# On secular changes of correlation between geomagnetic indices and variations in solar activity

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# On secular changes of correlation between geomagnetic indices and variations in solar activity

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[1] Geomagnetic indices can be divided in two families, sometimes called "mean" and "range" families, which reflect different interactions between solar and terrestrial processes on time scales ranging from hourly to secular and longer. We are interested here in trying to evaluate secular change in the correlations between these indices and variations in solar activity as indicators of secular changes in solar behavior. We use on one hand daily values of geomagnetic indices $D_{st}$ and $\zeta$ (members of the "mean" family), and $A_p$ and *aa* (members of the "range" family), and on the other hand solar indices *WN* (sunspot number), $F_{10.7}$ (radio flux), interplanetary magnetic field *B* and solar wind speed *v* over the period 1955–2005. We calculate correlations between pairs of geomagnetic indices, between pairs of solar indices (including the composite $Bv^2$), and between pairs consisting in a geomagnetic vs a solar index, all averaged over one to eleven years. The relationship between geomagnetic indices depends on the evolution of solar activity; strong losses of correlation occur during the declining phase of solar cycle 20 and in solar cycle 23. We confirm the strong correlation between *aa* and $Bv^2$ and to a lesser extent between $D_{st}$ and *B*. On the other hand, correlations between *aa* or $D_{st}$ and *v* are non-stationary and display strong increases between 1975 and 2000. Some geomagnetic indices can be used as proxies for the behavior of solar wind indices for times when these were not available. We discuss possible physical origins of sub-decadal to secular evolutions of correlations and their relation with the character of solar activity (correlation of DP2 substorms and main storm occurrence, generation of toroidal field of a new cycle during descending phase of old cycle and prediction of next cycle, and also links with coupling of nonlinear oscillators and abrupt regime changes).

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## 1. Introduction

[2] Geomagnetic indices are a measure of geomagnetic activity occurring over short periods of time [*Mayaud*, 1980] (see *Love and Remick* [2007] for a recent summary). They are useful for studies of upper atmospheric physics, solar-terrestrial relationships or removal of disturbed-time magnetic variations when studying the Earth's deep interior. They have been constructed in order to study the response of the Earth's ionosphere and magnetosphere to changes in solar activity. The Sun and geomagnetic activity are related through the solar wind, a fully ionized magnetized plasma that travels from Sun to Earth in a few days (for a general overview see, e.g., *Prölss* [2004] and *Meyer-Vernet* [2007]; for more focused issues, *Finch and Lockwood* [2007] and *Rouillard et al.* [2007]). Specifically, geomagnetic activity results from the interaction (compression and magnetic reconnection) between the solar wind and the magnetosphere. Geomagnetic indices are driven by combinations of solar wind variables, such as the interplanetary magnetic field and the solar wind momentum flux per unit time and area [e.g., *Svalgaard and Cliver*, 2007]. Complex interaction of the solar wind with the Earth's magnetic field produces electric currents and magnetic field variations that can be detected from the magnetosphere down to the ground. Irregular variations, i.e., the disturbance field, are measured by the level of magnetic activity, as opposed to regular variations that are attributed to the electromagnetic solar radiation [e.g., *Mayaud*, 1967]. The separation between these magnetic variations due to various solar effects remains a difficult matter [*Hirshberg and Colburn*, 1969; *Garrett et al.*, 1974; *Svalgaard*, 1977; *Feynman*, 1982; *Finch and Lockwood*, 2007].

[3] Solar activity can be measured through a number of indices or combinations of indices, such as sunspot number *WN* and radio flux *F*10.7 that vary with the electromagnetic output of the Sun, and interplanetary magnetic field strength *B* and solar wind speed *v* at Earth's distance that are measures of solar wind properties. Geomagnetic indices are divided in two families that may monitor different responses

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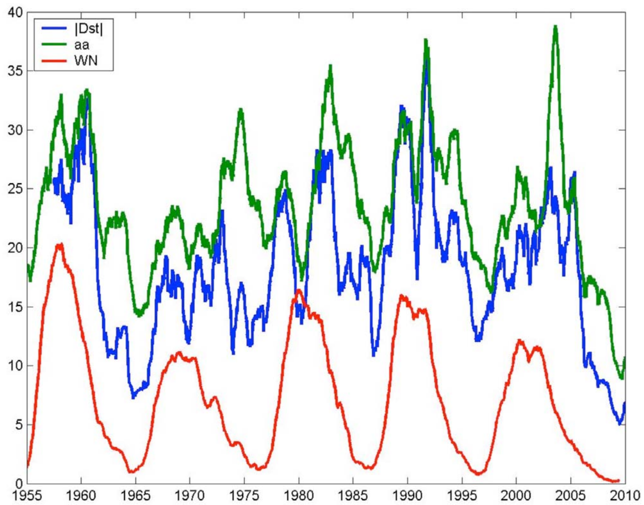


**Figure 1.** Evolution of 1 y averaged *mean* (|$D_{st}$|, blue) and *range* (*aa*, green) geomagnetic indices and solar activity (*WN*/10, red).

(or combinations of responses) to solar activity: indices such as $D_{st}$ (originally an hourly index monitoring the equatorial ring current) reflect properties of magnetic field disturbances usually integrated over one day (hence they are called "*mean*" indices – i.e., the 1st family of *Mayaud* [1980]), whereas indices such as $A_p$ or *aa* reflect the maximal values of these disturbances (during some period of time less than a day and called "*range*" indices – i.e., the 2nd family of *Mayaud* [1980]). In the present paper, we study the variations of long series of daily values of a number of geomagnetic indices and their correlations, between themselves and with various indices of solar activity, and underline results that may be of interest to users of these indices. We particularly focus on decadal to secular changes in these correlations and to times when sharper, significant drops of correlation coefficients occur, in the hope of further understanding corresponding changes in the Sun's activity. In order to avoid the influence of seasonal variations (f.i. in solar wind speed) [*Mursula and Zieger*, 2001], we consider series that have been averaged over one to several years.

[4] We recall the definitions of some of the above classical indices, and others that have been more recently introduced, in section 2 of this paper. In section 3, we compare the evolutions of several indices and study their correlations. More precisely, we look separately at correlations between two range geomagnetic indices, between two mean geomagnetic indices, and between a mean and a range index. We next compute correlations between solar indices, then between one solar electromagnetic output index and a geomagnetic index, and finally between a solar wind index and a geomagnetic index, in an attempt to identify the physical links between these systems. Results are discussed in section 4.

