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Solar Variability Influences on Weather and Climate: Possible Connections Through Cosmic Ray Fluxes and Storm Intensification

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The question of the mechanism for solar-variability effects on weather and climate can be separated into (1) the identification of the carrier of the solar variability and (2) the identification of the physical link between the carrier and the meteorological response. The suggestion that galactic cosmic rays (GCR), as modulated by the solar wind, are the carriers of the component of solar variability that affects weather and climate has been discussed in the literature for 30 years, and considerable evidence for it has now accumulated. Variations of GCR occur with the 11-year solar cycle, matching the time scale of recent results for atmospheric variations, as modulated by the quasi-biennial oscillation of equatorial stratospheric winds (QBO). Variations in GCR occur on the time scale of centuries with a well-defined peak in the coldest decade of the little ice age. Here we present new evidence on the meteorological responses to variations on the time scale of a few days. The occurrence of correlations of GCR and meteorological responses on all three time scales strengthens the hypothesis of GCR as carriers of solar variability to the lower atmosphere. The responses reported here include changes in the vertical temperature profile in the troposphere and lower stratosphere and in the northern hemisphere vorticity area index, associated with Forbush decreases in GCR. The meteorological responses to Forbush decreases are in the opposite sense but otherwise are quite similar to responses that immediately follow solar flares. This is to be expected, based on the hypothesis that particles with energy about 100–1000 MeV are the external forcing function for the tropospheric response, since large solar flares increase the particle flux and ionization and minor species production in the lower stratosphere, whereas Forbush decreases reduce them. The mechanism or mechanisms linking changes in low-energy GCR and other particles in this energy range of 100–1000 MeV to tropospheric temperature and dynamic responses have not been identified. This can be attributed to current uncertainties regarding the microphysical and electrical properties of aerosols and clouds. One possibility is that changes in clouds lead to changes in cloud radiative forcing. The height distribution of the tropospheric response and the amount of energy involved and the rapidity of the time response suggest that the release of latent heat could also be involved. These could lead to the observed tropospheric responses which are understandable in terms of changes in the intensity of cyclonic disturbances. Theoretical considerations link such changes to the observed latitudinal movement of the jet stream.

1. INTRODUCTION

Recent studies have provided a much clearer picture of the effects of solar variability on the middle and lower atmosphere. *Labitzke* [1987] and *Labitzke and van Loon* [1988] showed that the northern hemisphere wintertime (January–February) temperatures and pressures throughout the lower stratosphere and troposphere had clear relationships to the 11-year solar cycle when the winters were sorted according to whether equatorial stratospheric winds that undergo a quasi-biennial oscillation (QBO) were in their west phase (from the west) or in their east phase. On the century time scale, the historically recorded "little ice age" of Northern Europe coincided with the "Maunder Minimum" of sunspot occurrence in the period 1645–1715 [*Eddy*, 1976]. This region is strongly affected by changes in the jet stream and storm tracks related to the 11-year cycle [*Brown and John*, 1979; *Tinsley*, 1988].

On the time scale of a few days for solar variations and lower atmosphere response, there is a very large body of data, much of which has been reviewed by *Herman and Goldberg* [1978*a*]. Zonal and regional responses of the temperature profile and 500-mbar geopotential

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heights to large solar flares were found by *Schuurmans* [1965, 1979] and by *Schuurmans and Oort* [1969]. The most comprehensively studied short-term changes are those of the vorticity area index (VAI), which is an objective measure of the intensification of cyclonic storms and the deepening of low-pressure troughs. The index was defined by *Roberts and Olson* [1973], following earlier work on the relationship between magnetic storms and tropospheric storms in the Gulf of Alaska (see *Macdonald and Roberts* [1960], who also discussed possible amplifying effects of cloud microphysical processes). *Wilcox et al.* [1973, 1974] found decreases by 5–10% in the VAI, reaching a minimum the day after solar wind magnetic sector boundaries (SBs) crossed the Earth's location. The effect was greatest at the 300-mbar level, extending downward to about 850 mbar and upward to about 100 mbar. *Olson et al.* [1975] examined the VAI response to large solar flares (defining day 0) and found that by day 1 or 2 the northern hemisphere VAI had increased sharply to 5–10% above its background level, and by day 3 or 4 it had decreased to a value 5–10% below its preflare level. By day 5 or 6 the VAI recovered to the background level.

The evidence for the reality of a solar variability–weather connection is strong on each of these three time scales, and the main unresolved issue is the nature of the physical processes involved. This problem can be separated into two parts: the first is to identify the carrier or carriers of the solar variability to the lower atmosphere, and the second is to determine the mechanism or mechanisms that produce a very large energy amplification in the troposphere. In this paper we address the hypothesis that low-energy galactic cosmic rays (GCR) of about 100–1000 MeV, supplemented at times by solar protons and other particles in the same energy range, are the primary carrier of solar variability to the lower atmosphere.

In spite of the fact that the amount of energy in the GCR flux variations is almost the smallest of any of the candidates for carriers discussed by *Newkirk* [1982], this hypothesis is attractive for three reasons:

1. The main ionization and chemical minor species production associated with these particles is at 10–20 km altitude, which is low enough to influence the troposphere.

