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The search for possible effects of solar variations on weather and climate has been a subject of both scientific and popular interest for over a hundred years. The significance of suggested relationships has been mired in controversy throughout this time; statistical studies have not been adequate to give unequivocal answers to the question of the relative importance of solar pertubations on either weather or climate. Much of the doubt about the reality of such connections stems from a lack of identified, testable physical mechanisms that could link small variations in solar inputs to weather and climate.

A primary conclusion of this study is that advances in the understanding of possible effects of solar variations on weather and climate are most likely to emerge by addressing the subject in terms of fundamental physical principles of atmospheric sciences and solar-terrestrial physics. A principal goal is to determine the limits of variability of solar inputs to the atmosphere and the depth in the atmosphere to which these variations have significant effects.

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STUDIES IN GEOPHYSICS

Solar Variability, Weather, and Climate

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Solar Variability, Weather, and Climate

Geophysics Study Committee
Geophysics Research Board
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for this report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

In 1974 the Geophysics Research Board completed a plan, subsequently approved by the Committee on Science and Public Policy of the National Academy of Sciences, for a series of studies to be carried out on various subjects related to geophysics. The Geophysics Study Committee was established to provide guidance in the conduct of the studies.

One purpose of the studies is to provide assessments from the scientific community to aid policymakers in decisions on societal problems that involve geophysics. An important part of such an assessment is an evaluation of the adequacy of present geophysical knowledge and the appropriateness of present research programs to provide information required for those decisions.

The present panel of the Geophysics Study Committee endeavored to reassess the old and persistent question of solar variability and its effects on weather and climate in the light of modern knowledge of the Earth's atmosphere and current measurements of solar variability and to suggest areas of emphasis for its ultimate clarification. It was not our intent to weigh all the history of past endeavors in this area or to attempt to reach a verdict on a question that for so long has defied simple answers.

The preliminary scientific findings of the panel were presented at an American Geophysical Union meeting that took place in San Francisco in December 1978. These presentations and the resulting essays contained in this volume provide examples of current basic knowledge on the subject of solar variability and its effects on weather and climate. They also pose many of the fundamental questions and uncertainties that require additional research. In completing their papers the authors had the benefit of discussion at this symposium as well as comments of several scientific referees. Responsibility for the individual essays rests with the corresponding authors.

The Overview of the study summarizes the highlights of the essays and formulates conclusions and recommendations. In preparing it the panel chairman had the benefit of meetings that took place at the symposium and the comments of the panel of authors and other referees. Responsibility for the Overview rests with the Geophysics Study Committee and the chairman of the panel.

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Solar Variability, Weather, and Climate

Overview and Recommendations

INTRODUCTION

Man has always taken an interest in the weather and its day-to-day and seasonal changes. In recent years we have come to appreciate that the long-term average of weather—called climate—also varies and in ways that have direct impacts on life on our planet. Historical weather records and indirect and proxy indicators from trees, ice cores, and deep-sea cores leave no doubt that the climate of the past was not always like that of today. The potential economic and social impacts of even small changes in the climate of the Earth now seem profound, particularly in climatic zones where soil moisture or temperature are marginal for agriculture or subsistence. As an example, we know that during the 1970's drought in the Sahel expanded the southern limit of the Sahara desert bringing famine and suffering. Long-term climatic trends are equally real and equally important. In the course of the last 100 years, the average annual temperature in the northern hemisphere warmed about 0.5°C to a maximum in the 1940's, cooled for about 30 years, and may now have begun to warm again. Climatological data suggest that in Europe and the Americas the period between about 1430 and 1850 was significantly cooler than the present, and a period in the thirteenth century was the last time the Earth was as warm as it is today. The spectre of past ice ages reminds us that global climate has indeed changed and will surely change again.

We would like to predict, much better than we are now able, both weather and

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climate. Improved prediction, however, depends in great measure on a fuller physical understanding of the causes of weather and climate variability and the many ways these different mechanisms combine to produce eventual effects. Many factors are involved. Some climatic forcing functions may be unpredictable, and others may be so complex and interrelated that they are in practice indeterminate. We can envisage some, however, that are not. Among the possibly simpler causes are variations of the sun, whose inputs of heat and light provide most of the energy that drives the atmospheric circulation of the Earth.

The obvious terrestrial importance of the sun, coupled with hopes of simplicity and predictability, have made solar variations a popular subject for investigation by generations of scientists who have sought the causes of changes in weather and climate. Despite much research, no connection between solar variations and weather has ever been unequivocally established. Apparent correlations have almost always faltered when put to critical statistical examination or have failed when tested with different data sets. As a result the subject has been one of continual controversy and debate. Today, we are not much closer to a resolution of this important issue than we were a century ago, and the words of the eminent American astronomer, Charles Young, made in 1881, still seem to apply:

> In regard to this question the astronomical world is divided into two almost hostile camps, so divided is the difference of opinion, and so sharp the discussion. One party holds that the state of the sun's surface is a determining factor in our terrestrial meteorology, making itself felt in our temperature, barometric pressure, rainfall, cyclones, crops, and even our financial condition. . . . The other party contends that there is, and can be, no sensible influence upon the Earth produced by such slight variations in the solar light and heat. . . . It seems pretty clear that we are not in a position yet to decide the question either way; it will take a much longer period of observation, and observations conducted with special reference to the subject of inquiry, to settle it. At any rate, from the data now in our possession, men of great ability and laborious industry draw opposite conclusions.

What is evident in any critical examination of the field is that conclusions drawn from reported correlations between solar influences and the weather and climate are too often based on inadequate statistical tests and seldom if ever supported by an elucidation of testable, physical mechanisms that explain the purported connection. The latter fault may be partly due to our incomplete knowledge of the real variability of solar inputs to the Earth. It may also be due to our restricted understanding of the complex regions that separate the troposphere from the sun: the middle and upper atmosphere, the magnetosphere, and the interplanetary medium. Because of advances made in the past two decades in space physics and upper-atmospheric physics, a fuller understanding of the processes connecting these regions now seems within our reach. A more thorough understanding of fundamental questions of solar–terrestrial physics is the best hope for elucidating the more specific issue of the extent of solar influences on weather and climate. To expect to achieve real clarification by any other path seems to us to ignore both physics and history. *Our principal conclusion is that the subject of sun–weather and sun–climate relationships—long clouded by an ignorance of the sun–earth environment, colored by controversy, and tainted by a stigma that may have impeded clarification—should be approached from more fundamental physical directions and addressed in the broader framework of solar–terrestrial physics and atmospheric sciences.*

BACKGROUND

The possible role of the sun in altering the course of weather and climate has long been a subject of popular interest and an issue of serious concern in scientific research. To some, at first look, the question seems almost trivial—with an obvious answer dictated by common sense and intuition. The sun heats the land, the oceans, and the atmosphere;

solar radiation, coupled with the rotational inertia of the spinning Earth, provides the force that drives atmospheric circulation—the weather machine that creates the clouds, winds, rain, and snow. Known changes in the distribution of solar energy over the surface of the planet are clearly responsible for important differences between climatic regions, for the annual march of the seasons, and, as now seems likely, for the timing of recurrence of the major ice ages. In this the case is clear: the sun and the global distribution of its radiation are dominant factors in shaping weather and climate. From this a more speculative and possibly erroneous conclusion is sometimes drawn: both weather and sun are ever changing; is it not likely that the vagaries of the one are caused by variations in the other?

For centuries, and particularly since the recognition about 130 years ago of the cyclic nature of solar activity, innumerable attempts have been made to demonstrate the suspected sun–weather connection, with hopes of putting such a connection to use in practical weather or climate prediction. At first, when hopes were high, these attempts were exploratory and naive—simple examinations of local or regional weather records with expectations of recognizing telltale marks of solar periodicity (the 11-year sunspot cycle or the 27-day period of solar rotation) or the imprints of impulsive solar events. Gradually, with a more mature appreciation of the complexities of both solar and atmospheric physics, the search often became a sophisticated challenge aided by the power of statistical analysis to find the needle of solar influence in the haystack of weather records.

Over the years many have claimed to find it, in the form of possible correlations linking solar variations to specific weather parameters in limited areas or for limited times. However, in our view, none of these endeavors, nor the combined weight of all of them, has proved sufficient to establish unequivocal connections between solar variability and meteorological response. Some would disagree. But in pragmatic fact, lacking empirical data and without a demonstrable mechanism for the likely existence of such a connection, most practicing meteorologists have opted to ignore the variability of the sun as a significant factor in making weather and climate forecasts.

The simple logic that launched the original searches for significant sun–weather connections deserves closer scrutiny in the light of modern understanding of solar or atmospheric behavior. The outputs of the sun vary only minutely when total solar output is considered, and these fluctuations may be of no practical importance to meteorology. The role of the sun in producing global circulation, climatic zones, seasonal changes, and the recurrence of periods of glaciation is well recognized, but intrinsic solar variability is neither implied nor required to account for these phenomena. The simple changes in insolation responsible for these effects are predictable, far in advance, on the basis of known parameters of the orbit, figure, and motions of the Earth.

EVIDENCE OF A SOLAR CONNECTION

LESSONS FROM HISTORY

Long before the physical nature of solar variability was known, attempts were made to identify possible effects of simple solar features on the Earth's atmosphere. From the start, these efforts were concentrated on a search for possible impacts of sunspots on weather, presumably by simple blocking or diminution of sunlight. Such a connection was proposed by the physicist Charles Boyle in a letter to Robert Hooke in 1660. Similar speculations were surely made before that and were common enough during the seventeenth and eighteenth centuries to be found in literary references.

In 1801 the astronomer William Herschel attempted to quantify the association with a correlation he had noted between the times of prolonged sunspot absence and the English weather, as reflected in the price of grain on the London market. But it was the discovery of the cyclic regularity of sunspot occurrence by Heinrich Schwabe in 1843 that sparked explosive interest in the subject and set it on its present course. Cyclic phenomena have an almost hynoptic attraction to scientists and laymen alike, and the apparent cosmic regularity and presumed significance of the sunspot cycle have drawn a steady stream of determined attempts to link its ups and downs with supposed cycles in weather, agriculture, economics, health, and human behavior.

Impetus and encouragement were given to early searches by clear associations found in the 1850's between the sunspot cycle and the occurrence of the aurora borealis and a convincing correlation with disturbances in the Earth's magnetic field. These relationships, though of dubious connection to weather, were strong evidence of real, terrestrial effects. The 1870's and 1880's were characterized by a flurry of scientific papers purporting to have found connections between solar behavior (and more particularly the 11-year sunspot cycle) and the weather—as measured by monsoons in India, rainfall in Ceylon, temperature in Scotland, or the flow of the Thames, Elbe, or Nile rivers. A new day had dawned, some said, in which scientific research had made possible the prediction of the future, bestowing an ability to anticipate and thus conquer certain problems that plagued mankind. "The riddle of the probable times of occurrence of Indian famines," announced Sir Norman Lockyer in 1900, "has now been read, and they can be for the future accurately predicted." Their pattern of occurrence, he believed, seemed to fit the ups and downs of the sunspot cycle.

Then the bubble burst: one by one the simple relationships vanished when examined more critically or faded in the light of longer records. A now classical example[1] was a marked correlation between the annual sunspot number and the water level in Lake Victoria, which seemed clearly established in the then existing record that included two 11-year sunspot cycles. The connection seemed to imply a direct relationship between solar activity and rainfall in Africa. After the middle 1920's, however, the level of the lake failed to show any further connection with this solar parameter. By and large, scientists have come to attribute these early, apparent relationships to accidental coincidences in limited, unrelated data sets—perhaps examples of what Irving Langmuir later called "pathological science," in which our desire to find a certain result influences what we see or do not see.

On the other hand, we need not look far in modern geophysics to find an example, now resolved, where scientists drew conclusions based on logic or consensus but with limited data and insufficient physical understanding. Fifty years ago the notion of continental drift was criticized with arguments similar to those given today against connections between solar variations and weather—principally based on the absense of a driving mechanism. The possibility of moving continents seemed almost ridiculous in terms of the masses and energies involved, and evidence for continental drift was sketchy, qualitative, and controversial. We should be cautious in extending the analogy too far or in supposing that the eventual resolution of the sun–weather case need also be a reversal of opinion. Nevertheless, in the case of continental drift, as perhaps in this, what was needed to resolve the question was new and better measurements made at the lines of physical contact and interaction: in ocean bottoms where plates were formed and found to spread. Abruptly, the attitudes and approaches changed, and the old data were reanalyzed to produce what is surely one of the most far-reaching scientific advances of our time.

RECENT REPORTED EXAMPLES OF POSSIBLE SUN-INDUCED EFFECTS

Interest in possible sun–weather or sun–climate effects has been sustained by a continuous series of efforts purporting to find evidence of correlations on time scales from a few days to tens of thousands of years.[2] Four recent studies illustrate both the span and the complexity of the problem.

1. A probable connection between the effect of varying solar radiation received at the Earth and the run of climate over tens of thousands of years is the basis for the Milankovitch theory of orbital-induced triggering of major glaciations. Global temperature histories from deep-sea cores support the existence of recurrent global climate periodicities of about 23,000, 42,000, and 100,000 years.[3] These closely match known periodicities of variation in three fundamental parameters of the Earth's orbit: the precession of the equinoxes, the inclination of the Earth's axis of rotation, and the orbital eccentricity, respectively.

This effect is independent of intrinsic solar variation. Models of climatic response to changes in insolation caused by these orbital variations have the correct periodicity but are not wholly successful in reproducing the relative amplitudes of variation found in the climate data. Nevertheless, orbital variations remain the most thoroughly examined mechanism of climatic change on time scales of tens of thousands of years and are by far the clearest case of a direct effect of changing insolation on the lower atmosphere of Earth.

2. A possible correlation between century-long changes in the level of solar activity and climate has been suggested to be a result of an apparent coincidence between the Maunder and Spörer minima of reduced sunspot activity and periods of unusual cold during the Little Ice Age. The latter is a period of anomalous climate between about A.D. 1400 and 1850, when European and North American surface temperatures were about 1°C cooler than at present. Two prolonged periods of severe cold during the Little Ice Age coincide approximately with the Spörer and Maunder minima of solar activity, about 1410–1540 and 1645–1715, respectively, when solar activity was unusually low, as documented by historical and proxy solar records. Other, similar prolonged periods of uncommon solar behavior have subsequently been documented in the 7500-year radiocarbon record in tree rings. These, too, correspond roughly with periods of global cold, as determined from records of glacial advance. The reality of major solar changes of this scale, lasting about 100 years and surpassing the scale of the normal 11-year cycle of solar activity, now seems established. The possible connection of these solar features with terrestrial climate is controversial, however, because we have no knowledge of how they may relate to terrestrially important solar outputs and because their purported correspondence with climate effects rests on limited climate records.[4]

3. A recurrent period of about 22 years has been identified in the pattern of droughts in the western United States, as derived from studies of tree-ring widths, covering the last 370 years.[5] This periodicity coincides with the 22-year magnetic cycle of the sun, equal to two 11-year sunspot cycles. In addition, the drought pattern has been shown to follow the phase of the solar signal throughout most of the period of examination. No convincing mechanism that might connect so subtle a feature of the sun to drought patterns in limited regions has yet appeared. Moreover, the cyclic pattern of droughts found in tree rings is itself a subtle feature that shifts from place to place within the broad region of the study.

4. A possible link between changes in the dominant magnetic polarity of streams of charged solar-wind particles with upper-atmospheric circulation at the 300-mbar level is probably the best known and most thoroughly studied sun–weather effect. The medium between the sun and the Earth is filled by the flow of charged atomic particles from the sun, called the solar wind, which have been found to be grouped into large regions, or sectors, of dominant positive or negative polarity and are tied to similar, large-scale magnetic regions on the sun. These charged sectors in the solar wind sweep by the Earth with solar rotation and interact with the Earth's magnetosphere. The purported relationship to meteorological effects in the lower atmosphere is associated with times of sector-boundary crossings, when the dominant magnetic polarity of solar particles at the Earth switches. This association between solar-sector boundaries and the vorticity area index of tropospheric circulation has been subjected to intensive

statistical examination, since it seemed at first to offer a clear case of a detectable short-term, sun–weather effect.[6] The magnitude of the effect on upper air circulation is subtle and, if real, constitutes an effect of minor meteorological importance. Moreover, it now seems likely that as with many past examples the correlation is present only in certain periods and certain seasons—a fact that diminishes its initial apparent significance.

These four cases represent some of the most thoroughly examined examples of possible effects of solar variability on weather and climate, yet the evidence in each case is less than clear. In every case, contradictory interpretations have been brought forward. In no case other than the Milankovitch theory does a testable physical mechanism exist to explain the purported effect.

PHYSICAL CONSIDERATIONS

SOLAR VARIABILITY

A first requirement for any testable explanation of a sun–weather or sun–climate connection is a physical description of the variation of solar inputs at the Earth. We know from observational data that the sun does vary. The first clear evidence of this came in the early seventeenth century with the discovery that dark spots come and go across the solar surface. Subsequent study has steadily reinforced the notion that the sun is a variable star, whose spectrum of activity and change goes far beyond the appearance of sunspots on its white-light surface.[7] We have also learned that the underlying basis for all observed solar activity is a dynamic magnetic field generated within the sun and modulated in its effects by solar convection and rotation.

Sunspots themselves are the direct manifestation of concentrated magnetic fields of several thousand gauss. Other generally weaker fields persist over the solar surface and are ever changing. The impulsive dissipation of magnetic forces provides the energy of solar flares; arched magnetic fields give form to solar prominences that rise and sometimes erupt above the solar surface; magnetic fields mold the changing shape of the solar corona and fix the conditions that direct the solar wind outward into interplanetary space.

We are far less certain about the relationship of sunspots, solar-magnetic activity, or any other form of solar change to the terrestrially important outputs of the sun; the quantitative relationship between observed solar-surface variability; and the Earth's receipt of photons, particles, and magnetic fields.

The energy output of the sun is remarkably constant over the period for which measurements exist. We do not yet have a reliable, extended record of the total radiative output including the visible and near-infrared portions of the spectrum, which are responsible for all known direct solar effects in the lower atmosphere. But during the last 60 years, during which serious attempts have been made to measure it, the total radiative flux from the sun seems constant within rough limits of about ±1 percent. Recent and precise measurements from spacecraft reveal changes in the total solar flux at the level of a few tenths of 1 percent over several days. These changes are less than those due to the eccentricity of the Earth's orbit and, for the lower atmosphere, far less than the day-to-day modulation of effective solar flux due to global changes in cloud cover.

Portions of the solar spectrum that are known to vary significantly are at the extreme ends of the envelope of radiation that characterizes the sun's emission, particularly short-wavelength radiation in the x-ray and ultraviolet portions of the spectrum (see Figure 1). Of these, the ultraviolet wavelengths are most energetic and capable of inducing significant atmospheric responses. The variability of solar ultraviolet and x radiation is greatest at the shortest wavelengths and least at the longest, where there is more energy, so that the effective variability in terms of total energy is small. The

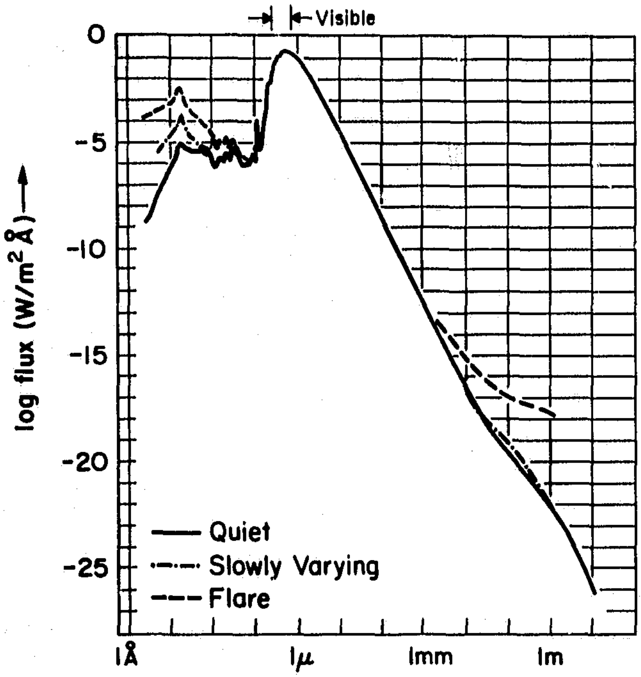

FIGURE 1 Energy versus wavelength distribution of the solar output.

sun also transmits energy to the Earth in cosmic rays and charged particles called the solar wind, which vary with solar activity. But particles received from the sun in the form of solar cosmic rays, the steady solar wind, or its frequent disturbances carry about 10^{-6} as much energy as the photon flux. In the near-ultraviolet, visible, and near-infrared regions, where the bulk of the solar energy is concentrated, the solar output hardly varies. (A modern summary of solar variability is the subject of Chapter 2.)

It can be concluded that as an engine of atmospheric circulation the sun is relatively steady and constant. Any mechanism linking intrinsic solar variations to climatic response must depend on fluctuations at the level of 1 percent or less in solar input, which, as emphasized in Chapters 3 and 6, is miniscule compared with the total kinetic energy of the lower atmosphere. The fluctuations in solar shortwave radiation and in solar particles and fields—which exert a dominant influence on the upper atmosphere—are considerable, however, and could influence conditions at some level of significance in the stratosphere and possibly the troposphere if suitable coupling mechanisms existed. Better measurements of solar inputs are needed as well as a fuller understanding of the processes of vertical coupling in the atmosphere.

UPPER-ATMOSPHERIC VARIABILITY

The upper atmosphere and the complex magnetic environment of the Earth are the filter through which any variable solar inputs must pass to reach the lower atmospheric levels where weather and climate are made. (A detailed review of these regions is given in the study *The Upper Atmosphere and Magnetosphere.*[8]) The character of the stratosphere and mesosphere (see Figure 2) is determined by a balance between absorbed solar radiation and outgoing atmospheric emission and by a balance between solar chemical production and destruction and atmospheric chemical loss (e.g., the production and destruction of ozone). The nature of the upper atmosphere is highly sensitive to changes in shortwave, solar-spectral flux.

As the density and internal atmospheric energy diminish at still higher atmospheric layers, the roles of the sun and of solar variability become more important. The tem-

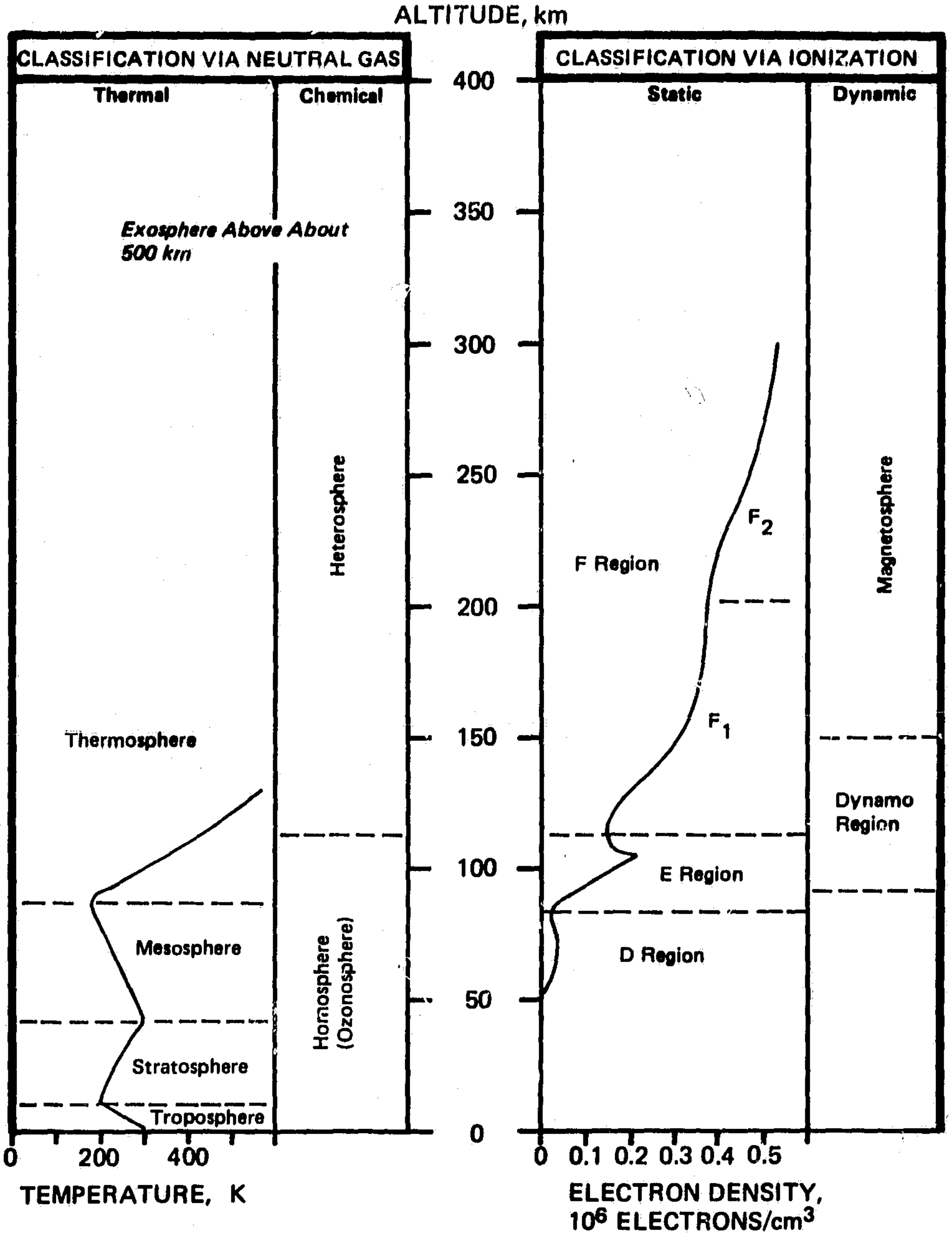

FIGURE 2 Classifications of the Earth's atmosphere.

perature and density of the thermosphere respond systematically to variations in solar activity. The nature of the ionosphere and the form of the magnetosphere are the result of solar inputs, and their changes are almost wholly dictated by the sun.

ENERGETICS

The parts of the solar output that are known to vary constitute less than 1 percent of the total budget of energy that the Earth receives from the sun (Figure 1). When this variation is compared with the total kinetic and thermal energy of the lower atmosphere (as shown in Chapter 3), it is far less than the total energy required to force direct changes, on a global basis, in atmospheric circulation. Moreover, the portions of the solar input that are known to vary are mainly absorbed or dissipated in the upper atmosphere. To have noticeable effects on the lower atmosphere these weak impulses must operate against a difference in density that increases by an order of magnitude for each 16-km decrease in altitude. The more energetic variable solar inputs, which are known to reach down the farthest (into the upper stratosphere), lose their intensity in a medium that is still 1000 times less dense than sea-level air. Thus for known solar changes to perturb the dynamics of the troposphere they must work through mechanisms that are complex and indirect: through electrical charging, induced changes in transparency, or trigger mechanisms by which a perturbation of very little energy somehow gains the leverage to produce an amplified effect. (A number of possible mechanisms linking solar inputs through various regions of the atmosphere are discussed in Chapter 6.)

THE NEED FOR CRITICAL STATISTICAL TESTS

Many of the pitfalls that hampered early investigations of sun–weather relationships still exist today. Paramount among them is the reliance on statistical tools that are too blunt or that are misapplied and a failure to demand appropriate critical tests for statistical significance. Statistics can be a powerful tool, but without a reasoned physical theory to guide selection it is all too easy to find accidental correlations in data as diverse and varied as meteorological records. Solar indices often are inappropriately chosen: this could hide real effects or introduce spurious ones. The sunspot number, for example, is a coarse and often irrelevant index for specific solar inputs to the Earth. Moreover, its annual or monthly average is grossly oversmoothed in comparison to the short time scale of individual solar events and their terrestrial impacts on the high atmosphere. Finally, the potential for autosuggestion is increased when the motive for the search is a preferred answer of practical, as opposed to scientific, importance. In this kind of prospecting there is little incentive to publish negative results, and, indeed, relatively few are found in the solar–weather literature.

Adherence to critical standards[9] in handling statistical data could avoid some of the confusion that has often characterized investigations in this area of research. (A further discussion of problems of statistical analysis is developed in Chapter 5.) These standards should include the following:

1. Understanding the properties of the data: errors, biases, scatter, autocorrelation, spatial coherence, frequency distribution, and stationarity.
2. Choosing statistical methods appropriate both to the properties of the data and the purpose of the analysis (e.g., description or prediction).
3. Critically examining the statistical significance of the results, and making proper allowance for spatial coherence, autocorrelations and smoothing, and data selection.
4. Testing the result on one or more independent data sets, or subsets, of the original data.

A PHYSICAL APPROACH

It would be foolish to dismiss all possibility of real connections between solar variability and weather on the basis of what has been tried in the past or on our present limited understanding of the physics of the atmosphere. Any improvement in our understanding of the processes that govern atmospheric behavior could be significant for science, regardless of whether it is useful in prediction. In this sense, solar perturbations may be thought of as natural tracers that can test the response of the atmosphere to an external impulse and the degree of horizontal and vertical coupling. We are only now within reach of a comprehensive picture of the interrelated solar–terrestrial system of which the meteorology of the lower atmosphere is but a part. We are still far from a full understanding of solar activity and as yet without a complete description of the real variability of all solar outputs, including the solar constant. Nor are we yet able to define with any certainty the levels in the atmosphere down to which all known variable solar inputs extend. To have an impact on meteorological processes, solar pertubations must somehow reach the troposphere. Changes in the solar constant, which is heavily dominated by visible and near infrared wavelengths, are directly transmitted to the Earth's surface. It is unlikely that simple connections linking other solar variations directly to the troposphere will be found, but until we know more of the coupling processes that link one part of the atmosphere to another we can say little of the plausibility of more subtle solar–weather effects that might operate through a chain of interactions.

We have recently come to appreciate the existence of secular solar changes that transcend in time, and perhaps in importance, the better-known 11- and 22-year cycles of solar activity. Studies of tree-ring radiocarbon reveal that in the last 1000 years solar activity has gone through at least three significant extremes, each lasting roughly 100 years. Preliminary examination of the longer tree-ring radiocarbon record suggests that such behavior was typical throughout the past 8000 years, with no dominant period apparent. The extent of corresponding changes in solar outputs and terrestrial inputs is unknown. This long-term solar variability—through persistence and greater range of variability—may be more effective than the more familiar shorter-term variations in altering the climate of the Earth.

Direct effects of solar variability have now been observed and measured throughout the solar–terrestrial system. Historically, these were observed as auroral displays and disturbances sensed by magnetometers at the surface of the Earth and later by ionospheric soundings and monitoring of secondary cosmic rays at mountain-top stations. More recently, we have made *in situ* and remote radar soundings of the composition and dynamics of the uppermost atmosphere as well as real-time probes of the disturbed topography of the magnetosphere. In addition, we have begun to monitor the variable inputs from the sun directly, from outside the atmosphere, through spacecraft measurements of the total solar flux and its spectral components and the flux and disturbances of the solar wind near the Earth.

The extent of solar influence on the atmosphere, including possible effects on weather processes, can now be tested by a combination of modeling of theoretical atmospheric responses and feedbacks and actual measurements taken in and above the stratosphere, where solar inputs are made and reactions occur. It is no longer necessary to rely only on remote observations of solar-surface features or on possible correlations with the mélange of diluted end effects in weather data.

There is no doubt that solar variations influence the upper atmosphere of the Earth in ways that at times overshadow all other known impulses. But how deep into the atmosphere do these solar effects extend, and how important are they, relative to internally driven changes in atmospheric circulation? How are thermospheric temperatures and winds affected by varying solar flux, and are these effects felt in the lower atmosphere? How are the properties of the stratosphere changed by the known variability of solar ultraviolet flux, and how might these changes influence the lower atmosphere? How is the amount and distribution of ozone and other trace substances altered by known changes in the input of solar radiation and particle flux? What are the links that tie disturbances in the magnetosphere or ionosphere to conditions lower in the atmosphere? How is the electrical field of the Earth (see Chapter 8) perturbed by impulsive solar events or by slowly changing solar activity? In what ways, if any, are these changes related to meteorological processes such as cloud formation or thunderstorms? What are the limits of variability, over short or long periods, of the various outputs of the sun? How, if at all, are these related to observed effects on the sun, the 11- or 22-year activity cycle, or longer trends of solar behavior?

These questions and others like them, all unanswered, focus on the key to the sun–weather question: conditions and processes in the upper atmosphere where observed solar inputs incite measurable responses. Some of the questions are now within reach of solution, given adequate attention, in the foreseeable future. A more physical framework for attack would shift attention from end effects in the lower troposphere to a more realistic assessment of the whole atmosphere. Such an approach would attack this old and persistent question not so much with the sword of statistics as with the scalpel of physics and not so much by reaching for an immediate or practical answer as by building a broader base of understanding of all of the atmosphere and all of the solar–terrestrial system. It would more fully recognize the existence of the varied medium that separates the lower atmosphere of the Earth from the sun and acknowledge the complex nature of global circulation, weather, and climate. Such an approach would build, in the tradition of experimental physics, on measurements of specific inputs and the study of specific processes at specific levels in the atmosphere, as part of the larger problem of understanding all of the Earth's atmosphere. It would press for *better* and more focused measurements, both of solar inputs and of atmospheric conditions and responses. And it would make use of simulations and models to separate atmospheric effects that now seem inseparable in the welter of real weather data. In such a reasoned approach, statistical analyses would follow the introduction of potential mechanisms, rather than the reverse, and negative answers could be as valuable as positive ones.

Of fundamental importance to the overall problem of solar–terrestrial physics, and therefore to the specific issue of possible solar effects on weather and climate, are better determinations of the range and variability of all the solar inputs to the Earth, including the flux of particles and fields, the solar luminosity, and the solar-spectral irradiance. Moreover, collection of the needed data must be pursued for a long enough period of time to test for climatically important variations on 11- and 22-year time scales. Such measurements would be most valuable if made at the top of the atmosphere and, where appropriate, as a function of depth into the atmosphere.

Accurate measurements of the total radiative flux (or "solar constant") have only recently been obtained with precision radiometers on the NIMBUS and SMM spacecrafts. Initial analysis has established the existence of variations in solar luminosity of a few tenths of 1 percent that persist for several days but leaves open the question as to the extent of longer and climatically more significant changes. Probably more important are detailed measurements of the solar-spectral irradiance, particularly in the near ultraviolet, where changes of importance to the chemistry of the upper atmosphere are known to occur.

Also needed is an improved theoretical understanding of the inherent causes of solar variability and the relationship of the terrestrially important outputs of the sun to observed indices of solar activity, such as the sunspot number, or cosmic-ray modulation. Any hope of making practical use of hypothesized sun–weather effects ultimately rests on our ability to predict and interpret changes on the sun. At present, solar physics can offer only the most tentative explanations of the *causes* of variable solar activity and little better than autoregressive predictions of the future phase and amplitude of the sunspot cycle. It is not obvious that we will ever be able to predict, far in advance or in detail, the occurrence of specific solar events, such as flares. The same may well be true of significant parameters of long-term solar activity, such as the 11-year sunspot cycle. What we can reasonably hope for is a better understanding of solar activity, its origins, and how observable solar activity relates to terrestrially important outputs of the sun.

A fuller understanding is needed of the electrical and magnetic environment of the Earth and its interaction with variations in solar-particle fluxes and fields. Two recently cited examples of solar–weather effects—the 22-year drought cycle in the western United States and the solar-sector boundary effect on atmospheric circulation—imply a possible connection with the extended magnetic field of the sun that is carried to the vicinity of the Earth by the solar wind. At the same time, our knowledge of the topography and dynamics of the Earth's magnetosphere and ionosphere, through which such impulses must react, is far from complete. An important goal in solar–terrestrial physics is to understand the processes of global atmospheric electricity, how the global circuit is perturbed by the sun, and the processes of physical coupling throughout the atmosphere.

To identify possibly subtle effects of solar-induced pertubations it will first be necessary to improve our understanding of the dynamics (meteorology) of the lower atmosphere and the roles of internal and external forcing. Numerical modeling of the global atmosphere is still at an early evolutionary stage and is unable to simulate all of the major aspects of the real behavior of weather or climate. Realistic assessments of suspected or hypothesized solar influences may require the use of such simulation models to guide the design of observational tests.

The past climatic variations over all the Earth need to be clarified for as long a period as possible into the past, as does the history of solar behavior. The known history of climate is far from complete, both in time and geographic sampling. Solar history, except for the last 100 years or so, is equally sketchy and is difficult to reconstruct in any detail. If we are to test the longer-term effects of solar variability on climate we will need to develop the history of solar behavior at least 100,000 years into the past, through whatever proxy data are available. The probable limit of tree-ring radiocarbon data for this purpose is about 10,000 years. The analysis of other solar-induced isotopes, such as beryllium-10 in ice and sea cores, promises a longer history of the sun's past behavior.

SUMMARY AND CONCLUSIONS

The search for possible effects of solar variations on weather and climate has been a subject of both scientific and popular interest for over a hundred years. The significance of suggested relationships has been mired in controversy throughout this time; statistical studies have not been adequate to give unequivocal answers to the question of the relative importance of solar perturbations on either weather or climate. Even the best of the purported correlations describe effects that are small compared with the normal fluctuations of weather variables. In many cases, reported correlations between solar activity and the weather rest on inadequate statistical samples; when data sets are expanded either temporally or spatially the apparent correlations are weakened or disappear. Much of the doubt about real sun–weather connections stems from a lack of proposed physical mechanisms to link known changes in solar inputs to weather parameters.

It is conceivable that solar variability plays a role in altering weather and climate at some as yet unspecified level of significance. Given what is now known of the complexity of global atmospheric circulation and what is not now known of the sun, the interplanetary medium, and the upper atmosphere, we think it is unrealistic to expect any improvement in the near future in weather and climate prediction based on solar-induced effects. A more immediate and, in our view, more appropriate goal for this area of science is to determine the limits of variability of solar inputs to the atmosphere and the depth in the atmosphere to which these variations have significant effects.

The persistent question of the extent of solar influence on weather and climate could be clarified considerably if emphasis were shifted from the traditional pattern of *search-*

ing for evidence to a more directed effort at *understanding the physics* of the atmosphere and the solar–terrestrial system as a whole. Such a shift would place greater emphasis on an improved understanding of the causes and extent of solar variability, on direct measurements of solar radiation and particulate inputs to the Earth, and on theoretical and *in situ* investigations of atmospheric perturbations induced by the sun and the mechanisms by which these disturbances may be transmitted downward through the atmosphere. This would require interdisicplinary efforts and more attention to the physics of the atmosphere. *In situ* measurements in the middle and upper atmospheres, the magnetosphere, and the interplanetary medium are now within the technical capability of modern space science and upper-atmospheric research. Advances[10] in our understanding of solar–terrestrial physics and the dynamics of the lower atmosphere should make it possible to specify the relative roles of external and internal forcing of meteorological changes, which is the key question in the sun–weather issue. Whatever the result and regardless whether solar-induced perturbations prove to be of practical, predictive value for weather or climate, the fields of atmospheric science and solar–terrestrial physics will benefit from the knowledge gained.

Toward this end, we make three general recommendations for future study in this field.

1. *The question of possible solar influence on weather and climate should be treated as part of the more general problem of the sun's effects on the atmosphere as a whole, within the established framework of solar–terrestrial physics and atmospheric science.* Significant advances in this specific subject must follow the overall pace of understanding of the other components of the sun–Earth system. For this reason we support the approach to basic understanding called for in *The Upper Atmosphere and Magnetosphere*,[8] *Upper Atmosphere Research in the 1980's*,[10] and *Solar–Terrestrial Research for the 1980's*.[11]
2. *More effort should be devoted to the development and testing of physical models of the effects of solar perturbations on the atmosphere and the mechanisms by which the different levels of the Earth's atmosphere are coupled.* A better definition is needed of the direct effects of variable solar inputs on the physics and chemistry of the upper and middle atmosphere, the composition and dynamics of these layers, and the interactive processes that couple the various regions of the atmosphere. Connections between the top of the atmosphere (where solar effects are known to dominate) and the troposphere (where weather is generated) are generally the weakest links in any chain that is hypothesized to connect the sun to weather and climate.
3. *The data base on which studies of sun–weather and sun–climate effects rest needs to be expanded and strengthened.* This should include: (a) continued measurements of the variability of the solar constant, solar spectral irradiance, and the flux of solar particles and fields for a long enough period of time to test for climatically important variations on at least an 11- and 22-year time scales; (b) new and innovative measurements of specific, solar-induced perturbations in the upper and middle atmosphere; (c) improved measurements of the Earth's electrical and magnetic fields and the changes induced by the incidence of solar particles and fields; and (d) an improved knowledge of the history of the past climate of the Earth and of the past history of solar behavior.

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I

BACKGROUND

A Review of Reported Relationships Linking Solar Variability to Weather and Climate

1

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INTRODUCTION

The century-old history of reported relationships linking solar variability to tropospheric weather and climate is beset with inconsistencies, contradictions, and inconclusive results. However, within this large body of reported connections, one can identify a number of results that seem worthy of further study and that support the possibility that solar variability may be related at some level of importance to changes in tropospheric weather and climate. Although none of the reported relationships verify such a connection, to many scientists they justify a search for physical mechanisms that must exist if such correlations are in fact real. The lack of well-defined physical mechanisms has hindered progress in the study of sun–weather connections and is in part responsible for much of the skepticism regarding the reality of a true cause and effect relationship.

Solar variability is discussed in detail in Chapter 2. In this chapter we define solar variability as perturbations in solar outputs associated with observable solar activity such as flares, plages, or sunspots or due to other solar irregularities such as coronal holes that, with solar rotation, modulate the Earth's receipt of solar photons, particles, or fields. We do not yet have a thorough, quantitative description of all solar outputs, including the total solar output or "solar constant." We do know that in specific spectral domains, such as the ultraviolet, the energy fluxes from the sun change significantly. However, a principal difficulty in identifying a causal relationship with tropospheric weather lies in the tremendous imbalance between the relatively small perturbations in solar energy output arriving at the Earth from activity-related events and the larger pertubations believed necessary to induce a recognizable tropospheric disturbance.

This chapter is intended as a summary of the types of correlations between solar variability and tropospheric weather or climate that have been reported in the literature. More extensive surveys can be found in recent reports by Shapley *et al.* (1975, 1977, 1979), Herman and Goldberg (1978b), Meadows (1975), King (1975), Wilcox (1975), Pittock (1978), Siscoe (1978), Bandeen and Maran (1975), McCormac and Seliga (1979), and Schatten *et al.* (1979). Here, we call attention to a sampling of modern results that typify the types of connections reported in the literature and to the uncertainties that in many cases accompany them.

The work reviewed here is restricted mainly to correlations with tropospheric phenomena. Little is said about the stratosphere and its response to solar activity, although some believe that it may be of strategic importance as a buffer zone, where highly variable solar ultraviolet and corpuscular (energetic particle) radiations modulate local chemistry and meteorology.

The reported connections presented here are divided into two general categories—long- and short-term relationships—to correspond roughly with climate and weather as customarily defined. Purported associations within each of those domains are grouped according to specific solar processes or meteorological effects. A section on a possible "electrical connection" is appended as an example of modern investigations that make use of reported correlations to attempt to define a physical connection between solar variability and tropospheric processes.

LONG-TERM RELATIONSHIPS

Long-term sun–climate correlation analyses most commonly search for a relationship between various tropospheric parameters and the 11-year sunspot cycle, the best known index of long-term solar variability. Figure 1.1 displays the annual mean sunspot number since 1610 (Eddy, 1976, 1979). We note that the 11-year cycle of solar activity is neither precisely periodic (a cycle can vary from 8 to 13 years) nor uniform in amplitude. These departures from a strictly regular periodicity provide unique signatures of solar variability, which can be used as tests of relationships between climate and solar activity; several studies have in fact suggested such associations.

The tropospheric variables for which a relationship with sunspot number is most commonly sought are simple indices of regional precipitation and temperature. Global maps purporting to show rainfall differences between times of high and low sunspot number were published as early as 1923 by Clayton and later expanded in similar studies by Shaw (1928). These authors also considered indirect indicators of precipitation such as snowfall and water levels of Lake Victoria and water levels of the Nile and Parana rivers. In each case their findings seemed consistent with a global picture of greater rainfall near the equator and at high latitudes at times of high sunspot number; in the temperate zone (20–40° latitude) a more complex pattern of both positive and negative correlations was claimed, which depended also on the season (see Figure 1.2). More recent studies of similar data (King, 1973, 1975; Bowen, 1975; Gerety *et al.*, 1977; Deshara and Cehak, 1970) are not consistent with the earlier findings, and in several cases fail to find any significant spectral peaks at 11-year periods.

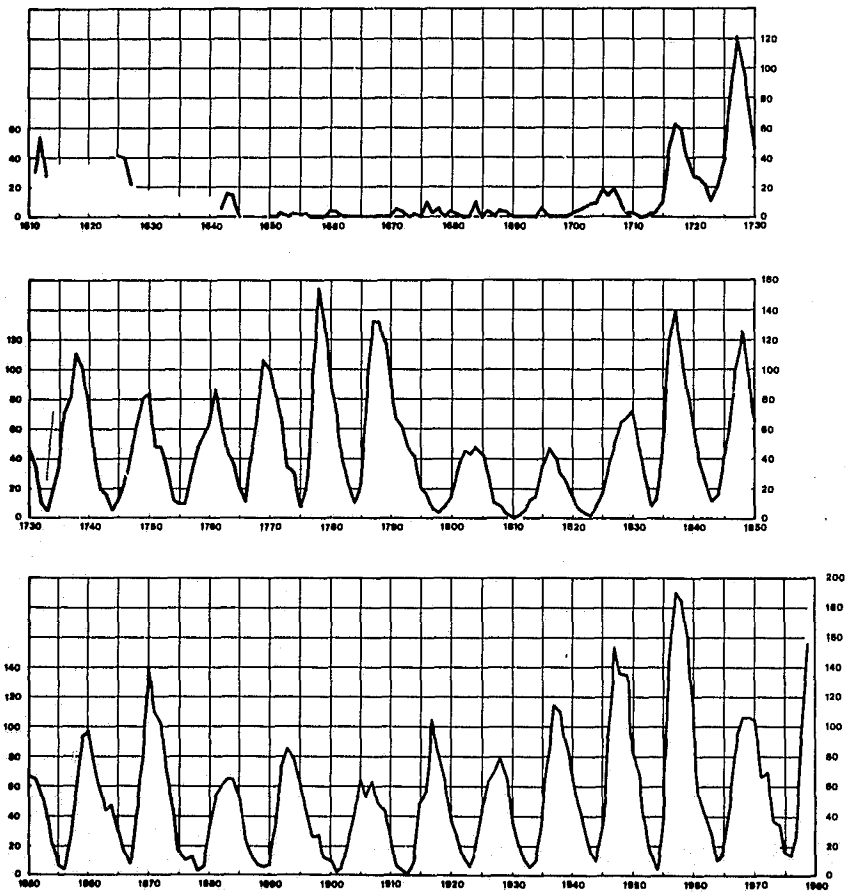

FIGURE 1.1 Annual mean sunspot numbers A.D. 1610 to present. Depressed period from about 1645 to 1715 is the Maunder Minimum (after Eddy, 1979).

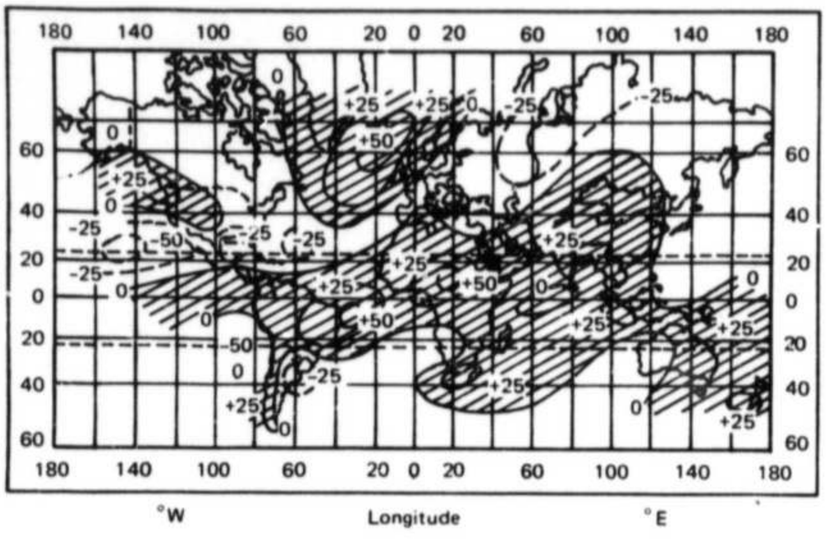

FIGURE 1.2 Global distribution of annual rainfall differences (in centimeters) between sunspot maximum and minimum found by Clayton (1923); shaded area is greater rainfall at maximum. Based on data from 1860 to 1917. More recent studies of similar data (see text) are not consistent with Clayton's findings.

A somewhat clearer picture exists with respect to the Hale double sunspot cycle of about 22 years, which is the full period of the known magnetic cycle of the sun. Surface observations of the sun made with magnetographs demonstrate that consecutive 11-year cycles are characterized by a reversal in magnetic characteristics, as observed in patterns of sunspot polarities and in the sign of the composite, polar field of the sun. A possible connection with climate has been made through the association of periods of drought in the midwestern United States with the Hale cycle, although King (1975) claimed to find this 22-year signature in rainfall at specific geographic locations, mainly in the tropics and subtropics. Roberts (1975), drawing on the work of Borchert (1971), Marshall (1972), and Thompson (1973), called attention to an earlier claim that periods of drought in the High Plains region of the western United States have shown a 20–22-year cycle of recurrence that seems linked in phase for the last 150 years to the Hale magnetic cycle of the sun. A similar possibility had been surmised by Abbot (1956) and by Douglass (1919, 1928, 1936) based on early tree-ring data.

