging model begins working much faster. At this stage currents from the highly conducting air above the cloud supply a steady current of negative ions to the upper cloud boundary. If the convective geometry is such that this upper boundary material is preferentially transported to lower regions of the cloud while air from the surface below the cloud is preferentially convected upward to the cloud top, then all of the necessary components for the production of a natural Van de Graaff generator are present. Positive space charge, which is produced by coronae in the strong fields below a thunderstorm, is supplied at the bottom of the convective flow and is carried upward while negative charge is supplied at the top of the cloud and is carried downward.

The electric field E at the surface of a spherical volume of radius R containing charge Q is

$$E = \frac{Q}{4\pi \varepsilon_0 R^2}$$

The adiabatic relationship for the rising spherical bubble is

$$P \left(\frac{4}{3} \pi R^3 \right)^{\gamma} = P_0 V_0^{\gamma}$$

Hence $E \propto 1/R^2$ and $R \propto P^{-1/3\gamma}$; this gives $E \propto P^{2/3\gamma} = P^{.48} \approx P^{1/2}$

If the pressure scale height is H then the electric field scale height of the bubble is 2H. For convective conditions we assume H = 8 km thus

$$E = E_0 \, e^{-z/16 \text{ km}}$$

We can obtain E_0 the self-field of the bubble from the change in E_A, the atmospheric electric field that occurs near the surface where the bubble originates. The average, net, space charge concentration $\overline{\rho}$ in the atmospheric layer of thickness Δz adjacent to the surface is given by

$$\overline{\rho} = \varepsilon_0 \frac{\Delta E_A}{\Delta z}$$

If this air is incorporated into the original bubble the self electric field becomes

$$E = \frac{R}{3} \frac{\Delta E_A}{\Delta z}$$

Taking $R = 2$ km, $\Delta z = 1$ km, and $\Delta E_A/\Delta z = 55$ V/m (See table 1), we find $E_0 = 37$ V/m. Hence

$$E = 37 \; e^{-z/16 \text{ km}}$$

In Table 1, E is evaluated and compared to E_A (§60 in Allen, 1963; also Table XXla in Israel, 1973). In this model we see that the electric field above the cloud is reversed at an altitude near 5 km by this convective mechanism.

TABLE 1

Height of Convected Volume	Self Field (V/m)	Normal Field (V/m)
0	37	130
1	35	75
2	33	45
5	27	15
10	20	5
15	14	2

The whole process is related to the initial electrical structure of the atmosphere. The key elements are the space charge near the surface and the altitude at which the field due to the cloud reverses the direction of the total electric field above the cloud. This altitude is a sensitive function of the initial conditions; compare the differences in Table 1. It would be quite possible for a relatively small change in the fair weather field to move this reversing altitude into or out of the range of cloud tops on a given day. If the cumulus clouds were incapable of reaching the electrical reversing altitude, then none of them would become strongly electrified. However, if the reversing altitude were lowered, then many of the clouds would penetrate it and become electrified.

Once the cloud is electrified, then the charging rate by the convective hypothesis would be closely related to the conductivity of the air above the storm. This happens because the current to the top of the cloud supplies the charge that is convected by the cloud motions and produces the electrified cloud. This gives the environmental electrical parameters yet another means of influencing the severity of the thunderstorm.

The big problem with this convective process is that it requires a very specific convective organization within and around the cloud. There is no firm evidence yet to support this system, nor is there good evidence to refute it, either. This problem is a good area for productive research in cloud modeling. Well-designed experiments can also be useful but they are extremely difficult to execute and interpret.

2. Inductive Charging--Another bootstrap hypothesis.

If one takes the view that the neophyte cloud is initially electrically passive, then the internal electric field should be in the same direction as the environmental electric field but perhaps 10 times larger in magnitude. Cloud particles (Figure 5) falling in this electric field are polarized, and when two particles make a close approach, the adjacent surfaces are oppositely charged. If the collision results in the coalescence to form a single particle, no charging occurs. However, if the collision is of the bouncing type, with the two particles separating after touching, then charge will be transferred with the smaller particle receiving the positive charge in the situation depicted in Figure 5. Because of the differential fall velocity of the various particles, the smaller particles will be carried systematically upward relative to the larger ones. This upward motion of positively charged particles increases the electric field in the interaction region providing positive feedback to the process. For individual particles the process becomes self limiting because as they become charged, the polarizing field produces smaller regions of opposite charge on the particle surface. The likelihood of a a)

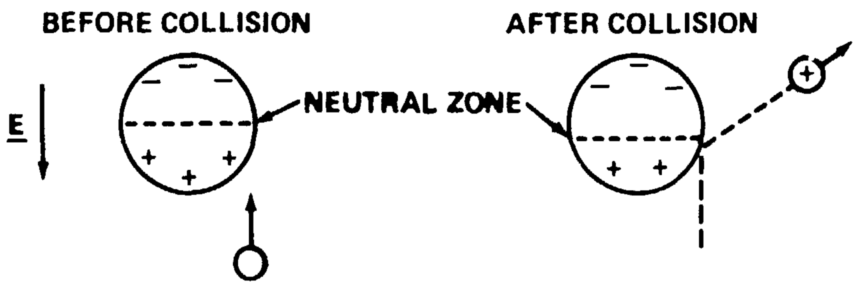

FIG. THE CHARGING OF A NEUTRAL HAIL PELLET POLARIZED IN A VERTICAL ELECTRIC FIELD BY ELASTIC COLLISION WITH A NEUTRAL CLOUD DROPLET.

b)

FIG. THE REDUCTION IN NET CHARGE ON A POLARIZED AND ELECTRIFIED HAIL PELLET AS A RESULT OF AN ELASTIC COLLISION WITH A NEUTRAL CLOUD DROPLET IN THESE APPROXIMATE SKETCHES OWING TO THE LACK OF SPACE.

c)

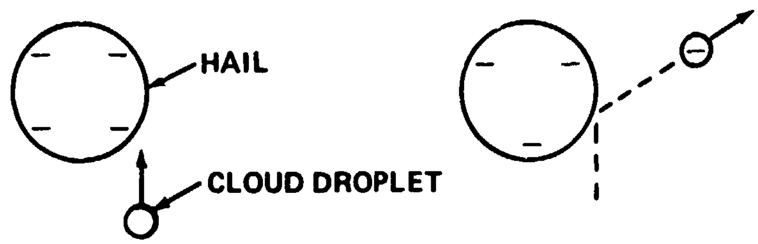

FIG. 2c. CHARGE TRANSFER BETWEEN AN ISOLATED HAIL PELLET AND A REBOUNDING CLOUD PARTICLE

FROM MOORE, C. B., AN ASSESSMENT OF THUNDERSTORM ELECTRIFICATION MECHANISMS, IN <u>ELECTRICAL PROCESSES IN ATMOSPHERES</u>, ed. BY H. DOLEZALEK AND R. REITER, pp. 333-352, STEINKOPFF, DARMSTADT, 1977.

FIGURE 5.

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bouncing collision inside the small zone becomes essentially zero at some specific charge.

Two completely different modeling experiments have been made to evaluate the response of cloud charging to the initial electrical state, one by J. D. Sartor (personal communication), and the other by H. Orville and coworkers (Orville et al., 1979). The models differed in several ways: (1) with and without ice present, (2) with internal enhancments due to cloud specified or included in the model, and (3) with 70% or variable increases in initial field. As we would expect, the numerical answers were different in detail, but both simulations gave answers in the same sense (increases in thunderstorm charging) and both found the electrical changes to be significant.

The cloud models that include electrical effects are still developing and are potentially much more complex than the models that ignore electricity. The work of the researchers that tenaciously pursue these electrical modeling efforts should be encouraged and supported.

3. Electrical Load Variation

This mechanism was touched upon earlier in the discussion of the convective charging mechanism but warrants fuller discussion in its own right because it can be operative whether or not the convective mechanism is an important aspect of the resulting thunderstorm electrification. The current flowing into the top of the thunderstorm may be viewed as an element of the cloud charging process as it is in the convective hypothesis or as a dissipation current as it is viewed by most of the other thunderstorm charging theories, which depend upon internal cloud processes to produce charging.

In the "classical global circuit" description of atmosphere electricity, the voltage source generated inside thunderstorms drives the balance of the global circuit. The potential of the "electrosphere," the highly conducting regions of the middle atmosphere, is determined by the voltage drops occurring between this layer (~ 50 km) and the tops of thunderstorms. In this variable load mechanism the effective resistance between cloud tops and the electrosphere is strongly modulated by solar activity; thus, the potential of the electrosphere and hence the entire fair-weather global electric field will be directly modulated by these solar-activity-driven conductivity changes (Markson, 1978). This mechanism is incomplete without then calling upon further coupling mechanisms to introduce this global modulation into meteorological systems.

Alternately one can invoke a more direct feedback system (as with the convective electrification approach) whereby a change in the electrical load on the cloud affects the internal electrical processes in the cloud. The evaluation of this mechanism depends upon a better understanding of cloud electrification.

For the reasons listed at the beginning of this section, an electrical coupling mechanism involving convective clouds appears to us to be more probable than the other pathways that have been considered. There are, unfortunately, too many unsolved problems in cloud electrification to assess quantitatively the mechanisms involving the electrified clouds. An obvious area that requires intensified research is cloud electrification and cloud modeling. It is also advisable to acquire data on ionosphere potential, thunderstorm activity, and solar activity in such a manner that their correlates can be evaluated on appropriate time scales.

Global Scale Processes

We do not view this category as an independent coupling mechanism because we are unable to identify a specific physical mechanism that has not already been discussed in a previous section. The global process discussed here is rather an overall systematic structure within which the various smaller scale mechanisms function.

An important contribution in recent decades to elucidating the details of the global circuit has come from the recent work of Hays and Roble (1979) who have constructed a numerical computer model of the global circuit that includes surface topography, atmospheric variations in both altitude and latitude, and anisotropic conductivities in the upper atmosphere with coupling to the earth's magnetic field lines through the inner magnetosphere. This computer model uses a rather coarse grid with respect to thunderstorm-scale processes but allows a much more sophisticated and realistic modeling of the larger-scale features of the global circuit. We are confident that this tool will provide a wealth of learning experiences as we continue to sort out the complexities of the solar-activity modulations of the parameters of atmospheric electricity. In fact, this model is probably the essential key needed to provide the global description of the electrical responses to the forcing functions. We encourage the further development of this research and the broader interaction of the atmospheric research community with this model's capabilities.

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Dr. Richard D. Cadle	Dr. Chung G. Park
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Dr. Anthony Illingworth	Dr. Bernard Vonnegut
Dr. Heinz W. Kasemir	Dr. Richard A. Wolf
Dr. John Latham	

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Report VI

Consideration of Cirrus Clouds as a Possible Sun-Weather Link

by

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I. INTRODUCTION AND GENERAL CONCLUSION

This report addresses the question of a cirrus cloud linkage between solar activity and weather on the earth. Sun-weather/climate studies cover a wide range of possible causes and effects; the field has recently been reviewed by Herman and Goldberg (1978).

1.1 Introduction

Roberts and Olson (1973a,b) proposed that cirrus cloud cover might be enhanced by extra ionization and particle nucleation following solar disturbances, giving rise to changes in pressure and circulation over large regions of the atmosphere. Evidence for solar flare influence on pressure-heights and temperature at the 200-300 mb level was put forth by Schuurmans and Oort (1969). Evidence for solar-induced increases of stratospheric intrusions into the troposphere was given by Reiter and Littfass (1977).

Beyond these and a few other intriguing suggestions of a reasonably direct solar influence on the high troposphere, little is known about the problem. The purpose of this report is to pull together the available information about the various steps in the sequence of events that has been suggested by Roberts and Olson (1973a,b). Therefore we consider how well the cirrus cloud cover is currently observed, how much ionization is created by energetic particles impinging on the atmosphere, the nucleation response to added ionization, and the effects of increased cirrus cover on the rest of the atmosphere. Figure 1.1 shows the scope of this project as conceived at the outset in April 1979.

1.2 General Conclusion

The overall conclusion of this study is that sufficient observational data do not yet exist for a good test of the suggested sun-cirrus-weather connection.

Also, the component processes are not well enough understood to permit one to make a solid theoretical estimate. The proposed chain of events seems entirely possible, and no convincing argument against it has, to our knowledge, been raised. Following Sections 2-6 that deal with components of "the cirrus connection"; Section 7 concludes with recommendations for improving our understanding of cirrus clouds and how they might be involved in sun-weather/ climate phenomena. The details of recommendations may also be found at the end of each subject-matter section.

CIRRUS CLOUD STUDY

- RADIATIVE EFFECTS OF CIRRUS CLOUDS
- CIRRUS PRECIPITATION EFFECTS
- OBSERVATION AND RECORDING OF CIRRUS CLOUD COVER
- MICROPHYSICS OF CIRRUS FORMATION
- ATMOSPHERIC IONIZATION BY ENERGETIC PARTICLES AND PHOTONS
- COMMENTS, CONCLUSIONS, AND RECOMMENDATIONS REGARDING SOLAR-TERRESTRIAL INFLUENCES

Figure 1.1. Scope of cirrus cloud study by Environmental Science Communication, 1979.

2. OBSERVATION AND RECORDING OF CIRRUS CLOUD COVER

This section discusses the routine observations of cirrus clouds that might make it possible (previously, now, or in the future) to decide whether solar events trigger the development of high clouds on some occasions. Though the time-categories are somewhat arbitrary, the class of "previous" technology includes all observations based on visual remote sensing from the ground (e.g., routine cloud cover observations) or on passive optical/sampling measurements from aircraft and balloons (haloes, aureoles, ice crystal types). By technology "now" we generally mean the global, passive sensing of clouds made possible by instruments on Nimbus, Tiros, and other satellites using visible and IR channels to distinguish between the high, middle, and low clouds. "Future" technology consists of advanced passive imaging devices and the new field of laser radar (lidar).

The question is whether these techniques have been used, or indeed are intrinsically capable of being used, either for sufficiently frequent, routine observations of cirrus clouds, or for fast-response observations following the onset of solar-induced disturbances of the earth environment. If the complement of observations is already fairly comprehensive, then answers to the sun-cirrus-weather question should be obtainable by combining existing data records and by intensifying certain measurement programs. On the other hand, if the body of available methods seems likely to let significant sun-cirrus events "through the net", then it is important to consider new measurements that would prevent that, and to intensify such existing measurement programs as would also catch sun-cirrus-weather events in the making.

First off it should be noted that no major piece of incontravertible evidence exists for a cirrus cloud linkage between solar events and the weather. Roberts and Olson (1973a,b) have suggested that such a linkage needs to be considered along with other mechanisms for coupling solar wind events into an atmospheric response. Dickinson (1975) has discussed the details of a possible solar ionization link with cirrus and stratospheric aerosols.

The point of view adopted here is that solar events may have a direct influence on cirrus cloud cover, that said influence may often be swamped by other influences such as tropical weather, that solar triggering of cirrus development probably requires a combination of physical circumstances that complicates a definitive verification, and that the means are or soon will be at hand for improved cirrus measurements that can greatly sharpen the sun-cirrus-weather inquiry.

The time resolution needed depends on the specific objectives of the observation. For global imagery of cloud cover to obtain unambiguous cirrus identification, a 3-to-6-hour sampling interval ($\sim 1/10$ day $\sim 10^4$ seconds) is probably adequate.* For local observations, such as continuous lidar or balloon soundings of ice crystals, humidity and temperature, the instrumental time resolution is very good (1-100 seconds) and the more important requirement is the duration of the measurements, which should be as long as possible in order to assess effects which may develop slowly. A sampling duration of order 1/2-2 days should be sufficient to accomplish this objective.

An acceptable cirrus measurement system should combine the global coverage (giving observations every 3 hours everywhere) with local observations in selected regions for continuous, detailed coverage bridging between satellite observations. The potential for this type of system may very well reside in the complement of cirrus measurements being made today; but, if so, such potential is not currently being realized either because of limitations of the instruments

*For comparison, the time for a solar-wind-borne disturbance to cross a characteristic dimension of the earth's bow shock—magnetospheric region ($\sim 20\ R_E$) at a velocity ~ 400 km/sec is about 300 seconds.

or the limited observing times available. In summarizing the past, present, and future technologies for observing cirrus clouds, part of our purpose is to stimulate the development and implementation of systematic cirrus observation systems.

Following subsections will discuss: (2.1) aspects of gas-to-particle conversion; (2.2) groundbased and aircraft observations of cirrus clouds; (2.3) satellite imagery of clouds, particularly cirrus; (2.4) lidar probing of cirrus clouds; (2.5) recommendations for improving the observational situation for cirrus clouds.

2.1 Gas-to-Particle Conversion: Needed Observations

The existence of water and other molecular clusters and hydrated positive and negative ions in the atmosphere affords possible mechanisms for the growth of small particles into larger ones. Regarding cirrus clouds it is attractive to suppose that a small incremental ionization, arising from solar phenomena, may enhance the formation of fine aerosols and ice crystals. Such a process would, overall, be very complex, to judge by what is known about various processes and states of aggregation of water. Demonstration of a few instances of cirrus production by incremental ionization in the upper troposphere would provide a valuable impetus to this field of work.

An important entity in the chain of neutral and ionized water clusters that may lead to stable ice crystals is the water dimer, $(H_2O)_2$. Bolander et al et al (1969) deduced a dissociative equilibrium constant for the water dimer from prior work by Keyes (1947). Dyke et al (1977) have measured properties of $(H_2O)_2$ using electric resonance spectroscopy on a molecular beam. A thermodynamic theory of nucleation specific to water clusters, $(H_2O)_n$, has been given by Daee et al (1972). Recently a kinetic theory treatment has been advanced by Pouring (1975) on the basis of Buckle's (1969) theory for cluster formation

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in a condensing, binary mixture of monoatomic gases. Castleman and Tang (1972) have studied ion-induced nucleation in water vapor, and their article contains many other references in this field. Considerable attention has been given to the possible roles of $(H_2O)_2$ in atmospheric phenomena, as discussed by Burroughs (1979).

Unfortunately very little information is available on the state of water clustering or the ion composition at cirrus altitudes (~9-12 km). Mohnen and Kiang (1978) estimate that the average ion concentration at 12 km is in the range 4500-7000 cm^{-3}; also see Section 6 of this report. They also conclude that at higher altitudes in the "Junge layer" (~20 km), the ion concentration has little impact on gas-to-particle conversion processes in the unperturbed stratosphere.

An important facet of solar-induced cirrus formation would surely be the ion composition and lifetime. Ion mass spectroscopy in the stratosphere above 35 km has been achieved by Arnold et al (1977, 1978). Ferguson (1978) has interpreted some of the observed positive ion mass peaks as protonated sodium hydroxide ions, e.g., $NaOH_2^+ \cdot (H_2O)_n$, and Kebarle (1977) has also discussed analogous ions involving KOH. Water cluster ions (e.g., $H_3O^+ \cdot (H_2O)_2$) have also been observed by Arnold et al, and by Arjis et al above 35 km. Negative ions such as $NO_3^- \cdot (HNO_3)_2$ and $NO_3^- \cdot (HCl) \cdot (HNO_3)$ have been reported by Arnold and Henschen (1978) in the stratosphere. Measurements of ion composition have yet to be made at cirrus altitudes, and one suspects that the ion population will be dominated by structures at least as complicated as the ones above. Hence it is currently not feasible to predict how the neutral and ionized molecular clusters will respond to incremental ionization as part of any overall gas-to-particle conversion posited for cirrus clouds. Improved knowledge of the ion and cluster composition is needed at these lower altitudes.

For the present, observations of instances of cirrus cloud formation, including measurements of humidity, temperature, ion concentration and aerosol particles, would constitute the most valuable and direct evidence for this type of link in the sun-weather chain.

Figure 2.1 shows possible routes for solar-induced cirrus formation. The thin lines indicate processes which are believed to be too slow to be of consequence. The medium and heavy lines indicate increasingly probable routes of cirrus formation. The most probable route for cirrus formation may be the enhanced gas-to-particle conversion of hygroscopic compounds, whose subsequent ionization could increase the probability of droplet formation, to be immediately followed by freezing.

2.2 Observations of Cirrus Clouds from the Ground and from Aircraft

This subsection describes selected studies made in the pre-satellite era, partly to point out the difficulty of getting thin cirrus data from that period, and partly to suggest a few data records that might be worth looking into for correlations between solar activity and cirrus cloud cover.

2.2.1 Cloud observations are made every three hours at surface weather observation stations throughout the world, and, at commercial airports, hourly cloudiness by height, amount of cloud and cloud type are reported. Of the several weather variables systematically recorded, only the clouds and the weather type require absolutely no supporting apparatus or instrumentation. Yet, while climatological data have been compiled into atlases for wind speed and direction, temperature, pressure, relative humidity and precipitation at the earth's surface, and height contours and the above quantities at several reference pressure levels in the troposphere and stratosphere, global atlases of cloud types and amounts remain today in their infancy.

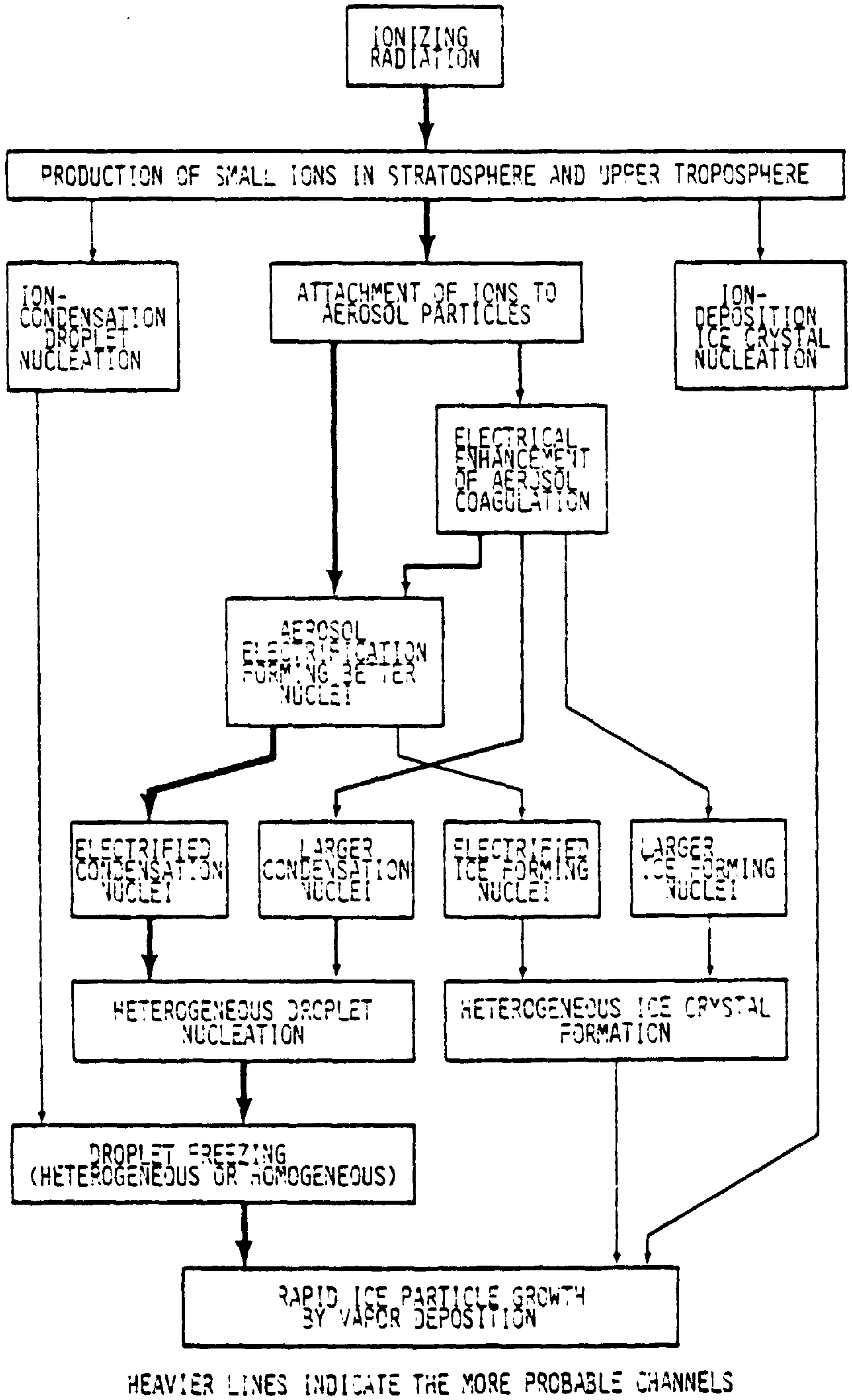

Figure 2.1. Possible solar-modulated cirrus formation mechanisms

Weather observations in the U.S. are archived at the National Climatic Center in Asheville, N.C. The data are generally believed to be of reasonable quality and completeness for observations since 1941. Earlier observational data are available for a more limited number of stations dating back into the 19th century. Global observational data are archived by the World Meteorological Organization.

The limitations of groundbased cloud cover data are widely recognized, notwithstanding the meteorological value of these long records that are useful for many purposes. Cole (1960) has noted some of the problems in groundbased data, and Fye (1978) has commented:

> "Some standing limitations of conventional data are...
>
> (a) Inaccurate total cloud estimates, especially when clouds are low and parallax error is the greatest. Cloud amounts are usually overestimated.
>
> (b) Inaccurate nighttime observations with a tendency to underestimate cloud amounts, particularly high clouds.
>
> (c) Variations in the reporting procedures and quality of observing procedures between countries.
>
> (d) Inaccuracy of cloud heights when estimated by observers and pilots and as determined by sounding instrumentation.
>
> (e) Instrumentation inaccuracies and transmission garbling."

Groundbased observation of cirrus clouds is hindered by several difficulties. (1) Groundbased observers experiencing fog or lower cloud cover may not observe cirrus cover, or may only see some cirrus cover through "holes" between the lower clouds. (2) Cirrus clouds, unlike stratus or cumulus clouds, do not have well-defined boundaries, and their areal coverage is difficult to assess. (3) Thin cirrus clouds frequently lack striations or other features which may aid thin detection by a groundbased observer.

Recent studies by the U.S. Air Force have attempted to quantify visible ranges and cloud-free lines of sight at various altitudes, latitudes and times of year (Bertoni, 1977a,b). Other studies have focused on cirrus ice particle distributions (Varley, 1978; Varley and Brooks, 1978).

Haurwitz (1972) reviewed existing cloud climatologies, because the data are of great importance in determining infrared radiative fluxes in the global system. Part of his summary of earlier works is shown in Table 2.1. Prior to the advent of satellite technology, the uncertainties associated with construction of cloud atlases yielded these laborious results having little value in analysis of radiative fluxes. Haurwitz also concluded that despite some significant advances to 1972 in the systemmatic, global coverage afforded by satellites, no radiatively useful direct measurements of cloud cover, differentiated by cloud type, were yet available.

2.2.2 A valuable compendium of information on cirrus clouds was prepared by R. G. Stone (1957) for the Air Weather Service, principally to disseminate information on cirrus forecasting techniques, and to stimulate further work on cirrus climatology and forecasting. The Air Force was increasingly concerned about reliable visibility in flight operations above 25,000 feet altitude. Stone's report repeatedly contrasts the quantity and nature of pilot reports vs. cirrus observations obtained from ground level. With reference to the problem of seeing through low and middle clouds to estimate cirrus cover, Stone remarks on p. 122:

> "The bias of having to use for data only days without obstructions preventing observation of cirrus is one that seriously limits the validity of studies of this type using surface cloud observations. Therefore aircraft cloud observations should be sought if at all possible."

Nonetheless this compendium covers a number of groundbased cirrus climatology projects, starting with the International Cloud Year (1896-7), as well as aircraft observational programs up to Project Cloud Trail in 1954-5.

Table 2.1. Total cloud cover summary, abstracted from Haurwitz (1972).

Author or Title	Area Covered	Form of Data	Remarks
C. E. P. Brooks (1927)	globe	ann. climat. lat. means in % cloud cover given sep. for land, ocean, and mean	tables
N. Shaw (1936)	globe	ann. and mo. climat. means in 1/10 cloud cover	maps prepared by Brooks 1921
W. F. McDonald (1938)	oceans	seasonal climat. means in 1/10 cloud cover	maps
B. Haurwitz and J. Austin (1944)	globe	Jan. and July climat. means in 1/10 cloud cover	maps
H. Landsberg (1945)	globe	Jan., Mar., May, July, Sept., Nov. climat. means in 1/10 cloud cover	maps in Handbook of Meteorology
R. N. Seide (1954)	N. Hemi.	spring and fall climat. lat. means in % cloud cover	graphs
K. Telegadas and J. London (1954)	N. Hemi.	summer and winter climat. means in 1/10 cloud cover	maps
W. D. Sellers (1958)	6 Ariz. cities	mo. means (1948-58) for var. hrs. of the day in 1/10 cloud cover and in freq. distr. for each 1/10 cloud cover	tables
F. E. Elliott (1960)	U. S. S. R.	mo. climat. means in 1/10 cloud cover	maps
M. Schloss (1962)	U. S. S. R.	summer and winter climat. means in % cloud cover	maps
E. de Bary and F. Moller (1963)	Germany	summer and winter morning and afternoon means (1936-40) in % cloud cover for diff. layers of the atm.	tables and graphs

Table 2.1. (Continued)

P. F. Clapp (1964)	$60^{o}N-60^{o}S$ around the globe	daytime means for Mar. - May 62, June-Aug. 62, Sept. - Nov. 62, and Dec. 62 - Feb. 63 in % cloud cover separately for sfc. and satellite obs.	maps; sfc. obs. from Landsberg
L. J. Allison and G. Warnecke (1967)	$85^{o}W-160^{o}W$ $25^{o}N-20^{o}S$	mo. daytime means for Jan. 1964 in 1/10 cloud cover-satellite obs.	maps
P. F. Clapp (1968)	N. Hemi.	late fall daytime means for each of the years 1962, 63, and 64 in % cloud cover	maps
A. H. Glaser et. al. (1968)	$100^{o}E-130^{o}W$ $37^{o}N-37^{o}S$	means for 15 May-31 Aug. 66 and 9 Oct. 66-28 Feb. 67 in % cloud cover-satellite obs.	maps mainly along coastal areas
F. A. Godshall (1968)	$30^{o}N-30^{o}S$ $90^{o}W-120^{o}E$	mo. means (1961-1965) for Jan. and Aug. in 1/10 cloud cover-satellite obs.	maps
E. Raschke (1968)	N. Hemi.	means for 16-31 May 66, 1-15 June 66, 16-30 June 66, 1-15 July 66, 16-31 July 66 in 1/10 cloud cover.	maps from E. T. A. C.
J. Sadler (1968)	$30^{o}N-30^{o}S$ around the globe	daily means for each day from Feb. 65 to Jan. 68 in 1/8 cloud cover, mo. means for each mo. from Feb. 65 to Jan. 68 in 1/8 cloud cover-satellite obs.	daily means on tape, mo. means on maps
P. Sherr et al. (1968)	globe and selected stations	mo. (for globe) and summer and winter (for stations) climat. means for var. hrs. of the day in freq. distr. of fractions of cloud cover-satellite and sfc. obs.	globe divided into to 29 geog. areas each having homogeneous cloud cover; globe-tables; stations-graphs
L. J. Allison et al. (1969)	$70^{o}N-10^{o}N$ around the globe	mo. means for each mo. from June 63 to Dec. 64 in 1/10 cloud cover	maps
van Loon (1971)	globe	Jan. and July climat. means in % cloud cover	tables; no inf. as to whether satellite or sfc. obs. or both used

These earlier projects are mentioned here because some of the data records might contain enough information for a fragmentary assessment of the sun-cirrus-weather connection, particularly if some of the intensively covered periods coincide with marked variations in solar activity. Project Cloud Trail, for example, was an extensive operation involving dual aircraft flights by 36 different fighter-interceptor squadrons during 1954-5, over 23 upper-air sounding stations in the U.S. The purpose was to observe natural cirrus occurrence and contrail* cloud formation at and above 25,000 feet. Apart from the statistical climatology summarized in Appendix A of Stone (1957), one suspects that the detailed Cloud Trail data records may contain instances in which upper atmospheric cloudiness may be compared to strong solar disturbances.

Another interesting study summarized in Stone's reports (p. 122-130) was H. Appleman's application of various forecasting parameters to cirrus cloudiness over selected North American Stations in the summers of 1951, 1952, and 1953. ("An objective method of forecasting of cirrostratus clouds"). Though some success was obtained, Appleman and Stone concluded that the available upper atmospheric data and interpretation left much to be desired in forecasting cirrus cover. In any case Appleman's records, particularly for Fairbanks, Alaska, might prove interesting to correlate with solar activity during the summers of 1951-3.

More generally Stone (1957) provides a detailed summary of the then-existing and proposed new forecasting methods, most of which were based on upper air information as opposed to surface pressure data. Fifteen different meteorological indicators are listed as inputs to these forecasting methods including, obviously, the humidity and temperature at cirrus altitudes. The scope of this data input will be of interest to those readers considering new meteorological studies of cirrus cloud formation and development.

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*Also see Downie and Silverman (1960).