2. Variations of amplitude of order 10–100% are present in the low-energy GCR, and it is not necessary to postulate highly nonlinear or triggered or bistable processes; essentially linear amplification processes are sufficient.

3. There are GCR variations that match the meteorological and climate responses on all three of the time scales discussed earlier. On the century time scale the decade of the 1690s in the coldest part of the "little ice age" coincided with a peak in the ^{14}C and ^{10}Be production from GCR; the latter was 70% above levels before and after, according to measurements of concentrations in Greenland ice cores [*Attolini et al.*, 1988]. There is an 11-year variation by about 50% in the GCR-produced ionization near tropopause heights and an 11-year variation by a factor of about 10 in its day-to-day variability [*Pomerantz and Duggal*, 1974]. The agreement between the periodicity of the GCR variations and meteorological and climate responses on the 11-year and century time scales and indications for its agreement on the day-to-day time scale have been discussed in the literature for 30 years. The present situation is that while a number of authors have considered GCR, supplemented at times by high-energy solar protons, as plausible carriers of the solar variability [*Ney*, 1959; *Markson*, 1971, 1983; *Dickinson*, 1975; *Herman and Goldberg*, 1978*b*; *Lethbridge*, 1981; *Roble and Hays*, 1982; *Ely and Huang*, 1987], this view has not yet been convincingly supported by detailed comparisons of time variations. While *Lundstedt* [1984] has made the claim that the well-known dip in VAI following SB crossings was caused by a decrease in GCR flux, *Lastovicka* [1987] has argued that this is not so, since the dip precedes the decrease.

A further examination of GCR variations and meteorological responses on the day-to-day time scale is warranted to test whether the hypothesis of GCR as carriers of solar variability can be convincingly supported by close correlations on this short time scale, as well as on the longer time scales, and to provide a larger data base of events that may provide clues to the mechanism or mechanisms linking the GCR variability to the changes in tropospheric temperature and dynamics. We will examine the tropospheric response to four sets of short-term solar variability events. Two were based on short-term increases in solar wind velocity (occurrence of "high-speed plasma streams") that either were, or were not, associated with solar flares and had larger and smaller reductions (Forbush decreases) respectively in cosmic ray fluxes. Two larger sets of events were selected purely on the basis of Forbush decreases greater than 3%. Addressing the question of the physical mechanism linking GCR to tropospheric temperature and dynamics, we will discuss GCR as carriers of both the short- and long-term solar variations in the context of possibilities for links between the resulting changes in the ionization and chemical production rate in the troposphere and lower stratosphere and in cloud microphysics and electrification processes. These could result in temperature and dynamics changes due both to a net release of latent heat, and to changes in cloud radiative forcing. Given that such processes do in fact occur, it would not seem difficult to account for intensification of cyclonic disturbances and changes in VAI and the observed longer-term changes in atmospheric distributions of temperature, pressure, and circulation.

2. RESPONSE OF TROPOSPHERIC TEMPERATURE PROFILE AND TROPOPAUSE PRESSURE TO HIGH-SPEED PLASMA STREAMS

The atmospheric response to short-term solar wind changes near the Earth has been examined using the data source of *Lindblad and Lundsted* [1981, 1983]. From their list of high-speed plasma streams (HSPS), defined by an increase in solar wind speed between consecutive days of at least 80 km s^{-1} , a set of stronger events has been selected, defined by $dV = (V_m - V_0) \geq 200$ km s^{-1} , where V_m is the maximum speed of the interplanetary plasma in the vicinity of the Earth, and

V_0 is the smallest speed on the first day. Over the period January 1966 through February 1978, there were 55 such HSPS associated with solar flares, and 196 HSPS not associated with flares. The distinction between the flare- and non-flare-related HSPS corresponds approximately to the distinction made by *Burlaga et al.* [1984] between transient shocks in the solar wind and continuous corotating high-speed streams. (Nevertheless shock-associated flows can sometimes result from mass ejections from the solar corona not associated with flares.) A number of terrestrial effects are associated with HSPS events, including magnetic storm related X ray emissions; thermal, chemical, and dynamical perturbations of the thermosphere; and penetration of fluctuating large-scale electric and magnetic fields to the surface. For many of the flare-related events there is in addition the reduction of the flux of GCR that penetrate to varying depths through the atmosphere (Forbush decreases), and for some there is precipitation of flare particles in the MeV to GeV range at high latitudes. These effects of solar wind disturbances have been described, for example, by *Akasofu and Chapman* [1972, particularly chap. 7] and more recent reviews are those in the series of U.S. National Reports to the IUGG. Thus in addition to GCR variations, there are a number of other candidates for carriers of solar variability to the lower atmosphere, and it is desirable to assess their role as forcing agents for the observed tropospheric responses.