A more thorough and comprehensive study of this effect was made by Mitchell *et al.* (1979), who used an extensive set of tree-ring data that sampled almost all of the continental United States west of the Mississippi River for the period 1600–1962. Their work reinforced the contention that the extent of drought in the western two thirds of the United States had varied with a quasi-periodicity of about 20–22 years during this time. Drought indices were reconstructed from tree-ring data for 40 geographic regions for this period, using tree sites that were selected on the basis of high sensitivity to changes in local precipitation, incorporating modern dendroclimatological techniques. Reconstructed drought indices were calibrated by comparison with the Palmer Drought Severity Index (PDSI) for the same geographical regions during the period 1931–1970. A year-by-year count of the number of regions with reconstructed drought indices of various thresholds is shown in Figure 1.3, taken from Mitchell *et al.* (1979). An apparent cyclicity is evident in most of the record, particularly when weaker droughts are included. Spectral analysis confirms a concentration of variance at periods near 22 years, generally in phase with the Hale double sunspot cycle (see Figure 1.4). The coherence in phase between periods of drought and the double sunspot cycle is not perfect, however, and as yet there is no plausible physical explanation for the relationship. The maximum extent of drought falls early in the double cycle, about 2 years after alternate minima; the minimum extent of drought occurs near year 15. Mitchell *et al.* (1979) also found evidence for a stronger relationship for the Hale cycles with large sunspot numbers, which reinforces the suggestion of a possible solar-activity link. However, Bell (in press) and Currie (1981b) pointed out that for part of the record the period of drought recurrence is closer to the 18.6-year period of revolution of the nodes of the lunar orbit, suggesting a possible tidal mechanism for the period of drought recurrence or, perhaps, a combined solar–lunar effect.

Numerous claims have also purported to demonstrate correlations between surface temperatures and solar variability, most often with the 11-year sunspot cycle. Köppen (1873, 1914) and Walker (1915) found what they thought to be a negative correlation with global annual mean temperatures, as one might expect from simple sunspot blocking. A similar result was found by Clayton (1923) and more recently by Craig and Willett (1951). Clayton (1923) also reanalyzed Köppen's data to test for an 11-year effect in zonal temperature trends. For data predominantly spanning the 19th century, he concluded that annual mean temperatures in the equatorial and temperate zones generally follow the suspected global trend in phase (negative) and magnitude (0.3–0.4°C), whereas subtropical, arid regions tend to show an opposite correlation with sunspot cycles. This result tempted Clayton to speculate that rainfall has an influential effect on the temperature structure. More recently, Currie (1974, 1979, 1981a) examined 85 years of temperature data (1884–1968) from 226 North American stations using the maximum entropy technique of power spectrum analysis. He found evidence of a small (0.1–0.3°C) modulation of about 10.7 years, present for only a third of the stations, all in the northeast.

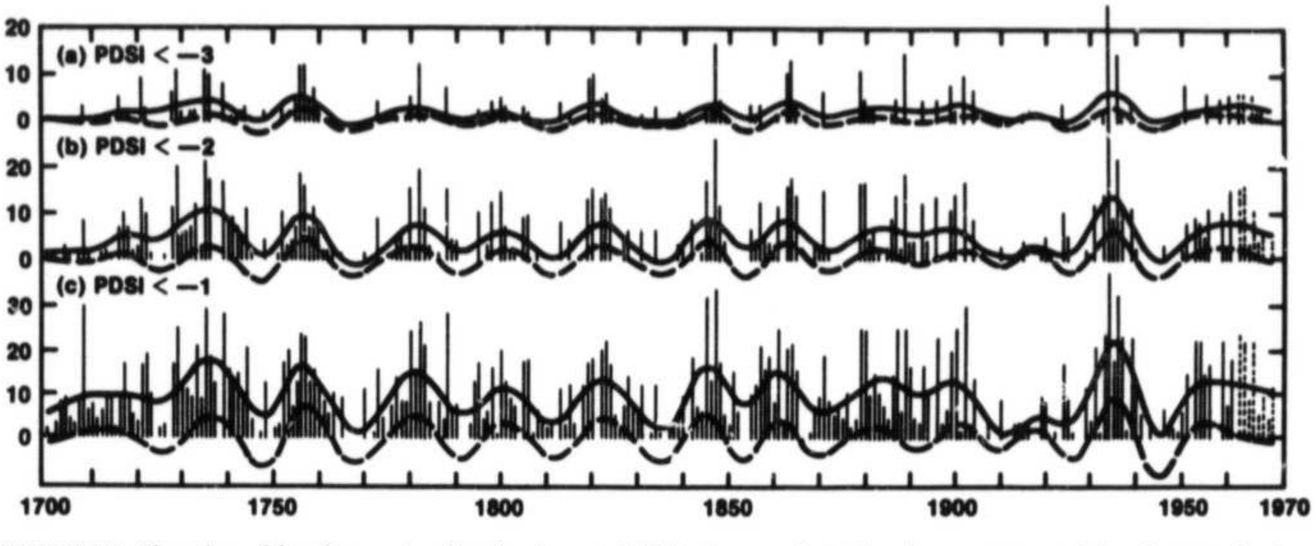

FIGURE 1.3 Chronology of drought areas (number of regions out of 40) for three PDSI limits, based on a reconstructed drought area index from 1700 to 1962 and on observed values after 1962. Periodic lines denote series after bandpass filtering (after Mitchell *et al.*, 1979, with permission of D. Reidel Publishing Company).

The phase of the claimed relationship is the same as that found by earlier workers: cooler temperatures at times of maxima in the 11-year sunspot cycle. Special methods of spectral analysis are necessary to find so small an apparent effect. At the same time, the cyclic effect that Currie found may well be too small to be climatically significant in any practical sense in the northeastern cities that are represented in his studies. Indirect and less convincing indications of a possible temperature connection with the 11-year cycle have been reported by a number of investigators. Examples include a possible relationship with the persistence of shore ice in Iceland (Clayton, 1923) and a suggested relationship with the length of the growing season at Kew, England (King, 1973).

In a more recent study, Hoyt (1979) found that surface-temperature anomalies in the northern hemisphere correlate well with another, unrelated characteristic of sunspots: the ratio of the mean size of the dark central regions of spots (sunspot umbras) to the outer, penumbral area. The two data sets studied by Hoyt show qualitative agreement for the last 100 years (see Figure 1.5) in the sense of secular or long-term trends, although he found a weak cycle of about a 20-year period in the umbral–penumbral data. Neither parameter seems related to the 11-year sunspot cycle in Hoyt's analysis. Hoyt (1979) noted that the umbral/penumbral ratio may be a measure of convective energy transport in the photosphere, which could make it a more sensitive index of solar luminosity and which in turn could have a more direct influence on the Earth's weather and climate.

Claims that the height of the tropical tropopause varies with sunspot numbers have been made by Stranz (1959), Rasool (1961), Cole (1975), and Gage and Reid (1981). Gage and Reid found a modulation in tropopause height of about 0.5 km peaking at times of maxima in the 11-year sunspot cycle; however, this was based on rawinsonde data from two tropical Pacific

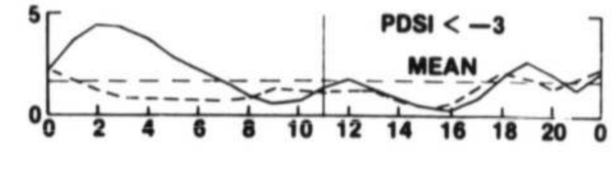

FIGURE 1.4 Mean relative drought area during Hale 22-year period. The high sunspot envelope refers to mean of cycles reaching strong sunspot maxima. The low sunspot envelope covers cycles reaching weak sunspot maxima (J. M. Mitchell, National Oceanic and Atmospheric Administration, personal communication, 1980).

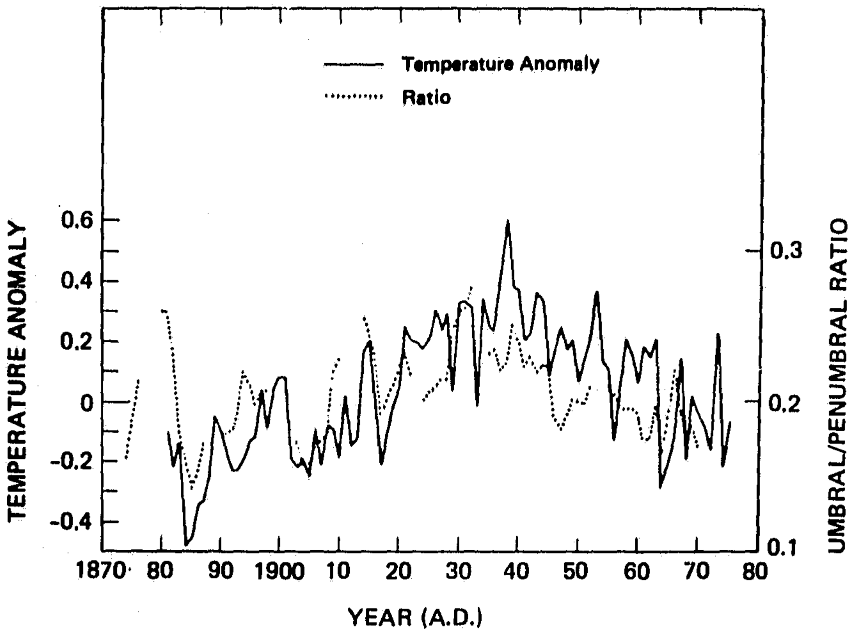

FIGURE 1.5 Relationship between sunspot umbral/penumbral ratio and surface temperature anomalies in the northern hemisphere found by Hoyt (1979).

sites that span only two solar cycles. They proposed that the mechanism for the effect may be a secular variation of about 0.5 percent (trough to peak) in the solar constant, in phase with the sunspot number, that produces a small modulation in the sea-surface temperatures in the tropics. This in turn is amplified at the tropopause through latent heat release in deep cumulus convection. Were this the case, one might expect to find direct evidence of a similar 11-year signal in land temperatures at the same latitudes or in yet-to-be obtained measurements of the solar constant made throughout a full solar cycle. Currie (1981a, 1981b) found an 11-year surface-temperature modulation that is 180° out of phase with what the Gage and Reid result might predict.

Both Eddy (1977) and Stuiver (1980) compared solar variations of longer term with climate data, on a scale of centuries, to test for possible correlations on long time scales. The Maunder Minimum of low sunspot activity (Eddy, 1976), which took place between about 1645 and 1715 (Figure 1.1), falls at a time of low temperature in Europe and North America, during the so-called Little Ice Age, as does the Spörer Minimum (about 1450–1540). Eddy (1977) pointed out the association of these features as a possibly important sun–climate effect in the sense that global temperature seemed to follow long-term highs and lows in solar activity. The comparison was based principally on Lamb's curve of winter severity in Europe during the period. Stuiver (1980) examined a more extensive set of climate data and an improved record of solar variability for the last millenium and concluded that there is no real evidence for a connection, perhaps because there is so little agreement between different climate indices.

The history of solar activity can be traced in crude terms about 7500 years into the past, through the analysis of the radiocarbon content in tree rings, which is an index of solar-wind conditions (Eddy, 1976, 1977; Stuiver and Quay, 1980). Although periods of anomalous solar behavior are well established in the longer record, the corresponding record of climate is not adequately defined to permit a definitive test of correspondence.

Clayton (1923) and Shaw (1928) compared global patterns of surface-pressure distribution with the sunspot number. These two investigators found results that were essentially similar. To analyze longer-term effects that might be due to the sun, Clayton calculated 5-year running means of pressure data to suppress the shorter-term variations that were presumed to be caused by internal fluctuations, utilizing weather records for the period from 1858 to 1920. He noted an apparent tendency during times of high sunspot number for the pressure to be high over the continents in local winter and high over the oceans in summer. He concluded that the equatorial zones show a decrease in pressure, whereas the continental zones poleward of 20° latitude show an opposite effect with greater sunspot activity. The semipermanent Aleutian (55° N, 180° E) and Icelandic (65° N, 40° W) lows were obvious exceptions to these apparent trends.

These possible associations were reasserted in more recent studies by King *et al.* (1977), who also claimed to show that the complex picture of pressure variations deduced by Clayton could be organized in terms of planetary standing waves. Their findings suggested that the amplitude of apparent pressure changes between high and low sunspot number can be described by Rossby–Haurwitz pressure waves (2, $-n$), where the indices (m, $-n$) refer to wave numbers of longitude and latitude, respectively. The maximum amplitudes of Rossby–Haurwitz pressure waves occur near 70° latitude. Using 70° data for January, King *et al.* (1977) also found a longitudinal pressure wave of wave number two with antinodes near 140° E and 340° E, although the data were sampled for only one solar cycle, causing the data to be of limited statistical significance.

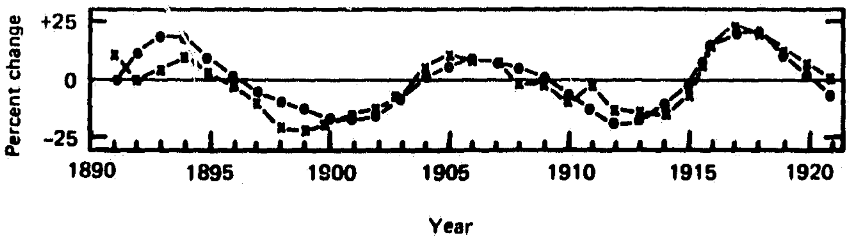

FIGURE 1.6 Departures of annual latitudinal range of anticyclones moving across Australia generally from west to east from normal range between 1891 and 1921 (Kidson, 1925; Bowen, 1975). The apparent close relationship found in this analysis does not continue in more recent data (Pittock, 1978).

Nastrom and Belmont (1980) found possible evidence for global planetary wave control of tropospheric circulation and a possible solar-cycle dependence. Their study correlated winter tropospheric winds measured from 1949 to 1973 with the 10.7-cm solar-radio flux (an index of solar activity) and found 11-year periodicities that are most pronounced north of 30° latitude near jet stream axes or planetary standing waves. However, since their study is based on only two solar cycles, it must be considered less than conclusive.

Other pressure-related phenomena that have been claimed to exhibit a solar-cycle dependence include small periodic fluctuations in the position of various semipermanent high- and low-pressure ridges (e.g., Mitchell, 1965; Angell and Korshover, 1974; Bradley, 1973; King, 1974). Schuurmans (1975) suggested a possible 22-year Hale cycle dependence for the longitudinal position of the Icelandic low in global atmospheric pressure.

Contradicting the results cited above are a number of studies that report solar-related effects in atmospheric pressure and circulation data that are inconsistent with those reported above, including work by Wexler (1956), Baur (1958), Willett (1961), and Parker (1976). Thus, as in nearly every other case in sun–weather studies, different studies give conflicting results.

In addition to the semipermanent pressure centers associated with general circulation, there are transient low- and high-pressure systems (cyclones and anticyclones, respectively) that may move over considerable distances and persist for several weeks. If solar perturbations could in some way affect the positions of semipermanent high- and low-pressure areas, these external influences could also affect storm-track orientation. Indeed, early work claimed to show that prevailing cyclonic storm tracks across North America tend to be displaced toward the equator at times of high sunspot numbers (Helland-Hansen and Nansen, 1920; Kullmer, 1933). In the southern hemisphere, particularly near Australia and New Zealand, Kidson (1925) and Bowen (1975) found similar results for eastward-moving cyclonic storms (see Figure 1.6), although Pittock (1978) showed that Bowen's finding breaks down in recent solar cycles. More recently, Brown and John (1979) investigated storm tracks crossing the North Atlantic into Europe and found evidence of a strong solar-cycle storm-track dependence for the last five solar cycles. In their study the average track displacement at high sunspot number is displaced about 2.5° south for storms crossing the region north of 50° N.

Storm frequency was considered by Reitan (1974), who was unable to find a good correlation with solar cycle. However, others (e.g., Zatopek and Krivsky, 1974) have reported a storm activity correlation over the oceans through observation of "meteorological microseisms." Their results show that for data for 1948–1966, frontal activity in the North Atlantic was greater during sunspot maximum years. However, because their result was based on data from only one and a half solar cycles, it must be considered a possible chance occurrence.

The frequency of thunderstorms, as measured in lightning activity, has also been thought to be related to solar activity (e.g., Septer, 1926; Shaw, 1928; Brooks, 1934; Stringfellow, 1974; c.f., Figure 1.7), although there is no general consensus as to whether there is a significant connection. Kleimenova (1967), for example, discredited much of the earlier work. Nevertheless, several qualitative suggestions have been made to explain these possible effects in terms of physical linkages (Markson, 1978; Herman and Golberg 1978a; Follin *et al.*, 1977).

Possible geologic evidence for an early sun–weather connection has been occasionally cited in studies of annually layered sediments and varves (e.g., Bradley, 1929; Anderson, 1961), where repeated patterns of 11 or 22 layers are inter-

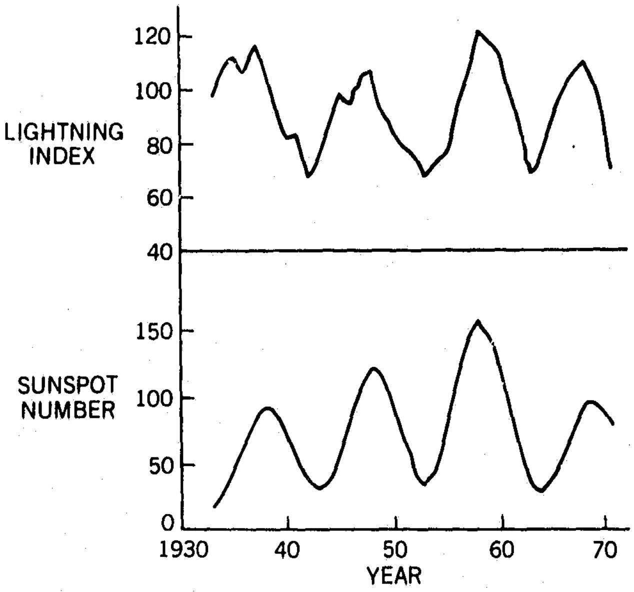

FIGURE 1.7 Five-year running means of average sunspot number (lower curve) and average annual lightning index for 40 stations in Great Britain (from Stringfellow, 1974). The apparent relationship shown here was not borne out by other studies of lightning incidence, which included data from the same area (e.g., Brooks, 1934; Kleimenova, 1967).

preted as solar effects. The presumption here is that sedimentation was governed by meteorological conditions, such as wind or rainfall, which in turn were dominated by solar variability. Recently, Williams (1981) found evidence of remarkably regular patterns in glacial varves from Australia with repeating sequences of 11 and 22 layers. The varves were deposited in the late Precambrian, about 680 million years (m.y.) ago. Williams argues that the strength of the Earth's magnetic field may have been considerably weaker than at present; at such times of reduced terrestrial magnetic-field intensity, solar-particle effects on the upper atmosphere of the Earth would be enhanced, leading to a more direct effect on weather and climate from solar variability. Still in question, however, is whether the sediment layers found by Williams represent annual features and whether the sun in Precambrian times exhibited an 11-year cyclicity as it does today; because of this doubt the relevance of the sediment data to solar influences is highly conjectural.

It must be emphasized that many of the reported relationships presented thus far have been subject to periods of breakdown or reversal. This can be taken as evidence against the reality of such effects, in the sense that some or all of the purported connections may be transitory and possibly accidental. On the other hand, Herman and Goldberg (1978b) noted an apparent concurrence of periods during which disparate meteorological parameters behave alike to either correlate or not correlate with sunspot numbers. Because the atmosphere is driven by numerous competitive effects, a possible interpretation may be that the relatively minor influence of solar activity may only become apparent during select periods when other competitive forces have weakened. However, if this more complex interpretation is valid, the value of suspected solar effects in practical weather forecasting could diminish to a level of insignificance.

SHORT-TERM RELATIONSHIPS

Short-term sun–weather relationships may be classified according to the type of direct or indirect solar perturbation that is presumed to be responsible, such as solar flares, geomagnetic disturbances, or short-term changes in the properties of the solar wind. The most commonly associated meteorological parameters include pressure, circulation, and thunderstorm activity. Short-term correlations between solar activity and meteorological parameters may be more difficult to recognize, because, if present at all, suspected solar effects must be identified against a background of internal and possibly stochastic fluctuations whose amplitudes may far surpass that of externally driven effects.

Typical of modern studies of possible solar-flare responses is that published by Schuurmans (1965) and Schuurmans and Oort (1969). They studied possible changes in the mean height of the 500-mbar pressure level (about 6 km altitude) in the 24 hours following the occurrence of 81 solar flares (importance 2+ or greater) using aerological data from 1020 stations that provided nearly hemispheric coverage for the northern hemisphere. They found, as a possible solar effect, an apparent pattern of changes in pressure heights that exhibited a cellular structure in polar regions that suggested wave patterns. Their result was consistent with the findings of Duell and Duell (1948), who found that within 2–3 days after selected geomagnetic disturbances, surface pressures at European stations tended to fall by about 2 mbar at the same time that surface pressure increased in the Greenland–Iceland area. Schuurmans and Oort (1969) studied changes in pressure levels at altitudes up to 50 mbar (20 km) and found the height of maximum change to be near 300 mbar (8 km) in the winter (Figure 1.8). Their study also suggested that the delay time of these apparent responses increased from high altitudes to low, from lags of about 6 hours at higher elevations to 2 days at the Earth's surface. The large vertical pressure gradients found by Schuurmans and Oort might be expected to produce a downward flow of air. This effect was possibly observed indirectly by Reiter (1973), who found greatly increased concentrations of the tracer elements ^{7}Be and ^{32}P in the atmosphere at Zugspitze, West Germany (elevation 3 km) on the second day following major flares of class 2 or greater. Reiter argued that these radioactive nuclides originate in the stratosphere by cosmic-ray spallation and can only reach the 3-km tropospheric level by downward mass transport of stratospheric air.

Data on thunderstorm frequency have been repeatedly examined to test for possible associations with solar-flare events (Markson, 1971; Bossolasco *et al.*, 1973a). The basis for suspecting solar connections with atmospheric electrical effects such as thunderstorm activity is the well-established link between solar flares and ionospheric disturbances and simple models that relate electrical effects in the troposphere to a global electrical circuit that includes the ionospheric potential

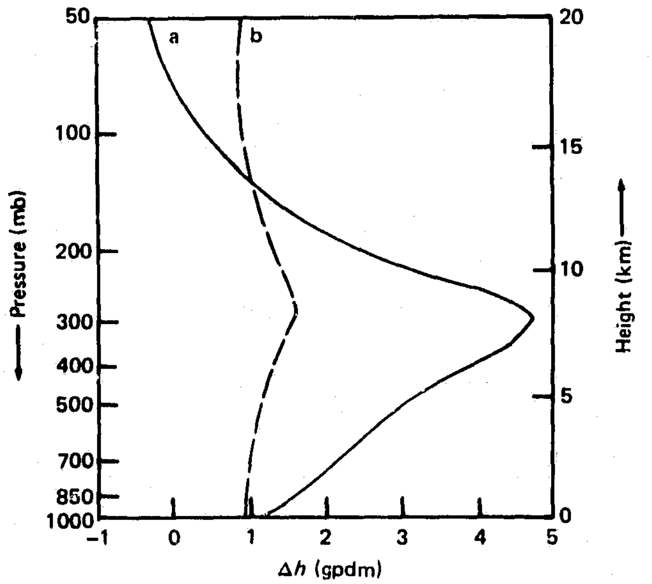

FIGURE 1.8 Difference in height of pressure levels over an ocean station (56.5° N, 51.0° W) before and after solar flares (curve a), compared to standard error of the mean (curve b), according to Schuurmans and Oort (1969).

(Markson, 1978). Bossolasco *et al.* (1973a) reported that thunderstorm activity in the Mediterranean area was enhanced, 50–70 percent above the normal background level, about 4 days after solar-flare eruptions. Markson (1978) found the same effect but with delays of about 7 days in North American data, with a maximum increase of 63 percent. However, the free parameter of such long and possibly arbitrary lag times, combined with incomplete thunderstorm data, leave room for a large uncertainty in the validity of both results. Supporting such findings are studies linking other atmospheric electrical parameters, such as air–earth current density, potential gradient, and ionization, with solar flares. Because the primary thunderstorm parameters used in these correlation studies relate to electrification, a link between solar flares (or other forms of solar activity affecting the geoelectric environment) and thunderstorms is an enticing but as yet unproven possibility.

Geomagnetic activity is an indirect measure of solar activity, but a direct measure of solar effects on the near-Earth environment. Early work by Duell and Duell (1948) endeavored to show that within 2–3 days after geomagnetically disturbed days in winter months, European surface pressure fell by an average of 2 mbar, coincident with a rise at least as great in the Greenland–Iceland area. Similar results were concluded by Mustel (1972) using winter data from 1890 to 1967 and by Sidorenkov (1974), who studied surface pressures between 1950 and 1970. Their findings generally agree with the results of Schuurmans and Oort (1969) for the effect of solar flares on 500-mbar pressure levels, as shown in Table 1.1. A number of other investigations have found surface-pressure responses to geomagnetic disturbances; however, Stolov and Spar (1968) and Stolov and Shapiro (1969) found no such evidence in the data they analyzed. Thus, evidence for a real solar effect on lower atmospheric pressure is still controversial.

One should expect to find stronger evidence of solar perturbations in higher-level pressure and circulation, although here, too, the case is also controversial. Sarukhanyan and Smirnov (1970) and Mustel (1970) concluded that the zonal character of upper-level atmospheric circulation is disrupted and meridional processes are enhanced during geomagnetically disturbed periods. However, Stolov and Shapiro (1971) challenged this claim. In a later paper, Stolov and Shapiro (1974) reported that the difference in height of the 700-mbar level between 20° N and 55° N increases by about 20 m in winter months, about 4 days after a geomagnetic disturbance. The 700-mbar level is nominally reached at an altitude of about 3 km. This change corresponds to an increase of 7 percent in the mean zonal wind flow.

The relationship of solar activity to the formation of low-pressure troughs has been intensively analyzed as a possible short-term, sun–weather effect that could be of practical importance in routine weather forecasts. Macdonald and Roberts (1960) first concluded that low-pressure troughs entering or forming in the Gulf of Alaska in the wintertime are deeper (more intense) when they are initiated 2–4 days following a major rise in geomagnetic indices. These troughs may be regarded as cyclonic waves that move in an eastward direction. Roberts and Olson (1973) extended the study in terms of a more general parameter of 300-mbar circulation—the vorticity area index (VAI), a measure of the area within which the absolute vorticity (or circulation) exceeds a specified value. They found that this meteorological index was also correlated with geomagnetic disturbances. The VAI had the possible advantage of removing some of the subjectivity in the description of the intensity of pressure troughs.

These preliminary findings of a correlation between the VAI and geomagnetic indices were later elaborated in terms of di-

TABLE 1.1 Comparison of the Atmospheric Pressure Changes That Are Reported to Follow Solar Flares and Geomagnetic Disturbances, According to Three Contemporary Studies[a]

	Approximate Center	Pressure Responses		
Geographic Areas	(Coordinates)	I	II	III
West Germany	55° N, 5° E	Rise	Rise	Rise
Eastern USSR	60° N, 135 ° E	Rise	Rise	Rise
South of Kamchatka	50° N, 165 ° E	Rise	Fall	Rise
Gulf of Alaska	55° N, 140° W	Rise	Rise	Rise
Western Canada	55° N, 115° W	Rise	Rise	No data
Kara Sea	70° N, 85° E	Fall	Fall	Fall
South Japan	45° N, 145° E	Fall	Fall	Fall
South of Aleutians	50° N, 175° W	Fall	Fall	No data
South of Iceland	45° N, 35° W	Fall	Fall	Fall

[a] Sources for pressure responses:

I. Schuurmans and Oort (1969); flare response, 500-mbar level; data for 1957–1959; 81 flare events greater than or equal to 2^+; 1 day after flare.

II. Sidorenkov (1974); magnetic activity response; surface; data for 1950–1970; 14 geomagnetic disturbances, 3 days after start of disturbance.

III. Mustel (1972); magnetic activity response; surface; data for 1890–1967; 834 geomagnetic disturbances; 2–4 days after start of disturbance.

rect, solar-wind parameters. The existence of well-defined sectors in the dominant polarity of the solar-magnetic field (carried by solar-wind particles) was a discovery by space physics that offered a new, possible mechanism of solar–terrestrial coupling. In particular, the alternation of the sign of the interplanetary magnetic field (IMF), carried in solar-wind "sectors," provides a possible switching mechanism for charged particles or magnetic-field interactions in the upper atmosphere, as the sign of the Earth's magnetic field remains fixed on these time scales. The occasions when the solar-wind polarity appears to reverse at the Earth—observable from spacecraft as interplanetary magnetic-sector boundaries—thus provided a new, independent index of solar variability that could be tested for possible connections with Earth–atmosphere effects. To first order these times of magnetic sector boundary (MSB) passage are independent of sunspot number or solar-flare occurrence, and they are reasonably well defined.

Soviet scientists were the first to relate atmospheric pressure (Mansurov *et al.*, 1975) and circulation (Kuliyeva, 1975a, 1975b) to the polarity of the IMF. Mansurov and his colleagues found, for example, that the average surface pressure at Mould Bay, Canada, was higher when the IMF was directed toward the sun. Changes in upper-level pressure with respect to the MSB were studied by Svalgaard (1973) at pressure levels between 850 and 30 mbar (1–25 km). He observed that at high latitudes, pressure-level heights increased (pressures rose at constant heights) a few days following an MSB crossing. The reverse was found to be true for midlatitudes.

The trough analysis of Roberts and Olson (1973) was extended by Wilcox *et al.* (1973a, 1973b, 1974) using the MSB and the total vorticity index summed over the northern hemisphere from latitudes of 20° N and poleward. The response they found for the VAI at the 300-mbar level to sector-boundary crossings is illustrated in Figure 1.9, from a sample of 54 sector-boundary crossings. They found that on the average the VAI decreases beginning about 2 days before the day of sector-boundary passage, with a minimum 1 day after. Afterward, the VAI rises to predisturbance values. Wilcox and his colleagues also reported that this effect virtually disappears in summer and at heights above 100 mbar (16 km). These results seemed to be reinforced by a subsequent analysis based on an increased number of data sets (Wilcox *et al.*, 1975) and by a critical statistical examination by Hines and Halevy (1975, 1977). More recently, however, Williams and Gerety (1978) criticized this result by showing that the apparent relationship disappears in newer data (1974–1977). Furthermore, Shapiro (1979) reanalyzed the earlier results of Wilcox *et al.* (1973a, 1973b) and was unable to reproduce their finding. In a more extensive test of the relationship using data from 1947 to 1970, Shapiro could again find no evidence of a connection between sector boundaries and the VAI. Shapiro (1979) used a somewhat different definition for the VAI from that applied by Wilcox *et al.* and added a sixth month (October) to the "winter" data; if these changes explain the discrepancy, however, they also restrict the possible application of the Wilcox *et al.* result. Although Wilcox and Scherer (1980) have responded to these critiques, we must conclude that the Wilcox *et al.* result is still open to controversy.

MSB crossings have also been tested for possible association with thunderstorm frequency, on the supposition that a magnetically induced effect might be discernible in atmospheric electrical activity. Markson (1971) was the first to apply this approach; he found an increased probability of thunderstorm occurrence in the United States within 1 day of sector-boundary crossing. The tendency was found for only one of the two possible types of sector polarity change: from a positive to a negative sector; no change was observed for crossings from negative to positive sectors. The statistical validity of these results has also been challenged by Shapiro (1979); moreover, they appear to be contradicted by a later conclusion reached by Bossalasco *et al.* (1973b), who found a 15 percent *decrease* of lightning frequency during positive to negative crossings in 10 years of Mediterranean data. They, too, found no apparent effect for negative to positive crossings. A more detailed analysis of the same phenomenon was also made by Lethbridge

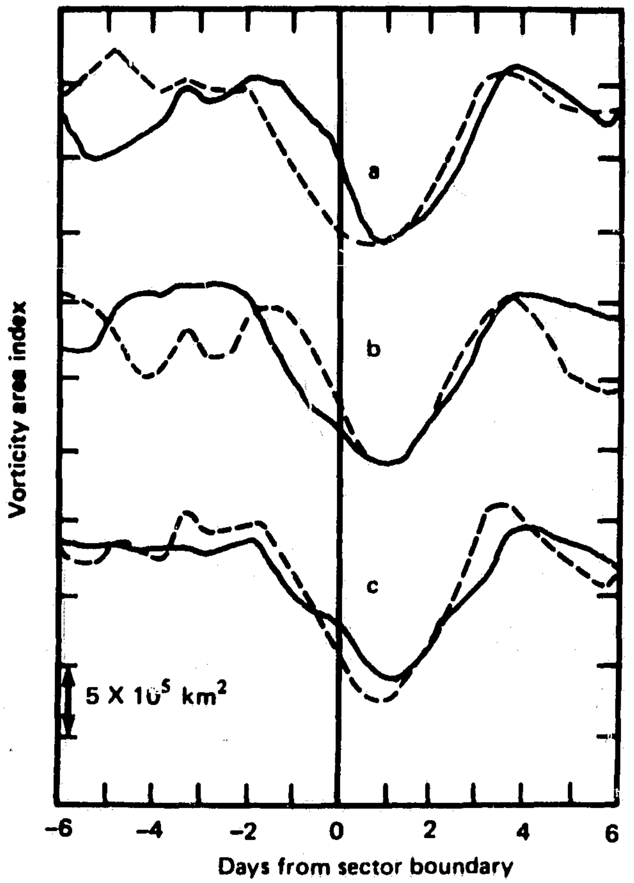

FIGURE 1.9 Average response of VAI at the time of a solar magnetic-sector boundary passage, according to Wilcox *et al.* (1973a). Curve a: dashed—30 boundaries separating positive from negative sectors; full—24 boundaries separating negative from positive sectors. Curve b: dashed—22 boundaries in second half of winter; full—32 boundaries in first half of winter. Curve c: dashed—28 boundaries in the interval 1967–1970; full—26 boundaries in the interval 1964–1966. Other investigators (see text) have been unable to reproduce this result, particularly in more modern data.

(1979), who tested 30 years (1947–1976) of thunderstorm data from 102 weather stations in the United States. She found the strongest indication of a possible solar signal for winter months in the 40–45° N latitude zone with peak activity occurring 1 day after positive to negative boundary crossings—i.e., in the same sense as Markson's conclusion. However, when the daily thunderstorm data were combined for all seasons and all latitudes and for both types of polarity reversals, Lethbridge could find no discernible response to MSB crossings.

THE ELECTRICAL CONNECTION

We have mentioned that electrical coupling presents a possible mechanism for a direct physical connection between the upper and lower atmosphere. Atmospheric electrical coupling offers a direct link from the upper to the lower atmosphere, occurs instantaneously, and could possibly affect meteorological parameters, such as aerosol formation and cloud growth. In this section some of the correlations between atmospheric electrical parameters and solar activity are reviewed. These correlations should not exist if classical atmospheric electricity concepts are valid, whereby the "global" circuit is an internal system driven by thunderstorms (see below) and shielded from external influences by the ionosphere. Several proposed mechanisms and new measurements are offered to illustrate how external effects may in fact perturb the internal system.

Figure 1.10 is a schematic diagram of the idealized atmospheric electrical circuits. There are, on average, 1500–2000 thunderstorms in progress globally at anytime, acting as a generator to deliver approximately 1500–2000 amperes to the ionosphere. This current returns to Earth through the more extensive fair-weather region, which can be characterized by the ionosopheric potential with respect to ground (V_I), the return current or air–Earth current density (J_c), and the total atmospheric columnar resistance (R). The vertical potential gradient (or electric field) is defined as E.

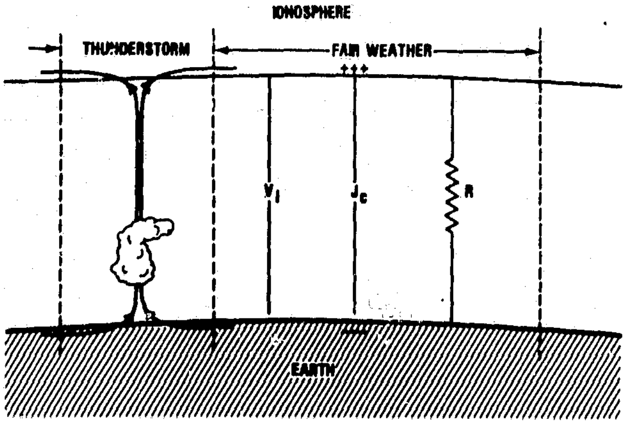

FIGURE 1.10 Schematic model of the global electric circuit, illustrating the thunderstorm generator, ionospheric potential (V_c), air–Earth current density (J_c), and total atmospheric resistance (after Herman and Goldberg, 1978b).

Observed parameters of the atmospheric fair-weather electric circuit have been examined for evidence of possible association with solar-sector boundary passages and solar flares and, on the longer term, for possible modulation by the 11-year sunspot cycle.

Reiter (1976, 1977) concluded that fair-weather measurements of E and J_c over the 11-year period May 1964 to February 1975, at Zugspitze, West Germany, were responsive to sector-boundary crossings. The result of Reiter's superimposed epoch analysis was that both E and J_c increased by 20 percent or more during the 2 days following a −/+ sector-boundary crossing in maximum solar-activity years. An increase also occurred for +/− boundaries but on the same day as the crossing date. A superimposed epoch analysis based on a shorter data span (March–November 1974) by Park (1976) indicated that the potential gradient E at Vostok, Antarctica, increased sharply by 20–30 percent beginning 3 days after boundary passages; the effect was more pronounced in the astral winter months than in the equinox months and, contrary to Reiter's findings, similar in nature for both +/− and −/+ boundary crossings. The difference in response time for the Vostock and Zugspitze electric fields remains unclear, although modeling results by Roble and Hays (see Chapter 8, in this volume) seem to attribute the different lag times to geographical differences.

Cobb (1967) compared atmospheric electrical properties with solar-flare data. He found that at the Mauna Loa, Hawaii, observatory (elevation 3400 m), E and J_c increased significantly after solar-flare eruptions. The potential gradient enhancements also were found to be correlated with solar radio-noise bursts (associated with flares) at Zugspitze (Reiter, 1972) and at stations within the Arctic Circle (Sao, 1967). Märcz (1976) found enhancements in E of 30–50 percent in Poland (approximately 51° N) associated with geomagnetic storms, which sometimes follow solar-flare eruptions within 2–3 days.

Recently, Markson and Muir (1980) reported an inverse correlation between ionospheric potential V_B and the bulk solar-wind velocity and have offered this as evidence of a close tie between solar activity and the atmospheric electrical circuit. However, since V_B correlates well with geomagnetic indices, which in turn correlate well with atmospheric electrical parameters, it still remains to be shown that V_B is a more realistic physical parameter with which to associate the atmospheric circuit.

Long-term measurements of the fair-weather electric field in the first two decades of this century suggest a possible increase in average field strength in years of maximum sunspot activity as compared with minimum years. This correlation has been found, however, only at certain selected European stations with no apparent influence at others (Herman and Goldberg, 1978b, page 139). Mühleisen (1971) examined the total ionospheric potential over West Germany throughout one solar cycle and found evidence, in this limited sample, of a positive correlation with annual mean sunspot number. To be convincing, however, a much longer period of correspondence needs to be demonstrated. If the total electrical potential is proportional to global thunderstorm activity, one might expect the latter quantity to be correlated with the 11-year sunspot cycle.

Several models have recently been proposed to explain purported connections between thunderstorm (lightning) occurrence and solar activity. However, none of these attempts complete the hypothetical chain to explain how modifications in the electrical structure of thunderstorms can affect local or global meteorological conditions. For example, an early concept by Ney (1959) considered the possible effects that external influences may have on the global electrical circuit. He suggested that thunderstorm activity could be modulated by solar variability through alteration of the electrical state of the middle and lower atmospheres. Markson (1971, 1975, 1978) extended the same general thesis and suggested that the electrical resistance of the atmosphere above thundercloud tops (the analog of a charging resistor) will be lowered when incoming cosmic particles increase the ionization in the upper atmosphere. In this way, the charging current is thereby increased, leading to an enhanced ionospheric potential and fair-weather electric field, as these parameters globally adjust to the increased charging current. The enhanced electric field is assumed to enhance lightning occurrence within thunderclouds, though by an unspecified mechanism.

Willett (1979) evaluated these ideas quantitatively but concluded that the magnitude of Markson's proposed mechanism is probably insufficient to account for the known effects. In addition, the flux of cosmic rays reaching thunderstorm heights in the tropical zones (where thunderstorms predominate) is weak and probably inadequate to account for significant modifications in the charging circuit.

In a more localized approach, Herman and Goldberg (1978a, 1978b) considered how cosmic rays and solar protons affect the local environment near thunderstorms and whether modifications in the local conductivity and electric fields can assist lightning generation. For the case of cosmic rays, the changes appear quantitatively reasonable if one accepts that an increase in the fair-weather field enhances the probability of thunderstorm formation under appropriate meteorological conditions (Chalmers, 1967). By this mechanism, solar-controlled variations in cosmic-ray intensity, particularly over the 11-year cycle, could modulate the fair-weather field and hence the rate of thunderstorm occurrence to produce the effect reported, for example, by Stringfellow (1974; see also Figure 1.7). It is not yet known, however, whether or how solar-proton events can affect tropospheric electrical structure since the (secondary) proton showers that these events produce are usually absorbed above 20 km.

Recent observations by Maynard *et al.* (1981) and Hale (1981) show the presence of large electric fields in the middle atmosphere (near 60 km altitude). Earlier, Hale and Croskey (1979) suggested that such fields in the auroral zone are highly sensitive to auroral phenomena, thereby providing an electrical link between the upper and lower atmospheres that can be perturbed by solar activity. Roble and Hays (1979; see also Chapter 7, in this volume) developed a global model for the various electrical parameters, which includes as input parameters orographic effects from the Earth's surface, the global thunderstorm distribution as observed from the DMSP satellite, and the latitudinal distribution of cosmic-ray flux. Their model reproduces effects at high latitudes that are induced by solar and/or magnetospheric disturbances as well as significant subsequent perturbations to the global electrical circuit.

Care must be taken in each of the above cases to separate electric field disturbances of solar origin from those induced by tropospheric storms. According to Cole (1976), the latter can develop a feedback phase relationship giving the appearance of magnetospheric origin.

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The Nature of Solar Variability

2

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INTRODUCTION

As early as 28 B.C., Chinese astronomers noted that the sun was occasionally marked by spots on its surface; much later, studies with the telescope demonstrated that these dark spots were indeed an intrinsic feature of the sun. It was not until the middle of the nineteenth century that Schwabe, a German amateur astronomer, noted the cyclic nature of sunspot occurrences. Fifty years earlier, William Herschel had hypothesized that the radiant output of the sun might also be variable, yet his search for direct evidence of this variation and of its consequences on terrestrial climate was unsuccessful. The study of solar–terrestrial physics has greatly advanced since Herschel's day; yet many of the questions posed at that time remain unanswered. We now know that solar variability is primarily a magnetic phenomenon, yet the possibility of climatically important variations of the total luminosity of the sun still remains to be settled. We are now aware of the presence of energetic particles and x-rays eminating from the sun and of a supersonic solar wind undreamed of in Herschel's day, but we still know little of the long-term variations of these solar outputs. Modern theory enables us to construct models of the interior structure of the sun; however, our understanding of the fundamental mechanisms driving the solar cycle is still elementary.

THE SUN AS A STAR

Considered as a star, the sun is among that populous group of relatively young, low-mass stars made luminous by the conversion of hydrogen to helium deep in its core. To place the sun in perspective, stars of 100 times the solar mass are rare, whereas stars of one tenth the solar mass abound. Likewise, hot blue stars with a luminosity 10^5 times that of the sun account for the astronomer's designation of the sun as a dwarf, although white dwarfs, which are the burned-out relics of stars that were once more luminous and massive, are typically 10^4 times fainter than the sun.

One of the triumphs of twentieth-century astrophysics was the realization that the apparently complex relationship of the masses, luminosities, radii, colors, and surface temperatures of stars could be explained by variations in only three basic properties: initial mass, initial chemical composition, and age. The latter property brings us to the largest long-term aspect

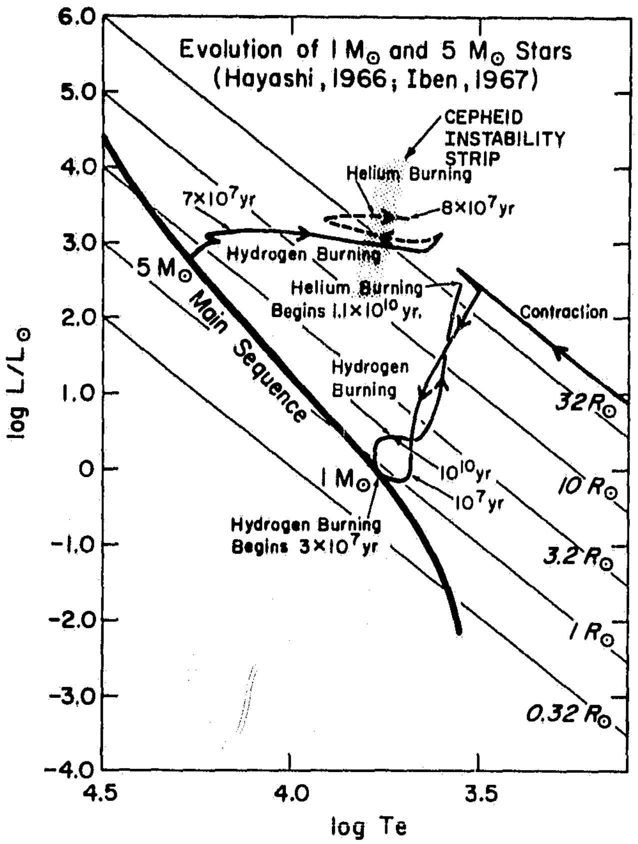


FIGURE 2.1 The evolutionary track of stars of one solar mass ($M_\odot$) and five $M_\odot$ across the temperature-luminosity diagram. Here T_e is the effective temperature of the star, L is the luminosity, and $L_\odot$ is the current solar luminosity. Stellar radii in units of the current solar radius $R_\odot$ are indicated by the diagonal lines. The main sequence shows the locus occupied by stars of various masses immediately following the initiation of hydrogen burning. Both pre- and post-main sequence evolution are displayed for the sun, whereas only the post-main sequence evolution is depicted for the $5M_\odot$ star.

of solar variability—the inexorable climb of luminosity as the sun ages (see Figure 2.1). Although not directly observable, this evolution of solar luminosity over the 4.5×10^9 year lifetime of the sun is well established by astrophysical theory and by comparison with the inferred evolution of other stars (Schwarzschild, 1958). The mechanism underlying this change is the conversion of hydrogen to helium in the core of the sun. The luminosity is a direct consequence of the accumulation of ^{4}He, which increases the average atomic weight of the sun's interior, subsequently increasing the compression and temperature.

That the early sun was only about 70 percent as luminous as it is at present leads to speculation on the effects of such a faint, early sun on terrestrial climate. Indeed, calculations (Budyko, 1969; Sellers, 1969; Schneider and Dickinson, 1974; North, 1975; Lindzen and Farrell, 1977; Coakley, 1979) suggest that if the Earth's atmosphere had its current composition, the Earth would have existed in a state of permanent glaciation since its beginning and would not yet have thawed out. Our own senses and geological evidence amply document the error of this conclusion. The resolution of this apparent contradiction between astrophysical and climatological theory lies in the fact that the early terrestrial atmosphere was poor in oxygen and rich in infrared-opaque gases, so that an enhanced greenhouse effect managed to keep the mean surface temperature of the Earth above freezing (Sagan and Mullen, 1972; Hart, 1978; Newkirk, 1980). Theory predicts that the luminosity of the sun will gradually climb by a factor of 3 over the next 6.5×10^9 years (Iben, 1967), at which time it will have exhausted its available hydrogen fuel. The surface temperature of the Earth will reach the boiling point of water at about the same time.

The chemical composition of the sun is slowly modified as the sun consumes its hydrogen fuel, which may produce a second long-term variation in solar luminosity. Somewhat out from the center of the sun, the temperature has dropped to the point where the conversion of hydrogen to helium effectively ends with the production of ^{3}He. Higher temperatures, such as those near the center, are required to complete the nuclear fusion processes that end with ^{4}He. Over a period of time the partly consumed ^{3}He accumulates in a zone about 25 percent of the way out from the center. This buildup of ^{3}He can produce a situation in which large-amplitude oscillations lead to a mixing of the partly consumed ^{3}He fuel into the interior and a rapid increase in the rate of energy production. The surface luminosity of the sun responds to such a mixing episode by a rapid decrease followed by a gradual rise—the entire excursion takes about 8×10^6 years (see Figure 2.2). Because the buildup of ^{3}He would begin again as soon as the mixing ceased, the possibility exists for mixing to recur, cyclically, with a period of approximately 3×10^8 years. Although the theory is not able to determine whether episodic ^{3}He mixing actually occurs in the sun or other stars, the presence of a "period" of 2×10^8 to 5×10^8 years (see Figure 2.3) in climatological variance (as determined from the geologic record) suggests that the sun may indeed be variable with such

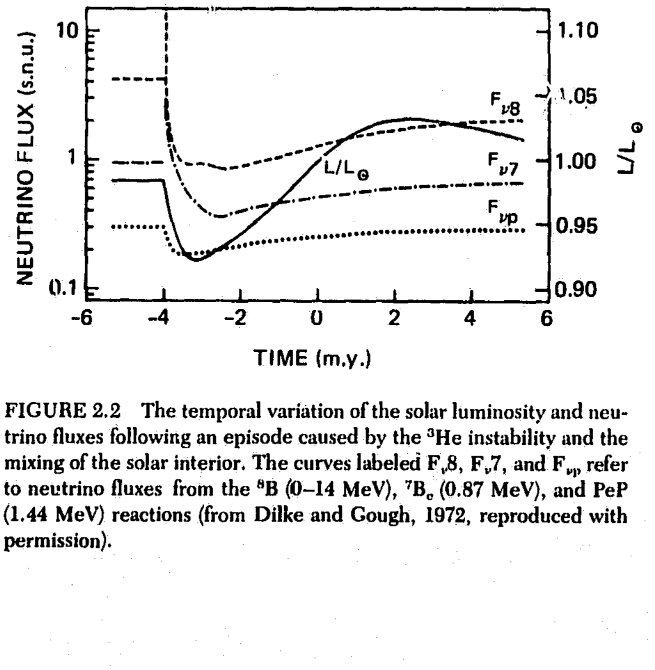


FIGURE 2.2 The temporal variation of the solar luminosity and neutrino fluxes following an episode caused by the ^{3}He instability and the mixing of the solar interior. The curves labeled $F_{\nu}8$, $F_{\nu}7$, and $F_{\nu p}$ refer to neutrino fluxes from the ^{8}B (0–14 MeV), ^7B_e (0.87 MeV), and PeP (1.44 MeV) reactions (from Dilke and Gough, 1972, reproduced with permission).

