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The links between atmospheric vorticity, radiation belt electrons, and the solar wind

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Abstract

The links between winter storm intensity and solar wind variations associated with Heliospheric Current Sheet (HCS) crossings are shown to be present in 1997 through 2002 data without the necessity of high stratospheric aerosol loading.

The peak values of winter storm vorticity are measured in terms of the 500 hPa vorticity area index (VAI) for the Northern Hemisphere, during extended winter months, November through March. Superposed epoch analyses are used, but instead of the key days being defined by heliospheric current sheet crossings as used formerly, they are defined by minima in the absolute flux of relativistic electrons (REF) > 2 MeV measured at geostationary orbit. Minima in the VAI were found approximately 3 days after the REF minima. Corresponding VAI minima were also found in response to the deepest minima in the solar wind speed (SWS). The SWS minima occurred approximately 2 days before the REF minima, and 5 days before the VAI minima. These results for the 1997–2002 period of low to moderate stratospheric aerosol loading are compared to periods of high loading that occurred between 1964 and 1994. The weaker VAI response in 1997–2002 is evidently due to the reduced aerosol loading, but there is uncertainty in the amount of weakening, due to the greater sensitivity gained by analyzing with respect to the deepest minima in REF or SWS rather than to times of HCS crossings, and the possibility of secular changes in the solar wind and in the magnetospheric relativistic electron populations.

Keywords: Atmospheric vorticity; Radiation belt electrons; Solar wind

1. Introduction

Correlations between winter storm vorticity changes, in November through March in the Northern Hemisphere, and solar wind magnetic sector boundary crossings (now known as HCS crossings) were demonstrated by Wilcox et al. (1973, 1974) and confirmed by Hines and Halevy (1977). The vorticity changes were objectively evaluated from global data bases of gridded atmospheric parameters in terms of the vorticity area index (VAI) as defined by Roberts and Olson (1973). The HCS crossings can be identified either from spacecraft measurements of the solar wind magnetic field, or from high latitude magnetometer signatures (Svalgaard 1971, 2011). The vorticity responses to the solar wind have small amplitude relative to their day-to-day changes, and it is necessary to make superposed epoch analyses of tens of events to demonstrate their presence. The VAI response was undetectable for a time after the mid-1970s, but was shown by Tinsley et al. (1994), Kirkland (1996), and Kirkland et al. (1996) that detectability varied with the extent to which there was a loading of the stratosphere with aerosols generated by large sulfate-containing explosive volcanic eruptions, notably Agung (from 1964), El Chicon (from 1983) and Pinatubo (from 1992). They also showed that the HCS crossings were associated with decreases of order 20%, lasting a few days, of the solar wind speed (SWS). During these decreases the relativistic electron flux (REF) precipitating from the radiation belts decreased, as

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did the ionosphere-earth (to land and ocean) current density (J_z) that flows through clouds as part of the global electric circuit. The association between HCS crossings and the SWS, REF and VAI decreases is illustrated in Fig. 1 (from Kirkland, personal communication, 1996, and Tinsley, 2005), which will be discussed in detail later.

The decreases in J_z associated with HCS crossings SWS and REF decreases are hypothesized to be due to changes in stratospheric column resistance (that is increased by volcanic aerosols); the changes are caused by the ion production in the stratosphere from the REF precipitation, as was modeled by Tinsley and Zhou (2006). The flow of J_z through clouds creates layers of space charge in accordance with Ohm's Law and Gauss's Law, due to the current density encountering gradients of resistivity caused by gradients in droplet concentration at cloud boundaries and within cloud structures (Tinsley et al., 1994). The electric charge on aerosol particles (especially cloud condensation nuclei and ice-forming nuclei) affect their interaction with droplets, and this interaction is qualitatively capable of explaining the observed responses of storm dynamics that are measured by the VAI to HCS crossings. In addition the VAI has been shown to respond to Forbush decreases of the galactic cosmic ray flux and to solar energetic particle events; both of which change J_z. Other meteorological parameters that are affected by cloud microphysical changes, such as cloud cover, surface pressure, and geopotential height, have been found to respond to changes in J_z or to HCS crossings (see reviews by Tinsley (2000, 2008 and references therein)).

