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On long-term variations of simple geomagnetic indices and slow changes in magnetospheric currents: The emergence of anthropogenic global warming after 1990?

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Abstract

We introduce very simple indices based on hourly mean values of geomagnetic components measured in observatories which we show can characterise many aspects of magnetic activity. When data from observatories with very long records (close to a century) are averaged over, say 11 yr (the solar cycle), these indices display remarkably similar time variations, allowing us to define an "overall magnetic trend" with smooth, decade long, variations separated by rather sharp extrema at 1956, 1968 and 1990. All 4 indices we propose (one for each component and a more complete one for the total vector variation) display essentially the same "overall magnetic trend" for all components and all observatories. The curves are however not strictly affine, and ratios of similar indices from two observatories vary, again with the same "overall magnetic trend", with amplitude variations up to 20%. Variations in our magnetic indices also correlate remarkably well with variations in classical, computationally more complex indices such as the magnetic index aa, with the sunspot (Wolf) number W, and solar irradiance S. This implies that both electromagnetic radiations and corpuscular flux in the vicinity of the Earth (whose original source lies in the Sun) are subject to the same variations; the current systems responsible respectively for the solar daily (regular) variation and irregular activity react roughly proportionally to the solar wind, due to corresponding changes in geometry of the magnetosphere. The "overall magnetic trend" bears some puzzling resemblances to long-term internal geomagnetic secular variations, with its discrete jerks. Finally, our indices and solar irradiance co-vary with long-term averages in global temperature of the lower atmosphere until approximately 1990, when the temperature curve sharply diverges upward. This lends support to the proposal that an anthropogenic component to the change in climate may not have been the dominant effect until the last decade of the XXth century.

Keywords: geomagnetic activity; magnetic indices; sunspot (Wolf) number; solar irradiance global temperature

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1. Introduction

Magnetic indices have been derived for decades to characterise magnetic activity, or part of magnetic activity: “any geomagnetic index should correspond to a single and well defined phenomenon” [1]. These indices were introduced at a time when computers were not available, and of course they were defined in such a way as to minimise tedious work as much as possible; the situation is clearly different today. In the present paper we characterise magnetic activity in a broad sense, using different very simple parameters, which we will also call indices. We consider long time periods, and show that all indices, in all observatories, display essentially the same temporal behavior (or signature) when time averaged. In other words, when taken in average over long enough running time intervals, the external magnetic field recorded at the Earth’s surface is, to a first approximation, simply the product of a time function by a space function. We have already demonstrated this property for time constants shorter than the ones considered in the present study [2]. In the present paper, we use long series–several decades long–of hourly mean values of the three components X (North), Y (East) and Z (vertical downwards) of the magnetic field from eleven observatories (the list of which is given in Table 1, together with the corresponding series length). We will also consider the sunspot (or Wolf) number W and the aa index [3].

2. Data series

2.1. Daily amplitudes and total vector variation

For each observatory, let us consider day k and hour t_{ik}. We define the daily range of X for day k as:

$$x(k) = \max X(t_{ik}) - \min X(t_{ik}) \quad (i = 1 \text{ to } 24).$$

i.e. as the maximum difference between hourly means of day k, and the same for the daily ranges y of Y and z of Z.

We next define the daily total vector variation as:

$$\boldsymbol{r}(k) = (1/24)\sum_{i=1}^{24}\left[\left(X(t_{ik}) - X\left(t_{i-1,k}\right)\right)^2 + \left(Y(t_{ik}) - Y\left(t_{i-1,k}\right)\right)^2 + \left(Z(t_{ik}) - Z\left(t_{i-1,k}\right)\right)^2\right]^{(1/2)}.$$

We chose the daily ranges x, y and z for simplicity and because they have been in use (and are therefore available) for a very long time (Maurain, see f.i. in [4], p. 222 Fig. 12); the $\boldsymbol{r}$ index provides a good estimate of the daily mean level variation in the vector field when sampled every hour. Obviously $x(k)$, $y(k)$, $z(k)$

Table 1

A list of the eleven magnetic observatories used in this study, with geographic and geomagnetic coordinates and period for which data are available (in 3 cases, two names are given because of a change in observatory location during the period of interest)

IAGA code	Name	Geographic		Geomagnetic		Time	
		Lat	Long	Lat	Long	From	To
DRV	DUMONT D’URVILLE	−66.66	140.01	−75.06	232.15	1957/04/05	2001/12/31
PAF	PORT AUX FRANCAIS	−49.35	70.22	−57.31	130.79	1957/10/01	2001/12/31
GNA	GNANGARA	−31.78	115.95	−42.71	187.94	1957/07/01	2001/12/31
WAT	WATHEROO	−30.30	115.90	−41.23	187.82	1919/01/01	1958/12/31
HER	HERMANUS	−34.42	19.23	−33.73	82.67	1941/01/01	2000/12/31
CTO	CAPE TOWN	−33.95	18.47	−33.12	82.06	1932/08/04	1940/12/31
BNG	BANGUI	4.43	18.57	4.45	90.33	1955/01/01	2001/12/31
KAK	KAKIOKA	36.23	140.18	26.62	207.77	1924/02/01	2001/12/31
ABN	ABINGER	51.18	359.61	53.58	84.55	1926/01/01	1956/12/31
HAD	HARTLAND	50.98	355.52	54.17	80.29	1957/01/01	2001/12/31
ESK	ESKDALEMUIR	55.32	356.80	58.04	84.07	1911/01/01	1999/12/31
SIT	SITKA	57.07	224.67	60.31	278.12	1902/03/02	2001/12/31
BLC	BAKER LAKE	64.33	263.97	73.67	319.15	1951/03/01	2001/12/31
GDH	GODHAVN	69.23	306.48	79.25	34.62	1926/02/01	2002/12/31