## 2. Geomagnetic and Solar Activity Indices

### 2.1. Geomagnetic "Range" Indices

[5] Three-hour *K* integer indices were introduced by *Bartels* [1938] with the intent to characterize geomagnetic activity. They have been in constant use since then. In his *Atlas of K indices*, *Mayaud* [1967] recalls that all transient variations recorded in observatories should be characterized by the *K*-index, once the longer term secular variation, the regular daily variation $S_R$ and the post-perturbation effects have been removed (by fitting a smooth curve to the data). A practical definition of *K* is given by *Knecht and Shuman* [1985, p. 4–27]: "The *K* index, a measure of the irregular variations of standard magnetograms, is an indicator of the general level of disturbance at a given observatory for each three-hour interval on the basis of the largest value of the 3-hr ranges in X, Y, D or H, where the range is the difference between the highest and lowest deviations from the daily regular variation" (for illustrations, see, e.g., *Mayaud* [1980, p. 26, Figure 9] and *Love and Remick* [2007, p. 511, Figure M32]). These largest range values are converted to an integer (from 0 to 9) using a quasi-logarithmic scale; the scale depends on the observatory and is intended to normalize the occurrence frequency of individual *K* values among a set of observatories and a (large) number of years (full description in *Mayaud* [1980]). Planetary-scale activity is measured with the $K_p$ index [e.g., *Bartels*, 1962; *Menvielle and Berthelier*, 1991], which is based on the average of fractional *K* indices from 13 subauroral stations (between geomagnetic latitudes of 48° and 63°) with reasonably good longitude coverage. $K_p$ has been continuously calculated since 1932 by the GFZ in Potsdam and is available at www.gfz-potsdam.de. The $K_p$ index is probably the most widely used of all magnetic indices. It is intended to express the degree of "geomagnetic activity," or disturbance for the whole Earth, for intervals of three hours in Universal Time [*Mayaud*, 1973]. In order to allow for simple averaging operations, the $K_p$ indices are next converted, by use of a table, from their quasi-logarithmic scale to a roughly linear scale (in nT), yielding the so-called 3-h *ap* index. Finally, index $A_p$ is defined as the average of the eight 3-h *ap* indices for the day. In the present study, we use this $A_p$ daily series.

[6] The derivation of the *aa* index is similar to that of $A_p$ [*Mayaud*, 1972], but is based on data from only two roughly antipodal observatories, Greenwich (and its successors Abinger and Hartland) and Melbourne (and its successor Toolangi). We use here the daily *aa* values, which are the averages of the eight three-hourly *aa* values for the day; *aa* is expressed in nT. *aa* values are available since the end of 1867. The first 100-year series was compiled by *Mayaud* [1973] himself and was found to be "*as homogeneous as possible.*" The 1-yr centered running means of *aa* are shown from 1955 to 2010 in Figure 1 ($A_p$ is extremely similar).

### 2.2. Geomagnetic "Mean" Indices

[7] In this paper, we use two indices of this type, a planetary one $D_{st}$ and a second one attached to each observatory, $\zeta$. The classical $D_{st}$ index was initially devised to study "*the temporal development and intensity of magnetic storms and the ring current*" [*Sugiura*, 1964; *Sugiura and Kamei*, 1991; *Menvielle and Marchaudon*, 2007]. The $D_{st}$ index is constructed from the recordings of the horizontal component *H* of the geomagnetic field for the five quietest days of the relevant month (after removal of the regular daily variation and of the secular variation of the main, internal field) from the four low to midlatitude observatories of Hermanus, Honolulu, Kakioka and San Juan. These were chosen on the basis of the quality of observations and because they were

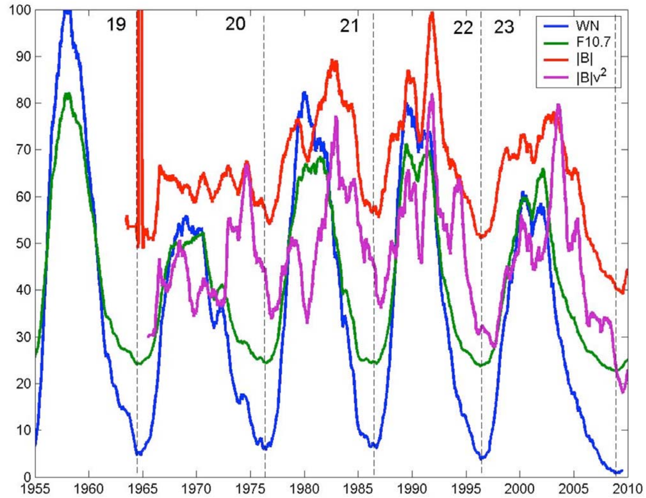


**Figure 2.** Solar cycle represented by 1 y averaged indices of solar activity *WN* (divided by 2, blue); $F_{10.7}$ (divided by 3, green), $|B|$ (multiplied by 10, red), $|B|v^2$ (divided by 30,000, magenta).

far enough from the equatorial and auroral electrojets and distributed reasonably evenly in longitude. The result is hourly values of the so-called local magnetic disturbance $D(t)$ at each one of the 4 stations [*Mursula et al.*, 2008]. The four data sets are normalized to the magnetic equator and their weighed average is the $D_{st}$ index. Daily mean values of $D_{st}$ are averages of the 24 hourly values for the day. The series of the storm-time disturbance index $D_{st}$ starts in 1957 and is calculated at the World Data Center WDC-C2 (Kyoto, Japan). It is one of the most widely used in academic research [*Love and Remick*, 2007]. In this paper we use both the hourly and daily values of $D_{st}$, as available at ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/DST/. In the following we use $-D_{st} \sim |D_{st}|$ (this is true because $D_{st}$ is negative most of the time).

[8] We have introduced in previous work [e.g., *Shnirman et al.*, 2010] simple indices $\zeta$ that belong to the same family type as $D_{st}$ (see also *Bellanger et al.* [2002] and index *IDV* of *Svalgaard and Cliver* [2005]). As is the case for index *K*, they can be measured for any single observatory. For day *t*, $\zeta(t)$ is the absolute value of the slope of the variation of the horizontal component $H(t)$ computed from three successive daily values $H(t-1)$, $H(t)$, $H(t+1)$ at the observatory. This kind of index can be traced back to the inter-diurnal variability *U* of $H(t)$ at a station, discussed by *Bartels* [1932] as a measure of geomagnetic activity at the station, based on the absolute value of the difference between $H(t)$ and $H(t-1)$ [see, e.g., *Svalgaard and Cliver*, 2005]. We call $\zeta(t)$ the "three-day running slope." $\zeta$ can be calculated for any observatory: we illustrate their use in this paper for the cases of Eskdalemuir (ESK), Hermanus (HER) and Abinger (ABG). The choice of $n = 3$ days in order to compute the slope is not critical: similar results are obtained as long as $n < 8$ [e.g., *Shnirman et al.*, 2010]. The $\zeta$ indices are interesting for several reasons: whereas $D_{st}$ is available only back to 1957, the $\zeta$ indices can be extended much further back in the past; also they have a local character (they are quickly calculated for any observatory) that can be used to check the homogeneity (or lack of) of a phenomenon, which is not possible with $D_{st}$.

