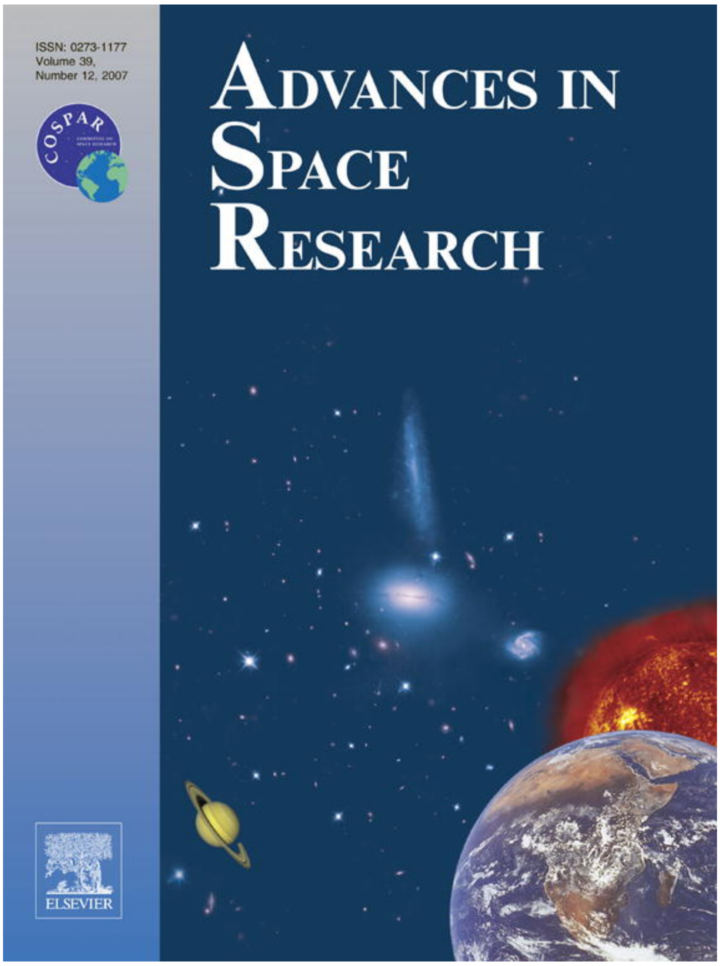
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Solar terrestrial effects of two distinct types

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Abstract

The occurrence frequencies or fluxes of most of the solar phenomena show a 11-year cycle like that of sunspots. However, the *average characteristics* of these phenomena may not show a 11-year cycle. Among the terrestrial parameters, some related directly to the occurrence frequencies of solar phenomena (for example, ionospheric number densities related to solar EUV fluxes which show 11-year cycle like sunspots) show 11-year cycles, including the double-peak structures near sunspot maxima. Other terrestrial parameters related to *average* characteristics may not show 11-year sunspot cycles. For example, long-term geomagnetic activity (Ap or Dst indices) is related to the *average* interplanetary solar wind speed *V* and the total magnetic field *B*. The average values of *V* depend *not on the occurrence frequency* of ICMEs and/or CIRs as such, but on the *relative proportion* of slow and high-speed events in them. Hence, *V* values (and Ap values) in any year could be low, normal or high irrespective of the phase of the 11-year cycle, except that during sunspot minimum, *V* (and Ap) values are also low. However, 2–3 years after the solar minimum (well before sunspot maximum), *V* values increase, oscillate near a high level for several years, and may even increase further during the declining phase of sunspot activity, due to increased influence of high-speed CIRs (corotating interplanetary regions). Thus, Ap would have no fixed relationship with sunspot activity. If some terrestrial parameter shows a 11-year cycle, chances are that the solar connection is through the occurrence frequencies (and not average characteristics) of some solar parameter.

Keywords: Solar parameters; Sunspot cycle; Interplanetary parameters; Terrestrial parameters

1. Introduction

One of the most spectacular variations of solar activity is the large 11-year cycle in sunspot numbers, superposed with small short-term fluctuations (peaks and troughs, Gnevyshev gaps GG) during the 2–3 year turmoiled interval near the sunspot maximum. This pattern is depicted by the occurrence frequencies of several other solar parameters. However, the physical characteristics of these parameters may or may not show a similar 11-year cycle. For solar effects carried over to interplanetary space and/or to terrestrial phenomena, it is important to know which aspect of solar activity is carried over, quantitative, qualitative, or a mixture of the two. In the present note, examples are illustrated to show such a distinction.

2. Solar parameters

Data used were obtained mostly from the NOAA website ftp://ftp.ngdc.noaa.gov/STP/SOLAR DATA/. Fig. 1 shows the plots of the 3-monthly running means of some solar parameters during the sunspot cycle 23 (1996–2005). The top plot (a) is for 2800 MHz (10.7 cm) solar radio emission designated by us as F10 (data obtained from radio telescopes presently operated by the National Research Council, Dominion Astrophysical Observatory, Penticton, Canada) and shows the 11-year cycle as well as two major Gnevyshev peaks (full dots, A and B) and the Gnevyshev Gap GG (Gnevyshev, 1967) in between (thicker line). The full rectangle shows the solar polar magnetic field reversals, first at the solar north pole in September 2000, and later at the solar south pole in August 2001 (Harvey and Recely, 2002). The next plot (b) is for Wolf sunspot number Rz (Waldmeier, 1961; McKinnon,