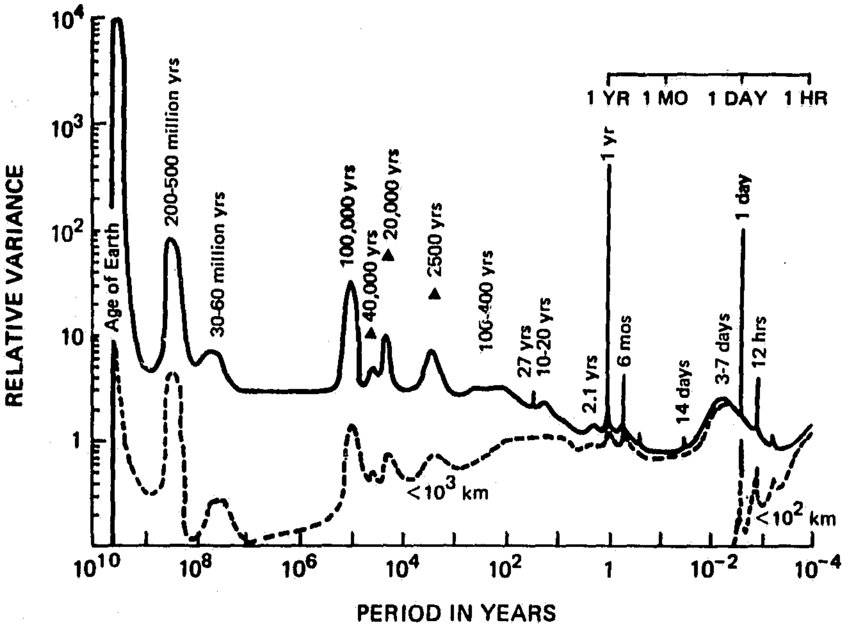


FIGURE 2.3 Estimate of the relative variance of climate over periods from hours to 4.6 $\times$ 10^9 years for all spatial scales (solid line) according to Mitchell (1976). The peaks between 10^4 and 10^5 years have been proposed as originating with well-established periodicities in the Earth's orbit (Hays *et al.*, 1976; but see Evans and Freedland, 1977). The peak at 3 $\times$ 10^8 years is hypothesized as being due to either ^{3}He mixing episodes or to the periodic passage of the solar system through dense interstellar clouds in the spiral arms of the galaxy.

a period; however, the evidence may only be circumstantial. An alternative explanation for this particular climatic "period" is that the rotation of the galaxy carries the sun every 2 $\times$ 10^8 years into dense interstellar clouds concentrated in the spiral arms of the Milky Way and that solar luminosity is modified by the rapid accretion of interstellar dust from the cloud. Distinguishing such astronomical causes of long-term climatic variation from terrestrial causes such as volcanism and continental drift remains a task for the future.

Intrinsic variations of the sun with characteristic times of 10^5 years or shorter, if they exist, would be expected to be associated with the convective zone and the solar-magnetic cycle. Operating on the same time scales are geometrical or orbital variations in the distribution of solar radiation on the Earth. The total flux of solar radiation received by the Earth varies by 7 percent during the year as a result of the eccentricity of the Earth's orbit, and the seasonal distribution of insolation with latitude depends on the inclination of the Earth's axis of rotation (the obliquity) and the position of the Earth in its orbit. The distribution of insolation may be specified by three parameters of the Earth's orbital motion: eccentricity, obliquity, and precession. As a result of both the pertubation of the Earth's orbit by the other planets and the gravitational torque of the sun and the moon on the oblate Earth, these parameters vary with periods of approximately 100,000, 41,000, and 23,000 years, respectively. Although for more than a century adequate information has existed to permit precise calculations of these perturbations, it remained for Croll (1875) and later Milankovitch (1930) to suggest that changes in the global distribution of radiation falling on the Earth might produce a climatic effect and for Hays *et al.* (1976) to uncover evidence from deep-sea sediments of such periods in the climate record (Figure 2.3). Orbital variations are not uniformly accepted as a pacemaker of terrestrial climate (Evans and Freedland, 1977), and quantitative modeling of this climatic effect is still at a rudimentary level. However, the effect, if real, is of profound importance because it allows an empirical determination of the sensitivity of terrestrial climate to changes in the incident solar flux.

STRUCTURE OF THE SOLAR INTERIOR

Much is known about the structure of the solar interior by inference from the sun's total energy output, chemical composition, radius, mass, and age. Using equations that describe the pressure, gravitational balance, conservation of mass, rate of nuclear energy generation, and the transfer of energy from the interior to the surface by radiation and convection, a description or *model* of the sun was developed (Schwarzschild, 1958) that uniquely fits the parameters observed above. (Such a model is shown in Figure 2.4.) At the sun's center, where the temperature is about 15 million degrees and the pressure about 10^{11} atmospheres, nuclear fusion reactions occur that convert hydrogen to helium and liberate the vast quantities of energy that ultimately leak to the surface to be radiated as sunlight. The energy-producing core extends to a radius of about 0.2 $R_\odot$ ($R_\odot$ is the solar radius of 700,000 km), beyond which the temperature is too low to sustain nuclear reactions. Surrounding this core is a radiative zone, where the energy created in the core diffuses outward by radiation. Above a distance of about 0.7 $R_\odot$ to the surface, however, the solar material becomes cooler and more opaque and practically all energy is carried farther upward by the circulation of convective eddies.

The nature of the outer layers of the solar atmosphere—the chromosphere, corona, and solar wind—is determined by motions in the convection zone. Here, the solar-magnetic field is generated and maintained, and all variations in the outputs of the sun over short time scales are produced. The key to understanding these variations is the solar-magnetic dynamo.

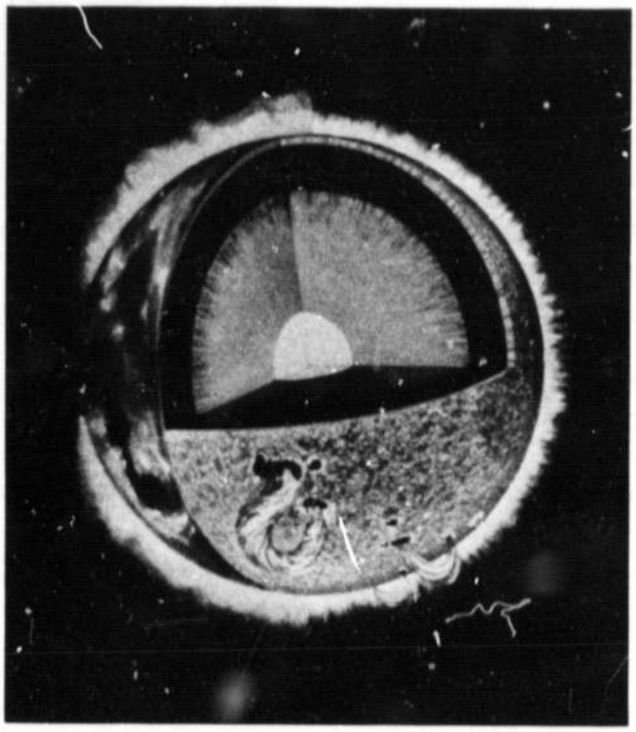


FIGURE 2.4 A cross section of the sun displays the inner energy-generating core (of about 0.2 $R_\odot$ in radius), the radiative envelope that extends out to about 0.8 $R_\odot$, and the outer convective shell. Motions in the highly electrically conducting material of the convection zone are the origin of the various ramifications of solar activity. Only the thin outer photosphere, the chromosphere, and the corona are directly observable; however, new techniques allow the properties of the interior to be investigated.

THE SOLAR-MAGNETIC CYCLE

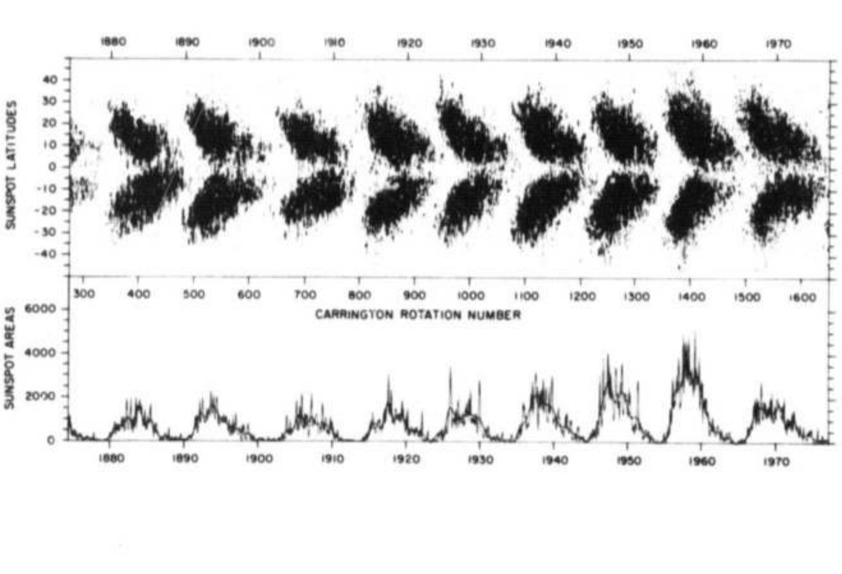
Although modern astrophysics has documented a broad variety of aspects of the waxing and waning of the solar cycle (Kiepenheuer, 1953; Zirin, 1966; Tandberg-Hanssen, 1967; Hundhausen, 1972), in both popular and scientific usage the term refers to the sunspot cycle, which is shown in Figure 2.5. This figure illustrates, in addition to the cyclical fluctuation of sunspot areas, that a given solar cycle begins with sunspots at high latitudes (about + 30°) and ends with spots close to the equator. Not displayed is the fact that the magnetic polarity of sunspot groups, taken as the sign of the magnetic field in the westernmost spots of each group, reverses after each cycle. Thus, the fundamental period of the sunspot cycle is, more correctly, 22 years, and the magnetic nature of the cycle is clear.

The fact that the solar cycle is magnetic in nature is emphatically displayed by modern observations of the magnetic field at the photosphere (see Figure 2.6). Sunspots, although they contain strong fields, represent but one aspect of the magnetic fields that define the solar cycle. Magnetic fields also occupy vast areas of the quiet solar surface, where they are clumped together into minute bundles of intense field strength. Even these bundles, however, are organized into coherent patterns, which at the largest scale define the general solar-magnetic field.

Solar-magnetic fields present many mysteries. For example, how does the field modify the structure of the solar atmosphere to form a sunspot, and why is the field in quiet regions of the sun concentrated into a network of bundles of intense magnetic field? What mechanisms drive the solar-magnetic dynamo to produce the field? Do other stars have similar magnetic cycles? What influence does the magnetic cycle have on the outputs of the sun in radiation, solar wind, magnetic fields, and energetic particles? How might the solar cycle change over hundreds or thousands of years? The underlying mystery is the solar cycle itself. To approach such questions, we must examine current knowledge of the fundamental mechanisms responsible for the solar-magnetic cycle.

The most generally accepted explanation for the solar cycle

FIGURE 2.5 In general, the solar cycle refers to the sunspot cycle, depicted here as a Maunder "butterfly diagram" (upper panel) and by sunspot areas (lower panel). In the former, the latitude and date of each sunspot group is represented by a vertical line. In the latter, sunspot areas in millionths of the area of the solar disk are plotted versus time (reproduced, with permission, from data supplied by the Science Research Council, Great Britain).



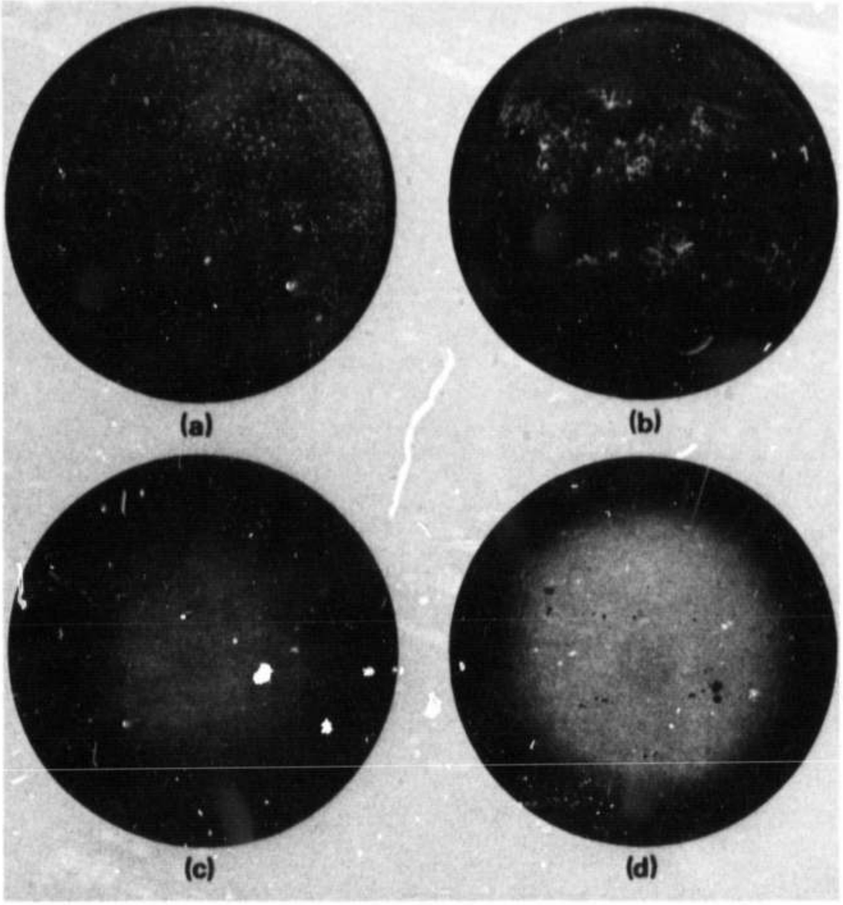


FIGURE 2.6 Full-disk magnetograms of the sun (a and b) show the distribution of the magnetic field and the magnetic polarity as light and dark regions, in contrast to white-light photographs (c and d) in which only sunspot regions are obvious. The variation of sunspots and intense magnetic fields with the solar cycle is illustrated by the comparison of a and c (made February 28, 1976, just after a minimum) with b and d (made December 10, 1979, near maximum) (white-light photographs courtesy of R. Howard, Mount Wilson Observatory; magnetographs courtesy of J. Harvey, Kitt Peak National Observatory).

is that it is driven by a turbulent dynamo in which two aspects of the convection zone combine to produce the magnetic field (see Howard, 1970; Bumba and Klezek, 1976). First, the sun rotates, and the interaction between the circulation in the convective zone and the rotation produces *differential rotation*, in which the period of the equatorial regions of the sun is shorter than that at higher latitudes. Second, the gas comprising the interior is highly electrically conducting—a property that "freezes" the magnetic field to a particular parcel of material as it moves about. Modern theory (e.g., Parker, 1979) indicates that these properties permit two processes to occur that are responsible for the operation of the solar dynamo. First, differential rotation stretches an initially poloidal field, wraps it around the subsurface layers of the sun, and creates an amplified toroidal field (see Figure 2.7a). Second, rising (or sinking) columns in the convection zone twist as they rise (sink) due to coriolis forces and impart this twist to the field (see Figure 2.7b).

The oppositely directed twists of rising and sinking elements might appear to exactly cancel each other, as would be the case in a homogeneous, horizontal fluid. However, in the solar convection zone, rising and sinking elements twist by different amounts because of the large-density gradient present in the convection zone and because the angle between the rotation vector at a given point and the direction of the gravity vector varies with latitude. Both these effects lead to a *net* twist applied to the magnetic field. This twist converts an initially toroidal or azimuthal field (Figure 2.7c) into a poloidal or meridional one of opposite sign. Differential rotation then stretches this new poloidal field into a toroidal one (Figure 2.7 a,b), and the process repeats. Thus, the solar cycle may be considered an engine in which differential rotation and convection drive the oscillation between the two (toroidal and poloidal) magnetic-field geometries.

Although the dynamo theory has proved successful in reproducing many aspects of solar activity, it has attracted a few critics (e.g., Piddington, 1978; Layzer *et al*., 1979) who favor the interpretation that the solar cycle is due to a deep-seated primordial field rather than one regenerated by turbulent motions. These researchers point out that the dynamo theory does not explain the concentration of magnetic fields into intense bundles either as sunspots or as the minute flux concentrations covering the quiet photosphere. These authors claim that, in addition, the flux bundles are not influenced by the fluid motions and that diffusion of the magnetic field is so unimportant that the fields erupting through the photosphere actually represent the remnant primordial magnetic field present in the nonconvective core. Piddington's (1978) arguments are qualitative and thus difficult to compare with the quantitative predictions derived from dynamo models. Layzer *et al*. (1979) were

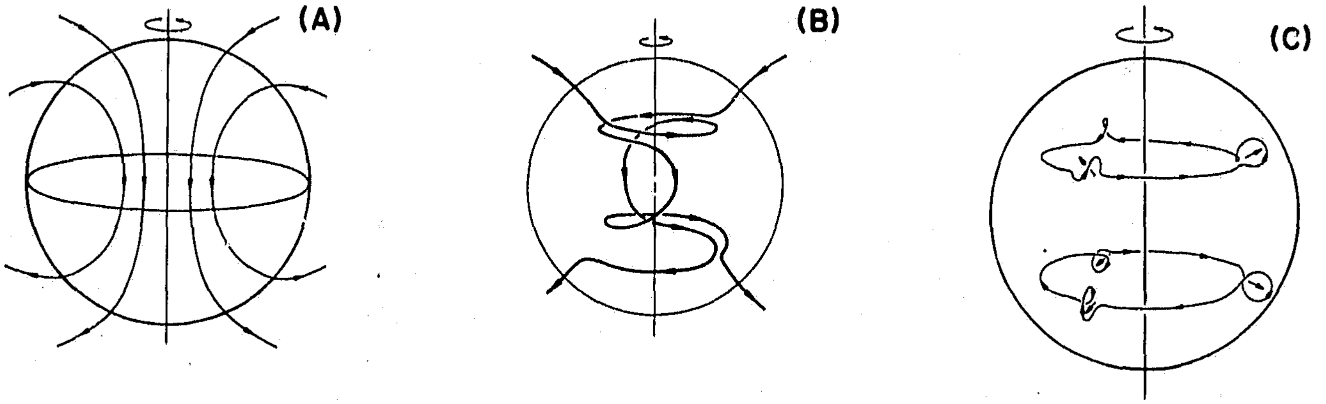
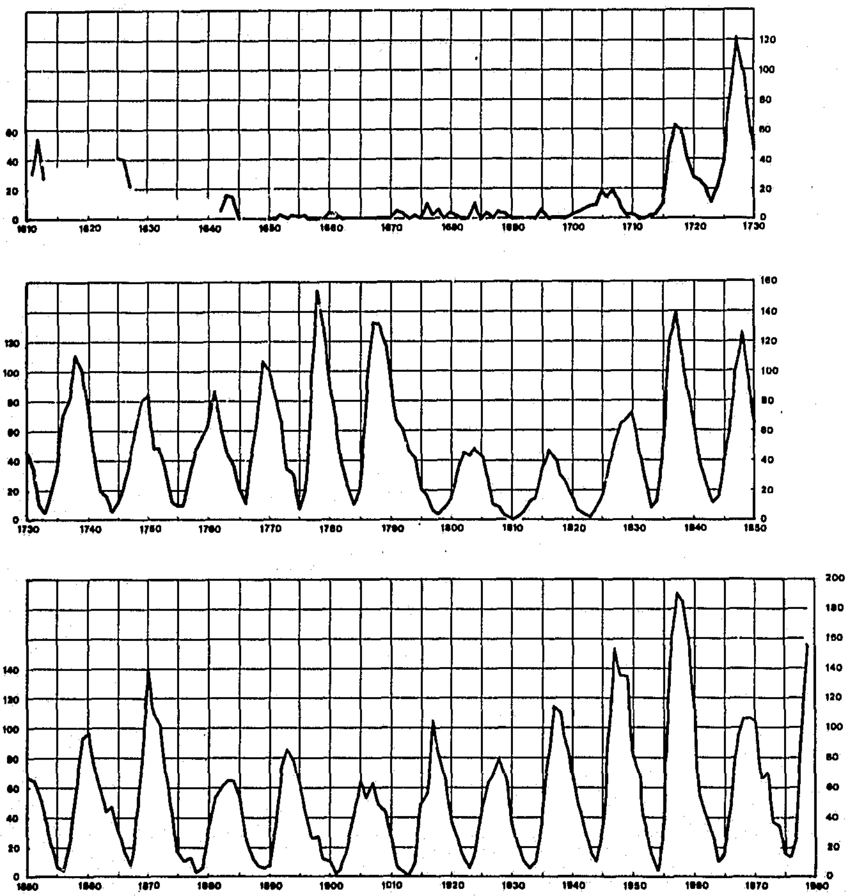


FIGURE 2.7 Differential rotation stretches an initially poloidal solar-magnetic field (A) to produce a toroidal field (B). The twist of rising convective cells produces a small poloidal field component (C). The integrated effect of many such cells and the dominance of rising cells eventually amplify the poloidal field, and the cycle continues (adapted from Parker, 1979).

the first to attempt to develop a primitive but quantitative model in which the primordial field plays an important role. The controversy between these two schools of thought ultimately focuses on the presence (or absence) of turbulent diffusion of the magnetic field. Without turbulent diffusion, dynamo-driven fields would rapidly amplify to a level at which the fields would choke off the fluid motions and the oscillation of the field would cease. With turbulent diffusion present, dynamo-driven fields would oscillate as observed and any primordial field would have died out long ago. Newly emerging

FIGURE 2.8 Annual mean sunspot numbers, 1610–1979. During the Maunder Minimum, solar activity (as measured by sunspot number) fell to an unprecedented low level for approximately 70 years centered about 1670 (from Eddy, 1979).



techniques such as solar seismology, which allow the motions of fluid below the solar surface to be ascertained (Hill, 1978) and which will provide a wide variety of tests of alternative ideas of the fundamental operation of the solar cycle, should help resolve this question.

One aspect of solar variability that has not been incorporated into the models of the solar cycle is the long-term variation of the envelope of activity. Historical records (Eddy, 1976, 1977) reveal that sunspots all but disappeared for about 70 years beginning in the 1640's—an episode of solar behavior now called the Maunder Minimum (see Figure 2.8). In addition, the inference of past solar activity from the rate of deposition of ^{14}C in tree rings (Eddy, 1978) shows that the range of solar activity that has occurred in the past 5000 years is considerably greater than indicated by historical observation and that other minima and maxima modulated solar activity at apparently random intervals in the past (see Figure 2.9).

Speculation concerning the nature of long-term solar variability ranges from the deterministic interpretation proposed by Dicke (1978) that the timing of individual solar cycles is determined by an accurate "clock" (but see Gough, 1978) to the stochastic models of Barnes *et al.* (1980). Barnes *et al.* noted that white noise, as limited by a narrow-band filter with an appropriate center frequency and width, can adequately represent both the statistical properties of long-term solar variability as well as such specific features as a Maunder Minimum. Although this numerical model can make no statements regarding the physical mechanisms underlying long-term solar variability, it does provide an objective background against which the claims of more elaborate models can be compared.

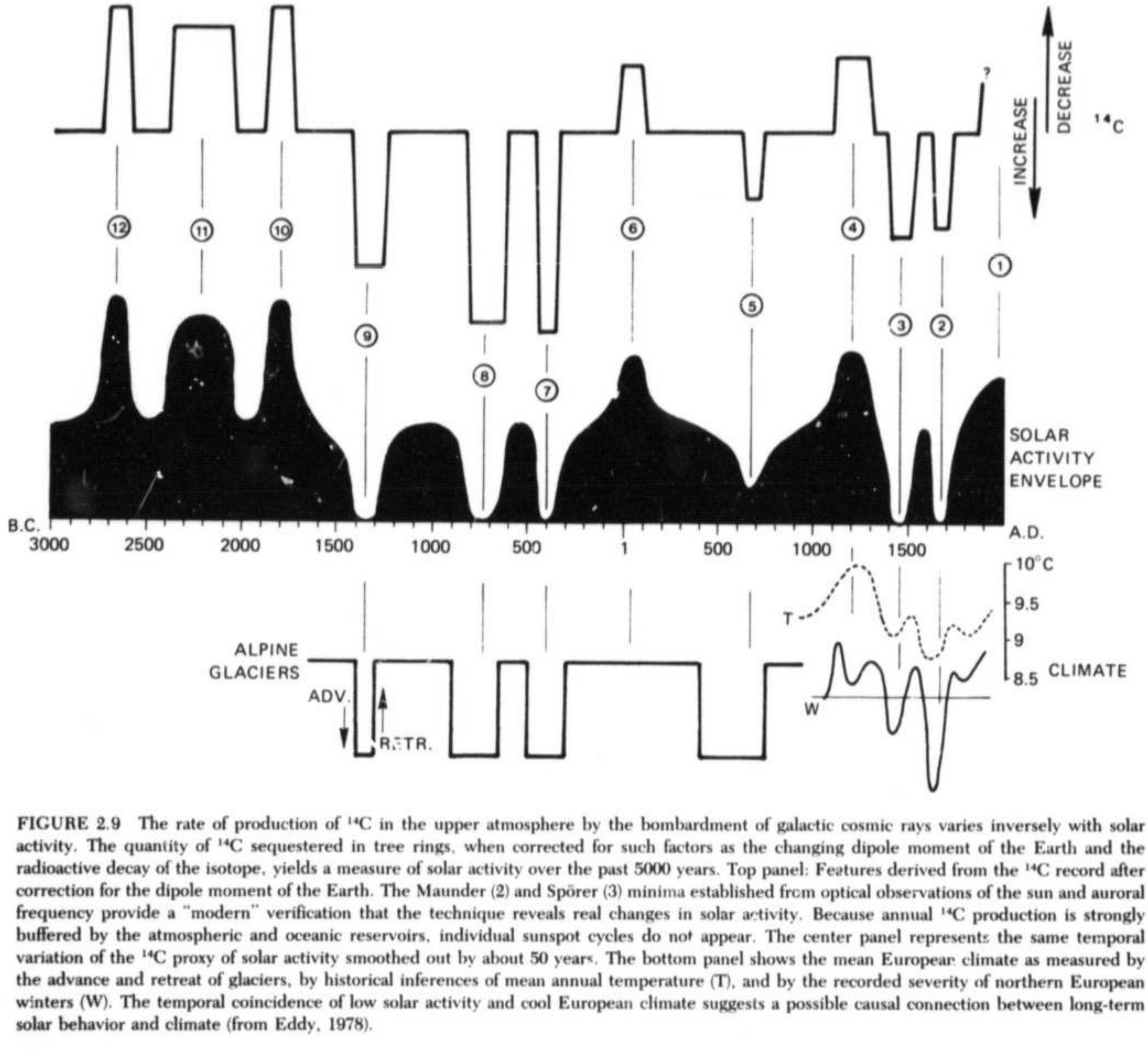


FIGURE 2.9 The rate of production of ^{14}C in the upper atmosphere by the bombardment of galactic cosmic rays varies inversely with solar activity. The quantity of ^{14}C sequestered in tree rings, when corrected for such factors as the changing dipole moment of the Earth and the radioactive decay of the isotope, yields a measure of solar activity over the past 5000 years. Top panel: Features derived from the ^{14}C record after correction for the dipole moment of the Earth. The Maunder (2) and Spörer (3) minima established from optical observations of the sun and auroral frequency provide a "modern" verification that the technique reveals real changes in solar activity. Because annual ^{14}C production is strongly buffered by the atmospheric and oceanic reservoirs, individual sunspot cycles do not appear. The center panel represents the same temporal variation of the ^{14}C proxy of solar activity smoothed out by about 50 years. The bottom panel shows the mean European climate as measured by the advance and retreat of glaciers, by historical inferences of mean annual temperature (T), and by the recorded severity of northern European winters (W). The temporal coincidence of low solar activity and cool European climate suggests a possible causal connection between long-term solar behavior and climate (from Eddy, 1978).

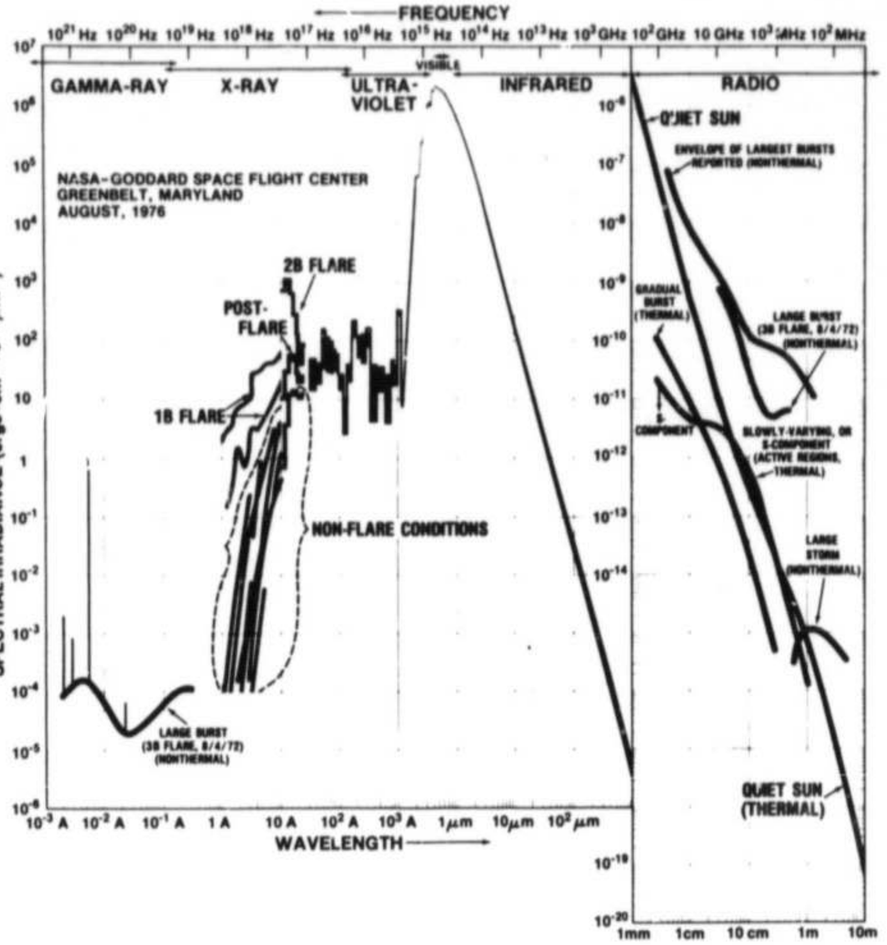


FIGURE 2.10 The spectral irradiance of the sun from x-rays to radio wavelengths. At radio, ultraviolet, and x-ray wavelengths, the output of the sun varies markedly (from White, 1977, with permission).

Within the context of the dynamo models, the long-term variability of the sun is presumed to originate in the feedback of magnetic fields on the fluid motions (e.g., Yoshimura, 1978). According to the primordial-field hypothesis, the same behavior is ascribed to the geometrical irregularity of the field buried below the convection zone. Neither type of model has advanced to the point where the statistical properties of long-term solar variability can be derived from first principles. The eventual modeling of this aspect of solar variability appears to be well in the future.

SOLAR OUTPUTS

The solar cycle has an intrinsic scientific fascination as a phenomenon that we do not completely understand; comprehending it has the added appeal that knowledge of solar variability may help us better understand the Earth's atmosphere. Whatever solar modulation of the terrestrial atmosphere may occur must arise from variations in the outputs of the sun of radiation, plasma, energetic particles, and magnetic fields. A summary of the solar-cycle variation of these outputs with particular emphasis on those aspects that may illuminate the mechanisms of solar activity is in order. [For more detailed discussions see White (1977).]

As shown in Figure 2.10, the global solar output of radiation shows considerable variation with the solar cycle at wavelengths shorter than 3800 Å and at radio wavelengths. At the extremes of both of these regions, in x-rays and in metric radio waves, the variation in global flux reflects the short-term, impulsive outputs of solar flares and their associated energetic particles and shock waves. Variations at these extreme wavelengths over a solar cycle largely show the statistical influence of increased flare frequency with high solar activity. In the ultraviolet, from 3800 Å to 1000 Å, the variation of solar flux generally reflects the presence of active regions and the modificaton of the structure of the solar atmosphere by magnetic fields. Although the general variation depicted in Figure 2.10 is well established, in some regions of the spectrum of particular importance to geophysics, e.g., from 3800 Å to 1800 Å, the exact fluctuation is poorly understood.

The important question of variations of the total luminosity of the sun—the integral under the curve in Figure 2.10—is of interest because even small changes in the total visible flux could produce a direct impact on the lower-terrestrial atmosphere. For example, a sustained reduction in solar luminosity of only 0.5 percent would drive the polar-ice sheets and temperate-climate zones over 160 km toward the equator (see Schneider and Dickinson, 1974; Wetherald and Manabe, 1975). However, the precision of our measurements of variations in total solar luminosity—the so-called solar constant—over times comparable to a solar cycle is still only about 1 percent (Hoyt, 1979); practically nothing is known about variations in the solar constant that might accompany fluctuations in solar activity of a longer period. At periods of a fraction of a cycle, recent observations (Kosters and Murcray, 1979; Willson *et al*., 1980; Hickey *et al*., 1980) suggest that variations in the total luminosity of about 0.4 percent might be associated with the rise in solar activity to the current (1980–1981) maximum. At shorter characteristic times of hours to several days, integrated flux measurements with an active-cavity radiometer (Willson *et al*., 1981) show variations as large as ±0.05 percent with time scales of minutes to hours and ±0.04 percent with time scales of hours to days. Some of the variations seen in the recent spacecraft data seem to be the result of simple blocking of photospheric radiation by sunspots; however, this is still a tentative explanation, and its relation to longer-term variations remains speculative.

The output of high-energy (cosmic-ray) particles by the sun is determined by the production and successful escape of such particles from a relatively small fraction of all the solar flares that occur. Thus, the solar-cycle variation of energetic particle events of solar origin, which extend up to energies of GeV/nucleon, reflects the increased frequency of flares during high solar activity (see Figure 2.11). Within any given energetic-particle event, the flux of particles at the Earth displays a characteristic rapid rise and slow exponential decline caused by the initial arrival of particles directly from the sun followed by particles that have diffused to the Earth by indirect paths (see Figure 2.12). A solar-energetic particle event displays such a steep decrease of flux with particle energy (see Figure 2.13) that the largest contribution to the energy flux is made by particles of lowest energy. However, on rare occasions (about five times during the 1968 solar maximum) the flux of protons with energies greater than 7 MeV rises to such a level that enhanced ionization is produced in the Earth's upper atmosphere over the poles to produce a polar cap absorption. On still rarer occasions (about 10 times per solar cycle), fluxes of high-rigidity (1–20 GV*) particles from solar flares exceed the background galactic cosmic-ray flux by about 10 times, and secondary neutrons detected at ground level experience a similar increase (Lanzerotti, 1977). The extreme rarity of such ground-level penetration of energetic solar particles restricts their consideration as important agents in any solar–weather linkage.

The outermost atmosphere of the sun is composed of the corona (see Figure 2.14) and the solar wind, which expands into interplanetary space at an average speed of about 400 km/sec. Since the corona is an excellent electrical conductor, its flow is guided by solar magnetic fields. Because of the well-known response

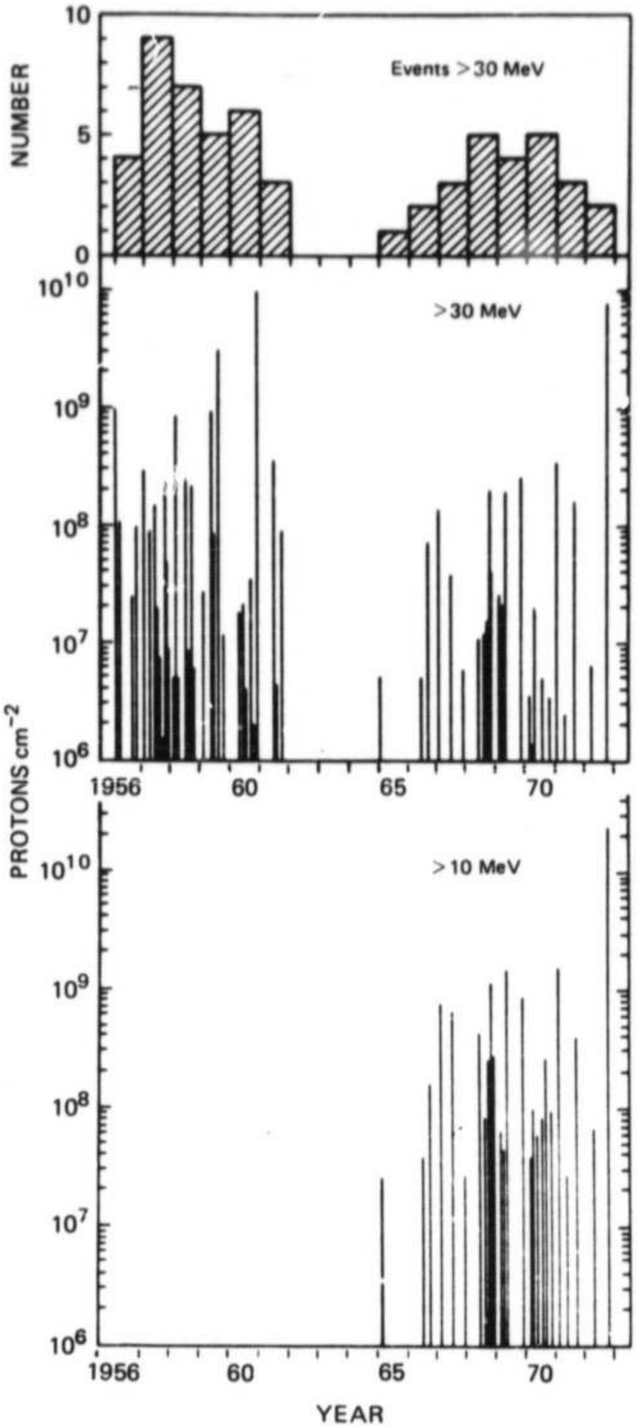


FIGURE 2.11 The variation of solar proton output with energies greater than 10 MeV and 30 MeV from 1956 through 1972 shows the influence of the sunspot maxima in 1957 and 1969. Data for the bottom panel do not exist prior to about 1960 (from Lanzerotti, 1977, with permission).

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*A 1-GV proton has an energy of 500 MeV.

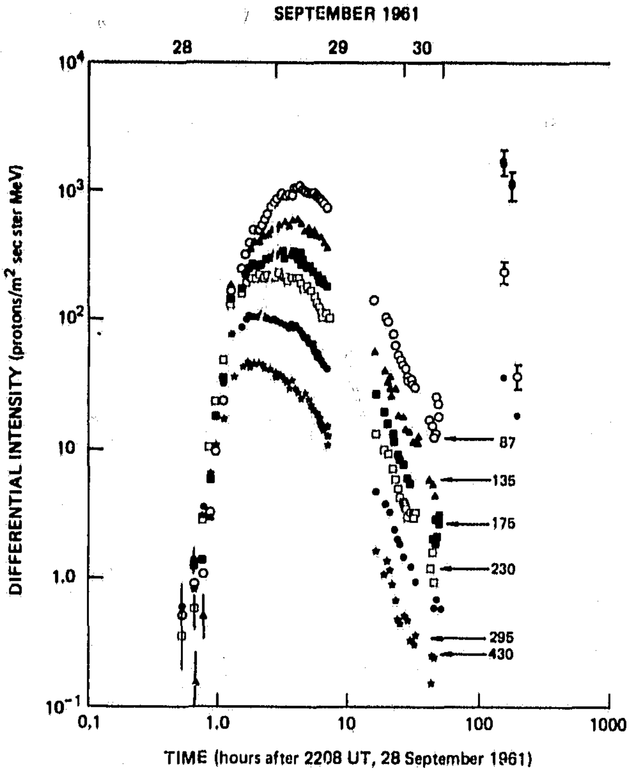

FIGURE 2.12 Energetic particles from a solar flare follow a typical rapid rise to maximum and a slow exponential decay (data are less complete at the lower energies (i.e., 2.2–14.5 MeV), but show a similar trend). The earlier arrival of the more energetic particles is clearly seen. The time delay from flare outburst maximum is caused by the existence of indirect propagation of particles on the sun and in interplanetary space. The exponential decay is ascribed to diffusion of particles in the solar system (adapted from Bryant *et al.*, 1965).

of geomagnetic activity to the solar cycle and the clear connection between the solar wind and geomagnetic activity, it might be expected that such average bulk properties of the solar wind—density, velocity, or mass flux—would vary directly with the solar cycle. Figure 2.15 shows that this is not so; the response of the solar wind to the magnetic cycle is far more complex than can be revealed by such simple averages. For example, high-speed streams in the solar wind occur much more frequently during the declining and minimum phases of solar activity. The association of such high-speed streams with coronal holes (see Figure 2.16), which originate where the solar-magnetic field is open to interplanetary space at the base of the corona, emphasizes the role of the large-scale, solar-magnetic field in determining the three-dimensional structure of the corona and solar wind throughout interplanetary space. As large-scale, solar-magnetic fields evolve during the solar cycle, they modify the corona (see Figure 2.17), the flow of the solar wind, and the physical description of the interplanetary medium.

Although our knowledge of the evolution of the three-dimensional morphology of the interplanetary medium during the solar cycle is far from complete, the broad outlines are beginning to emerge. During solar minimum the corona tends to be dominated by coronal holes extending approximately across the solar poles and with opposite magnetic polarity at the two poles. The tilted magnetic dipole on the flow of the solar wind produces a simple interplanetary geometry of the magnetic field with an approximately equatorial "skirt" separating the two polarities (see Figure 2.18). High-speed solar wind streams out at high latitudes, and the boundary between opposite polarities sweeps by the Earth to produce observed "sector" crossings twice during each solar rotation (a 28-day period). During high levels of solar activity, relatively short-lived, low-latitude coronal holes appear (see Figure 2.17), and the interplanetary field takes on a much more convoluted geometry. As it sweeps by the Earth the interplanetary field may reverse sign several times per solar rotation, and the lifetimes of individual high-speed solar wind streams decrease to several days to a week or so. As solar activity decreases from maximum levels, short-

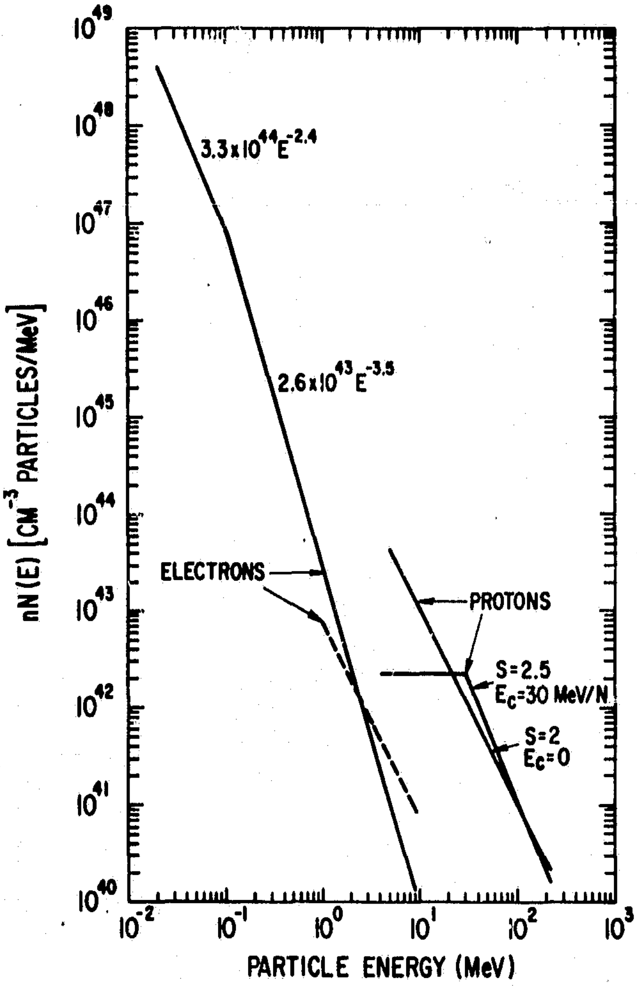

FIGURE 2.13 The flux of both protons and electons from a flare show a steep decrease with increasing energy (from Ramaty *et al.*, 1980, with permission).

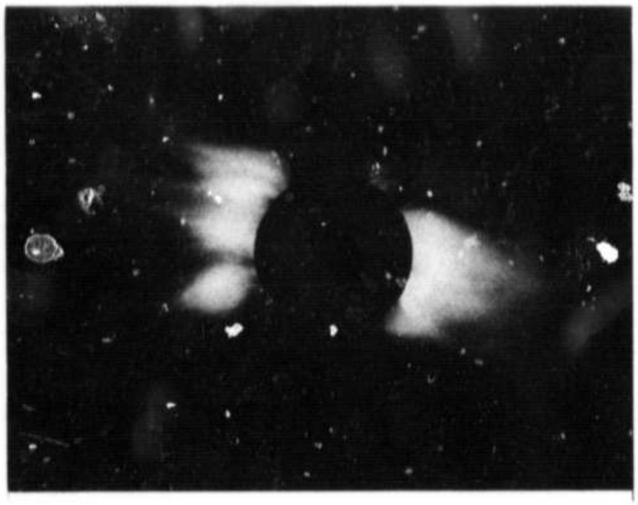

FIGURE 2.14 The solar corona observed during the total eclipse of June 30, 1973, with a radially graded filter that suppressed the high-intensity contrast between the limb and the outer corona. Coronal holes appear at the north and south poles. The large equatorial streamers are characteristic of the corona at sunspot minimum (photograph courtesy of the High Altitude Observatory).

lived, low-latitude coronal holes become less frequent and merge into low-latitude extensions of the increasingly dominant polar holes until the simple geometry of the polar holes is re-established at minimum.

Although not exactly a solar output, galactic cosmic rays reaching the Earth display an anticorrelation with solar activity that has been extensively documented although poorly understood (see Figure 2.19). Modern hypotheses differ as to the exact mechanisms causing this modulation of galactic cosmic rays; however, there is uniform agreement that inhomogeneities in the solar wind are responsible and that a complete picture of the three-dimensional structure and solar-cycle variation of the solar wind is required before the mystery can be solved. Interest in this modulation is intensified by the possibility that such particles, which penetrate into the lower atmosphere, may play a role in determining the electrificaton of the Earth's atmosphere and the fact that galactic cosmic rays produce isotopes such as ^{14}C, which are preserved in tree rings. The deposited isotope thus comprises an identifiable record of solar activity that extends far beyond written history.

TERRESTRIAL INPUTS

In Table 2.1 we compare several aspects of the solar-modulated inputs into the Earth's atmosphere. One frequently overlooked feature of these solar-modulated inputs is immediately apparent: the overwhelming concentration of the flux in the visible portion of the electromagnetic spectrum. The incident fluxes of solar-wind plasma, energetic particles, and high-energy photons taken together are smaller than that of visible radiation by more tham a factor of 10^6. Three other factors account for the difficulty in identifying a direct cause–effect relationship between solar-modulated inputs and terrestrial weather or climate. First, distinct variability occurs largely in the high-energy, low-flux constituents. Second, the most highly variable constituents are absorbed in the atmosphere high above the levels where weather and climate are thought to be determined. Third, the kinetic energy resident in the lower atmosphere is so large that it is difficult to imagine the state of the atmosphere being directly modified by measurably small changes in solar input. These factors do not vitiate, as is sometimes stated, the existence of solar–weather or solar–climate effects. They dictate only that the origin of such effects cannot exist in direct cause–effect relationships but must be in indirect or trigger effects.

An additional word is necessary regarding the time scales of these modulations. The shortest time scales are set by the implusive phase of flares, which have characteristic times of

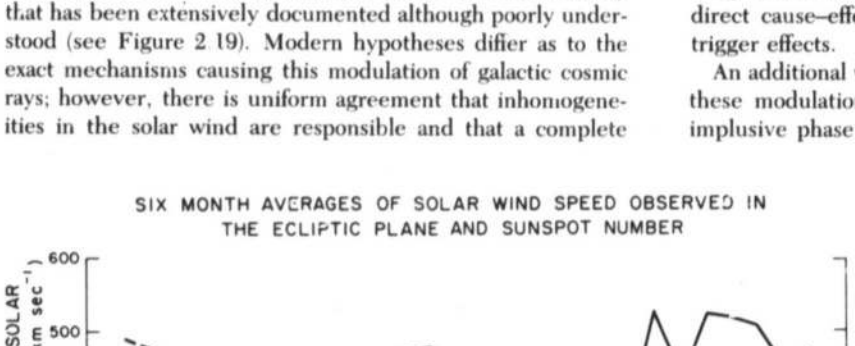

FIGURE 2.15 Such average solar-wind properties as the velocity show no simple sunspot-related variation during the solar cycle (from Hundhausen, 1979, reproduced with permission of the American Geophysical Union).