It should be stressed that the rather extreme HSPS events selected according to the criterion $dV \geq 200$ km s^{-1} are relatively rare, only four or five of the flare-related events per year on average, and a maximum occurrence (around solar maximum) of 10 per year. We study these as diagnostics; if short-term but rare GCR changes unambiguously affect the troposphere, then 11-year and longer-term GCR changes may do so also. Of the 196 nonflare events, 55 were selected to form a comparison set, with each as far as possible a match by having about the same value of dV and occurring near to the time of a flare event. In Figure 1, from the top down, we compare superposed epoch analyses of solar wind velocity (V) in the vicinity of the Earth, solar wind magnetic field strength (B), GCR flux at the surface, and tropopause pressure, using the first day of increase of solar wind velocity as the key day (day 0). For the flare-related events (solid curve) B increased by about 4 nT on average, relative to the previous level of 5–6 nT. The peak effect is on day 0. For the nonflare events there is an increase over several days preceding day 0, and a drop of 3–4 nT afterward. The bottom panel shows that the average Forbush decrease in the GCR neutron count rate at Dourbes, Belgium, was about 1% for the flare-related events. The peak effect is on day +2, and the percentage effect at 5–20 km altitude would have been several times larger [*Simpson*, 1957; *Pomerantz and Duggal*, 1974], since the main GCR flux at these heights is at lower energies, which are more strongly affected by the interplanetary magnetic field than the higher energy flux that reaches the surface. In the case of the non-flare-related events, the GCR change is smaller and of a different shape.

The bottom panel also shows the response to the HSPS in tropopause pressure measured by radiosondes above Berlin, from the data series *Meteorologische Abhaundlungen.* There is about a 20-mbar increase in tropopause pressure on day +2 that is more than two standard deviations above the mean. The response to the non-flare-related HSPS is less than one standard deviation. The changes associated with flare-related HSPS have not been found for lower speed streams than those selected here. The tropopause response also reveals itself as a change in the vertical temperature profile, and Figure 2 shows the average temperature change for the flare-associated events computed as a function of height, obtained by subtracting the profile for day −1 from that for day +2. The response is in the form of a heating by 2°–3°C near the tropopause height ($\approx$ 12 km), and a cooling by about the same amount near 5 km, resulting in a decrease in tropopause height of about 0.7 km, which is equivalent to a pressure increase of about 20 mbar. These tropopause height and temperature changes have been confirmed by direct examination of the measured parameters.

3. RESPONSE OF VAI TO FORBUSH DECREASES

In view of the tropospheric responses in Figures 1 and 2 being associated with Forbush decreases, it was decided to use specifically the days of onset of Forbush decreases as key days in a superposed epoch analysis of northern hemisphere 500-mbar VAI responses. A table of Forbush decreases greater than 3% observed by the Mount Washington neutron monitor was used [National Geophysical Data Center, 1985]. The energy of the particles monitored lies primarily in the range 1–10 GeV. Actually, a more appropriate GCR flux to use in comparison with VAI variations would be that of about a factor of 10 lower in energy, which is the main source of ionization and a source of chemical species in the lower stratosphere and troposphere. The neutron monitor data is used as a proxy for this lower-energy GCR flux, which is supplemented at times by particles in the same energy range energized in the Sun, the solar wind, and the magnetosphere.

The results of the superposed epoch analysis for 72 events from November 1955 through April 1962, and for 106 events from May 1963 through February 1982 are shown in Figures 3 and 4, respectively. The averaged variation of GCR observed with the Climax neutron monitor is shown for the same events. The VAI responses are further separated according to whether the events occurred in the winter months (November–March) or the remainder of the year (April–October), and according to whether they occurred in the QBO west or east phases. The results show that there is in general a reduction in the VAI associated with the reduction in GCR for both the 1955–1962 and 1963–1982 periods, that this occurs mainly in the winter, and that it is present for both QBO phases. A further subdivision of the winter data into east and west QBO phases (not shown) also resulted in the VAI reduction appearing about equally strongly in each phase. These events were not selected for steady solar wind or absence of