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Also it is reasonable to remind ourselves, in seeking for a possible sun-cirrus-weather linkage, that the atmosphere has to be prepared for cirrus cloudiness, at least with respect to temperature and relative humidity, before it can respond to an ionization trigger or particle seeding. This consideration must influence both the interpretation of old data and the planning of modern experiments, no matter what instruments are used for cirrus detection.

2.2.3 The Arctic regions, particularly near the Gulf of Alaska, have drawn much attention as possible sites at which solar activity might be particularly influential on the earth's atmosphere. Not all the diffuse optical phenomena seen there should be regarded as prime candidates for a sun-cirrus-weather connection.

An example of the ground-observational problem for diffuse cloudiness is afforded by the well-known "Arctic haze" often seen over the Arctic Ocean and immediately adjacent land areas. Mitchell (1958) summarized the findings from many years of Air Force flights under the Ptarmigan project, as part of his review of meteorological phenomena influencing visual range in the polar regions.

From sea level, and in the absence of height measurements (such as could be obtained from lidar), Arctic haze when detectable at all is perceived as a diffuse, high altitude layer that does not affect the visibility of distant ground objects but adds a reddish tint to the otherwise clear daylight sky color, and reduces the slant range visibility of stars at night.

The Ptarmigan measurements showed that this haze is tropospheric and often occurs over very large patches of order 1000 km in extent. Within the haze, the horizontal visual range can be as low as 3 km, and the temperature is typically -30°C to -35°C. The haze bands are typically 1-3 km thick and may occur singly or in multiple layers. Rahn et al. (1977) suggested that the Arctic haze depends on dust transported from the Gobi and Takla Makan deserts in eastern Asia.

It is clear that to catalogue such diffuse cloudiness or reduced sky-transparency as an indication of Arctic <u>cirrus</u> cloud cover, and in turn to attempt to relate these to solar activity, would mix together observations not necessarily connected* with cirrus clouds or with solar activity. The inadvertent inclusion of Arctic haze or other mid-tropospheric data in correlation studies between cirrus and solar events could degrade any <u>bona fide</u> sun-cirrus-weather evidence to the point of being inconclusive.

In order to make sure of the nature of the atmospheric aerosols that may be candidates for a correlation with solar activity, there is a great need for routine, remote measurements of the altitude dependence of aerosol concentration, size distribution, and the physical properties of the particles. In addition to the satellite temperature profiles and limb scanning instruments, two relatively recent developments are passive "solar aureole" measurements and the laser radar (lidar) technique (see subsections 2.2.5 and 2.4).

<u>2.2.4</u> An interesting application of the 3-hourly cloud cover data obtainable from the U.S. network of weather stations was reported by Machta (1971a,b) who investigated the trends in cirrus cloud cover between 1940 and 1970 for a number of locations where low and middle cloud cover was not so heavy as to preclude high cloud observations from the ground. The extreme case was Denver, where high cloudiness almost doubled from the mid-1950s to the mid-1960s. Figure 2.2 from Machta (1971b) shows the Denver increase along with data from two other western stations for the period 1949-1969. The annual averages of high cloud cover for all eight stations (not shown here) lie in the range 13/100-20/100.

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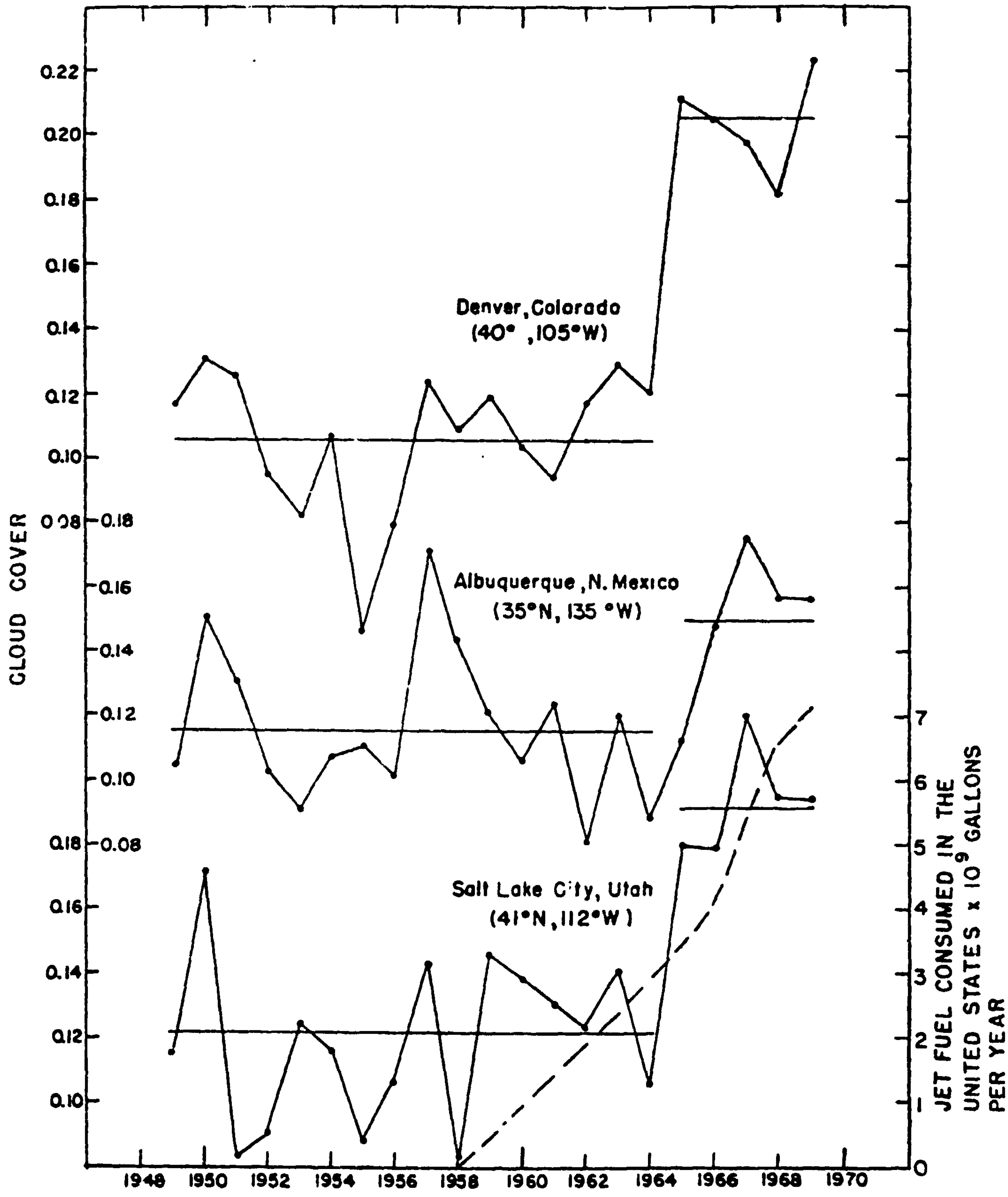
*Arctic haze might have some connection with these other phenomena, but that seems unlikely at present. A cloud climatology for the Arctic has been given by Vowinckel (1962) including seasonal averages for four types of cloud (cirrus is one of the types) based on records from 200 ground stations.



<u>Figure 2.2.</u> History of annually-averaged high cloud cover (with no low or middle cloud simultaneously) at selected U.S. locations, from Machta (1971b). The dashed curve shows the growth in jet fuel consumption by domestic commercial jet aircraft.

Machta's studies were undertaken to see whether there had been an increase of high cloudiness attributable to the development of high altitude, civilian aviation on a large scale. Though the individual stations (and various averages over the stations) showed definite increases of cirrus cloud cover during a time which might plausibly be equated with the rapid growth period of jet aviation, Machta pointed out features of the data that suggest a natural variability of high cloudiness. Also he called attention to the improvement of information on high clouds made possible by the very flight operations in question, whereby weather observers could obtain from pilots cirrus cloud data largely unavailable before 1958. On the other side of the question, Machta cited the commonplace observation that persistent decks of high cloud cover can be triggered by contrails, leading sometimes to a definite overcast of major jet airlanes. Further, Machta (1971b) notes that:

> "Observations of cloud amount and type, especially for high clouds, are uncertain. One will expect to find considerable variability due to random errors of observation."

and

> "...the incidence of natural cirrus cloudiness is much more common than might be evident to a groundbased observer. Pilots do detect high clouds when they are invisible to a ground observer."

It is interesting to note that the information available for Machta's studies seems to suffer from some of the same problems that one encounters in assessing the data base suitable for investigating sun-cirrus-weather connections, namely (1) that the traditional high cloud observations contain a high degree of scatter and (2) that the systematic effects sought may, partly for the first reason, be buried in fluctuations due to other phenomena.

2.2.5 Observations of detailed aspects of skylight (polarization, coloring, angle away from the sun) have attracted many optical meteorologists to work on methods for obtaining the altitude dependence of particle size distributions. This literature is too extensive to cover thoroughly here, and we will mention principally Hall's work in the late 1960s that was directed clearly to the cirrus problem. From an applications standpoint this work offers the prospect of a cirrus detection system that operates well from the ground under reasonably clear conditions. Hall (1967, 1968a,b) studied the excess clear-sky radiance in the infrared (8-13 μm) and concluded that cirrus clouds were the cause. Zenith radiances as small as 1/10 of that for observable cirrus clouds were detected, and an infrared solar aureole and skylight polarization were measured in the 8-13 μm region. Such thin cirrus have visible optical depths $\tau < 0.10$ and are hard for a conventional ground observer to detect via solar extinction alone.

Hall (1969) also demonstrated photographic methods for the visible and near IR that enabled the spatial extent and morphology of cirrus clouds to be observed better than with standard photography. Sensitivity limits on Hall's photographic method, as regards seeing very thin cirrus, are not given in the published article.

The use of sky-imaging techniques should be borne in mind in planning cirrus observations having a groundbased part, because they can quickly give some indication and location of cirrus cloudiness in a low cost manner. Obtaining aerosol size distributions via angular (or "aureole") scattering patterns has been discussed by Hodkinson (1966), Deirmendjian (1970, Green et al (1971), Post (1976), Twitty (1975), Twitty et al (1976), Volz (1978), Box and Deepak (1978), Deepak et al (1978), and Deepak (1977). Liou (1972) has treated light scattering by ice clouds. Lerfald (1977) discusses aureole photometric instruments. An important aspect of the interpretation of angle-dependent scattering in the atmosphere is polarization (e.g., see Sekera (1956), Coulson et al (1971), and Coulson (1978). Though it is an obvious drawback of all the passive methods that one must unfold distributions along the line of sight, impressive analyses of aerosol distributions can be made by these means. Whenever practical, they should be employed in conjunction with thermal radiometry and lidar observations.

2.3 Satellite Imagery of Clouds, Principally Cirrus

This subsection is meant to serve as a guide to sources of cloud cover information, particularly with reference to cirrus clouds, that has become available on a global basis *via* visible and infrared imagery. A few studies are cited that make use of this relatively new capability for global atmospheric measurements. For cirrus clouds, particularly thin cirrus having IR emissivities of order 0.1 or less, the value of the available data base is limited compared to the meteorological insights afforded by the interpretation of low- and middle-cloud cover. Improved instruments are very much needed for identifying thin cirrus, specifying their amount, height and temperature, and following their development on time scales of a few hours. A much improved cirrus cloud climatology is believed to be essential for climate modeling, and the detection of thin cirrus is important in assessing the likelihood of a sun-cirrus-weather connection.

2.3.1 A good starting point for the potential user of satellite-derived visible-IR cloud imagery is the W.M.O. document by Anderson et al (1973). Many examples of cloud pictures are shown, along with interpretations in terms of weather analysis (fronts, cyclones, etc.) and meteorological parameters (wind speed, wind direction, precipitation, etc.). Cirrus images and associated phenomena are discussed at length; their evident complexity suggests caution in seeking correlations between solar activity and cirrus cloud cover, either locally or on some globally averaged basis.

2.3.2 One form of cirrus activity that doubtless has little to do with solar distrubances is the cirrus canopy that develops over major storms such as hurricanes. Merritt and Bowley (1968) describe the interpretation of imagery from TIROS, Nimbus and ESSA satellites, showing the evolution of cirrus canopies over selected Atlantic Hurricanes in 1964-6. Much of the earth's cirrus cloud cover arises from such atmospheric motions that carry water vapor into the cold upper troposphere where saturation can then occur, motions originating in dynamical processes that are not associated with solar disturbances in any known way. This presents the scientist searching for sun-weather connections with a large source of noise from other effects.

2.3.3 Early studies of clouds from satellite platforms concluded that satellite observations yield smaller percentages of cloud cover than do surface observations (Glaser *et al* (1968), Barnes (1966), Clapp (1964). The reasons for this are believed to be:

- About half of the sky dome observed from the surface is less than 30° above the horizon, creating the possibility of observer bias in cloud amount when a substantial portion of the sky is blocked from the observer's view by the *sides* of clouds.
- Satellites have limited resolving power. Earlier satellites may have missed small amounts of cloud cover because of lack of resolution.
- Optically thin clouds (cirrus clouds) may scatter light into groundbased viewers' eyes, but may not be sufficiently dense to be detected by either visible or infrared sensors aboard satellites.

Fowler *et al* (1975) found that Landsat-1 matched the groundbased observations fairly well, for cloud cover in the range 3/10-7/10. The data also show that the satellite saw very little average cloud cover (<5%) until the surface observations attained values up to 25 percent. Though studies of this type are useful for certain meteorological problems, they are not sensitive enough for the thin cirrus problem, and therefore would seem to offer little help in searching for connections between ionization events originating at the sun and the onset of small particle formation in the earth's atmosphere.

2.3.4 Becker (1979) performed a comprehensive analysis of cloudiness by cloud type, as a function of latitude and longitude for January 1974 and July 1973. NOAA-2 satellite visible and infrared pictures were scanned daily in $10^{\circ} \times 10^{\circ}$ grids to determine amounts of various cloud types. Stratus clouds, for example, are bright (visible) and warm (infrared), while cirrus clouds are dark (visible) but cold (infrared). Patterns were also relied upon to discriminate between various cloud types. Figure 2.3 shows Becker's cirrus cloud cover summary for July 1973. His main concern in this work was not cloudiness per se, but rather estimation of the earth's radiation budget for the periods studied. In planning future studies of cirrus clouds, experimenters might do well to take account of procedures such as Becker's to establish regions in which cirrus are common or rare, depending on the season, and particularly where other clouds do not confuse or prevent good observations. Plates I and II (following Figure 2.3) show data used by Becker. In Plate I, the high clouds appear white in the IR image, and do not appear in the visible (Plate II).

2.3.5 A major compilation of worldwide meteorological cloud information is embodied in the 3D NEPH system that has operated since 1970 at the Air Force Global Weather Center (Fye, 1978). Naturally one would like to know how useful this data base is or will be for cirrus cloud studies. The answer is mixed, and depends on how thin the cirrus clouds are.

In 3D NEPH, satellite imagery is input both from the Defense Meteorological Satellite Program (DMSP) and from the NOAA satellites, basically in the form of

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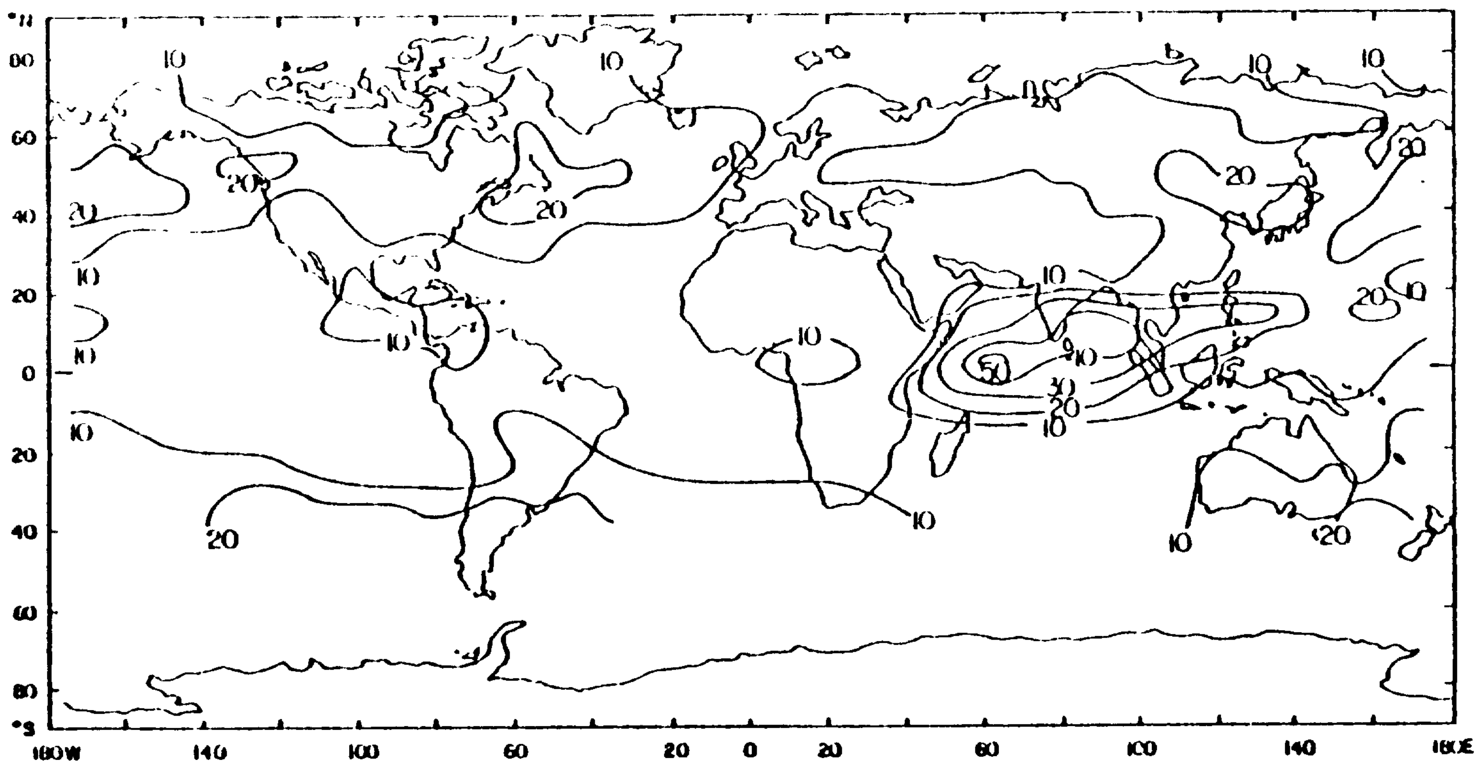

Figure 2.3. Cirrus distribution for July 1973 in percent of sky covered (Becker, 1979). Visible and near infrared data interpreted from NOAA-2 satellite.

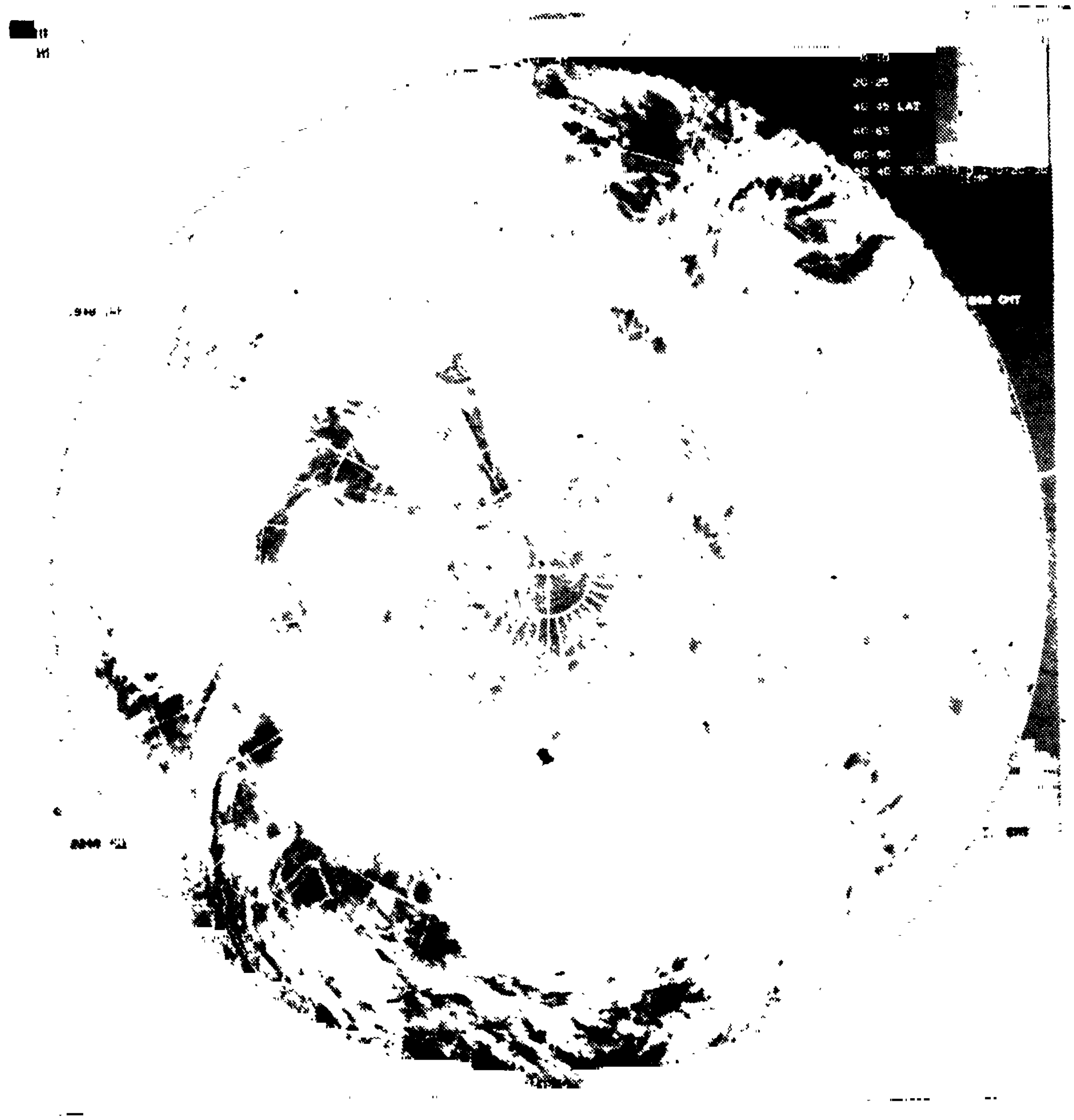

Plate I. NOAA-2 infrared imagery over South Pole, January 20, 1974. Australia at lower left.

Plate 11. NOAA-[illegible] visible imagery over South Pole, January 20, 1974. Australia at lower left.

grey-scale pixels (63 shades) having dimensions roughly 5 km x 5 km at the earth's surface. The output element of 3D NEPH is a suitable average of 64 of these pixels over ~ 40 km x 40 km squares to conform to a standard grid spacing. This entire output (Satellite Global Data Base) can be updated every 6 to 12 hours in the case of infrared data (and 18 to 24 hours for visible data) depending on the mix of local satellite crossing times and data availability.

3D NEPH has been continuously archived on magnetic tape since January 1971 by the USAF Environmental Technical Applications Center (USAFETAC), Scott AFB, Illinois. Magnetic tapes are physically stored at USAFETAC/OL-A, Asheville, North Carolina. Atmospheric altitude is divided into 15 layers in the 3D NEPH catalogue, the top two of which are approximately 7.9 - 10.7 km and 10.7 - 16.8 km.

In essence, 3D NEPH is a unique computer data set for obtaining rapid, comprehensive cloud analyses over the entire globe. The main purpose of 3D NEPH is to digest and reduce large quantities of meteorological cloud information, on a gridded and well-formatted data base suitable for multiple users. For scientists interested in <u>cirrus</u> clouds, particularly thin cirrus, the following caveat is important and has been cited (Fye, 1978) in an appendix on limitations of the present cloud analysis model:

> "Inability to detect thin cirrus clouds by the visual or infrared processors: This is an inherent limitation of the raw satellite data. When sufficient opacity renders thin cirrus detectable by the infrared processor, the height attached to the cloud top is in error (too low) to a degree which depends on the opacity of the cirrus. In extreme cases thin cirrus may be analyzed as stratus. This problem heavily depends on how the infrared data are tuned at the moment and on the availability of coincident visual data."

Therefore the use of the 3D NEPH system in a search for solar effects on cirrus requires one to be aware that thin cirrus may be missed, and likewise the opportunity to look for faint atmospheric effects associated with the more frequent, low amplitude perturbations of the atmosphere by the sun.

Other Air Force work (Conover and Bunting, 1977), based partly on 3D NEPH and partly on other satellite data bases, indicates that the altitudes and ice content of cirrus clouds may be usefully estimated from multispectral infrared radiances measured by the NOAA Vertical Temperature Profile Radiometer (Bunting, 1975). The applications of this work to the erosion of re-entry vehicles appears to have given rise to a shift of emphasis toward the Scanning Radiometer data, so as to bring out all large-particle (≳50 μm) clouds as opposed to cirrus alone. Reynolds and Vonder Haar (1977) have also discussed the merits of VTPR data.

Time has not permitted us to completely check out the cirrus cloud climatology capabilities of the present Air Force data systems. This is a promising area because of the increasing complexity of the satellite radiometers and the development of computer systems for handling the large amounts of data involved. The satellites used in the latter work were the polar-orbiting NOAA satellites ITOS-2,3,4 and 5 and the geosynchronous satellites GOES-1 and SMS-2. Currently we have only a rough indication of the limitations of this cirrus-detection method, as regards the thin clouds one needs to be able to detect in conjunction with solar-induced ionization in the atmosphere.

2.3.6 The use of satellite radiance data in the visible and infrared for identifying cloud types has been explored in detail by Vonder Haar and colleagues at Colorado State University, with particular attention to the cirrus problem. A bispectral method for determining cloud heights and amounts is described by Reynolds and Vonder Haar (1977) and is applicable to the data from all satellites such as SMS, GOES, DMSP and TIROS-N having simultaneous visible and IR imaging capabilities. Their analysis of NOAA-2 imagery in 1974-5 shows cirrus infrared emissivities as low as $\varepsilon = 0.15$. Subsequently Reynolds et al (1978) have described a technique of spectral differencing of image pairs that enables one quickly to distinguish various cloud types seen in satellite visible-IR imagery. Water vapor in the upper troposphere can influence all of these visible-IR methods, and Vonder Haar and Colley (1979) have recently studied how METEOSAT data can be inverted _via_ a tri-spectral approach to identify the water vapor contributions. Advances in this field are also being made by means of aircraft determinations of the IR radiation field over cirrus clouds (Szejwach. 1978) and by comparison of satellite radiance data with _in situ_ measurements of cloud properties (Bunting, 1978).

The consensus we have gleaned from many discussions is that the visible IR contrast methods can be pushed as low as about $\varepsilon = 0.1$ in the infrared; i.e., that cases in which $\varepsilon = 0.2$ are usually readily handled, while a cirrus IR emissivity of $\varepsilon = 0.05$ is a physical situation that one would rarely observe with any certainty by the currently available, passive methods. While a blanket statement of the limits of cirrus detectability is hard to come by, this provides an estimate of the degree of cirrus cloudiness that can at present escape detection by the most comprehensive, global methods at our disposal. The success of the existing satellite radiometers is remarkable in this respect, in view of the very few optical channels employed. On the other hand, the available data from lidar (laser radar) experiments suggest that there may be a _preponderance_ of thin cirrus that otherwise escapes observation, and is therefore unavailable for comparison with solar-induced ionization events in the atmosphere.

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2.4 Cirrus Observations by Means of Lidar

This section discusses the work that has been done in lidar observations of cirrus clouds, and mentions some current work in progress and proposed instruments for global cirrus surveys in future. The great interest in lidar for this purpose stems from (i) its range-resolving capability that specifies the altitude of optically backscattering layers, and (ii) the strong scattering signature of cirrus layers even when they are not visible to the naked eye or otherwise particularly sensible to passive instruments. A case is made here that lidar techniques may afford the best way of detecting and describing cirrus cloud layers, particularly when used in conjunction with passive radiometric techniques.

2.4.1 In contrast to the long records of passive observations of cirrus clouds which appear to yield limited information about the life histories of these clouds, the active studies by means of lidar have taken place mainly during the past 10 years and have concentrated on specific cloud areas and the attendant meteorology. A recent example of the gradually lengthening periods of lidar observations of cirrus is the work of Platt and his colleagues at the CSIRO in Aspendale, Australia (Platt, 1979a; Platt and Dilley, 1979). They stress the importance of simultaneous radiometric measurements of cirrus emissivity in the infrared. This enables one to evaluate the backscatter-to-extinction ratio and the albedo in the visible, as functions of altitude and temperature. A great deal about cloud particle properties, and the variation of particle types within any given cloud, can be learned from simultaneous active and passive measurements of this type. A detailed discussion of these considerations has been given by Platt (1973).

A striking feature of the results of this work is the predominance of optically thin cirrus. Figure 2.4 shows Platt's (1973) results for the occurrence

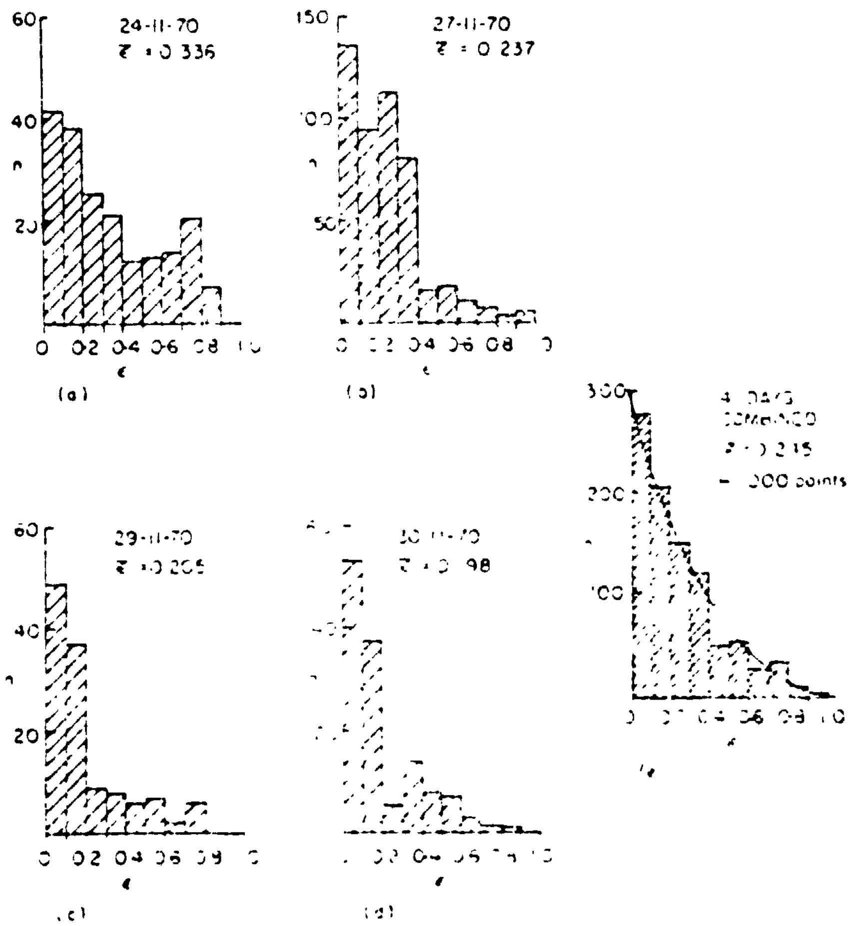


Figure 2.4. Occurrence-frequency histograms for cirrus IR emissivity, for four different cirrus systems and for the sum of all observations (Platt, 1973).

frequency of various values of cirrus IR emissivity during 4 days in 1970. In the recent series of measurements, March - August 1978, 53 percent of occasions showed a middle IR emissivity less than 0.3. That the histograms are still rising as ε decreases toward 0.1 suggests that further work may demonstrate a preponderance of even thinner cirrus. Certainly the conventional observability of these clouds from the ground or satellites diminishes as they become thinner, yet the lidar shows an increasing occurrence frequency in the instances studied. Inasmuch as the solar influence on the triggering and growth of cirrus cloudiness is perhaps weak and hard to detect, lidar seems in principle to be one of the more suitable, sensitive detectors with which to probe the possibility of a sun-cirrus connection.

An obvious question is the feasibility of lidar observations of cirrus over a proper and significant fraction of the globe that the solar influence can be assessed over time and more than just locally. A summary of lidar cloud studies, particularly those addressed to cirrus problems is given below. Indications of things to come can be seen with a few examples of recent and proposed work.

Two European groups now studying lidar backscatter from high clouds and aerosols are in Bergen, Norway (Singstad, 1979) and in Garmisch in Bavaria (Jäger et al, 1977; Reiter et al, 1979). Examples of their work are shown here in Figures 2.5 and 2.6. The depolarization signature of a cirrus layer is shown very clearly in Figure 2.5, as well as indications of aerosols at higher altitudes, the main concern of their most recent work (Reiter et al, 1979). Figure 2.6 shows the late evening descent of winter cirrus in western Norway (Singstad, 1979). A similar presentation for early summer cirrus in Australia is shown in Figure 2.7 (Platt, 1973).

