FORCING OF CLIMATE VARIATIONS BY MeV-GeV PARTICLES?

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ABSTRACT

There are three time scales for correlation of MeV-GeV particles (galactic and solar) with changes in the sun, and with weather and climate:

A. DECADAL/INTERANNUAL (with 11 and 22 year solar cycles and QBO),
B. CENTURY SCALE (with Maunder minimum etc.),
C. DAY TO DAY (with coronal mass ejections, solar wind sector structure etc.)

Day to day correlations are not understandable in terms of total solar irradiance or UV changes; but are understandable as solar wind/particle forcing. If solar wind/particle forcing can produce short term weather responses, it could also produce decadal and longer term climate responses. A possible chain of amplifying and coupling mechanisms involves: stratospheric ionization, electric fields and chemistry; aerosol nucleation; sublimation, freezing and condensation nuclei; cloud microphysics and particle size distributions; winter storm intensification; and changes in circulation.

CORRELATIONS ON THREE TIME SCALES

Examples of tropospheric correlations with solar and cosmic ray variability on the decadal/interannual time scale are given in Figure 1. Solar variability is represented by sunspot number. Changes in GeV particles are represented by both surface neutron monitor count rates (NGDC, 1989) and by the lower stratospheric flux of particles above about 500MeV energy for which data is from Soviet daily balloon measurements at Mirny and Murmansk (Lebedev Inst., 1968-73 and IZMIRAN 1972-89) together with measurements from Thule (Neher, 1971). The change in the MeV flux over the 11 year solar cycle is about 40%. Changes in tropospheric circulation and temperature are represented by the latitude shift in winter storm tracks in the eastern North Atlantic (Brown and John, 1979, and John, 1989, 1990); the frequency of winter cyclonic storms in the western North Atlantic for winters when the equatorial stratospheric winds are from the west (QBO West phase) (Labitzke and van Loon, 1989; John, 1990); and in winter surface temperature at eastern North American stations for QBO west phase (van Loon and Labitzke, 1989). The correlation in smoothed storm track latitudes with sunspot number for six cycles should be enough to rule out the accidental coincidence of decadal scale variations (Pittock, 1978). The storm track latitude shifts in the west phase of the QBO are about twice those in the smoothed data (Tinsley, 1988; John, 1990), but since the QBO phase is only known after 1952, we show the whole time series with east and west phase winters averaged with a five year running mean, with individual west phase winters superimposed after 1952. It is apparent that other sources of variance on the decadal/interannual time scale are of comparable importance to the presumed solar forcing, with candidates being volcanic activity, the El Nino-Southern oscillation, and internal variability. For the winter of 1989 the La Nina forcing appears to have dominated (Barnston and Livesy, 1989), however the 1990 winter (not shown) follows the solar variability trend, with storm tracks well south in the eastern Atlantic.