[9] The 1-yr centered running means of the absolute values of $D_{st}$ are shown from 1955 to 2010 in Figure 1 ($\zeta_{ESK}$ or any other $\zeta$ we have calculated are similar).

[10] Other indices have been derived over the years: $I_{aac}$ is a 27 day recurrence index based on half-day values of *aa* proposed by *Sargent* [1985]. It reveals lengthy periods when geomagnetic activity is faithfully repeated every 27 days at the end of each sunspot cycle. These end abruptly with the beginning of a new sunspot cycle and may correlate with auroral heights [*Sargent*, 1985]. A corrected $aa_C$ index has been proposed by *Rouillard et al.* [2007]. *Svalgaard and Cliver* [2005] have introduced a new geomagnetic index *IDV* and *Rouillard et al.* [2007] have developed a median index *m*. The latter two are based on hourly mean geomagnetic data, one discarding dayside data, the other not.

[11] *Mayaud* [1980] emphasizes the differences between the two families and recalls that "mean" indices have the great advantage of monitoring a single and well-defined phenomenon (ring current for $D_{st}$ or auroral currents for *AE*). The "range" magnetic indices (*aa* and $A_p$) are widely used as precursors for solar cycle prediction [e.g., *Ohl*, 1966; *Feynman*, 1982; *Thompson*, 1993; *Hathaway and Wilson*, 2006; *Hathaway*, 2008].

## 2.3. Solar Indices

[12] Solar activity may be represented by several solar indices. Two classical indices are related to the electromagnetic output of the Sun: the Wolf (sunspot) number (*WN*) series is the longest and most commonly used solar proxy, and the radio flux $F_{10.7}$ series is the longest series of instrumental solar observation. The international daily sunspot number index is available from 1850 on, at e.g., ftp:\\ftp.ngdc.org. The decimetric $F_{10.7}$ index is a daily measurement of the radio flux at 10.7 cm made at Penticton Observatory, available since 1947 (ftp://ftp.ngdc.noaa.gov). This index appears to be better correlated with EUV irradiance than sunspot number [*Donnelly et al.*, 1983; *Floyd et al.*, 2005; *Dudok de Wit et al.*, 2009]. Both indices carry essentially the same information in the present study when running means over 1-yr or more are calculated. The 1-yr centered running means of *WN* and $F_{10.7}$ are shown from 1955 to 2010 in Figure 2.

[13] More recently, data relevant to the solar wind and the interplanetary magnetic field (IMF) have become available (e.g., http://omniweb.gsfc.nasa.gov/form/dx1.html): the magnitude $|B|$ of the IMF and the solar wind plasma speed *v* at the Earth's orbit. An important and useful composite index is $B.v^2$ [e.g., *Rouillard et al.*, 2007; *Finch and Lockwood*, 2007]. Daily data for these parameters are available with reasonable coverage since 1965, although the total number of gaps remains episodically high until 1995. The 1-yr centered running means of $|B|$ and $B.v^2$ are shown from 1965 to 2010 in Figure 2.

## 2.4. General Behavior of Indices

[14] The Schwabe or "$\sim$11-yr" solar cycle is more or less clearly seen in all series plotted in Figures 1 and 2 though it is expressed in different ways. The evolutions of $|B|$ and $B.v^2$ (Figure 2) follow the sunspot number in cycles 21 to 23, but they are quite different in solar cycle 20. *Gosling et al.*

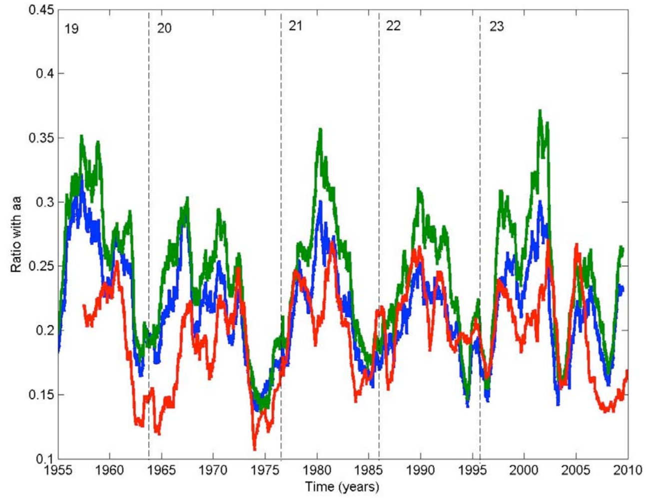


**Figure 3.** Ratios between 1-yr averaged mean indices $\zeta_{ESK}$ (multiplied by 1.2, blue), $\zeta_{HER}$ (green), and $|D_{st}|$ (divided by 4, red) and range index *aa.* Solar cycle minima are shown by vertical dashed lines and cycles are numbered above. Phase shifts between different ratios are seen f.i. around 1970 or 2005 (see text).

[1977] were the first to show that solar cycle 20 was indeed anomalous. As is noted above (and generally well known), *aa* and $A_p$ on one hand, $D_{st}$ and $\zeta$ on the other hand are very similar. All these geomagnetic indices display a similar evolution (even in detail) most of the time, though a strong loss of similarity between the two pairs (*aa*, $A_p$) and ($D_{st}$, $\zeta$) occurs between ~1973 and ~1977, i.e., during the declining phase of cycle 20 (as illustrated for *aa* and $D_{st}$ in Figure 1). $D_{st}$ and $\zeta$ more or less reflect the evolution of $|B|$, whereas *aa* and $A_p$ reflect that of $B.v^2$ (Figures 1 and 2). The anomalous cycle 20 for instance is expressed in a similar way in both geomagnetic and solar wind indices. This is explored in more detail with correlation functions in the next section.

### 2.5. Ratios of Geomagnetic Indices

[15] We have also calculated the time evolution of the *ratios* of range to mean indices, in order to complement the observations that can be made from Figure 1. We see in Figure 3 that these ratios are far from being constant: they vary by 100% about their mean value. They clearly display a remaining Schwabe cycle, with a time-varying structure that tends to repeat from cycle to cycle, with a double (or triple) maximum (at solar max) and a small secondary maximum ("rebound") near the time of transition between two cycles (at solar min), a structure that is similar to that of *aa* or $D_{st}$ themselves (Figure 1).

## 3. Correlation Between Indices

[16] As soon as 1932, Bartels found that the correlation between yearly sunspot numbers and his index of geomagnetic activity from 1872 to 1930 was as high as 0.88 [see *Gosling et al.*, 1977]. We have calculated the correlations between pairs of indices and studied their evolution at multiannual to multidecadal time scales, in order to test whether the evolution of solar activity influences not only geomagnetic indices themselves, but also their mutual correlations.

[17] Our study covers mainly the time period from 1955 to 2010 that is common to geomagnetic and solar indices (the $D_{st}$ index imposing a starting date after 1957). When solar wind indices are involved, the period can only start in 1965, and care should be exercised until 1995 because of gaps in the annual mean values. In what follows, we show a selection of the correlations we have calculated and indicate where well-known results are vindicated and where some new observations can be made (we do not show all the curves we calculated, since we omit those with little new information content).