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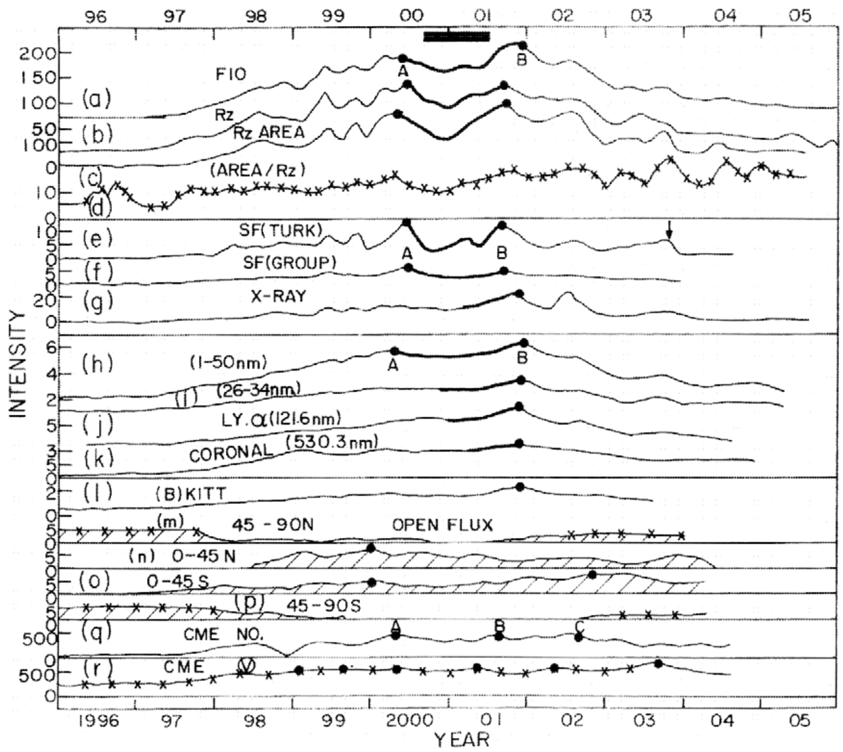

Fig. 1. Plots of the 3-monthly running means of some solar parameters during the sunspot cycle 23 (1996–2005). Top plot (a): 2800 MHz (10.7 cm) solar radio emission F10 showing two major Gnevyshev peaks (full dots, A and B) and the Gnevyshev Gap GG in between (thicker line). The full rectangle shows the interval during which solar polar magnetic field reversed. Plot (b): Wolf sunspot number Rz. Plot (c): sunspot area. Plot (d): *average area per sunspot*. Plot (e): Solar Flare index (SF TURK). Plot (f): Grouped SF index from the NOAA website. Plot (g): X-ray background. Plots (h, i, j, k): chromospheric and coronal EUV (1–50, 26–34 nm), Lyman α (121.6 nm,) and the coronal green line (530.3 nm). Plot (l): Kitt Peak observatory data.for average solar magnetic field *B*. Plots (m, n, o, p): fluxes of solar open magnetic fields at low and high solar latitudes. Plot (q): occurrence frequency of CMEs. Plot (r): *average* speed of the CMEs.

1987, presently generated by Solar Index Data Center, Brussels) and is similar to F10. The third plot (c) is for sunspot area (available from historical data bases like Greenwich Photoheliographic records but here obtained from the website based on Solar phenomena bulletins published by the Rome Astronomical Observatory). It is qualitatively similar to F10 and Rz. Does the average sunspot area (area per sunspot) remain the same during the solar cycle? For checking this, the 3-monthly area values in (c) were divided by the corresponding 3-monthly values of Rz. The fourth plot (d) shows the *average area per sunspot*. As can be seen, the plot is not similar to Rz, but shows an almost monotonic increase, with high values persisting well after Rz started decreasing. Thus, parameters dependent on sunspot area alone will not show a solar cycle variation like Rz. We do not know of any parameter which might be dependent on average sunspot area, but for that matter, we do not know any parameters which can be directly related to sunspot number Rz or the radio emission F10 either. Thus, all these could be only general, indirect indicators of trends in some parameters.

Some solar parameters are well-known for their physical effects on terrestrial parameters, for example, solar flare activity. Plot (e) shows the Solar Flare index (SF TURK) available from the Kandilli Observatory, Istanbul, Turkey (Ataç and Özguç, 1998 updated) and plot (f) shows the Grouped SF index from the NOAA website. The latter plot (f) is smoother, but the former plot (e) shows larger activities with prominent peaks in the middle of 2000 and the end of 2001 with a large gap in between (reduced flare activity in the GG interval AB of Rz and F10), and a prominent peak in the end of 2003 (October–November Halloween events, amplitudes reduced because of 3-monthly averaging). Plot (g) shows the X-ray background. (SOLORAD, GOES satellites). In the calculation of SF indices and X-rays, very prominent events are mostly omitted, but some effects might be still lurking. On the whole, these background fluxes increased parallel to the sunspot activity, except that some activity occurred during the sunspot declining phase too (2003). In general, parameters depending upon solar flare inputs should show sunspot cycle variation.

Plots (h, i, j, k) are for the chromospheric and coronal EUV (1–50 nm, 26–34 nm, SOHO/SEM data), Lyman α (121.6 nm, Woods et al., 2000 updated) and the coronal green line (530.3 nm, Rybansky et al., 1998 updated) fluxes. These are mostly parallel to the Rz plots, except that the second Gnevyshev peak B in the end of 2001 is much stronger than the first Gnevyshev peak A.

