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

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The main objective of the solar-weather relationships game, as most people seem to see it, can be stated as follows: To identify the sequence of processes that lead from some change in solar input to the Earth to a change in tropospheric circulation and weather.

As a practical matter this game can be played in at least two ways, each entirely legitimate; and these ways are:

(1) To suggest processes that must be related to each other by establishing significant *correlations* in their behavior.

(2) To explain how one process can be related physically to another through a cause-and-effect *linkage*.

While the real objective is always the same, as stated above, the two ways of playing the game have different scoring systems, and they are all too often carried out in different arenas. Here, at this symposium, we are endeavoring to bring them onto the same playing field.

The advantages of combining the two are pretty obvious: (1) suggests where the theoreticians should look for linkages; (2) suggests where to search for new correlations in the real world; and *both* suggest where we should make efforts to make new observations or rearrange the data from the old ones.

My assignment has been to take advantage of the ideas that have been written up before this symposium, together with what I have gleaned elsewhere about the subject, to try to summarize what kinds of observations should be emphasized in the future—especially observations from rockets and satellites, but not exclusively. Fortunately, we are not by any means starting from scratch, because a great fund of information already exists. My task is largely one of sifting out those factors which seem most likely to be important, based on what we have seen in the correlations and what have been suggested as theoretically possible linkages.

Since my paper was to be immediately followed by a panel discussion, it was designed to be a kind of springboard to launch a variety of ideas that need to be looked at critically. It started being revised in a matter of minutes after it was presented.

INPUTS FROM THE SUN, THE SOLAR WIND, AND THE MAGNETOSPHERE

It is clear that both the correlation approach and the identification of linkages must start with some conception about the inputs at the top of the atmosphere, and the *variations* of these inputs with varying solar activity. A great variety of *indices* have been used to tell when such variations occur, and part of the confusion in the solar-weather field, as has been pointed out many times, lies in the fact that different indices have been used by different investigators.

Table 1 is an incomplete but hopefully useful summary of such indices, relating to the Sun itself, the solar wind, and the magnetosphere. The

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

Point of observation	Indices		
	Magnetosphere	Solar wind	Sun
Surface of the Earth	K_p, C_i ([a]) Auroral activity Ionospheric features Radio wave absorption Ion and electron temperatures	Galactic cosmic rays Magnetic sector boundary crossings from polar magnetograms	Sunspots Solar flares (observed from H_α emission) Decimeter radio emission Direction of solar magnetic field Plages, faculae, etc.
Satellites	Precipitation of trapped electrons and protons Changing upper atmosphere density and temperature	Solar cosmic rays	Near UV (1800 to 3000 Å) Extreme UV (900 to 1800 Å) Soft X-rays (10 to 900 Å) Hard X-rays (<10 Å) Gamma rays (?)
Interplanetary probes	....	Interplanetary magnetic sector structure Plasma shock waves	

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

ionized regions of the ionosphere have been included along with the magnetosphere, since for the purposes of this review it would be fruitless to argue whether, for example, magnetic field changes are caused by processes in the magnetosphere or the ionosphere—they are in both, of course.

It is assumed that this audience is reasonably familiar with each of these indices, or changing features of the upper atmosphere and space, and their general significance. It will be useful, nevertheless, to point to some of the time lags that are associated with such indices, since the scenario that is enacted each time the Sun changes its activity or has a flare takes several days to play to the end.

In table 2 are listed the lags of some of the features that are being used currently by investigators of correlations over a period of days. These are the events that are generally attributable to solar flares, as observed optically or by increases in decimeter radio emission from the Sun (the latter being an observation that is not inhibited by clouds). The early atmospheric events, limited to the daylight side of the Earth, are caused by enhancement of X-rays and ultraviolet (UV) radiation that travel from the Sun at the speed of light, and the later terrestrial events occur when the energetic particles (protons) ejected from the Sun reach the magnetosphere and begin to perturb and penetrate it. The particles that reach the ionosphere at high magnetic latitudes (above $L = 4$), causing changes in electron density and auroral activity, are presumed to be in large part those that came from the Sun and were guided by the Earth's magnetic field, whereas energetic particles that arrive at lower magnetic latitudes are mostly trapped particles precipitated out of the radiation belts by wave-plasma interactions. (We are excluding here for the moment the very high energy "solar cosmic rays" and true cosmic rays.)