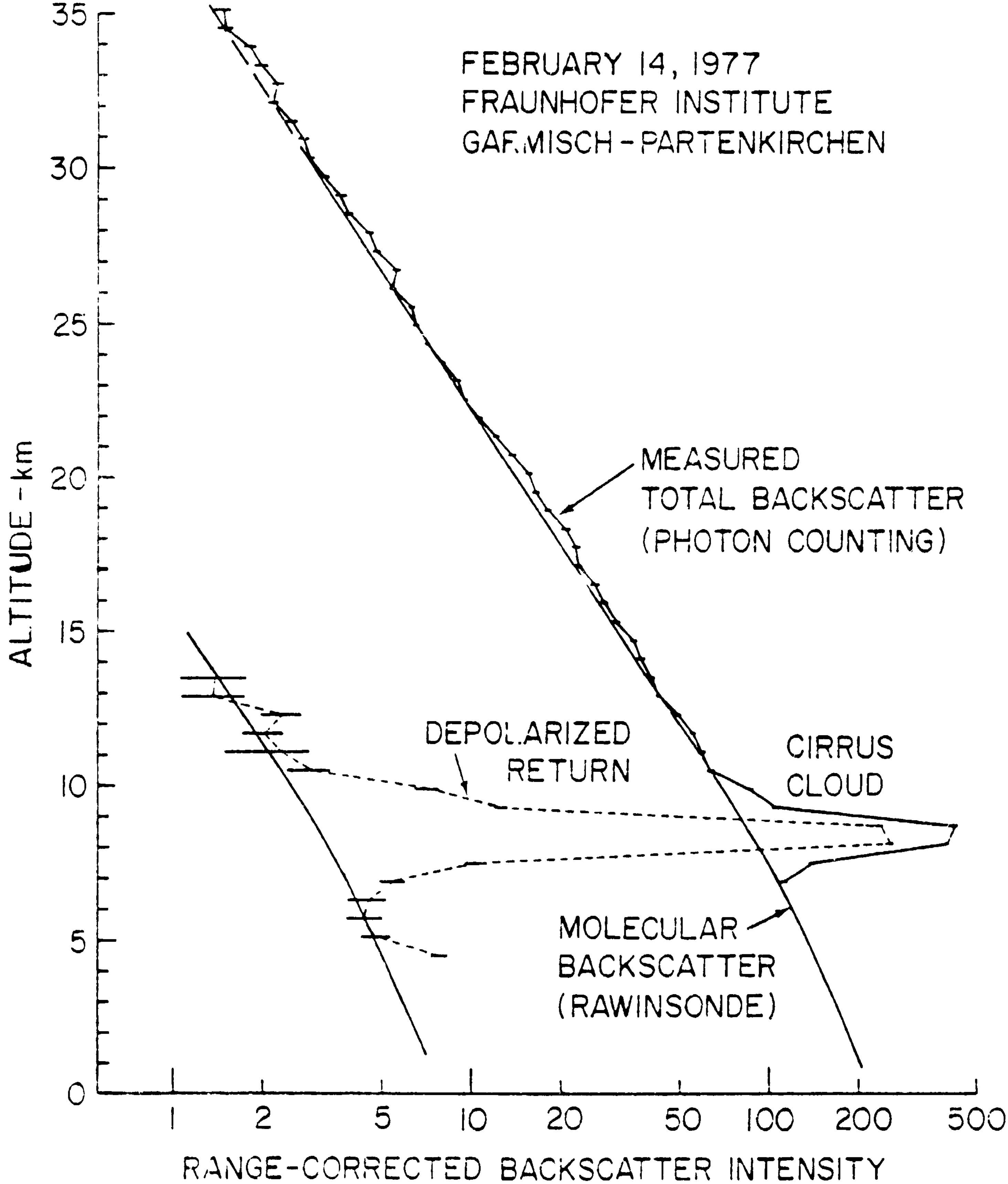
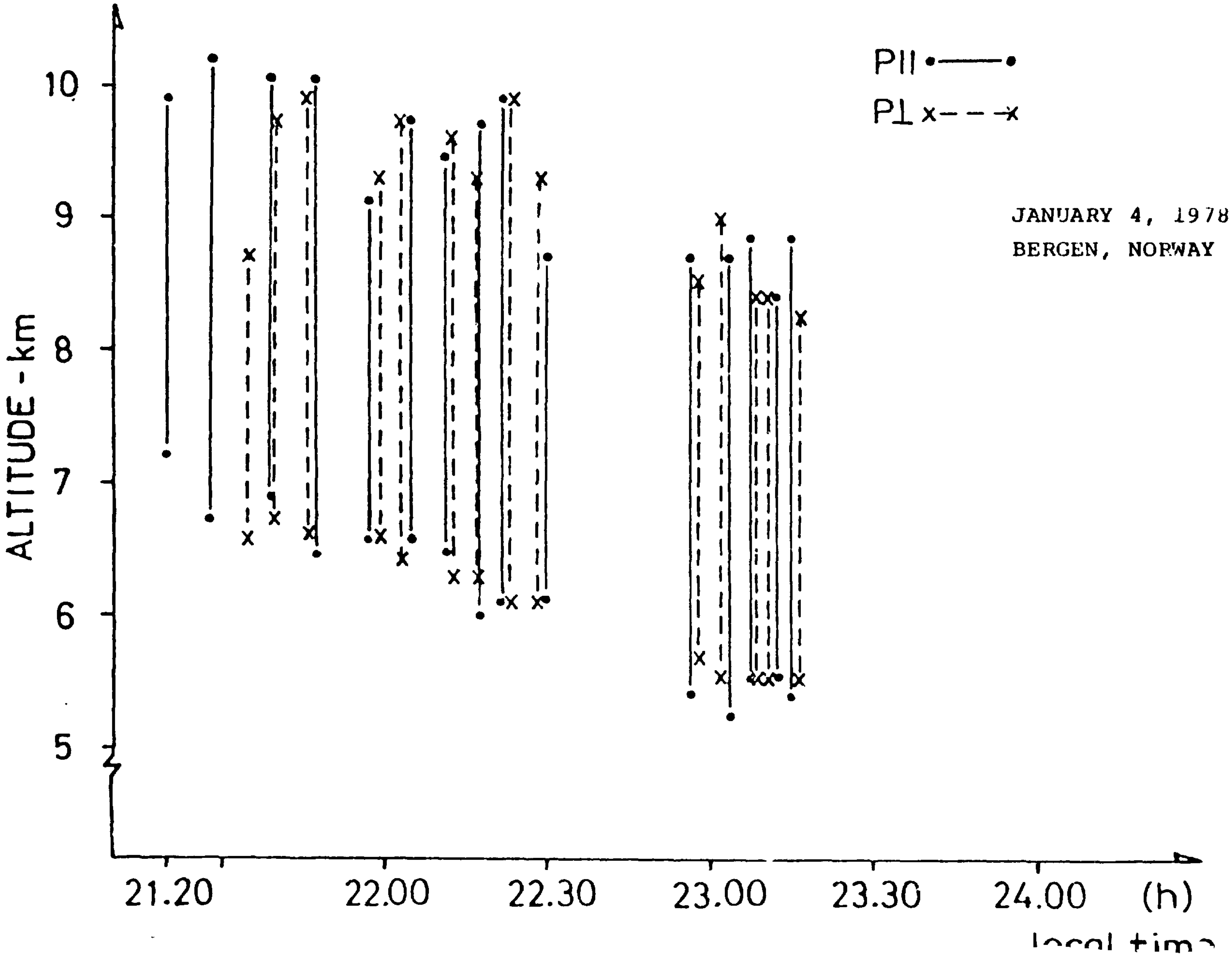


Figure 2.5. Lidar returns obtained in Bavaria by Jäger et al (1977). Cirrus and higher particle layers are shown.



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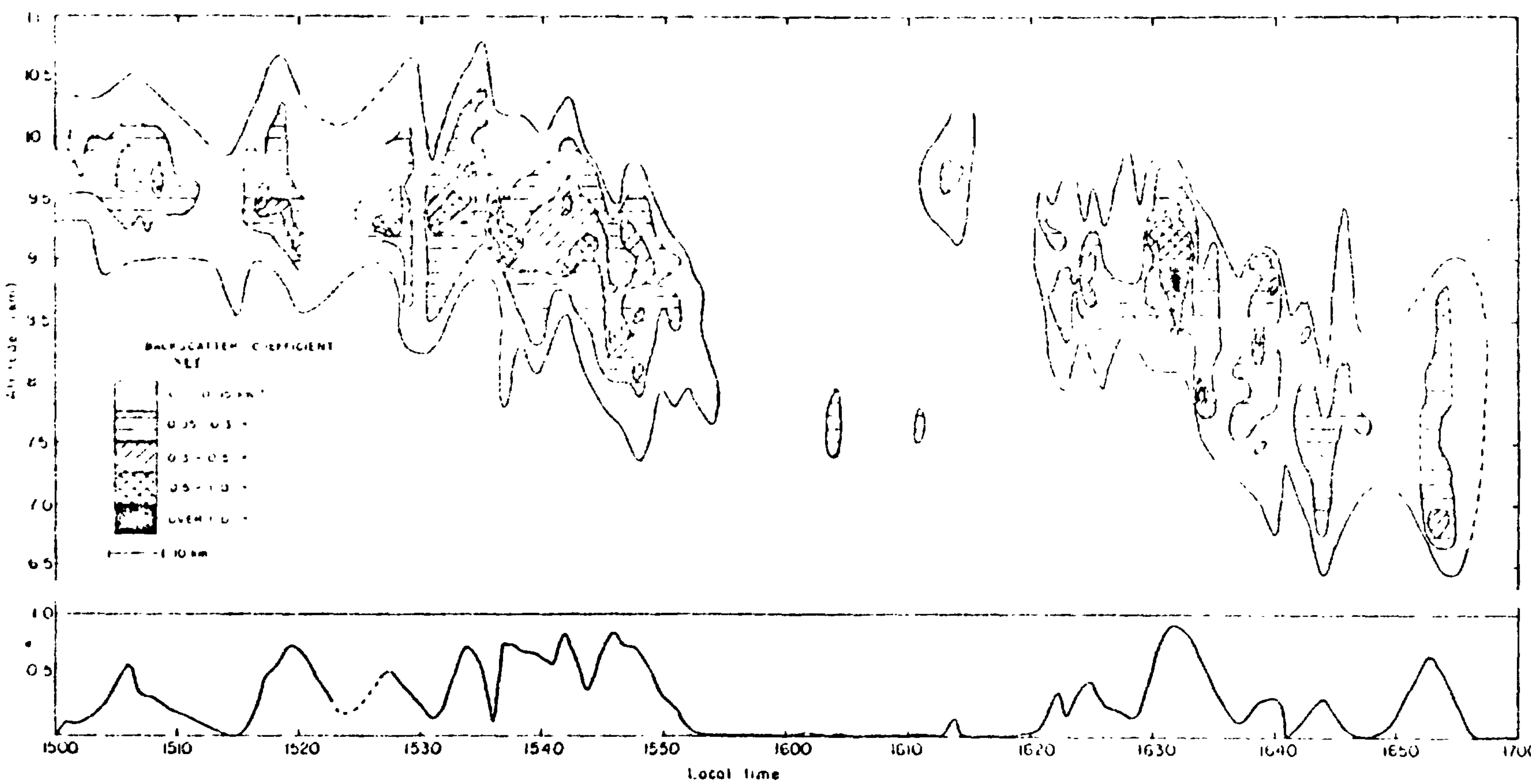

Figure 2.7. Altitude-time prof e of cirrus backscatter coefficients observed by Platt (1973). IR emissivity also shown in lower graph.

A variety of high cloud and aerosol studies was described at the Ninth International Laser Radar Conference in Munich (July 1979). We would particularly like to mention the Russian work reported by Zuev et al. (1979) using techniques that enable all four of the Stokes parameters of the partially polarized lidar return to be measured, enabling one to get at detailed information on the shape and orientation of scattering particles within clouds (see also Derr et al. (1974) and Houston and Carswell (1978). Also, many papers were given on early results of the SAM II and SAGE satellite experiments which include extensive passive aerosol measurements down to ~10 km and related lidar work carried out for "ground truth" purposes (Russell et al., 1979a; McCormick, 1979; Fuller et al., 1979; Grams et al., 1979; Hofmann et al., 1979).

A high priority has been given to cirrus cloud and other cloud/aerosol observations in the Shuttle Lidar Facility planning by NASA's Atmospheric Lidar Working Group (Browell, 1979a; Russell et al., 1979b, Browell, editor, 1979b). We quote a portion of the latter reference here, which succinctly summarizes the value of a specific cirrus lidar measurement capability proposed in that reference:

> "The unique ability of lidar to detect subvisible cirrus clouds is also worthy of mention. Previous groundbased and airborne lidar studies have detected tenuous cirrus clouds with water (ice) contents that were at least two orders of magnitude less than those associated with visible cirrus layers. Repeated lidar measurements in many latitudes have suggested that these subvisible cirrus layers are quite prevalent, but the lidar measurements to date have been too sporadic to provide a useful global or regional census. Also, these tenuous cirrus layers cannot be globally monitored by satellite multispectral radiometers since they are difficult to resolve unambigously against complex backgrounds and are not discernible in the visible spectral ranges. Such tenuous clouds could produce measurable effects in certain ERB channels and, if widespread and persistent, could significantly perturb the global radiation budget. Only a space-borne lidar, coaligned with an ERB sensor, could determine whether subvisible cirrus clouds were present in the ERB FOV during times of measured albedo changes. Such a space-borne lidar could also provide the first global census of the occurrence, height, density, and thickness of these tenuous clouds."

2.4.3 To complete this section, we wish to summarize much of the lidar literature on high clouds and polarization methods for the interested reader. Early cirrus observations were made by Evans (1965), Davis (1969), and Davis (1971). Attention to particulate layers very high in the atmosphere (60-140 km) was drawn by Fiocco and Smullin as early as 1963; much of this literature has been summarized in the Shuttle Lidar report (Browell, 1979b) including high latitude observations (Fiocco and Grams, 1966, 1969) at the altitudes of noctilucent clouds, and the first lidar studies of the stratospheric "Junge layer" (Fiocco and Grams, 1964; Grams and Fiocco, 1967). Following the work of Hall and Ageno (1970), Platt and Gambling (1971), and Platt (1973) on cirrus clouds, related lidar studies and calculations were made by Gibson et al. (1977), Liou (1977), Platt (1979), Platt and Dilley (1979), and Platt, Reynolds, and Abshire (1979). Lidar backscattering from the cirrus layer is often reported incidentally in accounts of higher altitude studies that concentrate on stratospheric particulates, e.g., McCormick (1975); Fegley (1976); McCormick et al. (1978); and Reiter et al. (1979).

The use of depolarization detection (given a cleanly polarized lidar transmission) was developed by Pyabatov et al. (1969), Liou and Schotland (1971), and Schotland et al. (1971), and has increasingly been used for water substance discrimination at various cloud levels from the cirrus layer on down (Pal and Carswell, 1973; Liou and Lahore, 1974; McNeil and Carswell, 1975, Sassen, 1976; Derr et al., 1976; Pal and Carswell, 1977; Allen and Platt, 1977; Platt, 1977; Jager et al., 1977; Abshire et al., 1978; Houston and Carswell, 1978; Sassen, 1978; Platt, 1978; Platt, Abshire, and McNice, 1978; Zuev et al., 1979; Sinestad, 1979; Reiter et al., 1979). Thus there is a growing accumulation of results on polarization studies of various clouds - and therefore a strong basis for increasingly reliable lidar measurements of cirrus clouds.

2.4.4 In a soon-to-be-published article, Platt, Reynolds, and Abshire (1979) report an important extension of cirrus cloud studies *via* lidar. They have combined groundbased lidar scans of specific-cloud systems with radiometric data from the SMS-2 and GOES-1 geostationary satellites. These measurements enable the visible albedo, infrared emissivity and visible optical depth to be determined simultaneously, and conclusions to be drawn about the shapes of ice particles in cirrus clouds. For this particular case study, the minimum values of infrared emissivity, visible albedo and visible optical depth were 0.2, 0.1, and 0.5, respectively. Because of the uncertain limits on cirrus visibility by present-satellite systems, it is not clear how far this dual, active/passive type of study can be pushed for the large class of cirrus in the "thin" category, say $\varepsilon < 0.1$. However, this work would seem to presage a period in which advanced optical methods can routinely be brought to bear on cirrus properties and morphology.

Uthe and Russell (1977) reported lidar studies of thin cirrus during all seasons of the year in the South Pacific, coupled with airborne measurements of ice water content and DMSP satellite observations of the same geographical area. In addition to comments on the climatological consequences of these clouds, they discuss data on the estimated optical depth which attains very low values (0.0015-0.03) in some cases.

Given the current thrust towards airborne and satellite lidar systems, there are good propsects for definitive studies of cirrus clouds even in the high-latitude and polar regions of the earth where observational coverage from the ground is compromised by the weather. Present indications are that lidar measurements will need to be complemented by passive, radiometric measurements. As in other work addressed to the question of solar triggering of cirrus development, it would seem most fruitful to carry out such lidar observations in those times and places where the atmosphere is the closest to saturated conditions. The simultaneous remote and range-resolving capabilities of lidar are very suitable for this purpose.

2.5 Recommendations for Improved Measurements on Cirrus Clouds

We have concluded that the cirrus observation data base is not adequate for answering the sun-cirrus-weather question. The appropriate recommendations therefore lie in the area of improved measurements, so that the relationships between cause and effect in cirrus clouds can be appreciated more fully.

The comments given here are concerned mainly with the proposed sun-cirrus-weather connection and are not particularly related to the larger context of climate models. For a recent discussion of parametrization of cloudiness for climate modeling, the interested reader should see Paltridge *et al.* (1968). Clearly, climate modeling will benefit from having the improved information from comprehensive cirrus measurements. The emphasis here is largely on optical remote sensing methods, except for certain *in situ* measurements mentioned in subsection 2.5.2.

With regard to the experimental categories listed below, it is recommended that:

2.5.1 Groundbased measurements

(a) Coordinated studies of the 200-300 mb level of the atmosphere be undertaken by means of lidar, radiometry, and "solar aureole" methods, to obtain the altitude dependence of particle size distributions in the cirrus layer and to follow the development of cirrus clouds. (Thin cirrus are of great interest, likewise the correlation of cirrus cloud cover with solar disturbances).

(b) Development and operation of the necessary instruments be supported, so that observations in clear sky areas can be more frequent and the global coverage can be extended to areas such as Scandinavia and the Gulf of Alaska. (Existing stratospheric aerosol lidar systems can also be used directly or adapted for cirrus observations.)

2.5.2 Aircraft/Balloon Measurements

(a) Routine visual sighting of cirrus by pilots be encouraged, particularly the altitudes and approximate visual contrast of thin cirrus.

(b) Application of lidar, radiometric and particle sampling methods be increased using aircraft, to obtain more information on altitude-dependent properties of cirrus than can be seen from the ground.

(c) Balloon-borne measurements of relative humidity, temperature, aerosols and ionization be performed concentrating on the altitudes typical for cirrus clouds, to identify any connections that the density of particulate may have with atmospheric ionization changes, including those initiated at the sun.

(d) Development of compact and simplified optical systems be supported, so that an enhanced program of cirrus measurements from airborne platforms will be effective and reasonably priced.

2.5.3 Satellite Measurements

(a) Research activities directed toward improved, passive cirrus cloud discrimination be supported, so that optimum use is made of existing satellite instruments and of design opportunities for future instrumentation.

(b) Data from limb-scanning instruments, such as SAGE and SAM-II, be reduced for as low an altitude as possible in hopes of obtaining global information on the cirrus layer, particularly thin cirrus. (See McCormick et al., 1979) for a discussion of SAGE and SAM-II.)

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(c) Shuttle lidar instruments be developed and used to measure aerosol density, cloud-top heights, and the altitude profiles of [H_2O], temperature and pressure (e.g., see Browell, 1979a,b).

(d) Appropriate mixes of the above techniques be employed (e.g., see Platt, Reynolds, and Abshire, 1979) for better interpretation of scattering, absorption, emission and extinction in terms of both the molecular and particle concentrations in cirrus clouds.*

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* Note added in proof:

Two recently published papers describe the principles and experimental results of new high cloud measurements in Australia by means of lidar backscatter and IR radiometry:

Platt, C.M.R., (1979). Remote sounding of high clouds: I. calculation of visible and infrared optical properties from lidar and radiometer measurements. J. Appl. Meteor., 18, 1130-1143;

Platt, C.M.R. and A. C. Dilley, (1979). Remote sounding of high clouds: II. Emmissivity of cirrostatus. loc. cit. 18, 1144-1150.

3. THE EFFECTS OF CIRRUS CLOUDS ON THE WEATHER

3.1 The Microstructure of Cirrus Clouds

Heymsfield and Knollenberg (1972) investigated the microstructure of cirrus clouds with an imaging ice particle detector. They found particles between the minimum detectable size (75 μm) and 2 mm to exist in concentrations up to 350 per liter of air. The ice water content was typically 0.05 to 0.25 g m^{-3}. They concluded that cirrus clouds consist of a localized generating region in which ice particles are nucleated in rather high concentrations, and a diffuse tail or veil which consists of the precipitating ice particles. Once nucleated, the ice particles grow by diffusion quite rapidly and then, acquiring a significant fall velocity, form a broad, optically thin veil.

Knollenberg (1972) and Heymsfield (1977) noted that droplet freezing is the more prevalent mode of cirrus ice particle formation, as evidenced by the predominant occurrence of bullet rosettes and other spatial ice crystals. The occasional occurrence of thin and thick hexagonal plate ice crystals observed by Heymsfield (1977) indicates sublimation nucleation of cirrus ice particles also occurs.

3.2 Postulated Mechanisms

There are two postulated mechanisms which describe how cirrus clouds may affect the weather. The first involves the precipitation of cirriform cloud ice crystals through a subsaturated layer and into a dense supercooled water cloud below. The second involves atmospheric destabilization by modulation of the cooling rate near the level of the cirrus cloud.

3.3 Seeding Effect

3.3.1 State of Knowledge

The simultaneous presence of ice particles and water droplets in clouds at temperatures below 0°C leads to a colloidal instability of the cloud microstructure which results in the rapid formation of precipitation-size hydrometeors. This, the Wegener-Bergeron-Findeisen mechanism (Pruppacher and Klett, 1978), is probably responsible for 90 percent of continental air mass precipitation in the mid-latitudes (Mason, 1971).

Cirrus clouds are all ice clouds which exist in the upper portion of the troposphere above the -40°C level. This temperature corresponds with that for which homogeneous ice formation in droplets becomes significant (one nucleus per milliliter water per second, Pruppacher and Klett).

The cirrus seeding effect was originally advanced by Bergeron (1950; see also Jiusto and Weickmann, 1973), who suggested that upper level cirrus clouds could provide ice seeds into lower level, supercooled water clouds. This "seeder-feeder" mechanism has been verified by radar observations of Cunningham (1952; see Mason, 1971) and Heymsfield (1977).

Since the cirrus ice particles must survive a fall of as much as three kilometers through subsaturated air, there has been a question of their ability to nucleate lower level supercooled water clouds. Precipitating veils have been studied _in situ_ by Braham and Spyers-Durham (1967) and Heymsfield (1975). Since the number concentration of precipitating ice particles below cirrus clouds may be only 0.1 to 10 per liter, the precipitating veils may not be visible to the distant observer.

Theoretical studies of ice crystal fall through the subsaturated air were conducted by Hall and Pruppacher (1976). They indicate that ice crystals greater than a certain initial size (about 12 µg) are capable of falling about

2 km through the NACA Standard Atmosphere at 70 percent relative humidity and about 3 km at 90 percent relative humidity. The actual temperature and humidity profiles influence the survival distance of the ice crystals.

3.3.2 Weak Points

Most of the theoretical microphysical mechanisms involved in the seeding mechanism are fairly well understood. The weakest point appears to be the ventilation factor determination for columnar ice crystals. Hall and Pruppacher (1976) noted the lack of appropriate experimental or theoretical values for the characteristic shapes and flow regimes of interest.

Heymsfield and Knollenberg (1972) found that localized generating regions exist in most cirrus clouds and contain high concentrations of large ice particles. Although no liquid water was measured, they believe liquid drops nucleated first, and then immediately froze. The predominant ice crystal form, a bullet rosette, is believed to be formed from polycrystalline frozen drops (Magono, 1968). Pitter and Pruppacher (1973) indicate that 10 μm radius drops falling in air freeze polycrystalline at -40°C and that 5 μm drops freeze polycrystalline at -50°C. Thus, the mechanisms of cirrus cloud formation often appear to be condensation, followed by droplet freezing. However, except for the obvious examples, such as cirrus generated by cumulonimbi, cirrus cloud generating regions and mechanisms of formation are not well documented. This uncertainty can be expanded in terms of cirrus cloud dimensions. Whereas most clouds have well-defined boundaries, cirrus clouds typically have poorly defined boundaries and structure due to their characteristic nature. It appears that the best conceptual model of a cirrus cloud is that of a localized generating region and a larger diffuse precipitating veil.

3.3.3 Research Needs

As identified above, two major gaps in the present state of knowledge should be studied:

- Ventilation coefficients for ice crystal shapes and size typical of cirrus clouds should be determined. These shapes include bullets, bullet rosettes, hollow and solid columns, and thick hexagonal plates. Ventilation coefficients are probably best determined experimentally using a wind tunnel or similar apparatus (Pasternak and Gauvin, 1960).

- Cirrus cloud generating mechanisms need to be better characterized through *in situ* measurements in generating cells and nucleus size and chemical composition measurements. Cloud chamber experiments can then use these results to investigate the effects of various parameters on nucleus activation. Heterogeneous nucleation theory is not yet sophisticated enough to lead experimenters, so it is prudent to seek empirical relationships based upon experimental results with the hope of guiding later theoretical development.

3.4 Radiative Divergence Due to Cirrus

3.4.1 State of Knowledge

Knollenberg (1972), studying cirrus clouds formed by jet aircraft contrails, found that ice particles tend to result from droplet freezing. Rapid cooling in contrails, up to almost 21°C per day, causes the ice particles to be cooler than the environment and hence to grow by vapor diffusion more rapidly.

Radiational cooling is characteristic of cirrus clouds and contrails near the tropopause between October and May in Northern Hemisphere midlatitudes. At higher altitudes, and during summer months, radiational heating dominates. The principal factor which determines radiative divergence is the window region between 6.5 and 14 μm. In summer, the window is "hot" and the radiation absorbed by cirrus ice particles exceeds that emitted. In winter, the window is "cold". Also, window radiation is reduced by intervening clouds (Knollenberg, 1970).

Roberts and Olson (1973) found relationships between a vorticity index or a similar trough index and the geomagnetic activity index for a target area north of 40°N and between longitudes 130° and 120°W. At 300 mb, they found a lag time of five days between occurrence of a geomagnetic event and a maximum vorticity index for seven winters (1964-1971). Additionally, they found a statistically significant relationship between geomagnetic activity and the subsequent magnitude of trough vorticity indices.

Their results corroborate similar findings by several groups and indicate a potential for both short-range and long-range weather forecast improvement if the physical mechanisms involved can be better understood. The authors speculate that, associated with geomagnetic activity, a significant number of ion pairs are produced in the upper troposphere. From such bi-polar ionization, it is postulated that cirrus clouds are quickly formed, and that the cirrus clouds modulate the blackbody radiation lost to space from the relatively warm Northern Pacific Ocean. Section 4 investigates the role of clouds to modulate radiation lost to space.

3.4.2 Weak Points

As noted by Roberts and Olson, the mechanisms of cirrus cloud formation due to geomagnetic activity are not completely known. Additionally, they do not offer rigorous treatment of the destabilization process due to the altered radiative transfer when cirrus clouds are present. Their results, however, are useful because they indicate that significant lag times (about five days) exist between geomagnetic activity and the subsequent vorticity index maximum. Their contention that a cirrus deck is rapidly formed may be an overstatement, though, alternatively, it appears that an optically thin, persistent cirrus layer may be slowly but continuously formed over several days' time.

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3.4.3 Research Needs

Theoretical models of radiative divergence are sufficiently advanced that, once cirrus properties are specified, the resulting radiative effects can be predicted. However, the global distribution of thin cirrus clouds is not well-known. Thus, the most urgent research needs concern the following:

- Development of instrumentation for detecting the presence of "invisible" cirrus clouds
- Formation of a continuous, large area thin cirrus survey program in collaboration with solar activity monitoring
- Simulation of observed thin cirrus cloudiness effect on radiative divergence.

These research needs are rather basic to the better understanding of how thin cirrus affect climate and how much thin cirrus variability is attributable to solar activity.

4. THE EFFECTS OF CIRRUS CLOUDS ON SUN-WEATHER RELATIONSHIPS

4.1 Introduction

Roberts and Olson (1973) found relationships between a vorticity index or a similar trough index and the geomagnetic activity index for a target area north of 40°N and between longitudes 180° and 120°W for the winter months November through March. At 300 mb, they found a lag time of five days between occurrence of a geomagnetic event and a maximum vorticity index for seven winters (1964-1971). Additionally, they found a statistically significant relationship between geomagnetic activity and the subsequent magnitude of the trough and vorticity indices.

The results of Roberts and Olson (1973) corroborate similar findings by several groups (e.g., Wilcox et al., 1974) and indicate a potential for both short- and long-range weather forecast improvement if the physical mechanisms responsible for such a link can be identified and understood. In a lengthy discussion of solar variability and lower atmosphere weather, Dickinson (1975) lists changes in the distribution of cloud cover as a possible physical mechanism linking solar activity and tropospheric weather. In particular, Dickinson (1975) and Roberts and Olson (1973) speculate that, associated with geomagnetic activity, cirrus clouds are formed in the lower stratosphere and upper troposphere. The cirrus clouds then trigger further tropospheric weather events through either radiative processes or precipitation of cirriform cloud ice crystals through a subsaturated layer and into a dense super-cooled cloud below. These two processes are discussed in more detail below along with recommendations for further study.

4.2 Radiative Modulation by Cirrus Clouds

Roberts and Olson (1973) speculate that cirrus cloud control of tropospheric weather in high latitude winter months might come about through the modulation of infrared radiation lost to space over the relatively warm North Pacific Ocean. The effect of a sudden formation of cirrus above a relatively warm surface, during low sun or darkness, would be to decrease the cooling rate below the clouds and increase the cooling rate above the clouds. The authors speculate, but do not show, that the resultant net heating below the clouds could perhaps induce the type of dynamical response observed.

Given the microphysical and radiative properties of cirrus, the vertical temperature and water vapor distribution and the solar position, the calculation of the vertical profile of the rate of radiative heating is a straightforward (albeit, computer-time-consuming) process (e.g., Lacis and Hansen, 1974; Ellingson and Gille, 1978). Dickinson (1975) indicates that the change in radiative heating in the atmospheric layer below the cirrus, when cirrus effects are included in the calculation, amounts to 0.1 K/day for "typical" cirrus during high latitude winter conditions. Dickinson estimates that a mean 0.1 K decrease in the temperature difference between atmospheric columns in middle latitudes would decrease the zonal mean westerly wind at the tropopause by about 2 m/sec. Although such approximate calculations are interesting, they do not allow for a test of the Roberts and Olson hypothesis. Such tests may only be performed with the use of somewhat sophisticated models of the dynamics of the atmosphere which also allow the radiative processes to be considered in some detail. Such calculations have not been performed for the type of winter situations studied by Roberts and Olson (1973).

Since the late 1960's a number of theoretical and observation studies of the interaction of convection with larger scale atmospheric dynamics in the tropics have taken place (e.g., BOMEX, GATE). These large projects have prompted a number of smaller studies attempting to show that certain cloud systems force an amplification of convection via radiative destabilization. Discussed below are three different studies which imply a link between cirrus formation and convection in the tropics via radiative processes.

Gray and Jacobson (1977) present observational evidence in support of the existence of a large diurnal cycle of deep convection over tropical oceanic regions. They hypothesize that this diurnal cycle is due to the large day to night variation in the radiational cooling of a mesoscale cloud region relative to clear areas, the principal modulator being the cirrus canopy over the convective elements.

Albrect and Cox (1975) used a time-dependent diagnostic model to determine the response of the tropical atmosphere to differences in the vertical profile of radiative heating. Although no interaction between the radiative and convective processes was allowed in this study, the authors found that the vertical structure of forced motion is very sensitive to the phase differences between the radiative and convective heating. In fact, the location of the radiative cloud relative to the convective area may play an important role in determining the intensity of convection.