### 3.1. Correlations Between Pairs of Geomagnetic Indices

[18] Figure 4a shows the correlation between 1 yr averaged "range" family indices *aa* and $A_p$, respectively in a 4-yr and an 11-yr centered window. Correlation, as is well known, is excellent, with values always exceeding 0.95 and

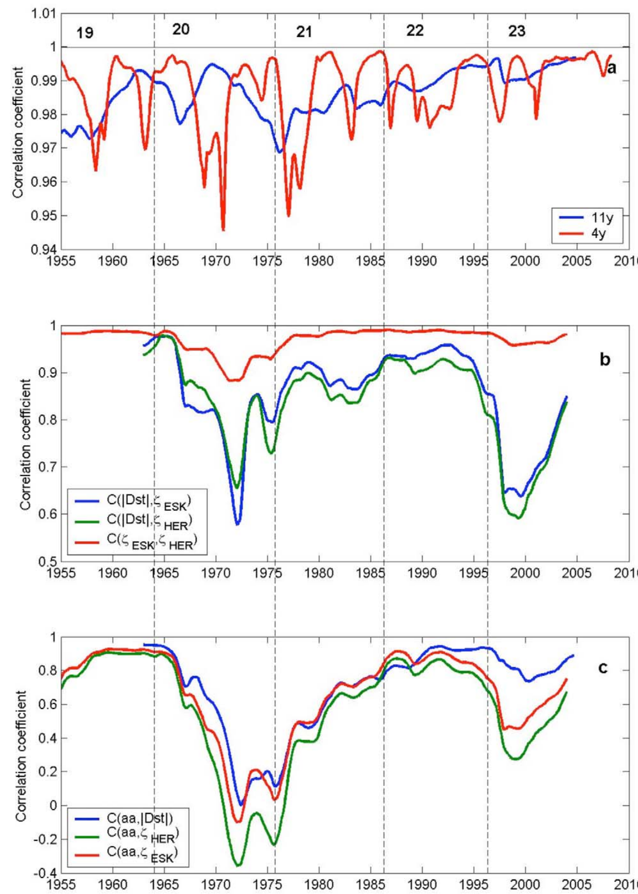


**Figure 4.** (a) Correlation between 1 y averaged range indices *aa* and $A_p$ in 11 y (blue) and 4 y (red) window. All windows are centered; dashed lines indicate solar minima; solar cycles are numbered above the panel. (b) Correlation between 1 y averaged mean indices $|Dst|$ and $\zeta_{ESK}$(blue); $|Dst|$ and $\zeta_{HER}$ (green); $\zeta_{ESK}$ and $\zeta_{HER}$ (red) in 11-y centered sliding window. (c) correlation between 1y averaged range *aa*-index and mean indices $|D_{st}|$ (blue), $\zeta_{HER}$ (green) and $\zeta_{ESK}$ (red).

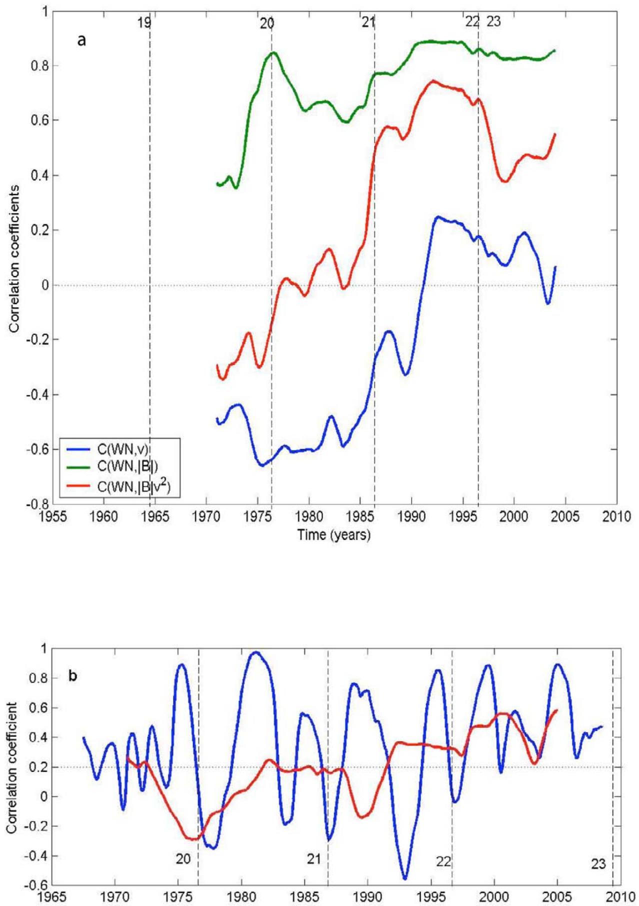


**Figure 5.** (a) Correlation between 1 yr averaged sunspot number WN with solar wind indices $|B|$ (green), $|B|v^2$ (red) and $v$ (blue). (b) Correlation of 1-yr running means of $|B|$ and $v$ within 4-yr (blue) and 11-yr (red) running windows. All windows are centered.

most of the time 0.97. There are slight temporary losses in correlation near 1970 (maximum of solar cycle 20) and 1977 (solar minimum between cycles 20 and 21).

[19] Figure 4b shows the correlations between 1 yr averaged "mean" family index $|D_{st}|$ and $\zeta$ indices in two observatories (Eskdalemuir and Hermanus) and between the two $\zeta$ indices themselves. The latter is excellent, above 0.95 most of the time, except for a small decrease near 1972 and an even smaller one near 2000. On the other hand, correlation with $|D_{st}|$ shows values often below 0.9 and two sharp drops (that we may call "de-correlation events") down to 0.6 near 1972 (declining phase of cycle 20) and 2000 (early cycle 23). This confirms the global validity of local $\zeta$ indices, and indicates that the "de-correlation events" seen when using $|D_{st}|$ are global events.

[20] Figure 4c shows the correlations between a 1 yr averaged "mean" family index $|D_{st}|$ or $\zeta$ and the "range" family index *aa.* All curves are essentially similar and show the high overall correlation between mean and range indices that occurs more than half of the time, contrasted with the two significant "de-correlation events," when correlation drops to $\sim$0.4 (year $\sim$2000) and even to negative values as low as $-0.3$ (year $\sim$1972). This quantitatively documents the strong loss of similarity of the two indices seen in Figure 1. It is well known [e.g., *Feynman*, 1982; *Feynman and Gu*, 1986] that mean and range indices are not strictly in phase with the solar cycle or with one another (Figure 1). Their correlation calculated without a lag depends on the phase of the cycle, and the actual lag varies with the cycle. Periods of large correlation drops between a range and a mean index are roughly the same as between two mean indices (Figures 4b and 4c).