A prominent feature of the photosphere is the magnetic field structure. Plot (l) shows the Kitt Peak observatory data for average solar magnetic field *B*. The variation is the same as for Rz, except that only Gnevyshev peak B is prominent. However, this is the closed solar magnetic field which does not get transferred to interplanetary space. For that, the relevant parameter would be (if at all) the open magnetic flux. Wang and Sheeley (2002) have calculated the open magnetic flux leaving the solar surface during every Carrington rotation since 1967. Plots (m, n, o, p) are for the fluxes at low and high solar latitudes. As can be seen, the flux is highly latitude-dependent. In low solar latitudes (<45°), the flux varies almost parallel to the sunspot cycle, but in higher latitudes (>45°), the variation is almost antiparallel to the sunspot cycle. However, the parallelism with sunspot activity is not perfect. Fluxes have rather broad plateaus (hatched) and considerable north–south asymmetry (see Kane, 2005a and references therein), high values persisting up to later years (2002–2003) in the southern low latitudes. Thus, parameters depending on the solar open magnetic flux would have complicated solar cycle dependence. Parameters responding to low solar latitudes will show solar cycle dependence similar to Rz, but for response to higher solar latitudes, the dependence will be antiparallel to Rz. If the response is to the whole solar disc, the solar cycle dependence will be obscure. North–south asymmetries in solar activity features (major flares, X-ray flares, sunspot numbers, sunspot areas, and many others) have been reported by many workers (see Kane, 2005a and references therein), but for terrestrial effects, it is doubtful whether these would be relevant as only whole disc emissions would be effective.

An important solar parameter is the Coronal Mass Ejection (CME) phenomenon, identified more than 30 years ago by Tousey (1973) in the OSO-7 data. A more copious data set for CMEs is now available from the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO), which images the corona continuously since 1996, covering a field from 1.5 *R*s to 32 *R*s. Gopalswamy et al. (2003, and references therein) studied the solar cycle variation of various properties of CMEs for cycle 23 (1996–2002) and reported an order of magnitude increase (12 times) in CME rate from solar minimum (1996) to solar maximum (2002). Plot (q) shows occurrence frequency of CMEs. As can be seen, CMEs increased almost parallel to sunspot activity. However, as noted by Gopalswamy et al. (2003), there was a phase shift, namely whereas sunspots reached a maximum in July–August 2000 (peak A), CMEs peaked about 2 years later, in August–September 2002. Plot (r) shows the *average* speed of the CMEs. It rose from a low value of ~250 km/s at solar minimum (1996) to ~500 km/s by the end of 1998, and remained at that level for a long time (till the middle of 2003) and then showed a spurt to ~700 km/s in October–November 2003 (Halloween events, 3-monthly means). Thus, parameters depending upon the speed V of CMEs would show a very flat solar cycle response. In Fig. 1, full lines represent occurrence frequencies and most of these show a sharp 11-year variation similar to sunspots. On the other hand, full lines with crosses represent specific characteristics of some parameters and these have a broad, flat solar activity response.

3. Interplanetary parameters

The Sun emits background electromagnetic radiation in various wavelengths (infra-red, visible, UV, EUV, X-rays) all the time, interspersed with intense temporary activities like solar flares. In addition, there is considerable particle (corpuscular) emission. There is an incessant flow of slow solar wind of speeds of ~250–400 km (Parker, 1959; Gold, 1959), often superposed by faster streams which cause shock-fronts by stream–stream interactions which, due to solar rotation, cause CIRs (corotating interplanetary regions, in interplanetary space) responsible for recurring (27 day) geomagnetic storms. Then, there are the CMEs spreading all around the Sun, with a small part heading towards the Earth. The CMEs get fairly modified by the time they reach the Earth's orbit (1 AU). Faster CMEs are decelerated and slower ones are accelerated (Gopalswamy et al., 2003; Gonzalez-Esparaza et al., 2003 and references therein). The interplanetary counterpart of CMEs, termed as ICMEs (Interplanetary CMEs as seen near 1 AU) are of dimensions ~0.2–0.3 AU and cross the Earth (or spacecrafts) in ~24 h. They generally have a shock front followed by ejecta, with complicated magnetic field configurations. About 1/3rd of the ICMEs are magnetic clouds, characterized by high magnetic fields, low proton temperatures, low Beta (ratio between thermal and magnetic pressures), and a smooth rotation of the magnetic components. In all these interplanetary structures, a southward component Bz of the magnetic field B is required for geoeffectiveness on a short-term time scale (Dst storms of a few hours). However, on long-term time scales (months), the role of Bz gets obscure and only total B matters. The effects of individual short-term structures are also obliterated and only long-term modifications of solar plasma and magnetic fields in the heliosphere can be observed, only as snapshots by spacecraft observations mostly in the vicinity of the Earth, and some at faraway locations deep in the heliosphere, as those of Pioneers. Fig. 2 shows the plots of 3-monthly running means of the interplanetary parameters. The top plot (a) is for sunspot number just for reference, and the rectangle shows the solar polar magnetic field reversals. The plot (b) is for the ICME occurrence frequency given by Cane et al. (1996, updated by private communication with Richardson in 2004). They chose only those events associated with cosmic ray Forbush decreases of at least 4%; hence, these are lower limits. As can be seen, there are considerable month-to-month fluctuations (poor statistics), but 12-month running means (superposed thick line) indicate a rough parallelism with sunspot activity. Plot (c) is for the occurrence frequency of CIRs (corotating interplanetary regions, Alves et al., 2006). Here too, month-to-month fluctuations are large, but the 12-month running means (superposed thick line) indicate an almost constant level throughout the sunspot cycle, but with