More recently, Ellingson and Serafino (1978) and Serafino (1979) have studied the sensitivity of the tropical ensemble convection model of Rodenhuis and Cheng (1979) to variations of the radiative properties of cirrus cloud cover. Shown in Figure 4.1 is the sensitivity of specific convection model parameters (total effective cumulus cloud area (TEFA) and total rain rate) as functions of

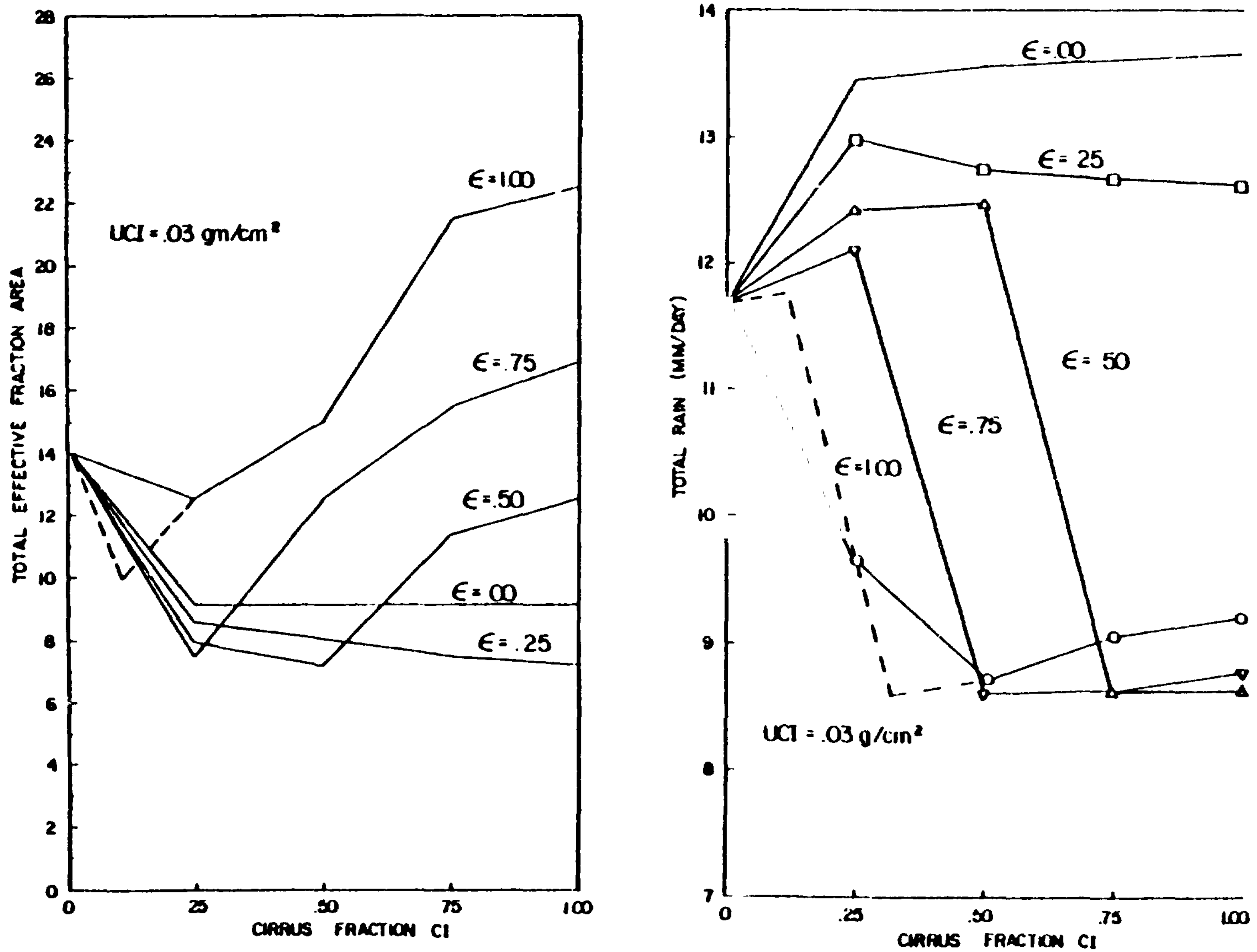

Figure 4.1. Ensemble cumulus results for different radiative properties.

cirrus cloud cover for various infrared cloud emissivities (E). It should be noted that the ensemble convection is occurring in an area of $4.5 \times 10^5 km^2$, UCI is the effective water vapor equivalent of the cirrus necessary for the solar radiation calculations (see Rodgers, 1967), and the cirrus is assumed to be 4 km thick with a top at 15 km.

Figure 4.1 shows that the model TEFA and rain rate are strongly dependent on the area and long wave properties of the cirrus. The minimum in the TEFA curves as a function of cirrus cover occurs where the infrared cooling in the cloud tops is just offset by the shortwave heating. Although in general the TEFA increases as the cirrus cover increases, the rainfall rate decreases because the cumulus clouds formed are not ones which rain appreciably.

It should be noted that the model results are dependent on whether the convection/cirrus are assumed to occur during the daytime, at night, or averaged over both (the results shown here). Daytime occurrence of cirrus in the model produces more rain but less cumulus cloud area than if the cirrus occurs at night. This again is the effect of solar heating partially or totally compensating for the increased longwave cooling in and above the cirrus. Therefore, the time of cirrus formation with respect to instabilities in a tropical wave pattern appears to be very important in the continuing convection. Perhaps this is a partial explanation as to why the Roberts and Olson effect is not seen in the spring and summer months (i.e., longwave cooling being offset by shortwave heating in the cirrus layer).

Finally, it should be noted that it has not been shown or implied that geomagnetic activity may be important in influencing tropical weather. What is important, however, is that the above discussed studies point the way to theoretical studies of middle and high latitude systems which should be explored.

4.3 Research Needs

Theoretical radiative transfer models are sufficiently advanced that given the cirrus properties, vertical profiles of radiative heating may be calculated. However, our knowledge of the effects of changes in the radiative heating profile is very small. Therefore, the most urgent research need is the design and carrying out of numerical simulation of cirrus effects on wintertime circulation patterns. Should such simulations confirm a positive effect of a cirrus link, the logical next steps would be the development of instrumentation for detecting the presence of "invisible" cirrus clouds followed by the establishment of a continuous, large-area thin cirrus survey program simultaneously with the monitoring of solar activity.

5. CIRRUS CLOUD FORMATION

5.1 Mechanisms of Cirrus Cloud Formation

Becker's (1979) investigation of monthly average areal coverage by cirrus clouds for July 1973 and January 1974 using NOAA-2 satellite viable photographs, indicates that the predominant modes of cirrus cloud production on the global scale are due to thunderstorms and monsoons.

For either of these mechanisms, uprising air from the storm core, containing droplets and ice crystals, eventually glaciates and exits the cloud. This results in the majestic anvil clouds which top vigorous cumulonimbi.

Other cirrus clouds are found associated with jet stream activity or are formed in conjunction with midlatitude storm systems as a result of moisture convection (Heymsfield, 1977).

A candidate solar-related cirrus cloud formation mechanism should be one which either directly forms or substantially contributes to cloud formation. The more probable mechanisms for such involve the roles of atmospheric small ions toward heterogeneous nucleation of droplets or ice crystals. Much less probable are the direct roles of small ions as droplet or ice crystal nuclei. Although small ions may not nucleate droplets or ice crystals, they are discussed below as a preface to the section on gas-to-particle conversion.

5.1.1 Small Ions

Small ions in the atmosphere consist of a single positive or negative charge about which as many as 10 to 30 oxygen and/or water vapor molecules tend to cluster. Both positive and negative small ions exhibit distributions in their mobilities (a measure of the ion's drift velocity per unit electric field intensity). The average small ion mobilities found in the laboratory (about 1 atm, 25°C) are

$$\left.\begin{aligned} K^+ &= 1.37 \\ K^- &= 1.89 \end{aligned}\right\} \quad (cm^2V^{-1}sec^{-1})$$

(Israel, 1970), with the mobility spectra exhibiting line structures of varying intensities when examined at high resolution (Nolan, 1920), with individual mobilities varying between about 0.3 and 2.0 $cm^2V^{-1}s^{-1}$.

Zeleny (1900) and Nolan (1930), among others, noted that the average mobility of small ions decreases with increasing relative humidity. Griffiths and Aubery (1929) found that negative small ion mobility decreases by 18 percent as the relative humidity increases from 0 to 100 percent.

Variation of small ion mobility with pressure and temperature is found from Lènard's mobility law (Israel, 1970):

$$k(p,t)=k\ (p_0,T_0)\ \frac{p_0}{p}\ \frac{T}{T_0}$$

Wigand (1921) found a more rapid increase in k with height in his balloon flights, probably due to the lack of a humidity term in Lenard's law.

It appears that small ion mobility variations at a given temperature and pressure are largely reflections of the amount of molecular clustering which occur under various conditions. The amount of clustering, and the types of molecules which tend to cluster, are important in gas to particle conversion kinetics.

5.1.2 Secondary Ions

The small ions do not constitute the only charged entities in the atmosphere, although they are the most mobile of charged bodies. They are not static entities, for they are constantly being produced, principally by cosmic radiation, and annihilated by recombination. Additionally, the small ions attach to aerosol particles and transfer their charges to the particles, thus forming the secondary ions. Secondary ions are much larger than small ions and, since they generally contain a single positive or negative electronic charge, are several orders of magnitude less mobile than small ions. Wait (1934) formulated a schematic representation of secondary ion formation (Figure 5.1, from Israel, 1970). Yunker (1940) obtained number distributions of ions characterized by their mobilities (Figure 5.2, from Israel, 1970). The gap between small ions and secondary ions as indicated by Yunker corroborates the hypothesis of Wait that ion growth is not a continuous, gradual growth (through consecutive accumulations of molecules) but rather a coagulation controlled phenomenon particularly dependent on the Aitken particle size distribution.

5.1.3 Heterogeneous Nucleation

Having surveyed characteristics of atmospheric ions, it is now helpful to survey atmospheric nucleation of droplets and ice crystals. It is significant to note that, with very few exceptions, nucleation from the vapor phase will always be heterogeneous. That is, the presence of a nucleus is required to overcome the initial energy barrier and to allow an ensemble of water vapor molecules to grow to a sufficient number that a stable new phase is established.

On the other hand, ice formation from the liquid phase, although usually heterogeneous, can occur homogeneously (in the absence of any ice formation nuclei) at temperatures below about -40°C. Therefore, a focus for solar-generated cirrus clouds may consider either heterogeneous droplet formation below -40°C or heterogeneous ice formation.

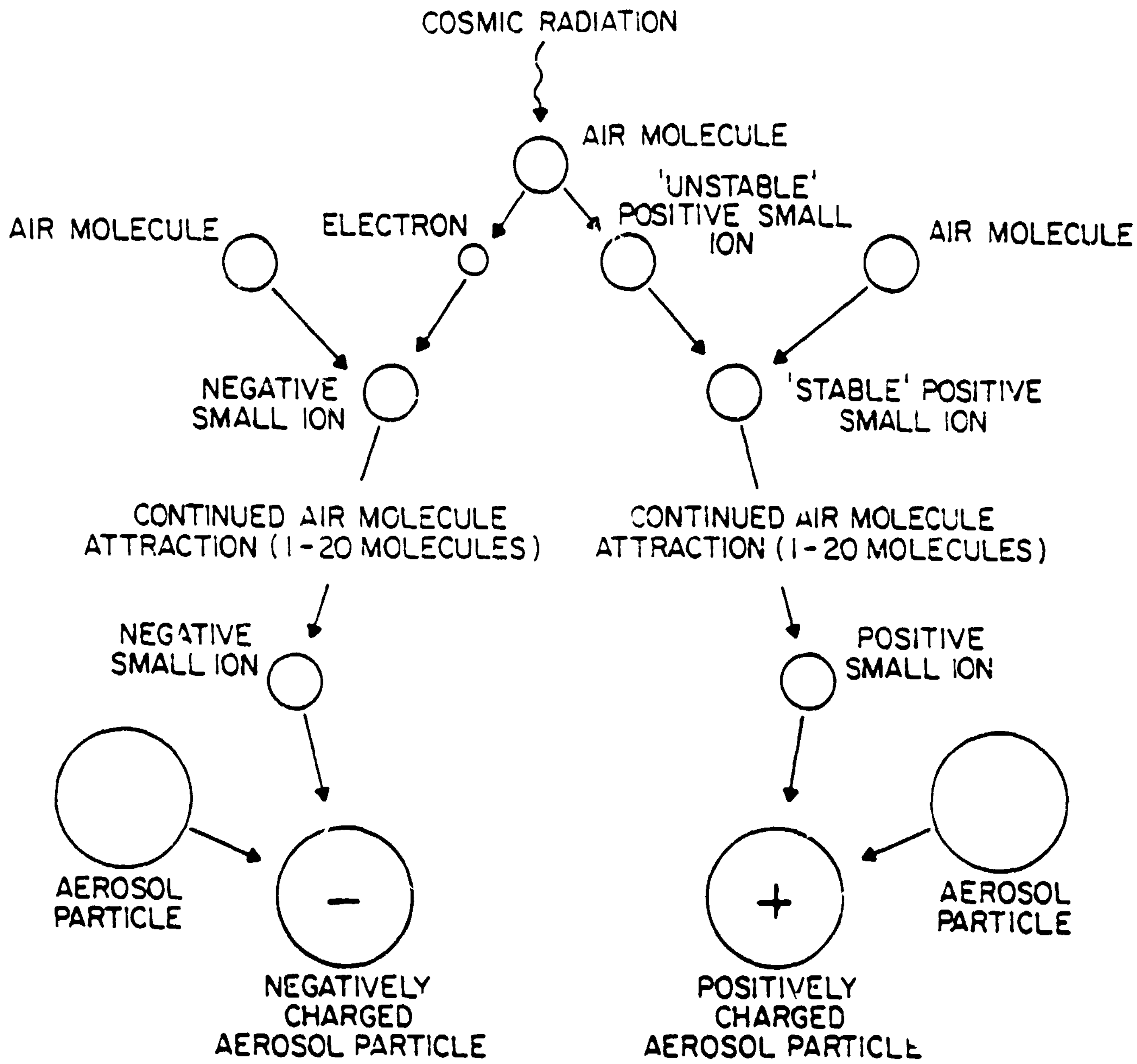

Figure 5.1. Schematic representation of secondary ion formation in the atmosphere, after Israël (1940) and Wait (1934)

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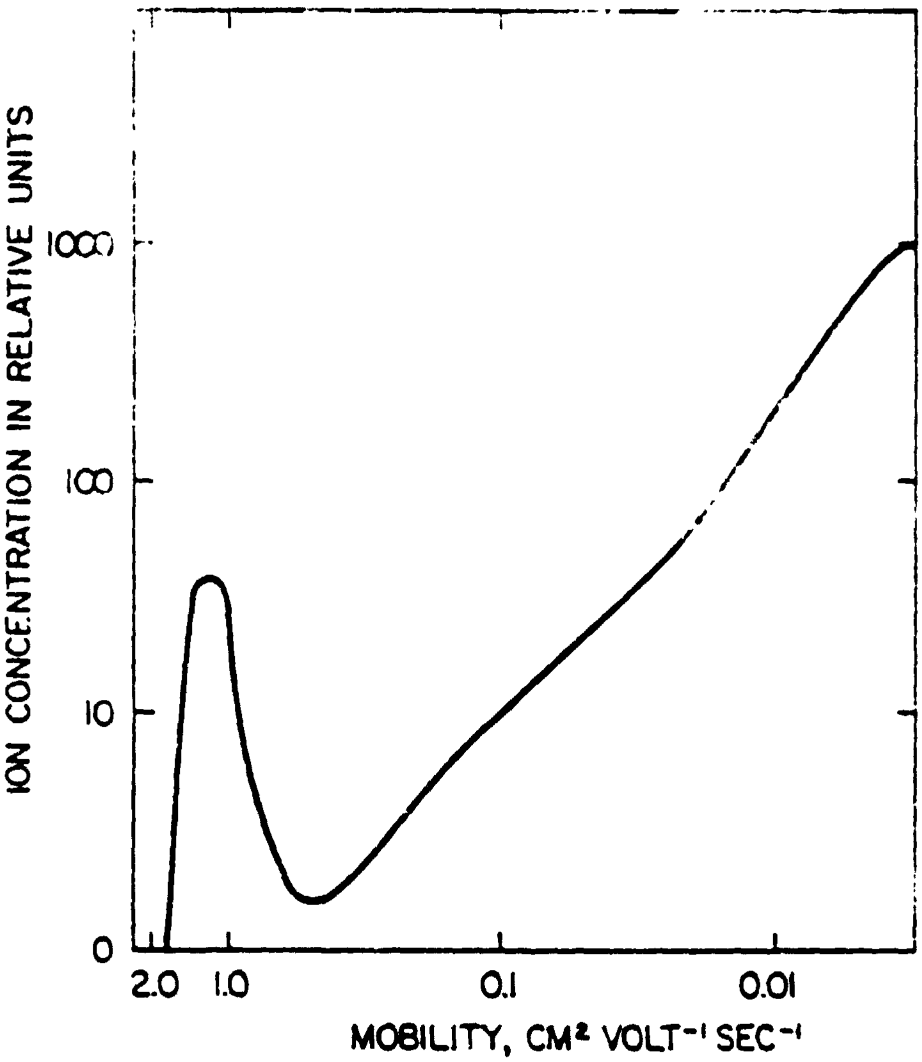

Figure 5.2. Ion spectrum according to Yunker (1940), after Israël (1970).

Heterogeneous drop formation nuclei are well-characterized (Byers, 1965). To be most effective, they should be large (greater than 0.1 um radius), and consist at least in part of a hygroscopic, water soluble salt. This latter point lacking, wettable insoluble particles are preferred nuclei to hydrophobic particles. Unfortunately, no substantive research has been conducted on the effect of aerosol charge on drop formation (Pruppacher and Klett, 1978).

Homogeneous drop formation on small ions is quite well-characterized by experiments and theory (Tohmfor and Volmer, 1938). The presence of negative small ions alters the onset of appreciable drop formation in otherwise clean, moist air. At temperatures between -5 and -8°C, the critical saturation ratio for drop formation in the presence of negative small ions is 3.7 to 4.2, compared with 4.6 to 4.9 when no ions or only positive small ions are present. (A saturation ratio of 3.7 corresponds to a relative humidity of 370 percent.)

Since the critical saturation ratio greatly exceeds values obtained in the atmosphere, and since it increases with decreasing temperature (at -55°C, the tropopa[illegible] emperature, the saturation ratio for homogeneous drop formation in the absence of ions is about 10), it is not feasible to pursue a homogeneous-ion drop formation mechanism in cirrus clouds. Similarly, the homogeneous ion ice crystal mechanism can be similarly discounted because, for any given atmospheric state, it is always easier to homogeneously form droplets than to homogeneously form ice crystals.

Heterogeneous ice formation nuclei are less well understood than drop formation nuclei. Several factors are known about what makes good ice formation nuclei. The best ice forming nuclei are water insoluble and contain a surface lattice of molecules or OH ions which closely approximates the molecular configuration of oxygen atoms on one of the low-energy faces of ice. Thus, silver iodide is often cited as a good choice as an ice formation nucleus because of its hexagonal crystallography and its close fit to the ice crystal basal plane lattice. These crystallographic criteria, however, are not complete (Boucher, 1969).

Studies of the effects of electric fields and aerosol particle charges on ice nucleation from the liquid phase indicate an enhancement of nucleability due to fields and charges (Pruppacher, 1963a). Other studies indicate that negatively charged aerosols are better ice nuclei than neutral or positively charged aerosol particles (Gabarashiveli and Gliki, 1967; Gabarashiveli and Kartsivadze, 1968; Abbas and Latham, 1969; Morgon and Langer, 1973; and Pruppacher, 1973).

External electric fields also appear to nucleate ice from the liquid phase when drop deformations or oscillations also occur. Experiments by Pruppacher (1936), Abbas and Latham, 1969; and Smith et al., 1971) fulfilled both of these conditions and achieved enhanced ice formation, while motionless drops in experiments by Doolittle and Vali (1975) and Dawson and Cardell (1973) resisted freezing in the presence of electric fields.

5.2 Possible Mechanisms for Solar-Cirrus Formation

5.2.1 The Environment

The focal point for solar induced cirrus cloud formation is the lower stratosphere and upper troposphere. Aerosol particle number concentrations decrease sharply with height at the tropopause and become quite low, about 0.1 cm^{-3}, about 4 km above the tropopause. Above 20 km, the Junge aerosol layer persists, although its overall behavior and the particle size and concentration are less uniform and universal than originally thought (Twomey, 1977).

Using x-ray fluorescence spectroscopy, Junge et al. (1961) found a large sulfur component of the stratospheric aerosol along with traces of iron and silicon. In later investigations, Friend (1966) found evidence that the stratospheric aerosol consists of ammonium sulfate or persulfate, and Bigg (1975) found evidence that liquid stratospheric aerosol particles contain sulfuric acid, while solid particles may be ammonium sulfate. Kiang and Hamill (1974) noted that most stratospheric aerosol particles are aqueous solutions containing sulfuric acid and possibly small amounts of nitric acid.

The emphasis of stratospheric aerosol composition is tied to (tropospheric) cirrus cloud formation by Dickinson (1975), who notes little distinguishability between stratospheric aerosol particles and particles just below the tropopause. Additional credence is gained when one considers the chemical compositions of sea salt and effective sea salt condensation nuclei. Although the predominant species in sea salt is sodium chloride, Dinger et al. (1970) found that heating sea salt aerosols to 300°C destroyed their activity as condensation nuclei, suggesting that the active component of sea salt is ammonium sulfate or ammonium chloride (sodium chloride withstands temperatures up to 500°C). Thus, it appears that ammonium sulfate, a prevalent stratospheric aerosol species, is an effective condensation nucleus.

Additionally, sulfuric acid also appears to be an effective nucleus due to its hygroscopic nature and to its extremely low vapor pressure. The latter property is believed to be crucial in the gas to particle conversion of sulfuric acid (Mohnen and Kiang, 1978).

Ion concentrations at the tropopause are dependent on several factors. The ion pair production rate has been demonstrated to be a function of altitude and solar cycle (Zikmunda and Mohnen, 1972). Typical values between 10 and 20 km appear to be 20 to 50 ion pairs $cm^{-3}s^{-1}$ (see Figure 6.6).

5.2.2 The Solar Link?

The enhanced ion pair production in the lower stratosphere and near the tropopause during periods of heightened solar activity may lead to cirrus cloud formation at times and in places where such would not occur otherwise.

Although direct ion nucleation of droplets or ice crystals can be ruled out, the ions may enhance aerosol coagulation growth, thereby forming better heterogeneous nuclei for cirrus cloud formation, or the ionization of aerosols may intrinsically lower the free energy barrier for nucleation of droplets or ice crystals, again improving the ability of aerosols to be active nuclei for cirrus cloud formation.

Mohnen and Kiang (1978) note that in the unperturbed stratosphere the gaseous H_2SO_4 concentration is too low to expect an ion to collide with such molecule during its average 500 to 1000s lifetime.

5.2.3 Ion-Induced Aerosol Formation

A gap exists between the known and observable and the theoretical description of gas to particle conversion. This gap represents a major link for the explanation of solar-induced effects on the weather.

It has been postulated that a change in the ion production rate caused by solar activity may affect the formation of strateopheric and near-tropopause aerosol particles which in turn modulate the formation of cirrus clouds (Dickinson, 1975). This theory has several attractive points:

- Coagulation growth of aerosol particles is a slow but continuing process. Thus, a modulating factor on gas to particle conversion could be expected to result in a low level, continuing supply of good cirrus nuclei.

- The gas to particle conversion process is demonstrably hastened when the bipolar ion concentration increases. Thus, a straightforward link appears plausible.

- The coagulation process is notably slow, which may contribute the greatest part of observed time lags between solar activity and atmospheric effects.

- The process is expected to be more pronounced at higher latitudes and over large regions when solar activity occurs. It thus occurs at places which are not greatly influenced by other modes of cirrus formation.

- The process may be expected to yield a low formation rate of nuclei per unit volume over large areas, thus possibly producing a vast, nearly invisible cirrus sheet.

Dickinson (1975) suggests that aerosols formed just below the tropopause may consist primarily of sulfuric acid, formed somehow by positive ion clustering. He indicates that such aerosols greater than 0.2 um radius (10^{-13}g) are effective condensation nuclei.

Hoppel and Dinger (1973) investigated the formation of aerosols from filtered atmospheric air samples taken above 15,000 feet. They found that when the air was irradiated by ultraviolet light, particles about 10^{-7} cm radius were formed, which subsequently grew by coagulation to form active condensation nuclei. No chemical analyses were made of the resulting aerosols.

Kiang et al. (1975) suggest that gas to particle conversion in the stratosphere will most likely occur via ternary nucleation involving systems of about 70 percent H_2SO_4, 10 percent HNO_3 and 20 percent H_2O.

If such systems occur, Mohnen and Kiang (1978) note that stratospheric sulfuric acid concentrations would be beneath the level at which ion clustering would achieve gas-to-particle conversion of that species.

5.3 Research Needs

- Upper-Tropospheric Aerosols. Dickinson's hypothesis requires experimental verification before it can be used to simplify the argument. There may well prove to be dissimilar tropopause-level aerosol sources and stratospheric aerosol sources, but the crucial measurement should be aerosols which are active condensation (or ice-forming) nuclei.

- Small Ion Kinetics. Positive and negative small ions are continuously formed at all atmospheric levels and at all times. It is necessary to understand their kinetics in order to assess the incremental effects due to changes in the ion pair production rate. Specific topics of concern include the kinetics of clustering and the interactions of ion clusters with Aitkin particles.

- Nucleability of Charged Aerosol Particles. Virtually no research has addressed the question of condensation or sublimation nucleation enhancement due to a net electrical charge on the aerosol particle.

- Thin Cirrus Cloud Modeling. Lack of a quantitative description of thin cirrus cloud formation and "precipitation" prevents a reasonable assessment of lag times and possible effects.

6. IONIZATION OF THE LOWER ATMOSPHERE

6.1 Rationale for Hypothesis that Cirrus Cloud Formation is Influenced by Variability of Ionization

In their initial work on the variability of the vorticity-area index over the Gulf of Alaska, Roberts and Olson (1973a,b) speculated that the sudden formation of cirrus clouds at high latitudes following pronounced changes in the level of solar activity might sufficiently alter the atmospheric radiation budget to affect the dynamics of the troposphere. As discussed in a later paper (Roberts, 1975) there is as yet little compelling evidence for an association between cirrus cloud formation and solar activity. Nevertheless, there have been reports of the formation of light scattering layers (Barber, 1955), increases in light scattering aerosol concentration (Vassy, 1956), and changes in atmospheric refractive index (Tilton, 1934) in response to strong solar, geomagnetic, or auroral activity.

Whether or not a cirrus cloud mechanism ultimately is shown to have any bearing on the vorticity-area index problem, questions have been raised concerning the possible role of ions in cloud formation. For example, Dickinson (1975) has suggested that cloudiness variations might be related to variations in ionization near the tropopause, possibly via the intermediary of ion-induced aerosol formation. Mohnen and Kiang (1978) have considered various ion-molecule interactions in the troposphere and stratosphere that may be relevant to such questions.

6.2 Production and Loss of Ionization

6.2.1 Rate Equations

The differential rate equations which describe the production and loss of ionization in the lower atmosphere can be expressed as:

$$\frac{dN^+}{dt} = Q - \alpha_d NN^+ - \alpha_i N^- N^+ \qquad (1)$$

$$\frac{dN^-}{dt} = -\alpha_i N^- N^+ + AN - DN^- \qquad (2)$$

$$\frac{dN}{dt} = Q - \alpha_d NN^+ - AN + DN^- \qquad (3)$$

where:

N^+ = positive ion number density

N^- = negative ion number density

N = electron number density

Q = electron-positive ion production rate

α_d = recombination rate coefficient of electrons and positive ions

α_i = recombination rate coefficient of positive and negative ions

A = attachment rate of electrons to neutrals

D = detachment rate of electrons from negative ions

and where the ion and electron number densities are related by the requirement to maintain charge neutrality

$$N + N^- = N^+ \qquad (4)$$

6.2.2 Rate Coefficients

Upper and lower limits and "selected" values of each coefficient, as tabulated by Cole and Pierce (1965), are shown as a function of altitude from 0 to 30 km in Figures 6.1 through 6.4. Also shown are more recent values taken from the Defense Nuclear Agency Reaction Rate Handbook (1972 and later revisions). These values are consistent with laboratory measurements for diatomic ions.

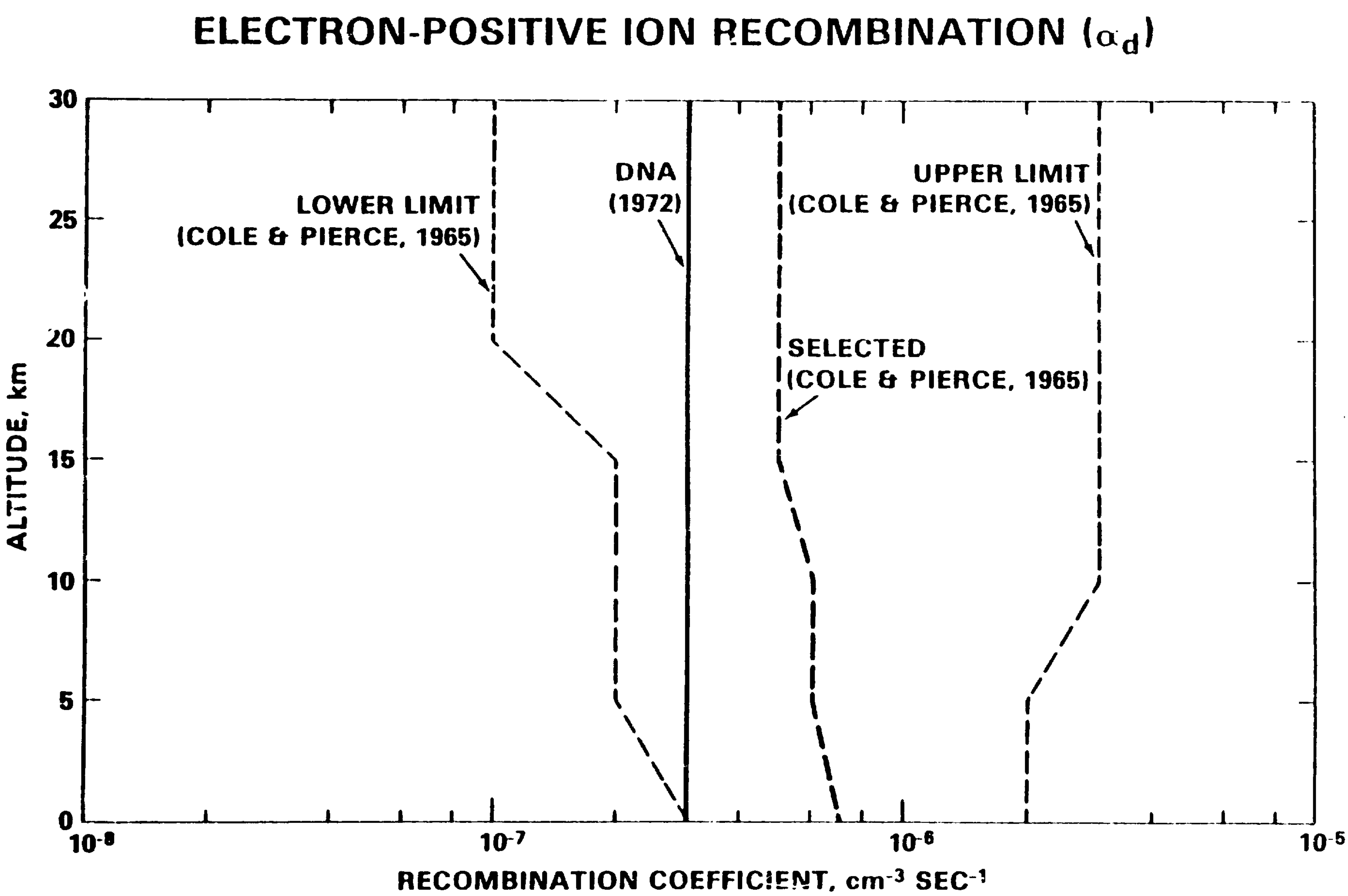

Figure 6.1. Recombination rate coefficient (α_d) of electrons and positive ions from tabulations in Cole and Pierce (1965) and the Defense Nuclear Agency Reaction Rate Handbook (1972).