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

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

Event	Lag, days
Enhanced ionization in ionospheric *D*-region on daylight side (radio wave absorption, fadeout, and such)	< 0.1
Polar cap absorption of radio waves (after major flare event)	0.5 to 1
Increased density and temperature in upper thermosphere (satellite drag increases, and such)	1
Magnetic storm, main phase	1 to 2
Ionospheric storm (for example, decrease in f_0 F2 at 45° latitude and above)	1 to 2

In a different category of solar indices is the solar wind's interplanetary magnetic sector structure, described at this conference in some detail in an earlier paper by John M. Wilcox. (See also Wilcox, 1968; and Wilcox et al., 1973.) Although the passages of the sector boundaries are statistically associated with a transition from "quiet" to "active" conditions on the Sun and back, that does not mean that solar flare activity is necessarily constrained in the same way. Furthermore, there is a 4.5-day lag between the passage of the sector boundary across the central meridian of the Sun and its passage by the Earth, due to the transit time in the solar wind; the average time between sector passages is about 8 days.

Clearly, the transition in thinking from flare-related effects to sector-passage effects will have to be done with care.

A rather different situation prevails when correlations are sought over a period of decades, correlations involving the 11- or 22-yr solar activity cycle. There is such good evidence that a variety of upper air phenomena and inputs to the atmosphere change in response to the solar cycle that it is not necessary to review the evidence here.

There is also one input to the atmospheric system that varies with the solar cycle and which directly reaches the Earth's surface, and that is galactic cosmic rays. They are sufficiently energetic to penetrate the Earth's magnetic field and its atmosphere, and the solar control of such cosmic rays is now fairly well explained in terms of their deflection in the outer reaches of the solar atmosphere by the magnetic fields embedded in it. (We will return to these cosmic rays later.) So far as we can determine, no similar variations of galactic cosmic rays can be attributed to shorter term solar events such as flares.

INTERNAL LINKAGES TO THE TROPOSPHERE

We must now remind ourselves that here we are interested in transmitting a signal from the Sun to the troposphere. Up to now we have dealt with the Sun and the obviously solar-connected events in the magnetosphere and *upper* atmosphere. How can the signal reach the *lower* atmosphere?

As a general proposition, it seems safe to say that the signal can only get down through the atmosphere with any appreciable strength (at least enough strength to trigger something) by directly penetrating it in the form of energetic particles or electromagnetic radiation, or by dynamical interactions between layers of the atmosphere. These processes seem to cover all the possibilities, but one has a feeling that in this business one is never safe from surprises. At any rate, we will summarize some of the facts in each of these three areas so that the possibilities will be clearer.

Direct Penetration of Particles and Bremsstrahlung

Particles with energies of from 0.1 keV to a bit over 100 keV, both electrons and protons, account for the excitation of the aurora at high magnetic latitudes, but the total flux of energy of such charged particles averaged over a few square kilometers must be less than 10 erg/cm^2 sec even at solar maximum, though their peak fluxes in the heart of an auroral arc can be more than 100 times larger (Friedman, 1964; Gregory, 1968). These particles derive their energies from the solar wind, though usually indirectly. Apparently there is also a small component of electrons with energies of several tens of keV that are precipitated from the radiation belts in brief pulses due to very low frequency (VLF) radio wave interactions with the trapped particles (Helliwell et al., 1973).

Some idea of how far such particles penetrate is given by table 3, taken from Gregory (1968) and Dessler (this symposium).

The very energetic particles referred to in table 3 are solar protons, with particle energies approaching 10^9 eV (1 GeV) but with fluxes that are usually many orders of magnitude less than that of the auroral particles. However, such fluxes may reach 0.1 erg/cm^2 sec over the whole polar cap for short periods during a major solar event (Gregory, 1968). Compare these energies with those for solar UV fluxes, given below.

A small fraction of the energy of energetic

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

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

electrons is converted to radiation as they collide with the molecules of the atmosphere, the energy conversion efficiencies ranging from about 10^{-3} for some visible and near UV excitations to 10^{-5} for X-ray bremsstrahlung radiation. The latter can be detected on occasion at balloon altitudes in the auroral zone (Brown, 1966) and is a good indicator of energetic electron precipitation. Nevertheless, the fluxes involved are clearly very small indeed, on the order of 10^{-4} ergs/cm^2 sec or less for the X-ray fluxes in the lower stratosphere during solar maximum, and perhaps reaching peak intensities of 10^{-2} to 10^{-1} ergs/cm^2 sec (Gregory, 1968, table 4, assuming 10^{-5} excitation efficiency for bremsstrahlung).