### 3.2. Correlations Between Solar Indices

[21] Correlation coefficients between solar "electromagnetic" indices (or proxies) *WN* and $F_{10.7}$ is known to be high and need not be illustrated further here. On the other hand, correlation between *WN* and solar wind indices varies, sometimes strongly, with time (Figure 5a). Whereas correlation of *WN* and $|B|$ remains positive and generally high after 1975, correlation with either $v$ or $Bv^2$ rises sharply from anticorrelation in 1975 to correlation in the early '90s. This is reminiscent of the evolutions of correlations of mean vs range geomagnetic indices (Figure 4c). The correlation between solar wind indices $B$ and $v$ is on average low ($\sim$0.2) and varies strongly with time (see oscillations in Figure 5b), and these two characteristics of the solar wind can be considered as independent. Detection of temporary losses in correlation of solar wind related parameters is hampered by the fact that the time series start at the end of cycle 20 and have significant gaps until 1995.

### 3.3. Correlations Between Geomagnetic and Solar Indices

[22] The *IDV*, $aa_C$ and $m$ indices (see section 2.2) have been related by *Rouillard et al.* [2007] to functions combining solar wind parameters, respectively $B$, $B.v^2$ and $B.v^{1/2}$. *Finch et al.* [2008] have introduced an index $\sigma_{28}^{H}$ based on monthly standard deviations in the $H$ component of the geomagnetic field; in auroral regions, this index correlates with solar wind speed $v$, whereas in the mid- and low-latitude regions it responds to variations in interplanetary magnetic field strength $B$. We next study the evolution of the correlation between a geomagnetic and a solar index.

[23] Figure 6 shows the correlations between sunspot number *WN* on one hand and geomagnetic range index *aa*, and mean index $|D_{st}|$ on the other hand. Correlation of $|D_{st}|$ with sunspot number is seen to be much better (most of the time >0.5) than that of *aa.* The latter displays a large decorrelation event (reaching anticorrelation at $-0.5$) between 1972 and 1976 and a smaller one near 2000. Figure 7 shows the correlations between other solar wind and geomagnetic indices. Figure 7a shows *aa* vs $|B|$, $|B|v^2$ and $v$, whereas Figure 7b shows $D_{st}$ vs the same three solar wind indices. We see that *aa* always correlates remarkably well (>0.9) with $|B|v^2$, so that one can reasonably be considered as a proxy of the other all the time (e.g., *Rouillard et al.* [2007] for $aa_C$). On the other hand $D_{st}$ correlates rather well with $|B|$ most of the time (>0.6), but they cannot be considered as reliable proxies of one another. The main observation, though, is that the other four correlations are non-stationary and increase with a significant upward, rather monotonic

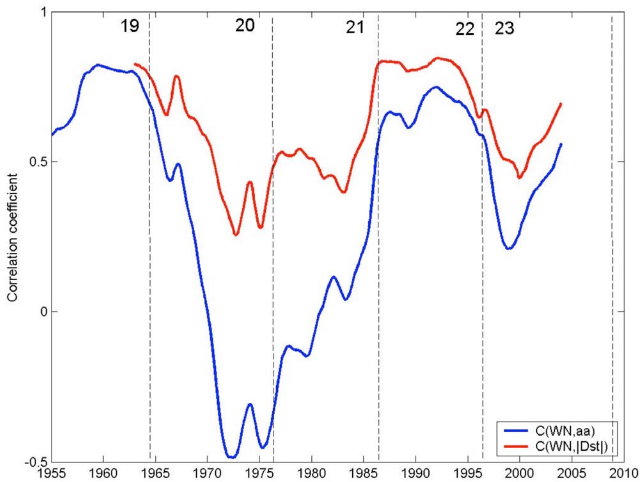


**Figure 6.** Correlation between 1 y averaged solar activity *WN* and geomagnetic indices: range (*aa*, blue) and mean (|*Dst*|, red).

trend at the multidecadal time scale (1975–2000). Such is the case for the correlations of *aa* vs |*B*|, and of $D_{st}$ vs $|B|v^2$ and *v*.

## 4. Discussion

[24] Because of the irregularity in both length and amplitude of the solar cycle and because its length (∼11 years) is not small compared to the length of some available series, one cannot estimate directly the phases of each index or their evolution. Yet, that there are phase shifts between different indices is seen in the original data (early 1970s, cycle 20, in Figure 1). Ratios between mean and range indices in Figure 3 also show phase differences in the beginning of cycle 20 (around 1965) and in cycle 23 (around 2005). The changes in phase shift in anomalous cycles are seen not only between series of mean and range indices, but also between different mean indices (i.e., within the same family).

[25] The ratios between "mean" and "range" indices underscore the difference between these two families of indices and the differences in the way they are affected by short-term events (Figure 3). Indeed, a major difference between what "range" indices (*aa* and $A_p$) on one hand, and "mean" indices ($D_{st}$ and $\zeta$) on the other hand capture from a given magnetic series can be illustrated in the case of an event of short duration, say ten to thirty minutes: such an event will affect a three-hourly index (range) *K* with its full amplitude but far less an index such as $D_{st}$ based on a linear mean daily value [see also *Menvielle*, 1979]. As a result, daily values of "range" indices reflect such short events more than those of $D_{st}$ and $\zeta$. In other words, "range" indices are more affected by the higher frequency content (periods of, say, a few tens of minutes) of magnetic variations ("magnetic activity"), whereas "mean" indices are more affected by lower frequencies (recall that we use daily values; "higher" and "lower" are meant with respect to the duration of one day, the interval over which our data series are first averaged). From a physical standpoint, we can speculate that the generation of toroidal field of a new solar cycle (from the poloidal field of the previous cycle) during the descending phase of the old solar cycle [*Legrand and Simon*, 1991] results in an increase of short-lived magnetic events, and therefore of *aa* (a "range" index) relative to $D_{st}$ (a "mean" index). This observation may be useful for solar cycle prediction.

[26] Some unusual features of the ratio minima observed in the declining phase of cycle 23 may explain why predictions of solar cycle 24 based on *aa* are quite scattered [e.g., *Hathaway and Wilson*, 2006; *Hathaway*, 2008; *Pesnell*, 2008]. The first minimum of the ratio $\zeta/aa$ in cycle 23 (near 2003; Figure 3) corresponds to high values of *aa* (Figure 1), whereas the second one near 2007 corresponds to low values of *aa*. We note that the values of the $\zeta/aa$ ratios attained at the secondary maximum between the two minima of cycle 23 are similar to those attained during the maxima of solar cycles 20 and 22 (Figure 3).

[27] We now turn to the information that can be gained from analysis of the correlations between series of indices (section 3).