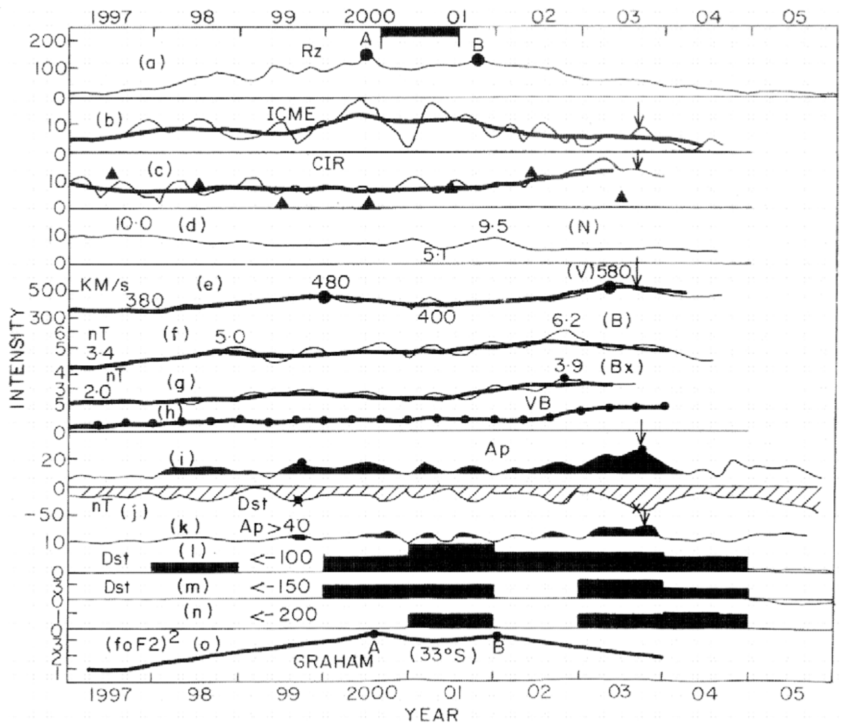

Fig. 2. Plots of 3-monthly running means of the interplanetary parameters. Top plot (a) is for sunspot number just for reference. The rectangle shows the solar polar magnetic field reversals. Plot (b): ICME occurrence frequency. Plot (c): occurrence frequency of CIRs (corotating interplanetary regions). The triangles in (c) show the occurrence frequency of MC (magnetic clouds). Plots (d, e, f): interplanetary parameters: number density *N*, average speed *V*, and magnetic field *B*. Plot (g): numerical value of the magnetic field component Bx. Plot (h): product *VB*. Plots (i, j): geomagnetic Ap (painted black) and Dst (shown hatched), respectively. Plot (k): occurrence frequency of days when the index Ap exceeded 40. Plots (l, m, n): occurrence frequencies of negative Dst levels exceeding 100, 150 and 200 nT. Plot (o): ionospheric number density $(foF2)^2$ (12-monthly means) for the location Grahamstown (33°S).

enhanced frequency in the declining phase of sunspot cycle (2003). This is because fast streams originate in coronal holes which shift to low solar latitudes and are more copious when sunspot activity is declining. The triangles in (c) show the occurrence frequency of MC (magnetic clouds, Dal Lago et al., 2001). These are very few and the statistics is poor, but the large frequencies in 1997 and 1998 (12 and 8 events) are comparable to those in 2002 (12 events). Hence, relationship with sunspot activity 11-year cycle is uncertain.

Plots (d, e, f) are for interplanetary parameters: number density *N* (mostly of protons), average speed *V*, and magnetic field *B* (data from NOAA website). The *N* values (plot d) were high in 1997 (low sunspot activity) and again in 2001–2002 (peak of sunspot activity). Hence relationship of *N* with sunspot activity seems to be obscure. The *V* values (plot e) started low (380 km/s) in 1997, rose to 480 km/s by 2001 end but then dropped to ~400 km/s in the middle of 2001 and then rose to ~580 km/s in the middle of 2003 and declined thereafter. There is a two-peak structure but it does not match with (gap is much wider than) the A, B peak structure of sunspot number Rz (the mismatch between the GGs in sunspots and gaps in other solar, interplanetary and terrestrial parameters and cosmic rays is discussed in detail in Kane, 2005b,c). In 2003, ICME frequency dropped but the CIR frequency increased and these were high-speed events, so average *V* values were high. Thus, *V* is affected by ICMEs as well as CIRs. Plot (f) is for the interplanetary total magnetic field *B* (from daily values of *Bx*, *By*, *Bz*, total *B* is calculated daily and then averaged over a month). It shows an almost monotonic increase from 3.4 nT in 1997 to 6.2 nT by the end of 2002, followed by a decline. Thus, *B* values follow the sunspot cycle only roughly, with no maximum corresponding to the sunspot peak A of 2000 and a maximum in 2002 end, almost an year later than the sunspot peak B of 2001. Plot (g) is for the numerical value of the magnetic field component Bx (Wang and Sheeley, 2002) and shows the same pattern as B. A physically meaningful parameter is the product *VB* (plot h) representing the 'electric field' carried by the solar wind (Ahluwalia and Kamide, 2005). This shows a substantial rise during 2003.

Thus, among the interplanetary parameters, only ICME occurrence frequency and the magnitude of interplanetary *B* show parallelism to sunspot activity in a rough way. The parameters *V* and *B* show large values in 2003 when sunspot activity had declined considerably to almost half its peak value in 2000–2001.