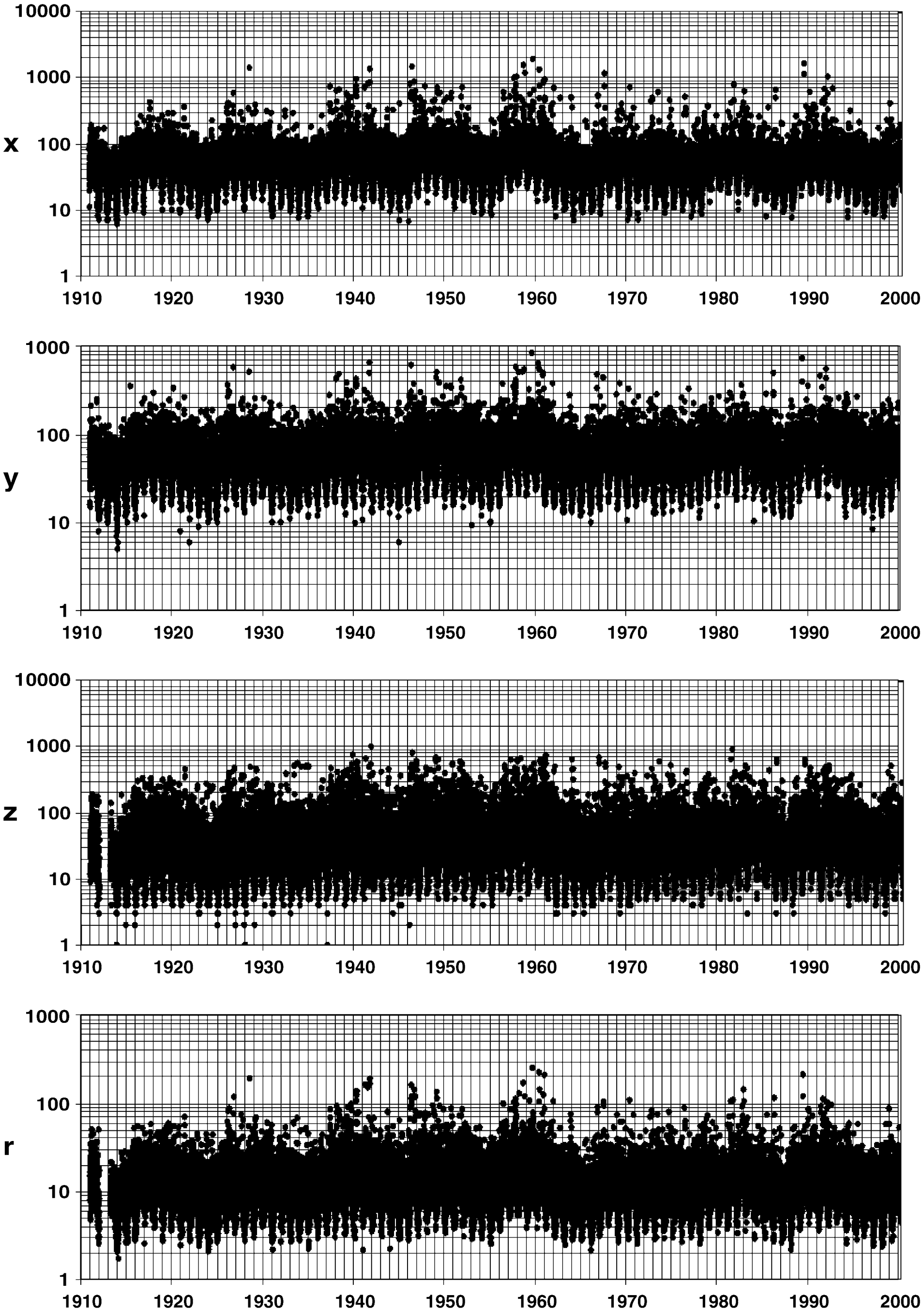


Fig. 1. Magnetic "indices" x, y, z (component indices) and $\boldsymbol{r}$ (total vector index), in nT, defined in the paper are based on the hourly mean values of the 3 components X (North), Y (East) and Z (vertical) of the geomagnetic field at Eskdalemuir observatory, over the period 1911–1999 (see Table 1). Note the logarithmic scale used for these strictly positive time series. Note also that the lower envelope clearly outlines the annual and solar cycle variations.

and $\boldsymbol{r}(k)$ increase monotonously when the sampling interval Δt_i decreases; but we limit our study here to hourly means. We keep in mind the fact that we are computing “weak” estimates of the daily ranges; this is not a serious drawback for reasons which will appear in the following. We first consider the data from a single observatory, Eskdalemuir, where the longest homogeneous series are available, then compare the results from ten additional observatories listed in Table 1.

2.2. Eskdalemuir observatory

The ESK series extend from 1911 to 1999. We start from the series $x(k)$, $y(k)$, $z(k)$ and $\boldsymbol{r}(k)$ as defined above, then compute derived series by taking running averages over time intervals with increasing lengths.