### 4.1. Time Evolution of Correlations

[28] As recalled in the introduction, the classical magnetic indices $A_p$, *aa* and $D_{st}$ have been devised to capture magnetic variations of different origins recorded in observatories. In

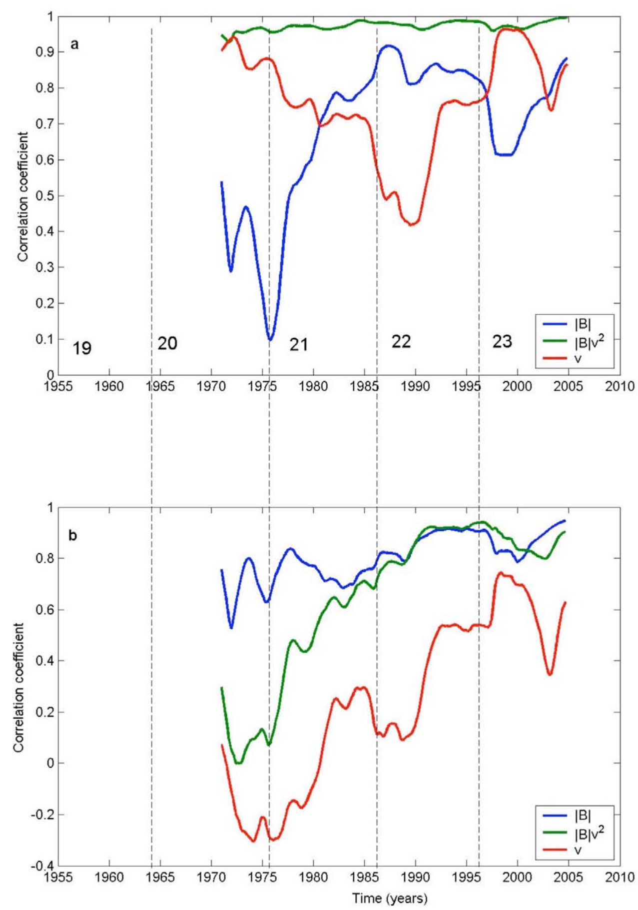


**Figure 7.** (a) Correlation between 1 yr averaged geomagnetic range index *aa* with solar wind indices |*B*| (blue), $|B| v^2$ (green) and *v* (red). (b) Correlation between 1 yr averaged geomagnetic mean index $D_{st}$ with solar wind indices |*B*| (blue), $|B|v^2$ (green) and *v* (red).

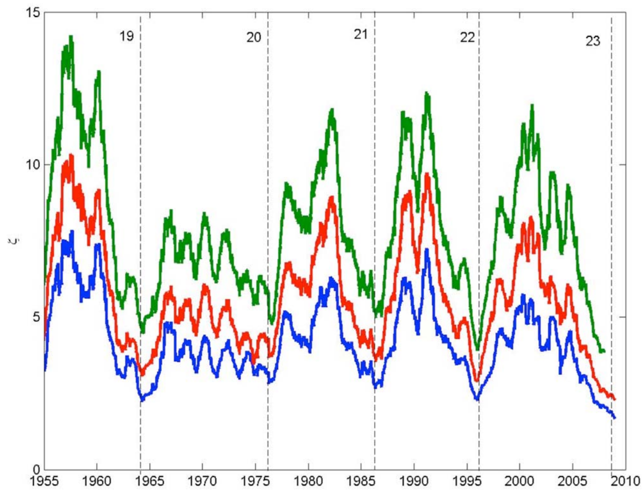


**Figure 8.** Evolution of one-year averaged $\zeta$ index at Eskdalemuir (blue), Alibag (green) and Hermanus (red).

particular, the distinction between "range" and "mean" indices reflects the fact that they are intended to monitor different processes, and could therefore be expected to display distinct time variations. Actually, these indices display correlated evolutions only over certain periods of time, during which they appear to carry essentially the same information; for instance we see consistently high correlation values during cycle 22 (Figure 4), possibly 19, and to a lesser extent 21, but not in cycles 20 and 23. Loss of correlation, sometimes quite strong and going all the way to negative (anti-correlation) values is seen to have occurred in almost all of the pairs of time series we analyzed: between geomagnetic indices themselves, even of the same family (Figure 4), between geomagnetic and electromagnetic solar parameters (Figure 6) and between geomagnetic and solar wind parameters (Figure 7). Even the correlation between *aa* and $|B|v^2$, which is by far the best and most stable one, actually shows a slight but clear decrease of correlation near 1970 and 2000 (on an enlarged figure, not shown here). The strong (and largest in the time span we study) drop of correlation coefficient in the declining phase of cycle 20 and the more moderate but significant (second largest) event occurring in cycle 23 are therefore notable, robust and global features of solar evolution, with a strong impact on all geomagnetic parameters. During these events, geomagnetic activity as measured by *aa* or $D_{st}$ (respectively) de-correlates from $|B|$ and $v$ (respectively).

[29] Another important observation is the lack of long-term stationarity of many of the correlations we have calculated: correlations tend to rise at the multidecadal time scale (between 1970 and 2005) for the pairs ($|B|$, *aa*) (Figure 7a) and ($v$, $D_{st}$) and ($|B|v^2$, $D_{st}$) (Figure 7b). Although solar wind data are not available prior to 1970, we see in Figure 6 that correlation of sunspot numbers with *aa* or $D_{st}$ display the same features for the time when both series are available, up to a scale factor. Therefore, it can be assumed that correlations between *WN* and geomagnetic indices remain good proxies, which can be used (f.i. for some solar wind related correlations) for earlier periods. We can infer that the growth in correlation for the two decades that follow 1975 was preceded by a fast drop in correlation in the rising part of cycle 20. The same general behavior is confirmed by the correlations of geomagnetic indices seen in Figure 4a and 4b.

### 4.2. Significance of Correlations

[30] The above discussion is of course valid only if the computed correlations are significant. We have attempted to determine quantitatively the statistical (and physical) significance of correlation values and their changes, notably the loss of correlation observed in solar cycle 20. For this, we have tested the simple hypothesis that loss of correlation would happen by chance, as a result of a stochastic perturbation of the system.

[31] The simplest model to test this hypothesis (and the first one we have tested) consists in simulating two series of independent values uniformly distributed on [0,1] (the nature of the noise is not very important since we integrate 365 daily noise values in annual means and thus tend to a normal distribution) with a mean correlation equal to that observed. We have generated 5000 (Monte Carlo) simulations and calculated the distributions of values of minimum and maximum correlation, $C_{min}$ and $C_{max}$. We have then determined the 5% significance levels of each one of these two quantities, i.e., the thresholds under (resp. over) which only 5% of the 5000 calculated $C_{min}$ (resp. $C_{max}$) values lie. For instance, for the pair of indices *aa* and $D_{st}$ (1957–2010), the observed mean correlation is $C(aa, D_{st}) = 0.69$. With our simple model, we obtain 5% significance levels of 0.957 for $C_{max}(aa, D_{st})$ and $-0.009$ for $C_{min}(aa, D_{st})$. The probability to have both *observed* values ($C_{min} = 0.00009$ and $C_{max} = 0.95$) by chance in the same series is therefore $(5\%)^2 = 0.25\%$. A second, more realistic, model includes a modulation of the noise by the solar cycle; the probability to obtain the observed values of $C_{min}$ and $C_{max}$ by chance is found to be even smaller than in the first model.