4. Terrestrial parameters

Terrestrial parameters are affected by solar activity in two ways. Direct electromagnetic radiations reach the Earth in a few minutes and cause enhanced ionizations in the upper layers. Solar flare radiation is known to cause increases in ionospheric number density within a few minutes and the effects last for several tens of minutes to few hours (e.g., Tsurutani et al., 2005). Since the flux of these radiations increases parallel to sunspot activity, terrestrial parameters related to ionization would show long-term parallelism with sunspots. The 12-monthly running means (thus, seasonal effects eliminated) of ionospheric densities not only show the 11-year cycle but also depict the double-peak structure (A and B) near sunspot maximum (Kane, 2006a). Likewise, thermospheric temperatures vary strongly over the solar cycle, by about a factor of two from solar cycle minimum to solar cycle maximum and densities can be larger by an order of magnitude (Walterscheid, 1989). In the mesosphere, trends are uncertain (Beig et al., 2003), but in the stratosphere, on the time scale of the 11-year solar cycle, the ozone response derived from available data is characterized by a strong maximum in the upper stratosphere, a negligible response in the middle stratosphere, and a second strong maximum in the tropical lower stratosphere, and the 11-year temperature response is characterized by a similar altitude dependence (Hood, 2004). For the troposphere where all climatic changes occur, Tsiropoula (2003) mentions that the literature contains a long history of positive or negative correlations between weather and climate parameters like temperature, rainfall, droughts, etc. and solar activity cycles like the 27-day cycle, the prominent 11-year sunspot cycle, the 22-year Hale cycle and the Gleissberg cycle of 80–90 years. Earlier, it was observed that many of these relationships were valid for restricted geographical regions and/or for limited short periods. However, this problem seems to have been resolved in recent years through recognition of the role of strong horizontal gradients in climatic zones, e.g., around the inter-tropical convergence zone. Small horizontal shifts in such regions can produce large signals. Solar cycle correlations here are significant – they point us to look for solar cycle effects that can move boundaries between climatic regions.

A notable feature of Sun-climate relationship is that TSI (total solar irradiance composed mainly of visible and infra-red), the mover of terrestrial climate, has a very small sunspot cycle variation (~0.1%, justifying the term 'solar constant') and hence, cannot possibly cause large climatic *changes*. Terrestrial meteorology is greatly dictated by circulation patterns which are caused by the rotation of the Earth and its tilt of 23° which causes seasons. A solar signal in these because of TSI changes of ~0.1% is unimaginable, though attempts are made to find mechanisms which would magnify this signal. On the other hand, the solar radiation reaching the surface of Earth is greatly affected by the magnitude and characteristics (optical depth etc.) of clouds and the variation of cloud coverage plays a very important role in modifying climate. Svensmark and Friis-Christensen (1997) seem to have detected a 11-year cycle in cloud coverage (amplitude ~2%) and link it with the 11-year variations of cosmic rays. Marsh and Svensmark (2000) have shown that there is a strong correlation between low liquid clouds (<3 km) and galactic cosmic rays. Recently, Harrison and Stephenson (2006) have provided strong statistical evidence for cosmic ray correlations with cloud cover. There is also much work underway to study cosmic ray effects on cloud chemistry (Kazil et al., 2006). A basis for a linking mechanism is proposed by Tinsley and his colleagues (Tinsley and Deen, 1991; Tinsley and Heelis, 1993), where it is assumed that electrically induced changes in the microphysics of clouds (electrofreezing) enhance ice nucleation and formation of clouds, and can lead to large scale changes in tropospheric circulation.

Along with variations of the electromagnetic radiation emitted by the Sun, SEPs (solar energetic particles, mainly protons and alpha particles) are also emitted. The 3-D Plasma and Energetic Particles (3DP) instruments on the WIND spacecraft are providing new insights on the origin of solar energetic particles. The main findings are that one class of electron events escaping from the Sun into interplanetary space are related to the impulsive phase of the flare (radio type III burst related events), but there is also a second class of events released after the impulsive phase of the flare that is possibly related to coronal shocks (Krucker, 2003). However, there is also evidence that particles accelerated by CME-driven shocks, rather than by flares, produce most of the largest particle events seen at 1 AU, even the ground-level events with particles of energies as high as ~20 GeV (Kahler, 1994). Solar proton events can occur any time, but there is a preference for occurrence during sunspot maximum. Relativistic electron fluxes (2–15 MeV) are also observed in interplanetary space. Their presence or absence is controlled largely by high-speed solar wind streams. The ionosphere, upper and middle atmosphere and probably troposphere of the Earth respond to rapid changes in energetic particle precipitation that accompany transient solar events. Some ionospheric disturbances are thought to be initiated by the deposition of protons and relativistic electrons to low altitudes that enhance ionization and cause plasma instabilities. The ICMEs (distorted form of solar CMEs near 1 AU), if encountered by the Earth, cause severe geomagnetic storms, if there is a southward component Bz. This feature was explained by Dungey (1961) as follows. As the geomagnetic dipole field is stretched in the magnetotail, a neutral sheet is formed, with geomagnetic field away from the Earth above the neutral sheet and toward the Earth below the neutral sheet. At the end, in a small region in the magnetotail far away from the Earth, the field is still north–south. If the field in the interplanetary shock has a component (negative Bz), which can neutralize the geomagnetic field, a neutral point is formed and solar wind gets an entry into the magnetosphere. Low energy particles spiral around the stretched geomagnetic field lines and impinge on the terrestrial atmosphere in the polar regions, causing enhanced aurora. Higher energy particles rush towards the Earth but are diverted around the Earth in circular orbits in the equatorial plane and cause large geomagnetic field reductions (Dst, storm-time disturbance depression of several tens of nT), which recoup slowly when the Earth comes out of the shock region and solar wind input stops. Thus, for geomagnetic storms to occur, two conditions are necessary. Firstly, the Earth should enter a disturbed region of high solar wind speed in the interplanetary space, and secondly, the region should have a magnetic field component (negative Bz), which can neutralize geomagnetic field in a small region in the magnetotail and create a neutral point, which facilitates entry of solar wind into the magnetosphere. If the region has a shock, a SSC (Storm Sudden Commencement) is produced. If the shock is not produced by a CME associated with a solar flare but is produced by a (fast) stream–(slow) stream interaction, the same conditions are still applicable. If there is no shock, there will be no SSC and only a smooth decrease in geomagnetic field will occur.