The fluxes of charged particles into the ionosphere at latitudes below the auroral zone are very much less on the average, but during major disturbances of the Earth's field these incoming particles appear at lower latitudes, sometimes almost to the equator.

Ionizing Radiation and Cirrus Clouds

One of the suggestions for an upper tropospheric link to solar activity depends on the ionizing radiation from auroral particles (or solar protons, perhaps) reaching as far down as the tropopause (the 300-mb level, say) and initiating the formation of cirrus clouds before they would otherwise form (Roberts and Olson, 1973). The resulting cloudiness would change the heat balance of the troposphere, it is argued, and that would have an influence on the development of tropospheric circulation—specifically, the deepening of troughs in winter.

While some traces of ionizing radiation, such as very energetic protons (see table 3) or bremsstrahlung X-rays from auroral electrons, can indeed get down to such altitudes on occasion (Brown, 1966; Blamont and Pommereau, 1972), the open question is whether they can nucleate clouds. Could such ions appreciably supplement or encourage the action of the condensation and freezing nuclei that are already everywhere in the atmosphere? Are there in fact increases of cirrus cloudiness following the precipitation of energetic particles at high latitudes? We will return to these questions later.

Ionizing Radiation, Thunderstorms, and the Earth's Electric Field

There is one other possible effect from ionizing radiation penetrating to the upper troposphere, and that is the increase that it would cause in the conductivity of the Earth-ionosphere column. An increase in the conductivity would cause more current to flow from the negatively charged Earth to the positively charged ionosphere, and this condition would ("all other things being equal") lower the potential gradient. If the effect occurred over a large area the decrease of potential gradient would be felt worldwide, and might interact with atmospheric electrical processes, especially thunderstorms. This effect is discussed in a paper by Markson at this symposium.

There is some evidence that thunderstorm activity is indeed related to solar activity (for example, Reiter, 1964; Bossolasco et al., 1972). Thunderstorms are presumably the generating mechanisms that maintain the fair weather potential gradient, and in turn they depend on the fair weather electric field to initiate the charge separation that increases the rate of coalescence of droplets (rate of rainfall), and that also, of course, leads to lightning (Sartor, 1969). A simple-minded line of reasoning, based on the above, would suggest that increased ionization from cosmic rays, solar protons, or bremsstrahlung would decrease thunderstorm activity due to the decrease in electric field (see fig. 1, Ney, 1959); but Bossolasco et al. (1972) have found exactly the reverse in their superposed epoch analysis of thunderstorm frequencies following an H_α flare.

We seem to have uncovered another case where apparent facts and simple theory are in

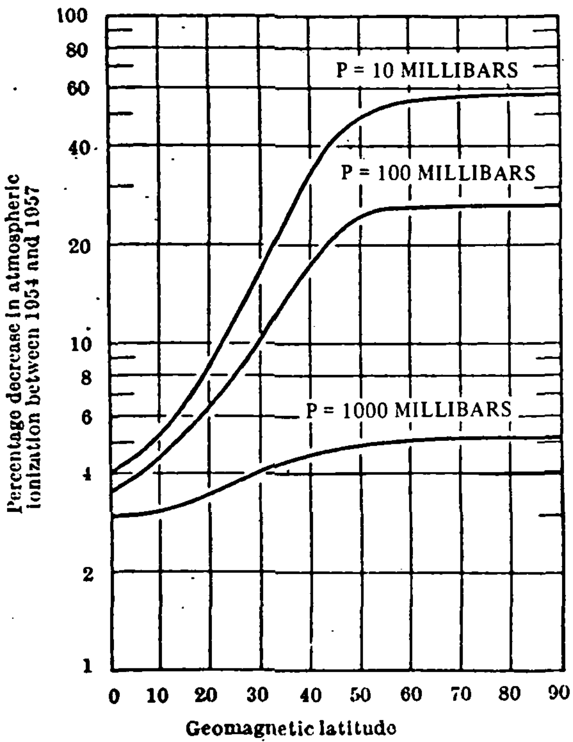

FIGURE 1.—Percent of reduction in atmospheric ionization during the last solar cycle. The percent of change is calculated with respect to the value of the ionization at sunspot minimum in 1954 (Ney, 1959). *P* is atmospheric pressure.

contradiction—too bad we have to be bothered with facts! Yet the conclusion is inescapable that if we are to unravel this possible set of linkages we need more and better data on thunderstorm frequency and global-scale electric fields.