Further analysis of the VAI responses to HCS crossings, using the ECMWF ERA-40 gridded meteorological reanalysis data set (instead of the NCEP-NCAR data used previously) was made by Prikryl et al. (2009a). They found VAI reductions at HCS crossings, not only for years of high volcanic aerosol loading, but for intervening years as well. In addition, they found similar responses in the Southern Hemisphere during the extended winter there (May through September). However, Prikryl et al. (2009a,b) offer an alternative mechanism for connecting the solar wind changes to the winter atmospheric vorticity changes; they hypothesize that atmospheric gravity waves are generated by energy input to the auroral ionosphere associated with HCS crossings, and that these propagate to low altitudes and low latitudes, with sufficient amplitude to trigger changes in the dynamics of winter cyclones.

In this paper we explore the VAI response to solar wind inputs during a low-to-moderate stratospheric aerosol period 1997–2002, and examine the detectability of the response. The VAI is calculated from relative vorticity of the ECMWF ERA-40 data set as it was defined by Roberts and Olson (1973a,b). However, instead of using HCS crossings as key days, we use the dates of minima in the SWS, and then, as an alternative, use the dates of minima of REF. On average, minima of SWS and REF occur within a few days of HCS crossings, as illustrated in the top two panels of Fig. 1, but individually this is not always the case. The hypothesis developed by Tinsley and Zhou (2006) is that the REF is the essential link between the solar wind and the VAI, with the REF being modulated by changes

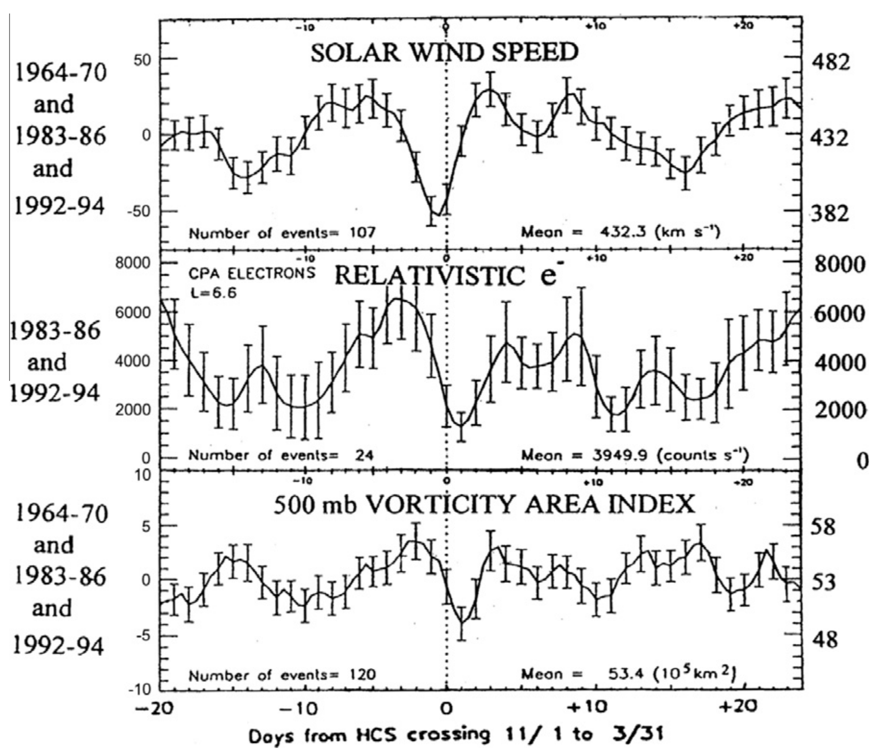

Fig. 1. Superposed epochs of (top) solar wind speed, (middle) MeV electrons at geostationary orbit, (bottom) 500 hPa Northern Hemisphere VAI. The key days were for HCS crossings during the extended winter (November through March), only in years of high stratospheric aerosol content during 1964–1994 as indicated on the left. Missing data for solar wind speed and for relativistic electrons gave a smaller number of epochs than the 120 HCS crossings.

in the SWS and other magnetospheric conditions, that are only approximately aligned with the HCS crossings. This suggests that using minima in the SWS rather than HCS crossings as key days should provide better alignment, i.e., more sharply focus the VAI responses. Going further, it suggests that using minima in the REF rather than in the SWS should provide even better alignment and selection of the deepest minima. Also, the use of SWS or REF minima rather than HCS crossings as key days allows us to examine the VAI response as a function of the absolute value of the SWS or REF at their minima.