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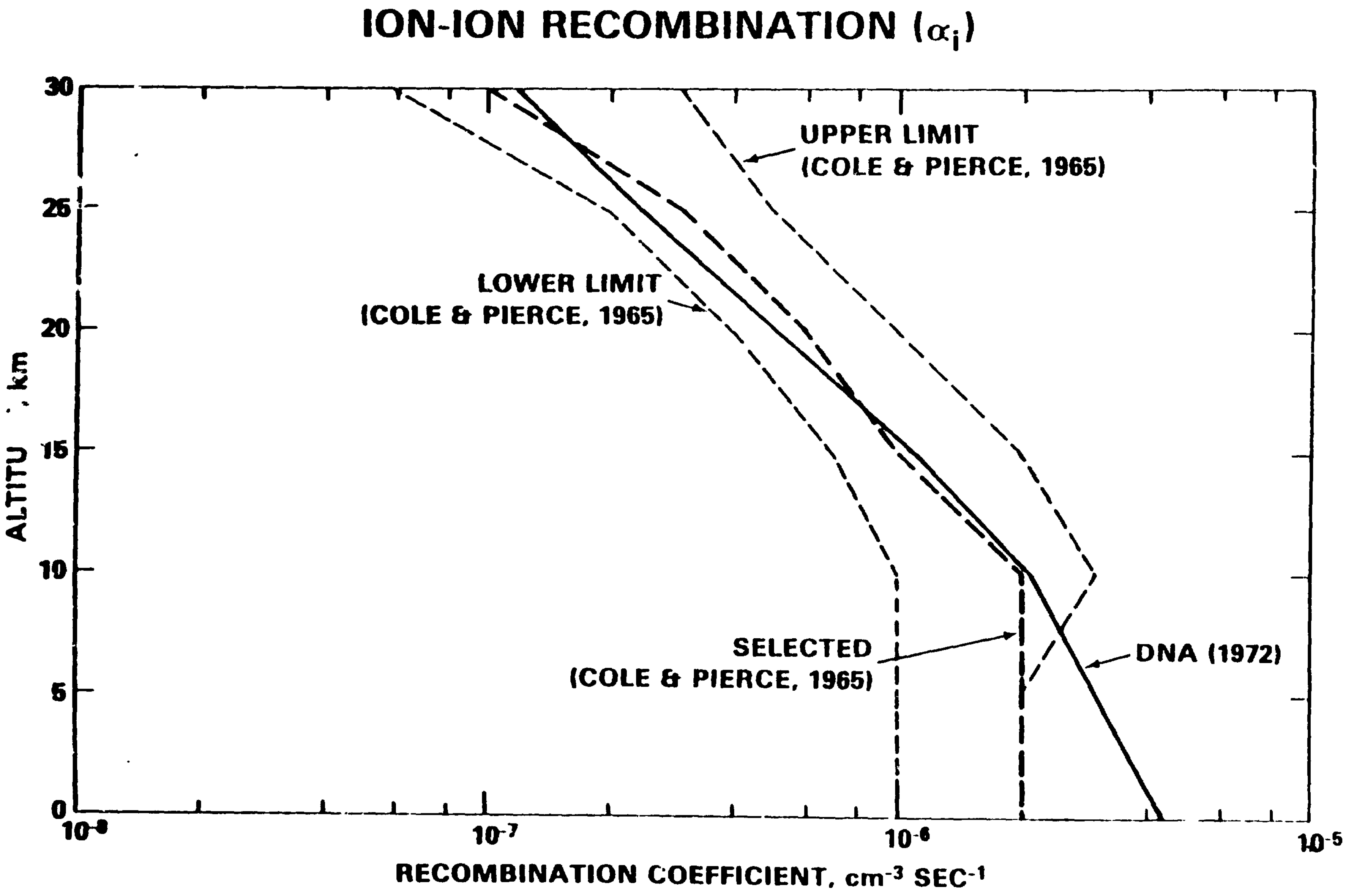
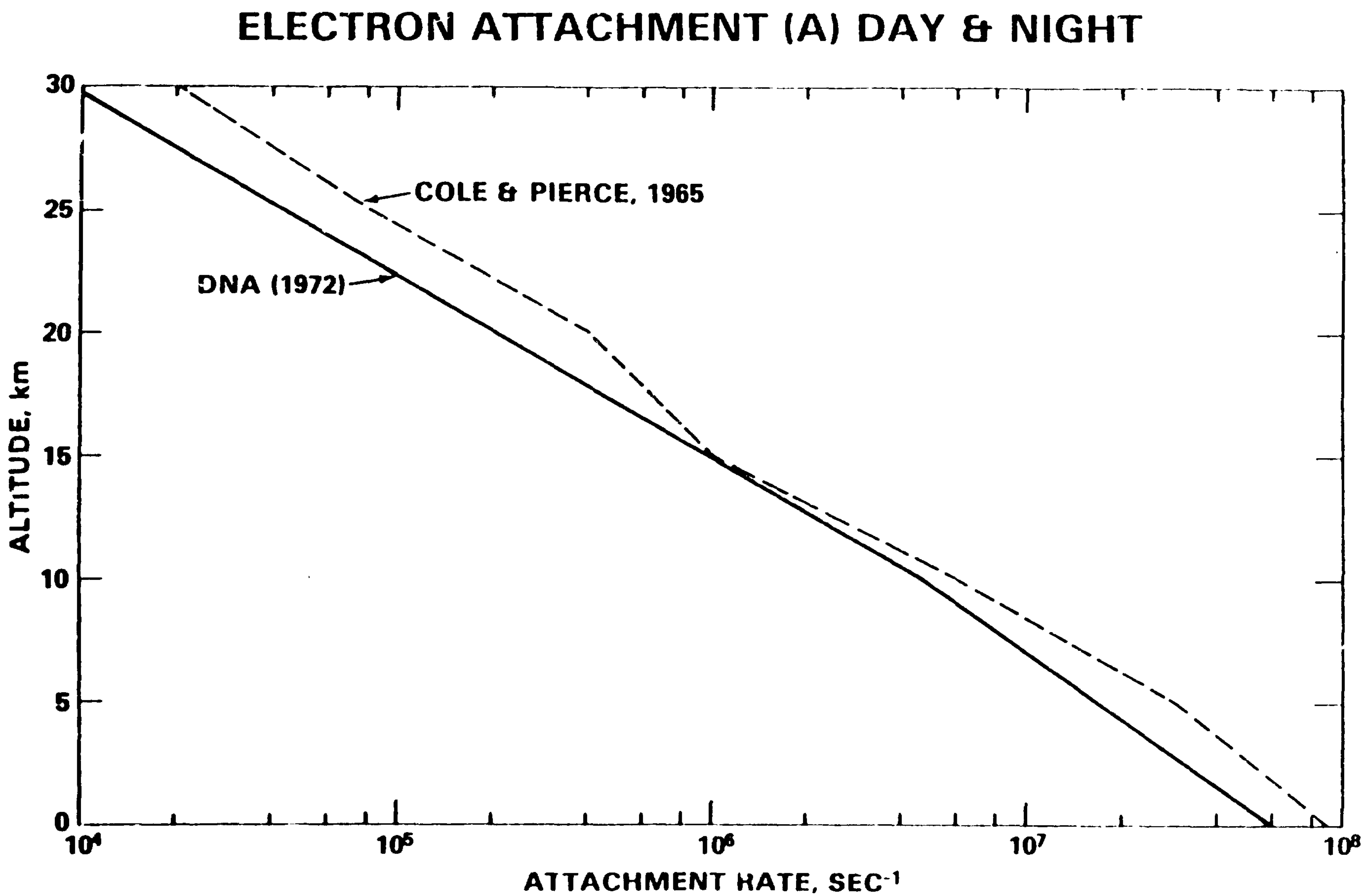


Figure 6.2. Recombination rate coefficient (α_i) of positive and neg ive ions from tabulations in Cole and Pierce (1965) and the Defense Nuclear Agency Reaction Rate Handbook (1972).



<u>Figure 6.3.</u> Attachment rate (A) of electrons to neutrals from tabulations in Cole and Pierce (1965) and the Defense Nuclear Agency Reaction Rate Handbook (1972).

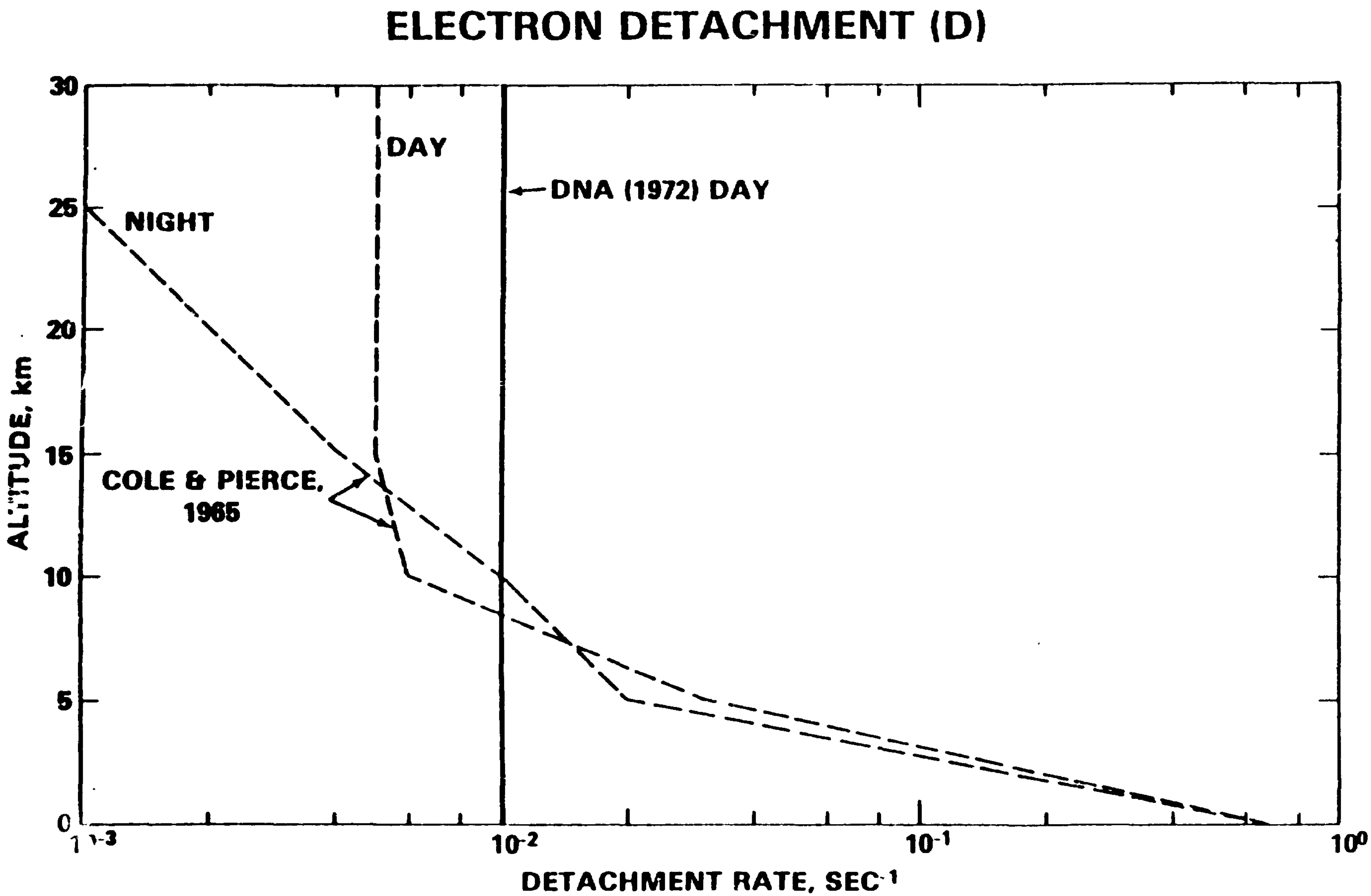


Figure 6.4. Detachment rate (D) of electrons from negative ions from tabulations in Cole and Pierce (1965) and the Defense Nuclear Agency Reaction Rate Handbook (1972).

In the region of the upper troposphere-lower stratosphere (~10-20 km) where cirrus clouds form, the uncertainty of "accepted" values for each coefficient is less than a factor of 2. Note, however, that reactions such as clustering of ions and attachment to condensation nuclei or dust, which may be important for cloud formation, have not been included in these lumped-parameter rate coefficients. Identification of the most important processes of these kinds, as well as measurements or estimates of the applicable rate coefficients, is still tentative.

6.2.3 Approximations Valid for the Lower Atmosphere

At the low altitudes of interest here, considerable simplification of the rate equations is possible. Specifically, for altitudes below 30 km, $N \ll N^-$ and $N^- \approx N^+$ are always valid assumptions and ion-ion recombination is the dominant process controlling the ion and electron density height profiles.

Typically, $N^-/N \approx 10^6$-10^9 (see, for example, Cole and Pierce, 1965). Thus, in (1)

$$\alpha_d N N^+ \ll \alpha_i N^- N^+$$

and (1) can be approximated by

$$\frac{dN^+}{dt} \approx Q - \alpha_i (N^+)^2 \qquad (5)$$

From (5) one can also show that the ionization density responds to (small) changes in the production rate (Q) with a time constant of order

$$\tau \approx (2\alpha_i N^+)^{-1} \qquad (6)$$

Since N^+ due to galactic cosmic rays (the main source of ambient ionization) is $\sim 5 \times 10^3$ cm^{-3} in the region 10-30 km (see next section), time constants in this region are of order 1-20 minutes.

For quasi-equilibrium conditions ($\frac{dN^+}{dt} = 0$), (5)

reduces to

$$N^+ = (Q/\alpha_i)^{1/2} \qquad (7)$$

for the positive ion density.

6.3 Ionization Sources

In this section we discuss the sources of ionization of the lower atmosphere and their variability. The purpose is to determine representative profiles of ion production rate and associated ionization density.

A recent review of direct energy inputs to the atmosphere (Rosenberg and Lanzerotti, 1979) leads to the conclusion that ionization sources for the lower atmosphere (<30 km) are limited to (1) galactic cosmic rays; (2) solar cosmic rays; (3) solar x-rays; and (4) bremsstrahlung x-rays from the precipitation of magnetospheric electrons.

In the absence of solar flare or geomagnetic storm activity, ionization by galactic cosmic rays is dominant in the lower atmosphere at all altitudes and latitudes.

6.3.1 Galactic Cosmic Rays

Variability. The latitudinal (i.e., geomagnetic cutoff) effect and the solar cycle modulation (inverse correlation with solar activity) substantially affect the cosmic ray flux incident on the atmosphere [e.g., see reviews by Rosenberg and Lanzerotti (1979) and Herman and Goldberg (1978)].

For example, at 10 km altitude the relative intensity of cosmic rays increases by a factor of 2 between the equator and the auroral zone. Beyond geomagnetic latitude 70°, essentially all cosmic rays have access to the top of the atmosphere and the effective cutoff is only atmospheric. Within the polar cap at an altitude of ~20 km the energy deposition (or ion production) rate varies by about a factor of 2 within one solar cycle and from one cycle to another.

The combined effects of latitude and solar cycle variation on the atmospheric ionization caused by galactic cosmic rays are best illustrated in Figure 6.5 (Herman and Goldberg, 1978; Ney, 1959). This figure shows for cycle 19 the percentage reduction of the rate of ionization between solar minimum (1954) and solar maximum (1958) as a function of altitude and geomagnetic latitude. At the 100 mb level (~16 km), approximately the height of the equatorial tropopause, the percentage change ranges from -4 percent near the equator to -25 percent in the polar cap. However, the polar tropopause is nearer to the 300 mb level (~10 km) where the percentage ionization rate change is probably ≤20 percent.

As regards sunspot numbers, cycle 19 is the largest on record. Thus, the percentage changes indicated in Figure 6.5 are probably as large as one can expect at these altitudes and latitudes from the solar cycle modulation of galactic cosmic rays. From (7) we note that a 20 percent change in Q represents only a $(1.2)^{1/2}$ or 10 percent change in the ionization density.

In addition to the solar cycle dependence, the galactic cosmic ray flux incident on the atmosphere experiences short-term variations associated with Forbush decreases, the recurrence of solar active regions (~27-day period), and the passage of solar magnetic sector boundaries (~7-day period). Variations of ionization density in the lower atmosphere due to the latter two effects probably do not exceed 10 percent.

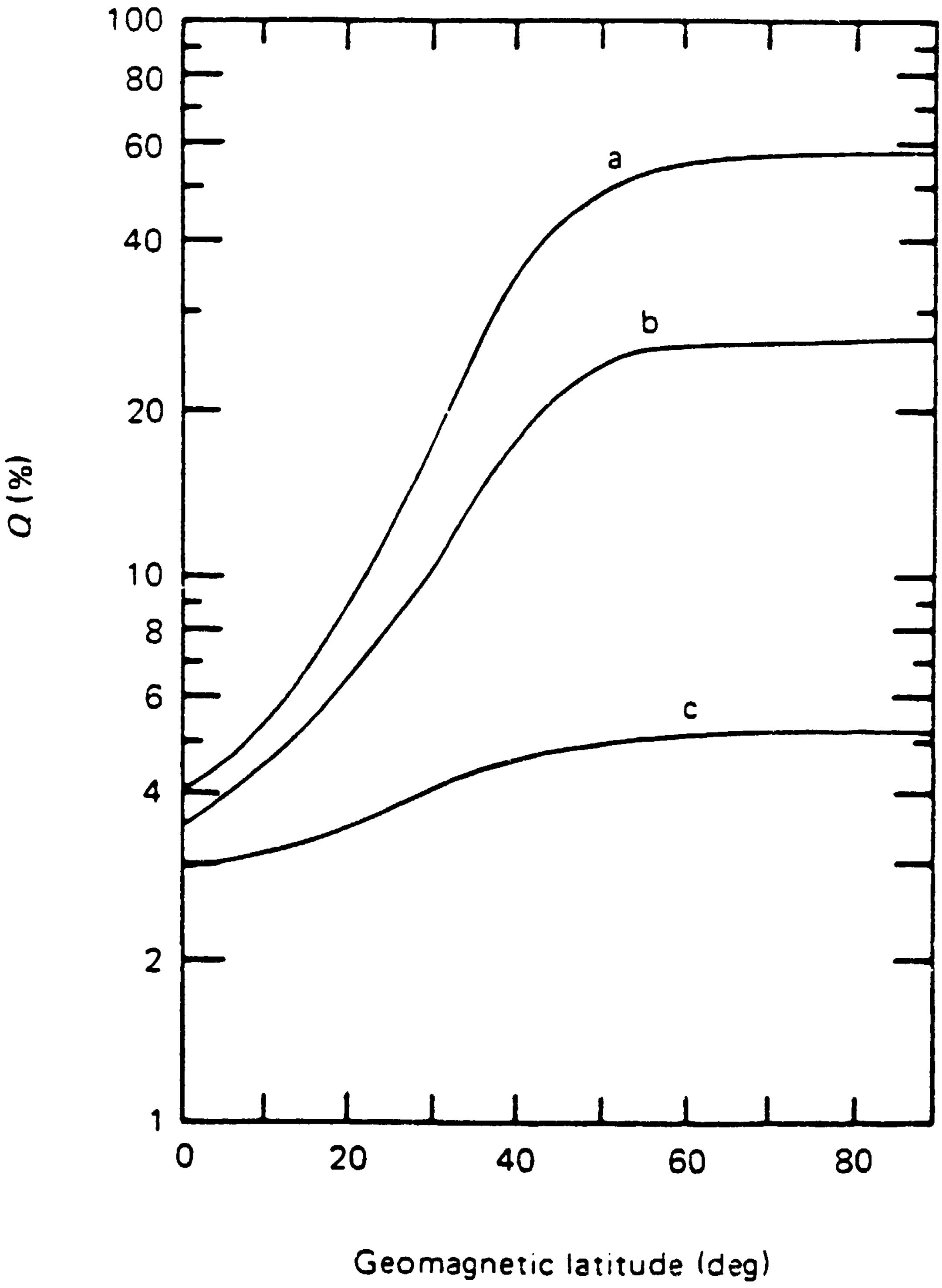


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Figure 6.5. Percentage reduction of ionization rate between solar minimum (1954) and solar maximum (1958). a) 10-mb level; b) 100-mb level; c) sea level (from Ney, 1959; Herman and Goldberg, 1978).

The Forbush decrease is a pronounced reduction of cosmic ray intensity (lasting for several days) associated with geomagnetic storms that follow major solar flares. Ground level intensity changes during Forbush decreases can reach 50 percent at high latitudes and 10 percent at low latitudes. Thus, it should be noted that the reduction of ionization density during Forbush decreases is expected to be comparable with the percentage change attributed to solar cycle modulation (Herman and Goldberg, 1978).

The major solar flares that give rise to Forbush decrease effects usually spawn solar cosmic ray events. However, most solar proton events are not sufficiently energetic to ionize directly at the level of the polar tropopause (see next section), and thus the Forbush decrease dominates. To enhance the ionization at this height for all but the most unusual solar proton events (the August 1972 events, for example) would require the downward transport of ions produced at higher altitudes (above 20 km).

Height Profiles of Ion Production Rate and Density. From the cosmic ray measurements of Neher (1971), Herman and Goldberg (1978) derived the altitude dependence of ion production rate shown in Figure 6.6 for two solar cycles. This profile refers specifically to the ionization rate over Thule ($\lambda_m \approx 90^0$), but it should also be applicable to geomagnetic latitudes as low as ~60° where the pronounced latitudinal (cutoff) dependence begins. The production rate exhibits a maximum of ~30-40 ion pairs cm^{-3} sec^{-1} near 13 km depending on the phase of the solar cycle and varies from ~25-30 $cm^{-3}sec^{-1}$ at 10 km to ~5$cm^{-3}sec^{-1}$ at 30 km.

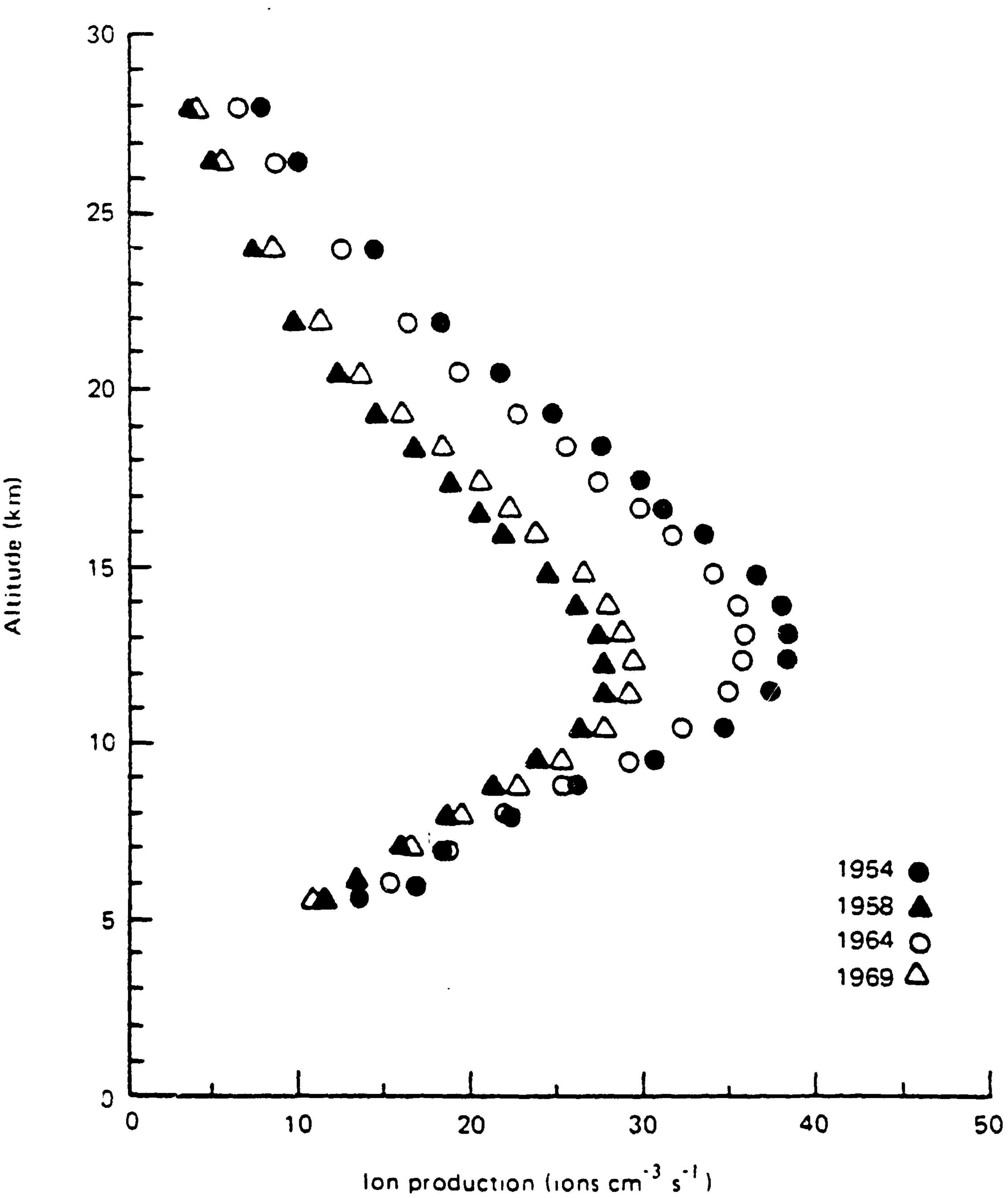

Figure 6.6. Altitude dependence of ionization rate in the polar cap over two solar cycles (Herman and Goldberg, 1978).

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Combining the Q values of Figure 6.6 with the α_i values (DNA, 1972) of Figure 6.2 in eq. (7), the height profile of ionization density $N^+(=N^-)$ shown in Figure 6.7 is obtained. The ionization density maximizes at ~20 km or above, but, as was remarked earlier, the variation with solar cycle at the polar tropopause is ≲10 percent. These results are compatible with the more rigorous calculations of Cole and Pierce (1965).

6.3.2 Solar Cosmic Rays

The entry of solar cosmic rays into the atmosphere is influenced by geomagnetic cutoff effects, as was previously described for galactic cosmic rays. However, because the solar cosmic ray spectra (almost exclusively protons) are considerably less energetic than galactic spectra, penetration is confined primarily to the polar caps.

A measure of the extent of solar proton bombardment of the atmosphere during solar flares, obtained from measurements of the ionospheric absorption of galactic radio noise, is shown in Figure 6.8 (Reid, 1974). The disturbed regions normally extend to the outer curve, at ~60° invariant latitude, which corresponds to a cutoff of ~100 MeV. Direct satellite measurements of solar proton fluxes at low altitudes agree with this estimate of equatorward penetration (e.g., see Engelmann et al., 1971).

Discrete solar proton events, capable of producing ionization deep in the atmosphere, may number as many as 6 to 12 per year during the active years of a solar cycle (Pomerantz and Duggal, 1974). Ionization rates due to solar protons have been computed for a number of flare events. Figure 6.9, from Potemra (1974), shows that the ionization rates can maximize at altitudes between 40 and 80 km, indicating that the spectra of individual events vary widely.

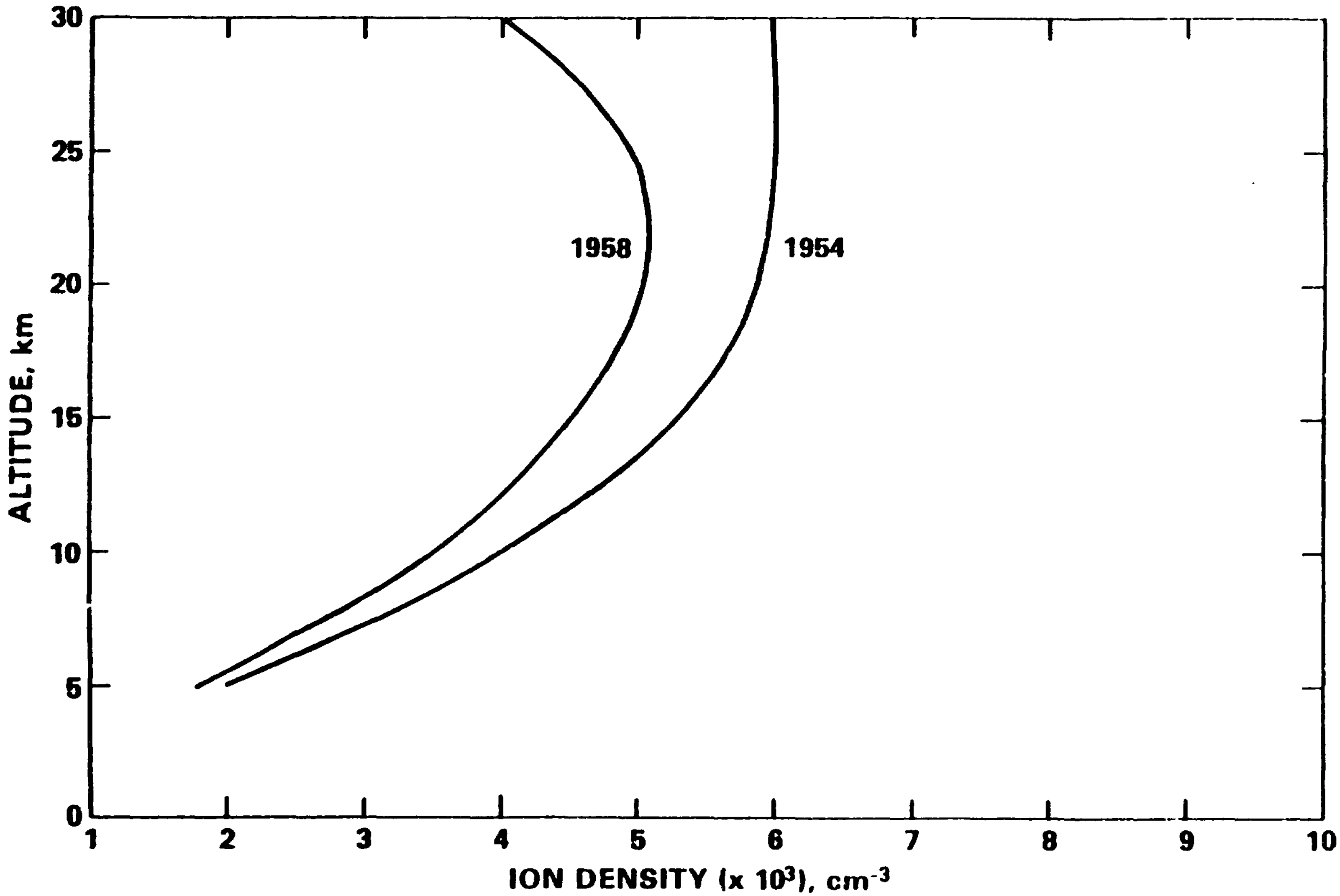

Figure 6.7. Altitude dependence of ionization density $N^+(=N^-)$ derived from the ionization rate profile of Fig. 6.6 and the α_i profile of Fig. 2.

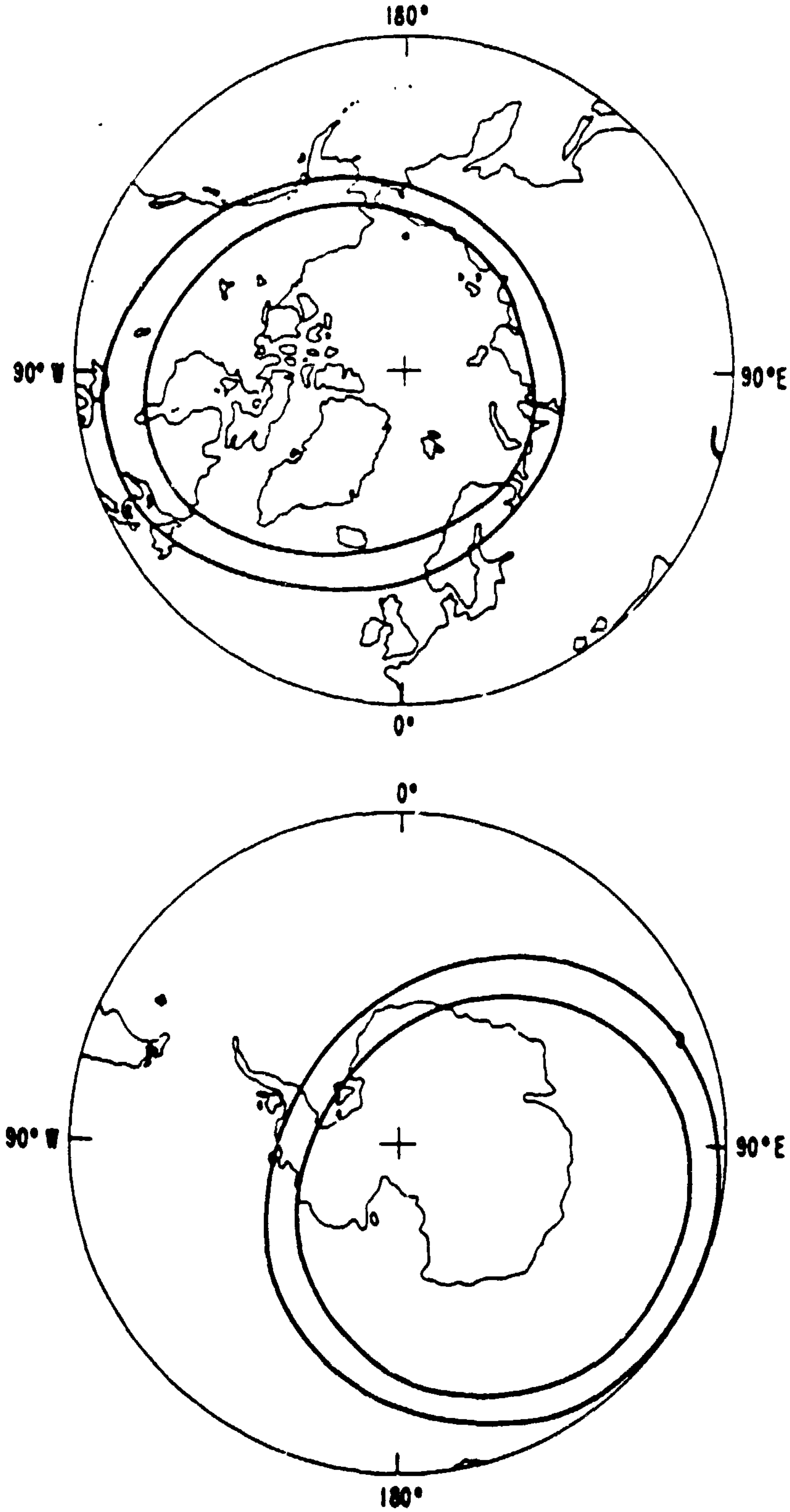

Figure 6.8. Spatial extent of ionospheric absorption of galactic radio noise caused by influx of solar flare protons. Disturbed regions normally extend to a cutoff latitude (outer curve at ~60° invariant latitude) equivalent to ~100 MeV protons; maximum disturbance effects occur within the inner curve (at ~65° invariant latitude) equivalent to ~10MeV protons (Reid, 1974).