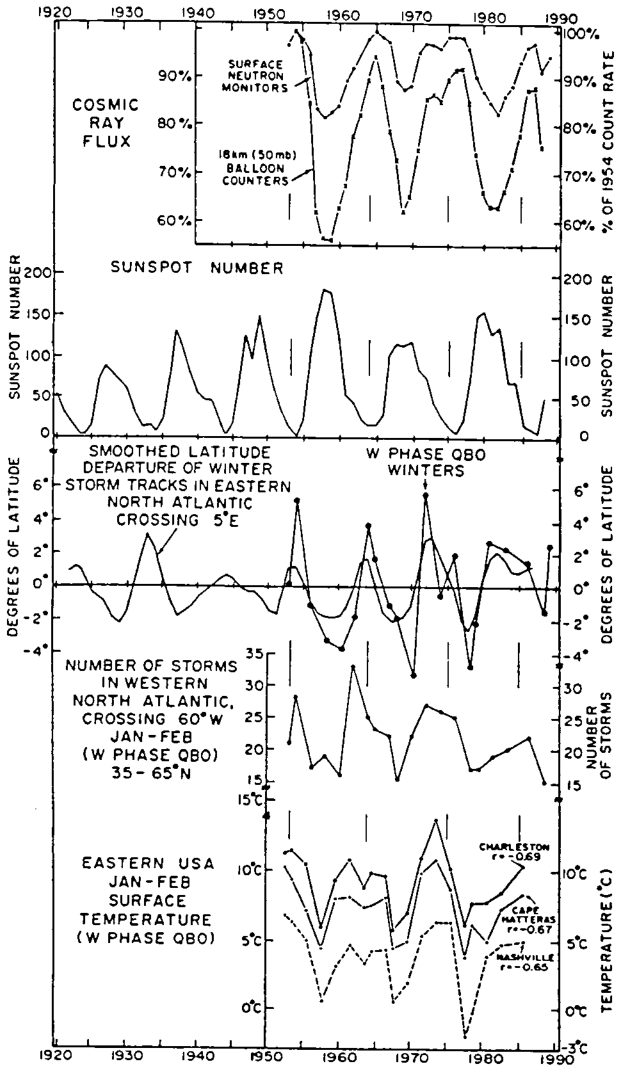

Figure 1. Correlation of solar and cosmic ray variability with tropospheric dynamics and temperature on the decadal/interannual time scale. The cosmic ray flux is from the Climax neutron monitor and daily Soviet Arctic and Antarctic balloon measurements supplemented by Thule measurements. The storm track latitudes are smoothed values for winter storms crossing 5°E above 50°N latitude, with unsmoothed values for QBO west phase winters superimposed. The storm frequencies are for those crossing 60°W between 35°N and 65°N for QBO West phase. Surface temperatures in Eastern North America are also for QBO west phase winters. See text for details and sources.

Evidence for solar variability on the century time scale and for tropospheric response to it was first given by Eddy (1976) relating solar variability in terms of the Maunder Minimum in sunspots to the "Little Ice Age" in northern Europe. The correlation was extended to earlier epochs with Carbon 14 concentrations as a proxy for solar variations, and indices of winter severity and glacial advance representing climate variations. It should be noted that Carbon 14 is a record of actual solar wind/GeV particle changes, and only by inference an indicator of possible irradiance and UV changes. Measurements of Beryllium 10 concentrations from Greenland ice cores (Attolini, et al., 1988) have shown an increase during the Maunder Minimum of 70% above the levels before and after, demonstrating directly that tens of percent changes occur in the GeV particle flux on the centennial as well as the decadal time scale.

On the day to day time scale, the first study showing a relationship of tropospheric storm intensification to the magnetic storms produced by coronal mass ejections was made by McDonald and Roberts (1960) for storms in the Gulf of Alaska. Figure 2 is from a recent study by Tinsley et al. (1989) relating high speed plasma streams in the solar wind (from coronal mass ejections) to changes in tropopause pressure over Berlin. The effect is clear over northern Europe,