Because the greatest reduction in J_z occurs with the greatest increase in stratospheric column resistance (S), which is in series with the tropospheric column resistance (T), and because the greatest increases in S occur with the greatest reductions in the absolute value of the REF, one expects the greatest VAI response with the deepest minima in the absolute REF, rather than in the minima with the greatest percentage reduction in REF relative to the preceding and following levels. As discussed by Tinsley and Zhou (2006), $J_z = V_i/(T + S)$, where V_i is the ionospheric potential, and only variations in S when its value is not negligible compared to T will affect J_z and clouds. In the first part of the analysis we identify minima in the SWS as a function of relative amplitude, and show the responses of both the REF and VAI to them. Then we independently identify minima in the REF, and sort them into two ranges, according to the absolute REF at the minima, and show the response of the VAI to the minima in each range.

2. Results

Fig. 2 shows sets of superposed epochs of the SWS daily time series with respect to key days which are its own minima. The minima and their relative depth are selected with reference to a sliding window of 13 days, with the preceding and following 'shoulder' values (p_s) being the mean for days 1 through 3 and 11 through 13, and the deviation from the shoulders (p_m) being the mean for days 6 through 8, so that the percentage deviation is: $y = ((p_m - p_s)/p_s) \times 100\%$.

The deviations can be positive or negative, and in Fig. 2(a) all 448 negative deviations for all months are used as key days for a superposed epoch analysis of ±30 days, extending before and after the key day. It can be seen that in addition to the main deviation, on days dropping to an average minimum of about 370 km s^{-1}, weak minima around days ±27 are present, related to the 27-day rotation period of the sun, and the tendency for solar coronal structure to persist from month to month. In Fig. 2(b) the superposed epochs are selected for the extended winters (November–March), and the minima are 'dispersed', i.e., in the many cases where the spacing of the minima is 5 days or less, the deepest minimum is selected. These, and the rejection of incomplete epochs near the ends of the seasonal intervals, reduce the number of epochs to 69.

In Fig. 2(c)–(e) the epochs are selected for the relative depths of the minima; in Fig. 2(c) the result is for 39 epochs for $y > 20\%$; in Fig. 2(d) we have 30 epochs for $y < 20\%$, and in Fig. 2(e) we have 12 epochs (a subset of Fig. 2(d)) for $y < 15\%$. For Fig. 2(c) the average minimum SWS is about 330 km s^{-1}; for Fig. 2(d) it is about 360 km s^{-1}; and for Fig. 2(e) it is about 370 km s^{-1}. These minimum SWS values can be compared with the minimum value in Fig. 1 of about 380 km s^{-1}. The minima in the regions of days ±(10–20) days in Figs. 2 and 1 are associated with intermittent and irregular 4-sector structure in the solar wind.

Fig. 3 shows superposed epoch results for the 1997–2002 time series of daily average REF, for the electron energy range >2 MeV, measured at geostationary orbit (at 6.6 earth radii) by the GOES (2011) satellites (http://www.swpc.noaa.gov). There are very large excursions in the daily average REF, from near 10^4 cm^{-2} sr^{-1} s^{-1} to above 10^9 cm^{-2} sr^{-2} s^{-1}. It has been shown by Li et al. (2001a,b) that the SWS is the most important parameter in the variation of REF at geostationary orbit. The REF particles are quasi-trapped, with the continual loss and precipitation into the atmosphere by pitch angle scattering being replenished by the production process, dependent on solar wind – magnetosphere interactions. The REF response to SWS shows a delay of up to a few days, dependent on the energy of the relativistic electrons and the height of the equatorial crossing of the magnetic field line on which the REF particle is quasi-trapped (as illustrated in Kirkland, 1996, Figs. 5.1 and 5.2). It is generally assumed that the component of REF precipitating into the atmosphere follows closely the REF that is quasi-trapped.

In Fig. 3(a) the key days are the 39 events for the larger SWS deviations >20%, and in Fig. 3(b) the same results are shown for an expanded time scale out to only ±13 days from the key day. In Fig. 3(c) the key days are the 30 events for the SWS deviations <20%, and in Fig. 3(d) shown again with an expanded time scale. The analysis for $y < 15\%$ was very noisy and is not shown. The REF minima for both $y > 20\%$ and $y < 20\%$ are centered on a delay of 2.5 days relative to the SWS minima.