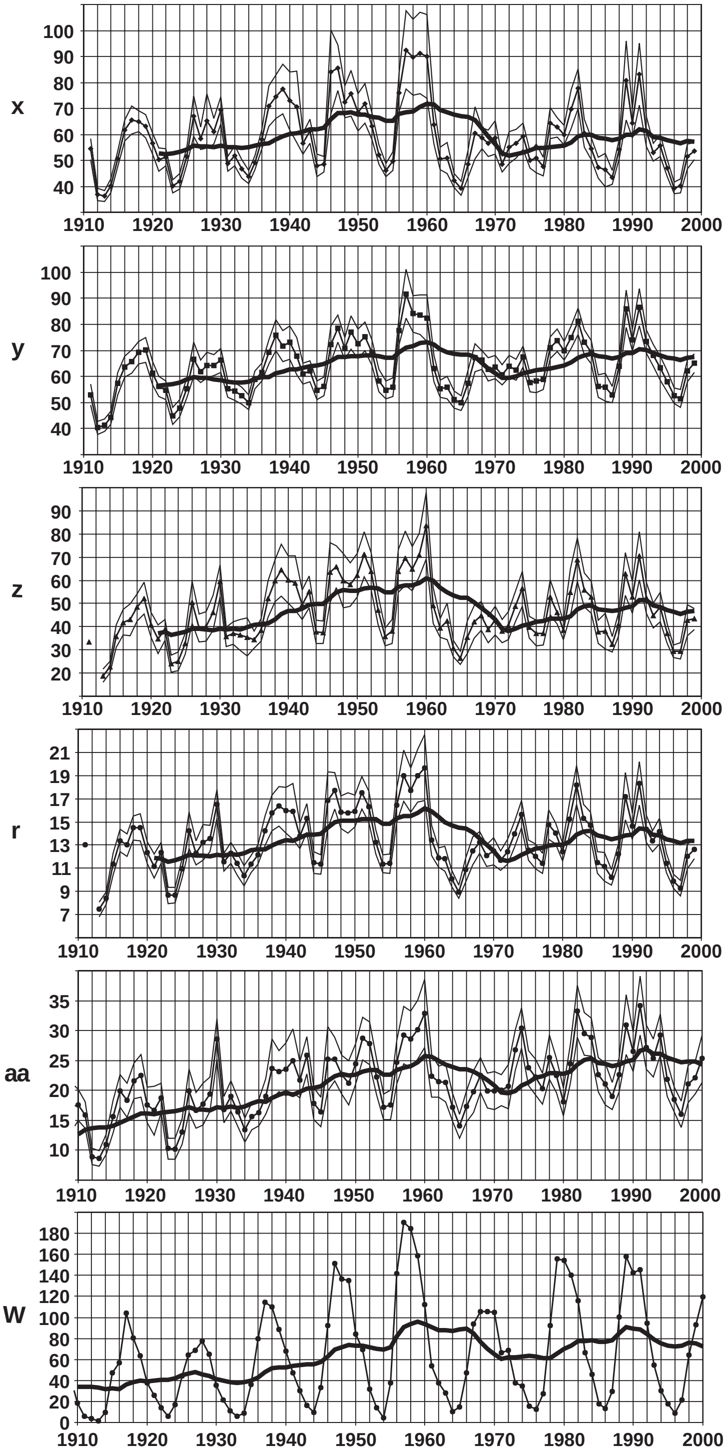
Fig. 1 displays the (89×365) daily ranges and total vector variation values $x(k)$, $y(k)$, $z(k)$ and $\boldsymbol{r}(k)$ on a logarithmic scale for ordinates. The annual variation and the solar cycle are clearly seen on all curves, especially on the lower envelope of each graph. Fig. 2 represents running averages of the same parameters over 1-yr time intervals, retaining only one value per year (i.e. the graph of annual averages). The aa index and sunspot number W, processed in the same way, are also represented. A daily average is computed from the 8 three hourly indices of the day. These x_1, y_1, z_1 and $\boldsymbol{r}_1$ curves are simply continuations of those first introduced by Maurain which covered the period 1883–1923 (see f.i. in [4], p. 222 Fig. 12), with some overlap. In that work, Maurain showed the influence of the solar cycle on the amplitude of the daily range of magnetic elements at the Val-Joyeux observatory (then the French national magnetic observatory). Although most graphs presented up to now are rather classical ones, we wish to emphasize two points.

1) We consider here all days, without discriminating between quiet and disturbed days. Both the solar regular variation S_R and all the components [3] of the so-called magnetic activity–with time constants on the order of an hour and more–enter in x, y, z and $\boldsymbol{r}$.
2) The similarity between $\boldsymbol{r}_1$ and (for instance) z_1 is striking, despite the fact that the second quantity is estimated from only two values $Z(t_i)$ and $Z(t_j)$ of the series, whereas the first is based on (3×24) values. This second remark is not independent from the first one. When considering annual averages of the index $\boldsymbol{r}$, obtained through a simple mechanical procedure, we basically obtain the same information as when we use aa, whose elaboration requires careful removal of the regular solar daily variation S_R! The correlation of all magnetic indices with W (the Wolf number) is also clear—and not a novel observation. But the annual means of W result in a smoother and more regular curve, whereas there is more correlated high frequency content in all other curves. We return to these observations in Section 3.

Fig. 3 displays the running 11-yr averages of our parameters (also shown, with a less convenient scale, in Fig. 2), the average value being assigned to the middle point of the 11-yr interval (~5 yr are lost on each side). In order to draw this graph (and subsequent ones), only one value per year was retained. We write these average series as x_{11}, y_{11}, z_{11} and $\boldsymbol{r}_{11}$. The four curves appear to be quite similar, though not strictly affine one to the other (see Section 3).

Let us go further in the analysis and retain only the five quietest days of the month, as given by the GFZ center (unfortunately not available prior to 1936). Magnetic variations on the quietest days are supposed to result almost only (some of these quiet days may not be that calm) from the solar regular variation S_R generated by the ionospheric dynamo. Fig. 4 represents the 11-yr average computed when only the five quietest days of each month are retained (yearly averages contain only 60 values). Comparing Figs. 3 and 4, it appears that the curves are not only similar within each figure, but also similar from one figure to

Fig. 2. Annual mean values of x, y, z and $\boldsymbol{r}$ from Fig. 1 (noted in the text x_1, y_1, z_1 and $\boldsymbol{r}_1$) with 99% confidence intervals (units as in Fig. 1 but with linear ordinate scales). Averages over 11 yr are also shown in bold without confidence interval (note: the values for these 11-yr averages are assigned to the last year in each 11-yr interval; this is the only figure for which this is the case). The two bottom curves are for the magnetic index aa and Wolf sunspot number W processed in the same way. Note the strong correlations, particularly between aa and magnetic indices, most prominently $\boldsymbol{r}$.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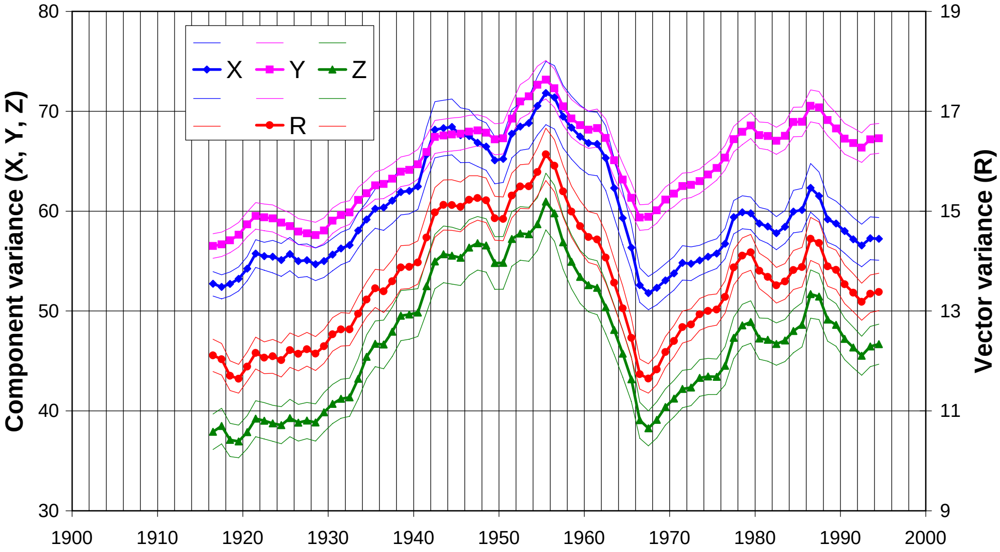