During intense geomagnetic storms, the Dst index can reach negative values exceeding 400 nT and considerable damages occur to communication lines, transformers, power grids, etc. As happened in the October–November 2003 storms, plasmasphere expands and, as pointed by Dr. Daniel Baker, Director LASP, University of Colorado, Boulder in a NASA News Letter, no matter what orbit we choose, there is the possibility that a spacecraft could get blasted by a significant dose of radiation. Effects of individual storms on short-time scales (few hours to days) are reported copiously in the literature. Here, we concentrate on effects of longer time intervals.

Geomagnetic activity is depicted by several indices, namely, Dst, Ap, AE etc. In Fig. 2, plots (i, j) show the 3-month running means of Ap (painted black) and Dst (shown hatched), respectively. As can be seen, after quiet levels in 1997, the levels increased in 1998 and oscillated there till 2002, but the ups and downs have no relation with the solar Gnevyshev Gap AB or with the solar polar magnetic field reversals during September 2000 and August 2001. In 2003, levels increased considerably, particularly during October–November 2003 (Halloween events, marked by an arrow). Plot (k) shows the occurrence frequency of days when the index Ap exceeded 40. Large values occurred during 2000–2003 with fluctuations unrelated to sunspot activity. Plots (l, m, n) are for the occurrence frequencies of negative Dst levels exceeding 100, 150 and 200 nT. Number of events is lesser in 2002 but this is *later* than 2000–2001 when the GG (AB) and solar polar field reversals occurred, in contradiction with Ahluwalia and Kamide (2005) who claimed simultaneous occurrences. Finally, plot (o) shows the 12-month running means of the ionospheric number density $(foF2)^2$ for the location Grahamstown (33°S), where the parallelism with sunspot activity (including matching with the double peaks AB) is seen (Kane, 2006a).

5. Correlations

Table 1 gives the correlation coefficients between the 3-monthly running means of the various parameters plotted in Fig. 2. The following may be noted:

(1) The sunspot number Rz is very well correlated ($+0.83 \pm 0.04$) with ionospheric number density at Grahamstown (33°S, 27°E), because the density changes are caused by the solar EUV flux, which has a clear 11-year cycle.

(2) The correlation of Rz with ICMEs is only moderate ($+0.50 \pm 0.08$), though ICMEs are more frequent during sunspot maximum. The low value of the correlation is because of the large fluctuations of ICME frequency during solar maximum. Remember that this ICME sample is not complete. From the CMEs emitted by the Sun, only a small fraction reaches the Earth and from these, Cane et al. (1996, updated by private communication with Richardson in 2004) have presented a list of only those that were associated with cosmic ray decreases exceeding 4%.

(3) CIR occurrence frequency is poorly related with Rz, mainly because CIRs occur copiously when sunspot activity is declining. For the same reason, ICMEs and CIRs have a low negative (-0.48 ± 0.08) correlation.

(4) The negative correlation (-0.59 ± 0.08) of interplanetary *N* with Rz is most probably fictitious. It did not hold good in earlier cycles (Kane, 2005c, Table 1).

(5) Rz and ICMEs have very low correlations with *V*, *B*, Ap or Dst, indicating no relationship; but CIRs are

Table 1
Correlation coefficients between the 3-monthly running means of various parameters

	Rz	ICMEs	CIRs	*N*	*V*	*B*	*VB*	Ap	Dst	Grah. (foF2)
Rz	1.00									
ICMEs	0.50	1.00								
CIRs	−0.18	−0.48	1.00							
N	−0.59	−0.16	−0.41	1.00						
V	0.25	−0.09	0.65	−0.71	1.00					
B	0.15	−0.17	0.62	−0.63	0.86	1.00				
VB	0.13	−0.17	0.67	−0.65	0.93	0.98	1.00			
Ap	0.23	0.07	0.49	−0.61	0.87	0.81	0.86	1.00		
Dst	−0.05	0.02	−0.24	0.26	−0.52	−0.55	−0.55	−0.76	1.00	
Grah. (foF2)	0.83	0.21	0.23	−0.73	0.54	0.55	0.52	0.48	−0.19	1.00

The standard errors are ±0.04 for correlations of ~0.80, ±0.05 for correlations of ~0.70, ±0.06 for correlations of ~0.60, ±0.07 for correlations of ~0.50 and ±0.08 for correlations of ~0.40 or less.

moderately well correlated (∼+0.60 ± 0.07) with *V* and *B*.

(6) Correlation of *N* with *V* and *B* (∼−0.60 ± 0.07) is probably fictitious, only for cycle 23 (Kane, 2005c, Table 1).

(7) *V* is very well correlated with *B* (+0.86 ± 0.04) but only in cycle 23, mainly because of the abnormal increases in October–November 2003.