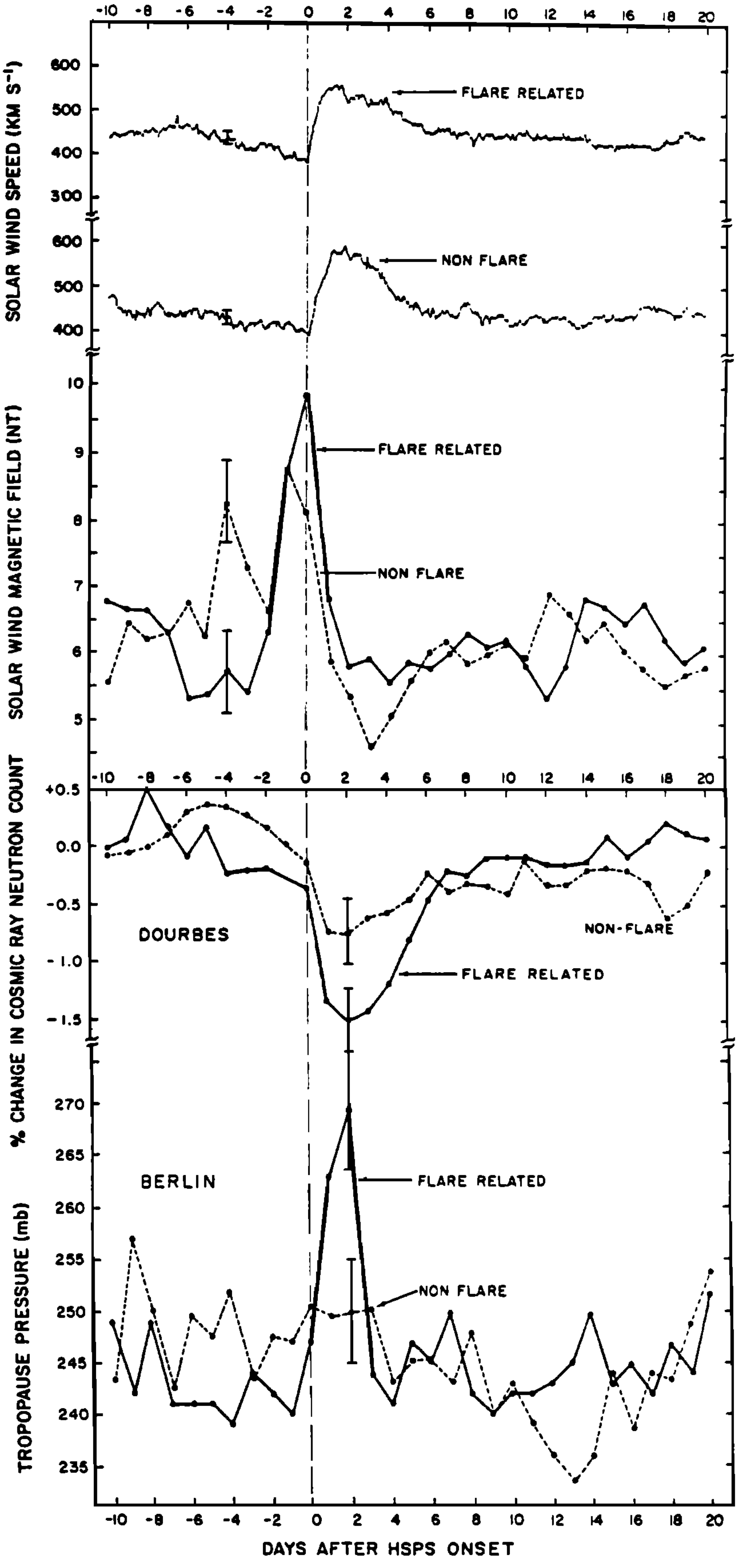

Fig. 1. Superposed epoch analysis for variability of solar-terrestrial parameters associated with 55 flare-related and 55 non-flare-related high-speed plasma streams in the solar wind, January 1966 through February 1978. (Top) Solar wind speed and magnetic field. (Bottom) Surface neutron monitor countrate from Dourbes, Belgium, and tropopause pressure from West Berlin. Length of error bars is two standard deviations.

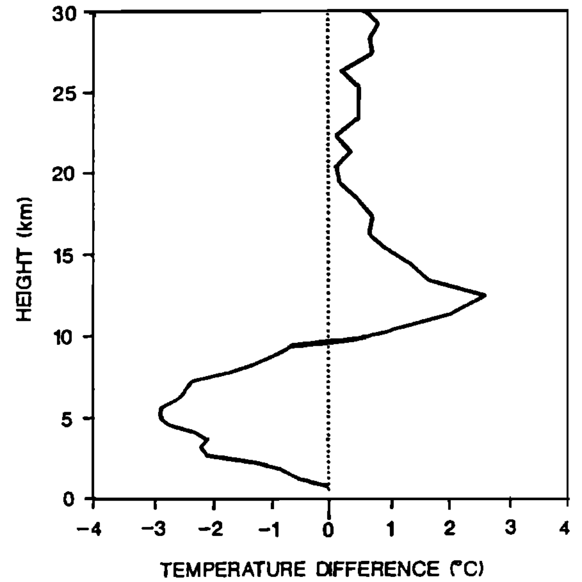

Fig. 2. Average atmospheric temperature change measures at West Berlin for the 55 flare-associated events of Figure 1, obtained by subtracting the profile for day −1 from the profile for day +2.

sector boundaries or other Forbush decreases preceding or following the event within the epoch used in the analysis, as has been the case in previous VAI analyses, and some of the "noise" in the VAI may be due to this.

If the hypothesis that galactic cosmic rays are the primary carrier of solar variability to the lower atmosphere is correct, one would expect that the VAI response to SB crossings might also be due to GCR. A comparison of GCR (Climax neutron monitor) data with northern hemisphere VAI similar to the above was performed using SB crossings as key days. The results are not illustrated here, but VAI variations showed the well-known dip [*Wilcox et al.*, 1974; *Hines and Halevy*, 1977] in the first and second days after the SB crossing. The effects were largest in winter and in the west phase of the QBO. A similarity of shape of the neutron monitor flux variation to the VAI variation was found for the 4 days preceding and 4 days following the SB crossing, which is consistent with the general hypothesis of GCR variations as the forcing agent for the tropospheric response. However, the amplitude of the average neutron monitor flux variation was only about 0.5%, and it is desirable to use balloon or satellite measurements of the low-energy (100–1000 MeV) flux, which has larger amplitude variations and perhaps a somewhat different phase relationship to SB crossings, to provide a more definitive test of the correlation.