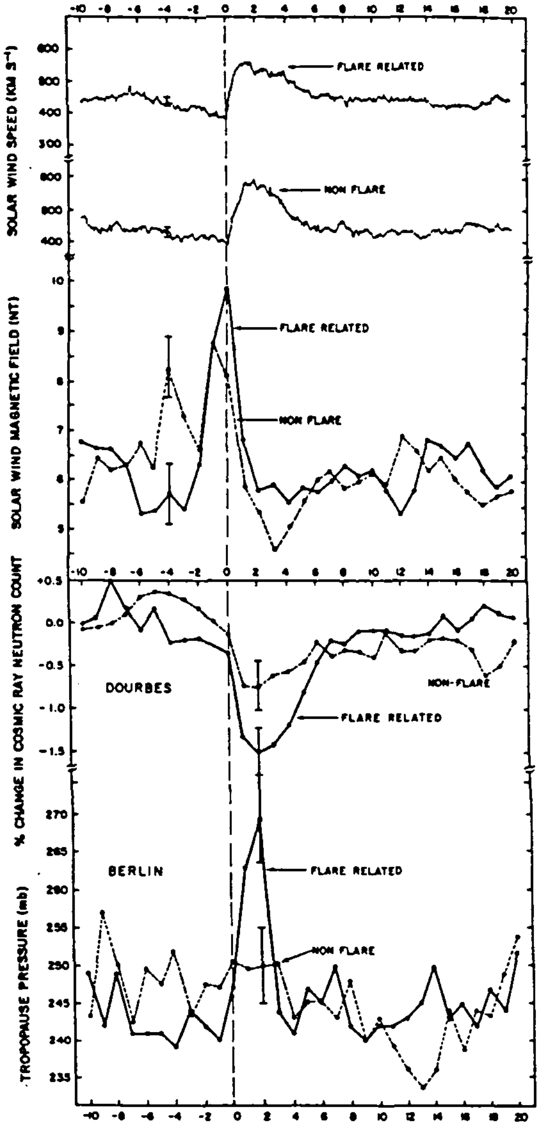

Figure 2. Superposed epoch analysis for variability of solar-terrestrial parameters with key days (day 0) the days of arrival of 55 flare related and 55 non flare related high speed plasma streams in the solar wind, Jan. 1966 through Feb. 1978. Upper panel, solar wind speed and magnetic field; lower panel, surface neutron monitor count rate from Dourbes, Belgium, and tropopause pressure from West Berlin. Length of error bars is two standard deviations.

corresponding to an increase in temperature by 2-3^0 C at the 200 mb level, and a decrease in temperature by about the same amount at the 500 mb level. The change on the day-to-day time scale in the MeV-GeV particle flux precipitating into the stratosphere that is associated with these events is known as a Forbush decrease in the cosmic ray flux. To test how well the troposphere responds to such particle flux changes in comparison to other inputs related to short term solar variability we have constructed Figures 3 and 4. Figure 3 contains superposed epoch plots with the key days (day 0) being the days of onset of Forbush decreases greater than 3% (NGDC, 1985). The particle fluxes are represented by the Climax neutron monitor count rate and the polar cap stratospheric balloon particle counters as in Fig. 1. The Ap and F10.7 cm indices represent the variation of geomagnetic activity and solar ultraviolet variations respectively. The tropospheric response is represented by the average over the northern hemisphere of the 500 mb Vorticity Area Index (VAI) (Roberts and Olson, 1973) which is a measure of the strength of cyclonic disturbances. The numbers in parenthesis are the numbers of events, which are different for different parameters on account of missing data. The comparison of the tropospheric variations for winter months (November through March) as compared with non-winter months shows that, consistent with earlier analyses, the characteristic dip in VAI on days 1 and 2 following the key day is a wintertime effect.