(8) Ap is very well correlated with *V*, *B* and *VB*. Since *V*, *B* are poorly correlated with Rz, Ap also is poorly correlated with Rz.

(9) Ap is fairly well correlated with Dst (−0.76 ± 0.05), but not completely. Dst correlations with *V* and *B* are only moderate (∼0.50 ± 0.07) in contrast to high correlations of Ap with *V* and *B* (+0.80 ± 0.04).

6. Conclusions and discussion

From the various comparisons presented here, the following conclusion can be drawn:

The occurrence frequencies or fluxes of most of the solar phenomena show a 11-year cycle like that of sunspots. However, the *average characteristics* of these phenomena may not show a 11-year cycle. The same is true for some of the interplanetary phenomena, though for some of them, even the occurrence frequency may not have a 11-year cycle exactly like that of sunspots. Among the terrestrial parameters, some related directly to the occurrence frequencies of solar phenomena (for example, ionospheric number densities related to solar EUV fluxes which show 11-year cycle like sunspots) show 11-year cycles, including the double-peak structures near sunspot maxima. Other terrestrial parameters related to average characteristics do not show 11-year sunspot cycles. A prominent example of this is the geomagnetic activity (Ap or Dst indices). On short-time scales, it is closely related to interplanetary solar wind speed *V* and the Bz component of the magnetic field, while on longer time scales, it is related to the average interplanetary solar wind speed *V* and the total magnetic field *B*. However, *V* is an average characteristics and depends *not on the occurrence frequency* of ICMEs and/or CIRs as such, but on the *relative proportion* of slow and high-speed events in them. Thus, even near the sunspot maximum when ICMEs are more copious, the average *V* for any year may be smaller than the average *V* for the previous or next year, if the middle year had a larger proportion (not total number) of slow ICMEs as compared to fast ICMEs. Hence, while expecting parallelism with 11-year sunspot cycle, attention should be paid as to whether the parameter concerned is related to the occurrence frequencies of some solar parameter or to its average characteristics, which may not show effects similar to sunspot cycle. On the other hand, if some terrestrial parameter shows a 11-year cycle, chances are that the solar connection is through the occurrence frequencies (and not average characteristics) of some solar parameter. This could be a clue for searching the physical mechanism involved, notably for some climatic changes for which physical mechanisms are still unknown. However, there is one exception, namely, Cosmic ray flux, which is not a solar phenomenon but gets modified by solar emissions in the heliosphere and shows a solar cycle variation antiparallel to sunspots, which may affect climate through effects on clouds. Incidentally, cosmic ray intensity also shows Gnevyshev type gaps near sunspot maxima, but the time matching is not perfect (Kane, 2006b).

Since *V* is poorly correlated with sunspot activity, Ap is also poorly correlated to sunspot activity. Was this always so in all previous cycles? Ap values are available only since about 1932, but data for an equivalent index aa (Mayaud, 1972) are available since cycle 11 (1867–1878). For these, Kane (2005b) mentions that aa had peaked structures but these did not match with Rz peaks. The correlations between Rz and aa index for cycles 11–23 were: 0.81, 0.44, 0.79, 0.38, 0.67, 0.44, 0.73, 0.31, 0.61, 0.00, 0.01, 0.49, 0.41. Thus, the correlations varied in a very wide range (0.00–0.81) and were positive at all only because near solar minimum, Ap and aa values were lower. Echer et al. (2004) mention that the variations of Rz and aa were in phase in the early period (cycles 11–14, around 1868–1910), but became out of phase in later periods, because the second peak of aa (related to high-speed streams from corotating structures in the declining phase of sunspot activity) has increased relative to the first peak of aa (related to coronal mass ejections) in recent decades.

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References

Ahluwalia, H.S., Kamide, Y. Gnevyshev gap, Forbush decreases, ICMEs and solar wind electric field: relationships. Adv. Space Res. 35, 2119–2123, 2005.

Alves, M.V., Echer, E., Gonzalez, W.D. Geoeffectiveness of corotating interaction regions as measured by *Dst* indices. J. Geophys. Res. 111, A07S05, doi:10.1029/2005JA011379, 2006.

Ataç, T., Özguç, A. Flare index of solar cycle 22. Sol. Phys. 180, 397–407, 1998.

Beig, G., Keckhut, P., Lowe, R.P.15 other authors Review of mesospheric temperature trends. Rev. Geophys. 41 (4), 1015, doi:10.1029/2002RG000121, 2003.

Cane, H.V., Richardson, I.G., von Rosenvinge, T.T. Cosmic ray decreases. J. Geophys. Res. 101, 21561–21572, 1996.

Dal Lago, A., Gonzalez, W.D., de Gonzalez, A.L.C., Vieira, L.E.A. Compression of magnetic clouds in interplanetary space and increase in their geoeffectiveness. J. Atmos. Sol. Terres. Phys. 63 (5), 451–455, 2001.

Dungey, J.W. Interplanetary magnetic field and the auroral zones. Phys. Rev. Lett. 6, 47–48, 1961.

Echer, E., Gonzalez, W.D., Gonzalez, A.L.C., Prestes, A., Vieira, L.E.A., Dal Lago, A., Guarnieri, F.L., Schuch, N.J. Long-term correlation between solar and geomagnetic activity. J. Atmos. Sol. Terr. Phys. 66, 1019–1025, 2004.

Gnevyshev, M.N. On the 11-years cycle of solar activity. Sol. Phys. 1, 109–120, 1967.

Gold, T. Plasma and magnetic fields in the solar system. J. Geophys. Res. 64, 1665–1674, 1959.