To make matters still more confusing, attempts to determine whether thunderstorm activity was correlated on a longer term with the solar cycle have so far been negative (Ney, 1959; fig. 2, Sparrow and Ney, 1971), in spite of the established fact (fig. 3, Forbush, 1957) that cosmic ray fluxes and their resulting ionization have a distinct solar cycle dependence.

Nevertheless, to carry the thunderstorm argument one step further, a possible link between changes in the worldwide potential gradient and global heat balance can be hypothesized due to the effects of the increased cirrus cloudiness with increased thunderstorm activity (Ney, 1959), and also the greater convective vertical transport of heat and moisture (Byers, 1965). The former would tend to cool the upper troposphere while the latter would tend to warm it, but not at the same places. This hypothesis can hardly be considered as past the handwaving stage.

Direct Penetration of Ultraviolet and X-Rays

The Sun's total output, the so-called "solar constant," does not vary by as much as 1 percent, which is the limit of our ability to measure its absolute value. Some solar physicists estimate a variation of less than 0.001 percent (Elske Smith, paper presented at this symposium). However, it has been known since the pioneering rocket flights of groups of Naval Research Laboratory (NRL) and Air Force Cambridge Research Laboratories (AFCRL) in the 1950's that X-ray fluxes change very markedly with solar activity, and UV fluxes also change but much less dramatically. All of these radiations must be measured above the atmosphere, because with wavelengths less than about 3000 Å they do not reach the surface.

An early summary of these variations of solar emission in the X-ray region is shown in figure 4 and the depths of penetration into the atmosphere for various wavelengths are shown in figure 5, both taken from Friedman (1964).

The situation regarding fluxes in the near and extreme UV is still not clear, since the authorities do not agree on the interpretation of the existing measurements and the measurements do not agree with theory (Breig, 1973; Roble and Dickinson, 1973). However, for these purposes it is probably enough that the integrated energy of solar flux below 1310 Å, excluding Lyman alpha radiation (L_α), is about 3 ergs/cm^2 sec, and the L_α flux around 1210 Å is 3 to 6 ergs/cm^2 sec. In the Schumann-Runge continuum between about 1310 and 2100 Å, the flux is about 240 ergs/cm^2 sec.

The penetration heights of these UV radiations are shown in figures 6 and 7, after Friedman (1960) and Watanabe and Hinteregger (1962).

Between 2100 and 3000 Å, the solar radiation is absorbed by the Hartley bands of ozone, mostly in the stratosphere (fig. 6), and the total flux involved when the Sun is directly overhead is about 17 W/m^2, or 1.2 percent of the 1400 W/m^2 solar constant (1 W/m^2 = 10^3 ergs/cm^2 sec).

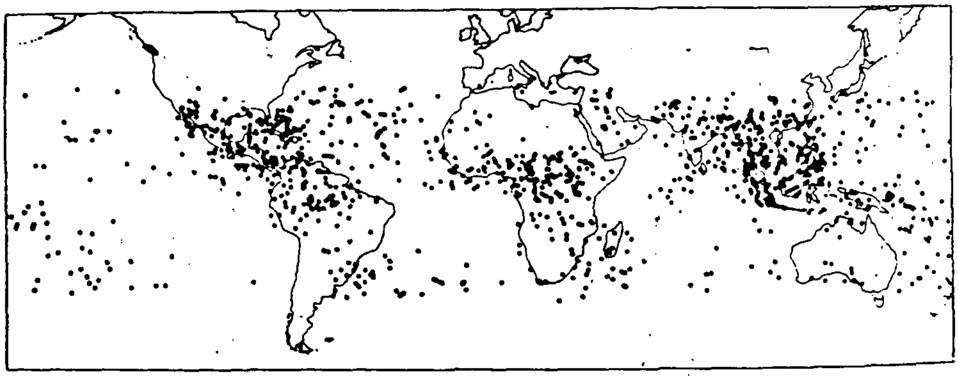

FIGURE 2.—Distribution of nighttime lightning storm complexes observed by photometers on board satellite OSO 5 (Sparrow and Ney, 1971).