Fig. 3. Same as part of Fig. 2, for 11-yr averages (this time with 99% confidence interval) of x, y, z (left linear scale) and $\boldsymbol{r}$ (right linear scale). Note: the values for these 11-yr averages are assigned to the middle of each 11-yr interval (this is different only in Fig. 2).

the other, and similar to the corresponding curve derived from aa, and to a slightly lesser extent W (the total amplitude of the variations of $\boldsymbol{r}$ computed for all days is about four times that of the variations of $\boldsymbol{r}$ computed for the 5 quietest days).

2.3. Results from ten additional observatories

Now that we have shown the similarity, at a given observatory, of the behavior of x, y, z and $\boldsymbol{r}$, for different choices of the days, we compare the $\boldsymbol{r}$ from the different observatories listed in Table 1. Fig. 5 represents the 11-yr running averages of $\boldsymbol{r}$, $\boldsymbol{r}_{11}$, at the eleven observatories, including ESK. Despite the different mean values of $\boldsymbol{r}$ (sometimes very different; note the two different scales used, one of which applies to the three observatories above 70° geomagnetic latitude) and the different amplitudes of its variation in the different observatories, all curves appear again to be remarkably similar, although not strictly affine. In

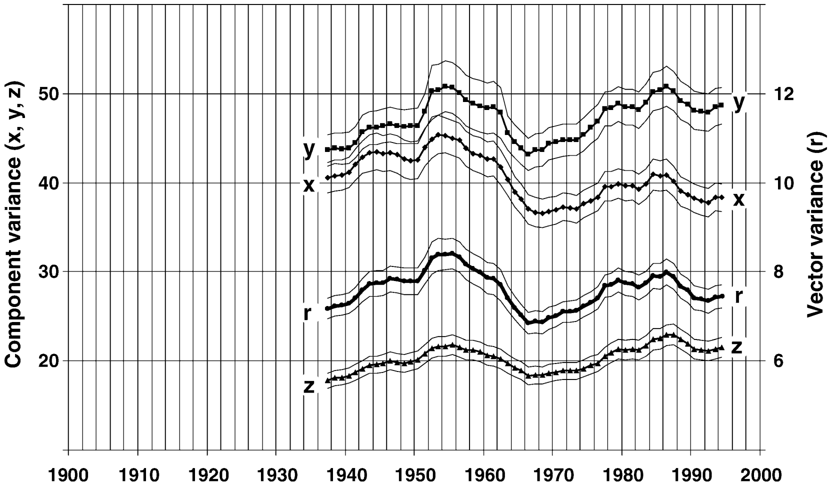

Fig. 4. Same as Fig. 3, but computed for only the five quietest days of each month.

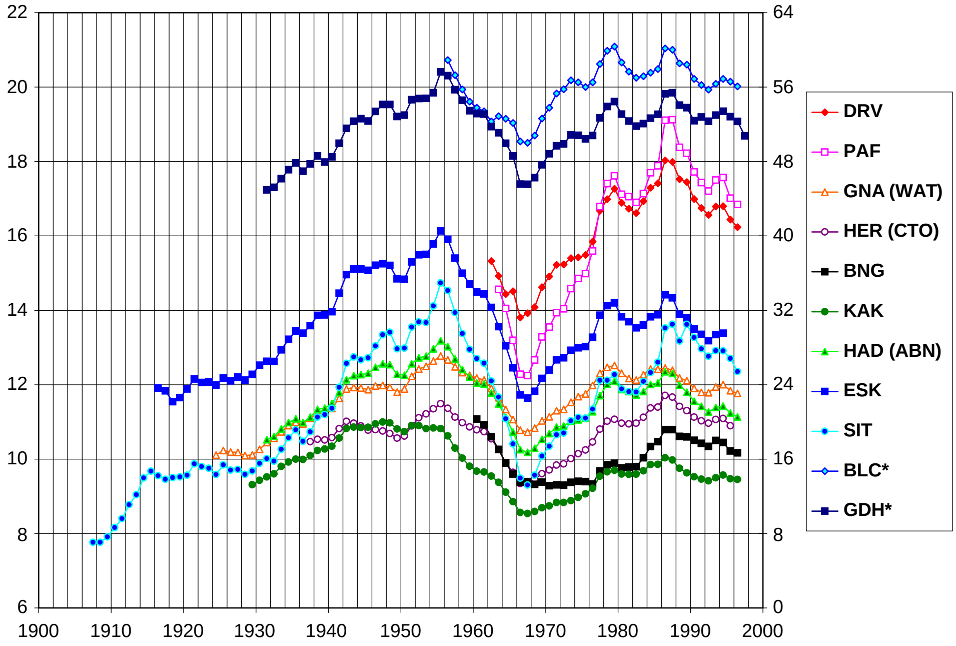

Fig. 5. Eleven-year running averages of ***r*** at the eleven observatories listed in Table 1. Observatories above 70° geomagnetic latitude have larger amplitudes and correspond to the ordinate scale on the right.