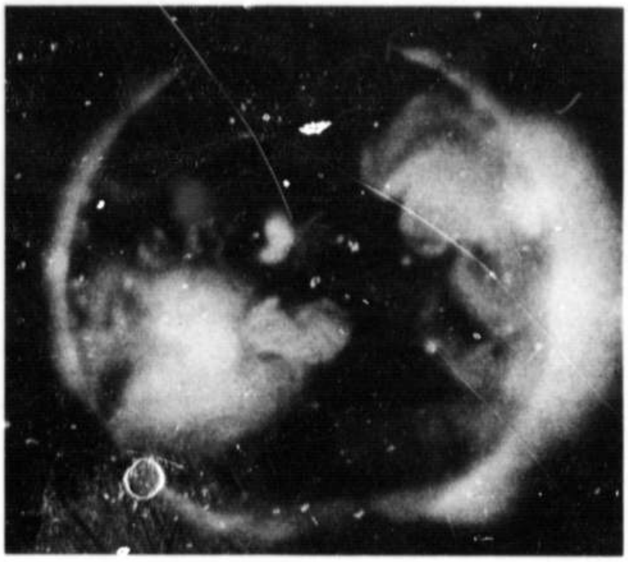

FIGURE 2.16 The solar corona as photographed in x-rays by Skylab on June 1, 1973, reveals the presence on the disk of coronal holes, which are regions of low density from which high-velocity plasma streams into interplanetary space (photograph courtesy of A. Krieger).

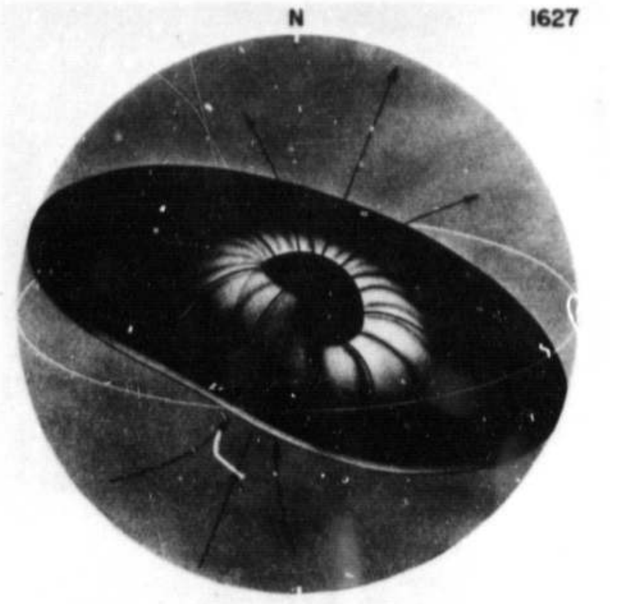

FIGURE 2.18 During sunspot minimum, coronal holes dominate the poles of the sun and the interplanetary separation of opposite magnetic field polarity regions resembles a ballerina's skirt close to the equator (photograph courtesy of A. J. Hundhausen).

seconds to minutes, and the thermal phase of flares, which have characteristic times of about 1/2 hour. The occurrence of flares, themselves, imposes a somewhat longer characteristic time for the x-ray, EUV, and radio output as well as on the occurrence of flare-produced blast waves in the interplanetary medium. During periods of high activity, small flares may appear at a rate of several per day, whereas major flares accompanied by the full panoply of hard x-ray emission, ground-level, solar–cosmic-ray enhancement, and interplanetary blast waves will erupt at a rate of perhaps a dozen per solar cycle. Intrinsic variability within active regions introduces considerable "noise" in most measures of solar activity (see Figure 2.20) at periods

FIGURE 2.17 Ground-based coronagraph observations at 1.5 $R_\odot$ show some of the changes in the geometry of the coronal holes produced by global magnetic fields during the solar cycle. The corona at sunspot maximum (1967) is characterized by short-lived, low-latitude coronal holes, whereas at sunspot minimum (1976) there are extensive, long-lived polar coronal holes. The overall effect of such changes upon the corona beyond 1.5 $R_\odot$ and the interplanetary medium remains to be explained (from Hundhausen *et al.*, 1981, reproduced with permission of the American Geophysical Union).

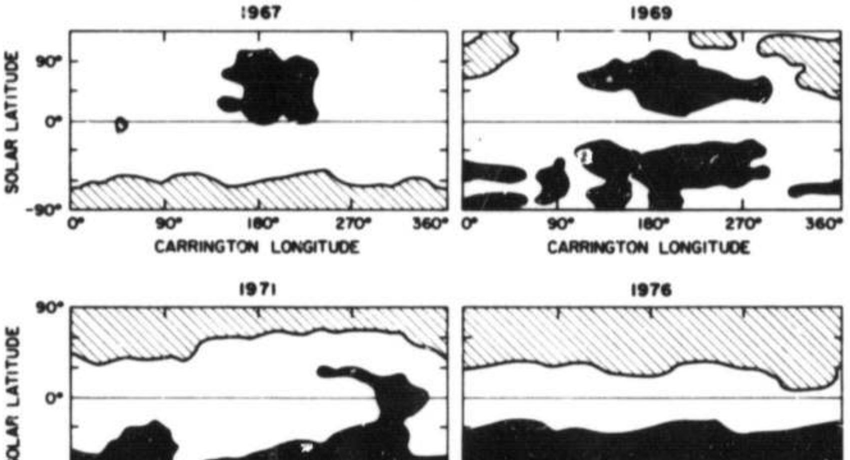

TABLE 2.1 Solar Modulated Inputs at the Top of the Earth's Atmosphere

	Wavelength	Particle or Photon Energy	Source	Quiet Flux (erg cm^{-2} sec^{-1})	Height Absorbed (km)	Absolute Variation (erg cm^{-2} sec^{-1})	Relative Variation	Time Scale of Principal Variation	Fluence* (erg cm^{-2} per event)	References
Electromagnetic radiation										
γ-ray	<1 Å	12 keV to 3.8 MeV	Impulsing. phase of most active flares	$<10^{-8}$	90	10^{-8}	Enhanced up to flux of 10^{-8}	Minutes	10^{-8}	Chupp *et al.*, 1975
X-ray	1–100 Å	120 eV to 12 keV	Impulsive and thermal phases of flares	10^{-1}	100	10^{2}	Enhanced up to 10^{3}×	Minutes to hours to ~ 11 yr	10^{-2}	White, 1977
Extreme ultraviolet	100–1000 Å	12 eV to 120 eV	Flares and active regions	2	100–300	20	Enhanced up to 10×	Hours to weeks to ~ 11 yr	—	White, 1977
Ultraviolet	1000–3650 Å	3.3 eV to 12 eV	Active regions	10^{5}	20–100	10^{4}	~ ± 10%	Weeks to ~ 11 yr	—	White, 1977
Visible	3650–7000 Å	~2 eV	Photosphere	10^{6}	0	$<2 \times 10^{3}$	<0.2%	Days to weeks	—	Willson *et al.*, 1981
Integral over the spectrum	—	~2eV	Photosphere	1.38×10^{6}	0	$<2.8 \times 10^{3}$	<0.2%	Days to weeks	—	Willson *et al.*, 1981
Solar wind plasma		~800 eV	Coronal holes + ?	0.7	Deflected by magnetosphere	~0.5	±70%	Hours to days	—	Feldman *et al.*, 1977
Solar energetic particles										
Low-energy events (protons)		>10 MeV	Impulsive phase of most active flares	up to 30	< 70 Primarily in polar regions	<4	10–10^{4}	Hours to days (occur several times per month during solar maximum)	10^{1}–10^{5}	Lanzerotti, 1977
High-latitude ground-level events (protons)		>500 MeV	Impulsive phase of most active flares	<0.4 (polar back-ground)	<30	<40	Enhanced up to 100× background	Minutes to hours (occur a few times per solar cycle)	10^{2}–10^{4}	Lanzerotti, 1977
Galactic cosmic rays		~5 GeV	Supernovae?	7×10^{-3}	~3	10^{-3}	<±15% (amplitude depends on latitude and altitude	~11 yr Forbush decreases lasting several days	—	Allen, 1963

Fluence is defined as the temporal integral of flux and is used here as the integral over a single event.

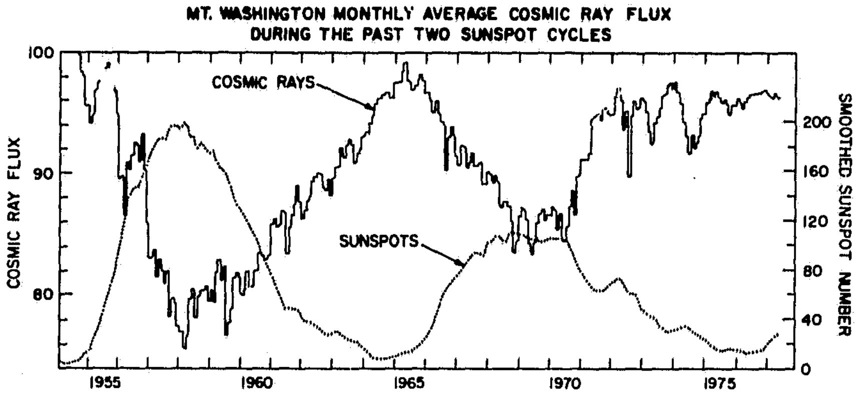

FIGURE 2.19 Galactic cosmic rays reaching the inner solar system and the Earth are modulated by solar activity. Knowledge of the three-dimensional structure and solar-cycle evolution of the solar wind far from the ecliptic is essential to an understanding of this phenomenon (drawing courtesy of A. J. Hundhausen from cosmic-ray data supplied by J. A. Lockwood).

in excess of a day. Of course, solar rotation introduces a modulation at a period of 28 days on almost all solar outputs at some level of significance. Whereas the presence of the 11-year sunspot cycle (or 22-year magnetic cycle) is well established and the existence of about an 80-year cycle is apparent in the sunspot record (Figure 2.8), the presence of periods shorter than 11 years remains questionable. The proxy record of solar activity, derived from tree-ring radiocarbon data (Figure 2.9), now extends over 7000 years, yet it shows no well-marked, long-term periodicity. It should be borne in mind, however, that the exact nature of solar variability on this long time scale is not known. The ^{14}C proxy of activity tells only of the solar modulation of galactic cosmic rays, which in turn reflects an unspecified property of the solar wind. However, the variations of such outputs as solar wind speed, EUV flux, and integrated radiation flux over such time scales are currently unknown. Long-term modulation of solar activity, or luminosity, is an open question of current interest.

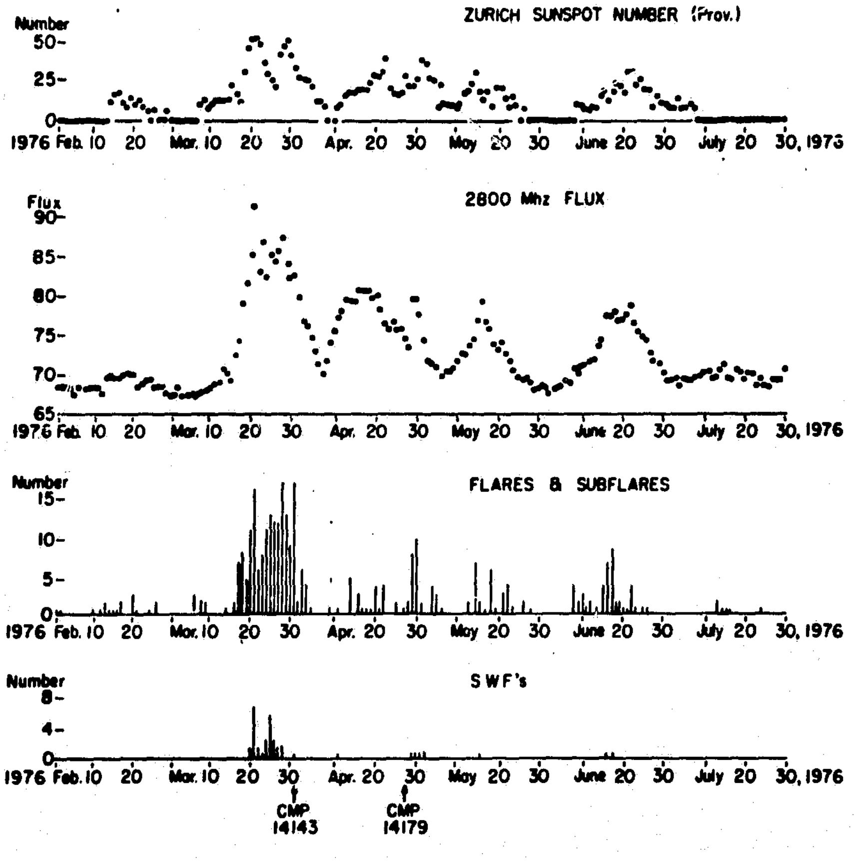

FIGURE 2.20 The daily values of a variety of solar activity indices show rapid fluctuations as well as an approximate 28-day modulation produced by solar rotation (from Dodson and Hedeman, 1977).

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The Nature and Origin of Weather Variability

3

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INTRODUCTION

Atmospheric variability occurs on all space and time scales. The atmosphere is a highly complex nonlinear system that is subject to a large component of random variability due to its internal dynamics. Thus, even under conditions of constant external forcing, weather and climate will vary. To assess the possible contribution of solar variability (i.e., variable external forcing) to the total range of weather and climate variations, it is necessary to understand the nature and magnitude of the natural internal variability of the atmosphere.

In referring to atmospheric variability it is useful to distinguish climatic variability from weather variability. Weather variability is determined primarily by the day-to-day evolution of the large-scale synoptic* pressure systems that dominate the atmospheric circulation pattern at any given time and produce the wind, temperature, and precipitation features that constitute the weather. Climate is simply the statistical result of averaging the weather over a period of time. Although a precise definition of the division between weather and climate is impossible, it is customary to regard variability on time scales of less than a month as weather and on scales of a month or more as climate. It must be recognized, however, that monthly and seasonal averages are subject to random fluctuations due to the nature of statistical sampling. These statistical fluctuations are referred to by Madden (1976) as *natural variability* because they are not associated with any change in the external forcing of the atmospheric system.

THE SPECTRUM OF WEATHER DISTURBANCES

For purposes of the present discussion, weather processes will be assumed have time scales in the range of a few hours to about two weeks. At the short-period end of the range are the so-called mesoscale features such as thunderstorms, and at the long-period end are the major synoptic scale cyclones and anticyclones. The division between large-scale weather features,

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*The term *synoptic* designates the branch of meteorology that deals with the analysis of observations taken over a wide area at the same time. It is used here to designate the characteristic scales of disturbances depicted on weather maps.

which are to be forecast individually, and small-scale features, which must be treated statistically as turbulent elements, depends on the time scale. For scales of a few hours, individual thunderstorms can be forecast, while for longer time scales only their statistical effects can be considered. Similarly, synoptic systems can be considered individually for periods up to a week or two, but for longer periods only their statistical effects on the climate can be studied.

Because of the nonlinearities associated with atmospheric motions, synoptic-scale weather disturbances exchange energy with both shorter-period and longer-period motions. At the high-frequency end of the synoptic spectrum there is a cascade of energy to the mesoscale as characterized, for example, by the process of frontogenesis. At the low-frequency end of the spectrum there is a transfer of energy to global-scale quasi-stationary disturbances. The energy of the synoptic-scale disturbances is maintained in the presence of these nonlinear transfers and frictional dissipation by a continual transfer of energy from the mean flow by the process of hydrodynamic instability. Enormous amounts of energy are involved in these transfers. Monin (1972) estimated that the total kinetic energy of the atmosphere is about 10^{21} Joules and that the average kinetic energy of a cyclonic storm is 10^{19} Joules (one megaton of TNT = 4×10^{15} Joules). At the observed rate of energy conversion, the time for complete replacement of the atmospheric kinetic energy is only a week. Thus, the average rate at which potential energy is converted into kinetic energy for the atmosphere as a whole is about 4 W m^{-2}. The average solar power absorbed per unit area of the Earth's surface is, on the other hand, about 210 W m^{-2}. Thus, the atmospheric "heat engine" has an efficiency of only about 2 percent. For comparison, the total solar flux incident at the top of the atmosphere for all wavelengths less than 250 nm is only about 0.2 percent of the solar constant. Thus, even a factor-of-2 variation in the shortwave ultraviolet flux over the course of a sunspot cycle as claimed by Heath and Thekaekara (1976) would, when account is taken of the 2 percent atmospheric efficiency factor, amount to a change in the average energy conversion rate of only 8×10^{-3} W m^{-2}. This is far less than the natural day-to-day variability due to random fluctuations in weather.

THE GENERAL CIRCULATION

Weather disturbances arise primarily as a result of instability of the mean flow in the atmosphere. This mean flow is referred to as the *general circulation.* To understand the nature and origin of weather disturbances it is necessary to consider the structure and dynamics of the general circulation. General circulation is determined not only by direct radiative forcing (differential heating) but also by the heat and momentum fluxes due to the statistical average of the transient weather disturbances. It is not really possible to consider the mean flow in isolation. However, the mean flow is ultimately maintained by the solar differential heating, i.e., the meridional gradient in the solar heating. Because of this differential heating the average temperature in the troposphere decreases with increasing latitude. As a result of the compressibility of the atmosphere the rate at which pressure decreases with height is inversely proportional to the temperature. Thus, the pressure difference between two latitudes measured at constant altitude must increase with height. On a nonrotating planet the winds would tend to blow down the pressure gradient from high pressure to low pressure. The rotation of the Earth causes atmospheric flow to be deflected to the right of its direction of motion in the northern hemisphere and to the left in the southern hemisphere (the so-called Coriolis effect). As a result the mean winds tend to be in geostrophic balance; that is, they blow parallel to the isobars (lines of constant pressure) with speed proportional to the pressure gradient force and with pressure to the right (left) in the northern (southern) hemisphere. Because the zonally averaged pressure gradient force in midlatitudes is directed toward the poles and increases with height, the mean winds are westerly and increase with height to form the so-called midlatitude jet stream with average maximum wind speeds of about 30 m/sec centered at 12 km near 30° latitude. The midlatitude jet stream does not, however, blow uniformly in a west to east sense at all longitudes. In reality, the disturbing influences of large mountain ranges and the land–sea contrasts in the transfer of heat to the atmosphere generate global-scale perturbations called *planetary waves* that cause the midlatitude westerly jetstream to deviate from its mean position along a sinuous path circling the globe. In the northern hemisphere the largest equatorward deviations occur over the eastern parts of the North America and Asia (see Figure 3.1). East of these regions, in the Western Pacific and Western Atlantic, the mean flow has strong poleward components and maxima in intensity (Blackmon *et al.*, 1977). Many of the transient weather disturbances of the midlatitudes originate in these regions and are carried along the *storm tracks* defined by the jet streams as indicated in Figure 3.2.

In addition to seasonal variations, the jet stream undergoes irregular fluctuations in location and amplitude that lead to fluctuations in the frequency and intensity of synoptic-scale weather disturbances. Of particular interest are the so-called blocking patterns that arise when stronger than normal planetary-scale wave patterns greatly increase the amplitude of the northward and southward deviations of the jet stream from its average position. Such blocking patterns may steer traveling weather disturbances either to the north or south of their usual tracks and thus are responsible for anomalous weather over periods up to several weeks in duration. The dynamic processes responsible for the development and maintenance of blocking patterns are not yet understood. Although there is some evidence that air–sea interaction processes may play a role (Namias, 1972), numerical simulations indicate that substantial variability of the planetary-scale circulation can occur due to purely internal dynamic processes. There is little evidence that changing external forcing of solar (or other) origin plays any significant role in such variations.

WEATHER DISTURBANCES

The transient synoptic-scale weather disturbances discussed in the previous section arise primarily from dynamic instabilities of the mean jetstream flow. These instabilities permit small

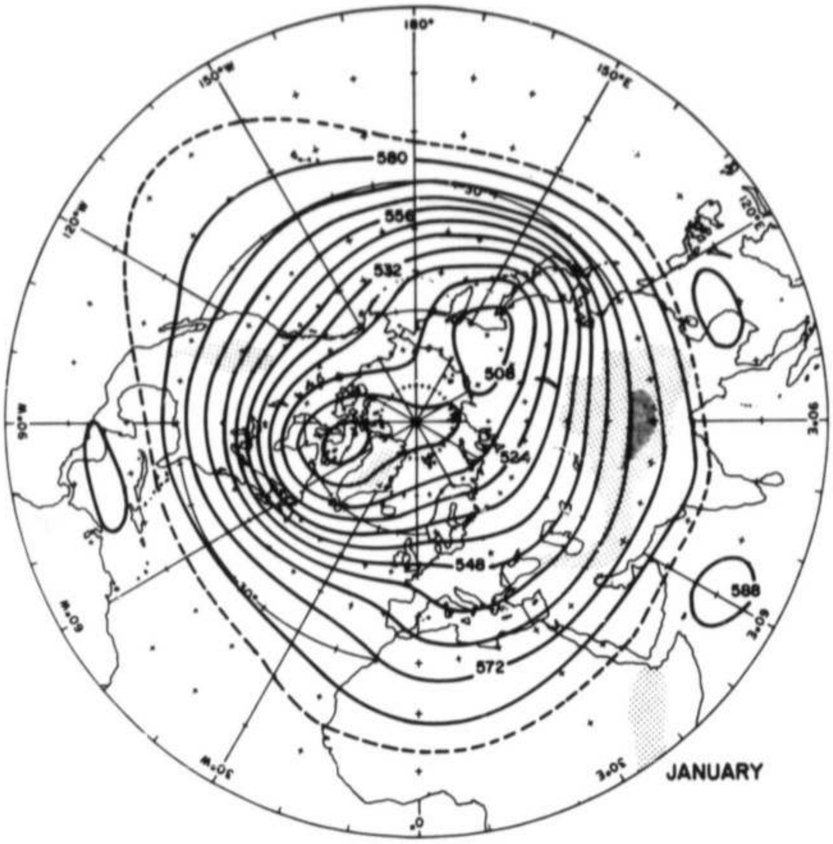

FIGURE 3.1 Winter mean topography of the 500-mbar (50-kPa) pressure surface in the northern hemisphere. Heights are labeled in dekameters. Mean winds blow parallel to the height contours with larger heights to the right facing downstream (after Palmen and Newton, 1969).

random perturbations, which are always present in a turbulent fluid such as the atmosphere, to amplify by drawing energy from the mean flow. Two types of instability are significant for the development of weather disturbances. The most important process is *baroclinic* instability, in which the potential energy stored in the mean flow is converted to potential and kinetic energy of the disturbances. Baroclinic instability is favored by a strong horizontal temperature gradient in the mean flow, or equivalently for a geostrophically balanced flow, by strong vertical shear of the mean zonal wind. Baroclinic disturbances go through life cycles of growth and subsequent decay on time scales of 1 or 2 weeks. The most rapidly growing baroclinic disturbances have horizontal scales of a few thousand kilometers, corresponding to 6–8 wavelengths around a latitude circle.

The second type of dynamic instability important for the generation of weather disturbances is *barotropic* instability, in which the kinetic energy of the mean flow is converted into disturbance kinetic energy. Barotropic instability is favored by strong horizontal shear in the mean wind field. Many of the smallest-scale (less than 1000-km wavelength) cyclonic disturbances that originate in association with the jetstreams are thought to be due to the barotropic instability mechanism. Perhaps more importantly, almost all tropical, synoptic-scale disturbances, such as the wave disturbances that move from east to west along the low-pressure band north of the equator called the intertropical convergence zone (ITCZ), are apparently generated through barotropic instability.

In summary, weather disturbances of synoptic scale are produced primarily by internal dynamic instability of the mean flow. Observed growth rates for such disturbances indicate that only energy conversion from mean flow energy to disturbance energy can account for the energetics of these systems. Direct external energy inputs that might be related to solar variability (e.g., radiative heating) operate much too slowly and are generally far too weak to compete with the dynamic instability mechanisms for changes occurring on the weather time scale. This, however, does not rule out the possible contribution of solar radiative heating variability for the longer-term climatic time scale.

As even ardent advocates of sun–weather relationships concede that energetic considerations are a formidable barrier to a direct effect of variable solar radiation on weather, it is usually argued that solar variability acts as some sort of triggering mechanism in the atmosphere. Monin (1972) pointed out that a triggering mechanism can only be effective if the atmosphere is in unstable equilibrium near a potential energy maximum so that a small external perturbation can cause a large change toward a stable state of potential energy minimum. However, internal hydrodynamic instabilities such as barotropic and baroclinic instability, which operate on the synoptic scale, and convective instability, which operates on the cumulus cloud scale, assure that the atmosphere never deviates far from a stable state. The crucial point is that there are many *internal* processes that quickly release any incipient instability so that no external triggering mechanisms are necessary to explain the atmospheric instability.

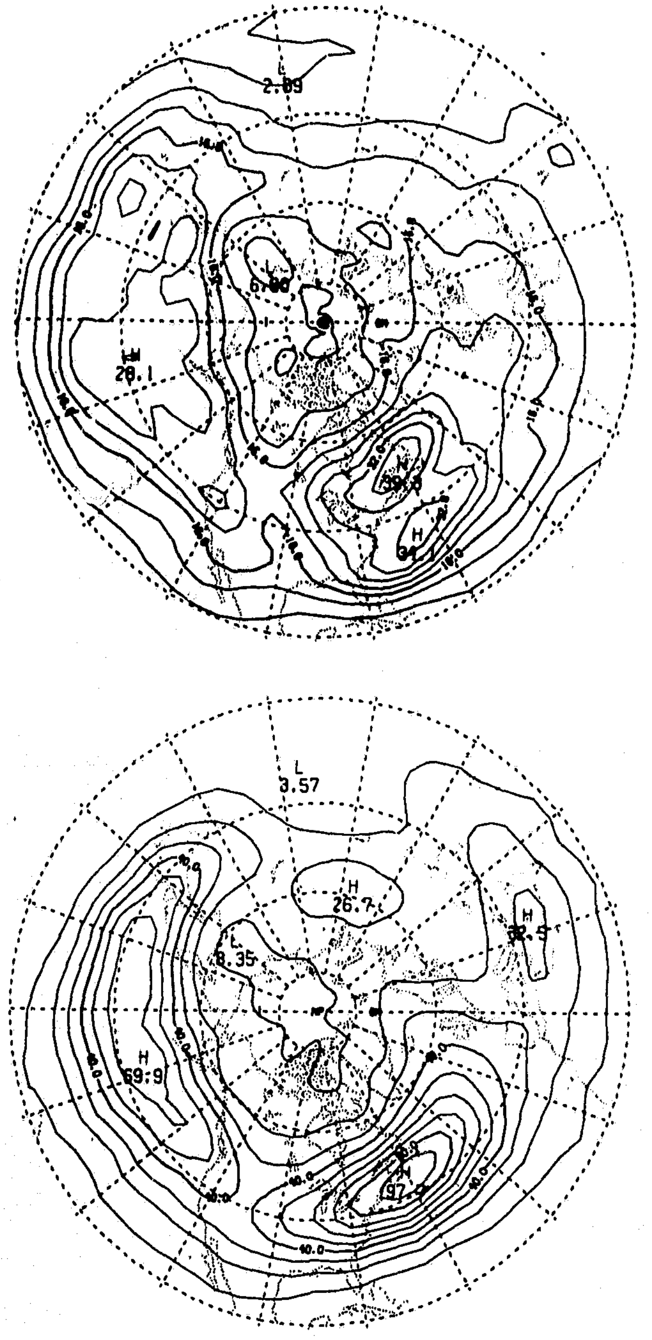

FIGURE 3.2 Variance of kinetic energy per unit mass associated with the meridional wind component of traveling weather disturbances. Note the high intensities in the Atlantic and Pacific jetstream regions. Units are m²/sec² (after Blackmon *et al.*, 1977).

MESOSCALE DISTURBANCES

The focus in the previous section was on synoptic-scale disturbances that have characteristic horizontal scales of a few thousand kilometers. The distribution of precipitation, which is the weather element of most interest to the general public, tends, however, to be organized on horizontal scales from 10 to a few hundred kilometers. The development and maintenance of such so-called mesoscale features is not satisfactorily understood at present. Convective processes are known to play an important role in many mesoscale disturbances, especially those that produce heavy precipitation. It appears that mesoscale disturbances can modify larger-scale (synoptic) disturbances on time scales of less than a day. Cumulus convection is the sort of "fast" physical process that might provide a link between solar variability and short-term weather variability. Again, though, a postulated link of this type must depend on some physical mechanism through which the sun could influence cumulus convection. The most plausible type of physical process that might be involved would be a process that modified the cloud microphysics. Weather modification experiments have indeed shown some evidence that manipulation of the cloud microphysics can create strong perturbations in the heat and mass fluxes in individual cumulus clouds. However, there is little evidence for any significant synoptic-scale response.

PREDICTABILITY

In recent years, dynamic forecast models have been used in a number of studies that clearly elucidate the importance and range of weather variability due to internal atmospheric processes. Such forecast models use numerical approximations to the basic equations that govern the motions of the atmosphere (i.e., mass, momentum, and energy conservation equations) in order to predict the evolution of velocity, pressure, and temperature fields, starting with a given initial state. Sophisticated forecast models may include many physical processes, e.g., solar and terrestrial radiation, clouds and precipitation, boundary-layer friction, interaction with topography, air–sea transfer processes, and parameterized small-scale turbulence processes. However, no forecast model has to date included any influences of a *variable* sun.

Although a proper representation of the various physical processes listed above is required if a model is to duplicate the observed *climate*, the short-range evolution of a given initial state is largely determined by basic dynamic processes, e.g., the advection of disturbances by the horizontal wind field. Because of unavoidable errors in the measurement of atmospheric variables and the inability of the observation network to resolve small scales of motion, there will inevitably be errors in the determination of the initial state. As a forecast proceeds, the natural tendency for instabilities to arise coupled with the inherent nonlinearity of atmospheric motions will cause the errors in the initial state to amplify and gradually affect the large scales of motion, so that the forecast will increasingly depart from the actual flow evolution.

One estimate of how this error growth establishes an upper limit for the inherent predictability of the atmosphere is shown

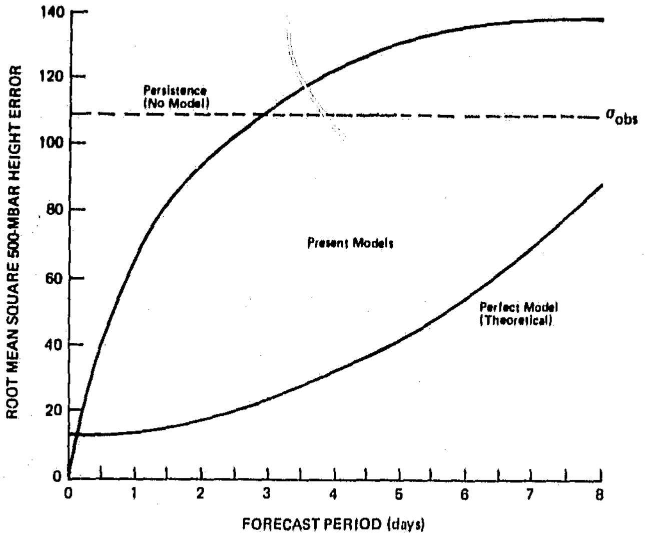

FIGURE 3.3 Growth of the root-mean-square 500-mbar (50-kPa) height error in meters as a function of the forecast period. The root-mean-square error is computed by taking the difference between observed and forecast heights at each grid point and squaring them, averaging over all grid points, and taking the square root (figure courtesy of C. E. Leith).

in Figure 3.3. This estimate has been obtained by running pairs of "forecasts," starting with slightly different initial states. Results from a number of such studies indicate that the doubling time for small random errors in the height of the 500-mbar pressure surface (a common measure of large-scale meteorological conditions in the midtroposphere) is about 3 days. Thus, the theoretical limit for useful predictions of the synoptic scale is about 1 to 2 weeks.

Actual predictive skill with present models is, as shown in Figure 3.3, much less than the theoretical limit imposed by inherent error growth. Both observation and analysis errors in the initial data may contribute to forecast error, but the primary sources of error in present models are believed to be due to model imperfections (Leith, 1978). As can be seen in Figure 3.3, the initial rate of error growth in present models is much greater than that of a perfect model. Furthermore, it turns out that the error growth is substantial at all scales from the planetary-wave scale down to the smallest resolvable scales.

Errors in present models may include numerical ones cause by inadequate representation of the continuous fields by finite numerical approximations as well as physical errors resulting from inadequate treatment of various physical processes. According to Robert (1976) the greatest error source in present models is inadequate horizontal resolution. (Current models typically represent the meteorological fields on a three-dimensional grid of points separated by distances on the order 300 km in the horizontal and 3 km in the vertical.) Of the various physical processes involved in weather disturbances, mountain effects and precipitation were cited by Robert (1976) as the most important error sources. Radiative heating operates too slowly to have a significant, direct influence on the short-term error growth.

Considerations of both theoretical and actual predictability are essential to a discussion of the possible role of solar variations on the weather time scale. As has been emphasized, internal dynamic processes (instabilities and nonlinear interactions) produce rather rapid divergence of two initially very similar atmospheric states. This type of error growth is an inherent feature of turbulent fluids and cannot be reduced by better formulation of the external physical forcing (e.g., including solar variability). However, more importantly, state-of-the-art models have a rapid initial error growth that is much greater than the theoretical limit. The poor performance of numerical models on time scales of only 24–36 hours is probably due to both numerical and physical shortcomings. However, of the various physical processes that might be solar related, only convective precipitation has the fast response required to be a significant factor on that time scale.

Individual convective cells cannot be explicitly resolved in forecast models but can only be represented statistically in terms of the large-scale forecast fields that are thought to control convection (i.e., vertical velocity and humidity). Current parameterizations of moist convection are rather crude and do not incorporate any explicit influences of the various cloud microphysical processes that might be affected by solar variability. However, there is at present little evidence that modification of the cloud microphysics (the basis of most weather modification efforts) would have any significant effect on synoptic-scale motions.

In summary, it seems that even if some subtle influence of solar variability on short-term weather processes were to be proven, the consequences of such a connection for operational forecasting would be small for at least two reasons: (1) only a tiny part of the total weather variance could possibly be solar controlled and (2) current forecast models have large rates of error growth because of improper handling of first-order physical and numerical effects. Inclusion of subtle second-order effects would not significantly reduce such errors.

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The Nature of Climatic Variability

4

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INTRODUCTION

Climatic variations (or fluctuations) might be said to begin where day-to-day weather variations leave off. Madden (1976) and others have noted that there is no clear boundary between the two types of variations but rather a gradual blending of weather into climate as increasingly longer time spans are considered. For purposes of this discussion, let us examine the temporal fluctuations of such elements as pressure, rainfall, or wind on all time scales longer than a few days. In so doing, we exclude the direct effects of the recurring, familiar cyclones and anticyclones of midlatitudes whose movements bring the most noticeable local weather changes.

Week-to-week fluctuations and fluctuations over longer periods are considered first, and we will continually question whether the statistical variability that occurs can simply be assigned to random combinations of daily weather sequences. Most of the physics of such daily sequences are fairly well understood; therefore, only an excess of variability—truly climatic variability—must be explained by reference to some longer-term atmospheric or outside mechanism.

Finding concentrations of significant extra variance tied to a narrow range of time scales is also of interest; exact cycles of periodicities would produce the most extreme concentrations, but such cycles (other than the annual march of the seasons) are in fact rare, weak, and hard to detect amidst the general irregularity. However, broad peaks of excess variance do sometimes appear in spectral diagrams (see Figure 4.8) calculated from long-term data records and perhaps signaling the existence of quasi-periodic variations in those records or at least showing a general tendency for the atmosphere to organize its fluctuations in certain favored ranges of periods.

As time scales of decades and longer are considered, random variations generated by the Earth's whole climate system rather than the atmosphere alone assume the background role in the spectral diagrams, somewhat in analogy to the role of daily weather variations in spectra focused on shorter periods. Spikes, peaks, or broader humps of seemingly excessive variance in any particular range of periods are judged against that more inclusive background.

Our account, inspired by Mitchell's (1976) general synthesis, relies primarily on fluctuations within the directly measured meteorological record of the last three centuries. Variations of less than a year, interannual variations up to a decade, secular variations from a decade to a century, and the long swings of climatic change up to the 100,000-year range are examined.

FLUCTUATIONS WITHIN A YEAR

When examined at any one moment, the atmosphere shows a distinct preference for certain spatial scales of wind and weather, largely dictated by the distribution of land and sea, by heating and cooling, and by its own instabilities as a fluid moving on a rotating sphere. It would divert our discussion too greatly to attempt a survey of this kind of organization, but one aspect should be singled out: the predominance of a continental or even larger scale in the movements of the great bulk of the air. Much of the energy of the winds resides in the zonal westerlies and easterlies—flows parallel to the Earth's latitude circles that vary with latitude and height but not with longitude. Much of the remaining energy is contained in just a few long wavelike variations of speed and direction along these currents. Figure 4.1 shows how rapidly the contribution to the total wind energy falls off with increasing hemispheric wave number after the first six harmonics have been accounted for.

Wind variations on a scale no larger than that corresponding to 4–5 waves around the hemisphere are mainly connected to the atmosphere's weather-bearing disturbances. Such disturbances form, move, and disappear rapidly enough to be filtered out by averaging over a week or more in the construction of charts (see Figure 4.2). Here we see a combination of two midatmospheric contour patterns for January 1977: 700-mbar pressure heights and departures of those heights from the 1948–1970 mean or "normal." Such departures are commonly called anomalies. The monthly average winds run approximately along the contours in the direction that keeps lower heights to the left and at a speed proportional to the closeness of the lines. The prevailing weather anomalies for the period are strongly associated with—though not entirely determined by—the location, orientation, and strength of the anomalies of the general flow. During January 1977, for example, the American Midwest experienced extreme cold.

Anomaly patterns of circulation retain a regional or continental scale, though with reduced intensity, when averages are taken over longer durations like seasons or years, or over clusters of months, seasons, or years. The circulation anomalies can be decomposed mathematically into combinations of a few building blocks, complementary patterns or principal components whose intensities vary independently of each other over time. Only 6–8 such components will usually account for two thirds of the total variance of a long series of maps. The remaining variance has the character of noise.

Even the large-scale, statistically significant principal components of the anomalies shown in Figure 4.2, however, cannot be assigned unambiguously to the category of short-term climatic fluctuations. A large part of the temporal variability of those components might be due to the random grouping together of daily weather variations, and only the residue can be called climatic variability of "climatic signal."

The question of the amount of climatic signal in global-scale patterns or their principal components has not yet been investigated. However, Madden (1976) showed that *local* monthly level pressures exhibit little or no climatic signal over much of the temperate zone of the northern hemisphere. Results from this kind of analysis, however, may be expected to differ from other meteorological elements—temperature, rainfall, wind, cloudiness, and so on.

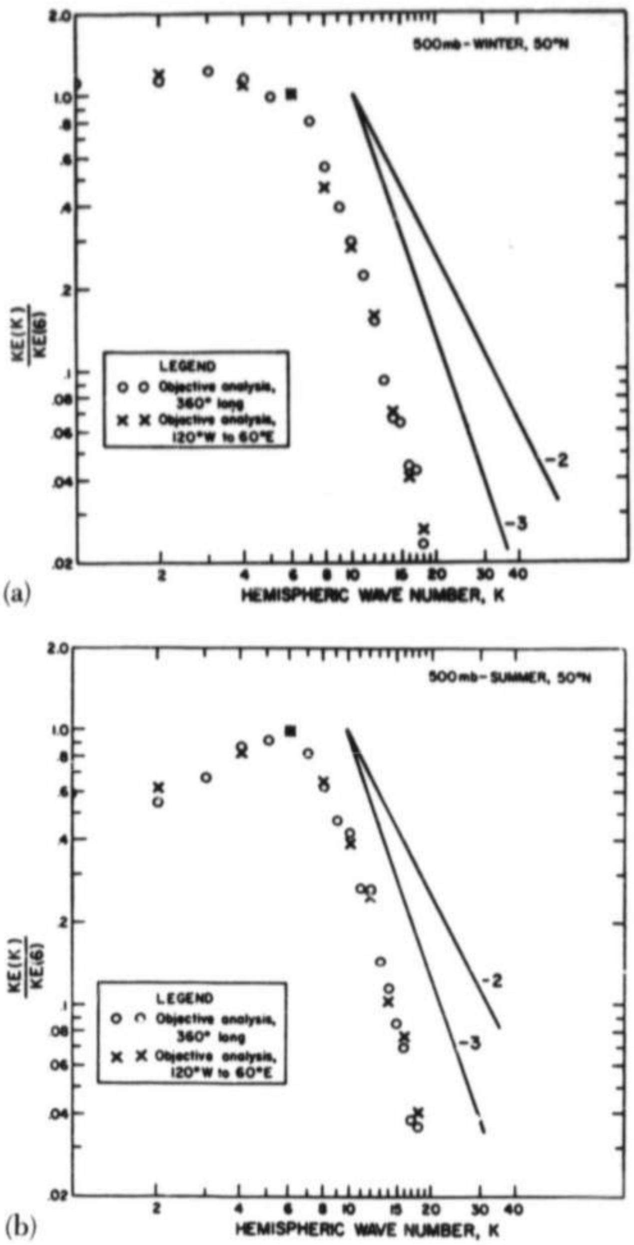

FIGURE 4.1 Kinetic energy spectra at 500 mbar and 50° N for the winter season (a) and the summer season (b). Spectral estimates are shown using data from all longitudes and for a 180° segment from 120° W to 60° E. All estimates have been standardized by division of the estimate for wave number 6 (from Julian *et al.*, 1970, reproduced with permission of the American Meteorological Society).

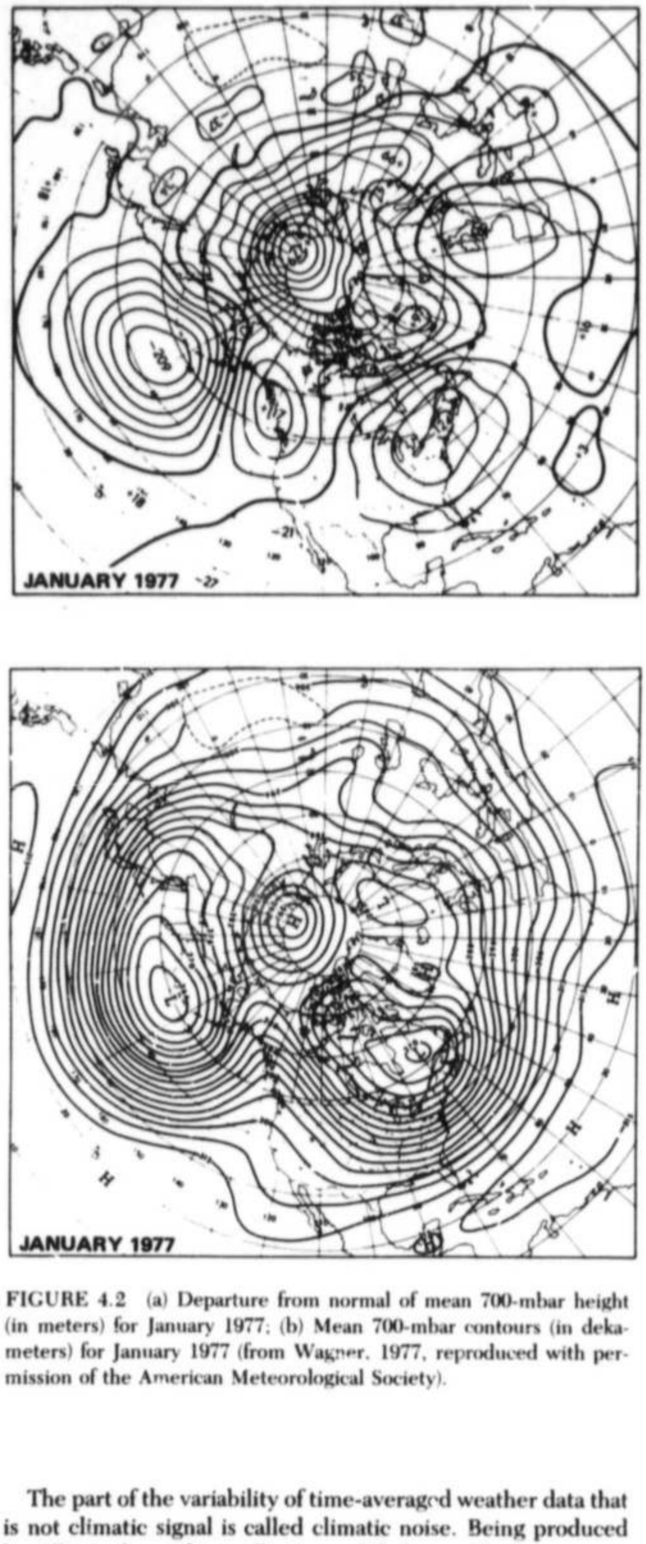

FIGURE 4.2 (a) Departure from normal of mean 700-mbar height (in meters) for January 1977; (b) Mean 700-mbar contours (in dekameters) for January 1977 (from Wagner, 1977, reproduced with permission of the American Meteorological Society).

The part of the variability of time-averaged weather data that is not climatic signal is called climatic noise. Being produced by effectively random collections of daily weather sequences, it becomes unpredictable as soon as the predictability of daily weather fades away. How quickly does this happen? Theory and some computational experiments imply that direct calculations of daily weather variations based on physical theory and measured starting conditions cannot be expected ever to extend usefully beyond 2–3 weeks. Such calculations are presently acceptable for only a week. For any time period beginning a few weeks in the future, then, the climatic noise component of the variability will not be predictable from measured conditions at time zero.

Climatic noise will also remain impervious to prediction from observations of *external* influences, such as solar variations, which might act on the dynamics of daily weather variations. The day-by-day consequences more than a few weeks after the action of an external influence will indeed be different than if that action had not occurred but not predictably so. Therefore, as only the nearly immediate atmospheric consequences of an external event may be predicted from that event, only an external event that is itself predictable beyond a few days can have predictable climatic consequences. Those consequences will be found in the climatic signal, not the climatic noise.

Although time-averaged weather data can be tested for the presence of a climatic signal amidst the noise, isolating and describing the specific signal (or signals) requires further analysis. The computation of variance spectra, which display the contributions of narrow bands of oscillatory frequency to the total variance of a time series, provides a useful basis. Many such spectra have been computed from atmospheric records made up of daily observations, and from them we may derive a tentative picture of the temporal structure of the shortest climatic variations, those occurring within a year but lasting longer than 3–5 days.

The most striking fact about fluctuations whose variance rises significantly above the general noise level is their preference for periods of 1–4 weeks. For the most part, however, these fluctuations are not found in individual station records. They show up instead in certain aspects of the atmosphere's global circulation—in the transports, transformations and general levels of energy, and in the general configuration of the zonal westerlies and easterlies and their wavy disturbances.

Some important facts about these global-scale fluctuations have recently been established. For example, the energy of the upper-level westerlies encircling the temperate latitudes of the southern hemisphere has a detectable pulse of about 3 weeks; in the northern hemisphere the pulse runs a little slower (about 24 days) and affects only the wave disturbances in the flow and the temperature gradients across it but not the strength of the average current. Another somewhat quicker pulse of about 2 weeks also can be found in the strength of the waves in the northern hemisphere's upper-level westerlies, and a weak trace of both pulses can be found at ground level if the winds are averaged along complete latitude circles. All these fluctuations (or vacillations) in the atmosphere's global flow are believed to arise from internal instabilities of its dynamics, i.e., from overshooting and compensatory relaxing of the processes of converting potential energy to the kinetic energy of wave motions, and from periodically intensifying, destabilizing the breakdown of the westerly currents into which the wave motions feed their energy (Hunt, 1978).

Another kind of partial breakdown of the westerlies, long known to forecasters as blocking, occurs regionally. The westerly current at some longitude meanders and splits, deflecting storms both north and south of their usual paths and, because of the general weakening of the flow, allowing them to decelerate. The split may remain more or less stationary, move downstream (eastward), or, more typically, upstream (westward) across oceans and continents. It usually lasts 1–3 weeks, occasionally longer (see Figure 4.3).

Fluctuations of 1–4 weeks are not confined to the troposphere, the weather-producing layer of the atmosphere below 8 miles altitude. The winds of the Arctic stratosphere carry heat poleward at a rate that tends to rise and fall every 1–3 weeks, and the winds and temperatures of the tropical stratosphere exhibit a 2-week oscillation. These fluctuations also have been ascribed to the atmosphere's internal dynamics, to free resonances, and to interactions among wave motions in both the stratosphere and troposphere.

Because a whole latitude zone of the atmosphere fluctuates in the ways we have described, through processes not fixed to particular longitudes, clear traces of the fluctuations need not—and generally do not—appear in records taken at fixed points. When one does, as in the 4-week pulse detectable in the winds and temperatures measured above the stationary weather ships of the North Atlantic, great uncertainty unavoidably remains in assigning the effect to any particular process (Hartmann, 1974).

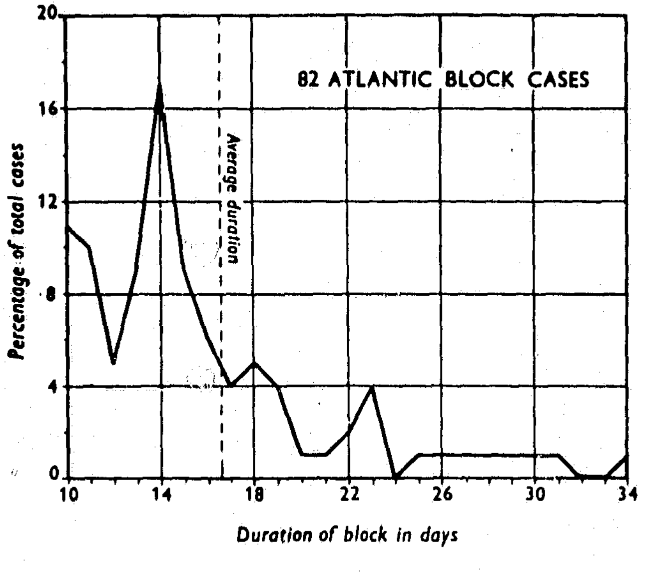

FIGURE 4.3 Persistence of blocking action in the Atlantic area; the straight-line frequency graph shows the distribution by duration of 82 cases of Atlantic block development. Cases (4 percent) with periods longer than 34 days are not shown (from Rex, 1950).