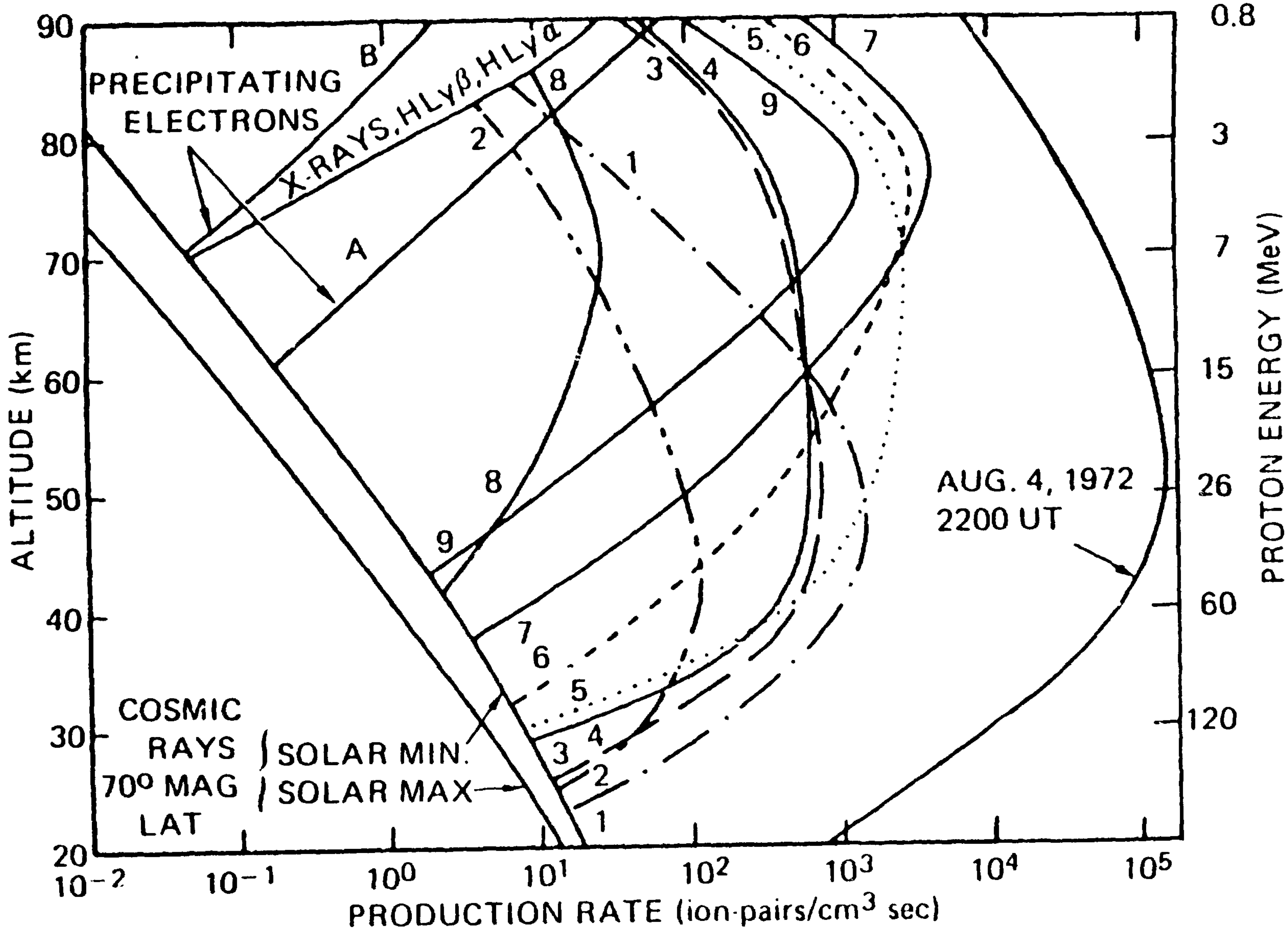

Figure 6.9. Ionization rates computed for several sclar flare proton events (Potemra, 1974).

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Furthermore, it is not uncommon for solar proton ionization to greatly exceed that due to galactic cosmic rays at altitudes from 20 to 30 km (such events must contain significant fluxes of protons with energies in excess of 100 MeV). However, as others have remarked (Dessler, 1975), it is difficult to visualize solar proton ionization as being a major factor in cirrus cloud formation because the top of the polar troposphere is at about 10 km where solar protons rarely penetrate. During the extremely energetic events that seem to occur once every few years, ionization enhancements may exceed galactic background levels at altitudes ≤ 10 km. But their rarity argues against their importance to cirrus cloud mechanisms.

On occasion the sun produces cosmic rays with energies as high as several GeV, which can be recorded at ground level. For an hour or so for each event, the events can exceed, by several tens to several hundreds of percent, the galactic cosmic ray intensity levels. Fewer than three dozen such events have occurred since their discovery in 1942 (Pomerantz and Duggal, 1974). Most (but not all) ground level events are followed by the regular, long (several days) proton events produced by the lower energy proton fluxes. The importance of ground level events for atmospheric processes and dynamics, other than for producing intense, short-lived atmospheric ionization, may be in any "triggering" process they may initiate.

6.3.3 Solar X-rays

X-rays entering the earth's atmosphere penetrate more deeply and ionize more uniformly than charged particles of the same energy. The x-rays are attenuated by photoelectric absorption and Compton scattering processes.

Penetration to altitudes below 30 km is limited to x-rays with initial energies greater than ~15 keV ($\lambda < 1$ Å). For photons of 100 keV energy, more than half of the energy flux is deposited below 30 km.

The steepness of the solar spectrum below 10Å makes the sun normally a weak emitter of X-rays in this region, although flux levels exhibit extreme variability with solar activity (Kreplin et al., 1977). Large increases of the flux of hard solar x-rays (λ<1Å) occur mainly in connection with the major flares that lead to solar cosmic ray (proton) events. As a rough guide, the frequency of occurrence of importance 3 flares varies from about 1 every 3 weeks during solar maximum to about 1 every 3 years during solar minimum (Smith and Gottlieb, 1974).

In contrast to solar particle events which may last for a few days to a week, hard solar x-ray events are typically short-lived ($\lesssim$15 minutes). In fact, the most energetic, impulsive phase of such events is confined to the first minute or two.

At the shortest wavelengths the x-ray energy flux may increase during solar flares by as much as 3 orders of magnitude over pre-flare levels, reaching values of ~3 ergs cm^{-2} sec^{-1} for λ<10Å. Nevertheless, the energy flux deposited in the atmosphere below 30 km appears always to be insufficient to produce ionization enhancements competitive with that of the galactic background.

The short duration of hard solar x-ray events and their relatively infrequent occurrence severely restricts their importance as a sun-weather coupling agent. Whether or not the ionization from solar flare x-rays can serve as a "trigger" source for some geophysical or meteorological process is unknown.

6.3.4 Bremsstrahlung X-Rays

Bremsstrahlung X-rays in the atmosphere are derived almost exclusively from energetic electrons which precipitate from the magnetosphere during auroras and geomagnetic storms (solar electrons are a less important source). For the electrons, the energy influx varies from 10^{-1} to 10^{+3} ergs cm^{-2} sec^{-1} in the auroral zone and from 10^{-4} to 10^{-2} ergs cm^{-2} sec^{-1} at middle latitudes. The corresponding bremsstrahlung flux is ~0.01 to 1 percent of the above values. During intense geomagnetic storms, the middle latitude flux values may go higher.

The spectrum of precipitated electrons in the auroral zone is characterized by the relatively low energy (<10keV) electrons that produce the visible aurora at night and the higher energy electrons (<40keV) that are principally responsible for the radiowave absorption recorded on the dayside by riometers. Midlatitude precipitation, generally, is characterized by high energy spectra.

Profiles of the ion production rate due to bremsstrahlung have been given for representative examples of electron energy spectra by Johnson and Imhof (1975), Reagan (1977) and Rosenberg and Lanzerotti (1979). Figure 6.10, from Rosenberg and Lanzerotti, shows that bremsstrahlung ionization falls to less than 10 percent of the cosmic ray ionization below 30 km, in general agreement with other calculations. Below 20 km, the bremsstrahlung contribution is negligible. This led Johnson and Imhof (1975) to conclude that bremsstrahlung is not an important factor in influencing cirrus cloud formation at the level of the midlatitude-polar tropopause.

Precipitation events containing electrons with energies in excess of 200 keV are known to occur during some geomagnetic storms and substorms. Evidence of unusually energetic electron spectra, including peaks at ~1 Mev, have been found in satellite data (Figure 6.11). Such events have been called relativistic electron precipitation events (rep) and may play a role in altering the stratospheric composition (Thorne, 1977). However, the frequency of occurrence, spatial extent, and intensity levels of such events have yet to be thoroughly investigated. Their significance, if any, for cloud formation processes, remains dubious at this time.

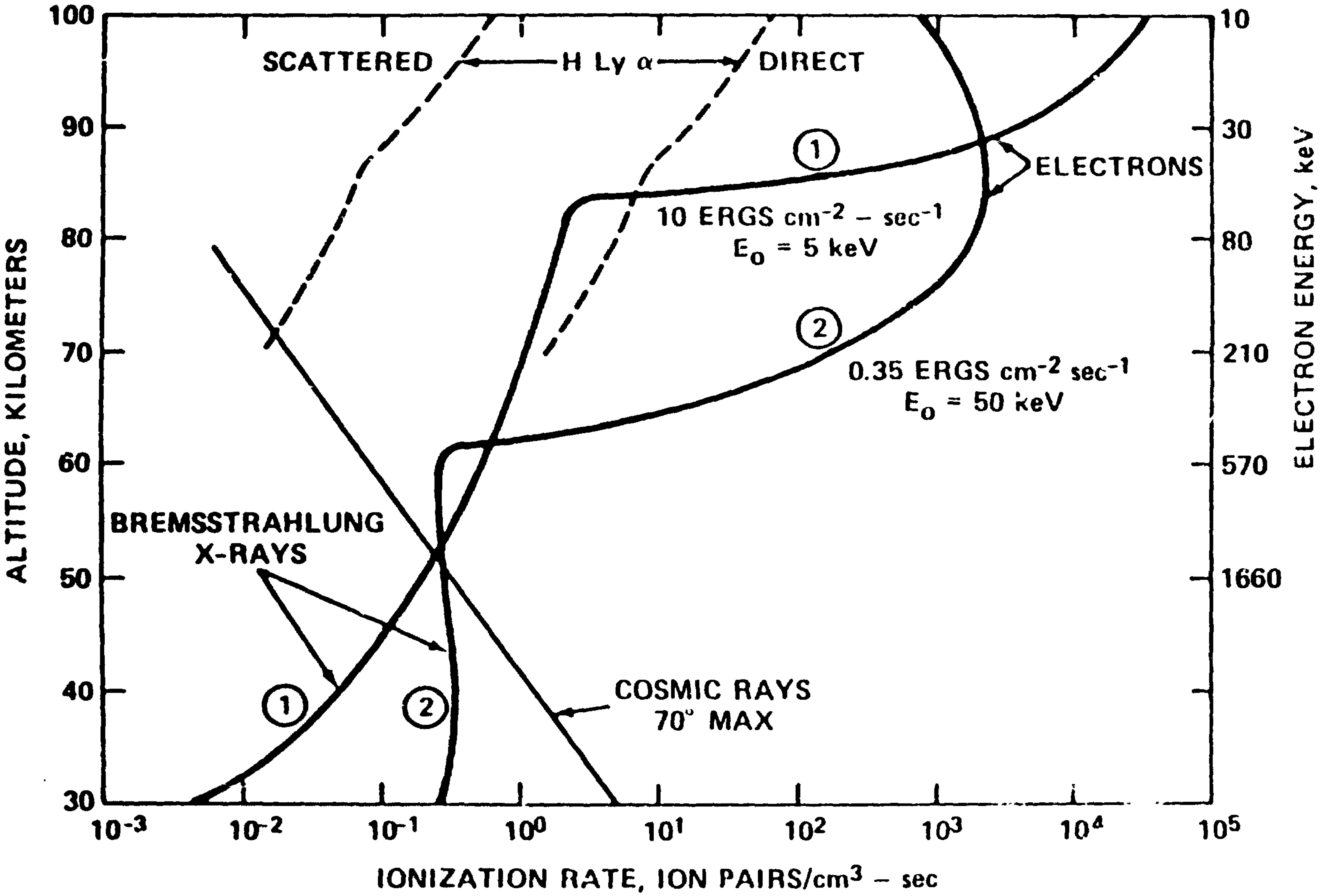

Figure 6.10. Ionization rates due to bremsstrahlung x-rays and parent energetic electrons for energy spectra characteristic of soft (auroral) and hard (dayside and midlatitude) precipitation fluxes (Rosenberg and Lanzerotti, 1979).

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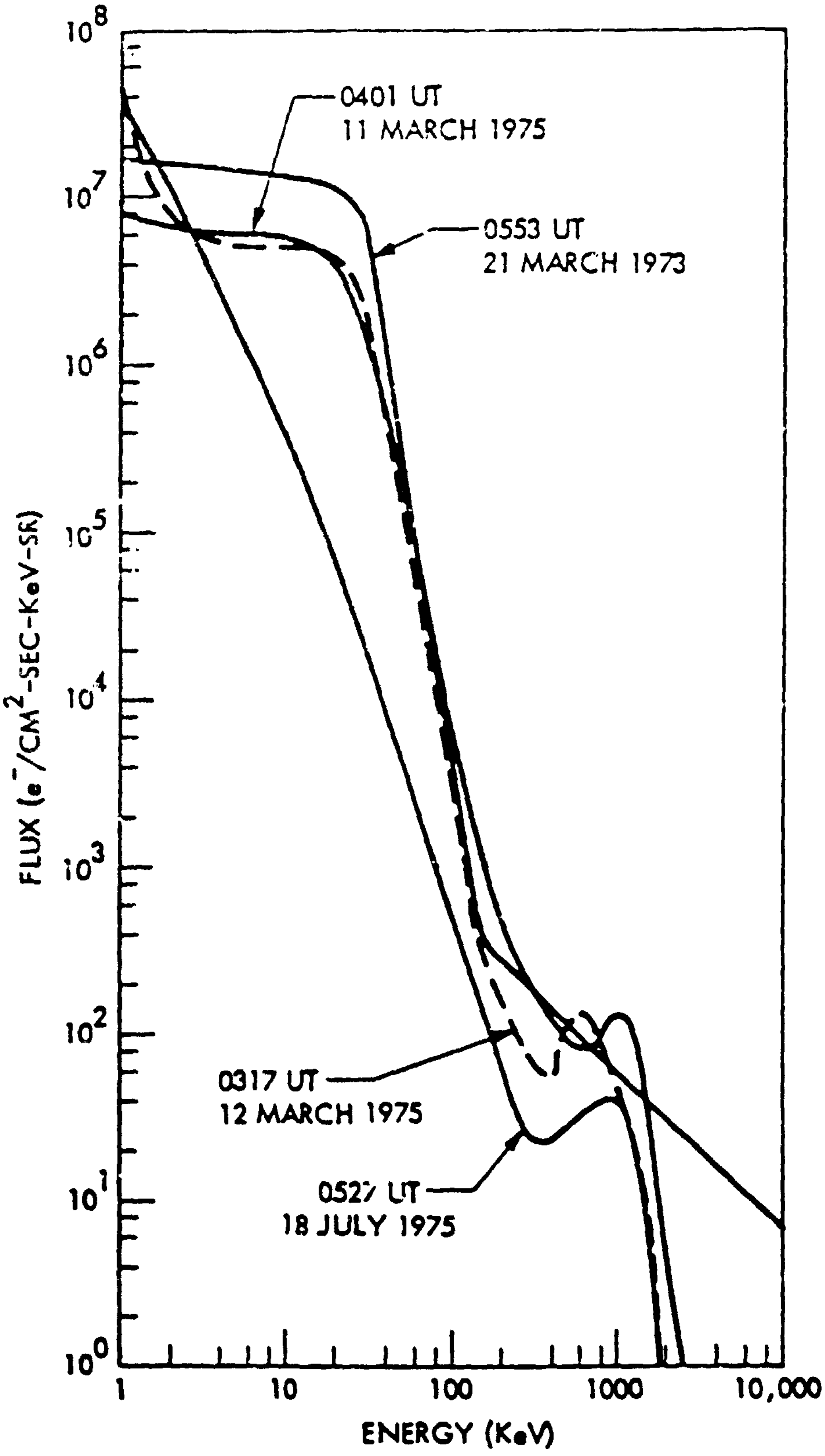

Figure 6.11. Spectra of unusually energetic precipitated electrons from low-altitude satellite data (Imhof et al., 1977).

6.4 Summary and Conclusions

Mechanisms for the formation of cirrus clouds at middle to high latitudes, which depend on altering the ionization near the tropopause pre-suppose the necessity to increase, rather than decrease, the ambient ionization. Both short-term and long-term dependences of galactic cosmic ray ionization on solar activity lead to ionization decreases, with minimum levels reached during the solar maximum phase. Significant ionization enhancements at the polar tropopause are rarely produc d directly by solar cosmic ray events. Solar x-ray and bremsstrahlung x-ray events are non-competitive at this heig t. The possibility that ions produced at greater heights by solar particle events or by the most energetic of magnetosphere electron precipitation events (via bremsstrahlung) are transported downward needs further investigation.

The hypothesis that a sun-weather coupl ng effect is involved in high latitude cirrus cloud formation rests in part on scanty observ tional evidence. A serious investigation of the plausibility of this mechanism will require:

1. The development of an index of cirrus cloudiness (perhaps semi-regional in the sense of, say, tropical, temperate, and polar) which could be correlated with measurements of ionization density.

2. A continuing program of ionization measurements at several latitudes (as above), which if carried out for several decades would provide a sufficiently long data base with which to begin statistically meaningful correlations.

7. SUMMARY OF RECOMMENDATIONS

The foregoing recommendations are re-organized and summarized here to serve the purpose of encouraging further research on cirrus clouds and their possible connection with sun-weather influences. While believing that there may indeed be something to this connection, we note that sufficient observational data on cirrus do not yet exist for a good test of the idea; also some of the processes involved are not yet described experimentally or theoretically, making it hard to fill in the observational gaps. Therefore our recommendations are pointed toward new information on the fundamentals of cirrus formation and influence in the atmosphere, and on the realities of cirrus processes as seen in nature or modeled in the laboratory.

7.1 CIRRUS OBSERVATIONS IN THE ATMOSPHERE

7.1.1 General

- Develop instrumentation for detecting presence of thin cirrus clouds.
- With such instrumentation, set up a continuous, large area thin cirrus survey program to be coordinated with routine monitoring of solar activity.
- Develop an index of cirrus cloudiness, that might even be regional (e.g., tropical, temperate, polar), which can be correlated with measured ionization density in the atmosphere (relates to 7.1.3 below).
- Evaluate certain records of cirrus cloud cover that might contain indications of a sun-weather connection.

7.1.2 Groundbased Measurements

- Conduct coordinated studies of the cirrus layer, preferably at several locations, by means of lidar, radiometry and solar aureole methods, to obtain the altitude dependence of particle size distributions and to follow the development of cirrus clouds.

- Concentrate observations in clear sky areas and in regions of special relevance to the sun-weather questions, such as the Gulf of Alaska.

7.1.3 Aircraft/Balloon Measurements

- Encourage increased pilot reporting of cirrus, particularly cloud heights, types and approximate visual contrast (or visibility).

- Develop compact and simplified optical systems and particle samplers, so that enhanced programs of cirrus measurements using airborne platforms will be effective and reasonably priced.

- Employ lidar, radiometry, particle sampling, ionization detectors and other devices on balloons and aircraft, to obtain more information on altitude-dependent properties of cirrus than can be seen from the ground.

- Identify the small positive and negative cluster ions at cirrus altitudes.

- Measure humidity, temperature, aerosols and ionization at cirrus altitudes to identify any connection that the particulate density may have with atmospheric ionization changes, including those initiated at the sun.

- Set up a continuous program of ionization measurements at several latitudes, with the intention of obtaining at least a decades-long data base, i.e., a long enough record for statistically meaningful correlation with other solar and atmospheric parameters.

- Determine the makeup of the active (ice-forming) condensation nuclei in cirrus clouds, and relate this to the composition of stratospheric aerosols to see if they are frequently different or the same, and whether there is a connection between the two that simplifies the process of cirrus formation.

- Concentrate airborne measurements in the region of cirrus generating cells, with particular attention to the size and chemical composition of the condensation nuclei (input for 7.2 below).

7.1.4 Satellite Measurements

- Increase research that will obtain improved cirrus cloud cover information from existing meteorological satellite imagery, and that will bring about better instruments for future work on cirrus.

- Support cirrus information-retrieval studies on the data base now being generated by limb-scanning instruments such as SAM-II and SAGE.

- Develop early Shuttle lidar instrumentation to measure aerosol density, ice crystals vs water drops, cloud-top heights, and the altitude profiles of [H_2O], temperature and pressure; this would be a forerunner of lidar measurements on a larger scale, as the coverage of the earth by Shuttle orbits increases.

- Use appropriate mixes of the above techniques, involving perhaps both active and passive optical observations (from orbit and the ground) for better interpretation of scattering, absorption, emission and extinction by cirrus clouds.

7.2 Laboratory Measurements

- Given *in situ* determinations of cirrus nucleus size and chemical composition, employ cloud chambers or a similar controlled environment to study the effects of various parameters on nucleus activation (input for 7.3 below).

- Measure the effects of having net electrical charge on an aerosol particle, as regards enhancement of nucleation into both the liquid (water) and solid (ice) state.

- Determine ventilation coefficients for ice crystal shapes and sizes (such as bullet rosettes) typical of cirrus, most likely under controlled conditions in a wind tunnel simulator of the cirrus environment (also input for 7.3 below).

- Identify kinetic processes for positive and negative small ions and measure their reaction rates, with particular attention to the kinetics of ion clustering and attachment to condensation nuclei or dust.

7.3 Theory of Cirrus Formation

- Employ nucleus activation data from cloud chambers as an empirical guide in developing a theory of heterogeneous nucleation.

- Quantitatively model the formation of thin cirrus (and "precipitation" from thin cirrus - see 7.4 below), so as to assess lag times of the atmospheric response to solar-induced ionization.

7.4 Theory of Cirrus Effects on Atmosphere

- Apply ventilation coefficient data on cirrus-like ice crystals in models of the seeding of other clouds by cirrus.

- Design and carry out numerical simulations of observed thin cirrus cloudiness on radiative divergence and wintertime circulation patterns.

7.5 A Measurement Strategy?

We note that the above list *(i)* is not prioritized, *(ii)* would require large amounts of support if funded in its entirety, and *(iii)* contains some elements of cirrus-related research that need to be carried out regardless of sun-weather studies. Therefore it seems appropriate to suggest a strategy relative to the sun-weather question alone, that is not meant to imply priorities in the larger field of cirrus cloud research. Figure 7.1 depicts one such strategy which seems reasonable. Starting from the present level (A)

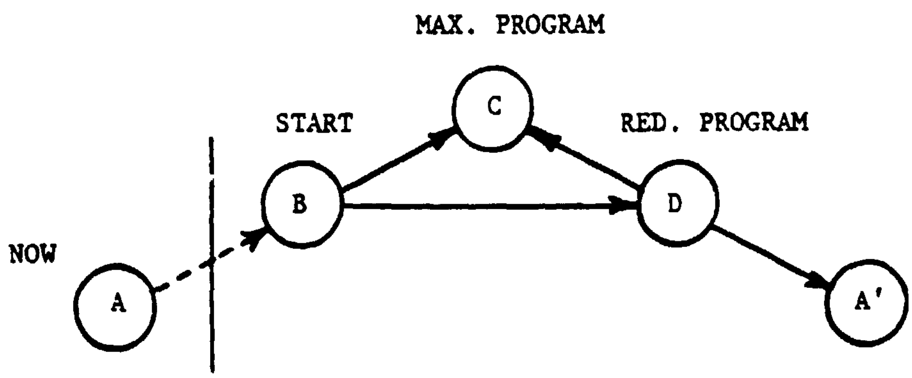

Figure 7.1. Schematic of additional study of sun-cirrus-weather effects

of cirrus cloud research, a reasonable first phase (B) would be to introduce cirrus cloud cover into a global circulation model, and then observe the induced changes in the 7-day predictions. The ensemble of these circulation and weather effects would be assessed for a variety of assumptions as to season, type and degree of global cirrus coverage, etc.

The emergence of large cirrus effects would call for a major research effort (C) entailing many of the items 7.1 - 7.4 above. A small predicted effect, on the other hand, might imply scaling the rest of the program down to (D): thin cirrus detection, cirrus and ionization measurements, and further work on statistical sun-weather relationships.

If none of these new levels of effort were to bear fruit, it would be difficult to justify a large program on the basis of sun-weather work alone. Cirrus research _per se_ would remain the principal justification, as at the present time, and the overall scientific attention to this field would reassume a level (A') comparable to the present level (A).

If, however, phase (D) were to result in persistent evidence of sun--cirrus-weather correlations, the underlying physics of the global circulation treatment (B) would need to be re-examined, and a go-ahead would be in order on the broader program of laboratory and field work, nucleation theory, etc. Thus phase (C) - i.e., the whole program - could evolve directly or indirectly out of research elements strategically chosen for investigation as needed.

These comments are not addressed to the larger field of cirrus cloud research in general, but only to the time-ordering of research elements bearing on sun-cirrus-weather relationships. Many of the research projects outlined above already exist, and should be accelerated solely on grounds of improved understanding about an important region and phenomenon in the atmosphere. In fact, it is in part the lack of basic knowledge about cirrus clouds that currently impedes our knowing whether the sun-cirrus-weather connection can really work or not. We believe that both an increase in the general level of research activity on cirrus clouds _and_ a new initiative on sun-cirrus-weather effects, such as we have outlined here, are desirable.

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Report VII

Thunderstorms and the Sun-Weather Problem

by

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THUNDERSTORMS AND THE SUN-WEATHER PROBLEM

by

J. D. Klett

Preface

It is generally believed that changes on the sun cause changes in the electrical state of the atmosphere. Furthermore, there is now considerable statistical evidence correlating short term solar and weather fluctuations. Therefore, the possibility arises that solar-induced changes in the atmospheric electrical state might somehow produce changes in the weather. The following two specific questions involving this possibility are recently being given increased attention:

(1) Given the statistical evidence that the fair weather electric field responds to short term solar fluctuations, how might such field changes influence the likelihood of thunderstorm development?

(2) Statistical studies suggest that thunderstorm activity increases following solar flares or solar magnetic sector boundary crossings. Assuming these are real effects, could they provide a physical basis for the observed statistical correlations between flares or sector boundary crossings and subsequent changes in the VAI (Vorticity-Area-Index)?

In order to help provide some information which might serve as a basis for answering these questions, in this report I discuss theories of cloud electrification, with emphasis on the possible influence of the ambient field on thunderstorm development, and mechanisms which might link thunderstorms with changes in the VAI.

1. Theories of Cloud Electrification

The construction of theoretical models of cloud electrification has long been one of the more fascinating, although controversial, areas of cloud physics. An abundance of possible charge separating mechanisms involving drops and/or ice particles have been suggested (see, for example, Mason 1971), but with few exceptions it is not very clear which combinations of them, if any, may be of significance in real clouds. A large part of the problem here stems from an insufficient knowledge of the quantitative details of the proposed charging mechanisms, especially in the context of a natural cloud environment. In addition, the sketchy and sometimes apparently inconsistent observational descriptions of electrified cloud states provide at best only a marginally adequate foundation for the construction of theoretical models.

Having thus prudently noted the risks of taking a position at this time, I nevertheless do feel it is possible to discriminate among the various schemes of cloud electrification suggested thus far. And this is especially true of the subset incorporating a significant coupling to the ambient electric field, which is my primary concern here. Of these there are just two prominent candidates, namely the theories of inductive and convective electrification.

The Convective Electrification Hypothesis (CEH)

a) Description of Mechanism: Grenet (1947) and, independently, Vonnegut (1955) proposed that a convective cloud may operate as an electrostatic energy generator according to the following scenario (see Fig. 1): In the early stages of the life cycle of a cumulus cloud, the main updraft carries with it positive space charge from the lower levels of the troposphere; hence the core of the cloud becomes positively charged. The electrified cloud soon acquires a negative charge layer at its edges due to cloud particle capture of negative ions drifting from clear air to cloud under the influence of the main positive charge. (In other words, the sharp conductivity gradient at the cloud boundary - cloud conductivities are typically one to two orders of magnitude less than outside at the same level in the case of weak electrification, and two to four orders of magnitude less for the case of strong electrification (see, for example, section 17.3 of Pruppacher and Klett (1978) - gives rise to a "traffic jam" effect of space charge buildup. This consequence of a conductivity gradient is also responsible for the net positive space charge found in the lower troposphere.)

As the cloud continues to grow and become a storm, strong downdrafts develop at its sides, carrying the negative charge layer to lower levels where it accumulates as a result of thermal stability. (These downdrafts are envisaged mainly as a dynamical consequence of the primary cloud circulation, in which downward motions at the cloud periphery are presumed to compensate for the air displaced by the main updraft structure. Local evaporative cooling of the cloud boundary regions by virtue of the entrainment of dry air is also thought to reinforce the downdrafts.) As the cloud sheds its negative charge via the downdraft, the main positive core is re-exposed, initiating again the negative "screening" charge formation process. Eventually, sufficient negative charge accumulates around the lower sides and base of the cloud to cause a strong reversal of the electric field at the ground beneath it. This leads further to point discharge of positive ions at the ground, which are carried by the main updraft into the cloud core, thus reinforcing its central positive charge. The continuance of this positive feedback cycle can thus lead to a strong buildup of electrostatic energy at the expense of the organized cloud convective motions.

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b) <u>Feasibility of Convective Electrification</u>: On close inspection this imaginative concept of cloud electrification can be found wanting in several respects. For example, observations generally do not support the notion of strong downdrafts at the flanks of a thunderstorm, even in its mature stage (see Fig. 2). Extensive and sustained downdrafts are observed (and theoretically expected) to be caused by precipitation, and so generally occur during and after the mature stage, usually subsequent to the period of rapid electric field growth, and usually at locations other than the cloud edges.

Also, it seems quite implausible that the negative screening layer charge accumulations, should they occur, could avoid being disrupted and dissipated by turbulent mixing and convective transport back into the updraft structures. And, even if they could survive such dynamical threats, one wonders how they could also be expected to evade neutralizing currents from the corona discharge they are supposed to initiate: One would expect the positive point discharge current to closely follow the electric field lines from the ground right back up to the negative screening layer charge, except possibly for a very small volume fraction which happens to get diverted by an updraft strong enough to overwhelm the conductive ion velocities. (It is interesting to note that if one follows the philosophy of the convective charging mechanism here, one might well expect the corona current to quickly mask the negative charge accumulations with still another screening layer, this time of positive charge!)

The CEM also ignores the fact that the cloud is exposed, at least in its early stages of development, to the fair weather electric field. Since clouds are poor conductors we would expect the fair weather field to drive a net flux of negative ions into the base of a newly formed cloud, and positive ions into its top. Therefore, the sign of the charge to be expected in the base and core of a young cloud depends on whether the net upward conduction current of negative charge is greater or less than the upward convection current of positive charge considered in the convection charging model.

A simple estimate of these competing currents may easily be made, using representative fair weather values for the various quantities (taken from section 17.1 of Pruppacher and Klett [1978]). Thus, if we assume a fair weather field of $E = 10^2$ Vm^{-1}, a negative ion concentration $n_- = 5 \times 10^2$ cm^{-3}, a negative ion mobility $B_- = 2$ cm^2 V^{-1} sec^{-1}, a reasonable updraft speed of $W = 1$ m sec^{-1}, and an average positive space charge density at cloud base level of $\rho_+ = 5$ e cm^{-3}, we find that the ratio of the convection and conduction currents is $\rho_+ W/en_-B_-E = 5 \times 10^{-3}$. Hence the field-driven deposition of negative ions should dominate completely, so that a young convection cloud should have a negatively charged base and core. This expectation is in fact generally supported by observations of fair weather clouds. For example, the field studies of Reiter (1964, 1969) showed that electrified stratocumulus, altocumulus, and convection cumulus clouds which contain neither ice nor precipitation-sized particles are electrically bipolar with a pronounced negatively charged base and a positively charged upper portion. Also Takahashi (1972) observed predominantly negatively charged drops in the bases of warm clouds in Hawaii.