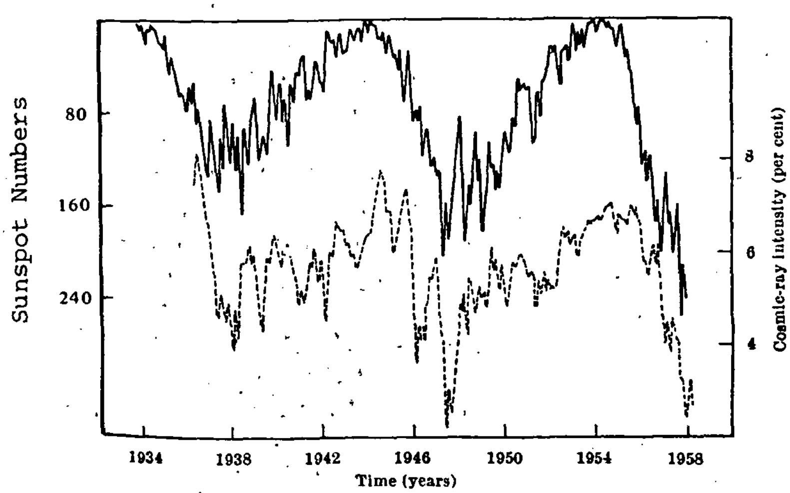

FIGURE 3.—Illustrating the "Forbush effect," the inverse correlation of cosmic ray flux and solar activity. Solid line is sunspot number; dashed line is relative cosmic ray intensity (Forbush, 1957).

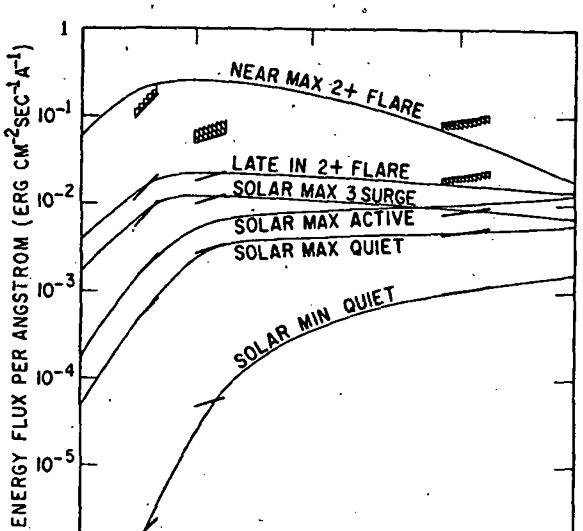

FIGURE 4.—Solar X-ray emission for various solar conditions. The curves indicate the approximate energy distributions for sunspot minimum, sunspot maximum, and solar flare conditions. The curves are drawn on the basis of measurements made in three wavelength bands, as indicated by the heavy bar segments. The slopes of the bar segments are the slopes of the assumed X-ray emission functions used to reduce the photometer responses to the energy fluxes plotted on the chart. Energy fluxes refer to values observed just outside Earth's absorbing atmosphere (Friedman, 1964).

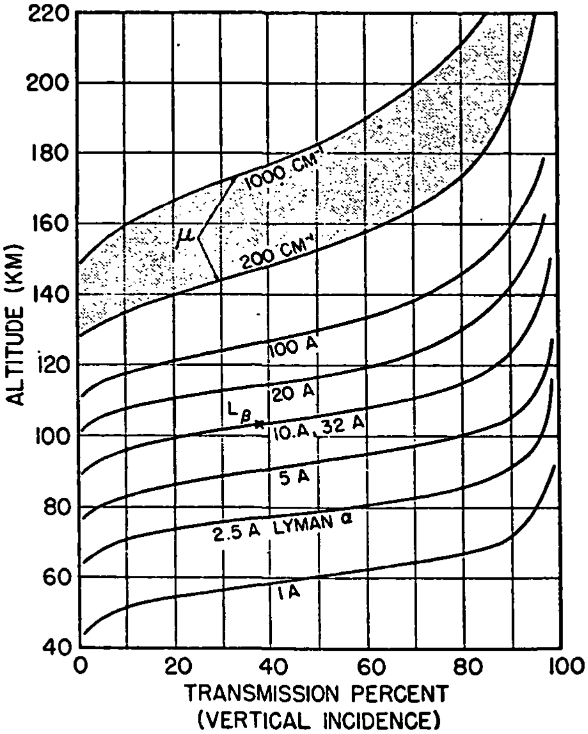

FIGURE 5.—Penetration of the atmosphere by solar X-rays and UV radiation. The shaded portion includes the broad range of wavelengths from 100 to 850 Å for which the linear absorption coefficients μ lies between 200 and 1000 cm^{-1} (Friedman, 1964).