Fig. 4 shows superposed epoch results for the daily 500 hPa VAI time series, derived from the ECMWF ERA-40 reanalysis meteorological data base, using SWS minima as key days. The key days in Fig. 4(a) through (d) were selected for each panel in the same way as those in Fig. 2(b) through (e). (The number of epochs included in Fig. 4(a)–(c) is up to 3 more than in Fig. 2(b), (c), and (e), because the analysis interval was ±15 days, rather than ±30 days, and a few less epochs were lost due to truncation at the beginnings or ends of the winter seasons.) In all panels of Fig. 4 a VAI minimum is evident near day +5, and is most clearly seen in Fig. 4(b) for SWS $y > 20\%$. There the VAI at the minimum is about 71×10^5 km^2, with a deviation (defined as before) of amplitude about 4.5×10^5 km^2. The noise level is shown by the standard deviation of the mean, and in Fig. 4(a), (c) and (d) the minima are weak in comparison to the noise level.

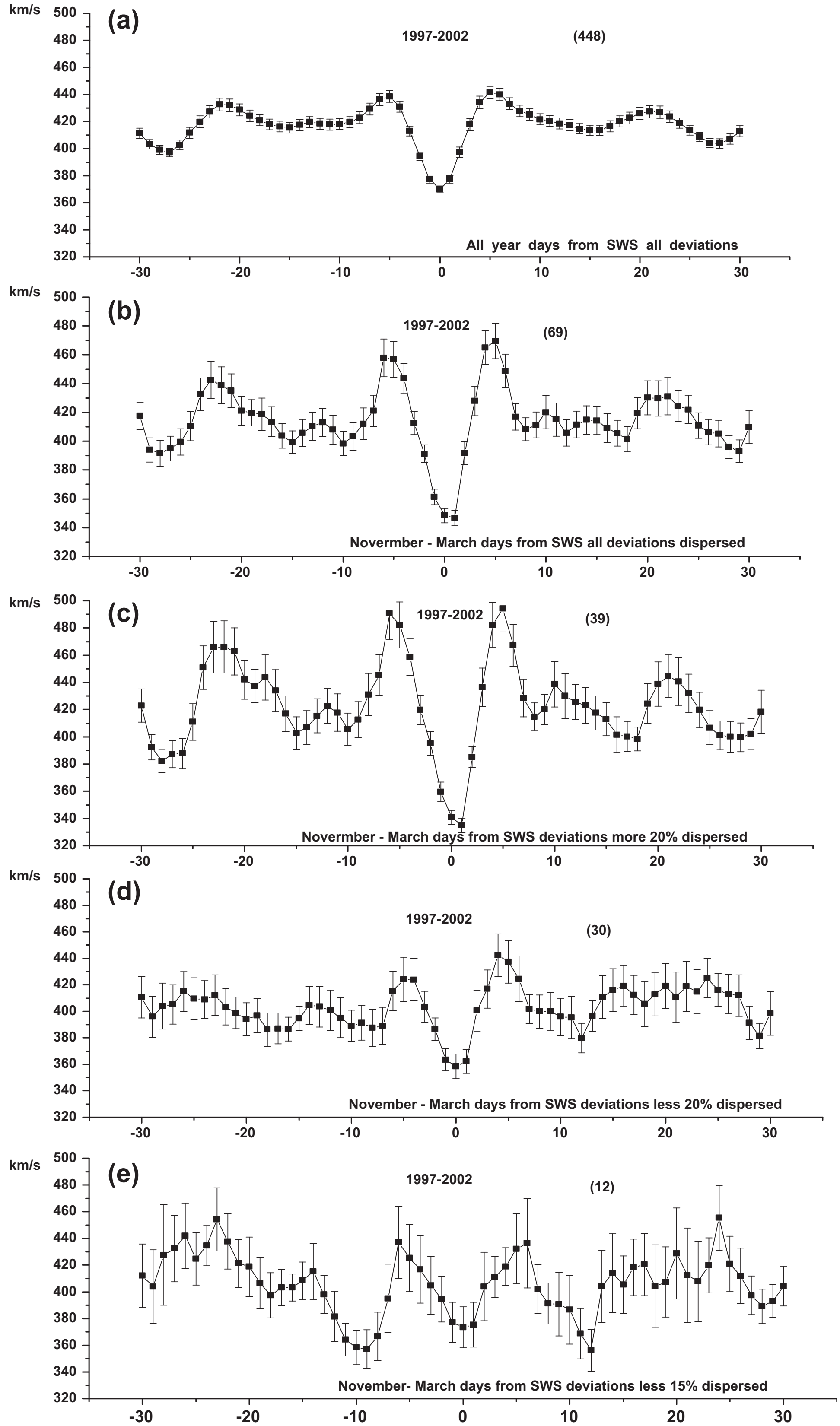