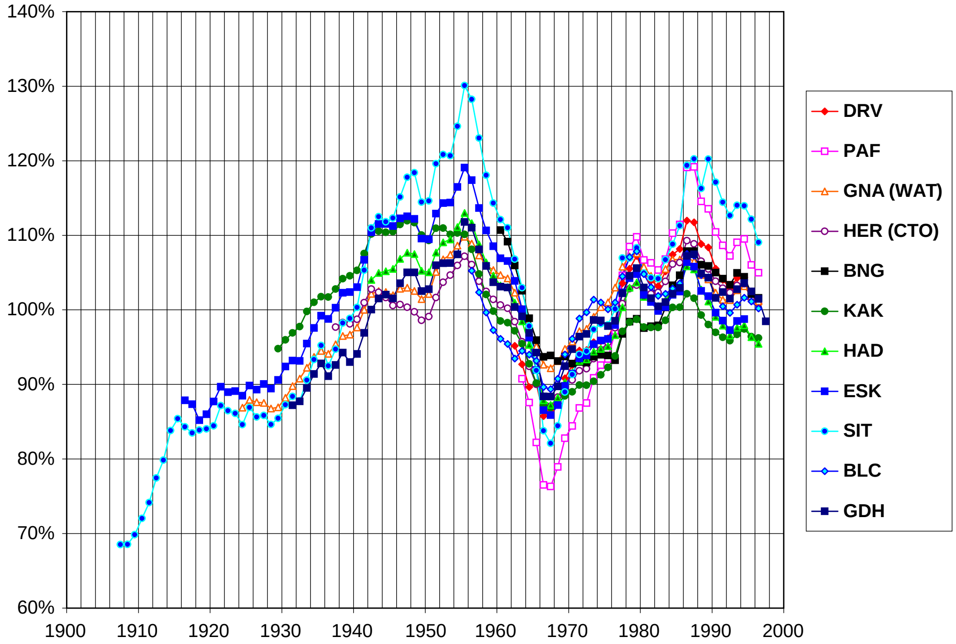

Fig. 6. Same as Fig. 5, but with all curves referred to the same average and normalized to this average (which is therefore by definition 100%). The overall tendency can be used to characterise an "overall magnetic trend" which applies to all indices, all components and all observatories (see text).

order to make the graphs corresponding to the different observatories easier to compare, we have, for each of them, normalized the value of ***r*** to its mean value over the whole time span covered by the corresponding series. Results are presented in Fig. 6. The figure clearly reveals an "overall magnetic trend", which actually applies to all curves evaluated so far over the last century.

2.4. aa Index, Wolf number and observatory data

Solar activity–through the solar wind and electromagnetic radiations–is the source of variations of the external magnetic field. The aa index [3], which covers a 140-yr long period, is aimed at characterising the so-called irregular activity (the daily regular variation being eliminated). It is natural to process the Wolf number W and aa series in the same way as observatory series [5]. Fig. 7 illustrates the results (see also Fig. 2). In order to make intercomparison of the curves easier, 11-yr averages have been normalized to their gross average over the 1952–94 time span, and ordinates are expressed in standard deviations computed for each parameter on this same time span. We have also added a last graph which represents (in the same way) variations of the so-called solar irradiance S (see Section 3.1). The $W(t)$ and $S(t)$ curves are very similar. The aa index closely follows ***r*** at the two observatories, although the relationship between the three parameters is not a simple proportionality and slowly varies with time.

3. Discussion

We have seen that the different magnetic parameters considered in this study (x, y, z and ***r***) from all observatories and the aa index, computed either using all days or only the 5 quietest days of the month, present the same "overall magnetic trend" when averaged over long enough time intervals (here 11 yr). And the trend of the Wolf number, processed in the same way, is similar to the trend of these magnetic parameters, although to a lesser degree of detail.

This might be considered as a trivial result: solar activity is responsible for all the variations of the external field; it is therefore not surprising to recover

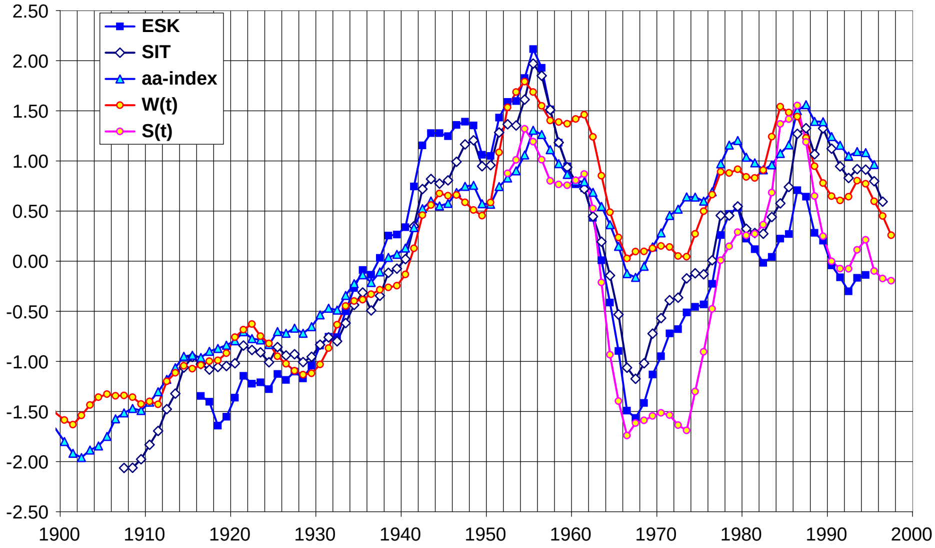

Fig. 7. Eleven-year running averages of ***r*** at Eskdalemuir and Sitka, compared to 11-yr running averages of geomagnetic index aa, sunspot (Wolf) number $W(t)$ and solar irradiance $S(t)$ (see text for references). All curves are reduced to their overall mean over the period, and scaled with standard deviation as unit.

its features (for which the Wolf number stands as a proxy) in the time evolution of magnetic parameters. But it was not obvious a priori that–even averaged over 11 yr–the range of the S_R variation, supposed to be driven by the electromagnetic (UV) radiation of the Sun, would follow solar activity (as measured by the sunspot number) in the same way as the aa index, aimed at measuring the irregular activity attributed to corpuscular flux [3]. If not looking for far-fetched interpretations, this would imply that both electromagnetic radiation and corpuscular flux in the vicinity of the Earth are subject to the same time variations, on the time scales considered; these variations are reasonably well represented by the Wolf number, and the current systems responsible respectively for S_R and irregular activity, whatever their complexity, react roughly proportionally to their source (electromagnetic variation or solar wind).