[32] A third model involves a phase shift of the modulation function that could explain the loss of correlation between the mean and range indices. We have constructed such a model, where the noise is again modulated by an 11-yr cycle, but now with a constant phase shift between the two series over the time span considered (and still the observed mean correlation relevant to the *aa* and $D_{st}$ series for 1957–2010). Free model parameters are adjusted so that the solar cycle amplitudes in both series are the same as the observed ones (the phase shift is 0.8 rad). In the 5000 (Monte-Carlo) simulations we performed, none resulted in the observed values of $C_{min}$ and $C_{max}$.

[33] In conclusion, de-correlation events cannot originate in noise; they cannot be obtained by chance even with a phase shift, if this phase shift is constant over the time span considered (the probability to obtain the observed $C_{min}$ - alone - in the third model is less than 1/5000). But correlation changes and de-correlation events (notably in solar cycle 20) might be due to variations in phase shift between the different indices.

### 4.3. Some Physical Considerations

[34] *Finch and Lockwood* [2007] have published an exhaustive survey of correlations between geomagnetic activity and the near-Earth solar wind and other planetary indices, but on shorter timescales from 1 day to 1 year. Their main conclusion is that $Bv^2$ and coupling function $P_\alpha$

proposed by *Vasyliunas et al.* [1982] provide the best correlation with geomagnetic indices. It is important to stress the fact that our analysis being based on running averages of the indices over 1-yr and longer time windows, we are discussing features with time constants longer than a year. We extend the conclusions for $Bv^2$, reached at shorter periods, at much longer decadal to multidecadal periods.

[35] *Woolings et al.* [2010] have recently used open solar flux $F_s$, which is derived from magnetic data, as a proxy of solar activity to demonstrate strong correlations with atmospheric (tropospheric) circulation at the global and regional scales. *Woolings et al.* [2010, Figure 1] shows that variations in $F_s$ reveal features not seen in other solar measures, such as for instance $F_{10.7}$. The time resolution of *Woolings et al.* [2010, Figure 1] does not allow one to identify the details seen in our analysis, but is compatible with them.

[36] As recalled above, $K$ indices are computed after removal of the regular daily variation $S_R$. This variation contains several parts, arising from different sources. The solar daily variation of quiet times $S_q$ at middle and low latitudes is due to the atmospheric dynamo that operates in the E layer of the ionosphere. In polar regions, there is an additional variation $S_q^p$ which can be attributed to a double vortex current system which also flows in the ionosphere at an average altitude of 110 km and is driven by electric fields in the magnetosphere [*Ratcliffe*, 1972]. When a magnetic storm occurs, following a flare or a coronal mass ejection [see, e.g., *Aschwanden*, 2006], one observes several superimposed phenomena: (a) the "disturbance corpuscular flow" DCF (i.e., the direct effect of the enhanced solar wind), (b) the "disturbance ring" DR (a modification of the ring current in the upper atmosphere), and (c) the "disturbance polar current" DP (additional currents flowing in the polar ionosphere). Although these tend to be more frequent in the main and recovery phases of magnetic storms, they are actually also seen during magnetic quiet times. They occur in two kinds, DP1 and DP2 [*Ratcliffe*, 1972]. DP1 events are associated with currents that flow toward the west round the auroral ovals surrounding the two magnetic poles and should not influence greatly $K$ indices in sub-auroral observatories. On the other hand, DP2 substorms (or fluctuations) [e.g., *Mayaud*, 1980, p.135] are due to an increase in the two ionospheric current vortices (within each hemisphere) that constitute the $S_q^p$ part of $S_q$. These vortices extend to mid-latitudes (the main one extends to dip equator latitudes) and their effects are observed outside of the polar regions, in the form of comparatively short-term changes [*Mayaud*, 1980]. So DP2 events influence *aa* and $A_p$. Based on these considerations, we can make the following proposal: when the "mean" ($D_{st}$) and "range" (*aa* or $A_p$) indices are well correlated (that is for instance $C > 0.6$), this might mean that DP2 substorms occur concurrently with the main storms themselves (thus DP2 with DCF and DR). Such would have been the case during cycles 19 and 22, and to a lesser extent 21 and 23. On the other hand, there would have been a significant drop of correlation coefficient, and possibly even anticorrelation of DP2 substorms and main storms in cycle 20, most notably its declining phase.

[37] The ∼30 year increase (1970–2000) in correlation of parameters reflecting the complex system of Sun-Earth magnetic relationships is reminiscent of the behavior of some coupled nonlinear oscillators [e.g., *Pecora et al.*, 1997; *Tsonis et al.*, 2007]. A network of coupled oscillators can synchronize its behavior, but as coupling strength continues to increase steadily, the synchronous state can eventually be destroyed. The increase in coupling strength might show as an increase in correlation, which we observe, and could eventually lead to a (chaotic?) change in the regime of solar activity, revealed by the sharp drop of correlation coefficient (that we have called a "de-correlation event"). The last full de-synchronization event could correspond to the de-correlation event at the end of cycle 20. Coupling strength would have dropped significantly, then resumed its growth leading to a new de-synchronization event which could be the de-correlation event seen in cycle 23. Because this drop of correlation coefficient is weaker and shorter than that in cycle 20, it may be that the solar regime is still in the process of changing and the beginning of cycle 24 could be equally or more anomalous. The declining phase of solar cycles is associated with polar coronal holes extending to low solar latitudes and during this time geomagnetic activity is strongly coupled to high-speed streams in the solar wind. This causes peaks in geomagnetic activity that are seen as secondary maxima (delayed by a few years from sunspot maxima) in many solar cycles (e.g., Figure 1). This could partly be an explanation for the occurrence of drops of correlation coefficient [e.g., *Sargent*, 1985], although such de-correlation events do not occur in the declining phases of other cycles. What was special in the declining phase of cycle 20 was the occurrence of very large low-latitude coronal holes, associated with weak solar polar magnetic fields [*Wang et al.*, 2009], and large solar wind streams, and this has also been the case for the recent solar cycle minimum at the end of cycle 23 (it has recently been suggested that the northern polar field would reverse in early 2012 [*Hoeksema*, 2011]).

### 4.4. More on Anomalies in Cycles 20 and 23

[38] The largest of the two main periods of significant drops of correlation coefficient between geomagnetic and solar indices (since 1955) that we have identified occurred in the early 1970s in the declining phase of cycle 20. It is so strong that it is immediately seen in some original data, without any processing (Figure 1). The other main period of low correlation occurred in the ascending phase of solar cycle 23.