Fig. 2. Superposed epochs of solar wind speed daily values in all years 1997–2002, where the key days were its own minimum values. (a) Key days are all 448 minima for all months, (b) 69 minima for only November–March and only the deepest minimum in a given 5-day window, (c) 39 minima for the deviation greater than 20%, (d) 30 minima for the deviation less than 20%, (e) 12 minima for deviation less than 15%. Error bars are standard errors of the mean.

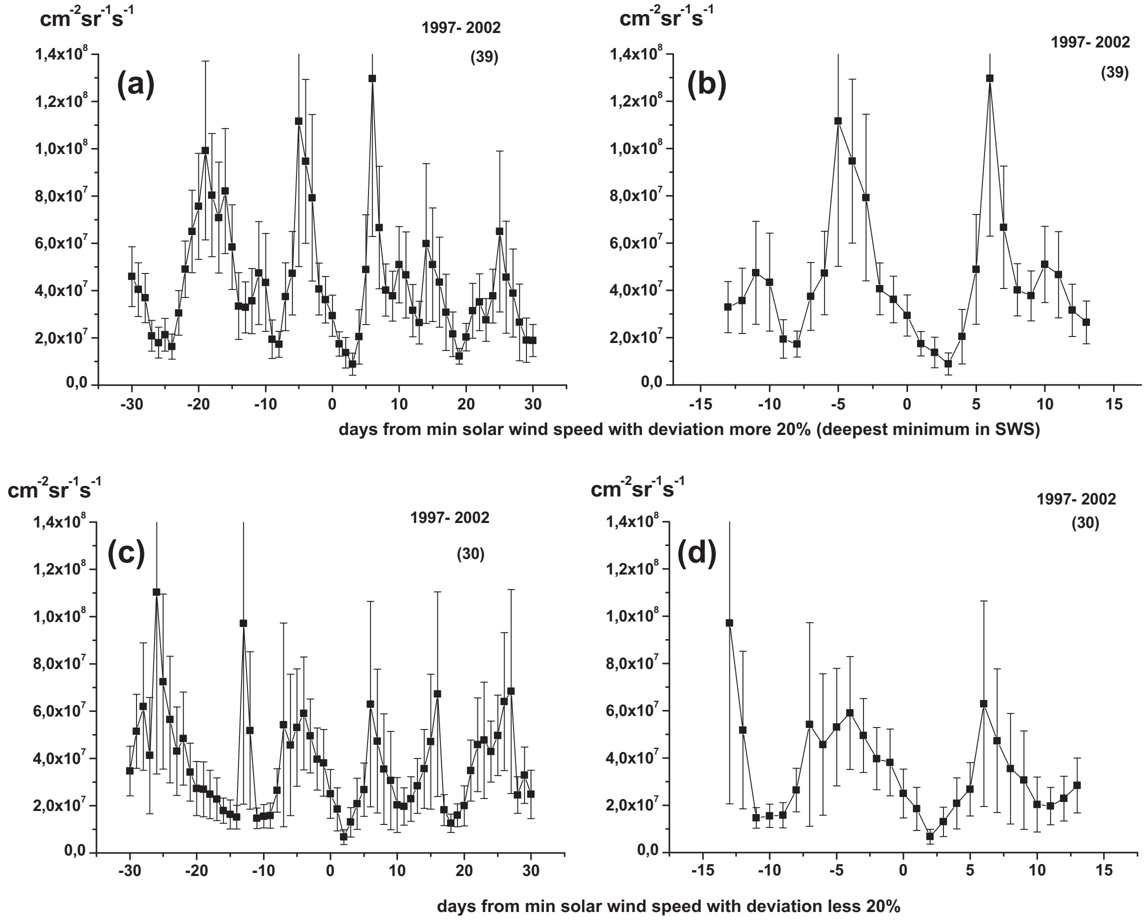

Fig. 3. Superposed relativistic electron flux daily values, with key days as in Fig. 2(c) and (d). The flux was measured at geostationary orbit for electron energy >2 MeV. In (a) the key days were minima of solar wind speed with deviation >20%, and the same results are in (b) but with expanded and truncated time scale. In (c) the key days were minima of solar wind speed with deviation <20%, and the same results are in (d) but with expanded and truncated time scale. Error bars are standard errors of the mean.