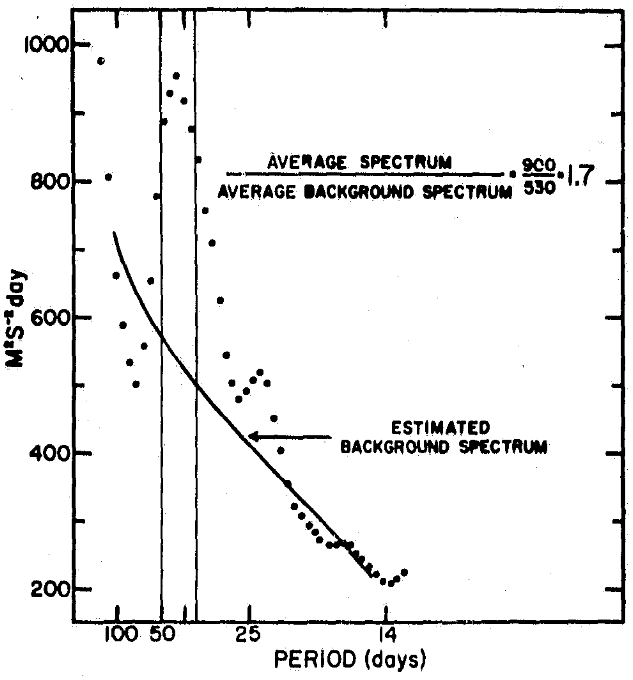

FIGURE 4.4 Variance spectrum of the 150-mbar zonal wind of Nairobi (1°10′ S, 36°55′ E, 1600-m elevation). Ordinate is linear and abscissa is linear with respect to frequency (from Madden and Julian, 1972, reproduced with permission of the American Meteorological Society).

The range of periods beyond 4 weeks but less than a year appears—by comparison with shorter periods—notably lacking in oscillations of any particular periods and in clear concentrations of variability in a range of periods. Only three exceptions stand out against the background of fluctuation at all periods that we have called climatic noise. One is a pulsation of 6–7 weeks in tropical pressures and zonal winds (see Figure 4.4). It is produced by a sequence of widely separated rising and sinking cells and connecting winds moving slowly eastward from the Indian Ocean, intensifying over Indonesia, and then dying away as they approach South America and the Atlantic. Another exception is the 9-week variation in Arctic and Antarctic pressures that marks a direct shift of atmosphere mass from one polar region to the other (Shapiro and Stolov, 1970). The third is a semiannual oscillation usually associated with the normal annual cycle of the seasons or with some longer-period oscillations.

Aside from these oscillations, there is also more persistence in U.S. seasonal temperatures over spans of half a year than could be accounted for by climatic noise (Namias, 1978). This effect can probably be attributed to the influence of other parts of the climate system, such as the upper ocean, that vary more slowly than the atmosphere.

FLUCTUATIONS OF BETWEEN A YEAR AND A DECADE

Because of the overwhelming dominance of the annual march of the seasons in most meteorological records, fluctuations with periods near a year are intrinsically hard to detect. One that has been clearly separated from the annual cycle is a significant oscillation of 11.6 months in the sea-level zonal index of the northern hemisphere's temperate latitudes (see Figure 4.5).

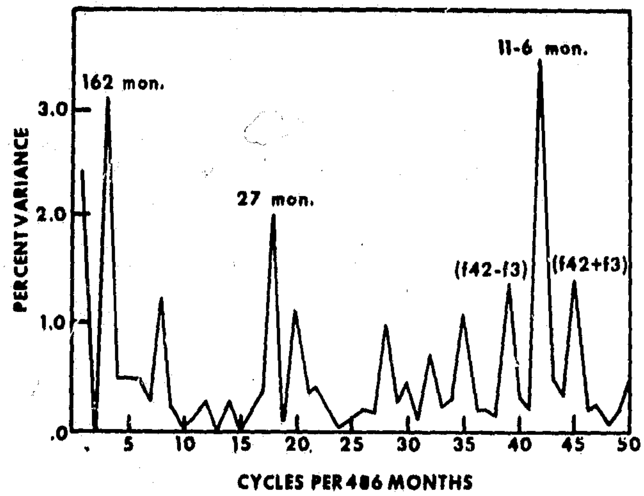

FIGURE 4.5 Periodogram for frequencies $f = 1$ to $f = 50$ for the departures of the index from the monthly normal for the years 1899–1939 (from Brier, 1968, reproduced with permission of the American Geophysical Union).

The zonal index, calculated from the average pressure gradient across latitude circles, estimates the average strength of the zonal westerlies close to the Earth along those circles. The period of this oscillation of the zonal index corresponds closely to a period of maximum mutual reinforcement of the lunar and solar-gravitational tides, called the tidal year. The physics of the correspondence, however, has not yet been investigated.

The strongest regular fluctuation of between a year and a decade is the 2.1-year quasi-biennial oscillation (QBO), which almost completely controls the variations of the winds of the tropical stratosphere (see Figure 4.6). Weaker echoes of this pulse have been found in many records outside the tropics (Figure 4.5) and below the stratosphere (Landsberg *et al.*, 1963), and they may also exist in the variations of the atmosphere's overall potential and kinetic energy. The QBO itself and a companion semiannual oscillation of the upper stratospheric winds are thought to be excited by wave energy pumped up from below (Wallace, 1973), but some of the apparent echoes at a distance might arise instead from negative-feedback interactions with the powerful annual cycle (Brier, 1978, Nicholls, 1978).

Besides the QBO, the most notable climatic fluctuation in the range from a year to a decade is the Southern Oscillation, which was discovered by Sir Gilbert Walker more than 50 years ago. Its clearest manifestation is in the movement of a great mass of air back and forth between the East Indies, near the equator, and the East Pacific, somewhat south of the equator (see Figure 4.7). The Southern Oscillation is not periodic; it tends to be completed in about 3 years, but may easily last as long as 7 years or as briefly as 2. Weaker branches of the oscillation have been found elsewhere in the tropics, and there are also pressure responses in the higher latitudes of both hemispheres. Meteorologists and oceanographers are now pursuing connections to tropical rainfall, the trade winds, the Pacific Ocean's boundary currents and equatorial currents, and even weather and winds in the midlatitudes. Although the physics of such a large and pervasive climatic phenomenon are far from being established, theoretical modeling simulations suggest that energy

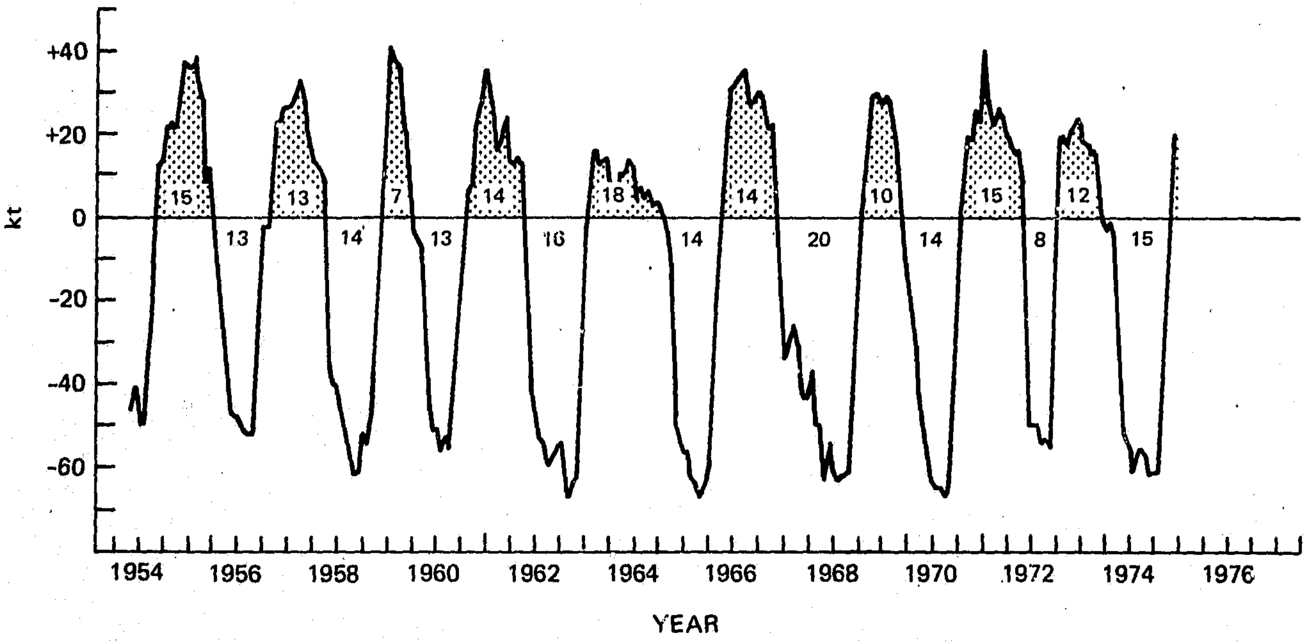

FIGURE 4.6 Mean zonal wind components (30-mbar) at Canton Island, Canada, on a monthly basis. Components toward the East are positive and stippled. Figures along the zero line indicate the duration, in months, of westerlies or of easterlies (from Ebdon, 1975).

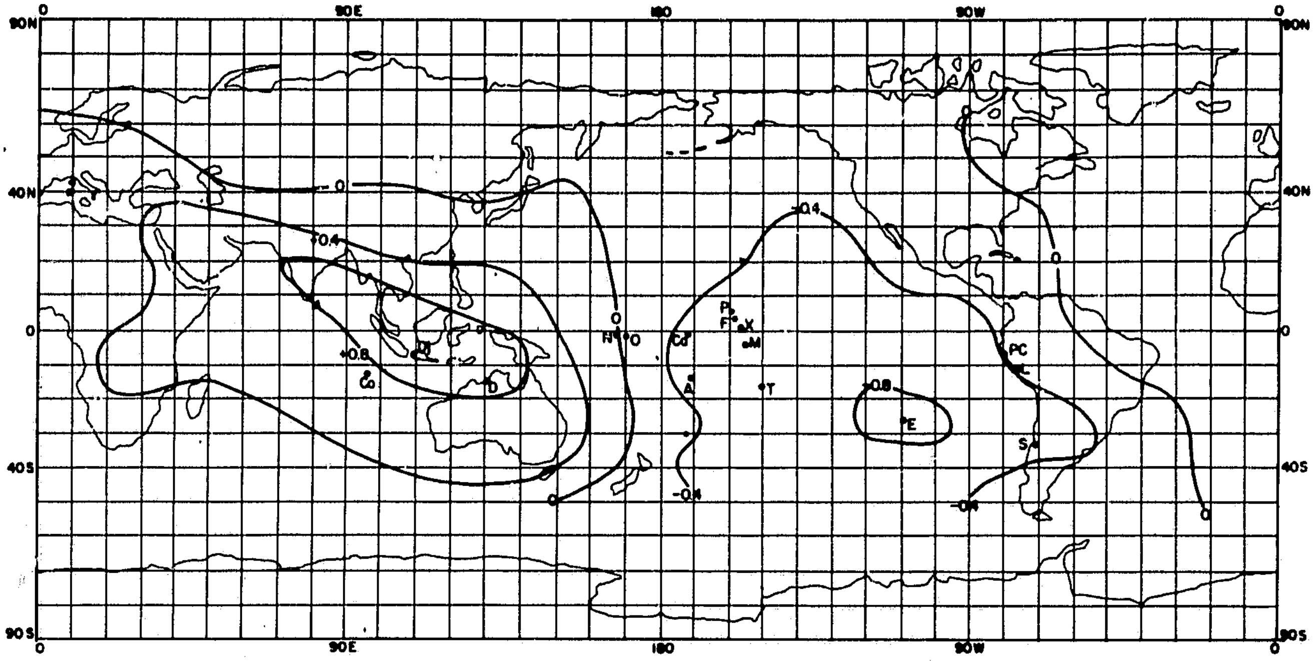

FIGURE 4.7 Schematic map showing isopleths of correlation of monthly mean station pressure with that of Djakarta, Indonesia (Dj) (from Julian, and Chervin, 1978, reproduced with permission of the American Meteorological Society).

exchanges between the upper layer of the tropical Pacific Ocean and the air above play a central role (Julian and Chervin, 1978).

In contrast to tropical records, midlatitude station records of temperature and precipitation do not seem to offer much evidence of major regularities in their fluctuations over a year to a decade other than perhaps the QBO (Madden, 1977; Williams, 1978). There is some persistence of summer temperatures from year to year, but otherwise it is largely climatic noise that rules the individual series. Taking a cue from the findings in the range of 1–4 weeks, we should perhaps turn again from local data to the whole atmosphere's circulation and energetics in search of clear signals. Global energy levels and rates of transformation are known to vary substantially (as much as 50 percent) from one year to another, but unfortunately the record of measurements, being only a decade long itself, cannot yet provide answers to our search.

There are somewhat longer records of the sudden mid-winter warming of the stratosphere that occurs in some years and not in others, but—again—there are too few instances to establish a pattern. This phenomenon, once attributed by some meteorologists to solar impulses, now seems more likely to be the product of a dynamic instability in the stratosphere set off by the intense amplification of a long-wave pattern in the westerlies of the troposphere below (Schoeberl, 1978).

Global average temperatures also vary irregularly within each decade. Although the individual annual values are plagued by too much uncertainty to support firm conclusions about the existence of regular fluctuations, part of the irregular differences among years can be assigned (Mass and Schneider, 1977) to an external physical cause, such as dust from volcanic explosions. The direct effect, a cooling of 0.2–0.3°C, seems most pronounced in the year or two following each incident.

FLUCTUATIONS OF BETWEEN A DECADE AND A CENTURY

In looking for regularities in climatic fluctuations that span decades to a century, the utility of directly measured meteorological data is exceeded. Because most local records are themselves too short to yield credible estimates of statistical regularities, combinations of data in spatial patterns—so important for seeking subtle effects—are almost entirely ruled out.

Gordon Manley's careful reconstruction of three centuries of air temperatures in central England provides a record long enough for getting a bird's-eye view of the whole range of periods. Figure 4.8 shows an analysis of the amplitude of the fluctuations by bands of frequency (scale below) or period (scale above). Only two peaks emerge strongly enough from the estimated noise level (lowest smooth line) to gain a fair degree of statistical significance. One, at the short-period end, is clearly the familiar 2.1-year QBO signal. The other, oppositely placed, is highest at about 100 years, but the low resolving power of the analysis for such long periods forces us to treat this as a uncertain location. A somewhat less impressive peak at 3.1 years may well represent an echo of the Southern Oscillation, but directly comparative analysis using cross-spectra would be

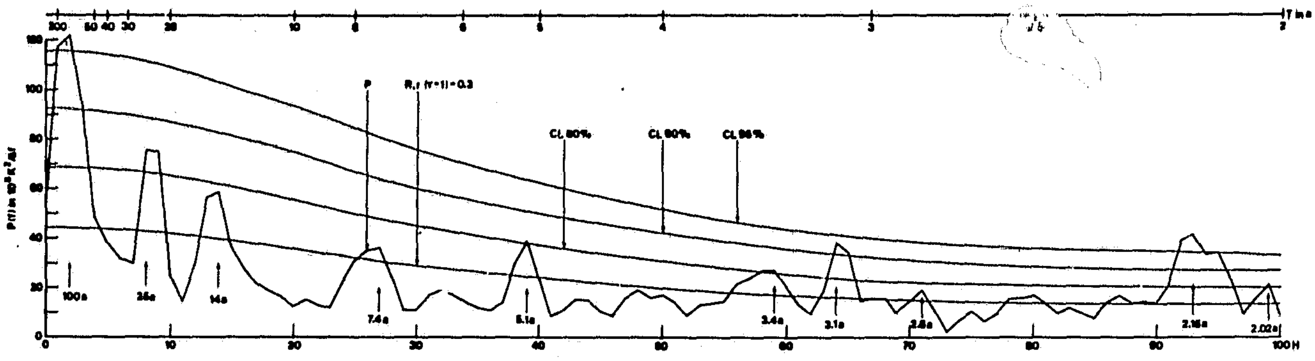

FIGURE 4.8 Variance (power) spectra of annual means from 1660 to 1969 of Central England air temperature (from Schönwiese, 1978, with permission).

needed to prove it. Even closer study would be needed to associate the next most prominent peak (22–25 years) with the solar-magnetic cycle of sunspots of about 22 years.

One lesser peak in Figure 4.8, at about 14 years, may have some connection to an unremarked feature of Figure 4.5. The spike at 162 months (13.5 years), like the one at 11.6 months, seems to be associated with a periodicity of maximum lunar and solar tidal force, in this case a maximum that repeats at exactly the same time each year.

The central England record can be combined statistically with a number of others to give an estimate of northern hemisphere temperature fluctuations since 1579 (Groveman and Landsberg, 1979). Spectra computed from this record also show significant QBO and 100-year signals as well as several in the neighborhood of 3 years, but none around 22 years.

The conventional type of spectrum analysis that produced Figure 4.8 serves well in delineating strong, broad signals against a background of noise, but a newer variant, called the maximum-entropy method (MEM), is gaining favor for the resolving power it brings to the search for weak but sharp signals. In Figure 4.9, MEM was used to find a counterpart to the solar-cycle signal in North American annual average temperatures. Since most of the available records spanned less than a century, the uncertainty of each individual analysis was compensated for by combining the results of many analyses in this diagram.

Students of climatic history are becoming ever more ingenious in devising stratagems to overcome the brevity of their meteorological data series. This is done most often by deriving long proxy or substitute climatic series from biological, geochemical, or other environmental measurements of the re-

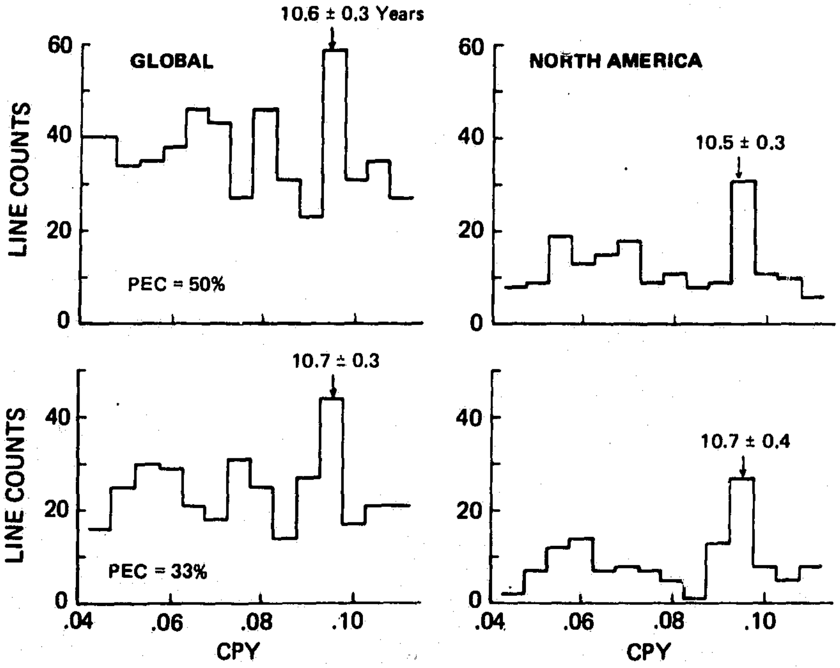

FIGURE 4.9 Line-count histograms from the 226 global spectrums and the North American subset (78 spectrums) for two prediction error filter lengths. For North America, lines cluster at 10.5 years in 63 percent of the spectrums, which is suggestive of a solar-cycle signal in the temperature data (from Currie, 1974, reproduced with permission of the American Geophysical Union).

sponse of natural processes to climatic variations. One of the most useful natural records is the width of annual growth rings in long-lived or well-preserved trees. Statistical calibration of a collection of tree-ring records against recent rainfall data enables climatologists to reconstruct long drought series. A three-century sequence of annual indices of the areal extent of drought in the western United States has now been calculated and shown to contain a substantial 22-year cycle (Mitchell *et al.*, 1979). The effect seems strong enough to be of practical importance for prediction if it can be located somewhat more precisely by region and season.

Although the meteorological records around the northern hemisphere are too short to yield a geographical pattern for the century-long swings that appear to exist in both hemispheric and central England mean temperatures, they can still be combined to depict the pattern of major trends over the last 100 years. Southern hemisphere data are too sparsely distributed, however, for such uses.

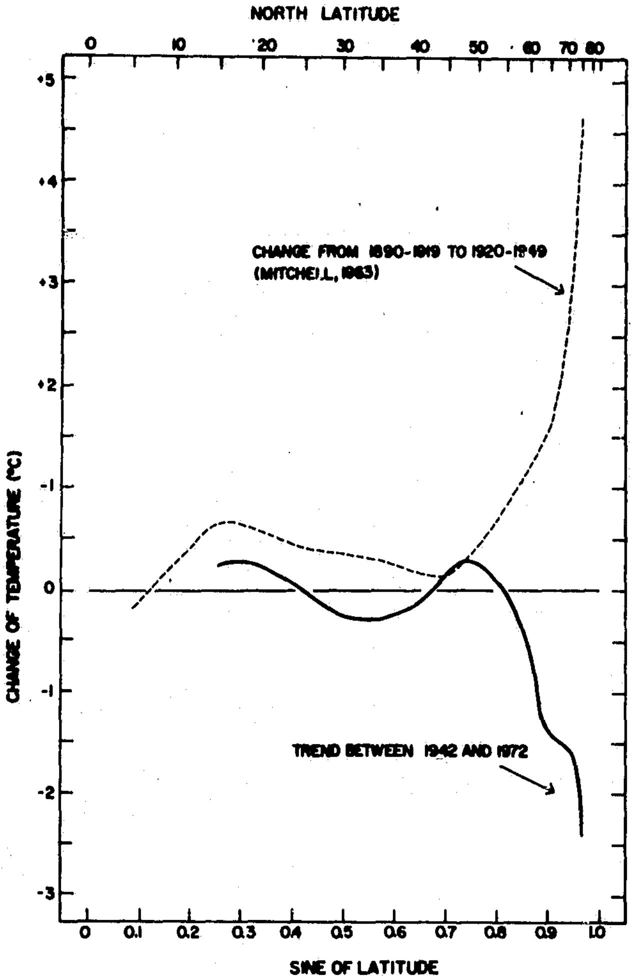

FIGURE 4.10 Meridional profiles of the change in the zonal mean winter temperatures from the 30-year means for 1890–1949 and 1942–1972 (from van Loon and Williams, 1976, reproduced with permission of the American Meteorological Society).

On the largest scale, the estimated mean temperature of the northern hemisphere had (underlying its shorter fluctuations) a rising trend of 0.6°C from the late 1800's to about 1940, followed by a falling trend of about equal slope that has since compensated for a little more than half of the earlier rise. Although detectable at some lower and middle latitudes, these trends (see Figure 4.10) have been predominantly concentrated in and near the Arctic in all seasons except summer. Furthermore, they have varied regionally on about the same scale as does the lower atmosphere's wind and pressure fields, whose recent winter decadal anomaly pattern is mapped in Figure 4.11.

How might these trends have developed? The lower atmosphere pumps heat toward the poles by means of regional horizontal circulations on the scale of that in Figure 4.11, at a rate depending on the strength and placement of those circulations. During the warming period before 1940, the rate of pumping (calculated from station temperatures and from low-level winds estimated from pressures) was significantly greater at the margins of the Arctic than it was during the subsequent period of cooling (van Loon and Williams, 1976).

Because of this finding, it may no longer be necessary to automatically invoke such external influences as solar variations, volcanic-explosion frequencies, or humanly generated changes in CO_2 and airborne dust to explain these particular trends. One recent simulation test by a theoretical climate model even implied that random, natural variations of the heat-pumping mechanism could produce equally large hemispheric temperature changes and trends (Robock, 1978). However, the same study also found that volcanic dust effects could have acted through radiative processes and the heat transport mechanism to produce large parts of the recent hemispheric temperature trends. Further calculations (Robock, 1979) suggest that volcanic dust helped produce not only the irregular fluctuations of northern hemisphere temperature over the last 400 years, but also the recent trends. Clearly, much remains to be done to determine the physics of the climatic trends of the last century.

Other trends may be associated with the northern hemisphere temperature trends shown in Figure 4.10. Some support, at least in sea-level pressure charts, can be found for the idea that short-period variability and the frequency of extreme events should decrease as the Arctic warms and increase as it cools. This response is expected to occur through a lessening of wind-energy generation in storms that develop along a zone of weakening temperature contrast between the Arctic and the midlatitudes and, conversely, through increasing energy generation by the storm development along a strengthening temperature contrast. Figure 4.12 shows that the frequency of extreme 5-day pressures over a strip of the North Altantic and western Europe did gradually drop to a minimum around 1940 and tended to increase thereafter but only within the context of strong shorter fluctuations that mask the statistical significance of the slower variation. In England, 5-day rainfall and temperature variabilities have been unaffected, however, by

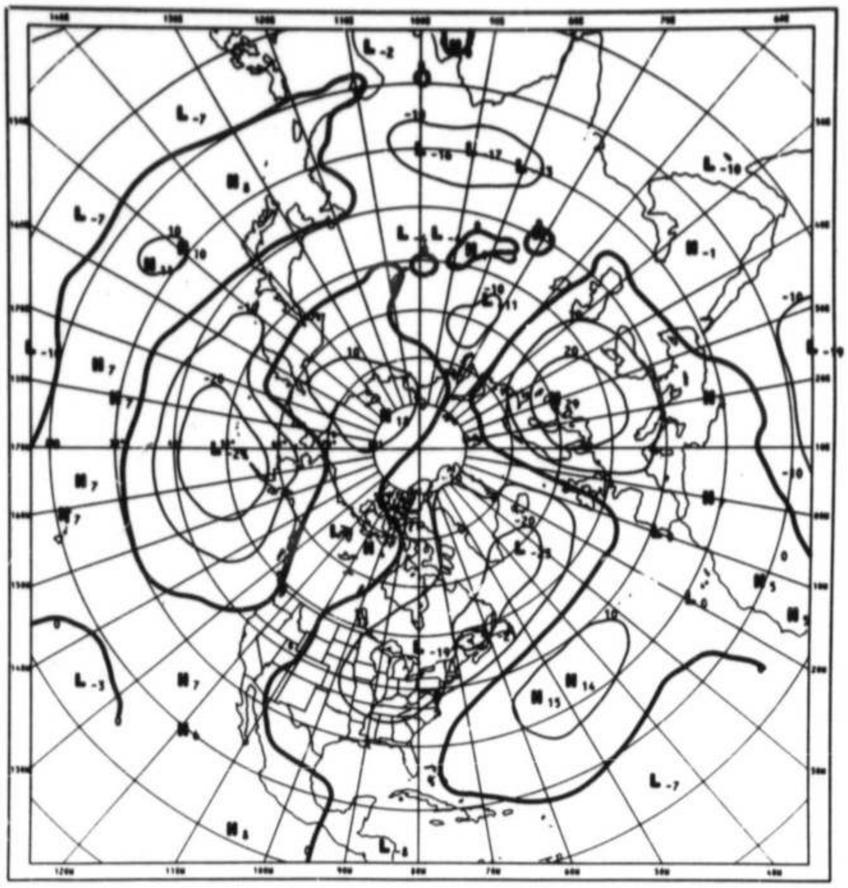

FIGURE 4.11 Seasonal 10-year mean, 700-mbar height for winters of 1968–1969 to 1977–1978 (from NOAA Climatic Analysis Center).

the larger-scale pressure pattern changes. In contrast, the frequency of extreme seasonal weather in England shows no consistent correlation with the northern hemisphere's major temperature trends (van Loon and Williams, 1978).

FLUCTUATIONS OF BEYOND A CENTURY

As we seek to establish the characteristics of the variations lasting longer than a century, instrumental records are discarded. Their replacements, historical documentation over the last 1000 years (Ingram *et al.*, 1978) and the proxy records such as tree rings, ice layers, fossil pollen, glacial positions, lake and ocean sediments, and shorelines (U.S. Committee for the Global Atmospheric Research Program, 1975; Fritts *et al.*, 1979) require painstaking analysis, chronometry, intercomparison, and calibration to elicit a readable picture of the climatic past.

Within the last million years, only four dominant regular oscillations are recognized: the great ice age swings of about 100,000, 40,000, and 20,000 years (see Figure 4.13) and, within the 10,000 years since the last glaciation, an apparent rhythm of about 2500 years in mountain glaciers and tree lines (U.S. Committee for the Global Atmospheric Research Program, 1975).

There also seems to be more irregular variability in the climatic record over periods of several centuries than might be expected from random combinations of shorter-term fluctuations (Kutzbach and Bryson, 1974).

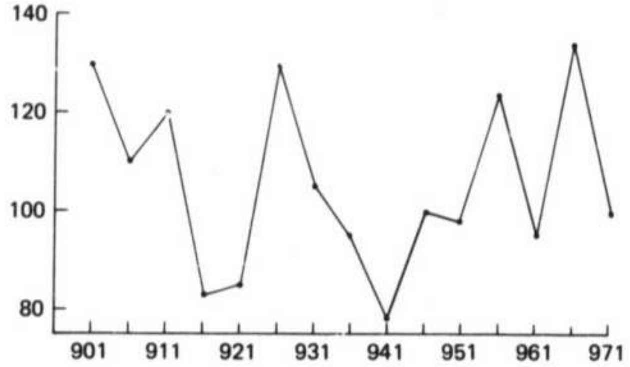

FIGURE 4.12 Number of grid points (per 5-year period) at which standardized anomalies of pentad mean pressure exceeded 2.5 standard deviations (from Ratcliffe *et al.*, 1978).

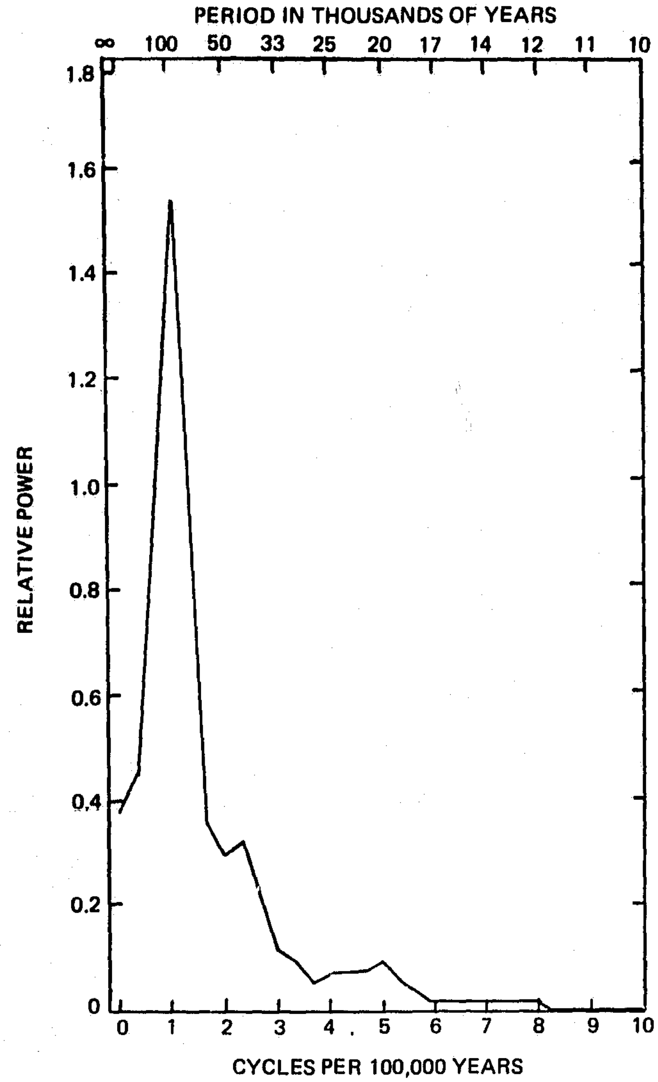

FIGURE 4.13 Power spectrum of climatic fluctuations during the last 600,000 years (after Imbrie and Imbrie, 1980). The data analyzed are time-series observations of oxygen-isotope ratios in fossil plankton in the upper portion of a deep-sea core in the equatorial Pacific.

A classic theory based on variations of solar heating controlled by slow changes in the Earth's orbit has once again taken the central role in explaining the onset of the great glaciations (Imbrie and Imbrie, 1980; Suarez and Held, 1979). The lesser fluctuations of the paleoclimatic record could have been produced by climatically external factors such as volcanism or solar variations, but they may have arisen largely as a consequence of climatic internal-feedback interactions among the atmosphere, oceans, and snow and ice cover. In such an internal process, the quickest fluctuations could act as essentially random forcing for the slower ones (Mitchell, 1976; Hasselmann, 1976; Kominz and Pisias, 1979). Assessing the contribution of any external factor to the interglacial fluctuations requires, therefore, not only a careful comparison between the external and internal irregular variations but also a physical hypothesis or model to guide and sharpen the comparison by suggesting subtle internal climatic responses to look for and critical tests to perform.

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Assessment of Evidence of the Effect of Solar Variations on Weather and Climate

5

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INTRODUCTION

The Russian meteorologist A. S. Monin (1972) stated that a connection between the Earth's weather and fluctuations in solar activity "would be almost a tragedy for meteorology, since it would evidently mean that it would first be necessary to predict solar activity in order to predict the weather." Monin himself saw fit to dismiss the collected evidence for the influence of solar activity on the weather, concluding that it "fortunately produces only an impression of successful experiments in autosuggestion."

On the other hand, the Soviet Union's First All-Union Conference on the Problem "Solar–Atmospheric Relationships in the Theory of Climate and Weather Forecasting," held in Moscow in 1972, reportedly resolved that ". . . investigations . . . in the USSR . . . make it possible to assert with assurance that solar activity and other space-geophysical factors exert a substantial influence on atmospheric processes. Allowance for these is of great importance in preparing weather forecasts."

In the West, a widely circulated paper on sun–weather relationships by King (1975) marshalled a striking array of published and unpublished evidence that despite some caveats was interpreted as support for such relationships. Other reviewers, however, have noted many contradictions in the literature. Tucker (1964) stated that "because of the inconclusive and sometimes contradictory evidence surveyed, a serious consideration must be whether the solar–weather relationship is likely to be a profitable hypothesis to pursue in the future." He commented that "much of the data has been handled badly . . . [and] investigators allowed preconceived ideas to affect their judgment. . . . Nevertheless some of the evidence cannot be dismissed. . . ." Gani (1975) concluded in a wider climatological context that "many of the arguments presented are based on poor foundations. . . . There is very little statistical analysis in the climatologists' work, and some of this is either superficial or wrong."

The confusion in the literature may rest in part on a conscious or unconscious shift in attitude toward placing the onus of proof on those seeking to disprove a solar activity–weather/climate link, in contrast to the traditional scientific attitude that an hypothesis is only an hypothesis until it is proven beyond reasonable doubt. Such a shift in onus of proof may well be appropriate for the making of decisions under conditions of uncertainty if the consequences of what statisticians term a type

II error (wrongly rejecting a hypothesis that is in fact true) are much greater than the consequences of a type I error (accepting a hypothesis that is in fact false) (see Pittock, 1972). Such a shift in onus of proof is a matter of value judgment that may be appropriate to a decision as to whether a certain line of scientific investigation is worth pursuing or supporting. If the potential benefits of a successful theory are large enough (e.g., accurate seasonal climatic forecasts) even a hypothesis having only a small probability of being true may be worth support and investigation. Such value judgments must not, however, be confused with scientific judgments as to whether a given hypothesis is true, which must be decided on the basis of a type I error assessment. For the sake of science the distinction between these two types of error assessment must be consciously and rigorously maintained.

In this chapter, which is in part a summary of a much longer review (Pittock, 1978), we will outline some of the pitfalls in the application of statistics to the problem, with illustrations from the literature. We will then summarize our principal conclusions and comment on their implications.

THE CONTEXT

Weather and climate are highly variable on all time scales, and only a fraction of that variability can reasonably be ascribed to sunspot cycles. For example, in Figure 5.1 the variance in 8 years of weekly measurements of the vertical distribution of ozone has been resolved into components related to synoptic weather variability and instrumental noise, to seasonal variations, to interannual variability, and to trend. The interannual component exceeded 20 percent of the total variance in the atmosphere only above about the 30-km level, and at no level did the component due to trend (i.e., variability on time scales greater than 8 years) exceed 4 percent of the total variance. If we are interested in an 11- or 22-year sunspot-cycle-induced signal in ozone distribution, we must examine only 4 percent of the total variance, the other 96 percent being for our purposes "noise." A similar situation arises in the case of many climatic time series. This imposes severe limits on the statistical confidence of conclusions drawn from necessarily limited data sets.

Climatic data tend to be highly correlated over large geographical areas, so there are severe limits to the extent to which we can substitute data from more stations for longer time series as a means of adding statistically independent information. Instead of N stations reducing the uncertainty of any estimate by a factor of $(N-1)^{-1/2}$, we are limited in the case of many climatic variables to as few as 10 or so independent pieces of information on a global scale, in which case our uncertainty is reduced only by a factor of about 3 no matter how many stations are used.

The variability of the solar constant over the sunspot cycle is generally considered to be less than 1 percent (White, 1977), although accurate, direct measurements of the solar constant from satellites did not commence until 1975. The latter suggest an upper limit of a few tenths of 1 percent may be more realistic. Physical hypotheses for an effect on the weather therefore tend to concentrate on "trigger" mechanisms of one sort or other, usually considered to be driven either by the more variable but energetically minute far ultraviolet radiation or by ionized particle streams modulated by the solar-magnetic field.

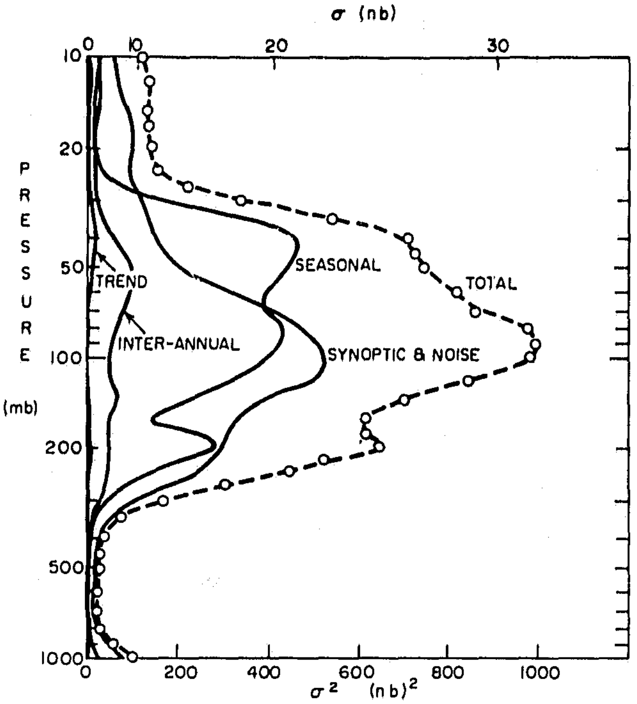

FIGURE 5.1 Allocation of the total variance σ^2 (nbar²) of the ozone partial pressure (nbar) over Aspendale, Australia (38° S, 145° E), between the time scales indicated. The vertical scale is ambient atmospheric pressure (mbar). Note the small proportion of the total variance in the longer time scales which could involve the single and double sunspot cycles (from Pittock, 1977).

Nearly all existing physical hypotheses have been proposed to explain observed and supposedly significant correlations between solar indices (such as sunspot numbers) and climatological data series. These correlations have occasionally been used to make predictions but unfortunately they have not been subject to independent and critical tests. Consequently, most of the literature must be assessed in terms of the true statistical significance of observed cycles or correlations. It is, again, an unfortunate fact that statistical tests of significance, unless the evidence is unambiguous and overwhelming, are hedged about with assumptions, qualifications, and uncertainties that make such purely statistically based conclusions suspect. One has only to consider the problems posed by data selection (whether conscious or unconscious, in space or in time), autocorrelations, smoothing, and *post hoc* hypotheses to realize that a serious difficulty exists.

STATISTICAL PROBLEMS

Different statistical methods differ greatly in their ability to identify recurrence intervals within, and to describe the properties of, a given data set. Some sophisticated modern techniques, such as the maximum entropy method and the noninteger technique of power-spectrum analysis, may well give precise descriptions of given data sets. However, there is an important distinction between such a *description* and the *prediction* of the properties of another data set from the same population. Methods that give a more detailed and sensitive description of one data set do not necessarily give a more reliable prediction of the properties of another (see Mock and Hibler, 1976).

Climatic data series are notoriously unstable in their statistical properties, i.e., they tend to be not "well-behaved" and to be nonstationary. A classical case in point is the data series for water levels of Lake Victoria in East Africa, shown in Figure 5.2. Brooks (1923) found a remarkable correlation of this series with sunspot numbers over the then known water record of about 20 years. No doubt some sensitive modern techniques would ascribe considerable power to a periodicity of about 11 years in this limited data set. Walker (1936), however, noticed the breakdown of this periodicity into what looked like the second harmonic. The heavy rainfall in 1961–1964 at Lake Victoria led to a rise in the lake's water level of about twice the amplitude of the earlier oscillations with only a slow fall since. There is also evidence of high lake levels for Lake Victoria in the late nineteenth century and of other major excursions in the paleoclimatic record.

The work of Bell (1977) clearly demonstrates the dangers of assuming that correlations that appear to be highly significant over short time spans are stable over long time spans. Bell calculated correlation coefficients over sliding 15-year intervals between various climatic time series and sunspots and found fluctuations ranging from +0.5 to −0.5 over different time intervals (see Figure 5.3). The use of different data intervals in the various studies largely accounts for the contradictions between various maps of surface-pressure differences between sunspot maxima and minima found in the literature and throws the real significance of these results into question.

This problem is partly overcome (in the sense that the statistical significance of the results is appropriately reduced) by making proper allowance for autocorrelations in each data series using the formula given by Quenouille (1952) for the reduction in the number of independent observations due to autocorrelations. However, as the autocorrelation functions themselves do not appear to be stable, this is not a complete solution even in this sense.

If, on the other hand, we suppose that the nonstationarity is due to real changes in the climatic system and that these changes will alter the climatic manifestations of a variable solar influence, the difficulty of establishing by statistical means a solar variability–weather/climate link is greatly increased. The nonstationarity of climatic time series calls for the development of a statistical theory of nonstationary processes, not only for the sun–weather problem but also for more general studies of climatic variability. Progress toward such a theory has hardly begun and may prove difficult.

The *a posteriori* selection of one data set considered to have statistically significant correlations or periodicities from a much larger quantity of data not showing these properties is another major problem in interpretation. Five data sets in each 100 independent sets might be expected to show any given correlation or periodicity at the 95 percent confidence level purely by chance. Such selection may be made unconsciously in the choice of area, variable, or epoch for investigation on the basis of a qualitative "feeling" that the given area is a profitable one to investigate. It may also be conscious but only implicit, e.g., in the analysis of data for Rajasthan, India, which is an area that was found to have a "significant" solar-cycle influence in an earlier analysis covering the whole of India. In the earlier analysis in question, data from 105 stations were first broken up at each station into six time series of seasonal distribution parameters, after which power spectrum analyses were performed on the resulting 630 sets of variables. Twenty-six cases in which an 11-year periodicity was significant at the 95 percent confidence level were found. Thus, 1 in 24 cases was significant, a result that is close to the 1 in 20 expected purely by chance. Similar criticisms can be leveled at various other analyses where "significant" effects have been found in just the proportion of the total data field that one might expect by chance.

"Apparently unjustified selectivity" of data has been alleged by Pittock (1978) in relation to a superficially impressive paper that reported apparently highly significant correlations between mean zonal annual precipitation series in the northern hemisphere and an index of solar activity. Both Pittock (1978) and Gerety *et al.* (1978), using the same methods on larger data samples, obtained substantially lower correlations.

King's review paper (1975) contains a number of impressive

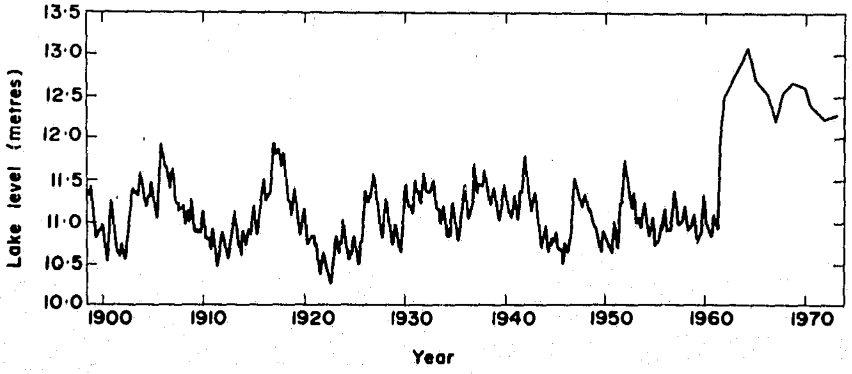

FIGURE 5.2 Water level in Lake Victoria from 1899 to 1973 as measured at the Jinja gauge (height in meters). Note the apparent nonstationarity of the data set; see the discussion by Rodhe and Virji (1976).

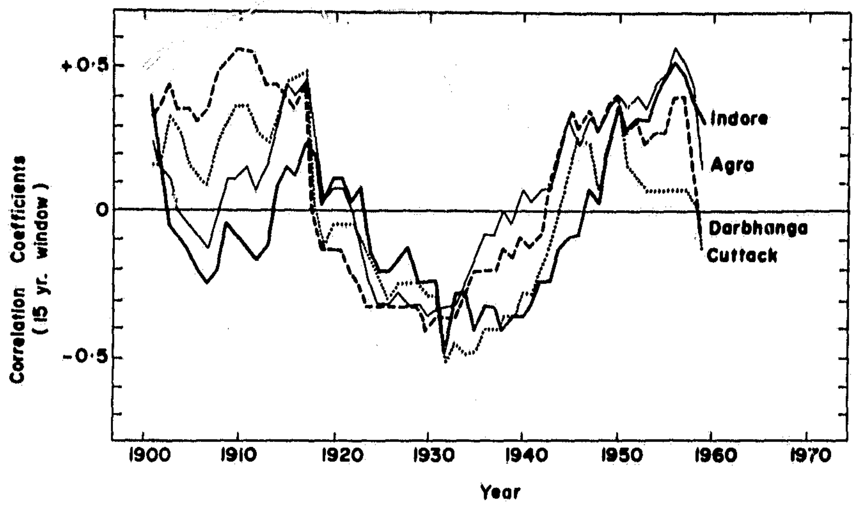

FIGURE 5.3 Variations of the correlation coefficient, calculated over moving 15-year intervals, between the mean sea-level pressure at the indicated stations in August and the mean annual sunspot number. In each case the 15-year correlation coefficient is for the 15 years following the indicated date. Note that the correlation coefficients vary from +0.5 to −0.5 over different 15-year intervals (after Bell, 1977).

curves that show data for favorably selected time intervals, most of which are highly smoothed, which improves the apparent correlations in a manner similar to autocorrelation. For example, as Pittock (1978) pointed out, King's Figure 3 depicts rainfall at Fortaleza, Brazil, but includes only the more favorable half of the available data. As Pittock noted, King's plot of central England temperatures in July includes only the data for 1750 through 1880, despite the availability of a series from 1659 to 1973; another plot, of the number of polar bears caught in southwest Greenland, includes only the more convincing half of the available record. Mason (1976) and Folland (1977) have pointed out that a claimed correlation of the 11-year solar cycle with potato yields in England for the period 1935–1959 does not hold over the longer period 1890–1935.

When data do not fit simple hypotheses it is tempting to elaborate a hypothesis to better conform to the available data. Thus, changes with time or from station to station in the sign of supposedly significant correlations of climatic parameters with sunspot numbers have led several authors to suggest that the effect of sunspots is reversed when some critical sunspot number is reached. The validity of such elaborated hypotheses must be tested on independent data. Bell (1977) pointed out that more recent data have not borne out one such hypothesis.

RESULTS ON LONG TIME SCALES (MORE THAN 30 YEARS)

Climatic fluctuations that may be associated with orbital variations of the Earth (which change the latitudinal and seasonal distributions of solar radiation) are not considered here (see Chappell, 1973; Hays *et al.*, 1976; Mason, 1976; Imbrie and Imbrie, 1980).

Numerous authors have claimed to find evidence of sun-related cycles in weather and climate, at a range of periodicities from less than a year to thousands of years or even longer [see the discussion by Khromov (1973), the summary by Shaw (1928), and the recent tabulation by Herman and Goldberg (1978)]. There appears to be little consensus in these claims except that many authors refer to quasi-periodicities around 11, 22, and 80–90 years. Direct verification of such quasi-periodicities, especially those as long as 80–90 years, is greatly handicapped by the fact that quantitative observations with instrumental measurements of both solar behavior and terrestrial climate are available only for the past century or two.

Nevertheless, there is at least the potential for the development of various lines of indirect (proxy) evidence, of a more or less quantitative nature, both for solar-activity variations and for climatic variations over longer historical periods. Recent work by Eddy (1976) and by Mitchell *et al.* (1979) indeed provide tantalizing evidence that points in the direction of possible long-term correlations between solar and climatic variations. There is an urgent need to refine such proxy measures, and to extend them in both time and space, to confirm whether such correlations are robust and of clear statistical significance.