[39] It has long been noted that cycle 20 was the weakest cycle since 1930 (cycles 12 to 16, from 1878 to 1933 all being smaller, but cycles 17 to 23 included, i.e., from 1933 to 2008, all being larger). *Gosling et al.* [1977] emphasized the unusual aspect of geomagnetic variations during cycle 20. They noted the very large peak in geomagnetic activity that occurred 6 years after sunspot maximum. They showed that whereas cycle 20 was rather normal in terms of sunspot number (using as a basis the average of the nine cycles 11 to 19, i.e., 1868 through 1965), it was strongly anomalous in terms of yearly *aa* index. This is clearly seen in Figure 1 around 1975. *Gosling et al.* [1977] further calculated cross-correlation curves between geomagnetic and sunspot activity and found that in cycle 20 the former lagged the latter by 5 years, compared to the average 1 or 2 years in the nine previous cycles. They attributed the large secondary peak in *aa* index during 1972.5–1975 to an unusual combination of very broad, recurrent, major geomagnetic disturbances, closely coupled to an average solar wind speed unusually

greater near solar minimum than near solar maximum. They also concluded that coronal holes must have been in some way unusual at that time. The anomalous length (Daily record of sunspot groups of the Royal Greenwich Observatory (RGO), National Geophysical Data Center, Boulder, Colorado, 1996, available at ftp.ngdc.noaa.gov) and shape [*Wilson et al.*, 1996] of cycle 20 have also been noted. *Blanter et al.* [2005] showed that there was a strong anomaly in the Markov radius of correlation of both sunspot number *WN* and *aa* index.

[40] The irregularity of solar cycle 20 is also reflected in the evolution of the 1-yr running means of the $\zeta$ index: the fundamental ~11-yr period observed in all solar cycles 19 to 23 takes a remarkable form in cycle 20, displaying a series of smaller oscillations with a quasi-biennial period (~1.8 yr; Figure 8). Other observations of phenomena in the same period range include fluctuations in sudden storm commencements (SSC) during cycles 11 to 22, with periods in the 1.6–1.9 yr range [*Mendoza et al.*, 1999], cosmic ray intensity variations in the outer heliosphere measured by Voyager, with period ~1.8 yr [*Kato et al.*, 2001], and cosmic ray intensity as recorded at Huancayo observatory, with period ~1.68 yr [*Valdes-Galicia et al.*, 1996; see also *Rouillard and Lockwood*, 2004]. Periods of all these phenomena are close to the one we observe.

[41] The anomalous character of cycle 23 has been discussed by, e.g., *de Toma et al.* [2004], *Agee et al.* [2010], and *Russell et al.* [2010]. It is also anomalously long and has an unusual shape; strong irregularities in UV/EUV radiation [*Lukianova and Mursula*, 2011] and solar flares [*Kossobokov et al.*, 2011] have been reported. Cycle 23 also violates the even-odd sequence of solar cycles [*Gnevyshev and Ohl*, 1948]. There is a large variation in predictions of the following cycle (24) given by different techniques [*Pesnell*, 2008] and even by similar techniques [*Hathaway and Wilson*, 2006; *Hathaway*, 2008].

[42] Although it is not possible to propose any definite conclusion based on such a small number of events, we suggest that the fall of correlation between "mean" and "range" geomagnetic indices and many solar parameters during the rise of cycle 23 (Figures 4, 6, and 7) may reflect changes in solar dynamo properties (and their solar surface manifestations) and be the reason of the instability of current predictions of cycle 24. Both surface and deeper processes are involved in the solar dynamo; time evolution of the magnetic field at the surface of the Sun depends on the evolution of the magnetic field inside it. And a number of physical processes that take place at the surface of the Sun change the distribution of surface magnetic fields, that could have important roles in structuring the solar wind and, as a result, affect geomagnetic phenomena, coronal hole distribution and number of sunspots (altering the relative contributions of coronal mass ejections and high-speed streams driving geomagnetic activity). For instance, an increased number of intense susbstorms may have been driven by intense high-speed streams during the minimum in sunspot activity during cycle 20 (1974–1976).

## 5. Summary and Conclusion

[43] We have analyzed long series of daily values of "mean" and "range" geomagnetic indices, respectively the planetary $D_{st}$ and the more recent $\zeta$ indices [*Shnirman et al.*, 2010], and the $A_p$ and *aa* indices. We have compared all data series in the period from 1955 to 2005. As is well known, members of the "mean indices" family are strongly similar to each other most of the time, and so are members of the "range indices" family. The Schwabe ~11 yr cycle is seen more or less clearly in all series (sunspot cycles, solar radio flux at 10.7 cm and solar wind). However, we note a conspicuous break in that similarity in the early 1970s, during the declining phase of cycle 20, and another smaller one in cycle 23. We have calculated the correlation coefficients of pairs of geomagnetic indices as they evolve in time in a systematic way. We have also studied the time evolution of correlation coefficients of geomagnetic versus solar electromagnetic and solar wind related indices. This leads both to some well-known and several new observations. Strong loss of correlation or even anti-correlation occurs at the same time for most pairs of geomagnetic and solar indices, with two significant events in cycles 20 and 23. Several of these correlations are non-stationary and vary strongly in time at decadal to multidecadal time scales, in an irregular non-periodical way. For solar wind parameters, an overall rising trend is seen between 1970 to 1995, or even 2000 (Figures 4, 6, and 7). The correlation of *aa* to $Bv^2$ is very high and stable over the 35 years when both time series are available, so that *aa* can reasonably be used as a proxy of $Bv^2$ for earlier times when solar wind parameters had not started being measured regularly. The correlations shown here suggest which geomagnetic indices can be used as reasonable proxies of some solar indices in the pre-1970s era. *Rouillard et al.* [2007] have used in a similar way combinations of geomagnetic indices to derive solar wind speed *v*, IMF strength *B* and open solar flux $F_S$ from 1895 to the present. In order to do this, they calculated correlation coefficients over shorter durations (1/8 to 365 days) and, based on them, concluded that, over the period from 1903 to 1956, solar wind speed increased by ~15% and $F_S$ by ~85%. *K* indices and indices derived from them contain several parts and we suggest that a component of the disturbance polar current, DP2 substorm events, which are due to increases in ionospheric current vortices and extend down from polar to midlatitudes, influence "range" indices *aa* and $A_p$; DP2 substorm occurrences would have ceased to be correlated with main storms ($D_{st}$) in the declining phase of cycle 20. "Range" indices appear to be more affected by the high frequency content of magnetic activity than "mean" indices (such as $D_{st}$), causing some of the observed departures in behavior of members of both families. We have finally noted that increases in correlation of solar parameters could reflect an increase in the coupling between components of a complex system of nonlinear oscillators [*Tsonis et al.*, 2007]. This could have resulted in "catastrophic" regime changes that would translate into de-correlation events. This could apply to cycles 20, 23 and possibly still be going on during the current anomalous cycle 24. There could be a link with episodes of weak solar polar magnetic fields [*Wang et al.*, 2009].

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