Fig. 5 shows superposed epoch results for the VAI time series, with in this case the key days being minima in the REF. The REF minima were determined in the same way as for the minima in the SWS, except that it was not possible to categorize them by % reduction, on account of the huge dynamic range of the REF time series. Instead, the minima were divided into two categories, based on the absolute REF at the minimum. In Fig. 5(a) the 514 key days are for minima with electron flux given by $10^5 < \mathrm{REF} < 10^7\ \mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$. There is no detectable VAI response to these key days. In Fig. 5(b) the VAI response is for 54 key days in the range $10^4 < \mathrm{REF} < 10^6\ \mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$ and in Fig. 5(c) the same result is shown with an expanded time scale. There is a clear minimum on day +3, where the value of the VAI is again about $71 \times 10^5\ \mathrm{km}^2$, and the deviation again about $4.5 \times 10^5\ \mathrm{km}^2$.

3. Discussion

3.1. Timing of minima

We examine the timing of the minima in the VAI with respect to those of the REF and SWS, and to the days of the HCS crossings. For the high stratospheric aerosol periods during 1964–1994 shown in Fig. 1, the average HCS crossing occurs about 1 day after the SWS minima. The REF minima (for only 1983–1994 data) is centered about 2 days after the SWS minima. The VAI minima are at essentially the same time as the REF minima. For the 1997–2002 period, Fig. 3 shows the REF minima are centered about 2.5 days after the SWS minima. Fig. 5(b) and (c) shows the VAI minima are centered about 3 days after the REF minima, in contrast to their essential simultaneity in the 1983–94 time period.

There is an internal consistency among Figs. 3–5 in that Fig. 4 shows the VAI minima centered about 5 days after the SWS minima, with 5 days being approximately the sum of 2.5 days from SWS minima to REF minima (as also in Fig. 1 for 1983–1994) plus 3 days for REF minima to VAI minima. However, there is an unexplained variation in the delay between the REF and VAI minima, when comparing 1997–2002 data with 1983–1994 data. The source of the variation is unclear, and may be related to changes in the energization and precipitation of magnetospheric electrons. It may be important that the REF data in Fig. 1 were for integral electron fluxes above 200 keV (Kirkland, 1996,