Evidence of long-term variations in solar activity has been developed from historical sources by Eddy (1976, 1977) and from carbon-isotope studies by various researchers (e.g., Damon *et al.*, 1978). The latter is based on the effect of solar activity in changing the cosmic-ray flux incident on the Earth's atmosphere, which is responsible for the production of radioactive carbon-14. These radioactive atoms become trapped in living matter, such as tree rings, where they decay slowly at a known rate. Using long and accurately dated tree-ring series, it is possible to allow for the decay rate and estimate the cosmic-ray flux at known times in the past (Stuiver and Quay, 1980). This can then provide an index of historical changes of solar activity, with a resolution of the order of decades.

The widths of tree rings can be related to climatic variations (Fritts, 1976) using instrumental weather records for calibration. These provide a means of estimating past climatic variations year by year, for as far back as dated tree-ring series exist. The longest such tree-ring series now available date back more than 9000 years. The University of Arizona's Laboratory of Tree-Ring Research has used this approach to reconstruct the climatic record of western North America for more than the last 5000 years, and the results show broad agreement with

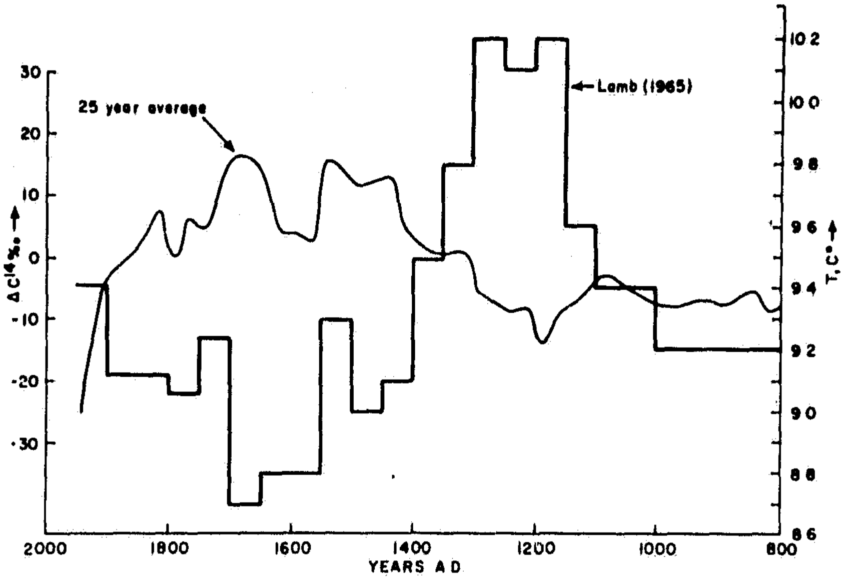

FIGURE 5.4 Carbon-14 isotopic anomalies (expressed in units of δ^{14}C o/oo) and temperature variations over the last millennium. The δ^{14}C values are 25-year averages. The temperatures are Lamb's (1965) estimates for average annual temperatures prevailing in central England (from Damon *et al.*, 1978). The δ^{14}C values are thought to be an index of solar activity.

the Holocene record of glacial events (Denton and Karlen, 1973).

Other forms of proxy climatic data, notably lake varves containing pollen that can be associated with varying climatically sensitive vegetative cover (see Webb, 1980), also have the potential for providing long climatic time series, with a time resolution of 50 years or better in some cases. Other isotopes, notably cosmic-ray-produced beryllium-10, may also provide proxy records of solar activity. Indeed, beryllium-10 has advantages over carbon-14 in that interpretation of the results may be less complicated by large storage terms that could themselves be climatically sensitive. With the development of improved techniques of mass spectrometry using particle accelerators (Arnold, 1978; Raisbeck *et al.*, 1978) it should be possible to measure beryllium-10 in ice cores such as those from the Greenland ice sheet. In principle, time resolution of 20 years is possible going back perhaps 10^5 years.

Preliminary results based on historical evidence of variations in solar activity and on tree-ring climatic reconstructions (Eddy, 1977; Mitchell *et al.*, 1979) are consistent with the idea that the Earth's climate is generally cooler and wetter when the sun is relatively inactive on a time scale of half a century or more (see Figure 5.4). This evidence principally involves a coincidence between the Maunder Minimum (around 1645–1715) in solar activity and the Little Ice Age. A much longer time series will be necessary to establish such a relationship with statistical significance. It does, however, suggest that the sun may not be a constant star on this time scale, and that slow variations in the "solar constant" (which are beyond the range of accuracy and length of record of direct measurements) could indeed be occurring, and contributing to climatic variation. Energetically this is more attractive than solar-induced climatic variations on shorter time scales, as relatively large changes in the solar input may be involved and their effects may in some way be cumulative over many years.

Recent work by Stuiver (1980) has indeed compared a record of carbon isotopes from tree rings with various proxy climatic records since about A.D. 1000 (see Figure 5.5). This study yielded "negative" results in the sense that a relationship between the climatic time series and the carbon-14–derived record of solar change could not be confirmed.

RESULTS ON INTERMEDIATE TIME SCALES (SINGLE AND DOUBLE SUNSPOT CYCLES)

A review of the literature on atmospheric pressure variations over the single and double sunspot cycles (Pittock, 1978) shows that various claimed variations are mutually contradictory and generally not significant when allowance is made for autocorrelations and spatial selection. As Bell (1977) pointed out, the results can depend on which particular sunspot cycles are used in the analysis.

Comprehensive recent studies on surface temperature variations, notably that of Gerety *et al.* (1977), show no significant relationships to solar cycles, with the exception of some weak local or regional relationships revealed by maximum entropy spectral analysis. None of these relationships, however, appears to be sufficiently well defined to be useful in prediction.

Several comprehensive studies of precipitation data, notably those by Rodriguez-Iturbe and Yevjevich (1968), Dehsara and Cehak (1970), and Gerety *et al.* (1977) give negative results. The exceptions are studies of Indian rainfall and that of Xanthakis (1973), both of which claim significant results. The results of the former are not significant when proper allowance is made for *a posteriori* selection of the results, whereas the latter was not borne out when larger data samples were used (Gerety *et al.*, 1978; Pittock, 1978). A series of papers on rainfall in southern Africa do not appear to be based on long enough records to have validity as a basis for prediction, a conclusion reinforced by the fact that fragmentary records for earlier years in the same area reflect different behavior.

Correlations have been claimed between thunderstorm activity and sunspot cycles. These are generally contradictory, or small and nonsignificant. The notable correlation of +0.88 claimed by Septer (1926) and Brooks (1934) for Siberia was not borne out by Kleimenova (1967). The strong correlation for Britain cited by Stringfellow (1974) is in conflict with the results of other surveys.

Correlations of ozone content with solar cycles remain controversial. The most comprehensive recent analysis by Angell and Korshover (1976) shows global variations of ozone with solar variations to be "not quite significant." Hill and Sheldon's analysis (1975) of the Arosa total ozone data (1932–1974), which has been said to have a solar-cycle component, found different periodicities for the ozone and sunspot series, with a cross-correlation of the two series showing "no significant phase lag relationship between them."

Claimed correlations of sunspot numbers with tropopause height appear to be based on inadequate data, or are mutually contradictory. Claimed correlations of other climatic variables with sunspot cycles are in general equally unconvincing, with several comprehensive studies of river flows, tree-ring series, and varves giving negative results.

Recent results by Mitchell *et al.* (1979), based on tree-ring data in the western United States, appear to demonstrate the existence at about the 99 percent confidence level of a 22-year cycle in the area of drought in the western United States during the period 1600–1970, even though this is not evident in individual tree-ring series in the region that were used to reconstruct the drought chronology. The cycle in the drought-area index appears to be related in phase with the double sunspot cycles (although there is some phase shifting) and thus with variations in the solar-magnetic field. Its general significance, however, may be limited by its regional nature, and it would appear to have little predictive value at present.

Williams (1981) reported clear 11- and 22-year cyclical patterns in late Precambrian glacial varves in Australia. If the sun can be assumed to have had similar cyclical behavior 680 m.y. ago and if the layers are in fact annual, this provides some of the clearest evidence yet for a solar-cycle influence on the Earth's climate. The cyclical component is, however, so strong

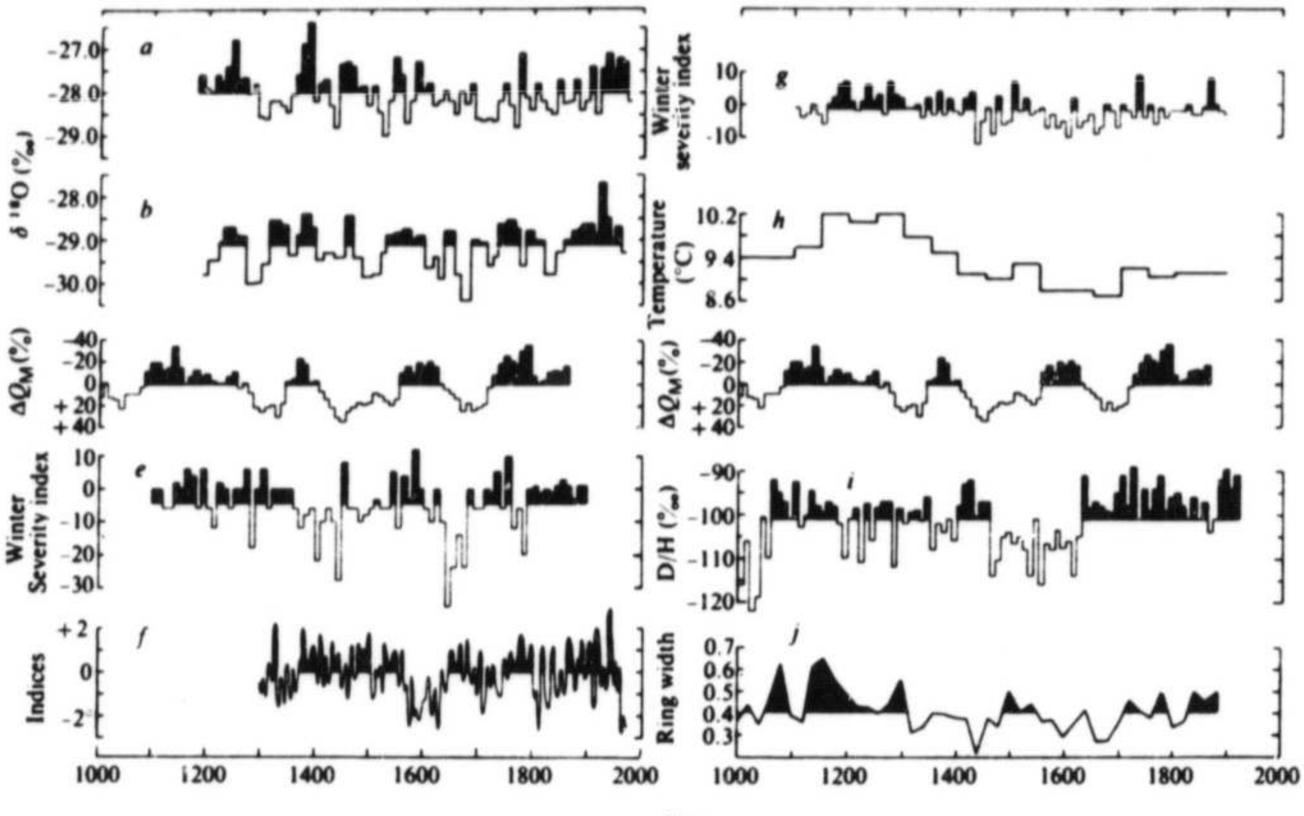

FIGURE 5.5 A comparison of various climate records with the ^{14}C production rate record (from Stuiver, 1980). The climate records *a* and *b* refer, respectively, to the ice-core oxygen isotopes from Devon Island and Camp Century; *e* is a winter severity index for Russia; *f* is the tree-ring density from Switzerland; *g* and *h* are a winter severity index and the mean annual temperature for the United Kingdom, respectively; and *i* and *j*, are, respectively, the deuterium isotopes from tree rings in Nevada and the tree-ring widths from Nevada.

that Williams (1981) argued for a much weaker terrestrial magnetic field for that time, which would allow charged particles from the sun to have a greater effect than it does today. Williams's evidence supports the possibility of a solar-cycle influence but not its importance to modern climate.

The relevance to longer (climatic) time scales of possibly significant short-term correlations between meteorological indices and the passage of solar magnetic-sector boundaries has yet to be established.

RESULTS ON SHORT TIME SCALES

The problems of identifying short time-scale associations between solar and meteorological variables not only include a number of the same knotty statistical problems involved in identifying long-term variations but are compounded by the large number of both meteorological and solar parameters that are available for test correlations. Inasmuch as there is no well-grounded theory for predicting the nature of expected relationships (and thus for suggesting how to limit or focus the search for correlations) the available parameters and the range of variations that can be derived from them are limited only by the imagination of the investigator. It is reasonable to assume that an investigator, fishing in the vast ocean of solar and meteorological variables, may test the interrelationships among many of these variables before finding one that seems noteworthy. This type of postselectivity, often unconscious, complicates the already complex problem of assessing statistical significance. It is, therefore, almost axiomatic that newly uncovered associations be greeted with healthy skepticism regardless of their apparent significance. The problems in designing statistically impeccable solar–weather studies are too great to permit much reliance on calculated statistical significance for newly uncovered associations. More rigorous and demanding tests of reality are required, with strong preference given to attempts to replicate the results in independent data. In any such independent test it is necessary either for the experimental design to follow faithfully the design used in the original study or to specify *a priori* how it will differ. It is also necessary to specify beforehand how much deviation from the original results can be tolerated without rejecting the original hypothesis.

Energies involved in solar variations are apparently so small compared with the steady solar component as to rule out any direct thermodynamic forcing of the lower atmospheric mass and wind fields. Therefore, attention must be paid to any reasonable hypothesis that is capable of releasing some of the atmosphere's stored potential energy. To date, few such hypotheses, or even speculations, have been advanced.

One intriguing hypothesis, put forth by Roberts and Olson (1973), invoked increases in high-level cirrus clouds following solar-particle invasions that produce increased ionization at stratospheric and perhaps upper-tropospheric levels. The ions presumably act either by increasing the efficiency or number of sublimation nuclei. A widespread increase in cirrus, particularly if concentrated at high latitudes, could affect the latitudinal gradient of the radiation balance and thereby the large-scale mass and wind fields. Unfortunately, an attempt to verify this hypothesis by direct measurement was unsuccessful. Such a straightforward and rational mechanism should not be rejected out of hand since the test may not have been a sufficiently definitive one. It would be worthwhile to try to design a more definitive test of the idea that global cirrus cloud cover may be associated with solar-particle emission.

Markson (1978a) advanced an hypothesis in which solar variability affects current flow from thunderstorms and thus modulates the global-scale electric field. He speculated that if the electrification of developing convective clouds depends on the initial electrical state of the atmosphere, then solar-controlled changes in atmospheric electricity could to some extent control thunderstorm development. This proposal merits attention because it offers a pathway for variable solar activity to influence tropospheric processes by affecting the release of atmospheric potential energy.

Markson drew upon the work of a number of authors, principally Reiter (see Reiter, 1977, for a partial listing of references) and Cobb (1967). These authors, among others, in an extensive series of studies, have discussed the possibility of correlations between various indices of solar-energy variations (e.g., solar flares, solar 10-cm radiation flux, geomagnetic disturbances, and interplanetary magnetic-sector boundary passages) and the atmospheric electric field together with the air–earth electrical current density. Many, perhaps most, of these studies lack the necessary statistical controls and tests of reliability to warrant serious consideration, but others cannot be so easily dismissed. In particular, Cobb (1967) reported the occurrence of an average 12 percent increase in the fair-weather air–earth current at Mauna Loa (Hawaii) one day after solar flares. Although this increase appears to be statistically significant, Sartor (1971) criticized Cobb's results because of their fair-weather bias. However, Cobb's results seem impressive and warrant a definitive attempt at verification with independent data.

According to the classical view of atmospheric electricity, tropospheric variations of the atmospheric electric field and air–earth current density correspond to variations of ionospheric potential that can be most reasonably explained by worldwide variations in the total conduction current flowing to the ionosphere from worldwide thunderstorms. Markson (1971), the first to use sector-boundary passages as fiducial marks in a sun–weather correlation study, claimed to find a connection between the timing of sector-boundary passages and thunderstorms. He found an apparent "signal" of twice the background standard deviation; however, this cannot be accepted as statistically convincing because the nature of the signal was not specified *a priori* and it would have been considered just as significant had it arisen in any one of 8 segments in his 8-day normalized sector interval. Nevertheless, based on results such as these, Markson (1978a) presented the outlines of a complex mechanism starting with solar modulation of ionizing radiation in the lower stratosphere and leading to worldwide thunderstorm generation and the meteorological consequences of increased moist convection. Although the hypothesis is speculative and rests on shaky observational studies, it does have the merit of tapping the atmosphere's supply of potential energy. Consequently, it deserves further study, focusing on those aspects that are subject to test and verification. Unfortunately, air–earth current is not a commonly observed meteorological variable. It would seem possible, however, to carry out a definitive test of another crucial aspect of Markson's ideas: the association of solar variability and thunderstorms. A tentative test of such an association (Shapiro, 1979) involving 13 years of daily thunderstorm data for a series of stations along the east coast and through the Midwest of the United States failed to show evidence of a correlation with solar variability.

Markson (1978b) presented the results of a more extensive examination of 30 years of U.S. thunderstorm data. Although the results are somewhat different from his 1971 study, he feels there is sufficient consistency among the three separate 10-year segments of data to indicate a significant solar signal. This conclusion however is not based on a definitive test of significance, and the results appear capable of other interpretation. Furthermore, month-by-month correlations between Markson's daily U.S. thunderstorm data for the 13-year period shows that the two thunderstorms indices are sufficiently related (average monthly correlation coefficient is 0.53), so that it is unlikely that a significant solar signal would be present in one data set without some similar tendency in the other.

Wilcox *et al.* (1973, 1974) described an association between the passage, near Earth, of solar magnetic-sector structure boundaries and a vorticity area index derived from a quasi-conservative, large-scale atmospheric parameter, the absolute vorticity. This result was noteworthy both because of its magnitude and its consistency, as shown in a variety of tests. Furthermore, because absolute vorticity is a meteorological parameter recognized as having physical significance for the large-scale atmospheric circulation, an association of such magnitude appeared to represent substantial evidence of a real solar–weather relationship. The interest generated by this work has resulted in a number of efforts to amplify and clarify the results. Prominent among these is the exhaustive analysis conducted by Hines and Halevy (1977). They concluded, in agreement with Shapiro (1976) based on a somewhat different analysis, that the statistical significance of the Wilcox *et al.* (1974) result was statistically significant at about the 5 percent level, a conclusion since concurred by the original authors. Hines and Halevy were at first skeptical of the physical reality of the result, but their analysis led them to the view that the work appeared sound and that a physical explanation for the result should be sought. The results of Wilcox *et al.* (1976) were cited by Hines and Halevy (1977) as reinforcing that view.

The present status of this work involves a continuing concern about the statistical and physical meaning of the basic Wilcox *et al.* result. A number of unresolved problems of interpretation of the basic Wilcox *et al.* result (VAI response to magnetic-sector boundary passages), which appear to compromise the result in various respects, follow:

- The effect was unaccountably absent in a study of 19 new cases analyzed separately by Hines and Halevy (1977), although it was present in another group of 27 new cases.
- The effect could not be verified in a separate analysis by Shapiro (1979) who used a 500-mbar vorticity area index (vai) akin but not identical to the VAI of Wilcox *et al.** and covering 238 key days in the period 1947–1970 (e.g., see Figure 5.6).
- The effect appears to be confined to the five winter months November through March (Wilcox and Scherrer, 1979). It is puzzling that the effect appears to be altogether absent in October, despite the early transition to winter by that time of year in the higher latitudes, which contributes substantially to the VAI.
- The effect was not detected in an analysis of VAI for the period 1974–1977 (Williams and Gerety, 1978), although it was independently confirmed to exist during the period 1963–1973 originally studied by Wilcox *et al.* (1976). Wilcox and Scherrer (1979) proposed that the breakdown of the effect after 1973 might be attributable to a change in the large-scale atmospheric circulation then and that the sun–weather effect may in general vary with the state of the terrestrial atmosphere. Admitting such a possibility, Williams (1979) nevertheless stressed the *post hoc* nature of this explanation and the clear need for confirmation with independent data.
- The VAI (or vai), which reflects locally high concentrations of vorticity in upper-air troughs, is found to be only weakly correlated with more general hemispheric-scale measures of vorticity, circulation energy statistics, and other large-scale meteorological parameters (Bhatnagar and Jakobsson, 1978; Williams, 1978). Under these circumstances, it is difficult to appraise the meaning of VAI in practical terms and to convince oneself that VAI is a fundamental entity of clear meteorological significance. On the other hand, this weak correlation is not a compelling reason to question the reality of the Wilcox *et al.* effect per se, which is apparently confined to extrema of vorticity (Larsen, 1978).
- Unlike statistics of most standard meteorological parameters, statistics of VAI are found to be erratic and to have little continuity or persistence from day to day. A casual examination of a time series of daily values of VAI (see, e.g., the list in Shapley and Kroehl, 1977) is sufficient to confirm this behavior and emphasizes the difficulty of deriving reliable estimates of local vorticity concentrations from operational upper-air meteorological charts and analyses.

Newer findings that tend to support the basic result of Wilcox *et al.* include the following:

- The effect (i.e., the VAI response to magnetic-sector boundary passages) could be replicated on the basis of 81 sector boundary passages not included in the original analysis and on the basis of 46 boundary passages identified by spacecraft measurements, which rules out possible "back door" correlation

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*Wilcox *et al.*'s VAI is defined as the sum of the area north of 20° N at 300 mbar over which the absolute vorticity exceeds 2.0×10^{-4}/sec plus that over which it exceeds 2.4×10^{-4}/sec. Shapiro's vai is defined as the sum of the area between 20° N and 70° N at 500 mbar over which the absolute vorticity exceeds 1.8×10^{-4}/sec plus that over which it exceeds 2.0×10^{-4}/sec (Shapiro, 1976). The linear correlation coefficient between daily values of VAI and vai for the 24-year period of 1947–1970 is 0.83 (Shapiro, 1979).

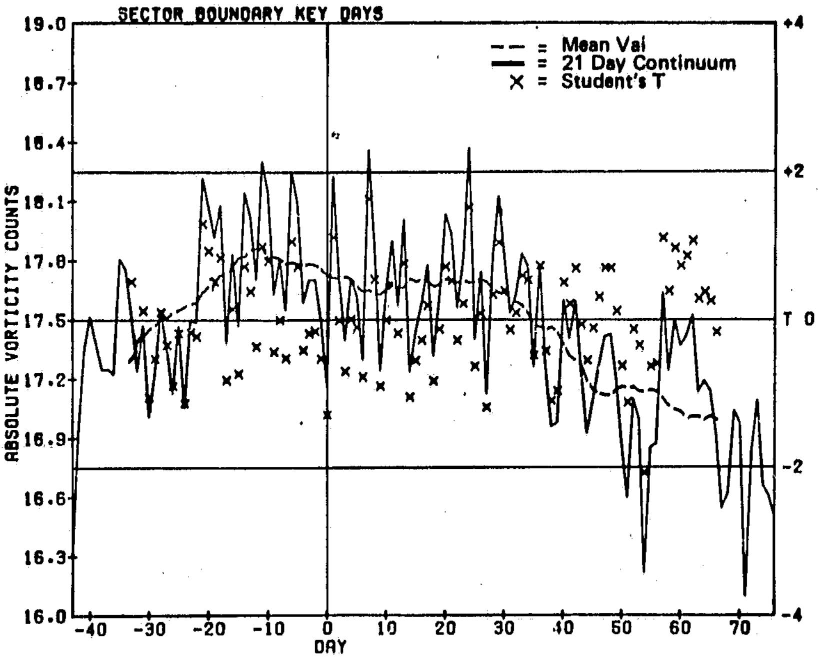

FIGURE 5.6 Superposed epoch analysis of a 500-mbar vorticity area index (vai) for winter (November–March) covering the time period 1947–1970. Day 0 is a day of Earth passage of a solar magnetic-sector boundary. The ordinate is a daily count of the number of grid points between 20° and 70° N where the geostrophic absolute vorticity equals or exceeds 1.8×10^{-4}/sec plus the number exceeding 2.0×10^{-4}/sec (from Shapiro, 1979).

effects through terrestrial influences on magnetic-sector structure (Wilcox *et al.*, 1976).

- The effect could be replicated in VAI in two different latitude zones (35–55° N and 55–90° N) despite indications that such parallel VAI behavior is uncharacteristic of VAI variability in general (Wilcox *et al.*, 1976).
- The effect was found to be enhanced in an analysis of 18 cases when the magnetic-sector boundary passages were followed by proton streams believed to reflect unusually disturbed solar-wind conditions (Wilcox, 1979).
- Short-range forecasts of VAI, based on a National Weather Service numerical prediction model for North America using a limited fine mesh (LFM) grid, were found to be less skillful 12 and 24 hours after magnetic-sector boundary passages than at other times, implying an influence on atmospheric circulation consistent with the hypothesis of an extraterrestrial stimulus (Larsen and Kelley, 1977). However, questions remain of the statistical significance of the results of Larsen and Kelley (Shapiro and Stolov, 1978).

Despite the noisy and erratic behavior of VAI, Knight and Sturrock (197[illegible]) presented some evidence of an association between VAI and A_p, a planetary index of geomagnetic disturbance. For the 7-year interval 1964–1970, they found that power (variance) spectra of VAI and A_p are each elevated for periods near the average solar-rotation period of 27 days. They estimated that the joint probability of such spectral enhancement is about 2 percent for the specific period of 27.49 days. This estimate of statistical significance is, however, subject to uncertainty because it must allow for the lack of independence among the spectral estimates when the spectral resolution exceeds the capacity of the time series, as it does in this case. A direct estimate of the coherence between vai and A_p for the longer interval of 1947–1970 shows relatively high coherence at 27.0 days. However, on the basis of physical reasoning as well as the fact that the vai spectrum contains virtually no power near 27 days, Shapiro (1979) concluded that this relatively high coherence does not represent a physically real association.

It is possible to rationalize in various ways the lack of confirmation of the Wilcox *et al.* result both for the years before 1963 and for the years after 1973. The most robust hypothesis, however, currently appears to be that the apparent correlation for the period 1963–1973 is either a sampling fluctuation or at best a transient relationship that need not repeat itself in the future.

CONCLUSIONS AND RECOMMENDATIONS

In summary, there is at present little or no convincing evidence of statistically significant or practically useful correlations between sunspot cycles and weather or climate on intermediate time scales. This conclusion seems justified despite massive literature on the subject. On these time scales the evidence suggests that if in the future more data and better analyses should succeed in verifying statistically significant relationships, they will nevertheless account for so little of the total variance in the meteorological record as to be of little practical value. This conclusion might be obviated if a more complex hypothesis were developed capable of accounting more subtly for a greater proportion of the variance, at least on a regional basis. Such a hypothesis would not be established as a viable theory, however, until such time that it can be used to make detailed predictions that are verified in independent data.

One such possibility is the hypothesis that the climatic system is in fact nonstationary in the sense that more than one climatic state is possible and that solar variations affect different climatic states differently. Such a hypothesis, however, requires not only a detailed description of the various climatic states and of the solar influence on them but also the development of a statistical theory of nonstationary time series. These are major tasks for the future.

On longer time scales, where the possibility of physically significant changes in the "solar constant" exists, there is some evidence suggestive of a relationship between solar variations and climate, although this has not been confirmed by the recent work of Stuiver (1980). Long proxy records of solar activity using carbon-14 in tree rings (Figures 5.4 and 5.5), and of climatic variables, exist or can be developed for some localities. Other proxy records may also be developed. These may lead to the establishment of statistically significant relationships. This task is worthy of considerable effort.

On the short time scale(s) characterized by the solar rotation, solar magnetic-sector boundary crossings, solar flares, and related events, there is a voluminous and confusing literature. As with the literature on the intermediate time scale, our review has found that many of the claimed relationships are based on inadequate analysis. Nevertheless, several results appear to be convincing in a statistical sense, e.g., those relating solar magnetic-sector boundary crossings and geomagnetic activity to variation in the VAI (Wilcox *et al.*, 1976; Hines and Halevy, 1977; Knight and Sturrock, 1976). Other related studies, however, have drawn negative or inconclusive results (e.g., Bhatnagar and Jakobsson, 1978; Shapiro, 1976, 1979; Shapiro and Stolov, 1978; Williams and Gerety, 1978), so that in the absence of detailed and testable physical hypotheses of causal mechanisms the results that in isolation appear to be statistically convincing are not so persuasive as to enable us to dogmatically assert that solar–weather relationships on this time scale have been proven to exist. The demands of a physical mechanism, repeatability, and predictability have not yet been satisfied to a sufficient degree.

Nevertheless, the few statistically suggestive results found to date and those rational physical speculations that have not been shown to be untenable do give reason for further careful investigation and some cause for hope. This is reinforced by the much greater relative availability of data on short time scale(s), which should enable much more credible statistics to be derived. Indeed, on these time scales it is much easier to gather independent data sets with which to test mechanisms and predictions.

There is another reason for expecting significant progress to be more likely on shorter time scales: the climate system recovers from (or damps out) short-term disturbances in the global energy balance, usually in a matter of days or weeks. For example, major snow storms sweeping across North America often leave huge areas of greatly increased albedo that reflect an appreciable fraction of the total incoming solar radiation back into space. Instead of such storms leading via the "snowblitz" mechanism (a positive feedback) to an ice age (Flohn, 1974), negative feedback takes over and the climatic system quickly returns to its average state.

In the same way, the much less energetic disturbances of solar origin, while they may trigger sizable transient atmospheric effects, may soon have those effects damped out. If such solar-induced transient effects can be understood and predicted the possibility is raised of significant improvements in short-term weather forecasts, even though significant effects on longer time scales might not be established.

Although we have found a great deal that is wrong or confusing in the literature, we have also found results that give grounds for hope and that point to potentially profitable areas for research. We feel bound, however, to comment on the disturbing frequency with which errors, fallacies, and biases appear in the literature. These provide some justification for the extremely critical stand taken by Monin (1972) when he wrote of "successful experiments in autosuggestion" and the equally critical comments by the Russian reviewer Khromov (1973). The state of the literature has given rise to a great deal of skepticism on the part of the meteorological community in particular; consequently, research in this area has suffered from a lack of expert meteorological input. This provides adequate justification, if such is needed, for a critical review such as this, which we hope will set the record straight and serve to guide others who might usefully contribute to this area of research.

Future developments in the field may indeed prove promising, at least in terms of gaining a better understanding of how the atmosphere works. However, claims to the effect that relationships between solar variability and weather or climate are already established as a useful basis for improved weather or climate predictions must be treated by both researcher and consumer with a high degree of skepticism at this time.

POSTSCRIPT

This chapter was mostly completed in 1980 and, apart from some minor amendments, reflects the thinking of the authors at that time.

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II

POSSIBLE MECHANISMS

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Possible Physical Mechanisms: Dynamic Coupling

6

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The total solar flux reaching the top of the atmosphere (the solar constant) is clearly a primary determinant of climate. It is easy to show on the basis of energy-balance arguments that significant variations in the solar constant will cause changes in climate (see Schneider and Dickinson, 1974). However, most postulated solar influences on weather and climate depend not on variations in the total solar flux but rather on variability in the short-wavelength tail of the solar-radiation spectrum or in the flux of solar-produced, high-energy particles incident on the atmosphere. Variations associated with the sunspot cycle, the solar-rotation period, and transient events such as flares are all in this class of solar influence.

Physical effects that are communicated directly to the troposphere by such solar variations seem to be limited to changes in the concentration of ions and variations in the atmospheric electric field. Most of the direct effects of solar variability occur in the upper atmosphere, especially in the thermosphere (see Figure 6.1). Thermospheric temperatures are primarily controlled by absorption of solar extreme ultraviolet (EUV) radiation in wavelengths less than 100 nm. The magnitude of the solar EUV output increases by a factor of 2 from solar minimum to solar maximum. This leads to a corresponding increase of several hundred kelvins in the neutral-gas thermospheric temperature (Roble, 1977). Large temperature variations in the thermosphere are also associated with the 27-day solar-rotation period and irregular events, such as solar flares.

Variations in the solar EUV cannot directly influence the thermal structure of the mesosphere and stratosphere because radiation of wavelengths less than 100 nm is almost totally absorbed above 90 km. In the mesosphere the primary solar absorption is in the far ultraviolet (100–200 nm), which is almost entirely absorbed in the photodissociation of molecular oxygen. In the stratosphere the primary absorption is in the near ultraviolet (200–310 nm), which is strongly absorbed in the photodissociation of ozone. The extent to which radiation in the 100–200 nm and 200–310 nm ranges varies over the solar cycle is not known. However, because the 100–200 nm wavelength range contains only 0.01 percent of the total solar power, even a factor of 2 variation would represent a rather small perturbation in the total energy balance of the mesosphere. On the other hand, the strong absorption of the 200–310 nm radiation in the ozone layer centered at 50 km makes it likely that variations of the solar flux in that wavelength range (containing 1.75 percent of the total solar power) would have a measurable

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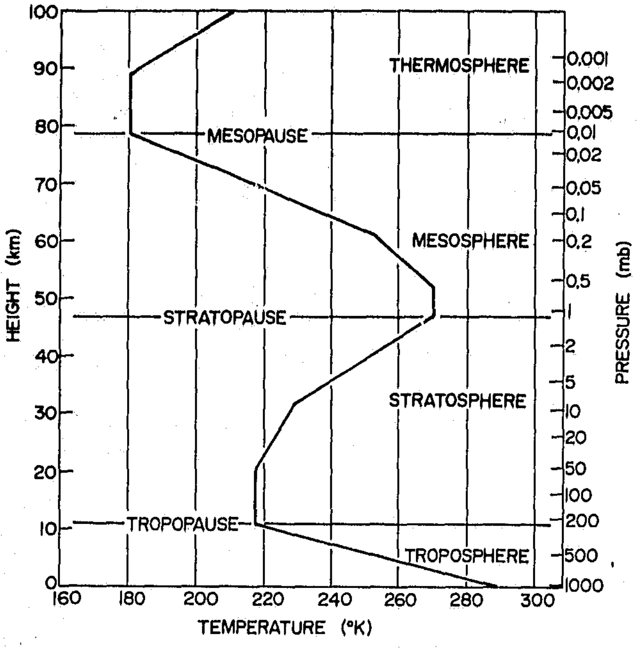

FIGURE 6.1 Vertical temperature profile for the U.S. standard atmosphere showing nomenclature used for various layers in the atmosphere.

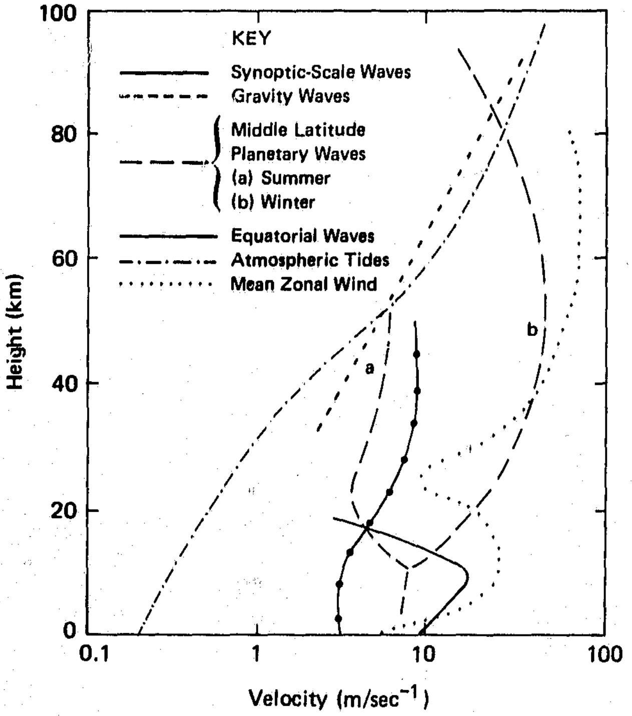

FIGURE 6.2 Schematic vertical distribution of wind amplitudes associated with various types of atmospheric motions. Note the strong difference between summer and winter for midlatitude planetary waves (from unpublished diagram by T. Matsuno).

impact on the temperatures of the upper stratosphere. A number of observational studies have attempted to confirm a solar-cycle influence on stratospheric temperatures. (These are reviewed by Geller and Alpert, 1980; see also Chapters 7 and 8.) Although some of these studies apparently show temperature oscillations in the upper stratosphere of several degrees that are in phase with the solar cycle, none of the studies involves a sufficiently long time series to be statistically significant. At present the evidence for solar-cycle variations in stratospheric temperature and ozone concentrations must be regarded as merely suggestive.

Assuming that solar variability does in fact influence the temperature structure in the upper stratosphere and mesosphere (50–80 km), it is still necessary for that influence to be communicated from the upper atmosphere to the troposphere for there to be an influence on weather or climate.

It has long been recognized that any mechanism that could provide this required vertical coupling must be rather indirect. The pressure and density of the atmosphere decrease by one order of magnitude for each 16-km increase in elevation. As the amplitudes of the large-scale wind and temperature variations in the 50–80 km range are not significantly greater than those associated with tropospheric jet streams (see Figure 6.2), the energy density at 80 km is about 10^{-5} of the energy density in the troposphere, while even at 50 km the energy density is only 10^{-3} of its tropospheric amplitude. Thus, the direct driving of weather or climate variations by solar processes that produce even large changes in the 50–80 km height range is not possible simply because the energy involved is so miniscule. Any viable coupling process must be rather subtle in nature. Such a process might involve radiative, chemical, electrical, or cloud-microphysical effects. Whatever the physical mechanism involved, it would ultimately have to influence the dynamics of the atmosphere in order to produce weather or climate variations.

Since the work of Charney and Drazin (1961), it has been recognized that the upper and lower atmospheres are dynamically coupled on the meteorological time scale primarily through the so-called planetary waves. Planetary waves are disturbances in the atmospheric pressure, velocity, and temperature fields, which are of global horizontal extent. They are primarily generated by flow over topography and by longitudinally dependent heat sources. Under suitable conditions, such waves can propagate energy and momentum vertically over many scale heights. In particular, Charney and Drazin (1961) showed that planetary waves can propagate vertically through the stratosphere and mesosphere only if the mean background zonal flow is westerly (west to east) and is less than some critical speed. The critical speed for propagation depends on the zonal wavelength of the disturbance, and for typical conditions only zonal wave numbers 1 and 2 (one or two wavelengths around a latitude circle) can propagate a significant distance into the stratosphere. If the mean winds are easterly, as is typical in the stratosphere and mesosphere during the summer months, planetary waves generated in the troposphere are damped rapidly with height (as shown in Figure 6.2), and little dynamic coupling exists between the upper atmosphere and the troposphere.

During the winter, however, when the mean zonal wind is westerly, stationary planetary waves generated by topography and land–sea heating contrasts may propagate freely throughout much of the stratosphere and mesosphere. According to the Charney–Drazin theory, however, the "refractive index" for planetary-wave propagation is sensitive to the mean wind distribution in the stratosphere and mesosphere. In particular, the so-called turning point, the level at which the waves are reflected, is simply the level at which the mean zonal wind equals the critical speed referred to above. Hines (1974) speculated that changes in stratospheric or mesospheric flow related to solar variability might, therefore, alter the reflection/absorption of planetary waves and, thus, through wave interference produce effects in the troposphere. This mechanism, unlike other dynamic processes, provides a possible link between solar variability and tropospheric weather and climate, which might be significant despite the huge energy difference between the solar input and the weather or climate response.

Geller and Alpert (1980) used a theoretical model to test the possible influence of solar-related changes in the stratosphere and mesosphere on planetary waves forced by topography and diabatic heating in the troposphere. Since the wind and temperature fields in the stratosphere and mesosphere are closely coupled because of the twin constraints of hydrostatic and geostrophic balance, any change in the radiative-energy balance should change the mean flow distribution. This in turn should change the reflection/absorption characteristics of the vertically propagating planetary waves and, hence, might produce changes in the circulation pattern in the troposphere.

The efficacy of the planetary-wave coupling mechanism depends, of course, on whether the "signal" produced by anomalous reflection can be transmitted from the level of reflection to the ground in the presence of mechanical and thermal dissipation. At the mesopause level (80 km), mechanical dissipation apparently damps out all disturbances on time scales of only a few days. Thus, it is highly unlikely that solar-related disturbances in the atmospheric structure at the mesopause could be propagated all the way down to the troposphere. In the stratosphere, mechanical dissipation is small but thermal damping due to infrared emission by CO_2 tends to dissipate temperature perturbations with a time scale of about a week in the upper stratosphere and two to three weeks in the lower stratosphere. Because the vertical energy transmission speed for planetary waves is only 6–10 km per day, it is clear that thermal damping should play an important role in limiting the amplitude of solar-related planetary-wave anomalies. In fact, Geller and Alpert (1980) found that an imposed wind anomaly of maximum amplitude 10 m/sec and limited vertical extent as shown in Figure 6.3 produced detectable effects on the tropospheric circulation only when the anomaly was centered at or below the 35-km level. Even for an anomaly centered at 35 km, the effects at the ground are limited to latitudes poleward of 60. Only when the mean wind anomaly is moved to below 30 km do hemispheric-wide changes occur in surface pressure and wind distributions, as shown in Figure 6.4. At present, however, there is little evidence that sufficiently strong variations of the solar-ultraviolet flux occur to produce the large changes in radiative heating required to generate such anomalous mean winds in the *winter hemisphere* (where the solar heating from absorption by ozone is small). In addition, modeling studies suggest that planetary-wave adjustment to changed zonal flow occurs on a time scale of a few weeks or more. Thus, this sort of process seems to be applicable only to long-term solar variations. It is unlikely to be a viable mechanism to account for postulated short-term solar–weather relationships such as the correlation between the vorticity area index and solar magnetic-field sector-boundary crossings discussed in Chapter 5.

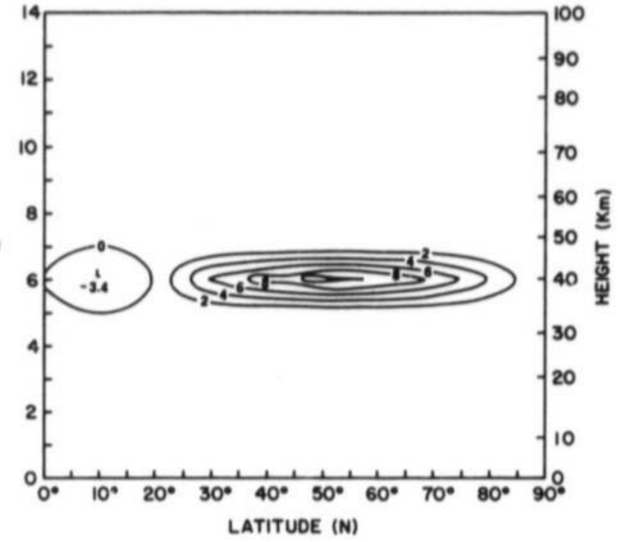

FIGURE 6.3 Latitude-height distribution of the mean zonal wind anomaly pattern used by Geller and Alpert to test the sensitivity of tropospheric planetary waves to upper-atmospheric wind distributions (units, m/sec) (after Geller and Alpert, 1980).

For such short-term solar–weather effects, the physical coupling mechanism, whatever it may be, must be able to operate on the fast (1 or 2 days) time scale of synoptic weather disturbances. Changes in the radiative energy budget involving

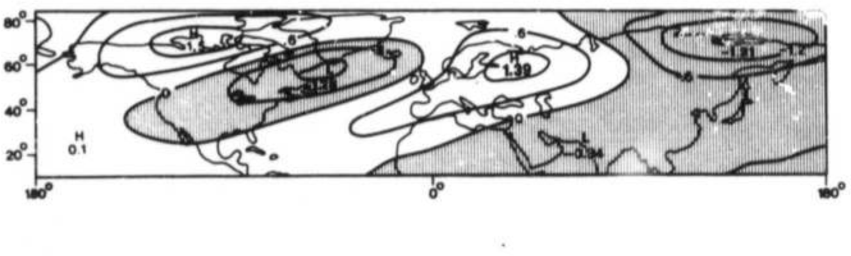

FIGURE 6.4 Surface-pressure anomaly pattern (i.e., deviation from normal pressure) for a northern hemisphere winter with anomalous mean zonal wind pattern similar to that in Figure 6.3 but centered at 28-km height (units, mbar) (after Geller and Alpert, 1980).

cloud variability, for example, could not produce significant effects on the time scale of 1 or 2 days. The most likely candidate for short-term solar–weather coupling is cumulus convection. Convective clouds are efficient elements for the redistribution of energy and momentum in the troposphere. Significant changes in the intensity or distribution of convection in a synoptic-scale system would be effective in changing the synoptic fields on a time scale of 1 or 2 days. Dickinson (1975) pointed out that solar-induced fluctuations in cosmic-ray intensity that produce changes in the ion concentrations in the upper troposphere might possibly affect cloud nucleation processes. Solar-related variations in the atmospheric electric field have also been suggested as a modulating mechanism for convection. Unfortunately, there is little evidence that the overall intensity of cumulus convection is controlled to any significant extent by the details of cloud microphysics or atmospheric electric fields.

In summary, there are possible dynamic processes involving planetary waves and convective clouds that might provide coupling between solar variability and short-term fluctuations in weather and climate. However, in both cases the arguments at present involve considerable speculation.

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Coupling through Radiative and Chemical Processes

7

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INTRODUCTION

This paper discusses the direct effects of solar variability in the middle atmosphere (i.e., the stratosphere and mesosphere) that may occur through coupling between radiative and photochemical processes. The significant solar-driven processes in the middle atmosphere involve the chemistry of neutral trace species (particularly the ozone chemistry) and the heating that results from solar absorption by ozone (O_3) and oxygen. The ozone layer in the middle atmosphere is maintained by a balance between the production of odd oxygen by photodissociation of oxygen (in the 1200–2500 Å wavelength region) and a complex series of chemical processes. Ozone absorbs solar ultraviolet (UV) radiation in the 0.18–0.31 μm region as well as visible radiation in the 0.45–0.7 μm region. This ozone solar absorption is the dominant energy source for the region above 25 km in the middle atmosphere wherein the globally averaged thermal structure is largely maintained by a balance between ozone solar heating and infrared (IR) cooling by CO_2, H_2O, and O_3. Furthermore, the ozone concentration itself if influenced by the atmospheric temperature because the reaction rates of various chemical processes controlling the production and loss of ozone are strongly temperature dependent. The thermal and dynamic structure of the middle atmosphere is significantly influenced by the above-mentioned interaction of solar radiation, ozone chemistry, and ozone solar heating.

Another important energy source for the middle atmosphere is the deposition of mechanical energy by planetary-scale pressure disturbances (also referred to as planetary waves) propagating vertically from the troposphere. The magnitude of energy deposited by these waves depends on the transmissivity of the middle atmosphere to the propagating waves, which in turn is strongly influenced by some of the general-circulation characteristics of the middle atmosphere, i.e., the zonal winds, the vertical temperature gradient, and the radiative dissipation processes. These characteristics are in turn significantly influenced by interactions between radiation and chemistry. The troposphere and the stratosphere are dynamically coupled through these vertically propagating waves. There is also troposphere–stratosphere radiative coupling that arises from stratospheric solar absorption, which helps modulate the solar radiation incident on the troposphere. The warming of the stratosphere by solar absorption and by the absorption of IR radiation emitted by the troposphere determines the magnitude of IR radiation emitted downward by the stratosphere into the troposphere. The nature of the troposphere–stratosphere, radiative–dynamic coupling is illustrated schematically in Figure 7.1.

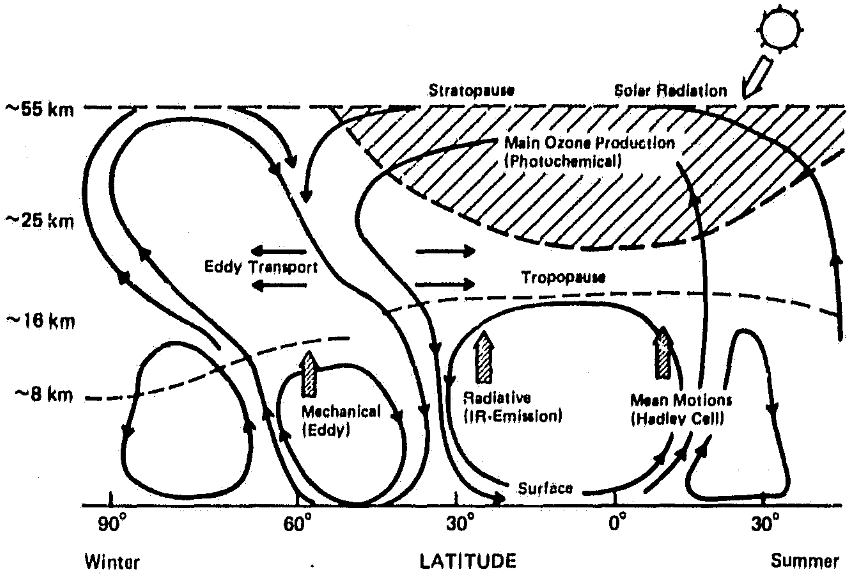


FIGURE 7.1 A schematic diagram of the radiative–dynamical coupling between the troposphere and the stratosphere (after Ramanathan, 1980).

In summary, the general circulation of the middle atmosphere is maintained by mutual interactions of radiation, chemistry, and troposphere–stratosphere dynamic coupling. Of particular interest to this discussion is the fact that these interactive processes give rise to the possibility that the effects of solar variation in the stratosphere can be transmitted down to the troposphere. The radiative–dynamic coupling between the mesosphere and the troposphere seems negligible; hence, our discussion will focus on the troposphere.