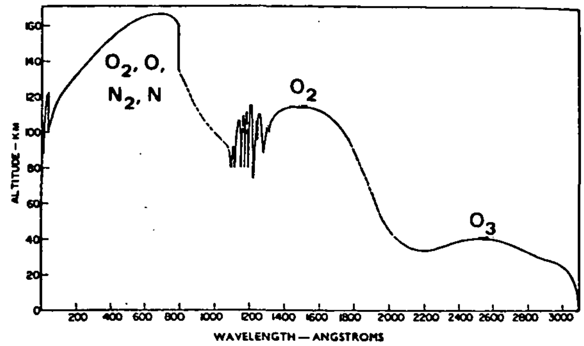

FIGURE 6.—Penetration of solar radiation into the atmosphere. The curve indicates the level at which the intensity is reduced to e^{-1}. Absorption for wavelengths greater than 2000 Å is principally due to ozone, for those between 850 and 2000 Å, to molecular oxygen, and for those less than 850 Å, to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

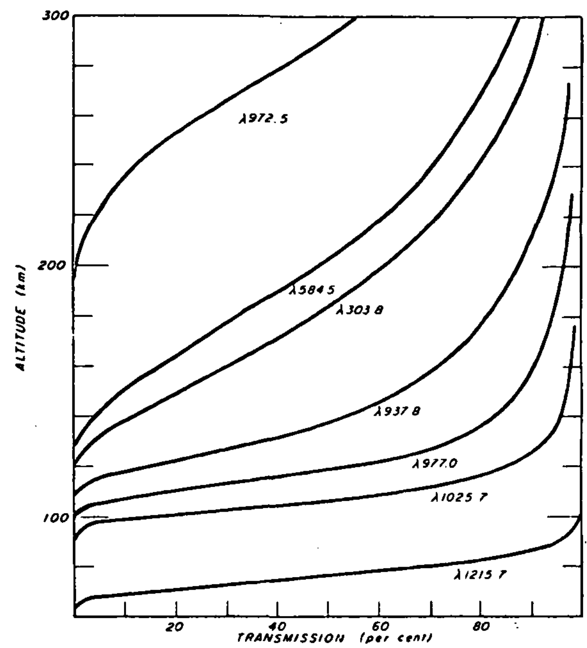

FIGURE 7.—Penetration of the atmosphere by solar UV radiation (Watanabe and Hinteregger, 1962).

This is an appreciable flux, and its absorption accounts for the warm stratosphere. There is, again, conflicting evidence concerning the variation of this near UV flux with solar activity. It could vary by a small amount—perhaps a percent or so (Heath, paper presented at this symposium). However, even a 1 percent change of the 2100- to 3000-Å radiation would amount to 170 ergs/cm^2 sec, and this is over 0.01 percent of the solar constant and a factor of 10 times more than the solar physicists expect (Smith, paper at this symposium).

In view of the fact that this near UV part of the solar radiation flux does reach the stratosphere and troposphere directly, it is clearly a prime contender for attention as a possible solar-atmosphere link, and it is unfortunate that we cannot say more about its variations.

Propagation of Gravity and Planetary-Scale Waves

The fact that gravity waves (with horizontal scales of a few hundred kilometers) and planetary waves (with horizontal scales of a few thousand kilometers) can both propagate vertically and transport energy and momentum makes them a promising link between troposphere and mesosphere or thermosphere. However, because the density falls off exponentially with height, the transport of energy or momentum *downward* has a trivial effect on the lower atmosphere; transport of energy and momentum *upward,* on the other hand, can and does have a very marked influence on the winds and temperatures of the upper atmosphere (Hines, 1960; Dickinson, 1968; Lindzen, 1969).

This preferred direction of transport of energy and momentum has led Hines to argue that at least a part of the correlations that have been uncovered between tropospheric and ionospheric events are actually due to the tropospheric control of the ionosphere, and therefore are not related to solar activity. In order to get around this argument several investigators have resorted to the Wilcox solar wind magnetic sector passages instead of geomagnetic storms as indicators of solar input changes, since no one can argue that the troposphere has an influence on the solar magnetic field.

A new thought has been brought forth by Colin O. Hines at this symposium, a variation on the gravity wave theme. The idea is that gravity waves and the related planetary waves can be reflected in the upper atmosphere, the conditions for reflection depending on the wind shears and temperature structure there. Changing solar activity does influence circulations and temperatures in the thermosphere, as we know; so why might not such changes cause the reflecting characteristics of the upper atmosphere to return the energy of the troposphere-generated gravity waves on some occasions and not on others, depending on solar activity? The energy involved in these reflected waves, given some constructive or destructive interference with the initial disturbance, could presumably be enough to change things in the troposphere, since the troposphere generated the waves in the first place.