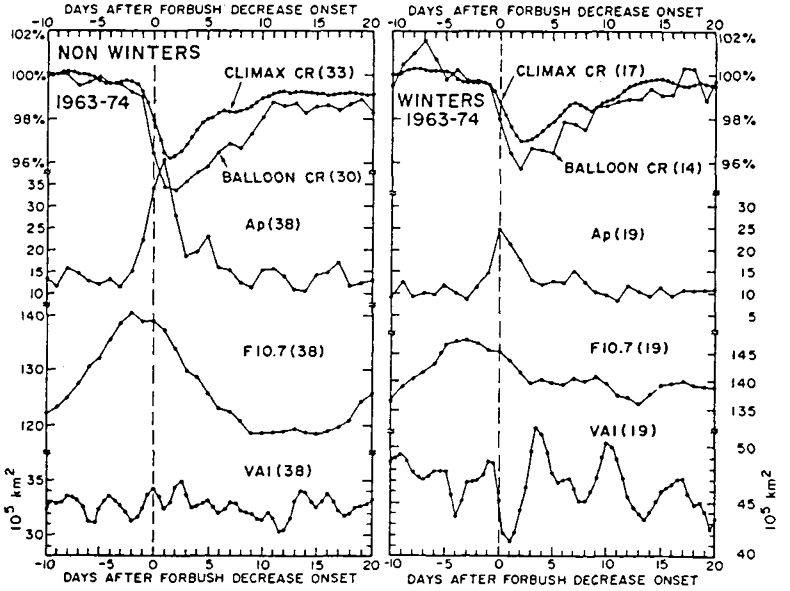

Figure 3. Superposed epoch plots with the key days (day 0) being the days of onset of Forbush decreases at Mt. Washington greater than 3%. The particle fluxes are represented by the Climax neutron monitor count rate and the polar cap stratospheric balloon particle counters as in Fig. 1. The Ap and F10.7 cm indices represent the variation of geomagnetic activity and solar ultraviolet variations respectively. The tropospheric response is represented by the average over the northern hemisphere of the 500 mb Vorticity Area Index.The numbers in parenthesis are the numbers of events, which are different for different parameters on account of missing data. Results for winter months (November through March) in the left panel are compared with non-winter months in the right panel.

Figure 4 contains superposed epoch plots with the key days in the top two panels being the days of onset of Forbush decrease as before, and in the lower two panels the key days are the days of onset of magnetic storms with a Ci increase greater than unity (Stolov and Shapiro, 1974). Other quantities are as in Figure 3. The hypothesis that short term tropospheric forcing is due to solar UV irradiance changes (represented by F10.7 cm variations) can be seen from Fig. 3 to be not supported, due to their longer time scale, which is essentially the time scale for solar rotation. While the F10.7 index does not always accurately represent the amplitude of solar UV variations, it does have the same time scale for variations (Barth et al., 1990).

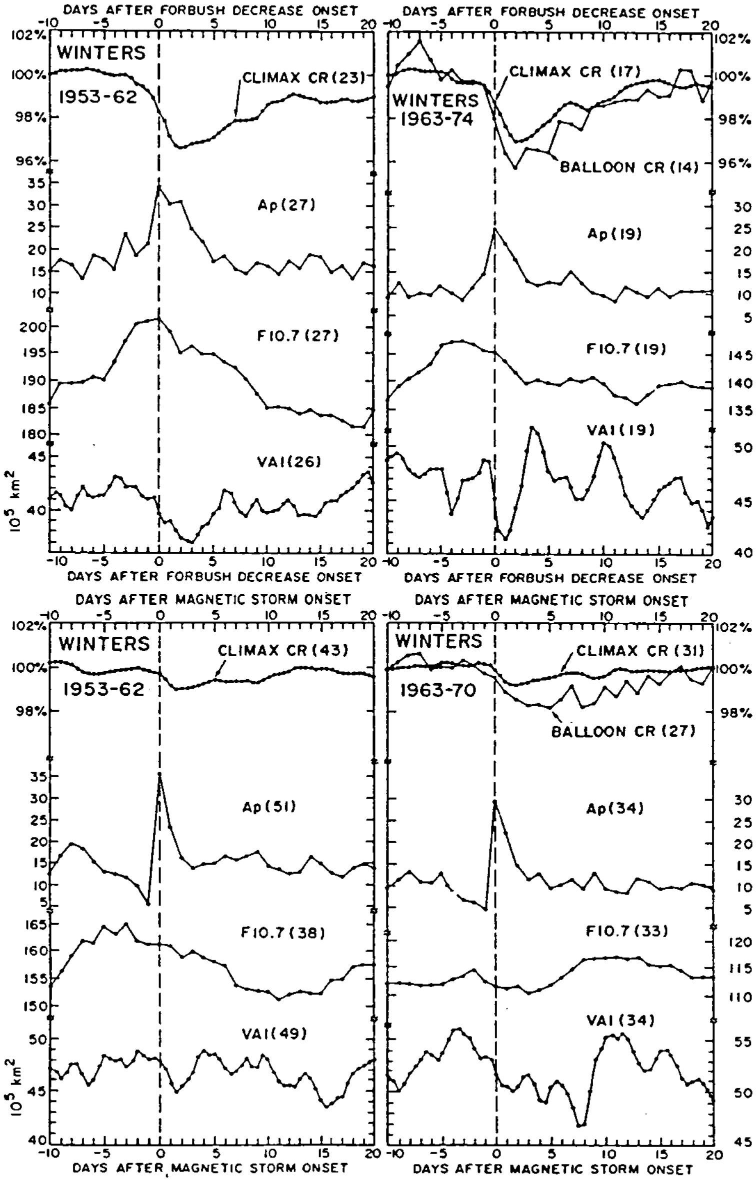

Figure 4. Comparison of superposed epoch plots using Forbush decrease days as the key days (top panels) with plots using days after magnetic storm onset (lower panels) as key days. The left panels are for winter months 1952-62, and the right panels for 1963-74. Otherwise the format is as for Fig. 3. See text for details.