It is of interest to know to what extent the key days of the HSPS events or the Forbush decreases coincide with each other and with those of the SB crossings. A comparison of HSPS and SB key days showed that there were 26 coinciding within ±2 days, out of 55 HSPS events and 300 SB events, from January 1966 through February 1978. A comparison of Forbush decrease and SB key days showed 34 coincidences within ±2 days, out of 102 Forbush decreases and 399 SB events from October 1965 through February 1982. A comparison of HSPS and Forbush decrease key days showed 21 coincidences within ±2 days out of 55 HSPS events and 59 Forbush decreases from January 1966 through February 1978. The data sets are thus more independent

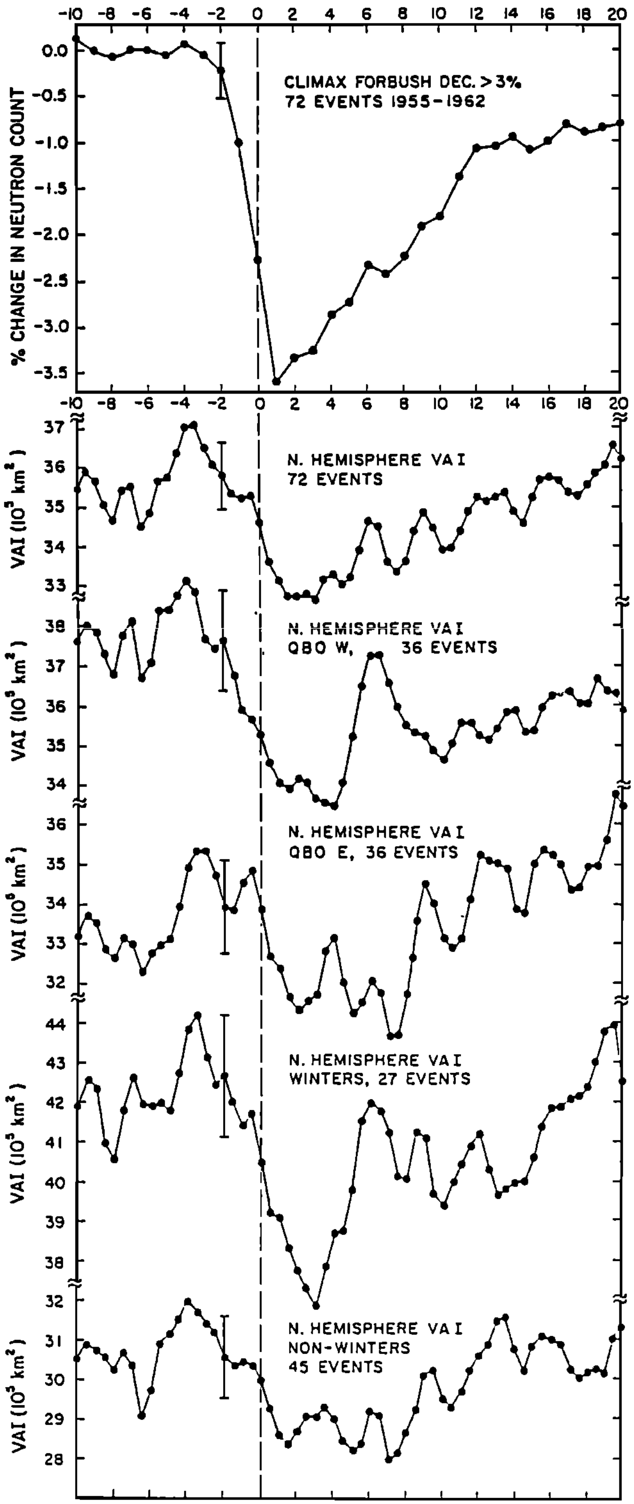

Fig. 3. Superposed epoch analysis of changes in hemispheric vorticity area index and Climax neutron monitor countrate associated with 72 Forbush decreases in November 1955 through April 1962, with breakdown by QBO phase and winter-nonwinter intervals.