The above qualitative indications and observational evidence for the cloud charge structure to be expected in the absence of precipitation charging processes is also entirely consistent with theoretical simulations of the CEH carried out to date (Ruhnke, 1970, 1972; Chiu and Klett, 1976; Chiu, 1978). Ruhnke calculated the electric fields and charges one would expect in response to a fairly simple steady pattern of solenoidal flow intended to represent approximately the circulation of an isolated convective cloud. The cloudy region of nonzero liquid water content was assumed to be a spherical volume lying within the updraft of the flow. Chiu and Klett (1976) used the analytical, axially symmetric, nonprecipitating convective cloud model of Gutman (1963,

1967) in their numerical study of the feasibility of convective electrification. They included the transport of charge by convection, conduction, and turbulent diffusion. The conductivity gradients which might lead to charge accumulations were accounted for by relating the dependence of cloud conductivity on liquid water content through the actions of microphysical ion capture processes. Chiu (1978) based his study on a modification of the time dependent numerical cloud model of Liu and Orville (1969), in the most comprehensive and sophisticated modeling effort yet attempted. (Chiu's model is described more fully in section 2.)

The important point to be made here is that all of these theoretical studies demonstrated that for usual conditions of cloud formation a charge distribution in general qualitative agreement with that discussed above is produced, namely a negatively charged core capped by a relatively thin positively charged upper layer. (However, Chiu and Klett also found that convective transport of positive charge may dominate the conductive transport of negative charge, and thus produce a cloud of polarity opposite to the usual case, if the cloud forms near ground level. This happens primarily because higher concentrations of positive space charge are then available to be carried aloft into the cloud. But even for this atypical situation, the space charge played a very inactive role, and functioned mainly as a passive marker of the cloudy air. In particular, the overall state of electrification remained weak.)

It should be stressed that these theoretical formulations have included the essential physical mechanisms which have been purported to lead to convective electrification, and that, especially in the case of Chiu's study, this has been accomplished in the context of a realistic cloud environment. Therefore, I believe the negative implications for the CEH should be taken seriously by those who continue to advocate it. So far, however, their response has been simply to ignore these results, the preponderance of observational evidence over many years, and the even more important recent new field data (discussed below) supporting the idea that precipitation charging is crucial to cloud electrification. Despite the evidence that the CEH is untenable, it is nevertheless still so much a part of the cloud physics landscape that no doubt further reference to it as a viable mechanism will continue to be made.

The Theory of Inductive Electrification

a) Description and Elementary Theoretical Considerations: The physical basis of induction charging is quite straightforward, and may easily be illustrated by considering the case of uncharged spherical particles exposed to an ambient, downward directed electric field of strength E. The polarization charge induced on an isolated conducting sphere by the ambient field is expressed (in e.s.u.) by the surface density $\sigma = 3E \cos\theta/4\pi$ where θ is the polar angle measured from the lowest point of the sphere; thus the lower hemisphere is positively charged, and the upper hemisphere negatively charged. Therefore, if such a sphere were to experience on its lower hemisphere a momentary electrical contact with, and subsequent separation from, a similarly polarized smaller sphere, there would result a net negative charge on the larger sphere and a positive charge of equal magnitude on the smaller sphere (see Fig. 3). Elster and Geitel (1913) were the first to point out that such a process of inductive charge transfer, occurring throughout a cloud and followed by the large scale separation of charge through relative sedimentation under gravity, would serve to increase the in-cloud electric field in the sense normally observed in thunderstorms.

Elster and Geitel also provided a simple estimate of the maximum charge transfer that could occur for the case of an uncharged sphere of radius a_2 which contacts the lowest point ($\theta = 0$) of an uncharged sphere of radius $a_1 \gg a_2$ in ambient field E. In this case the smaller sphere will acquire a charge

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with average density equal to $\pi^2/6$ times the density of charge on the larger sphere at the point of contact, since the curvature of the larger sphere can be ignored (the capacitance of the small sphere in contact with a conducting plane is $C_2 = a_2\ \pi^2/6$). Thus the maximum charge that can be acquired by the small sphere is approximately

$$\frac{\pi^2}{6}\ (4\pi a_2^2)(\frac{3E}{4\pi}) = \frac{\pi^2 E a_2^2}{2} \approx 5Ea_2^2\ .$$

For a breakdown field of 10 e.s.u. = 3 x 10^5 Vm^{-1}, this charge for a one mm diameter sphere is approximately 0.1 e.s.u. or 30 pC. This charging magnitude is large enough to suggest that induction charging can produce strong cloud electrification.

However, any quantitative assessment of the efficacy of induction charging (also referred to as polarization or influence charging) must take into account several other factors as well. For example, let us first consider the more realistic situation where contact occurs for $\theta \neq 0$, and the spheres initially carry charges Q_1 and Q_2. Then, by a simple extension of the arguments given above, the charges after contact and separation will be Q_1' and Q_2', where $Q_2' = \frac{\pi^2}{6} a_2^2\ (3E \cos\ \theta + Q_1'/a_1^2\ )$. On writing $Q_2' = Q_2 + \Delta Q$ and $Q_1' = Q_1 - \Delta Q$, we thus find that the charge transferred is given by

$$\Delta Q = \frac{\pi^2}{2}\ E\ a_2^2 \cos\ \theta + \frac{\pi^2}{6} p^2 Q_1 - Q_2 \qquad (1)$$

where $p = a_2/a_1 \ll 1$. (The problem of finding ΔQ for arbitrary p on the interval $0 < p < 1$ has been solved by Davis (1964).) This expression shows that induction <u>dis</u>charching may occur also; i.e., ΔQ may be negative for sufficiently large θ and $Q_2 > 0$. Since θ represents the polar angle between the point of contact and the electric field, and since the latter may have a large horizontal component in some cloud regions, we see that even collisions restricted to the lower hemisphere of the large sphere may result in $\Delta Q < 0$.

Consideration of the electrical contact angle Θ brings additional problems into focus. Thus, to evaluate ΔQ in Eq. (1) we must have available eith theoretical or experimental information on the collision trajectories of charged particles in a background electric field. But such information is presently available only for a limited range of radii, field strengths and directions, and charges. Furthermore, we must determine the Θ-dependence of the probability that separation actually occurs after contact is made. Very little quantitative information is available on this point. The best we can say is that laboratory evidence implies that coalescence should generally follow a collision between drops under natural conditions unless they are larger than a few hundred microns in radius (see section 14.8.1 of Pruppacher and Klett (1978)). This behavior, combined with the observed tendency of drop charge to enhance the coalescence probability, leads one to suspect that the effectiveness of inductive charge transfer must be quite small for water drops. Also, the high coalescence probability suggests that there is a tendency for this charge separation mechanism to be "shorted out" as large drops rapidly accrete smaller oppositely charged droplets (e.g., Colgate (1972), Moore (1975)).

Some of these difficulties can be avoided by applying the inductive charging mechanism to ice-ice or ice-water interactions, since for these the separation probabilities, $\varepsilon(\Theta,\vec{E},Q_i,a_i)$, are expected to be significantly higher than for water-water (though unfortunately very little quantitative information is available on the actual values of ε). On the other hand, for such interactions an additional physical barrier to charge separation may enter in, namely the relatively long relaxation time for charge conduction through ice ($\approx 10^{-2}$ sec at -10°C). In addition, the more complex geometry and dynamics for these cases greatly complicates the quantitative assessment of the relevant processes and parameters.

In addition to the microphysical uncertainties associated with the operation of induction charging as pairs of cloud particles interact, one should, of course, not lose sight of the larger scale problem of demonstrating quantitatively how a myriad of such interactions might lead to strong cloud electrification. Here just the bookeeping problems look enormous. As for a reasonably rigorous treatment it appears one should account simultaneously for the growth and charge histories of populations of particles over a seven order of magnitude range of sizes (from < 10^{-2} μm for condensation nuclei to > 10^{4} μm for raindrops and > 10^{5} μm for hailstones), a four order of magnitude range of electric field strengths (from a fair weather value of < 10^{2} Vm^{-1} to a breakdown value of 10^{5} - 10^{6} Vm^{-1}), and at least an eight order of magnitude range of particle charge.

b) <u>Feasibility of Induction Charging in Light of Field Evidence</u>: In spite of the difficulties mentioned above, since recent field research on thunderstorms strongly suggests that only a rather specific set of conditions leads to strong electrification, the problem of assessing charging mechanisms is perhaps more tractable than might be expected. The recent evidence includes these findings:

1) The charge resides in areas of freezing temperatures. (eg., Brook and Krehbiel, reported in <u>MOSAIC</u>, Nov/Dec 1978, p. 6)

2) The regions of strong charge typically contain precipitation, usually in the form of graupel (soft hail), as well as supercooled water drops and ice crystals. (e.g., ibid., Krehbiel et al (1976))

3) In regions of strong charge, precipitation particles, as opposed to the smaller cloud particles of greater total area, are often the major charge carriers. (Gaskell et al, 1978a,b)

4) Regions of strong charging are rather modest in extent, perhaps typically of the order of one kilometer or less. (eg., Winn et al (1974), Gaskett et al (1978a,b))

5) In an active charging region lightning discharges may occur every 30-40 sec., with subsequent field recoveries which are approximately linear in time. (Winn and Byerly, 1975)

The above field evidence strongly supports precipitation charging mechanims in general, and the theories of induction charging and thermoelectric charging in particular. (The latter theory holds that charge will be exchanged between ice particles at different temperatures if they make momentary contact. The physical basis for the theory is that: 1) The concentrations of hydrogen and hydroxyl ions in ice increase rapidly with temperature. 2) The diffusivity of hydrogen ions is greater than that of hydroxyl ions, at a given temperature. This implies there should be a net flow of positive charge down a temperature gradient in ice. Laboratory evidence has verified this expectation and shown that the transferred charge can sometimes be quite substantial. For example, Reynolds et al (1957) estimated that a charge of 5×10^{-4} e.s.u. was carried away by an ice crystal of 50 micron radius after colliding with an ice sphere a few degrees warmer. Breakdown fields have been reached in highly idealized model studies based on elementary charge tansfers of this magnitude. The literature is also replete with similar model studies based on induction charging; thus in this respect the two charging mechanisms are on somewhat equal footing.)

Charge Relaxation Times and Separation Probabilities

The fact that highly localized, vigorous precipitation charging has now been so well documented tends to vitiate many of the objections that have been raised against induction charging. For

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example, one can argue qualitatively that the possible limiting factors of finite charge relaxation times and small separation probabilities, which in principle should both interfere with all ice-ice charge exchange mechanisms, cannot in fact be very important, or the observed charges could not have occurred (except for the unlikely possibility that some as yet unidentified, but extremely powerful, charge exchange mechanism is responsible for the observed charges). Furthermore, the concern about small separation probabilities has generally been expressed in the context of drop-droplet or graupel/hail-droplet interactions, whereas the observations stress the importance of ice-ice interactions. For these the separation probabilities are known qualitatively to be much higher, perhaps even approaching unity for cold graupel-ice crystal collisions.

Electrostatic Levitation Effects

Similarly, for several reasons the inhibiting effect of electrostatic reductions in particle terminal velocities on charge separation rates, a point raised by Kamra (1970) and others, now appears to be of minor importance: 1) Only the most extreme charges and fields lead to significant velocity changes for most precipitation particles. 2) The fact that regions of strong fields are highly localized minimizes the role played by electrostatic levitation. This has been verified by Illingworth and Latham (1977), who made calculations of the electrical evolution of a cylindrical cloud of defined width, depth, and updraft structure. The role of electrostatic levitation had been previously overestimated by others because of their use of the one dimensional, parallel plate capacitor model, which ignores all cloud structure and yields a uniform field throughout the charging zone. 3) A theoretical study of stochastic charging and precipitation growth in a one dimensional cloud model suggests that electrostatic levitation may even lead to larger ultimate field strength (Levin, 1976). This is due to a retardation of the charging rate relative to the mass growth rate for precipitation experiencing levitation, so that a longer time but ultimately a larger field is required for levitation to limit further field growth. (A similar coupling phenomenon was found for the case of separation probabilities and maximum field strength; i.e., a lower choice of separation probability led to a greater maximum field.) However, the conclusions of Levin are likely overdrawn, because of the deficiencies of the one dimensional cloud model, noted under point 2) above.

Multiple Collisions and Recombination

The argument of Colgate (1972) and Moore (1975), that multiple collisions between charged hydrometeors and smaller cloud particles charged by earlier interactions should significantly interfere with or even "short out" the induction charging mechanism, appears likewise to be ill-founded. In Moore's treatment, extremely small separation probabilities were employed, based on a pessimistic interpretation of the charge separation rates observed for ice particle-water drop interactions by Aufdermaur and Johnson (1972). And, if the tendency for charge recombination was thereby exaggerated, it is no doubt drastically overstated for the case of ice-ice interactions which available field evidence shows now to be the more relevant precondition for strong electrification. Furthermore, the one dimensional cloud framework was used, which in effect provides an unrealistically large volume for the operation of the discharge process. By way of contrast, we note that in the cylindrical cloud study by Illingworth and Latham (1977), referred to above, the effects of multiple collisions were found to be of minor importance. For example, they found that for the case of active charging regions of realistic dimensions, two successive collisions of an ice crystal with hail pellets within the regions of intense field are unlikely to occur, for realistic particle concentrations. A similar result is implied by the study of Chiu (1978), discussed in section 2.

In Colgate's (1972) earlier treatment of the recombination problem for a warm cloud, he invokes a model in which a negatively charged drop falls through a cloud of positively charged smaller drops. The specific drop charge (charge/mass) is argued to be a strongly decreasing function of size, so that the transport length for neutralizing the drop charge becomes comparable to the optical mean free path in the cloud, of the order of 10 meters. This model appears to have negligible observational support at present. In addition, it should be reiterated that an attack on precipitation charging mechanisms in the context of warm cloud electrification now seems pointless.

Intervals Between Lightning and Field Recovery Rates

The short intervals of 30-40 sec. between lightning discharges reported by Winn and Byerly (1974) (Fig. 4) tend to support induction charging, since in the right circumstances induction can lead to a very rapid, nearly exponential growth rate in electric field. On the other hand, Winn and Byerly noted that the observed linear recovery rate of the field between discharges disagrees with certain model calculations of induction charging, which yield predictions of initial rapid field growth followed by a later slowing near breakdown. However, some of this non-linear character is due to the incorporation of unrealistic ionic dissipation currents in the models, which are tailored to avoid the embarrassment of predicting huge fields. Furthermore, the prediction of an exponential growth rate in field is not necessarily inconsistent with the observations, if the interval between discharges is less than the e-folding times of the field. This appears to be the case for at least some of the field changes shown in Fig. 4.

Particle Charge Measurements

Some very recent measurements of particle charges in thunderstorms (Gaskett et al., 1978a,b) are claimed by the authors to demonstrate that induction charging could not have played a major role in the storms investigated (see Fig. 5). The principal argument here is simply that some of the measured charges on precipitation elements far exceed the values that the authors regard as the maximum possible under induction charging, namely

$$Q_m = 5.5\ E\ d^2 , \qquad (2)$$

where Q_m is in pC, E in kV cm^{-1}, and d is the diameter of the spherical particle in mm.

However, Eq. (2) is in fact the maximum charge magnitude only under the restrictive condition that the sphere of diameter d encounters much smaller uncharged spheres. We can derive Eq. (2) from Eq. (1) by setting $Q_2 = 0$ (the condition of uncharged smaller spheres) and $\Delta Q = 0$ (the condition of equilibrium); the result is $Q_{1max} = -3Ea_1^2 \cos\theta = -2Ea_1^2$ on setting $\cos\theta = 2/3$, or $\theta \approx 48^\circ$, the value corresponding to geometrical sweepout and a separation probability independent of θ. This result, so far expressed in e.s.u., equals Q_m in magnitude on introducing the mongrelized units of Eq. (2) (d(mm) = 20 a(cm), E (kV m^{-1}) = 0.3 E (e.s.u.), and Q(pC) = $10^3/3$Q (e.s.u)).

From this derivation of Q_m it is easy to see that if a sphere charged to Q_m were to encounter a smaller charged sphere, an even greater charge could be induced on the larger sphere. This follows directly from Eq. (1) with Q_1 = Qm; then Q_1' = Qm + Q_2. Still larger charges could be attained by the interaction of charged spheres of comparable size. For example, from Davis (1964) it can be shown that for $a_1 = a_2$ we have, in place of Eq. (1), $\Delta Q = (Q_1 - Q_2)/2 + (\pi^2/6)\ Ea_1^2 \cos\theta$, so that the charge on sphere 1 (still the upper sphere, referring to Fig. 3) after the induction transfer is

$$Q_1' = \frac{Q_1 + Q_2}{2} - \frac{\pi^2 E a_1^2 \cos\theta}{6} \quad (3)$$

Thus, for $Q_1 = Q_2 = -2Ea_1^2 = -Q_m$ (again with $\cos\theta = 2/3$), we find $Q_1' = -Q_m(1 + \pi^2/18) = -1.55Q_m$. The limiting charge on sphere 1 after infinitely many equivalent interactions with spheres charged to $-Q_m$ is $Q_{1\infty}' = -Q_m(1 + \pi^2/9) \approx -2.1Q_m$. As another example, if we consider the further interaction of a pair of spheres each bearing Q_1', yielding charge Q_1'' on sphere 1, followed by the further interaction of a pair each bearing Q_1'', etc., then we find after a sequence of n such interactions the charge $Q_1^{(n)} = -Q_m(1 + n\pi^2/18)$. For example, after four interactions sphere 1 will carry a charge $Q_1^{(4)} = -3.19Q_m$. (Incidentally, the expected low values of cloud conductivity imply that no significant erosion of such large charge values by ionic dissipation currents would likely occur.)

The point of these admittedly artificial calculations is to emphasize the stochastic aspect of induction charging within any cloud region of active charge separation. To suppose all solid hydrometeors interact inductively only with small uncharged ice particles is analogous to expecting that all large drops of comparable size in a warm cloud grow at the same rate.

For the same reason it is also naive to expect induction charging to lead to a particle charge vs. size distribution of the form $Q \propto d^2$ (cf. Eq. (2)). The absence of such a relationship in the data of Gaskell et al. (1978a) is interpreted by them as an argument against induction charging: "No evidence was found for the Q/d^2 pattern of charging predicted by the inductive mechanism," (ibid., p. 459). We see from the preceding discussion that the coefficient between Q and d^2 is actually a function of the number of interactions with other charged particles. But this number is a random variable, so that a charge distribution of the form $Q \propto d^2$ actually is not to be expected.

The charge distribution which evolves will be further complicated by whatever degree of collection growth occurs. Qualitatively, it is easy to see that this process should produce some particles with charges much larger than the limit imposed by Eq. (2), since induction charging yields a specific charge which is a decreasing function of particle size. In addition, the sharp curvatures of particles like conical graupel and ice crystals should further enlarge the range of possible charge transfers.

Another relevant feature of the data displayed in Fig. 4 follows from the authors' accompanying statement: "Comparison of the rates of arrival of the Q and d pulses show that about 95% of the particles carried charges below the detectable limit (±25pC) even though a small minority had charges of up to ±250 pC." (Gaskell et al., 1978b, p. 636). From this it seems one can infer that to some extent their measuring apparatus tended to filter out most of the ordinary events, especially at the smaller particle sizes, so that the data shown reflects not the average outcome of the precipitation charging mechanisms, but rather mostly the relatively large fluctuations at the large end of the charge spectrum.

What About Thermoelectric Charging?

It is natural to ask whether the data of Fig. 4 could be readily interpreted in terms of thermoelectric charging. If so, induction charging might thus be indirectly discredited. This brings up an interesting point, namely that the role of thermoelectric charging in thunderstorms is even harder to evaluate than that of induction charging, because there is not yet any concise theoretical statement, analogous to Eq. (1), for the expected elementary thermoelectric charge transfers. Nor is there

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very much in the way of consistent laboratory data as to what the transfers should be. While it is true that just the theoretical accessibility of induction charging has been partly responsible for its ascendancy to the position of most-favored candidate for cloud electrification, this same characteristic has also brought it under much vigorous (if not rigorous) critical scrutiny. It is not at all clear that the theory of thermoelectric charging, which has so far evaded serious criticism because it is at the same time physically plausible and quantitatively nebulous, can fare as well when it is finally understood in more detail. (Of course, the same goes for other conjectured charging mechanisms.)

Qualitatively, the contribution of thermoelectric charging should increase under those conditions which maximize the temperature differences between the larger hail-like particles and the smaller ice crystals. For example, under conditions of below zero temperatures and rapid water condensation (i.e., strong updrafts), the temperature of the hail or graupel may approach 0° C, owing to the release of latent heat as it rapidly accretes supercooled water drops. At the same time, any small crystals present should be nearly at the ambient temperature, which may be several degrees colder. Such conditions would obviously favor thermoelectric charging. However, they also favor induction charging since they imply high ice concentrations and large wind shear, which will increase the frequency of ice-ice interactions. Hence it is difficult to discriminate between the two charging mechanisms on the basis of the observation (e.g., Lhermitte, reported in MOSAIC, Nov/Dec 1978) that lightning formation is correlated with intense cloud convection and possibly wind shear.

It thus appears that one cannot choose between the thermoelectric and induction charging mechanisms from the available field evidence. It seems most reasonable at this time to assume the two processes often occur simultaneously, perhaps with induction charging dominating in the later stages after the initial priming of electric field growth by thermoelectric charging, and that the combination is potent enough to account for the observed electrification. Some rudimentary theoretical calculations carried out recently are not inconsistent with this expectation (Illingworth and Latham (1978); Kuettner et al. (1978)). Both studies postulated dynamically steady two dimensional clouds with specified flow patterns. The former assumed ice-ice separation probabilities of unity, while in the latter they were set equal to 0.9.

2. Influence of the Ambient Field on Thunderstorm Electrification

If we grant the likelihood that induction charging is a very important contributor to intense cloud electrification, there is an important implication for the sun-weather problem: Because of the characteristic dependence of the particle induction charging rate on the prevailing electric field (Eq. (1)), the strong possibility arises that (solar induced) fair weather field enhancements could increase the probability of thunderstorm occurrence. Some computer modeling studies by Sartor on this possibility are reported by Markson (1978), and in MOSAIC, Sept/Oct (1978). For example, in the latter reference it is claimed that: "...if the strength of the electric field in the model upper atmosphere is increased by about one third, then the electric field inside a lightly electrified cumulus cloud can jump from perhaps 1,000 volts per meter to 100,000 volts per meter."

Unfortunately, these claims appear quite misleading and exaggerated in view of the way the results were obtained. Sartor (personal communication, 1979) used the two dimensional cloud model of Kuettner et al. (1978). It is characterized by a prescribed steady vortex circulation, with the option of a superimposed linear vertical shear in the horizontal wind. Primarily as a consequence of the assumed steady flow, there is nothing in the model to prevent the electric field from growing indefinitely with time at an approximately exponential rate. Therefore, the effect of increasing the initial field is merely to shorten the time required for the field to reach any specified value. In other words, for the particular example mentioned above the cloud electric field would have reached 100,000 Vm^{-1} anyway (and more, given enough time), even if the initial field had not been increased; it simply would have taken a little longer to do so. In the context of the sun-weather problem, this means that such an electrification model can at best only make predictions concerning the timing of any observed enhancements in thunderstorm electrification following flares or other solar disturbances. And since in this model the calculated phase shifts would probably be of less than a few minutes duration for initial field enhancements of one third or more, even this application seems rather futile.

It appears that the natural life cycle of a cumulus cloud must be considered in any modeling effort to assess the dependency of thunderstorm occurrence on initial ambient field strength. Some progress along these lines has been made recently by Orville et al (1979) (also Orville, personal communication, 1979), who have investigated the problem using the cloud electrification model of Chiu (1978).

The Chiu Model

I believe Chiu's work represents an important advance in the art and science of numerical modeling of cloud electrification, and so I will digress here briefly to describe the model and some of its predictions. It is based on axisymmetric modification of the slab-symmetric, time dependent numerical model of Liu and Orville (1969). An electric force term is added to the equations of motion to simulate any direct electrical influence on the air motion. Charge transport by electrical conduction, air convection, turbulent mixing, and the charged particle flux are all simulated. Full dynamical-microphysical-electrical interactions are allowed for, as are the mechanisms of particle charging by ion attachment and induction.

Chiu studied the particular case of a warm cloud. (Most of the model features would also apply at least qualitatively to a cloud with an ice phase as well. The model is presently being extended to include the simulation of hail and ice crystals growth and electrification processes.) The liquid water is partitioned into characteristic populations of cloud droplets and precipitation drops. An exponential (Marshall-Palmer) distribution is used to represent the raindrop spectrum. The cloud droplets are assumed to be of uniform size, depending on the local cloud water content, the number concentration remaining constant. Cloud water may "autoconvert" to rainwater when the cloud water content exceeds 2 g kg^{-1}. Whenever the ambient air is in an unsaturated condition, cloud droplets and raindrops evaporate, cloud droplets first, and then the raindrops.

For the drop-droplet interactions, the electrical contact angle is assumed to be $\theta = 48^o$ ($\cos \theta = 2/3$) and the separation probability is taken as $\varepsilon = 0.02$ or 0.04, in the absence of reliable computed or measured values. From the charge which is separated in a given time step, the resulting electric field change is computed by solving Poisson's equation for the entire cloud. The influence of the electric field on drop velocities is included, as is the effect of its direction on the induction charge transfer process. The history of the average charge transfer occuring between drops and droplets per unit cloud volume is followed, so that all but the stochastic aspects of recombination and multiple collisions are included as well.

The results of the computations are encouragingly realistic. For example, for the case of $\varepsilon = 0.02$ and a droplet concentration of 300 cm^{-3}, a maximum vertical electric field of 1.4×10^4 V m^{-1} is achieved in about 28 min., which is well within the range of

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observed growth rates. Also, the rapid growth of the field does not occur until precipitation forms and induction charging commences. Prior to the formation of precipitation the cloud electrical state is in conformity with the theoretical expectation and observational evidence described in Section 1.: The cloud is weakly electrified, with a negatively charged base and core and a relatively thin upper layer of positive charge. Convective electrification does not occur. With the onset of induction charging the charge distribution soon evolves into a main dipole structure (positive above, negative below) which is in general accord with observations.

Later on, a smaller positive charge center appears below the main negative one. This comes about because of two factors: 1) the strongly reversed field in the region beneath the main negative charge, and 2) the arrival of and formation of rain within this same region. This leads to induction charging of polarity opposite to the usual case, which eventually results in a net accumulation of positive charge residing on the precipitation near cloud base. The appearance of such a lower positive charge center has also been recorded in the literature on thunderstorms. For example, Mason (1971, p. 514) states that, "In the majority of storms there was also evidence of one or more localized regions of positive charge in the base of the cloud, these being usually associated with heavy rain."

Predictions of Chiu's Model of the Influence of the Ambient Field

Let us now turn to the numerical experiment recently performed with Chiu's model to gauge the possible connection between fair weather field changes and thunderstorm occurrences. On increasing the initial field at ground level from 100 Vm^{-1} to 170 Vm^{-1}, Orville found the eventual maximum vertical field increased rather modestly, from 9×10^3 Vm^{-1} to 2.2×10^4 Vm^{-1}. Thus a 70% boost in the fair weather field led to about a 140% increase in the final field. For both runs the electrification growth lagged the rainwater content field growth slightly (by 2-3 min.). This is qualitatively reasonable, since the formation of precipitation is requisite to induction charging. No changes were noted in the cloud dynamics or precipitation efficiency. However, the latter quantity would be affected mostly by electrostatic changes in the collision and coalescence efficiences, and such possible changes were not allowed for.

These results tend to support the idea that thunderstorm occurrence should increase following ambient field enhancements. That is, the bias toward increased cloud electrification following such enhancements might, for a given set of meteorological conditions over a wide area, push enough additional clouds over the threshold to thunderstorm status that the effect could be seen rising above the usual meteorological noise.

In view of the sophistication of Chiu's cloud electrification model and its success in simulating many of the observed features of the different states of evaluation of electrified clouds, it seems our best theoretical tool at present for further explorations of this problem, and of thunderstorm electrification in general. It is hoped that further improvements in the model will be forthcoming soon, such as the inclusion of the ice phase and thermoelectric charging, electrostatic effects on collection efficiencies, and stochastic aspects of particle charge and growth.

3. Some Possible Influences of Thunderstorms on Changes in the VAI (Vorticity-Area-Index)

Statistical studies suggest that thunderstorm activity increases following solar flares or solar magnetic sector boundary crossings. Assuming these are real effects, they may provide a physical basis for the observed statistical correlations between flares or sector boundary crossings and subsequent changes in the VAI.

Markson (1978) has described how the general circulation might be influenced by changes in thunderstorm activity (see Fig. 6). According to this view, increased thunderstorm activity in the tropics could release more latent heat and hence boost the circulation of the equatorial Hadley cell. This intensified circulation would eventually be communicated to the other Hadley cells as well. Consequently, a greater low level convergence in the polar front region might occur, leading to increased storminess (i.e., an increase in the VAI).

This suggested link between thunderstorms and changes in the VAI seems physically plausible, but unfortunately its quantitative feasibility appears quite difficult to assess. Two possible difficulties with it are: 1) The time lag between increased thunderstorms in the tropics and enhanced vorticity in the mid-latitudes via the proposed mechanism may be too long to explain responses in the VAI to solar disturbances. 2) The statistical correlations of thunderstorms and the VAI to solar disturbances are weak. Therefore, even if they are real it is not clear that one such response in the tropics could survive meterological noise over a significant fraction of the earth and then trigger another weak response in the mid-latitudes.

A somewhat more localized version of a possible connection between thunderstorms, the general circulation, and the VAI has also been suggested by Markson (1978) (see Fig. 6). In this scheme the north-south temperature gradient across the polar front is increased by virtue of thunderstorm-enhanced precipitation just south of the front. This would again lead to mid-latitude vorticity intensification.

This mechanism also seems plausible, but as before the tie-in to the general circulation likely implies responses too slow and long-lasting to be compatible with the statistical evidence of possible correlations between solar variability and VAI changes.

A more transient, synoptic scale connection between thunderstorms and the VAI may come about because of the cold front which accompanies a developing baroclinic wave (see Fig. 7). If the thunderstorms which often accompany a cold front were intensified by solar disturbances, any increase in precipitation efficiency which might result thereby would lead to a direct and rapid increase in the heat input to the system, and also to a net increased low level convergence. This would likely intensify the baroclinic wave instability, leading to increased vorticity (the degree of "waviness" of the 500-mb contours in Fig. 7 provides a very direct qualitative measure of the magnitude of the VAI). On the other hand, there is also the possiblity that the increased release of latent heat might locally decrease the advection of cold air below the 500-mb trough and slow the development of the system. Hence this mechanism might also provide for temporary decreases in the VAI.