The Ap index variation provides a test for possible forcing by magnetic-activity-related effects associated with the coronal mass ejections, e.g. bremmstrahlung X-ray radiation from the precipitation of keV electrons, or from large scale magnetospheric convection electric fields. We see that with keying by Forbush decrease there is a significant dip in the hemispheric VAI on days 1 and 2, for 1953-62 as well as for 1963-74. In the bottom two panels, the selection for and keying on the days of onset of the magnetic storms has strengthened and sharpened the Ap variation, but smeared out and weakened the Forbush decrease variation, compared to the top two panels. It has also weakened the dip in VAI on days 1 and 2. This is evidence that the forcing is by particles, and not by other inputs related to magnetic activity.

The same transient response of the VAI (a dip on days 1 and 2 following the key day) is found when the key day is the day of a solar wind magnetic sector boundary crossing (Wilcox et al. 1973). There is a transient decrease of about 0.5% in the cosmic ray flux from day -1 to day +2 (Schuurmans and Tinsley, 1989), making the particle flux to VAI relationship similar to that for the Forbush decreases. Figure 5 compares the variations in superposed epochs for the years 1953-62, 1963-74 and 1975-82. The sector boundary effect on cosmic rays was reduced and of a different character before 1963 and after 1974, as also was the Ap response and the VAI response. Thus any solar wind forcing related to its sector structure must be considered non-stationary, and the weakness or absence of a tropospheric correlation after 1974 should not be used to discount the significance of the correlation for 1963-74.

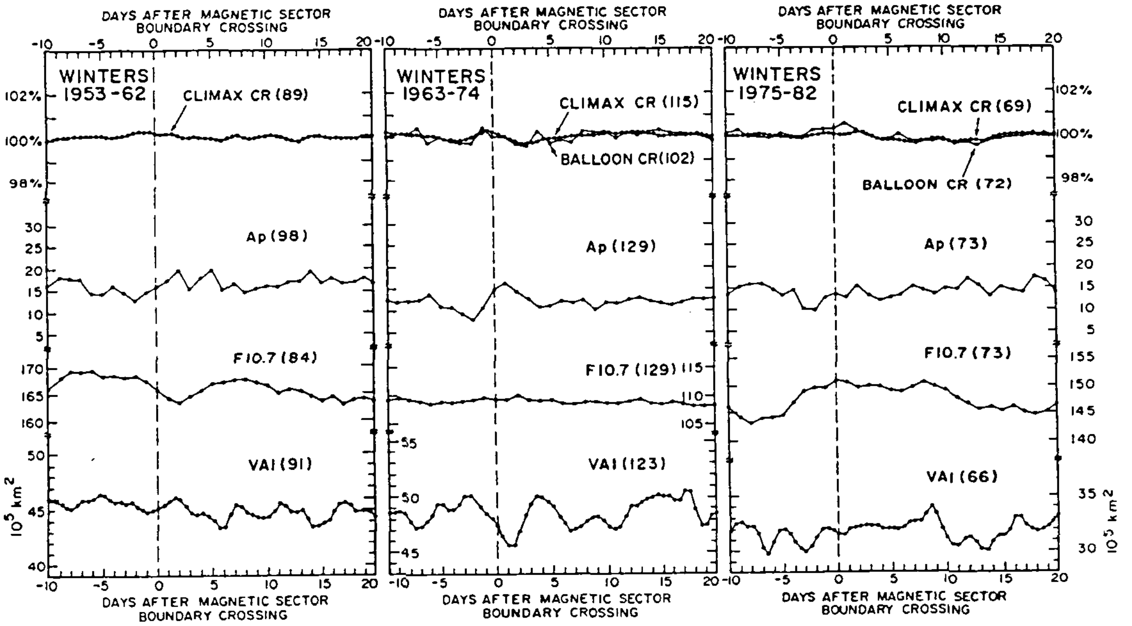

Figure 5. Comparison of superposed epoch plots with key days being the days of solar wind magnetic sector boundary crossing, for winter months. Panels from left to right are for 1953-62, 1963-74, and 1975-82. Otherwise the format is as for Fig. 3. See text for details.