While the suggestion is most ingenious, it appears that Hines has not yet been able to show in any detail how such a mechanism would actually work in the real atmosphere. We can predict, however, that this concept will attract others to pursue it as well, since until it is either demonstrated as correct or laid to rest as another bad idea it will serve as a source of frustration to all those seeking linkages in the solar-weather game.

CONCLUSIONS

Having tried to set down some of the main factors in the complex question of how solar changes could cause changes in tropospheric weather, we are more than ever impressed by the fact that relatively little progress has been made in finding completely believable links that could account for the apparent correlations that exist. Out of all the ideas and suggestions, however, a few seem to still hold some promise of providing the answer (or part of it), and these are the ones that should obviously be pursued.

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

(1) Continuous monitoring (by geosynchronous and polar orbiting satellites) of the energy and pitch angle distribution of geomagnetically trapped electrons and protons in order to determine when they are precipitated into the lower ionosphere. (The recent work of Helliwell et al. on wave-plasma interactions in the auroral zone will add fuel to this fire.) The most interesting information probably pertains to the auroral particles trapped at around $L = 4$, but attention should also be given to the particles that can be precipitated at lower latitudes.

(2) Monitoring from balloons in the region of the tropopause (10 to 15 km) the incidence of ionizing radiation and any accompanying changes of temperature, conductivity, ozone amount or ultraviolet flux, and so on. (This would be an extension of Blamont's and Pommereau's experiment (Blamont and Pommereau, 1972).)

(3) Continuous monitoring from a satellite of absolute solar flux in the near UV, between 2100 and 3000 Å. This should be done in several broad spectral bands, in order to establish any changes that would influence energy deposition (heating rate) and ozone formation in the stratosphere. (D. Heath of GSFC has tried to do this already in Nimbus 3, 4, and 5.)

(4) Monitoring ozone distribution in the region above 30 km, which can be done globally from satellites by techniques such as the Backscattered Ultraviolet (BUV) experiment on Nimbus 3,

would also throw light on solar UV changes in the 2100- to 3000-Å region.

(5) Observations of wind systems in the mesosphere and lower thermosphere are possible by a variety of ground based (for example, radio meteor drifts) and rocket (for example, grenades, smoke trails) techniques, and should be tied to the proposition of Hines concerning the possible reflection of gravity and planetary waves under changing solar inputs. The theoretical work has apparently not yet pinpointed where one should look, however.

In a somewhat different category are the atmospheric features that may be closely related to changing solar inputs—perhaps even directly related. Any change in the circulation, patterns and weather must be the result of a change in the heating and cooling of the atmosphere, so we should look for evidence concerning these energy-controlling mechanisms. In addition to the possible control of stratospheric temperature through the UV-ozone interaction (already covered above) there are two others that deserve our attention:

(1) Cirrus formation at high latitudes due to the nucleating effects of ionizing particles could be detected from satellites through optical techniques or through the effect of a cirrus deck on the upward infrared radiation in the atmospheric window. Cirrus is difficult to detect in the visible or near infrared, so the second alternative may be more promising. W. O. Roberts and his colleagues are attempting to make observations of cirrus formation by the second alternative.

(2) Thunderstorm activity, as pointed out, may be related to solar activity, and since thunderstorms transport heat and water vapor from the lower troposphere to the upper troposphere at low and middle latitudes, and also influence the amount of cirrus cloudiness, they play a role in the overall heat balance. There are both optical and radio techniques that could be used to monitor thunderstorm activity globally with the help of satellites (Jean, 1973; Sparrow and Ney, 1971).

(3) The frequency of occurrence of thunderstorms probably depends on the global fair-weather electric field, and this field must be, in turn, maintained by thunderstorms. To monitor the fair-weather electric field at representative sites, avoiding local interference as much as possible, is one of the aims of the proposed Atmospheric Electricity Ten-Year Program (Dolezalek, 1972). (See also Cobb, 1967.)

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DISCUSSION

HAURWITZ: I do not think I understood the role played by gravity waves. Now, if I followed you correctly, gravity waves, which propagate upward from the ground—there is really very little energy compared to the energy of the motion at the ground anyway—would under certain conditions be reflected from above. So, little energy comes back to the ground, and this situation should not produce a noticeable effect on the ground.