We now come to a point which has not, to our knowledge, received much attention up to now. To a first approximation, the graphs representing the variations of all parameters are similar (see again Fig. 6 for example). Nevertheless, no scaling allows to perfectly superimpose all curves from each observatory.

Fig. 8 displays the ratios $\rho_{ij}=\boldsymbol{r}_{11}(O_i)/\boldsymbol{r}_{11}(O_j)$ for the three observatories ESK, SIT and HER, after each of them has been normalized to its gross average ("baseline") and its variations expressed in units of standard deviation ("scale"). The ratios change a lot and these variations are statistically significant: this means that the configuration of the magnetosphere changes with time constants which are those of the curves of Fig. 8; for instance, the geometry of electric currents generated by the ionospheric dynamo in the E layer and the geometry of the polar electrojets both change in unison over these time scales of a few years to a few decades.

This evolution can be illustrated in yet another way. On Fig. 9, we plot in a log–log diagram all values $\boldsymbol{r}(k)$ at a given observatory (O_i, here for instance ESK) versus those at another observatory (O_j, here for instance SIT) for all times k within a certain interval of time T_m (here 10 yr) centered on year m (here 1991). We see another geometrical expression of the excellent though not strictly linear correlation between the variation ranges at the two observatories. We next compute the slope $b_{ij}(T_m)$ of the best fitting (though not exact) regression line for the observed cloud of data points, and plot in Fig. 10a

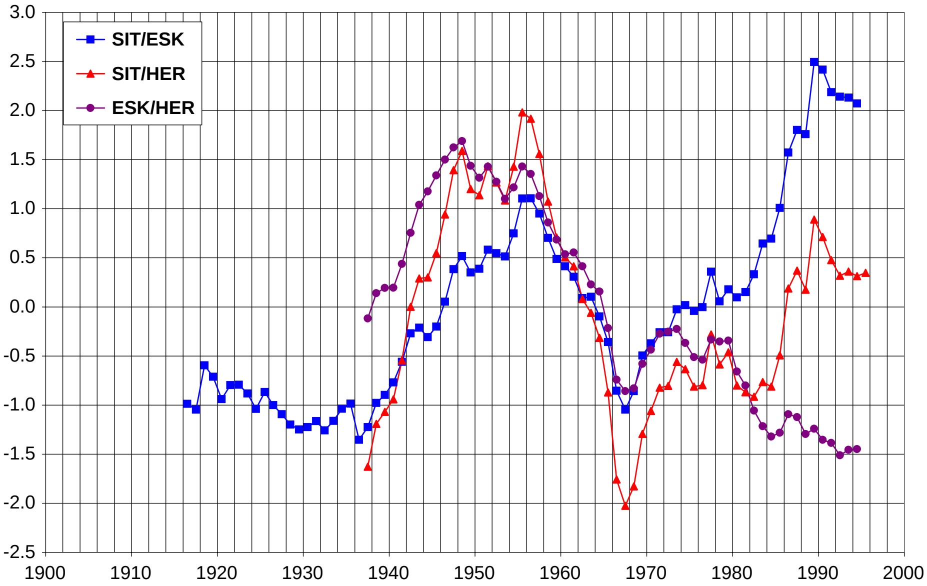

Fig. 8. Two by two ratios of the 11-yr running averages of the $\boldsymbol{r}$ index at the three observatories of Hermanus, Eskdalemuir and Sitka; each ratio is normalized to its overall average (baseline) and standard deviation (scale).

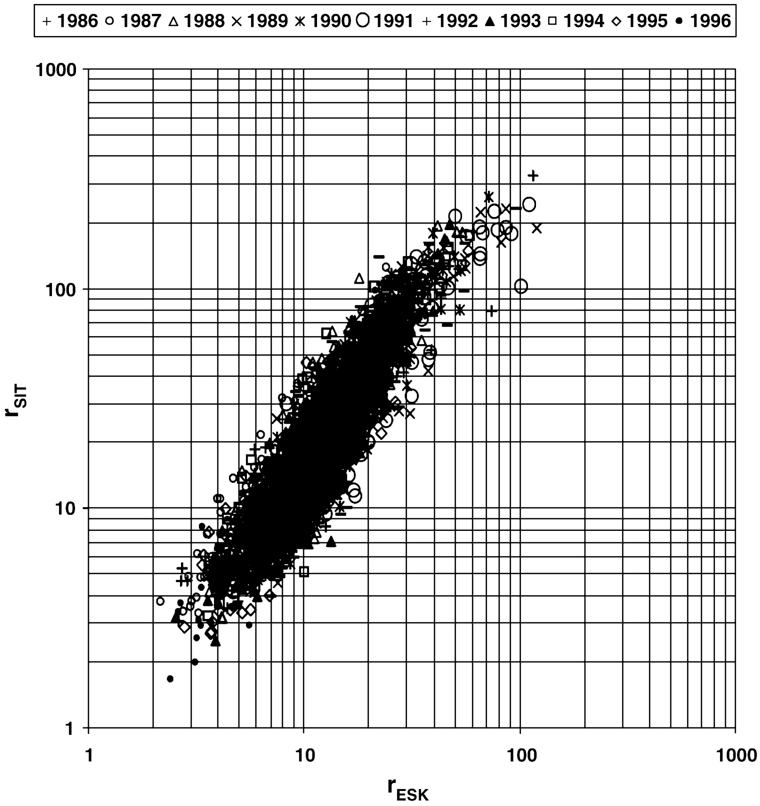

Fig. 9. Correlation between corresponding values of the ***r*** index at Sitka and Eskdalemuir (all values over the 10-yr period from 1986 to 1996). Note a strong though not strictly linear co-variation of the two series (in log–log scales).

the time evolution of this slope as a function of year m (center of 10-yr time-window) for the couple ESK-SIT. The graph $b(m)$ shows again a remarkable structure, consisting to first order of a series of decade long uniform periods separated by rather sharp changes at a small number of discrete years (about 1956, 1968 and 1990; see [5]). The resulting trend is quite reminiscent of the "overall magnetic trend" identified in all previous graphs (e.g. Fig. 6, with a reversal in sign). The same behaviour is not seen (or actually expected) in all pairs of observatories (for instance Hermanus versus Eskdalemuir for reasons possibly linked to its intense and complex secular variation—see Fig. 10b and below).