DISCUSSION

The tropospheric changes on a timescale of 1 or 2 days following the arrival of coronal mass ejections at the earth do not seem understandable in terms of forcing by total solar irradiance or UV changes, which have a timescale related to solar rotation and development of active regions of a week or more. If, as seems more likely, solar wind/particle forcing is producing short term weather responses with particle flux changes of less than 10%, then the decadal and century timescale changes in flux by tens of percent should be capable of producing the observed longer term climate changes.

The question remains of the intermediate mechanisms involved. We have been approaching it from two directions; from the sun and from the troposphere, with the aim of converging on a candidate set of coupling and amplifying processes, perhaps in the stratosphere. From the solar end, for short term forcing, we have concluded that solar wind modulation of MeV-GeV particle precipitation into the stratosphere is the best supported candidate. From the tropospheric end, the analysis of Hines and Halevy (1977) of the related VAI response to solar wind magnetic sector boundary crossings indicates that the tropospheric effect is an amplification of a pre-existing dynamical variation, rather than the generation of a new variation. The latitude shifts of storm tracks shown in Figure 1 are explainable in terms of the intensification of cyclonic storms (through changes in the parameters of the feedback processes involved) with changes in the momentum radiated out of the jet stream by waves (Tinsley et al. 1989). The observed decreases in VAI on the short time scale are equivalent to the reduction in storm frequency at solar maximum on the decadal time scale, as shown in figure 1. The situation as discussed above is represented in Figure 6.

An enhancement in a positive feedback process for winter storms in the Gulf of Alaska and the North Atlantic (the longitude region at highest magnetic latitude where cold continental air encounters a relatively warm ocean, with significant potential for diabatic heat release) could provide the necessary amplification. Thus we are led to consider whether particle precipitation could affect storm cloud processes. There are two broad categories of mechanisms that have been suggested that could produce changes in clouds. These are represented in the two branches inside the speculative box of Figure 6. Changes in atmospheric electric fields are produced by changes in precipitation affecting conductivity in parts of the global electric circuit. Changes in ions are involved in the suggestion by Dickinson (1975) that ion induced nucleation might compete with homogeneous nucleation of H_2SO_4 aerosols from the gas phase. Some support for this has come from the inference that homogeneous and perhaps ion induced nucleation of gaseous H_2SO_4 is occurring in the winter Arctic and Antarctic stratospheres (Hoffman, 1990; Hamill et al. 1990; see also Rosen and Hoffman, 1983). In addition, particle precipitation would increase the production of OH and the conversion of SO_2 to H_2SO_4 (see Herman and Goldberg 1978, p 262-3). Also, under conditions of severe denitrification, the production of NO_x might increase the production of the nitric acid trihydrate aerosols of type I polar stratospheric clouds. Since both sulphate and nitrate aerosols act as efficient condensation nuclei, and perhaps also freezing and ice nuclei, they can affect cloud processes when present in potential cloud forming regions.