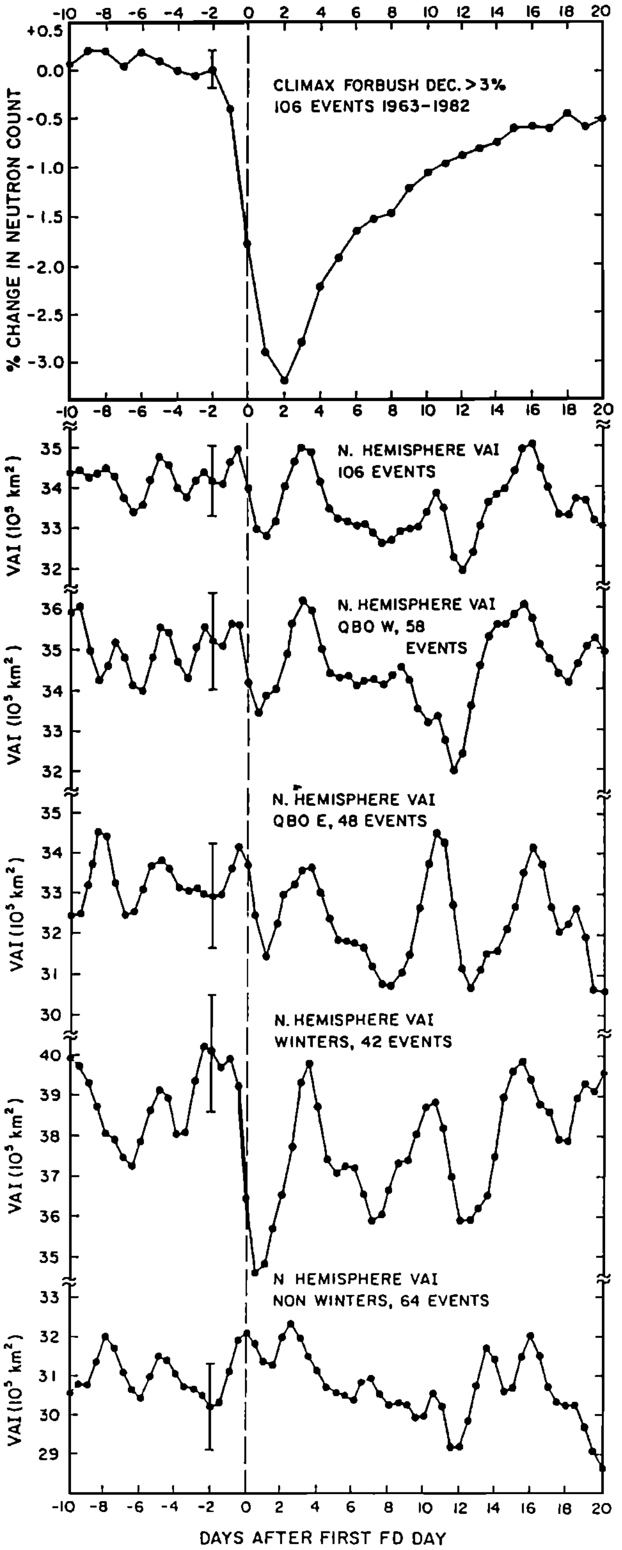

Fig. 4. As for Figure 3, except for 106 Forbush decreases in May 1963 through February 1982.

than might have been expected. Since the coincidences were spread through the ±2 -day intervals, some of the broadening of the responses and some of the noise that is apparent in a given VAI plot appear to be due to uncertainties in timing and uncertainties in identifying and isolating all of the variability in the solar carrier.

4. PLAUSIBILITY OF GCR AS CARRIERS OF SOLAR VARIABILITY TO THE LOWER ATMOSPHERE

The behavior of GCR and meteorological variables in Figures 1–4 show that GCR have appropriate time variations to be carriers of the short-term solar variability to the lower atmosphere. The responses are strongest in the winter season. An independent line of evidence that supports this interpretation is the comparison with solar flare effects. The study by *Schuurmans and Oort* [1969] of the responses to 81 large solar flares between 1957 and 1959 found a change in temperature profile with an average heating of about 1.2°C near 4 km and a cooling of about 1.7°C near 11 km, which occurred within about 6 hours of the flares. This temperature response is in the opposite sense but is otherwise very similar to the response for Forbush decreases shown in Figure 2. It was also strongest in winter. *Schuurmans* [1979] found that these flares were followed by a zonally averaged 500-mbar height decrease at high latitudes in both northern and southern hemispheres, with a height increase for the lower latitudes. This height change would be associated with a change in zonal winds and vorticity, with the effect equivalent to an increase in VAI. That flares in fact produce an increase in VAI was demonstrated by *Olson et al.* [1975], who found an increase in VAI by 5–10% on day 1 and 2 following 94 large flares in winters 1955–1969. The increase changed to a decrease on days 3–4, which is when magnetic storm activity and Forbush decreases would be occurring. Thus the dynamical response for the flares was also opposite to that for Forbush decreases. The two opposite perturbations to the temperature profiles in fact are just like those associated with the passage of surface highs and lows [*Haurwitz*, 1941].

A large fraction of solar flares are associated with proton fluxes in the 100- to 1000-MeV range that enter the high-latitude regions and have the opposite effect to Forbush decreases; that is, they increase, rather than decrease, the production of ionization and chemical minor species in the lower stratosphere. Thus we see that the flare response, combined with the Forbush decrease response, strongly supports the hypothesis that the external forcing function for the tropospheric response is particles in an energy range of approximately 100–1000 MeV. A further deduction is that several hypotheses, that magnetic storm fluctuating electric fields or keV auroral particle precipitation or other effects associated with magnetic storms are the forcing function for the short-term solar variability, are excluded by the flare response occurring in their absence. Also, the hypothesis of the forcing being due to flare X ray and UV is excluded by the absence of any (negative) excursions of these during magnetic storms. Finally, we see that the "early" and "late" effects of flares discussed by *Schuurmans* [1979] are the separate effects of flares and Forbush decreases. While the flares and Forbush decreases that we have been considering are comparatively rare, around 10 or so per year, they are important as diagnostics for understanding the longer-term tropospheric responses, since they are equivalent to the increases and decreases on the 11-year and longer time scale of the ever present low-energy GCR flux.