What could the causes of long term time changes in the geometry of the magnetosphere be? Because of the small number of observatories studied so far, the answer to this question lies beyond the scope of the present paper. We have seen that solar activity undergoes strong variations over the last century, and that these variations are correlative to variations in magnetic indices (as is well known). Changes in geometry of the magnetosphere could be due to these very changes in solar activity, through complex magnetohydrodynamic solar wind–magnetosphere interactions. The fact that the ρ and b variations (at least for the ESK/SIT pair of observatories) look like the magnetic indices variations would favour such a hypothesis.

Another puzzling feature we wish to underline is that the external field, averaged as above, displays decade time constants similar in a way to those of the internal field. The plot of Fig. 10a, with alternating straight line segments and rather sharp changes at a small number of maxima and minima, is reminiscent of the plot of secular variation (e.g. [6]), although the dates of the maxima do not necessarily correspond to the dates of the geomagnetic jerks. We do not intend to overemphasize this observation or to establish a

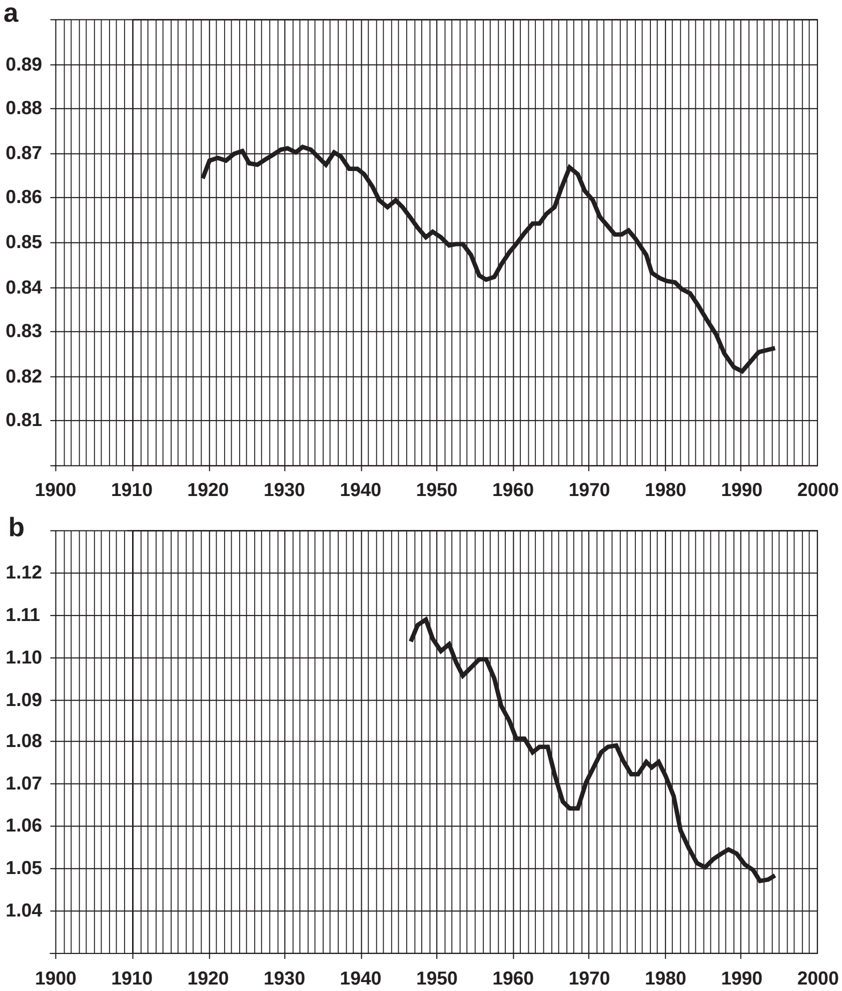

Fig. 10. (a) Time-evolution of the slope *b* of the best fitting straight line to the plot of Fig. 9 for Eskdalemuir and Sitka; (b) same as (a) for the pair Eskdalemuir–Hermanus.

definite correspondence between the ratios of ρ and *b* parameters and internal secular variation. Nevertheless, the hypothesis that main field variations would cause variations in the geometry of the magnetospheric and ionospheric current systems is not that fanciful: this geometry is indeed tightly constrained by the configuration of the main (internal) field. For example, any rotation of the Gauss dipole or shift of the eccentric dipole has an immediate effect on the geometry of the magnetosphere. The relative changes in the main field can reach 5%, at some places, over only a few decades, and even much more if one isolates particular non-dipolar features of the field.

3.1. A relation between magnetic and temperature variations?

The Earth's temperature evolution has been compared with the evolution of the solar irradiance (e.g. [7]). Total solar irradiance *S* has been directly measured since 1978 only, using radiometers aboard spacecrafts; reconstructions are used before this date [8], based on the 140-yr long aa series [3] or long series of spectroheliographs [9]. We observed that the evolutions of aa and *S* are indeed similar (Fig. 7), although not proportional. Solanki [7] compared the *S* and climate curves (average hemispheric