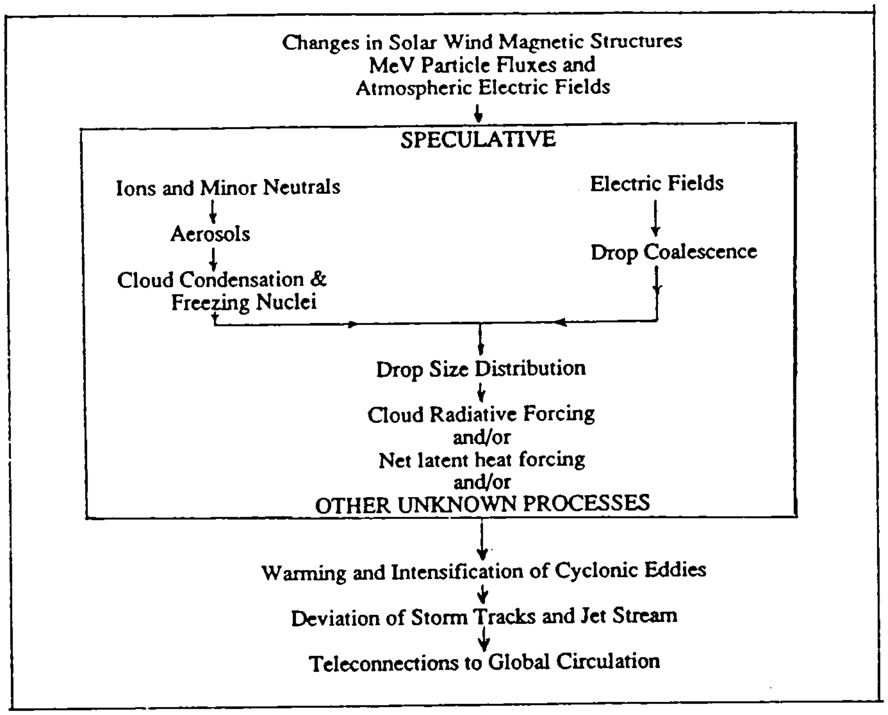

Figure 6. Possible relationships between forcing by solar wind magnetic structures, producing changes in MeV-GeV particle precipitation, atmospheric electric fields, aerosol and cloud microphysical processes, and tropospheric temperature and dynamics.

In the region of winter cyclones tropopause fold events are likely to occur (Browell et al., 1987) with the transport of cold humid tropospheric air into the stratosphere. On the contact surface with the condensation nuclei-rich stratospheric air a layer of cirrus may form that would be enhanced for higher ionization rates. Or merely the horizontal advection of low latitude (high tropopause) air into high latitude (low tropopause) air could provide the same contact. One possibility is that enhanced high cloud opacity would trap heat in the cyclone, which would increase the vertical advection and release of latent heat. Another is that sedimentation from the high cirrus would affect the particle size distribution and precipitation and re-evaporation of cloud droplets, and thus the net release of latent heat at lower levels. Such latent heat would feed back into intensifying the cyclone (Pauley and Smith, 1988). All such mechanisms must remain speculative until data is available on the response of clouds in such storm systems to changes in ionization and electric fields. It is also possible that aerosol transport processes with longer time scales may affect cloud opacity and albedo on longer time scales, and affect regions outside of cyclones.

CONCLUSIONS

Changes in ionization production in the lower stratosphere by a few percent during Forbush decreases have been shown to correlate well with changes in winter tropospheric dynamics by a similar relatively small amount. Changes in ionization production by tens of percent on the decadal time scale have been shown to be correlated with changes in winter storm frequencies by tens of percent in the western North Atlantic. Changes in total solar irradiance or solar UV do not have time variations to match the tropospheric variations on the day to day time scales discussed here. Forcing related to magnetic activity is not supported. Thus solar wind/MeV-GeV particle changes appear to be the only viable forcing function for these day to day variations. If solar wind/particle forcing of a few percent amplitude can produce short term weather responses, then observed changes by tens of percent on the decadal and centennial time scale could produce climate changes on these longer time scales. The changes in circulation involved would produce regional climate changes, as observed.

At present the relations between stratospheric ionization, electric fields and chemistry and aerosol and cloud microphysics are poorly known, as also between the latter and storm feedback processes. However, the capability for investigating these relationships now exists, and has recently been most successfully used for elucidating the stratospheric chemistry and cloud microphysics associated with the Antarctic ozone hole. The economic benefits of being able to predict winter severity on an interannual basis, and the extent to which climate change related to solar variability will add to or subtract from the greenhouse effect, should be more than adequate to justify support for research in this area.

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