Because of the coupling between radiation and chemistry, solar variations can influence the climate of the middle atmosphere through its effects on the ozone chemistry and/or directly by its effects on solar heating. The possibility has been suggested that ozone (total ozone in some stations and ozone content of a certain layer in the middle atmosphere in other stations) is positively correlated with sunspot number (e.g., Willet, 1962; Rangarajan, 1965; Dütsch, 1969; Paetzold, 1969, 1973; Paetzold *et al.*, 1972; Christie, 1973; Angell and Korshover, 1976). Suggestions of ozone–sunspot number correlation date back to the early 1900's (Humphrey, 1910). To be sure, other investigators have found less (or no) evidence to support an ozone–sunspot number correlation (e.g., London and Kelly, 1974; London and Oltmans, 1973, 1977; Angell and Korshover, 1978a). An important source for the discrepancy is the choice of the ozone data. London and Oltmans, for example, analyzed 27 years of total ozone observations at Arosa and Oxford and found little evidence of an ozone–sunspot number correlation. Since the data for these two stations are continuous in time, London and Oltman's conclusion is statistically valid. The validity of their results to the overall problem may be open to question since two stations are clearly not enough to sample the Earth. On the other hand, the evidence for ozone–sunspot number correlations is derived from data that include several stations located in different parts of the world. This approach suffers from lack of a continuous global data base of a sufficiently long period (greater than 25 years). The issue of ozone–sunspot correlation is controversial and the conclusions either for or against the existence of a correlation are based on an analysis of 15–20 years of data (with sparse spatial coverage), which is not long enough to establish an 11-year sunspot cycle of ozone variations.

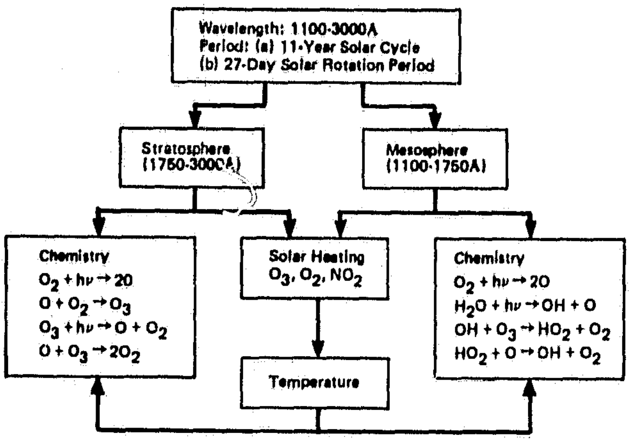
Evidence also exists for an in-phase correlation between stratospheric temperature and sunspot number. Such an in-phase relationship has been shown by Schwentek (1971), Zerefos and Crutzen (1975), and Zlotnick and Rozwoda (1976) for high latitudes in the northern hemisphere. More recently, Angell and Korshover (1978b) and Quiroz (1978) examined the rocketsonde data at high latitudes extending from 8° S to 64° N for solar cycle 20 (the period 1965–1977) and found a stratospheric temperature increase of about 2–3 K during 1965–1970 and a larger decrease of about 4–5 K after 1970. This variation is essentially in phase with the sunspot cycle.

Several plausible mechanisms have been postulated to explain the suggested ozone and temperature variations in terms of variations in solar activity. Basically, as illustrated in Figure 7.2, these mechanisms fall under two categories.

The first category considers a variation in the solar flux of UV radiation that is in phase with the sunspot cycle. In this mechanism, increased (decreased) UV radiation produces more (less) total ozone. But, as will be explained in more detail later, the vertical distribution of ozone change (both the magnitude and the sign) is complicated and depends strongly on the spectral distribution of the change in solar radiation. The increased UV radiation enhances the solar heating of the stratosphere, causing the temperature to rise. Thus an in-phase variation of solar-UV flux with sunspot number would produce an in-phase variation of temperature with sunspot number. Because of the temperature dependence of stratospheric chemistry, as illustrated in Figure 7.2, the temperature change and ozone change interact with each other.

In the second category, solar activity influences ozone by modulating the concentration of nitrogen oxides (NO and NO_2,

(a) SOLAR UV-FLUX VARIABILITY



(b) SOLAR MODULATION OF NITRIC OXIDE

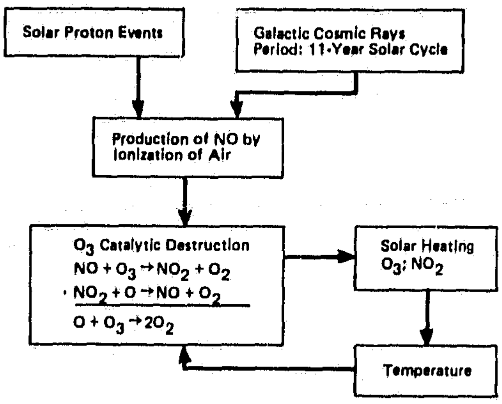


FIGURE 7.2 Schematic illustration of mechanisms that relate solar activity to variations in middle-atmospheric temperature and humidity.

hereafter referred to as NO_x). The NO_x destroys O_3 through the following pair of catalytic reactions:

$$NO + O_3 \rightarrow NO_2 + O_2,$$

$$NO_2 + O \rightarrow NO + O_2.$$

Below approximately 50 km, the above catalytic destruction of O_3 by NO_x is an important process for determining the concentration of O_3. The natural source of NO_x in the atmosphere is provided by the reaction of nitrous oxide (N_2O) with excited oxygen atoms [$O(^1D)$]. An additional source of NO is provided by the flux of solar and galactic cosmic rays. This source of NO, which is influenced by solar activity, provides another link between solar activity and ozone variations.

In what follows, the magnitude of model-estimated ozone and temperature variations in the middle atmosphere may result from the above-postulated mechanisms. The considerations also include the nature of the tropospheric effects that may be produced by the ozone and temperature variations through troposphere–stratosphere coupling mechanisms.

MIDDLE-ATMOSPHERIC EFFECTS

UV VARIABILITY

Of the various postulated mechanisms, possible variations in the solar-UV flux associated with the solar cycle are potentially significant because of their global-scale effects on ozone and temperature. Significant solar-flux variations from solar minimum to solar maximum seem to be well established for wavelengths below 1800 Å. For example, solar-cycle variations in Lyman (1216 Å) are well documented. The Lyman α variations mainly influence the mesospheric heating rates and chemistry. Of importance to the stratospheric climate are the solar-flux variations beyond 1400 Å. In this spectral region the case for solar-flux variability is not adequately established. There are only a few sets of measurements available and, based on these few measurements, Heath and Thekaekara (1977) constructed a model for the solar-flux variations in the 1800–3000 Å region. This model, reproduced in Figure 7.3, shows the envelopes of the data obtained near solar maximum and solar minimum. As shown in the figure, the solar flux at 1750 Å is larger by a factor of 2.5 at solar maximum than at solar minimum, and the magnitude of variation decreases with wavelength to a value of 1.8 at 3000 Å. But, as Heath (1977) pointed out, several researchers have disputed the large magnitude of solar-flux variation shown in Figure 7.1. For example, Simon (1977) argued that the number of reliable measurements in Figure 7.3 are too few to establish a definitive trend.

Recent model studies (Callis and Nealy, 1978; Penner and

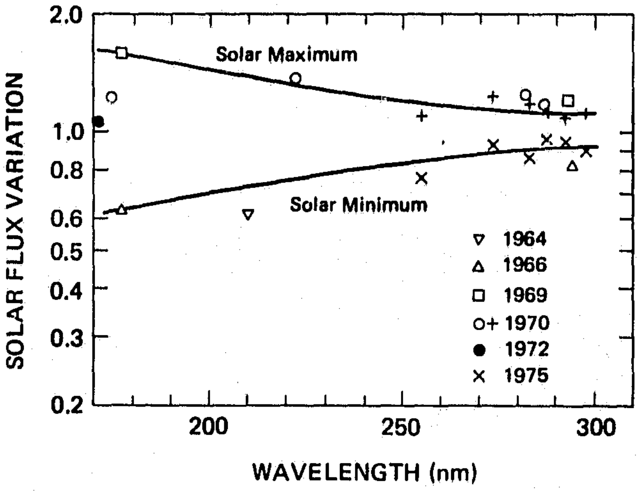


FIGURE 7.3 Variations based on observations made from 1964 to 1975 of solar spectral irradiance apparently related to the 11-year sunspot cycle (after Heath and Thekaekara, 1977).

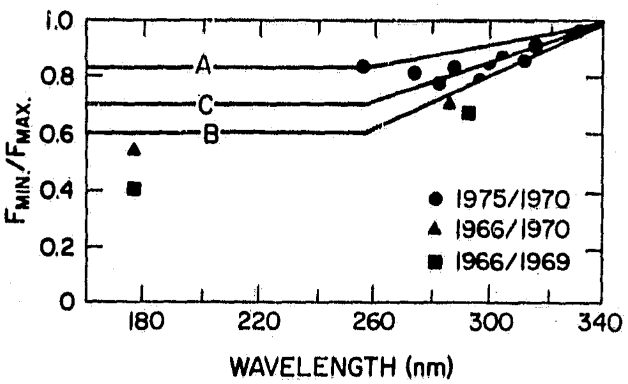


FIGURE 7.4 Ratio of solar flux from solar minimum to maximum as a function of wavelength. Data points are from Heath and Thekaekara (1977) and NASA (1977) (after Penner and Chang, 1978, reproduced with permission of the American Geophysical Union).

Chang, 1978; Callis *et al.*, 1979) indicate that solar-UV-flux variations of the type shown in Figure 7.3 would cause appreciable variations in ozone and temperature. These studies used a one-dimensional photochemical model with coupled radiation. The models computed the vertical distribution of trace species (including ozone) and temperature. The distribution of trace species is computed by a transport-kinetics model that solves the species conservation equations for 20 or more species. The conservation equations consist of 80 or more chemical-kinetic reactions and about 25 or more photolysis processes. The vertical transport of trace species is treated by a one-dimensional diffusion approximation. This admittedly crude representation of the transport processes occurring in the real world has been the subject of extensive discussions in the literature (e.g., NRC Panel on Atmospheric Chemistry, 1976). The vertical distribution of temperature is computed by coupling the transport kinetics model with a radiative-convective model. The radiative-convective model fixes the lapse rate within the troposphere and computes the stratospheric temperature by assuming that the stratosphere is in radiative equilibrium; i.e., at each altitude within the stratosphere, solar heating is balanced by IR cooling. The model includes IR cooling and solar heating by CO_2, H_2O, and ozone. The ozone cooling and heating are computed by employing the ozone distribution computed by the transport kinetics model. Thus the model chemistry and radiation are fully coupled. Despite its one-dimensional treatment and the inherent simplifications, the model is considered useful for obtaining a preliminary estimate of the response of stratospheric ozone and temperature to variations in solar flux.

Penner and Chang's (1978) results for the response of the stratosphere to variations in solar-UV flux are shown in Figures 7.4, 7.5, and 7.6. Figure 7.4 shows three models of assumed solar-flux variation from solar minimum to solar maximum. Between 1800 and 2500 Å, the assumed solar-flux variation is somewhat smaller than Heath and Thekaekara's value shown in Figure 7.3. Penner and Chang suggested that the B curve represents the largest probable variation (based on available data). The model calculations shown in Figures 7.5 and 7.6 adopt the C curve in Figure 7.4. From Figure 7.5, O_3 and temperature increase in the stratosphere from solar minimum to solar maximum, except the region above 40 km, where ozone decreases. The increase in temperature is due to the increased UV heating by ozone absorption. The increased UV heating is primarily caused by the increased UV flux and to a lesser extent by the ozone increase. The increase in ozone is largely due to

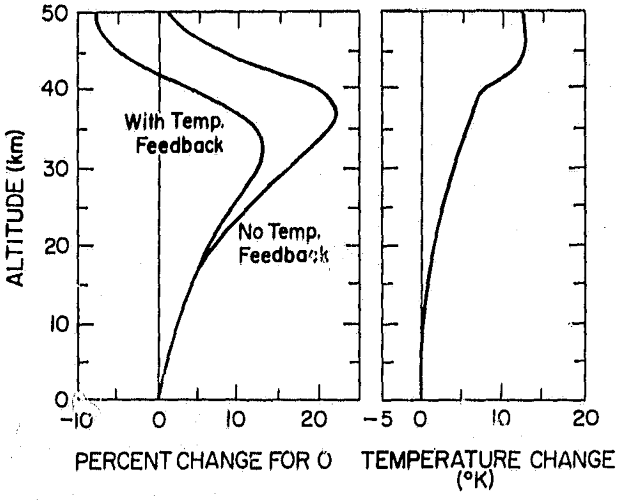


FIGURE 7.5 Percent change in O_3 [100 (max − min)/min] and temperature change from solar minimum to maximum. Solar flux was varied by the amount shown by curve C in Figure 7.4.

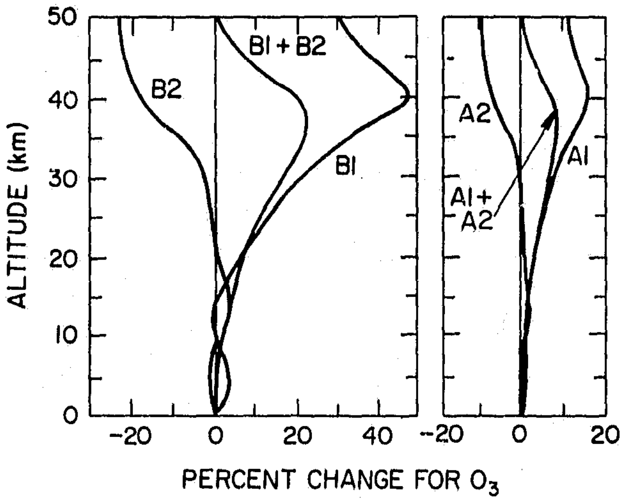


FIGURE 7.6 Percent change in O_3 from solar minimum to solar maximum. Solar flux was varied by the amounts shown by curves A and B of Figure 7.4. For curves A1 and B1, only the portion below 255 nm was varied. For curves A2 and B2, the portion above 255 nm was varied (after Penner and Chang, 1978, reproduced with permission of the American Geophysical Union).

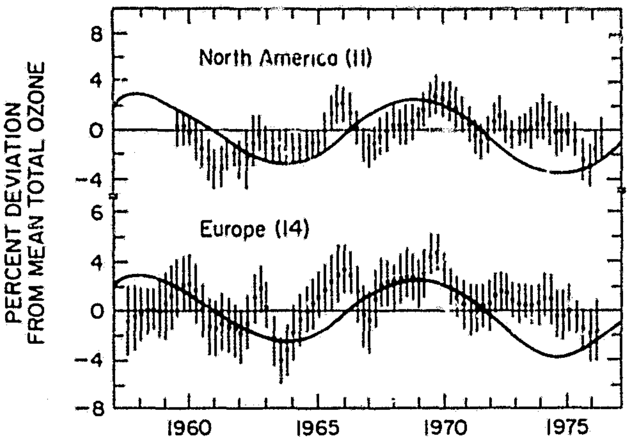


FIGURE 7.7 Comparison of calculated ozone deviations to the analysis of the observed ozone variations for Europe and North America by Angell and Korshover (1978a) (after Penner and Chang, 1978, reproduced with permission of the American Geophysical Union).

the increased production of oxygen atoms through photolysis of O_2

$$O_2 + h\nu \rightarrow O + O \qquad \text{(Reaction 7.1)}$$

that which reacts with oxygen to form ozone

$$O + O_2 + M \rightarrow O_3 + M. \qquad \text{(Reaction 7.2)}$$

Reaction (7.2) and the two-body reaction

$$O + O_3 \rightarrow O_2 + O_2 \qquad \text{(Reaction 7.3)}$$

are temperature dependent, and the net effect of the temperature dependence of these reactions is to make ozone changes negatively correlated with temperature changes. Consequently, as shown in Figure 7.5, ozone increase is smaller for the case that includes temperature feedback. The result for "no temperature feedback" was computed by fixing the temperature to a reference value and letting only the trace-species chemistry respond to the UV-flux variations. At altitudes above 40 km, the temperature increase is about 10 K and because of this large temperature increase the ozone decrease caused by the temperature dependence of Reactions (7.2) and (7.3) overwhelms the photolytic production of O_3 through Reaction (7.1). As a result, ozone decreases with an increase in the UV flux.

The magnitude and sign of ozone change caused by UV-flux variations are extremely sensitive to the spectral distribution of the flux variations. This sensitivity is illustrated in Figure 7.6, where the curves marked A1 and B1 show the effect on O_3 caused by varying UV flux below 2550 Å. Photons with wavelengths less than 2550 Å produced odd oxygen through the photolysis of oxygen [see Reaction (7.1)], whereas photons in the entire wavelength region 1800–3000 Å are absorbed by ozone, causing the photolytic destruction of O_3,

$$O_3 + h\nu \rightarrow O + O_2.$$

Consequently, as illustrated in Figure 7.6, O_3 decreases above 30 km when the solar flux in the wavelength region 2550–3100 Å increases. The point illustrated by Figure 7.6 is that, before we can make any reliable estimates of ozone variability related to solar cycle, it is essential to know the spectral distribution of UV-flux variations.

Penner and Chang (1978) and Callis *et al.* (1979) calculated ozone and temperature variations over a complete solar cycle by letting the solar flux vary sinusoidally with an 11-year period. It is difficult to validate one-dimensional model predictions because the model represents annual global mean conditions, whereas the spatial coverage of observations is too poor to obtain global averages. Such limitations notwithstanding, comparison of model predictions with observations reveals areas of agreement and disagreement. Figures 7.7 and 7.8 compare Penner and Chang's model estimates for ozone change with those revealed by observed ozone records. Penner and Chang chose ozone records of North America and Europe for com-

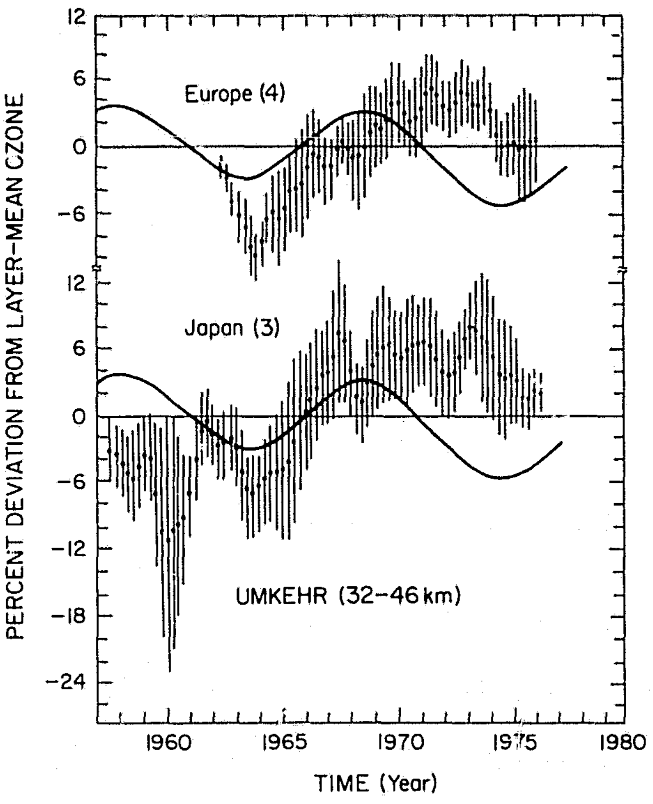


FIGURE 7.8 Comparison of calculated layer-mean ozone variations to the analysis of the Umkehr-measured variations for Europe and Japan by Angell and Korshover (1978a) (after Penner and Chang, 1978, reproduced with permission of the American Geophysical Union).

parison because these areas had the largest number of stations and were considered to be more reliable.

The model simulates the observed total ozone increase from the mid- to late-1960's and the reduction from 1969 onward. However, the decrease in the observed ozone record seems to have leveled off after 1972, a feature that is not simulated by the model. A similar discrepancy exists between the model and observations in the layer mean variation shown in Figure 7.8.

Figure 7.9 shows a comparison of a model with observations for the temperature variations. The model simulates both the amplitude and phase of temperature variations for the 26–35-km layer, but discrepancies exists for the upper layers.

Finally, there are postulated variations in the solar-UV flux associated with the 27-day solar-rotation period (Heath, 1973). The variation is maximum around 1100 Å (about 50 percent from maximum to minimum) and decreases with increasing wavelength to a value of about 1 percent at 20000 Å. Frederick (1977) computed the effects of this variation on the O_3 distribution. Because the shorter wavelengths (1500 Å) are absorbed mainly in the mesosphere, the effect on O_3 is mainly felt above 65 km, where O_3 decreases with increased solar-UV intensity. The maximum effect occurs at 75 km, where the computed ozone varies by 20 percent during a solar-rotation period. However, the temperature change induced by a 20 percent ozone variation in the upper mesosphere should have negligible effects on the lower atmosphere.

MODULATION OF NO

It was first proposed by Ruderman and Chamberlain (1975) that solar modulation of NO produced by galactic cosmic rays may be adequate to explain the ozone variations suggested by observations. Galactic cosmic rays produce NO in the stratosphere by ionizing the air (Warneck, 1972; Brasseur and Nicolet, 1973). There is a well-established variability in the ionization rates with the 11-year sunspot cycle (Crutzen, 1977). The ionization rate is low during sunspot maximum and high during sunspot minimum. Consequently, during solar maximum, production of NO is decreased, which causes a reduction in the rate of catalytic destruction of ozone. The cosmic-ray source of NO is smaller by about 30 percent at solar maximum than at solar minimum. This mechanism may explain qualitatively the observed variations of total ozone. But a follow-up study by Crutzen (1977) indicated that this mechanism can explain only 10 percent of the observed ozone variability (see Feshenfeld *et al.*, 1976; Ruderman *et al.*, 1976).

Solar-proton events also can modulate stratospheric NO production. Crutzen *et al.* (1975) estimated the production of NO through ionization of the air during solar-proton events to be significant enough to cause appreciable ozone reductions. For example, calculations by Heath *et al.* (1977) showed that the intense proton event of August 1972 caused an O_3 reduction of about 20 percent in the upper stratosphere (about 35–40 km). Heath *et al.* (1977) also demonstrated that their model calculations of O_3 reduction are in good agreement with satellite O_3 observations. The solar-proton events are of short duration (less than a week), and their effects on NO production are restricted to polar regions. However, since the lifetime of NO in the stratosphere is long (months or greater), the NO produced in the polar regions can be transported globally, resulting in a globalwide effect on ozone. But the dilution of NO caused by the transport would imply that the global-scale ozone perturbation would be considerably smaller than the local values estimated by Heath *et al.* (1977).

TROPOSPHERE EFFECTS

Ozone and temperature variations in the middle atmosphere may influence the climate of the troposphere through radiative and dynamic interaction between the troposphere and stratosphere (Figure 7.1).

RADIATIVE INTERACTIONS

Stratospheric ozone affects the solar and IR (terrestrial) radiative energy input to the troposphere. Solar absorption by stratospheric ozone modulates the amount of solar energy incident on the troposphere. Ozone also absorbs and emits IR radiation in the 9–10 μm spectral region. Absorption of solar radiation and absorption of 9–10 μm IR radiation (emitted by the troposphere) by the stratospheric ozone warms the stratosphere, which enhances the IR radiation emitted by the stratospheric gases, i.e., CO_2, O_3, and H_2O. The IR radiation emitted downward contributes to the tropospheric energy input.

Consequently, perturbation in stratospheric O_3 would perturb the IR solar-radiative energy input to the troposphere. In general, an increase in stratospheric ozone would decrease the solar radiation reaching the troposphere, causing a tropospheric cooling. On the other hand, because the stratosphere with increased ozone is warmer, the IR radiation emitted downward by the stratosphere to the troposphere is larger, which would tend to warm the troposphere. (The above sequence of events would operate in the reverse direction for a decrease in ozone.) The net effect depends critically on the vertical distribution of the ozone perturbation (Ramanathan and Dickinson, 1979). For a uniform increase (decrease) in stratospheric ozone, the IR warming (cooling) effect is slightly larger than the cooling (warming) by the decreased (increased) solar radiation incident on the troposphere. Calculations using a one-dimensional radiative-convective model by Ramanathan *et al.* (1976) showed that a 10 percent uniform increase (decrease) in stratospheric ozone warms (cools) the surface and troposphere by about 0.1 K.

Because the net effect of ozone change on the surface temperature depends strongly on the vertical distribution of ozone perturbation, it is difficult to extrapolate the results of Ramanathan *et al.*'s (1976) calculations to the type of ozone change estimated to occur from solar-variability effects. As mentioned earlier, the model results (Figure 7.4) indicate that hypothesized solar-variability effects on ozone are concentrated mainly above 25 km. For such a vertical distribution of ozone increase (or decrease), the IR warming (cooling) effect would be smaller because any change in the IR emission above 25 km would be absorbed within the lower stratosphere and hence would not penetrate to the troposphere. It is difficult to guess even the

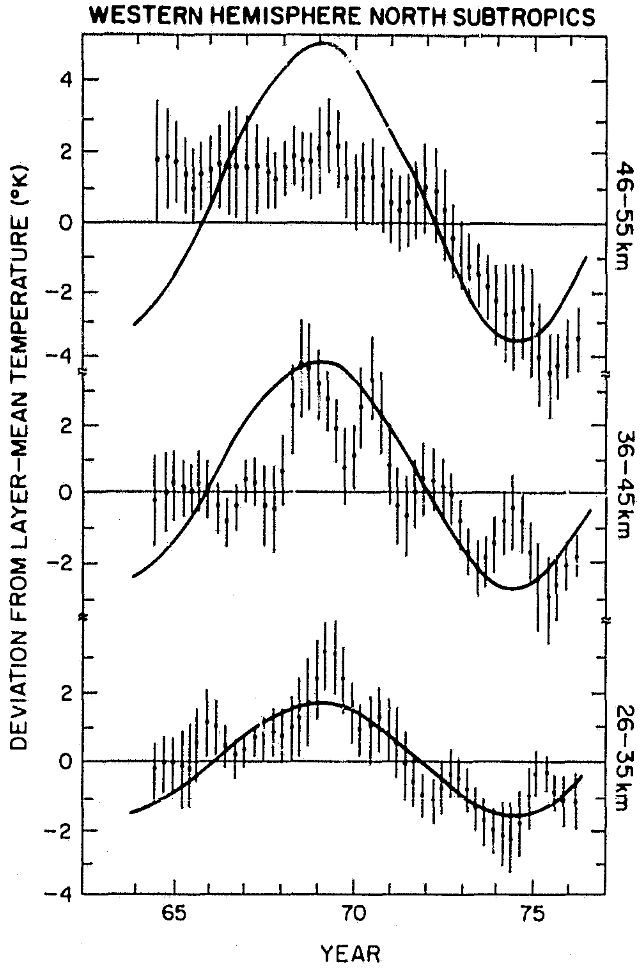


FIGURE 7.9 Comparison of calculated layer-mean temperature changes to the analysis of rocketsonde-measured temperature changes for the north subtropics of the western hemisphere by Angell and Korshover (1978b) (after Penner and Chang, 1978, reproduced with permission of the American Geophysical Union).

sign of the effect on the troposphere without performing actual model calculations. However, such calculations may not be necessary because the hypothesized variations in total ozone content are small. Model calculations and analyses of ozone records discussed earlier indicate a maximum variation of about 5 percent in the total ozone from solar maximum to solar minimum. From calculations of Ramanathan *et al.* (1976) we estimate that a 5 percent variation in total ozone may cause a maximum effect of 0.05 K (either cooling or warming) on the surface temperature, which of course should be considered a negligible effect. A more detailed review of the ozone–climate problem is given in Ramanathan (1980).

DYNAMIC INTERACTIONS

The mechanisms by which changes in the middle atmosphere can be transmitted to the troposphere by dynamic coupling are described in Chapter 3 of this volume and, hence, will not be discussed here. We will discuss the possible effects of solar variability on those features of the middle atmosphere that determine the dynamic coupling mechanisms.

Above 20 km in the stratosphere, the zonal winds and the latitudinal temperature gradient undergo significant seasonal variations. During winter the temperature decreases from equator to pole, accompanied by strong westerly winds (i.e., blowing from west to east). This pattern reverses in summer, i.e., pole-to-equator temperature gradient and easterlies. These seasonal reversals are primarily determined by the latitudinal distribution of ozone solar heating. In addition, the vertical temperature gradient above 20 km at most latitudes is primarily determined by the corresponding vertical distribution of ozone solar and IR heating. As discussed earlier, the zonal wind distribution and the vertical temperature gradient play an important role in determining the transmissivity of the stratosphere to upward-propagating planetary-scale waves.

For ozone variations that are hypothesized to occur during galactic cosmic rays and solar-proton events, the resulting influence on the latitudinal and vertical gradients of solar heating seem to be too small to influence either the latitudinal or vertical gradient of temperature. On the other hand, solar-UV-flux variations with magnitudes similar to those proposed by Heath and Thekaekara (1977) can have substantial effects on both the latitudinal and vertical gradients of heating rates. For example, from Figure 7.4, we estimate that the vertical temperature gradient between 20 and 40 km changes by about 20 percent from solar minimum to solar maximum. (Recall that the UV-flux variation adopted for the results in Figure 7.2 is substantially smaller than that proposed by Heath and Thekaekara.) Similar changes can be expected in the latitudinal gradient of solar heating.

The calculations of Callis *et al.* (1979) suggest that at 45 km, for globally averaged conditions, the solar heating rate varies from about 8.5 K per day to about 11.5 K per day from solar minimum to solar maximum. Changes in globally averaged solar-heating rates would in general be accompanied by changes in the latitudinal gradient of heating. For example, during winter when solar heating is zero at the poles, the equator-to-pole gradient of solar heating will change with a change in the globally averaged solar heating.

RADIATIVE-PHOTOCHEMICAL DISSIPATION

Because the planetary waves are planetary-scale pressure perturbations, they are also associated with temperature perturbations. These temperature perturbations are damped by long-wave-radiation emission. The rate at which radiation damps these waves (the so-called Newtonian cooling coefficient) increases with altitude from about 0.02 day^{-1} in the lower stratosphere to about 0.2 day^{-1} in the upper stratosphere. Within the upper stratosphere the rate of radiative damping is significantly accelerated by the coupling of O_3 chemistry and temperature. O_3 production in the upper stratosphere depends primarily on photolysis of O_2, which is weakly temperature dependent, but the O_3 destruction processes are strongly temperature dependent. Increased temperatures, for example, en-

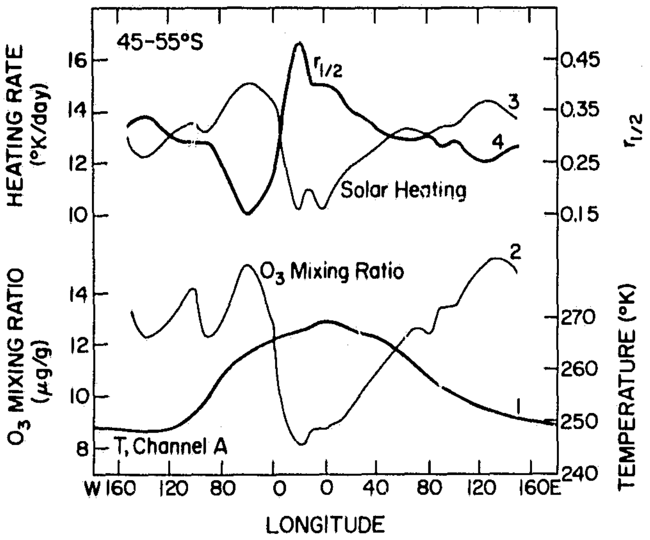


FIGURE 7.10 Longitudinal variations in midlatitude southern hemisphere springtime O_3 and temperature (at 2 mbar) as measured by Nimbus IV and the corresponding variation in the 1-mbar to 2-mbar ozone mixing ratio ($r_{1/2}$). Computed longitudinal variations in solar heating are also shown (from Ghazi *et al.*, 1979, reproduced with permission of the American Geophysical Union).

hance destruction of odd oxygen through chemical processes that depend on activation energy, with a consequent reduction in O_3. The reduction in O_3 decreases O_3 solar heating, which tends to dampen the initial positive temperature perturbations. Several theoretical studies (e.g., Blake and Lindzen, 1973) have indicated that this radiative-photochemical coupling accelerates the upper-stratospheric radiative damping by a factor of 2. Recently, Ghazi *et al.* (1979) made model calculations of longitudinal variations in solar heating from satellite observations of longitudinal variations in O_3 at 2 mbar for 45–50° S latitude during spring. Their calculations, shown in Figure 7.10, suggest that the negative correlation between longitudinal O_3 variations and temperature variations doubles the radiative damping rate at 2 mb, which confirms the earlier results based on theoretical model calculations. This aspect of the problem is being mentioned because the postulated solar-UV variability associated with the 11-year sunspot cycle will modify the magnitude by which radiative-photochemical coupling accelerates the radiative damping rate. For example, a fixed increase in O_3 (associated with negative temperature perturbation of the planetary waves) will cause a larger increase in solar heating during UV maximum than UV minimum. This effect is of importance primarily in the upper stratosphere where most of the O_3–UV absorption takes place.

CONCLUSIONS

Postulated mechanisms linking solar variability with observed variations in stratospheric ozone and temperature consist of two categories: (1) variations in solar-UV flux in the 1700–3000 Å spectral region associated with the 11-year sunspot cycle and the 27-day solar rotation period and (2) solar modulation of the production of NO by galactic cosmic rays and solar-proton events. The estimated magnitude of ozone and temperature variations in the middle atmosphere caused by the second category seems too small to have nonnegligible effects on the troposphere.

Variations in solar-UV flux can have significant influence on the temperature and ozone of the middle atmosphere, provided the magnitude of UV variations is as large as that suggested by Heath and Thekaekara (1977). The perturbations in the solar and IR radiative energy input to the troposphere caused by the above variations in stratospheric ozone and temperature are small and have negligible effects on the tropospheric climate. However, the perturbations in latitudinal and vertical gradients of solar heating caused by UV-flux variations above 30 km may have a nonnegligible influence on the tropospheric circulation through dynamic coupling mechanisms. The magnitude of such effects cannot be estimated at this time because of the lack of detailed model studies.

Unfortunately, as pointed out by Heath (1977), the solar variations in the 1750–3000 Å region are poorly understood, and the suggested variations by Heath and Thekaekara are considered controversial by their colleagues. Clearly, more work needs to be done before the magnitude of the variations can be well established. Such an endeavor seems particularly worthwhile because of the potential effects of UV variability in the climate of the middle atmosphere.

ACKNOWLEDGMENTS

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Solar–Terrestrial Effects on the Global Electrical Circuit

8

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Since the earliest studies of atmospheric electricity, there have been many attempts to ascertain a solar–terrestrial relationship correlating ground currents, electric fields, and thunderstorm frequency with aurorae and variations in solar activity. Ground-based aircraft and balloonborne instruments have detected atmospheric electrical responses to solar flares, solar-cycle variations, solar magnetic-sector boundary crossings, geomagnetic activity, and even auroral displays. Often these solar- and upper-atmosphere-induced variations of the global atmospheric electrical circuit are difficult to identify because they are superimposed on complex electrical variations associated with meteorological and anthropogenic processes in the lower atmosphere.

Recently, atmospheric electricity has received renewed interest as a solar–terrestrial coupling mechanism (and a possible sun–weather coupling mechanism) because it may bypass many of the theoretical difficulties associated with dynamic coupling between the upper and lower atmosphere (Markson, 1971). For example, atmospheric heating caused by solar flares and auroral activity produces large global dynamic responses in the neutral thermosphere, as discussed by Roble (1977); however, at a few scale heights below the thermosphere, the heating is believed to be too small to produce any dynamic perturbations. On the other hand, upper-atmospheric electrical effects—such as the generation of large horizontal-scale potential differences by the magnetosphere, particularly at high latitudes, and changes in electrical conductivity caused by changes in cosmic rays or by ion production from energetic particle precipitation—may perturb both the electric current and the field patterns of the global circuit that is mainly established by thunderstorms. If these perturbations in lower-atmospheric electrical properties somehow affect cloud microphysical processes, thunderstorm-charging mechanisms, or thunderstorm-current output, there might be a way in which solar–terrestrial variations modulate the internal energy of clouds or thunderstorms (Sartor, 1965, 1980; Markson, 1971, 1978, 1979; Herman and Goldberg, 1978; Markson and Muir, 1980). Furthermore, these authors suggest that a modulation of large-scale convective systems could in turn drive the tropospheric circulation changes. The entire chain from solar–terrestrial electrical effects to changes in tropospheric forcing is complex and difficult to establish. This report considers the evidence of a solar–terrestrial effect through changes in atmospheric electric fields and currents but not the connection to cloud microphysics or possible changes in tropospheric forcing.

GLOBAL ELECTRICAL CIRCUIT

According to the "classical picture" of atmospheric electricity (Dolezalek, 1972), the totality of thunderstorms acting together at any given time charges the ionosphere to a positive potential of several hundred thousand volts with respect to the Earth's surface. This difference in potential drives a vertical electrical current from the ionosphere to the ground in all nonthunderous or fair-weather regions. The fair-weather electrical current varies according to the ionospheric potential and the total columnar resistance between the ionosphere and the ground. The global electrical circuit is shown in Figure 8.1. Dolezalek (1972) indicated that the vagueness in the words "classical picture" is deliberate because, as yet, there is no experimental proof for the concept. The fundamental problem of atmospheric electricity is determining the origin of the electrical current flowing in the atmosphere. The consensus of most atmospheric scientists is that the worldwide network of thunderstorms does act to maintain the global fair-weather electrical current; however, this concept has not been proven, and there are still many difficulties associated with it, as described by Dolezalek (1972) and Orville and Spencer (1979).

In the classical picture, the thunderstorm acts as a generator in the global circuit and provides a net current, which in the average flows upward from a cloud top toward the ionosphere and upward from the ground into a cloud base. The current flowing upward from the top of a thundercloud is all conduction current because cosmic-ray-induced ionization maintains relatively high conductivity in the upper atmosphere.

Our knowledge of the magnitude of these upward conduction currents is not very reliable. Estimates based on aircraft measurements over thunderstorms indicate that currents of between 0.1 and 6 A (average value 0.5–1 A) per thunderstorm are flowing upward toward the ionosphere. More recently, balloonborne sensors at an altitude of 35 km have been used to detect regions of upward-flowing currents from thunderstorm areas (Holzworth, 1981).

The number of thunderstorms acting simultaneously at any given time is also uncertain, but recent estimates are between 1500 and 3000 A. If each thunderstorm cell produces a mean current of 0.5–1 A, the global current can be estimated at 750–3000 A. There are secondary local and regional current generators also acting at any given time, such as showers, continuous rain, sandstorms, and snowstorms. These secondary generators produce local effects and are not believed to be coupled to the upper atmosphere and the global circuit.

The estimates of currents flowing from the ground into the bases of thunderstorms are even more uncertain on a global scale. The electrical charge released from the ground by point or corona discharge (e.g., from trees, bushes, grass, and buildings) underneath a thunderstorm plays a dominant role in the transfer of charge between the Earth and thunderstorms. In addition, lightning and precipitation currents, which can be in either the same or opposite direction, are important charge-transfer mechanisms. One recent estimate by Mühleisen (1977) is that global corona currents carry about 700 A and that the total lightning current at any time is about 400 A.

These upward currents are counteracted by a downward precipitation current of about 200 A, leaving a new upward current of about 900 A from all sources. The total currents into thunderstorms should balance the currents flowing back to the Earth in fair-weather regions. Mühleisen (1977) emphasized that all of these values are questionable and should be updated continuously as new information becomes available and subdivided for moderate, tropical, and subtropical climates. There is also need to continue monitoring the number of lightning flashes on a global scale (Turman, 1978; Orville and Spencer, 1979). Furthermore, many questions remain about the current output of thunderstorms, which is one of the most important

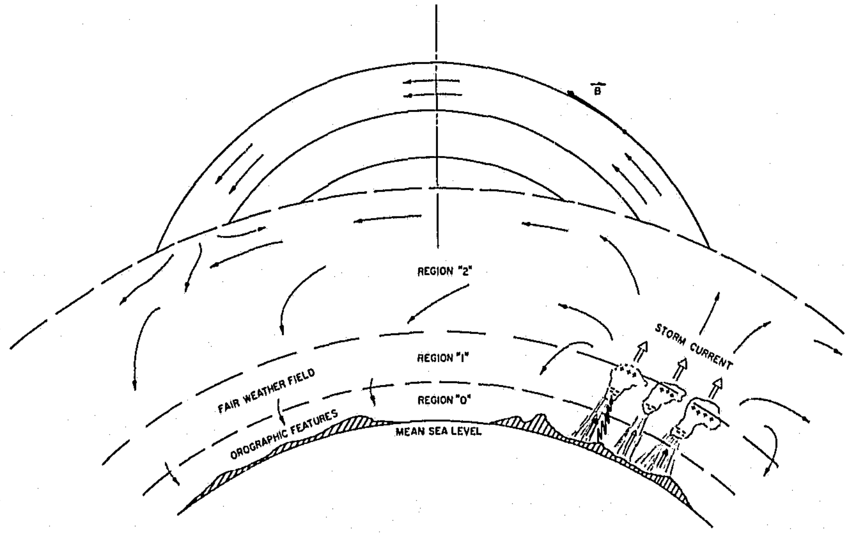


FIGURE 8.1 Schematic diagram of a global electrostatic model of atmospheric electricity. Vector B illustrates the Earth's geomagnetic field line (from Hays and Roble, 1979, with permission of the American Geophysical Union).

parameters in the global atmospheric circuit. For example, do lightning-intensive tropical thunderstorms have a larger or smaller output than thunderstorms in moderate latitudes? And is there a greater output from mountain thunderstorms than from, say, oceanic thunderstorms?

It is easier to estimate the local power of the global circuit outside of the generator area. The current density over land varies greatly with local terrain; however, measurements indicate a current density of about 10^{-12} A/m^2 over inhabited and industrialized areas and about 2–4 × 10^{-12} A/m^2 over vegetated grounds and deserts. The values over the oceans have been estimated to be 2.5 × 10^{-12} A/m^2 for the Pacific Ocean and 1.6 × 10^{-12} A/m^2 for the Atlantic Ocean, with the difference attributed to greater air pollution over the Atlantic. The current density on high mountain peaks should be much greather than that at sea level. The columnar resistance over mountainous areas is much smaller than over flat land, and as much as 20 percent of the global current may stream toward high mountain peaks.

Columnar resistance is an important element in the global atmospheric electrical circuit, especially with respect to possible solar–terrestrial effects. The conductivity of the atmosphere is primarily maintained through the ionization of atmospheric gases by galactic- and solar-cosmic radiation. Near the surface of the Earth, there is an additional component due to ionization associated with the radioactive decay of certain crustal materials. The columnar resistance is the vertical integral of the specific resistivity at any given location between the ground and the ionosphere. Because the conductivity of the atmosphere increases nearly exponentially with altitude, the bulk of the total columnar resistance occurs in the lower atmosphere, with 90 percent of the total resistance below 10 km. Figure 8.2 shows the percentage of columnar resistance in different atmospheric layers and the percentage of variation of ionospheric potential with altitude (Markson, 1976). Only 10 percent of the total columnar resistance and ionospheric potential occurs above 10 km, where large variations in ion production may result from known solar–terrestrial influences, such as polar-cap-absorption events (Reid, 1974) and auroral ionization. Because stratospheric and mesospheric conductivity affects less than 10 percent of the total columnar resistance, large variations in upper-atmospheric conductivity are generally believed to result from solar–terrestrial influences, which may occur without greatly affecting the global resistance. However, during solar flares, the hard component of the cosmic-ray flux that maintains the electrical conductivity of the troposphere is known to vary, producing ground-level events that have time scales of hours and cosmic-ray decreases (Forbush decreases) with time scales of a few days (Forbush, 1966; Pomerantz and Duggal, 1974). Forbush decreases are more frequent with percentage decreases that vary from 1 to 20 percent. A typical value for the global resistance is 270 Ω when mountains are considered. The resistance of the Earth without mountains would be 70 Ω greater.

On the basis of these estimates of the global current and total global resistance, the ionospheric potential would vary between 70 kV and 800 kV. The average of the measurements reported by Markson (1976) and Mühleisen (1977) is 240 kV. Markson's measurements show considerable variation from day to day and even hour to hour, indicating the workings of complex generators and loads in the global electrical circuit.

All of the atmospheric elements of the global circuit have some type of diurnal variation. The global ionospheric potential, the air–earth current, and the potential gradient in the free atmosphere above the exchange layer all have a diurnal variation in universal time (UT) (see Anderson, 1969; Markson,

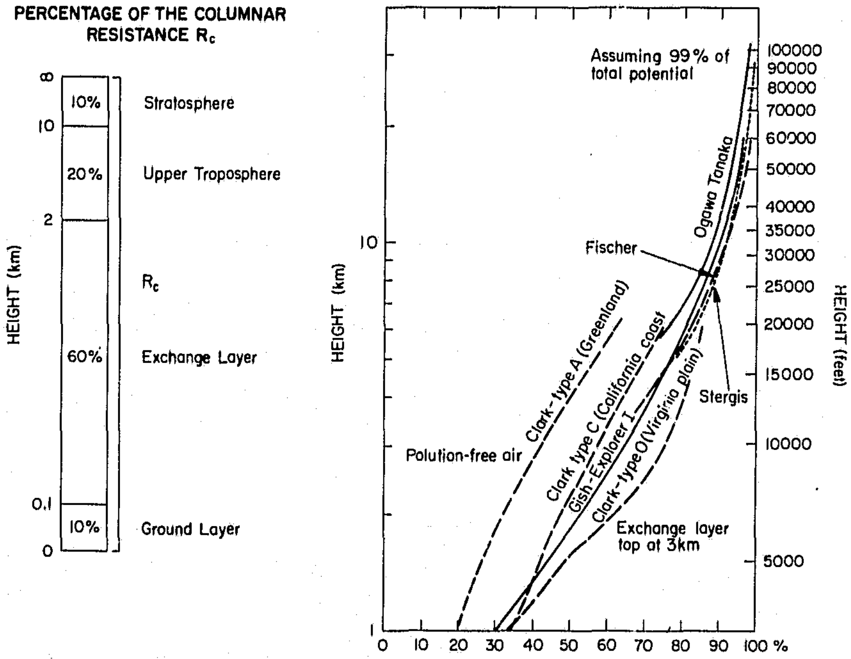


FIGURE 8.2 Percentage of the total columnar resistance, R_c, in various altitude intervals (Mühleisen, 1977). Percentage of variation of ionospheric potential with altitude (from Markson, 1976, with permission of the American Geophysical Union).

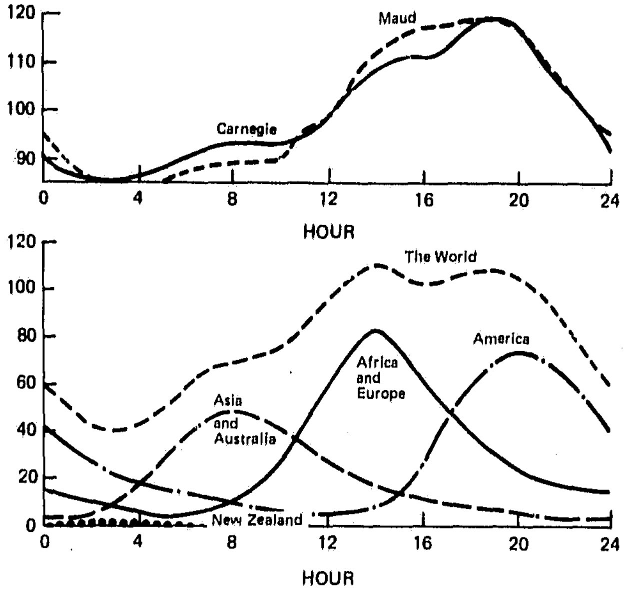


FIGURE 8.3 Diurnal UT variation of normalized electric field intensity over oceans, percentage variation (top), and diurnal UT variation of land thunder area (× 10^4 km^2) (bottom) (Chalmers, 1967).

1976). A universal time variation of atmospheric electrical parameters was first defined by measurements aboard the Carnegie Magnetic Survey Ship expedition in 1928–1929. Statistically, the minimum values occur near 0400 UT, whereas the maximum values occur near 1900 UT. This diurnal variation is difficult to measure from the ground because of temporal variations in space charge and conductivity in the air near the Earth's surface. Whipple and Scarse (1936) showed that the global diurnal variation of the number of thunderstorms in universal time has a similar shape to the Carnegie measurements, as shown in Figure 8.3. The peak in thunderstorm area occurs near 1900 UT, when the combined effect of thunderstorms on the American and African continents maximizes during the local afternoon hours. The corresponding minimum occurs when maximum heating occurs over the Pacific Ocean, where the effects of intense continental heating are absent. The correspondence between the universal diurnal variation of measured electrical parameters and thunderstorm area has been considered the strongest argument for the theory that thunderstorms act as generators in the classical picture of atmospheric electricity.

A common measurement in atmospheric electricity is the potential gradient or electric field at the Earth's surface. This parameter is highly variable and is dependent on such factors as meteorological influences, air pollution, clouds, and orography. Under thunderstorms, the electrical potential decreases with altitude, suggesting a current flow into the storm. In fair-weather regions away from local influences, the electric potential increases with altitude, indicating a current flow to the ground. Near the equator at sea level, the Carnegie ship in 1928–1929 measured a potential gradient of 120 V/m, which increased with latitude to values near 155 V/m at 60° N and S latitudes. This variation with latitude is consistent with what one expects from variations in conductivity due to the magnetic latitude shielding effect of cosmic-ray production (Israël, 1973). The potential gradient also decreases with altitude.

Another important parameter of the global electrical circuit is the relaxation time at various altitudes; this is the "switch-on" time for the establishment of a final steady state from an arbitrary initial state. In the upper atmosphere near 70 km, it is 10^{-8} sec, at 18 km about 4 sec, and near the Earth's surface about 20 min. The relaxation time at the Earth's surface is about 10^{-5} sec. The electrical circuit of the Earth has been described as a spherical capacitor with the atmosphere as a dielectric between two highly conducting plates—the ionosphere and the Earth's surface. If all thunderstorms suddenly ceased operating, the global circuit would discharge to 1/e in 20 min. As this has never been observed to happen and variations are only about 20 percent of the mean, thunderstorms must be operating continuously over the Earth's surface.