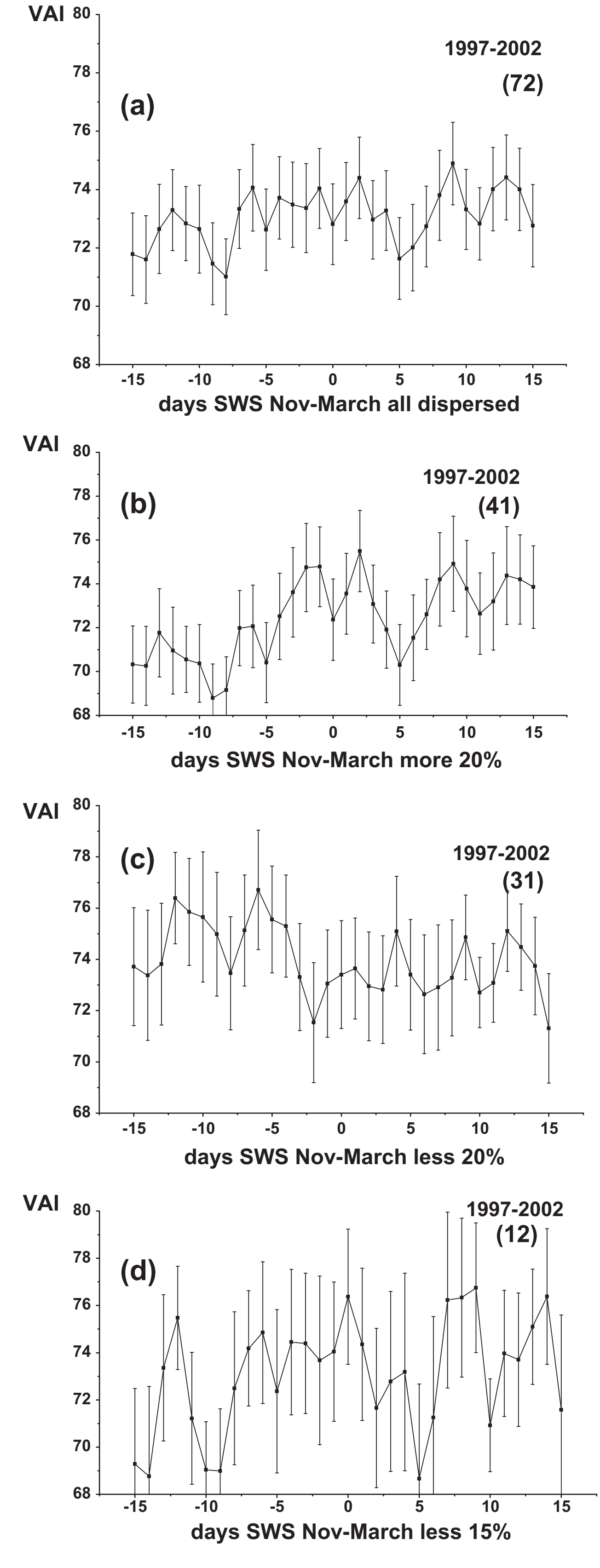

Fig. 4. Superposed VAI daily values, with key days being as used in Fig. 2(b)–(e), with some extra epochs in (a), (b) and (c) because of reduced truncation at the beginnings and ends of the windows. Error bars are standard errors of the mean.

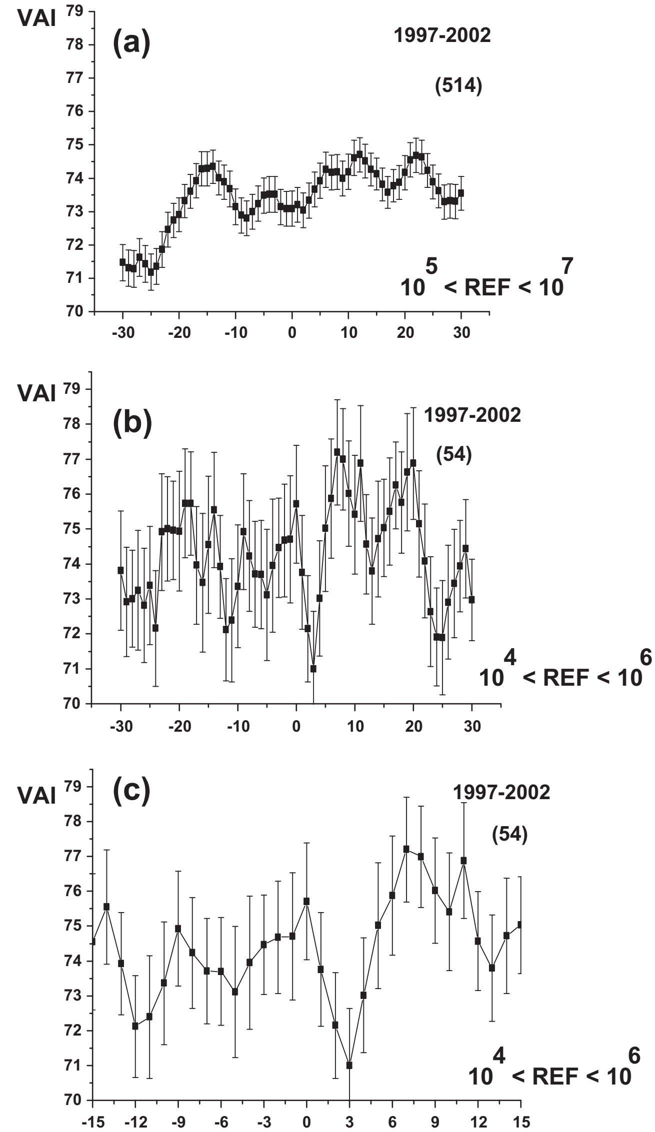

Fig. 5. Superposed daily VAI values, with key days being minima of the relativistic electron flux, determined independently of the solar wind speed, and for minimum electron flux in two ranges, (a) 514 key days in the range $10^5 < \mathrm{REF} < 10^7$ cm^{-2} sr^{-1} s^{-1} and (b) 54 key days in the range $10^4 < \mathrm{REF} < 10^6$ cm^{-2} sr^{-1} s^{-1}. In (c) the same result as (b) is shown with an expanded and truncated time scale. Error bars are standard errors of the mean.