Gonzalez-Esparaza, J.A., Lara, A., Perez-Tijerina, E. A numerical study on the acceleration and transit time of coronal mass ejections in the interplanetary medium. J. Geophys. Res. 108 (A1), 1039, doi:10.1029/2001JA009186, 2003.

Gopalswamy, N., Lara, A., Yashiro, S., Nunes, S., Howard, R.A. Coronal mass ejection activity during solar cycle 23, Proc. ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment, pp. 403–414, Tatranská Lomnica, Slovakia, ESA SP-535, (Ed. Wilson) ESTEC, Noordwijk, The Netherlands, September, 2003.

Harrison, R.G., Stephenson, D.B. Empirical evidence for a nonlinear effect of galactic cosmic rays on clouds. Proc. Roy. Soc. A 462 (2068), 1221–1233, doi:10.1098/rspa.2005.1628, 2006.

Harvey, K.L., Recely, F. Polar coronal holes during cycles 22 and 23. Sol. Phys. 211, 31–52, 2002.

Hood, L.L. Effects of solar UV variability on the stratosphere, in: Pap, J., Fox, P. (Eds.), Solar Variability and Its Effects on Climate, AGU, Washington D.C., pp. 283–303, 2004.

Kahler, S.W. Injection profiles for solar energetic particles as functions of coronal mass ejection heights. Astrophys. J. 428, 837–842, 1994.

Kane, R.P. North–south asymmetry of some solar indices. J. Atmos. Sol. Terres. Phys. 67, 429–434, 2005a.

Kane, R.P. Which one is the 'Gnevyshev' gap? Sol. Phys. 229, 387–407, 2005b.

Kane, R.P. Short-term periodicities in solar indices. Sol. Phys. 227, 155–175, 2005c.

Kane, R.P. Are the double-peaks in solar indices during solar maximum of cycle 23 reflected in ionospheric foF2? J. Atmos. Sol. Terres. Phys. 68, 877–880, 2006a.

Kane, R.P. A detailed comparison of Cosmic ray gaps with solar. Gnevyshev Gaps Sol. Phys. 236, 207–226, 2006b.

Kazil, J., Lovejoy, E.R., Barth, M.C., O'Brien, K. Aerosol nucleation over oceans and the role of galactic cosmic rays. Atmos. Chem. Phys. 6, 4905–4924, 2006.

Krucker, S. On the origin of solar energetic particle events, in: Klein, L. (Ed.), Lecture Notes in Physics and Astronomy, Energy Conversion and Particle Acceleration in the Solar Corona, vol. 612. Springer, Berlin/Heidelberg, pp. 179–192, 2003.

Marsh, N., Svensmark, H. Cosmic rays, clouds, and climate. Space Sci. Rev. 94, 215–230, 2000.

Mayaud, P.N. The aa indices: a 100-year series characterizing the magnetic activity. J. Geophys. Res. 77, 6870–6874, 1972.

McKinnon, J.A. Sunspot numbers 1610-1985, UAG Report 95, NOAA Boulder, Colorado (USA) pp. 112, 1987.

Parker, E.N. Extension of the solar corona into interplanetary space. J. Geophys. Res. 64, 1675–1681, 1959.

Rybansky, M., Rusin, V., Minarovjech, M. The green coronal index and soft X-ray flux. Sol. Phys. 177, 305–310, 1998.

Svensmark, H., Friis-Christensen, E. Variation of cosmic ray flux and global cloud coverage-a missing link in solar-climate relationships. J. Atmos. Sol. Terres. Phys. 59, 1225–1232, 1997.

Tinsley, B.A., Deen, G.W. Apparent tropospheric response to MeV-GeV particle flux variations: a connection via electrofreezing of supercooled water in high-level clouds? J. Geophys. Res. 96, 22283–22296, 1991.

Tinsley, B.A., Heelis, R.A. Correlations of atmospheric dynamics with solar activity. Evidence for a connection via the solar-wind, atmospheric electricity, and cloud microphysics. J. Geophys. Res. 98, 10375–10384, 1993.

Tousey, R. The Solar Corona, in: Rycroft, M.J., Runcorn, S.K. (Eds.), Proceedings of Open Meetings of Working Groups of the 15th Plenary Meeting of the Committee on Space Research (COSPAR), Madrid, Spain, May 10–24, 1972, Akademie Verlag, Berlin, Pergamon, Oxford, 1973.

Tsiropoula, G. Signatures of solar activity variability in meteorological parameters. J. Atmos. Sol. Terres. Phys. 65, 469–482, 2003.

Tsurutani, B.T., Judge, D.L., Guarnieri, F.L.16 others The October 28, 2003 extreme EUV solar flare and resultant extreme ionospheric effects: comparison to other Halloween events and the Bastille Day event. Geophys. Res. Lett. 32, L03S09, doi:10.1029/2004GL021475, 2005.

Waldmeier, M. The Sunspot Activity in the Years 1610–1960. Schulthess and Company AG, Zurich, 1961.

Walterscheid, R.I. Solar cycle effects on the upper atmosphere: implications for satellite drag. J. Spacecraft Rockets 26, 439–444, 1989.

Wang, Y.M., Sheeley, N.R. Sunspot activity and the long-term variation of the Sun's open magnetic flux. J. Geophys. Res. 107 (A10), doi:10.1029/2001JA0005000, 2002.

Woods, T.N., Tobiska, W.K., Rottman, G.J., Worden, J.R. Improved solar Lyman irradiance modelingfrom 1947 through 1999 based on UARS observations. J. Geophys. Res. 105, 27195–27215, 2000.