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

KELLOGG: I can only point out one fact. One of the difficulties the general circulation modelers have if they do not handle the upper boundary right is that the energy of the system really is changed by the reflection of gravity waves in the model. Now, the models, of course, sometimes generate more gravity waves than the real atmosphere, particularly during their initial startup, when you perturb them. Nevertheless, they do represent an appreciable factor in the overall energy of the atmosphere.

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

It might be interesting to see and, if possible, to make some observations of whether gravity waves at say, 100 or 150 km, are more in evidence at certain times of solar activity than at other times. That would be an additional suggestion for things that possibly could be studied.

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

NOYES: The disagreement attributed to Don Heath and Elske Smith is only apparent because they are talking about somewhat different spectral regions. Dr. Smith is talking about the visible region of the spectrum where if you look at the Sun it looks like a pretty homogeneous ball with a few sunspots that occupy only infinitesimal area. And her figure of a very small percentage modulation due to sunspots is due mostly to that. In the visible, you cannot see the active regions or plages, except at the limb with very, very small contrast. However, in the far ultraviolet these plages occupy a much larger fraction of the surface area and they cause a larger modulation.

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

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

NOYES: I think I would argue strongly you could not see a change in the solar constant of the integrated luminosity of the Sun of anything like a percent. It is going to be a small fraction of a percent. But certainly in the near ultraviolet, you could see much larger modulations.

HEATH: From what I have seen over a part of the solar cycle, the change in the solar constant would be of the order of a tenth of a percent or less. I talked to Elske Smith and there really is no contradiction, we were talking about different things.

And I would like to make one other statement, and that is that Dr. Kellogg was talking about the ozone data. We now have completely reduced 1 yr of the total ozone data for every day of the year from 80° to −80°. We are now going into the high level distribution, and one of the first things we are going to look for is different types of periodic phenomena and see if we can find any, find what meteorological system or any other external system that they may be correlated with.

We do see that in the wintertime, especially in the southern hemisphere, there are very strong fluctuations in the total ozone. These fluctuations have periods of the order of 7 to 10 or 12 days. These are zonal means. As far as this analysis goes, we have averaged the ozone around the world in 10° bands of latitude on a daily basis. And there are really very large fluctuations in the southern hemisphere in the wintertime, and there are fluctuations in the northern hemisphere in the wintertime but they are not nearly as pronounced. And the equatorial regions are extremely constant. I hope that these data will become available very shortly.

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

MARKSON: Since you devoted quite a bit of your talk to thunderstorms, I would like to make a few comments. You assumed that all thunderstorm theories depended on environmental conditions. I would like to point out that the majority of thunderstorm theories do not; they involve, for example, temperature gradients, splintering, splitting of crystals, and riming-icing theories, all the things that have to do with particles.

Secondly, you implied that a change in conductivity, per se, would affect the electric field through the atmosphere, while recognizing that this conductivity variation would be in the upper atmosphere. The columnar resistance above 10 km is about 10 percent the total columnar resistance, and at 20 km it is about 2 percent. This is why my conclusion was that, even if you make a complete conductor out of the atmosphere above these heights, you have not changed the electric field in the lower region. Therefore, look toward changes in the current, possibly from thunderstorms, as your mechanism.

Third, another thing about thunderstorms, if they were changed, is that you have a nice source of cirrus clouds, which could affect your radiation budget.

And finally, a comment on the idea that the thunderstorm variation over the world could be measured from places like the Zugspitze or Mauna Loa with ground measurements: It takes a week's data under the most favorable conditions, at the best possible stations including the Arctic and ships at sea, to see the diurnal variation. But I think we have proven now that from airplanes flying well above the mixing layer, out over the ocean in maritime air, you can see the diurnal variation immediately.

Robert Anderson of the Naval Research Laboratory and I made measurements simultaneously, 7000 km apart, and our data correlated at the 99-percent significance level. And I think this agreement points to the fact that now we have a way to look at worldwide thunderstorm activity, which then could be compared to the solar variation.

KELLOGG: I would just like to make one comment on what you said. You are saying, in effect, that we ought to measure the potential gradients on a worldwide basis, and thereby monitor thunderstorms. But this does not answer the question of what made the thunderstorm activity change, or what changed the potential field. That is, if it is solar-related, then we still have to find that trigger, that handle, that the Sun has on the lower atmosphere. It is not enough to say that thunderstorms change. I agree with you, thunderstorms change, but what made them change?

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