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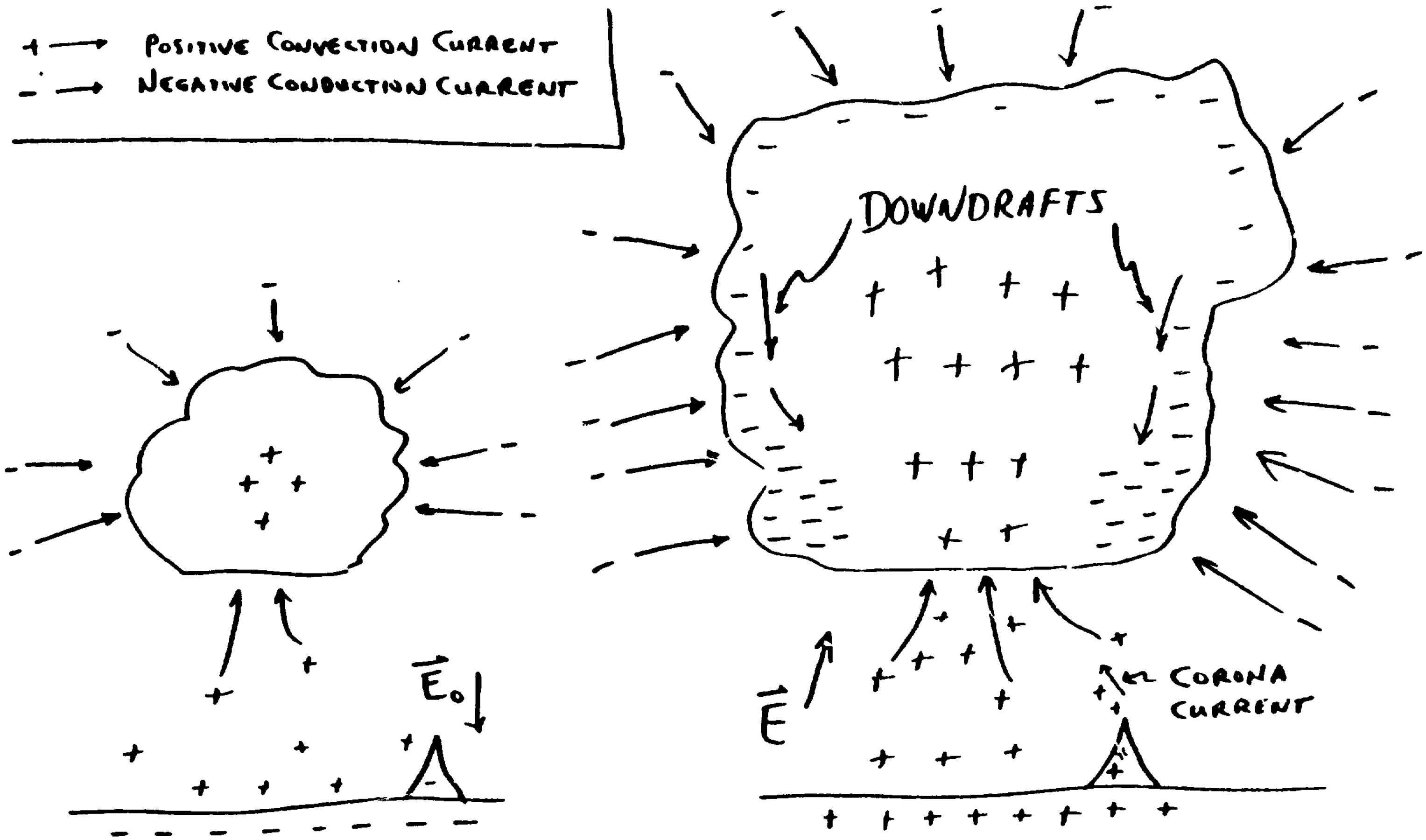

Incipient Stage

Mature Stage

Fig. 1: Schematic of Convection Charging

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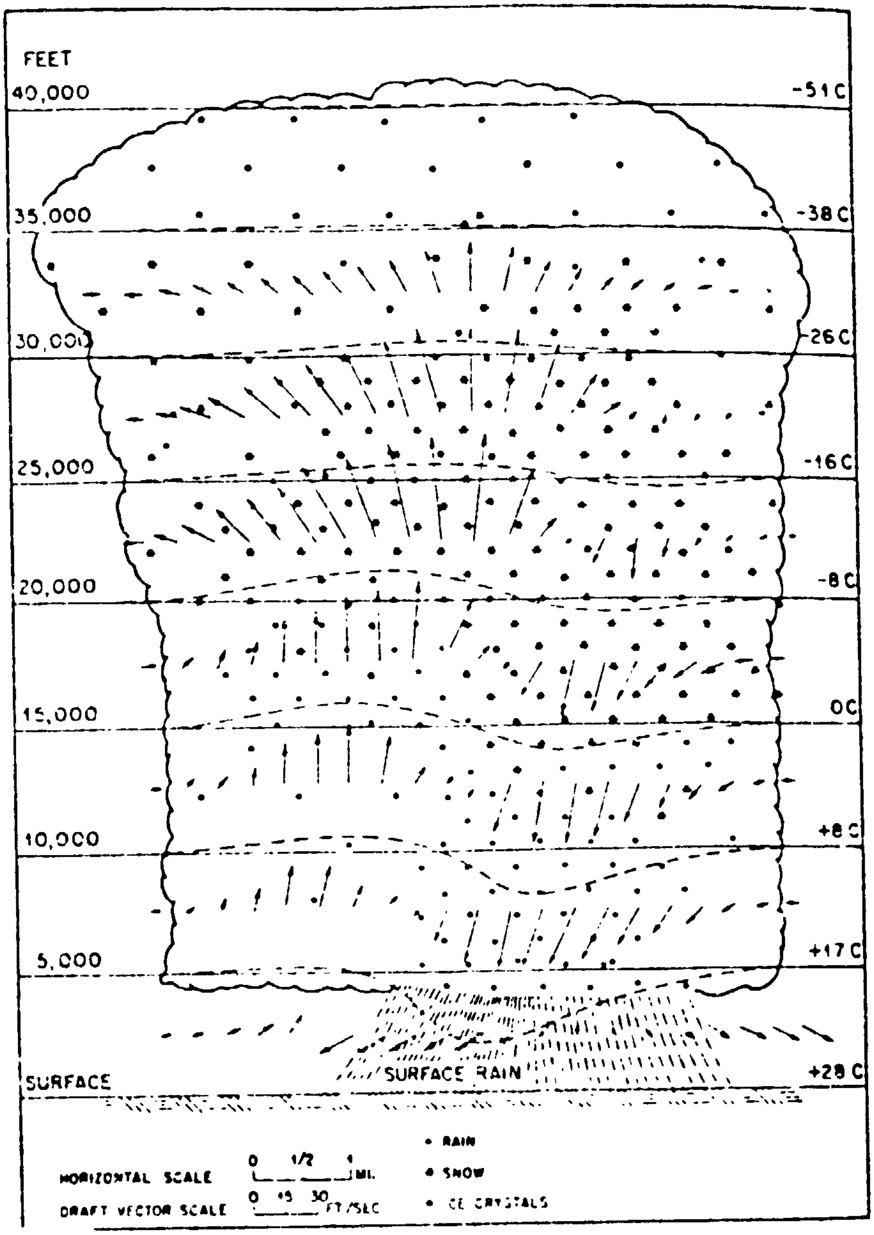

Representation of a thunderstorm cell in mature stage, including air motions (arrows on vector scale given in lower left), hydrometeors, and temperatures (dashed lines). (From Byers and Braham, 1949.)

Fig. 2

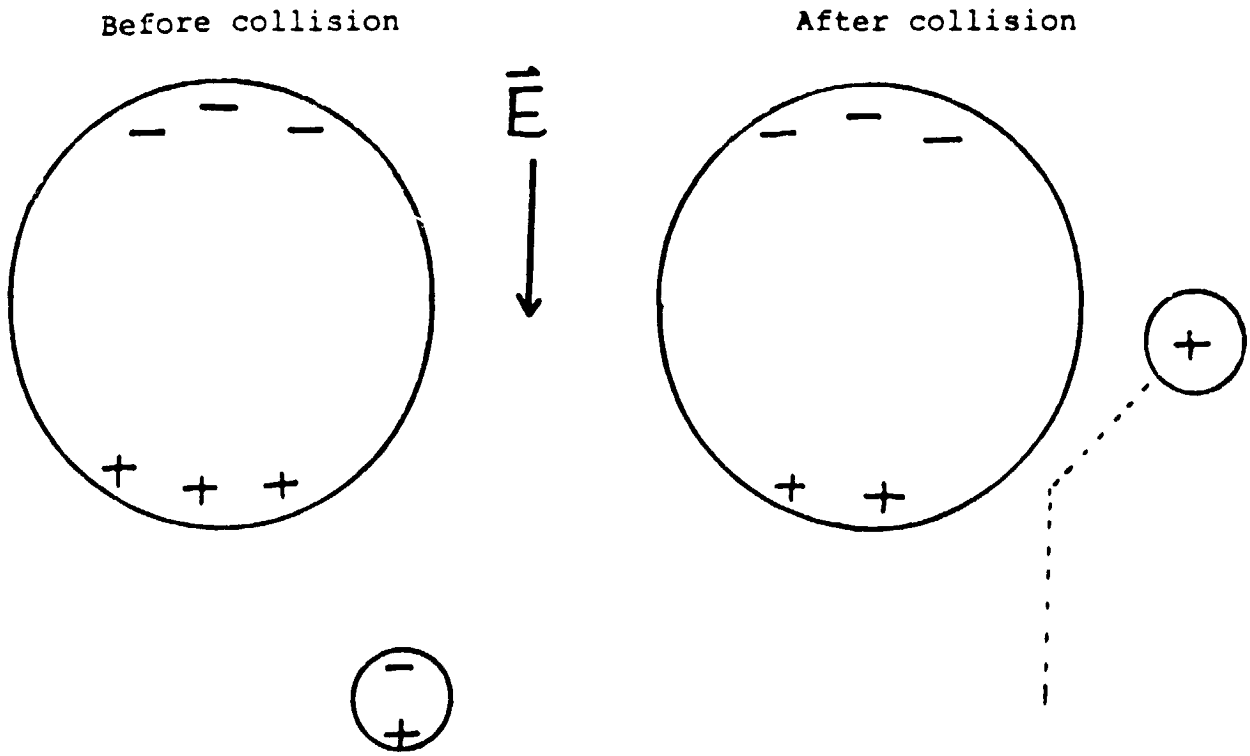

Fig. 3: Schematic of Induction Charging

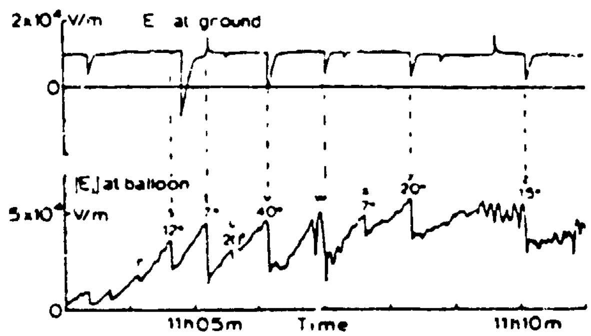

Fig. 4: Enlarged portion of the electric records from 20 Aug., 1974. Some electric field changes due to lightning flashes are labelled with lower case letters. (Winn and Byerly, 1975)

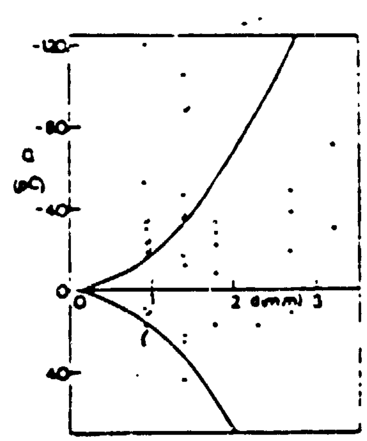

Fig. 5: Charge/size (Q/d) coincidences measured in penetration 1 on 15 Aug. 1977 (65 sec.). The solid lines are theoretical maxima (Eq. 2) operating in a breakdown field of 300 kV/m. (Gaskell et al 1978b)

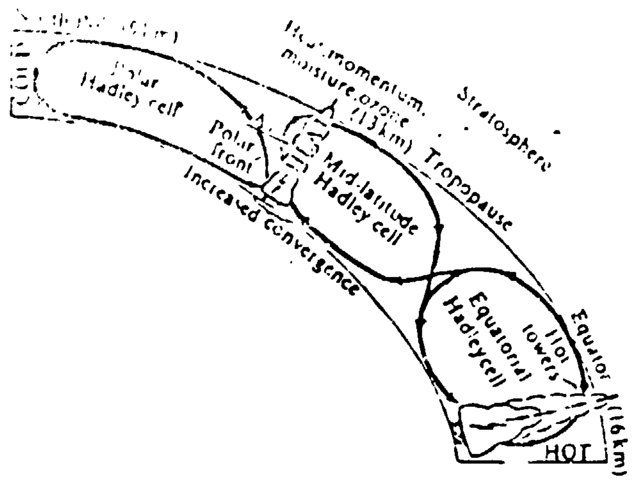

Fig. 6: Longitudinal cross-section of atmosphere illustrating how solar modulation of cloud physical processes might influence the general circulation. (Markson, 1978)

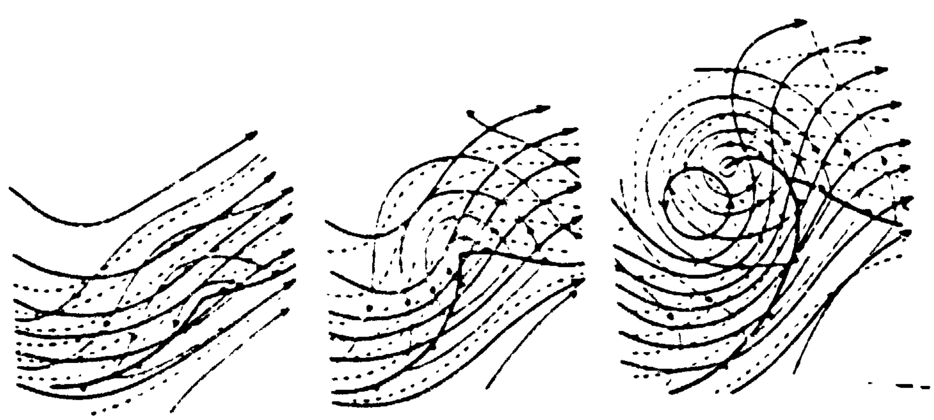

Fig. 7: Schematic 500 mb contours (heavy lines), 1000 mb contours (thin lines), and 1000-500 mb thickness (dashed) for a developing baroclinic wave. (Holton, 1972)

Report VIII

The Influence of Solar Variability on Terrestrial Weather and Climate

by

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1.0 INTRODUCTION AND OVERVIEW

From the time of the discovery of the solar cycle (Schwabe, 1843), popular folk wisdom has held that variations in solar conditions can influence the behavior of the earth's atmosphere. Scientific efforts to investigate this problem have not been as fruitful as one might wish. The reasons for this condition are the complex nature of the phenomena in both the solar and terrestrial atmospheres, the difficulty of statistically separating a solar "signal" from the higher amplitude "noise" of terrestrial atmospheric fluctuations, and the unknown nature of the relevant coupling processes between the two.

As a step in overcoming these difficulties, the Marshall Space Flight Center sponsored a study of the mechanisms by which solar variability might influence terrestrial weather and climate. This report is one part of that study. It is an examination of the feasibility and relevance of various mechanisms by which variations in solar outputs might be coupled through the heliosphere to ultimately influence the lower atmosphere.

The sun generates a variety of outputs all of which influence the earth in one form or another. Solar electromagnetic radiation may be divided into the steady photospheric component and a (much less energetic) component from higher layers of the solar atmosphere which is demonstrably variable on time scales from seconds to decades. The greater part of the photospheric radiation reaches the surface of the earth and provides the power source for the atmospheric heat engine. Even a small variation in this component could cause major effects in the lower atmosphere. The electomagnetic radiation from higher layers in the solar atmosphere is primarily at shorter wavelengths. Very little of the total solar luminocity is involved. These radiations are absorbed in the upper layers of the terrestrial atmosphere. Any effect they might have on the lower atmosphere would have to be mediated by coupling processes involving the interaction of the various regions of the earth's atmosphere.

The sun is also the source of the magnetic field which permeates the heliosphere. This magnetic field is not steady. As seen from the earth it varies periodically in direction and to a lesser extent in magnitude. The interplanetary magnetic field is also subject to magnetohydrodynamic waves. All of these variations have their direct or indirect origins at the sun. This variable magnetic field impinges on the earth's magnetosphere. There it gives rise to a variety of phenomena, e.g., geomagnetic effects, particle precipitation, etc., which influence the ionization balance, chemical composition, and temperature of the upper atmospheric regions of the earth. It is not obvious how variations in these upper atmospheric parameters affect the properties of the lower atmosphere.

In addition to electromagnetic radiation, the sun is a copious emitter of particles. The sun continually emits streams of plasma, called the solar wind. It is the solar wind which convects the heliospheric magnetic field past the earth's magnetosphere. Intermittently, solar events accelerate particles to higher energies and these particles reach the earth's environs. In some cases, these energetic solar particles enter the atmosphere producing enhanced ionization at high lattitudes. On rare occasions, solar accelerated energetic particles reach the surface of the earth.

The variable solar wind and interplanetary magnetic field also modulate the flux of galactic cosmic rays reaching the earth. These cosmic rays are a major source of ionization at certain levels in the atmosphere. Their flux is lower during periods of maximum solar activity and higher during periods of minimum solar activity. There are also variations in galactic cosmic ray flux associated with particular solar flare events.

Thus, one finds a large number of variable solar outputs which could be responsible for variations in terrestrial weather and climate if mechanisms coupling the upper and lower atmosphere could be developed and one solar output, photospheric radiation, which could directly effect the lower atmosphere if its flux were sufficiently variable.

These considerations would be totally academic in the absence of statistical evidence relating solar variability and terrestrial weather and climate. A great many authors have investigated this question. Unfortunately, much of this work has been marred by various methodological problems, primarily statistical in nature (see Pittock, 1978). Siscoe (1978), however, lists three phenomena as possible examples of solar influence on terrestrial weather and climate. These are, in order of decreasing time-scale:

1. The apparent correlation between terrestrial climate and the general level of solar activity (e.g., Maunder minima, etc.) (Eddy, 1977);

2. The reported relationship between the 22-year solar magnetic cycle and the incidence of drought in the western United States (Mitchell et al., 1979); and

3. The apparent signature of solar magnetic sector boundary crossings in the atmospheric vorticity-area index (Wilcox et al., 1973).

Accordingly, it is appropriate to search for mechanisms which could be responsible for these three phenomena.

Herman and Goldberg (1978) and Goldberg and Herman (1979) have provided an extensive review of possible sun-weather links. In general all of the processes they discuss can be classified into three areas:

1. Possible variations in solar luminosity of sufficient magnitude to affect the terrestrial heat-balance;

2. Solar induced variations in the middle atmosphere (15 - 100 km) which could modulate the reflection, transmission, amplification, etc., of inputs and processes in the lower atmosphere; and

3. Solar induced variations in the atmospheric electrical circuit.

Processes in the second and third categories would require an elucidation of the mechanism by which a solar induced variation in the upper or middle atmosphere could affect the lower atmosphere. In general, these mechanisms were considered by the two other teams involved in the MSFC study.

In the remainder of this report, we will be concerned with the manner in which one could determine the solar output whose variation might be responsible for a particular terrestrial effect. Section 2 is a consideration of the conclusions which can be drawn from the time-scales of the three statistical phenomena which are indicative of variable solar influence on the lower atmosphere. Section 3 suggests possible observations that might help to elucidate the candidate processes.

2.0 TIME SCALES

To a solar or heliospheric physicist the time scales involved in various possible terrestrial atmospheric reponses to solar variability provide clues to the possible solar outputs which might induce these responses. An atmospheric response at a particular period is likely to be associated with some member of the class of solar outputs that vary with that period. Unfortunately, the statistical problems mentioned above prevent one from drawing firm conclusions based on the absence of particular time scales. At the current state of the art, this is as likely to indicate a signal-to-noise problem as it is to indicate an absence of atmospheric response at that time scale.

The shortest time scale for which a reasonable correlation between solar variability and the terrestrial atmosphere can be considered as demonstrated is that involved in the relationship between atmospheric vorticity-area index (VAI) and the passage of solar sector boundaries past the earth. The VAI is a measure of the area at the 300 mb level of the earth's atmosphere at which the vorticity exceeds a specified level. This is effectively a measure of the intensity of low pressure troughs. Wilcox et al. (1973) showed that if the VAI data were superposed using the date of sector boundary passage as a time indicator, on the average, the VAI started to decline one day before sector boundary passage, reached a minimum about a day and a half thereafter, and then began to rise again. The effect is only valid in the winter.

Interplanetary magnetic sector boundaries are the projections along the Archimedean spiral of reversals in the polarity of the large scale solar magnetic field (see, for example, Hundhausen, 1977). Accordingly, one might conjecture that a terrestrial phenomenon correlated with interplanetary sector boundary crossings would be related to solar outputs which vary in correspondence to the large scale structure of the solar magnetic field. This is not much help. Large scale solar magnetic structure is related to the global distribution of active regions (e.g., Levine, 1977). Accordingly, any solar output that varies with the distribution of active regions, as do almost all of the temporally varying radiative outputs and as does the frequency of solar flares, will have a frequency component in its variation at a rate which is consistent with the time scale of sector boundary crossings and more or less synchronized to it. By the same token, the large scale solar magnetic structure determines not only the positions of interplanetary sector boundaries, but also the locations of coronal holes (e.g., Krieger, 1977) and, hence, the locations of high speed solar wind streams (Krieger et al., 1973). Thus, one must add to the candidate mechanisms any which depend on the velocity of the solar wind (or the convection of interplanetary magnetic field past the magnetosphere) as well as those which depend on the variation in solar radiative outputs.

Consideration of the terrestrial atmosphere, however, allows the elimination from consideration for the driver of VAI correlation of any mechanism involving an atmospheric response too slow to follow changes in solar outputs on a time scale of order one day. For the same reason, one can probably eliminate variation in the total solar luminosity as the driver of the VAI correlation. Recent results from SMM (Hudson et al., 1981) indicate that the total solar luminosity does vary with the area and darkness of sunspots, but only by ~0.2%, significantly less than the percentage which would be necessary to produce short term terrestrial effects. To zeroeth order, the solar luminosity is reduced by

$$A_{spot} \; \sigma \; (T_{phot}^{4} - T_{spot}^{4}).$$

This would be hardly adequate to produce any short term terrestrial effects.

The relationship between periods of drought in the western United States and the 22-year solar magnetic cycle is substantially more suggestive. The interesting point is that the period of this relationship is twenty-two years rather than eleven years.

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The level of solar activity varies on a roughly eleven-year cycle. The primary difference between succeeding eleven-year cycles is the alternation in magnetic polarity of the preceding and following portions of active regions in the northern and southern solar hemispheres and correspondingly the ultimate magnetic polarity of the solar poles in each succeeding eleven-year period. Accordingly, a complete solar magnetic cycle is twenty-two years in duration. Any mechanism relying on variations in solar radiative output, whether in the form of spectral variations or in the form of variations in total luminosity would be expected to show an eleven-year periodicity rather than the observed twenty-two year period. While it is certainly true that, over the last few solar cycles, odd-numbered cycles have been more active than even ones, this effect is small compared to the magnitude of the eleven-year variation, and it vanishes (along with the precision of the solar data) if carried back far enough into the past. On the other hand, the drought cycle seems to extend back for at least 300 years. Accordingly, the strength of this correlation suggests a relationship to solar magnetism.

The effect might possibly be related to the alternation between one eleven-year cycle and the next in the season of the year when the (small) average angle of the interplanetary magnetic field points in the southward direction, which leads to more efficient transfer of energy from the heliosphere to the magnetosphere (e.g., Svaalgard, 1977). This could only be significant if there is a meteorologically significant difference between the responses of the northern and southern terrestrial hemispheres to that energy transfer at a particular seasons. It is not at all obvious how an effect such as this could lead to drought, but the 22-year periodicity suggests a search for mechanisms related to phenomena governed by the interaction of the geomagnetic and interplanetary magnetic fields.

A clue to such a mechanism might be the fact that drought conditions are associated with alternating solar minima, rather than solar maxima. Obviously, impulsive non-recurrent disturbances of quiescent heliospheric conditions associated with solar activity are more frequent at or near the solar activity maximum than they are at solar minimum. Accordingly, a mechanism dependent upon slight deviations in the average properties of the heliosphere is more likely to make itself felt at solar minimum.

Alternatively, there is some evidence that the drought periods actually occur during the rising phase of the solar cycle (Olson, 1979). A mechanism prevalent during the rising phase of the solar cycle might be related to the disturbance of average conditions by the increase in activity associated with the new solar cycle. Again, the twenty-two-year period implies that the effect would be related to the relative direction of the interplanetary and geomagnetic fields.

The reported correlation between the long-term average level of solar activity and the earth's climate raises the possibility of still other mechanisms which might act on a longer time scale. In particular mechanisms dependent upon changes in solar radiated flux become plausible.

Eddy (1977) has found evidence to support the conclusion that the solar cycle is substantially less regular both in amplitude and duration than has commonly been supposed. In particular, there have been periods in historic times when the manifestations of solar activity have essentially disappeared. The most recent of these was the so-called Maunder minimum when between about 1645 and 1700 sunspot activity vanished and aurorae were less frequently reported.

Eddy (1977) has reported earlier such periods by relying upon the average ^{14}C content of tree rings. Medium energy galactic cosmic rays, which impinge on the upper atmosphere of the earth, produce ^{14}C, some of which is eventually assimilated into plant matter. The flux of cosmic rays is inversely correlated with solar activity during periods of normal solar cyclic behavior. In particular, cosmic ray flux (and hence ^{14}C production) rises when solar activity is low and declines when solar activity is high. Accordingly, the ^{14}C abundance in the atmosphere (and in tree rings) should be inversely correlated with the long-term average (over 20 years or so) level of solar activity.

Eddy has found both periods when the average level of atmospheric ^{14}C was lower than it is today and periods when it was substantially higher. He identifies the periods of low ^{14}C with high solar activity and the periods of high ^{14}C level with minima in solar activity. The most recent period of high solar activity seems to have occurred in the thirteenth century.

Historically, it is well known that during the Maunder minimum the climate in northern Europe was unusually cold. Moreover, Eddy has correlated periods of advance and recession of northern European alpine glaciers with solar activity as reflected in the ^{14}C record. The glaciers advanced during periods of low solar activity, such as the Maunder minimum or the earlier sixteenth century Sporer minimum, and receded during periods of high solar activity as in the thirteenth century.

Climatic changes in northern Europe do not necessarily imply worldwide climate changes, nor do they imply, even if the changes were worldwide, that they would all be in the same sense. The worldwide average temperature might even increase while that in northern Europe was declining. The result of this uncertainty about conditions in other terrestrial areas is an inability to distinguish between possible explanatory mechanisms.

The simplest possible mechanism would be a decline in total solar luminosity as the amplitude of the solar cycle declined. If this were the case, one would expect a decline in average temperature worldwide. More complex mechanisms invoke changes in solar spectral irradiance as a function of the activity level. These mechanisms make different predictions about climatic changes in other parts of the world that might be expected to accompany the advance or decline of European alpine glaciers. For example, equatorial temperatures would be anticipated to rise in some models and to fall in others. Accordingly, determination of conditions at other terrestrial locations might be a good discriminant among models attempting to explain Eddy's results.

At this point there is no generally accepted explanation for the variations in the rate of solar activity reported by Eddy. Accordingly, it is difficult for solar physicists to predict how potentially important solar outputs might vary under circumstances of decreased or enhanced average solar activity. Naively, one might assume that if there were no solar active regions (e.g., a Maunder-like minimum), the flux of short wavelength chromospheric and coronal radiation would decline to the level normally observed at solar minimum. It is not at all obvious, however, that the decline would not be greater (or less) than that in some wavelength bands. Similarly, while modulation of the galactic cosmic ray flux is assumed to decrease under conditions of minimum activity and increase under conditions of maximum activity, it is not at all obvious how important heliospheric constituents like the solar wind and the interplanetary magnetic field would behave, even though cosmic ray modulation is functionally dependent on a combination of these parameters. A great deal of solar physics will have to be done before the solar and heliospheric conditions prevalent during a period of solar activity unlike the present could be predicted.

3.0 RELEVANT SOLAR AND HELIOSPHERIC OBSERVATIONS

At the present time, our understanding of the mechanisms by which solar variability influences terrestrial weather and climate is so rudimentary that almost any observation that increases our understanding of the sun, the heliosphere, or the earth is relevant to the problem. There are, however, areas of solar and heliospheric physics which deserve emphasis because of the light they might shed on the mechanisms coupling solar variability to the earth's atmosphere.

The first area is that of solar variability and solar activity itself. At this time, our understanding of the processes which generate the solar magnetic field and which give rise to the solar cycle are not adequate to allow us to understand phenomena like the existence of Maunder minima or, conversely, periods of higher than normal activity. In order to improve our theories, we must have a much better idea of the nature of the processes that generate solar magnetism. The principal observational task here is to obtain more detailed measurements of the subsurface differential rotation pattern via the relatively new study of solar oscillations. The variation of solar surface differential rotation patterns with lattitude and the possible existence of meridional circulation also requires further observation. Hopefully, these observations would lead to a better theory of solar magnetism which could lead to an understanding of the circumstances associated with levels of solar activity different from those of the present time.

We need a much clearer concept of the response of the solar luminosity to magnetic activity and to its absence. High precision measurements of the solar constant from space have just begun. As yet no program exists to obtain such data on a regular basis calibrated with sufficient precision to permit observation of solar cycle variations. This would be particularly important to solar physics because we are still puzzled by some aspects of energy transport through the convection zone. In the same context, it would also be worthwhile to attempt the observation of the solar diameter and figure with sufficient precision to observe variations over the solar cycle.

The total solar luminosity is proportional to both the fourth power of the solar surface temperature and to the area of the solar surface. Thus a variation in solar luminosity might be detectable as either a change in solar surface temperature or a change in radius. Even in the absence of a variation in the total energy generated by nuclear processes in the solar interior, a change in surface temperature or surface figure could produce a temporary change in solar luminosity. Such a variation in the temperature or area of the photosphere might be a result of the same process that would modify the rate of solar activity, e.g., a change in the rate of convective energy transport. At this point, the mechanisms giving rise to solar activity are not well enough understood to make any definite statement.

The quantitative response of variable solar outputs to changes in the behavior of the solar cycle is also problematic. Unfortunately, our understanding of cosmic ray modulation is insufficient to allow us to state whether a change in the average atmospheric ^{14}C level reflects a change in average solar wind velocity, average interplanetary magnetic field strength, the variance of these quantities, or even the spectrum of the variations in these quantities. Similarly, while we are beginning to understand the variations over the solar cycle of the properties of the solar chromosphere and corona, we know that even at solar minimum, the characteristics of these layers are related to the characteristics of subsurface solar velocity fields and the properties of the solar magnetic field. Because we cannot, at this time, predict the properties of those velocity fields or the configuration of the solar magnetic field during a period of lesser or greater solar activity than those we are accustomed to, we cannot really predict the level or spectral distribution of variable solar radiations under such conditions.

To achieve an understanding of the initial steps in coupling mechanisms which rely on changes in the flux of variable solar outputs affecting the upper and middle atmosphere, we must therefore attack some of the key questions in solar and heliospheric physics, the problems of the heating of the chromosphere and corona, the acceleration of the solar wind, the modulation of galactic cosmic rays, and the interaction of the interplanetary medium with the magnetosphere.

As an example of such mechanisms, consider the possible role of atmospheric ozone as a coupling agent between solar variability and the lower atmosphere. It has been suggested (see Herman and Goldberg, 1978) that variations in the ozone layer density could modulate the amount of solar UV radiation reaching the lower atmosphere. The resulting variation in heating would lead to temperature changes and consequent changes in atmospheric circulation patterns. The concentration of ozone in the atmosphere is determined by a complex chain of processes which are beyond the scope of this article. In general, though, ozone is created by solar ultraviolet radiation at wavelengths less than about 2420 Å and destroyed by chemical reactions with oxides of nitrogen (NO_x). The ozone effectively absorbs solar radiation at wavelengths below about 3000 Å. The NO_x is created primarily by cosmic ray interactions in the atmosphere. One might postulate that during a period of high solar activity the sun emits more short wavelength radiation, producing more ozone, and modulates cosmic rays more deeply, producing less NO_x. The ozone concentration should rise. The opposite effect should occur during periods of minimum solar activity. The magnitude of these effects (and secondary effects which could upset the balance) depends on the relative importance of the changes in source and sink terms which originate in very different physical processes in the solar atmosphere, the heliosphere, and the magnetosphere.

In order to examine such a mechanism, one would have to understand the processes governing atmospheric ozone creation, distribution, and destruction, and the mechanisms coupling these to the lower atmosphere. Ideally one would then have a model, into which one could enter the relevant fluxes of the solar variable quantities. The first step, therefore, is the generation of the model. The single most important ingredient in either a photochemical or radiative-photochemical model would be full disk measurements of solar ultraviolet flux at about 5 Å resolution. At this time, there still exist significant uncertainties as to the absolute value and variability of the UV flux. The absolute value of the solar flux in the 2000 Å range is probably on the order of 25%. This immediately sets a limit on our ability to perform accurate photochemical calculations of stratospheric ozone. Knowledge of the variability of this flux over the solar cycle is required if we are to interpret variations in ozone quantity and distribution.

Of themselves, these measurements would mark a significant advance for atmospheric physics. To relate these results to a model of climatic change in response to solar variability, we would need to know how the solar quantities would vary under conditions we have not observed. This would require an understanding of chromospheric and coronal heating which can only be obtained by an intensive program of imaging and spectroscopic observation of the solar atmosphere at short wavelengths.

Similar chains of reasoning can be applied to other possible mechanisms relating solar variability and terrestrial climate, e.g., solar induced variations in atmospheric electrical conductivity or solar induced variations in auroral precipitation. In every case, one finds that the solar and heliospheric phenomena postulated to be responsible for the modulation of terrestrial conditions are not sufficiently predictable at our present state of knowledge to allow a definitive statement. While this may seen to be a very pessimistic conclusion, this author does not view it so. Almost anything we learn about the mechanisms of solar variability is bound to advance our understanding of solar-terrestrial coupling mechanisms. Progress is certain to be at least as rapid as that in solar and heliospheric physics or meteorology. Because of scientific feedback processes, it will probably be more rapid. Accordingly, the author is optimistic that progress in understanding solar variability will lead to the ultimate solution of the sun-weather-climate problem.

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