The question of the physical link of the MeV particle fluxes to tropospheric responses remains to be addressed. Such a mechanism is clearly going to involve a very large amplification of the energy contained in the variable component of the MeV particle flux. According to *Newkirk* [1982], the variable component of the GCR flux is of order 10^{-3} ergs cm^{-2} s^{-1}. Cloud microphysical processes could conceivably provide much of the needed amplification. The maximum changes in temperature for the Forbush decreases and flare events occurred near 12 km and 5 km, which includes the cirrus-forming height range and the height range where in regions of uplift, associated especially with wintertime cyclonic disturbances, there is latent heat release occurring from conversion of water vapor to liquid and liquid to solid. *Pauley and Smith* [1988] showed that latent heat release exerted important direct and indirect influences on the development of a synoptic-scale wave system containing an extratropical cyclone, particularly below 500-mbar (5 km), with latent heat release producing heating of up to 15°C per day. Also, changes in the production of cirrus clouds would affect albedo to visible radiation and absorptivity to infrared. Thus changes in cloud microphysical processes associated with variations in GCR ionization could significantly affect the air temperature and dynamics of a cyclone. Only very small amounts of energy are required to initiate changes in these processes, if changes in condensation nuclei or ice nuclei are involved. If electric fields are involved in the cloud microphysics, then this is the height region where the conductivity is lowest and where only a small amount of energy in the form of a change in ion production has the greatest effect on the conductivity and electric field.

An hypothesis linking the solar and cosmic ray changes on both short and long time scales to tropospheric and lower stratospheric changes is that (1) an increase (decrease) in ion and minor species production in this region is reflected in changes in cloud microphysical and cloud electrification processes, so that (2) there are changes in cloud radiative forcing, and where there is condensing vapor or evaporating droplets or supercooled water in regions such as cyclonic eddies in the jet stream, there is an increase (decrease) in the release of latent heat associated with the changes of state of water that (3) affect the vertical temperature gradient and that this in turn (4) increases (decreases) the intensity of the cyclonic eddies and thus increases (decreases) the vorticity area index. It is likely that (5) there will be associated changes in wave activity that generate a divergence in the momentum flux in the general circulation and that (6) these thereby produce latitudinal shifts in the mean latitude of the jet stream and in averages of storm track latitudes.

While changes in latent heat release would generally be associated with individual storms, this is not necessarily the case for changes in cloud albedo and absorbtivity. If these changes occur over a large region, say poleward of the jet stream, they could produce a change in temperature profile in that region that would affect the pressure gradient across the jet stream, leading to a change in the average intensity or frequency of cyclonic eddies. There is an increase in the number of low-pressure areas crossing 60°W meridian between latitudes 40° and 50°N, for the QBO west phase for minimum solar activity [*Labitzke and van Loon*, 1989], and this frequency change is associated with a downstream shift in the latitude of the jet stream and storm tracks in the eastern North Atlantic [*Brown and John*, 1979; *Tinsley*, 1988]. This frequency change may be produced by a localized latent heat release in the storms, or by a distributed effect due to cloud and radiative changes over a large area, and in either case, the association with the jet stream latitude shift can be understood theoretically if the increased frequency of lows at solar minimum (about one low every 4 days, compared to about one low every 8 days at solar maximum) leads to a greater divergence of momentum flux, by greater generation of waves, including gravity waves, that propagate out of the region. As discussed, for example, by *Hoskins* [1983, p.190–193], this will lead to a downstream poleward movement of the jet stream and storm tracks, in accordance with the observations. Also, *Pauley and Smith* [1988] found that the effect of releases of latent heat in their simulated cyclonic disturbances was to intensify the storm and cause the downwind storm track to shift poleward.

5. DISCUSSION OF POSSIBLE RESPONSES OF CLOUD MICROPHYSICS AND CLOUD ELECTRIFICATION

The purpose of this section is to point out that a number of possible cloud processes have been suggested in which amplification of a small GCR signal could conceivably influence latent heat release and the radiation balance, through changes in cloud albedo and absorptivity. However, there is a lack of definitive observations and accepted theoretical models for the cloud electrification and cloud microphysical processes involved, which would permit evaluation of the effects of variable ionization and chemical production by low-energy GCR. Thus it is difficult to show that any specific cloud microphysical process responding to GCR variability would produce the observed atmospheric dynamical responses, and it is not the intent to evaluate the likelihood of any here. It is not the case that general limits on available energy or on amplification factors have been established that would rule out such processes. Research on a broad front is required to evaluate a number of speculative processes, of which the following is a sample related to the changes by a few tens of percent in ion production and ion concentration and conductivity in the upper troposphere and lower stratosphere:

5.1. Changes in Electric Fields

These have been discussed by *Roble and Hays* [1982], *Roble* [1985], *Herman and Goldberg* [1978*b*], *Markson and Muir* [1980], and *Markson* [1981, 1983]. Increases in conductivity above electrified clouds result in a greater charging current to the highly conducting "electrosphere" above 20 km, which inreases the global vertical electric field that is considered in many theories of cloud electrification to be amplified in cloud electric fields [*Beard and Ochs*, 1986, Table 9.1; *Krehbeil*, 1986]. Increases in lower troposphere fields and decreases in higher-altitude fields could result. Changes in cloud electrification fields in storms could affect cloud microphysics, such as the rate of coalescence of small drops into larger ones [*Freire and List*, 1979], and thus cloud albedo and infrared absorptivity, in addition to affecting the rate of reevaporation and precipitation and the net latent heat release of the storm. But, as discussed by *Beard and Ochs* [1986], much more research is needed before cloud electrification processes can be said to be understood.

5.2. Changes in Vertical Transport of Charged Particles and Water

The increase in conductivity and associated increase in global vertical electric field [*Markson*, 1981, 1983] must increase vertical ion transport. *Ely* [1979] suggested that changes in the fair-weather electric field would produce changes in water vapor mixing ratio in the cirrus-forming region, as water became attached to ions moving through the region. A much stronger effect would occur above thunderstorms, where the electrosphere-charging current ($\approx$ 1 A per storm) and potential difference ($\approx 10^8$ V) could produce a rapid exchange of tropospheric and stratospheric ions and charged aerosols and water that becomes attached to these particles. The effect of this transport on the formation of fair-weather and thunderstorm cirrus and on cloud microphysics within storms remains to be worked out.

5.3. Changes in Nucleation Processes

In the height range 10–15 km at high latitudes, the major producer of nitric oxide and related compounds (in addition to ionization) is GCR [*Nicolet*, 1975], with a maximum at solar minimum. At higher altitudes several other sources predominate that maximize at solar maximum. The extent to which the concentration of, say, HNO_3 in the high-latitude winter stratosphere reflects these changes in production rate depends sensitively on transport processes [*Garcia and Solomon*, 1983; *Jackman et al.*, 1987]. These transport processes are not well known, and high-latitude observations in the lower stratosphere are not in good agreement with models [*Jackman et al.*, 1987]. It has been hypothesized that aerosols that act as condensation or ice nuclei may grow from cluster ions containing nitrate ions and nitric acid and sulphuric acid and water, as multiion complexes (MIC) [*Arnold*, 1980; *Heitman and Arnold*, 1983]. Also, small sulphuric acid aerosols can grow by absorption of the nitric acid [*Tolbert et al.*, 1988] and, presumably, by absorption of MIC. The size distribution of cloud particles is responsive to the concentration of condensation nuclei, and the size distribution may affect the rate of coalescence and reevaporation. Again, there are large uncertainties in the composition of condensation and freezing nuclei, and further research is needed in this area as well.

The long-term variations for winter are fundamentally affected by the QBO. Speculative processes include differences in the way in which the short-term changes in cyclonic activity affect atmospheric circulation through dynamical interactions with the stratosphere, which undergoes QBO variations. Related effects have been discussed by *Dameris* [1988]. Chemical effects are also plausible. *Gray and Pyle* [1989] have shown that near the equator the east and west phases of the QBO are associated with upward and downward transport, respectively. Any resulting changes in minor constituents could be carried to high latitudes by the general equator-to-pole stratospheric circulation. *Newell et al.* [1969] have shown that there are significant changes in temperature in the tropical troposphere and stratosphere on the QBO time scale. Recently, *Hamill and Fiocco* [1988] have suggested that the temperatures at the tropical tropopause are low enough for the formation of "polar" stratospheric clouds that could freeze out HNO_3. Even at higher altitudes and middle latitudes, where stratospheric temperatures are higher, the QBO-related temperature changes are likely to affect the absorption of NO and its derivatives on sulphate aerosols [*Tolbert et al.*, 1988]. Thus there is the possibility that the equatorial QBO and the still unexplained high-latitude QBO contribute to cloud microphysical changes by variations in the transport of minor constituents that become incorporated into stratospheric aerosols, and thence into condensation and freezing nuclei. The lifetime of HNO_3 in the upper troposphere and lower stratosphere is months to years, and the lifetime of ions is only a few hours. Thus while in the short-term the atmospheric responses may be due mainly to changes of the ion concentration, the longer-term responses may depend also on transport of the minor neutral constituents, as affected by the QBO.

6. CONCLUSIONS

The present work has shown that the hypothesis that low-energy (about 100–1000 MeV) GCR, supplemented occasionally by other particles in the same energy range, are carriers of solar variability to the lower atmosphere is supported by close correlations on three time scales: (1) a few days (2) 11-years, as modulated by the 2.2-year QBO, and (3) of the order of a century. The opposite tropospheric responses found for Forbush decreases, as compared to solar flares, greatly strengthens this hypothesis, while excluding other candidates for carriers. While the mechanism or mechanisms linking GCR changes to weather and climate responses have not been identified, this can be attributed to current uncertainties regarding the microphysical and electrical processes of aerosols and clouds, and their responses to changes in stratospheric ionization.

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