p. 84) whereas the REF data in Figs. 3 and 5, from the GOES satellites) were integral energy fluxes above 2 MeV. Kirkland (1996, Fig. 5.2) shows that at geostationary orbit the minima for fluxes above 1.4 MeV is delayed by about a day compared to those above 200 keV. For fluxes above 2 MeV the delay is likely to be longer. Also, the VAI minima are the summation of responses over latitude 20°N to 80°N, and, as noted, the delay between the REF minima at different latitudes (i.e., feet of different field lines) is variable, (Kirkland, 1996, Fig. 5.1). The physics of the link between REF and VAI deserves much further investigation, including effects of secular changes in the solar wind; in quasi-trapped REF versus precipitating REF, and differing responses of the stratospheric conductivity to REF precipitation for high stratospheric aerosol loading as compared to moderate or low loading. Also, the mean VAI level may be important; it averaged 53×10^5 km^2 for 1964–1996, whereas in 1997–2002 in Figs. 4 and 5 it averaged near 74×10^5 km^2.

3.2. Magnitude of the VAI response

The dip in the VAI on day 3 in Fig. 5(c) where REF minima are used as key days can be compared with that of Fig. 4(b) when SWS minima were used as key days. The deviation relative to the shoulders on either side of the dip is about 4.5×10^5 km^2 in each case. For the 1964–1994 periods in Fig. 1 with high stratospheric aerosol loading and when HCS crossings were used as key days, the dip was about 6×10^5 km^2 after some smoothing by a 1–2–1 day filter. However, the comparison of these two values appears to underestimate their ratio, as the minima of the SWS and REF used in Figs. 5(c) and 4(b) were a subset of all SWS and REF minima, whereas the use of HCS crossings in Fig. 1 allows no selection, such as on magnitude of the SWS or REF deviation, to be made. Also, the 1964–1994 VAI values were obtained using the NCEP-NCAR reanalysis data, and the 1997–2002 VAI values were from the ERA-40 reanalysis, and there appear to be different amounts of smoothing during the process of assimilation of observations into the models. This may mean that unexpected excursions (i.e., due to physical processes not included in the assimilative model) such as might be due to solar wind inputs are not fully assimilated.

While it is clear that the VAI responses to changes in the SWS and REF are greater for periods with high stratospheric aerosol loading than at other times, the amount of the increase remains uncertain. The results are consistent with the findings of Prikryl et al. (2009a). However, they offer no support for the hypothesis (Prikryl et al., 2009b) that the mechanism involves atmospheric gravity waves generated in the auroral ionosphere; but instead, the detailed relationship to fluxes of relativistic electrons that affect stratospheric conductivity support the hypothesis of effects on cloud microphysics due to changes in the global electric circuit.

It appears that the deepest minima in the SWS are quite good proxies for the deepest minima in the REF, in both relative and absolute values. While the REF is considered to be the more proximate causal factor in the VAI response, measurements of its variations are more dependent on satellite orbital and instrumental energy range parameters than SWS measurements. Thus, in view of the present results a comprehensive and self-consistent analysis of the periods for which SWS data are available (i.e., 1964 to the present) would be valuable, along the lines of that given in Kirkland (1996, Fig. 4.2); also Kirkland et al. (1996, Fig. 2), but with key days defined instead by minima in the SWS. A sorting of the minima by their absolute speed, as well as by their % deviation, would be informative. To the extent that REF data are simultaneously available, a parallel analysis of the response of the VAI to REF minima is desirable.

4. Conclusions

An analysis of 1997–2002 data for VAI responses to minima in the relativistic electron flux >2 MeV measured at geostationary orbit has shown VAI decreases 3 days after the REF minima, where the REF minima were in the lowest range of absolute values. Similar responses were found when the analysis was made for VAI responses to minima in the solar wind speed, selected for largest decrease relative to average values up to 6 days before and after. These selected minima also corresponded to low absolute REF values, and occurred approximately 2 days before the REF minima, giving the VAI reductions an approximately 5 day delay relative to the SWS minima. The results are compared to 1964–1994 results keyed to HCS crossings, at times of high stratospheric aerosol loading. The delay between the REF minima and VAI minima appears to be different in the two eras, and this is a result that could be clarified by further analysis. With selection of key days based on either the amplitude of the SWS deviations, or on absolute REF values at REF minima, it is shown that the VAI response to solar wind variations can be found without the necessity of high stratospheric aerosol loading.

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