MEASUREMENTS OF SOLAR–TERRESTRIAL INFLUENCES ON ATMOSPHERIC ELECTRICITY

The possibility that aurorae may affect the Earth's atmospheric electrical circuit has been considered since the early days of atmospheric electricity studies. Wijkander (1874) indicated that the onset of the northern lights caused the air at Spitzbergen to become negatively charged, and Andrée (1890) reported that the fair-weather electric field diminished during active auroral periods and then recovered to initial values a few hours later. Israël (1973) reviewed the evidence for solar–terrestrial influences in measurements of the ground electric field. His review indicates that "terrestrial periods," which include diurnal and annual periods, are strongly evident in the data but that "cosmic periods," such as the 27-day and 11-year periods, are evident only weakly, if at all. Many of the more recent statistical studies correlating thunderstorm frequency with solar flares, solar magnetic-sector boundary crossings, and others have been reviewed by Markson (1971, 1978) and Markson and Muir (1980).

There are a number of measurements of electrical variations that suggest a solar–terrestrial influence on the global atmospheric electrical circuit. The measurements show variations associated with solar fares, solar magnetic-sector boundary crossings, geomagnetic activity, aurorae, differences between high and low latitudes, and solar-cycle variations. The evidence for each variation is examined below.

SOLAR FLARES

One of the earliest investigations of the effects of solar activity on atmospheric electricity was that of Bauer (1924), who found that the electric field at the ground increased during periods of increased "sunspottedness." Reiter (1969) reported that the daily means of the ground potential gradient, *E*, and air–earth current, *i*, increased from the first day a solar flare appeared until the fourth day, when they attained maxima. Reiter's measurements were made from a mountain station at Zugspitze, West Germany (2964 m), where 70–80 percent of the columnar resistance between the ionosphere and the Earth's mean sea-level surface is below the station. Therefore, measurements of *E* and *i* were not greatly influenced by variations in columnar resistance, and the influence of solar events could be studied. Measurements made over the past 20 years have consistently shown a significant increase (about 50–60 percent on the average) in both the air–earth current and the potential gradient at the station following solar flares. Figure 8.4 shows a superposed epoch analysis of *E* and *i* following Hα solar flares occurring near the central meridian of the sun (between 20° W and 20° E) from February 1967 to May 1969. Both *E* and *i* clearly show an increase for two or three days following the flare onset, with a gradual return to preflare conditions a few days later.

Cobb (1967), making measurements from the low-latitude station on Mauna Loa, Hawaii (4170 m), also found evidence of a solar influence on the atmospheric electrical elements. During a 1-year measurement period beginning in September 1960, there were times of considerable solar activity, with 28 solar flares of Class 3 or greater and 42 magnetic storms. Following a solar-flare eruption, the air–earth current increased an average of 11.7 percent from its established normal values (see Figure 8.5). In approximately 80 percent of the cases, this increase occurred in the first 24 h after a flare. Sartor (1980) also reported a similar solar-flare effect on the electric field as measured at Niwot Ridge, Colorado (3744 m).

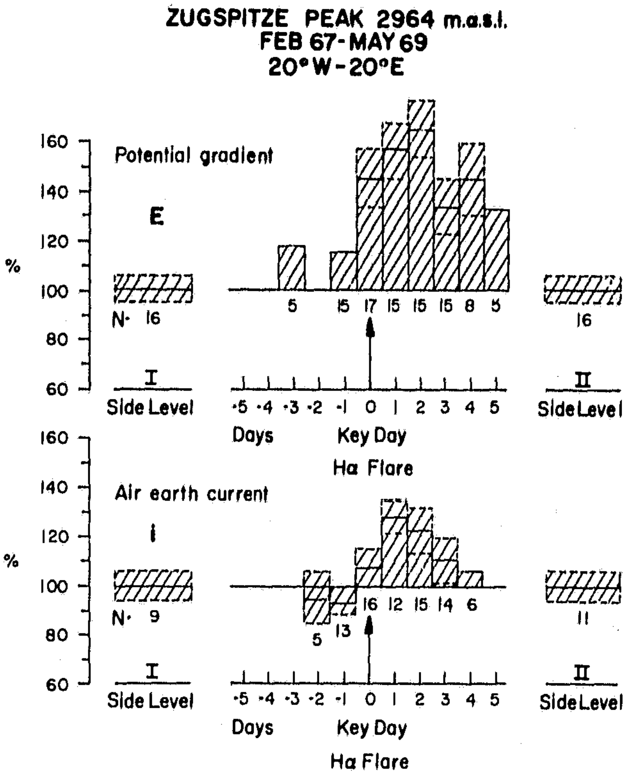
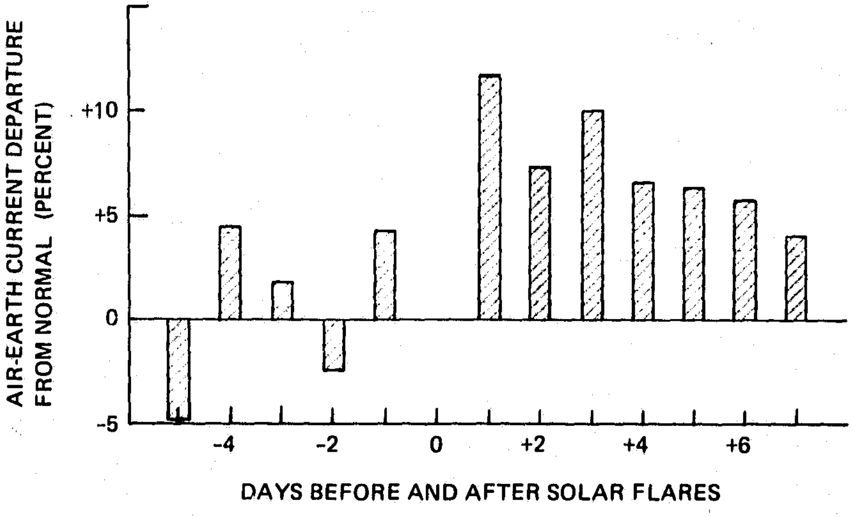


FIGURE 8.4 Grouping of hourly means (percentage) of electric field (top) and air–earth current (bottom) around flare days during 3 years of generally low solar-activity levels (1964–1967) as measured at the Zugspitze stations (Reiter, 1969).

Recent balloon measurements in the high-latitude stratosphere also have shown electrical responses to solar activity. Holzworth and Mozer (1979) showed that solar-controlled ionizing radiation can have large effects on the electrical conductivity down to at least 15 km at geomagnetic high and midlatitudes. The large measured increase in electrical conductivity corresponded with a decrease in the vertical electric field measured during the August 1972 polar-cap-absorption event. Cobb (1978) made balloon measurements of the air–earth current density at the South Pole before and after a solar flare. Balloonborne sensors were released at approximately 0300 UT each day for five consecutive days during the period November 22–27, 1977. The measured air–earth current density profiles are shown in Figure 8.6. The first balloon was released at 0255 UT on November 22, 1977, 7 hours before a solar flare occurred,

FIGURE 8.5 Average daily departure from normal of the fair-weather air–earth current before and after solar flares (Cobb, 1967).



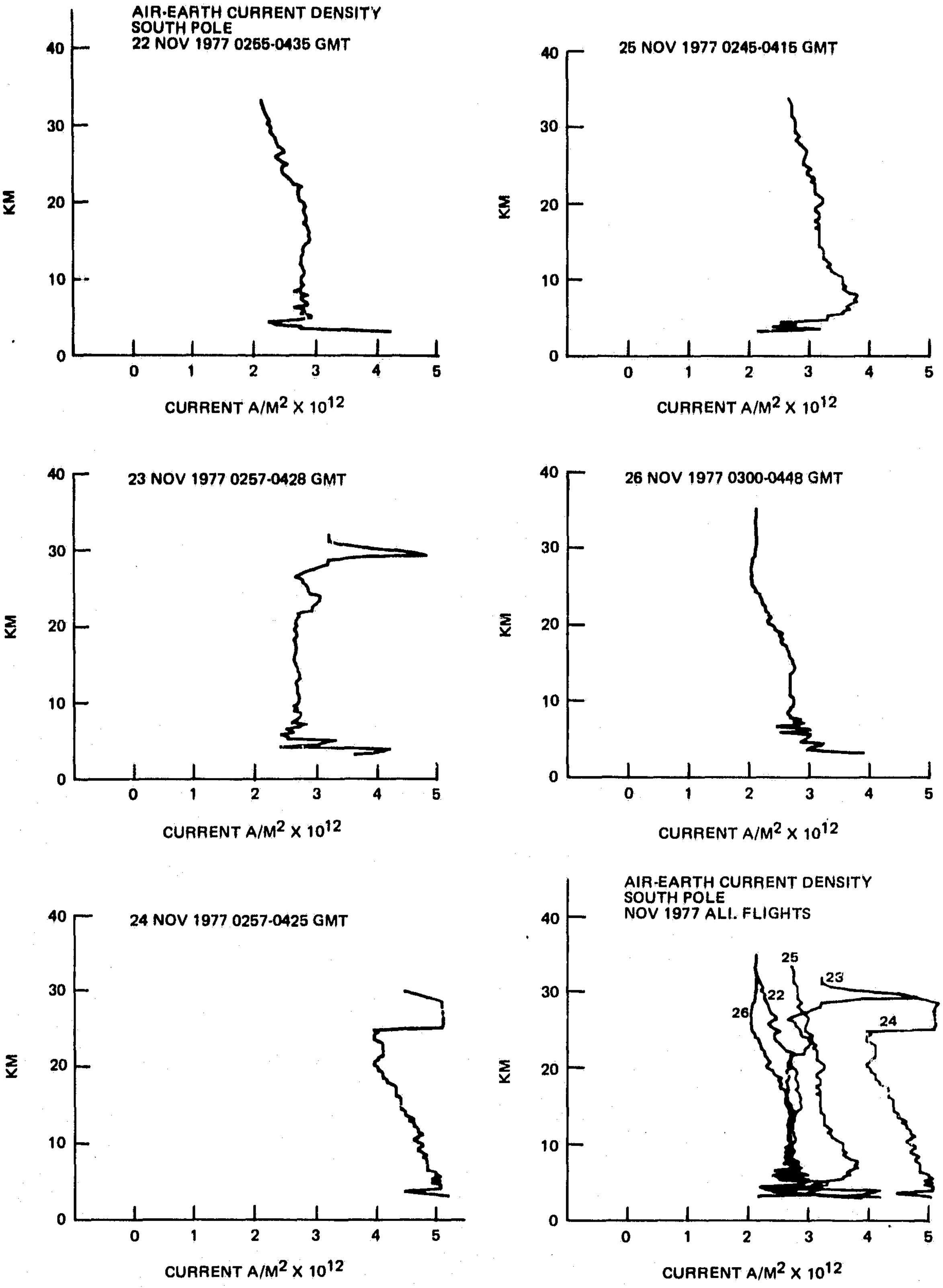


FIGURE 8.6 Air–earth current densities measured during balloon flights from the South Pole during November 22–26, 1977. A solar flare occurred at 0945 UT on November 22 (after Cobb, 1978).

and the measured air–earth current density was typical of other balloon measurements made by Cobb (1977). The second balloon was released about 17 hours after the solar flare, and through the first 25 km the current was nearly identical with the first flight. However, above 25 km the measured air–earth current was much higher. It is not clear whether the abrupt increase was due to a space charge encountered or to a temporal effect, as the balloon takes time to rise through the layer. The following day the entire air–earth current density profile was enhanced by 70 percent from preflare conditions. Two days later the measured air–earth current density profile returned to preflare conditions. Mühleisen (1971) also showed that the ionospheric potential difference inferred from measurements made at widely separated mid- and low-latitude stations is generally small. However, during one strong solar event, he found a 60-kV ionospheric potential difference between two stations.

These measurements strongly suggest a solar influence on the parameters of the global electrical circuit. Through the years there have also been many reports relating increased thunderstorm frequency to solar flares (e.g., Markson, 1978, 1979, for a review). The main question is: Can the observed effects be caused by changes in electrical conductivity alone, or is it necessary to involve changes in the thunderstorm generators to account for the observed effects?

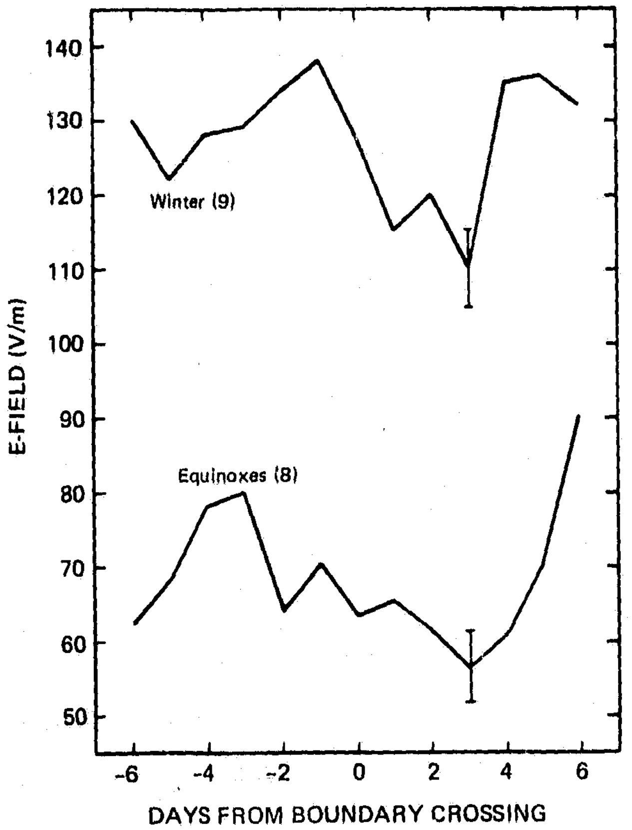


FIGURE 8.7 Average behavior of the Vostok electric field at the approximate times of solar magnetic-sector boundary crossings for winter and equinox data. The numbers in parentheses indicate the number of cases (from Park, 1976a, with permission of the American Geophysical Union).

SOLAR MAGNETIC-SECTOR BOUNDARY CROSSINGS

Markson (1971) first called attention to the effects of solar magnetic-sector boundary crossings on atmospheric electrical parameters and possible increases in thunderstorm frequencies. Since then, Park (1976a) and Reiter (1977) both reported variations in the measured air–earth current and the potential gradient at the ground during solar magnetic-sector boundary crossings. Park's measurements of the atmospheric electric field were made during the period March–November 1974 at Vostik, Antarctica (78° S, 107° E), which is at the south geomagnetic pole. Although he obtained only 17 measurements during solar magnetic-sector boundary crossings, his results show that the electric field is depressed by about 15 percent 1–3 days following the passage of solar magnetic-sector boundaries, and the effect is more pronounced in the austral winter, when Vostok is in continuous darkness (see Figure 8.7). Figure 8.7 also shows a large seasonal variation, with the field being much stronger in winter than during equinoxes. No significant difference was found between the away-to-toward sector boundaries and the toward-to-away sector boundaries.

Reiter's (1977) measurements were made from the high mountain observatory at Zugspitze, West Germany, over a period of one solar cycle. His results show that, in cases when the magnetic-field polarity changes from toward the sun to away from the sun, the ionospheric potential significantly decreases on the day before and, on the day after the passage, it increases by about 20 percent. If the magnetic polarity changes from away from the sun to toward the sun, the ionospheric potential is again observed to change: on the first and second days prior to the passage it is clearly decreased, whereas on the day of the passage it is already back to normal. The amplitude of the variation for this case is 10 percent. Figure 8.8 summarizes the E and i variations during a sector boundary passage, along with several parameter variations determined from other studies such as the beryllium-7 concentration at Zugspitze, the vorticity area index, and the K_p variations inferred during passage of magnetic-sector boundaries.

GEOMAGNETIC ACTIVITY

Cobb (1967) showed that the monthly variation of the air–earth current from mean values at Mauna Loa, Hawaii, is correlated with Bartel's magnetic character index, C_p. Such a correlation for the period September 1960–September 1961 is shown in Figure 8.9. There is good correlation between the most "magnetically disturbed" months of October and July and the least disturbed months of January and August. Cobb also compared the daily variation of C_p and measured the air–earth current density; although the overall correlation is not as good as for the monthly variations, there appear to be interesting upper-

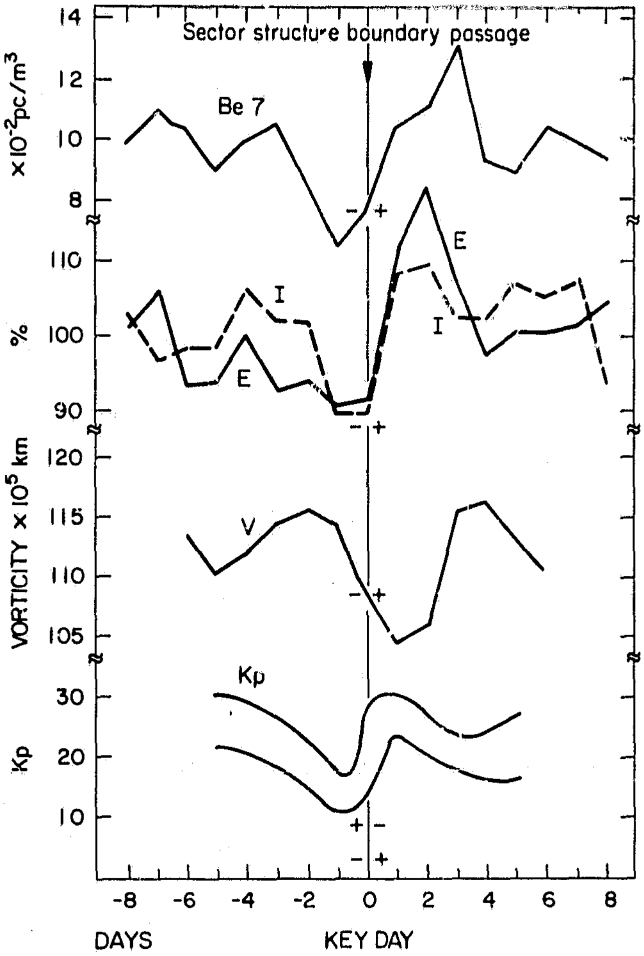


FIGURE 8.8 Comparison of several superposed epoch analyses: concentration of beryllium-7 (Be-7) in air at 3 km above sea level, key day −/+, period 1973–1974; electric field, *E*, and air–earth current density, *I*, at 3 km above sea level, key day −/+, period 1967–1971 with maximum solar activity; northern hemispheric vorticity area index, *V*, key day −/+, period 1964–1970; and planetary magnetic-field index, K_p, sector-boundary passage, irrespective of polarity, period 1967–1969 (Reiter, 1977).

atmospheric effects influencing the electrical parameters at low altitudes.

Märcz (1976) also reported a measured increase of the ground electric field for several days following high ionospheric absorption events associated with geomagnetic activity. Measurements made from observatories near Nagycenk, Hungary, and Swider, Poland, showed an increase of 12–46 percent (depending on the time of day) in the potential for several days following high-absorption events.

AURORAL EFFECTS

On the whole, the available data on the influence of aurorae on ground potential gradient and air–earth current are inadequate and contradictory. During the Second International Polar Year (1932–1933), Israël (1973) found that the potential gradient and air–earth current both experience a fluctuating variation with an aurora: a peak of approximately 155 percent of the mean value occurs 6–8 minutes before the aurora, and a minimum value of some 65 percent occurs 10 minutes after onset. More recently, Freier (1961), Olson (1971), and Lobodin and Paramonov (1972) reported auroral effects on vertical electric fields measured on the ground. In general, they reported a decrease in the electric field that later recovers to pre-auroral conditions. Figure 8.10 shows the results of Lobodin and Paramonov (1972), who examined electric-field data from eight high-latitude stations. Seven of the stations were in the northern hemisphere between 41°41′ N and 80°37′ N. One station was located in the southern hemisphere at 66°33′ S. The results from the northern hemisphere stations showed that appreciable variations of electric field begin 3–4 hours before the onset of an aurora and last up to 3 hours after its appearance. The mean decrease in *E* during the aurora is 23–32 percent for continental stations and 8 percent for the eastern Siberia Sea. In the southern hemisphere the potential gradient increased by 36 percent of the mean. In the northern hemisphere the decrease averaged 4 percent for weak aurorae, 6 percent for medium aurorae, 14 percent for strong aurorae, and 20 percent for very strong aurorae.

Shaw and Hunsucker (1977), on the other hand, analyzed measurements of the ground electric field and found no auroral effects at College, Alaska (65° N), even when the ionosphere is disturbed and there is violent visual auroral activity.

DIFFERENCE BETWEEN HIGH AND LOW LATITUDES

Kasemir (1972) examined the atmospheric electric field, current, and conductivity data recorded during the International Geophysical Year in 1958 at Thule, Greenland (78° N), which is near the north magnetic pole. He also examined atmospheric electric-field measurements made during the International Year

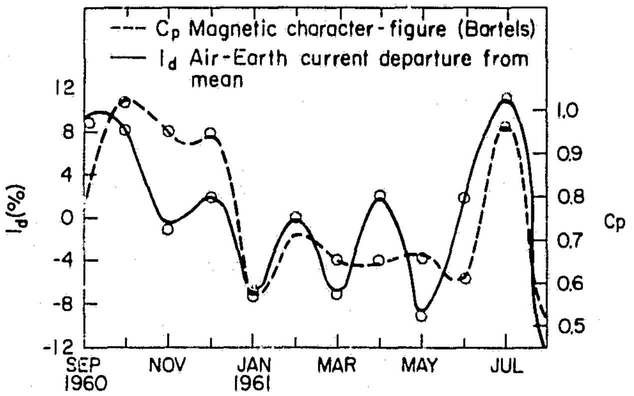


FIGURE 8.9 Monthly variation of air–earth current departure from mean at Mauna Loa, Hawaii, and the Bartels magnetic character-figure from September 1960 to September 1961 (from Cobb, 1967, reproduced with permission of the American Meteorological Society).

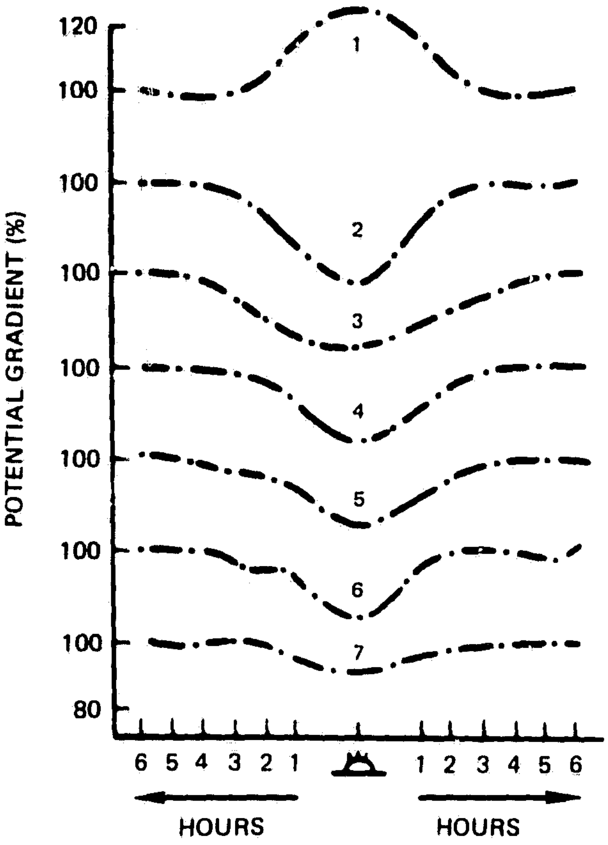


FIGURE 8.10 Potential gradient variation during aurorae: (1) Mirny Observatory (66°33′ S, 93°00′ E), (2) Kheis Island (80°37′ N, 58°03′ E), (3) Cheluskin Cape (77°43′ N, 104°17′ E), (4) Uakutsk (62°05′ N, 125°45′ E), (5) Leningrad (59°48′ N, 30°18′ E), (6) Vysokaya Dubrava (56°44′ N, 61°04′ E), and (7) Tbilisi (41°41′ N, 44°57′ E) (Lobodin and Paramonov, 1972).

of the Quiet Sun in 1964 at the Amundsen–Scott station at the South Pole. The diurnal UT variation averaged over the year of the normalized current at Thule and the normalized field at the South Pole show surprisingly good agreement. Compared with the oceanic diurnal UT variation at low and midlatitudes measured during the cruises of the Carnegie Institution's ship, the polar curve shows a similar shape but a much reduced amplitude (see Figure 8.11). The maximum and minimum in the polar regions are 1.07 and 0.92 of the mean, whereas the corresponding values on the oceans are 1.20 and 0.85. The cause of the approximately 30 percent reduction in the diurnal amplitude is not known; however, Kasemir (1972) suggested that there is a strong possibility that an agent other than worldwide thunderstorm activity may modulate the electrical circuit at high latitudes.

Cobb (1967) also reported on potential gradient and air–earth current density measurements at the South Pole station during the period November 1972 through March 1974. The percentage of variation of the air–earth current density measured at the South Pole closely followed the diurnal UT percentage of variation measured earlier at the Mauna Loa low-latitude station, although the mean values for the two stations are different. The diurnal UT variation of the potential gradient at the South Pole, however, is displaced by several hours compared with the Mauna Loa measurements.

Cobb (1967) also made balloon measurements to as high as 35 km at the South Pole station. Two aspects of the soundings emerged. First, the current is usually not constant with altitude even in the stratosphere; second, the average current in the stratosphere may vary by an order of magnitude from day to day.

SOLAR-CYCLE VARIATIONS

There is a long-period variation in cosmic-ray radiation that is inversely correlated with sunspot activity (Forbush, 1966; Neher, 1971). At 15 km the ionization rate may vary by 51 percent (conductivity by 23 percent), while at 20 km the ionization rate varies by about 76 percent (conductivity by 33 percent) at high latitudes. At 20 km the average conductivity variation through a solar cycle is about 18 percent at midlatitudes and about 10 percent near the equator.

Mühleisen (1977) derived the ionospheric potential variation of the global circuit over an 11-year solar cycle by balloon radiosonde ascents. His results suggest a solar-cycle variation of ionospheric potential opposite to solar activity as characterized by the relative sunspot number. During solar minimum the ionospheric potential had values near 350 kV, whereas it decreased to 250 kV near solar-cycle maximum.

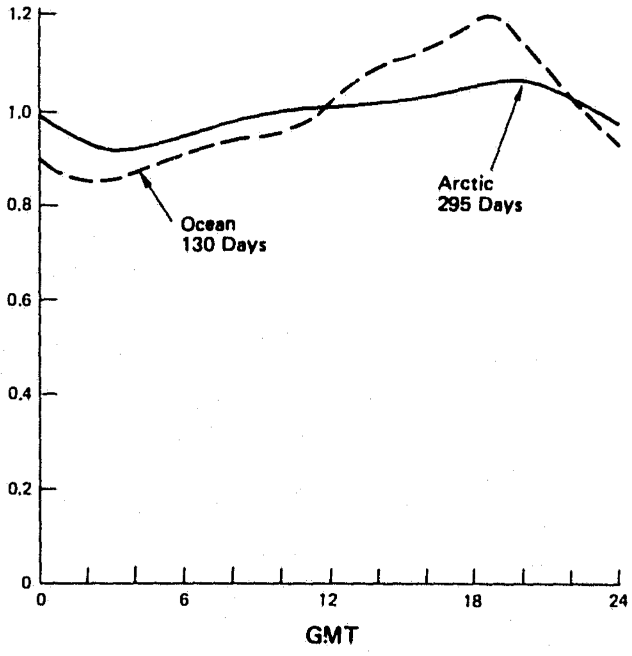


FIGURE 8.11 Normalized diurnal variation of the air–earth current density and electric field in the Arctic and Antarctic, 1958 and 1964 (solid line). Normalized diurnal variation of the atmospheric electric field on the oceans (dashed line) (Kasemir, 1972).

Olson (1977) measured the variation of the air–earth conduction current density through the period of a solar cycle (see Figure 8.12). The maximum current density occurs near solar-cycle minimum, as determined by the sunspot number, and minimum current density occurs near solar-cycle maximum. The data were divided into two sets: one for the hours near the maximum in the UT diurnal variation and one for the minimum (Markson, 1978). The scatter plots in the lower portion of Figure 8.12 show a negative correlation between air–earth current density and sunspot number for both data sets.

Markson and Muir (1980) found an inverse correlation between the solar-wind velocity and the Earth's ionospheric potential. The solar-wind velocity is known to be inversely correlated with the galactic cosmic radiation that maintains the Earth's atmospheric electrical conductivity. The correlation between cosmic-ray radiation and ionospheric potential indicates a solar influence on the parameters of the global electrical circuit.

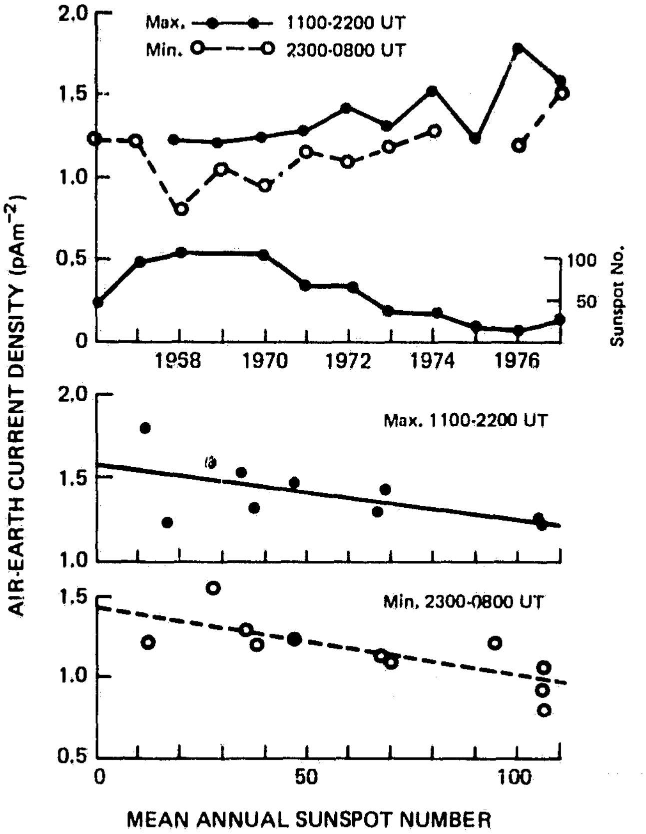


FIGURE 8.12 Variation of the air–earth conduction current density through the period of a solar cycle, as determined from balloon measurements by Olson (1977). The data are divided into two sets, one corresponding to the hours of the minimum electric field of the "unitary" diurnal variation. Scatter diagrams showing the inverse correlation between current density and sunspot number have been made for each data set (from Markson, 1979, with permission of D. Reidel Publishing Co.).

NUMERICAL MODELING OF THE GLOBAL ELECTRICAL CIRCUIT

Another method of determining possible solar–terrestrial effects on the global atmospheric electrical circuit is numerical modeling. By imposing variations of electrical conductivity known to occur during solar flares or variations in potential generated by the upper-atmospheric generators, it is possible to calculate the effects on the global electrical circuit parameters, such as changes in current density or potential gradient, and to compare the calculated variations to measurements. Models of the global electrical circuit have been constructed by Kasemir (1977), Volland (1977), and Hays and Roble (1979). A schematic diagram of a global quasi-static model formulated by Hays and Roble is shown in Figure 8.1. Within this model it is assumed that thunderstorms act as dipole current generators, each with a positive center at the top of the cloud and a negative center a few kilometers lower than the positive center. In fair-weather regions far away from the storm centers, the distribution of the electrostatic potential above the Earth is determined by the current return from the sources to the Earth's surface. The geometry of the model is based on an atmosphere broken into four coupled regions. Region 0 represents the lower troposphere, which has a variable conductivity in the horizontal and vertical; it also includes the Earth's orography. Region 1 represents the upper troposphere below the negative current source region within the thunderstorm, and Region 2 represents the stratosphere and mesosphere above the positive current source region of the thunderstorm. For regions 0, 1, and 2 the electrical conductivity is assumed to be isotropic. Region 3 represents the ionosphere and magnetosphere above the dynamo region, where the electrical conductivity is anisotropic and where magnetic conjugate regions are conducted along geomagnetic field lines through the magnetosphere. The mathematical details of the model, the boundary conditions, and the matching between various regions are described by Hays and Roble (1979). By specifying the latitudinal and height distributions of electrical conductivity, established by cosmic-ray activity, and a current output from thunderstorms, distributed in accordance with the known distribution of hourly thunderstorm occurrence, Hays and Roble (1979) demonstrated that many of the calculated features of the global circuit were consistent with observed properties. They also used the global model to examine possible solar–terrestrial perturbations to the circuit caused by changes in electrical conductivity associated with solar flares and Forbush decreases. Their results showed that changes in the cosmic-ray ion production rate that affect the electrical conductivity of the lower troposphere are capable of altering the global distribution of electric fields and currents. The variations arise from small changes in the total columnar resistance between the ground and ionosphere and, more importantly, changes in conductivity that affect the current output from the highly idealized thunderstorms within the model. Perturbations of ± 10–15 percent in the ionospheric potential and total current flowing in the circuit were calculated for the assumed electrical conductivity changes associated with solar-flare ionization increases and subsequent Forbush decreases. These idealized numerical experiments suggest that perturbations to the global electrical circuit are possible through changes in cosmic-ray ion production rates associated with solar–terrestrial events. More realistic models are necessary to determine the magnitude and global redistribution of electrical current and field changes caused by solar–terrestrial perturbations so that model predictions can be compared with observations.

In addition to perturbations of the global electrical circuit caused by variations of the cosmic-ray ionization rate, there are also perturbations caused by the downward mapping of the upper-atmospheric dynamo potentials. There are at least two ionospheric electrical generators that can produce large horizontal-scale potential differences within the ionosphere that couple into the global electrical circuit. These are (1) the ionospheric dynamo and (2) the magnetospheric dynamo associated with plasma convection at high latitudes.

IONOSPHERIC DYNAMO

Below about 80 km the mobility of ions and electrons is dominated by collisions with the neutral gas, and the electrical conductivity is isotropic. Above 80 km the electrons become bound to the Earth's geomagnetic field line; for ions this process happens above 140 km. This difference in behavior between the electrons and ions makes the electrical conductivity anisotropic above 80 km. Global atmospheric tides are generated in the upper atmosphere by diurnal variations of solar heat input and gravitational forces of the sun and moon. The winds in the dynamo region force plasma across the geomagnetic field lines, and this interaction causes large-scale electrical currents to flow.

The magnetic effects of these electrical currents, as observed on the ground, are known as *Sq* (solar quiet) and *L* (lunar gravitational) variations. An empirical model of the ionospheric dynamo potential determined by Richmond (1976) from incoherent scatter radar data is shown in Figure 8.13. The values are valid between 0° and 60° latitude. At higher latitudes, potentials from magnetospheric generators must be considered. Volland (1972, 1977) showed that the large, horizontal-scale potential differences (about 10 kV) generated in the ionospheric dynamo region map downward into the lower atmosphere. The ionospheric dynamo perturbs the low-latitude potential and electric field at the ground by about 6 percent of the tropospheric fair-weather potential and electric field established by thunderstorm charging. The pattern shown in Figure 8.13 will rotate with the sun around the Earth, giving a systematic pattern at ground level. Blanc and Richmond (1980) showed that during geomagnetic storms thermospheric winds acting in response to heating by auroral activity produce the ionospheric disturbance dynamo. Large, horizontal-scale potential differences of about 25 kV are generated by the ionospheric disturbance dynamo, and these potentials are superimposed on the quiet ionospheric dynamo. The combined potentials map into the lower ionosphere. Such potentials may be responsible for the correlation between air–earth current and geomagnetic activity, as observed by Cobb (1967) on Mauna Loa, Hawaii.

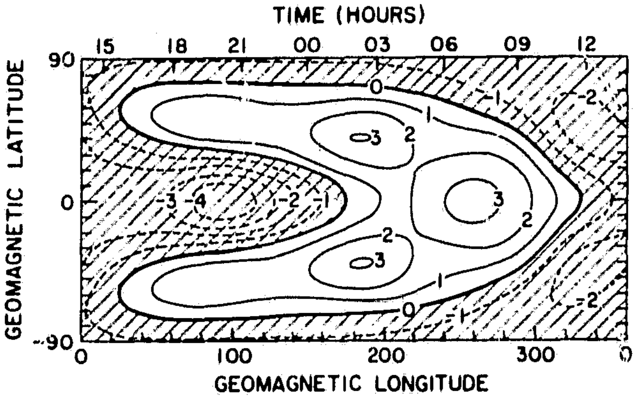


FIGURE 8.13 Quiet-day F region electrostatic potential pattern (kV) in apex latitude–local time coordinates. Values above 65° latitude have no significance (from Roble and Hays, 1979, with permission of the American Geophysical Union).

MAGNETOSPHERIC DYNAMO

The interaction of the solar wind with the Earth's geomagnetic field and the magnetospheric effects of this interaction have been described by Hill and Wolf (1977) and Burch (1977), respectively. This interaction gives rise to a large-scale flow of plasma across both magnetically conjugate polar caps; this flow is associated with a dawn-to-dusk potential drop across both caps. Heppner (1977), using satellite data, constructed empirical models of the potential distribution around the polar magnetic cap. Figure 8.14 shows the potential pattern for both a geomagnetically quiet and a disturbed period. During quiet times the potential drop is typically 50–70 kV, and the pattern is generally confined to magnetic latitudes greater than 60°. During geomagnetic storms and substorms, and possibly during solar-flare activity, this pattern expands equatorward and the potential drop increases to 150–250 kV. This potential pattern is maintained by pairs of field-aligned current systems, each carrying approximately a million amperes, with current densities of 10^6 A/m^2; it is also dependent on the ionospheric conductivity. There are variations of this potential pattern with the direction of the interplanetary magnetic field, and it appears that the negative perturbation of the ionospheric potential on the dusk side is greater than the positive perturbation on the dawn side of the polar cap. There is still much uncertainty associated with the time-dependent behavior of the potential pattern; however, it is anticipated to be highly variable. Park (1976b) and Roble and Hays (1979) discussed the mapping of the high-latitude magnetospheric potential pattern to the ground. Calculations showed that the magnetospheric generator can produce perturbations of ±20 percent in the air–earth current and the ground electric field at high latitudes under the pattern during geomagnetic quiet periods. During geomagnetic storms the high-latitude perturbations may be much larger. Roble and Hays (1979) examined the coupling of the high-latitude potential pattern into the global electrical circuit, including the effects of the Earth's orography and the tilted geomagnetic and geographic poles. Because the magnetospheric potential pattern is sun aligned in geomagnetic coordinates, a ground station will measure variations organized in magnetic local time (Figure 8.15). For early magnetic local times the ionospheric potential perturbations to the Earth's potential gradient are positive. For later magnetic local times the perturbations are negative. These variations are superimposed on the UT variation of potential gradient at the Earth's surface because of the diurnal variation of thunderstorm frequency. Measurements at high latitudes should be interpreted in terms of variations of ionospheric potential, as well as in terms of thunderstorm-frequency variations. The coupling of the magnetospheric generator and the electrical circuit at high latitudes needs to be examined. Theoretically, such a coupling should occur; however, there are no conclusive observations to support the theoretical predictions of effects near the ground. Mozer and Serlin (1969) and Mozer (1971) detected horizontal electric fields associated with the magnetospheric potential pattern penetrating down to balloon altitudes. Kasemir (1972) reported that the diurnal UT variation of the potential gradient at both the Thule, Greenland, and South Pole stations is 30 percent less than the global low-latitude UT variation attributed to variations in thunderstorm frequency, which may indicate the influence of the magnetospheric generators. These observations are suggestive,

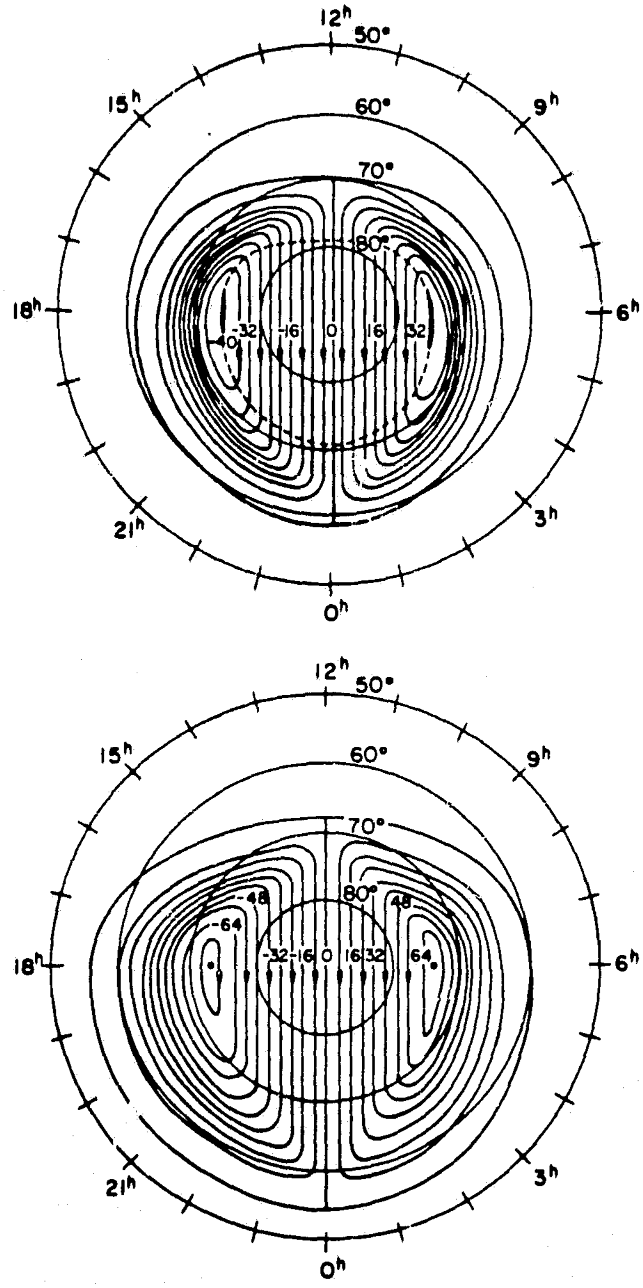


FIGURE 8.14 A sun-aligned empirical model of the potential distribution across the magnetic polar cap. Shown at top is the geomagnetic quiet model with a 72-kV dawn-to-dusk potential drop; at bottom is the geomagnetic disturbed model with a 140-kV dawn-to-dusk potential drop (from Heppner, 1977, with permission of the American Geophysical Union).

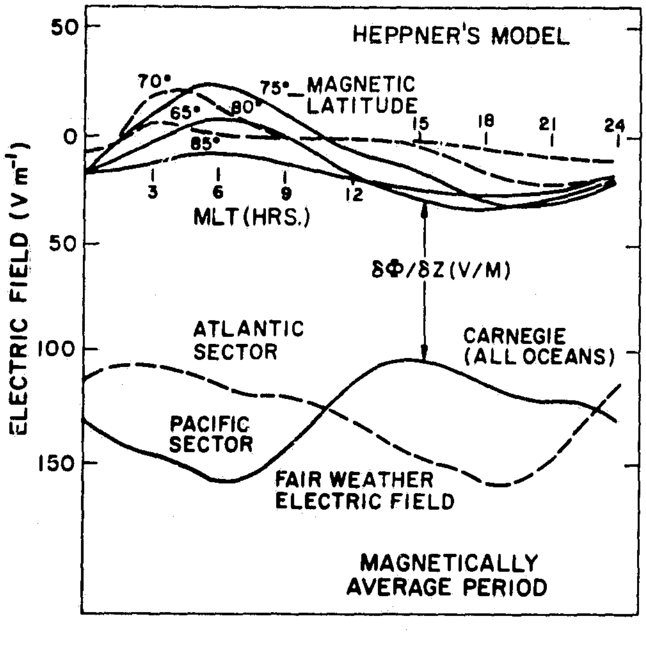


FIGURE 8.15 Calculated diurnal variation of ground electric field (V/m) as a function of magnetic local time. The upper curves are diurnal variations in the effect of the ionospheric potential perturbation on the ground electric field at various magnetic latitudes calculated by using Heppner's (1977) model for a magnetically average period. The lower curves are the diurnal (UT) variation of the ground electric field measured during the Carnegie expedition in magnetic local time for stations in the Atlantic and Pacific sectors. The total potential gradient variation is determined by the difference between the upper and lower curves as indicated.

but a systematic observational program is needed to study the possible coupling of magnetospheric processes with the lower atmosphere.

POSSIBLE COUPLING TO CLOUD PHYSICS AND THUNDERSTORM-CHARGING PROCESSES

Both the experimental evidence presented in the previous section and the theoretical studies made with a global model of atmospheric electricity indicate that a solar–terrestrial coupling through atmospheric electricity exists. The coupling is revealed through observed changes in the global distribution of the air–earth current and the electric field that occur during solar–terrestrial events.

Some of the observed changes can be understood through changes in electrical conductivity and the coupling of upper-atmospheric generators into the global electrical circuit. But not all of the changes can be attributed to these effects alone. For example, the observed increases in ionospheric potential, air–earth current, and electric field at the ground for several days after a solar flare indicate an increase of the generator power output into the global electrical circuit. If there was a generally accepted theory of thunderstorm electrification, it would be possible to examine such a coupling. However, in the absence of a generally accepted model, it is not possible to complete the link between the observed solar–terrestrial effect (changes in current and electric field) and a sun–weather effect (i.e., solar modulation of thunderstorms and possible tropospheric circulation changes). Markson (1971, 1978) and Markson and Muir (1980) presented a thunderstorm model that allows an increased current output from thunderstorms into the global electrical circuit due to increased ionization and hence electrical conductivity between the cloud top and ionosphere. Willett (1979) presented a different model in which the current output during similar solar–terrestrial events is not a large as that predicted by Markson. Herman and Goldberg (1978) suggested that the Forbush decrease, commonly associated with solar flares, enhances the fair-weather electric field in the troposphere, which in turn enhances cloud microphysical processes and thunderstorm development. Sartor (1965, 1980) argued that changes in the fair-weather properties in the vicinity of developing thunderstorms during solar–terrestrial events are greatly amplified by the induction-charging mechanism, thereby affecting thunderstorm growth and development. The sensitivity of the thunderstorm to solar–terrestrial perturbations is strongly model dependent. The construction of theoretical models of thunderstorm electrification is an active, and controversial, area of cloud physics. Some thunderstorm models are voltage generators, and others are current generators; until more is known about the details of the thunderstorm generator, it will not be possible to properly assess the mechanism leading to a possible sun–weather effect.

There are many cloud microphysical and cloud electrification processes that are dependent on the electrical state of the atmosphere (Pruppacher and Klett, 1978). As the electrical state of the atmosphere is altered during solar–terrestrial events, there is a probability that certain processes of thunderstorm development can be affected. If thunderstorm development can be shown to be affected during solar–terrestrial events, such information may be useful in identifying the important microphysical processes operating within the clouds. The probability of an electrical coupling mechanism between cloud microphyscial and electrification processes during solar–terrestrial events appears strong enough that further research in this area is warranted.

DISCUSSION

Both experimental evidence and theoretical calculations made with a model of global atmospheric electricity indicate that there is a global redistribution of electrical currents and fields during solar–terrestrial events; such redistribution suggests an electrical coupling that could affect microphysical processes down through the atmosphere to the ground. But as yet there are no generally accepted conclusive data to support the link between solar activity and thunderstorms or cloud processes.

Model calculations suggest that it is necessary to consider the entire electrical circuit from the magnetopause to the ground when analyzing ground-based, balloon, aircraft, and satellite data. One segment of the classical picture of atmospheric electricity suggests that there is an equalizing layer at 60 km, where upper-atmospheric electrical effects are shielded from lower-atmospheric electrical effects; this needs to be modified to account for the observed coupling.

The observational evidence presented in the previous sections suggests solar–terrestrial coupling, but a well-coordinated observational program is necessary to establish the nature and characteristics of the global response. Such a program should include measurements from satellites, rockets, aircrafts, balloons, and ground-based stations.

Whether atmospheric electricity represents a link between the sun and weather is not clear. Several mechanisms by which thunderstorm development and electrification might be affected by changes in the properties of the global circuit have been proposed, but geophysical data to support them are lacking. Global satellite measurements of lightning frequency and optical-power output may be a key in identifying the response of global thunderstorms to solar activity. If satellite measurements of lightning activity can establish a statistically significant increase or decrease in thunderstorm frequency correlated with solar flares, solar magnetic-sector boundary crossing, geomagnetic activity, aurorae, or the solar cycle, then atmospheric electricity is an intriguing possibility for the physical mechanism in a sun–weather relationship. Measurements that could shed some information on the nature and extent of electrical coupling during solar–terrestrial events have been proposed by Markson (1979) and Markson and Muir (1980). By monitoring the ionospheric potential either through a tethered balloon or a series of balloon flights it should be possible to derive a global geoelectrical index that would be useful for identifying important solar–terrestrial events that couple into the global electrical circuit. There are many uncertainties in the chain of physical processes leading to a change in weather systems but the evidence appears to warrant further consideration, and

FIGURE 8.16 Thunderstorm near Boulder, Colorado (NCAR photo).

investigations in this area should be considered part of solar–terrestrial research.

Finally, it should be emphasized that progress in understanding solar–terrestrial coupling requires a collaborative effort between observation and theoretical modeling. For example, by requiring agreement between theory and observations, it may be possible to derive information from a numerical model, such as the global distribution of electrical-conductivity variations during a solar flare, that would be difficult and expensive to obtain experimentally. Likewise, numerical experiments with a global theoretical model of atmospheric electricity may suggest certain experimental efforts to examine solar–terrestrial coupling mechanisms. The search for solar–terrestrial coupling mechanisms through atmospheric electricity should give us a better understanding of the Earth's natural electrical environment (Figure 8.16).

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