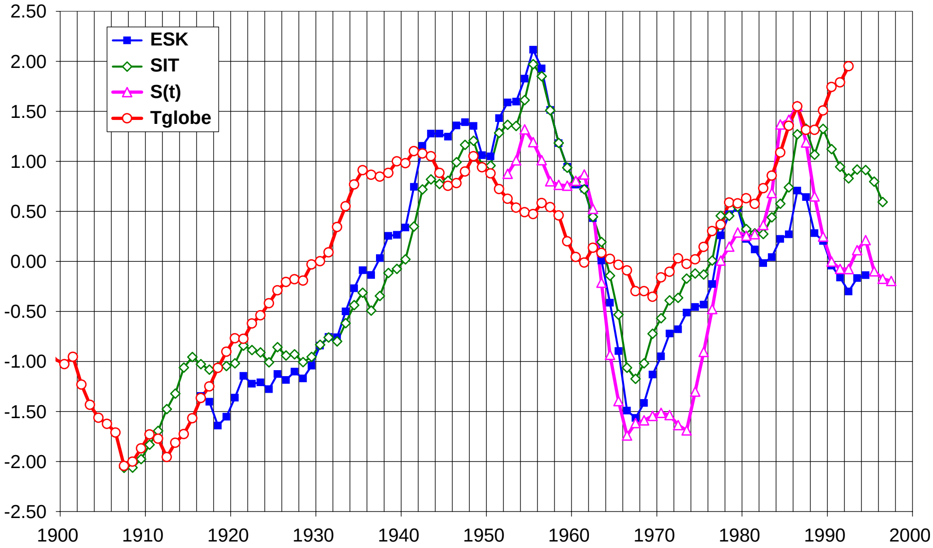

Fig. 11. Time evolution over the XXth century of the 11-yr running averages of our magnetic indices ***r*** for Eskdalemuir and Sitka, solar irradiance $S(t)$ and global mean temperature $T(t)$ (see text for sources of data and comments).

temperatures T in the lower atmosphere of the Northern and Southern hemispheres) and concluded that all curves (smoothed also by 11-yr running means) run on the whole parallel to each other before 1980; the irradiance curve may even be slightly ahead of Earth's temperature (their Fig. 11). After 1980, however, the Earth's temperature exhibits a remarkably steep rise, while irradiance does not (Solanki [7], who is quite cautious in his conclusions). Foukal [9] also concludes in favour of a high degree of correlation between variations in total irradiance between 1920 and 1998 and variations in global temperature. Foukal claims a much lower correlation between temperature and UV irradiance. We note that the discrepancy between the trends in solar irradiance and temperature after 1980 is less clear on Foukal's [9] than Solanki's [7] graphs. The comments which apply to composite irradiance can also be made with respect to the magnetic indices we introduce in this paper. A possible relationship between solar activity–measured through its magnetic proxies–and climate is certainly worth considering further. Fig. 11 displays the evolution of temperature T (e.g. [10,11]), total irradiance S and our characteristic overall magnetic trend. We note how closely the two magnetic ***r*** indices for Eskdalemuir and Sitka follow solar irradiance in the period where the three time series are jointly available. Even fine details, with durations less than 5 yr, are correlated. The same applies to a slightly lesser degree to the global temperature curve. Interestingly, the temperature curve seems to be slightly ahead of the magnetic and solar irradiance curves from 1910 to 1960, whereas they seem to be in phase in the following, perhaps better constrained, 40 yr. It is clear from the latest curves that after 1990 global temperature rises sharply (though this may to some extent depend on which global temperature estimate is used), whereas other indices (magnetic and irradiance) decline.

4. Conclusion

Long-term changes in magnetic activity over the last century, as characterised by daily indices of different kinds, present a typical trend illustrated by Fig. 6 (for example): a smooth increase from 1900 to 1956 (reaching some 30%), then a quasi-linear decrease of nearly the same amplitude, with a minimum around 1968 and a new rise to a maximum around 1988. This pattern is the same for activity attributed to electromagnetic radiation and for activity attributed to the solar wind. The time varying ratio of the slope of variations in one observatory versus another (in log–log space) also reflects the same features, with sharp maxima in 1956, 1968 and 1990. In a recent paper [12], we have shown that the amplitude of the 6-month spectral line in geomagnetic variations displayed a strong quasi-sinusoidal variation (the amplitude varying by a factor of 1.7 over the 1930–1993 time interval). This variation was attributed to a modulation in solar activity. There is no doubt that this modulation is the same as the one we have uncovered in the present paper (although there is some amplification in the amplitude of the 6-month line variations, its relative variations being significantly larger). Other magnetic parameters should display the same pattern.

The increasing trend in the aa index at the turn of the 20th century has been known since the work of Mayaud [3]. Measurements of the near-Earth interplanetary magnetic field reveal that the total magnetic flux leaving the Sun has grown by a factor of 1.4 since 1964 and surrogate measurements of this field indicate that the increase since 1901 has been a factor of 2.3 [8]. Stamper et al. [5] have studied possible causes of this century long increase in geomagnetic activity, using annual means of the aa index as a means of quantifying the phenomena. They have analysed in more detail changes during solar cycles 20, 21 and 22. Friis-Christensen and Larsen [13] first proposed a correlation between the length of the solar cycle and the Northern hemisphere land surface temperature. Variations in the Earth's (so-called) "temperature", over the last century and until 1990, indeed bear a resemblance with the ones represented by the "overall magnetic curve" identified in this paper. But at the beginning of 1990, the temperature curve appears to diverge from that based on magnetic parameters. To what extent is the Earth's temperature controlled by solar activity prior to 1990? And to which extent does failure of the Earth's temperature variations to follow those displayed by solar irradiance and magnetic indices reveal the onset of an anomalous situation, that could be linked with human interference? These important questions are certainly worth considering further [1,7,9,14]. In any case, the loss of correlation between temperature on one hand, solar irradiance and our very simple magnetic indices on the other hand might be an interesting way to attempt to date when anthropogenic global warming emerged from "noise" to become a robust physical observation.

Looking now at the results from the different observatories, it appears that, although the variations of the parameters at all observatories present the same overall pattern, representative curves are not strictly affine: the ratio of the values of the parameters (indices) as computed at two observatories varies with time by up to about 20%, sometimes over only a few decades. This reflects a change in the geometry of the current systems responsible for magnetic variations, whose amplitudes are characterised by our indices. This could be made more precise by using a larger number of observatories; unfortunately there are not many long homogeneous series which are available. In any case, magnetic observatory data are now easily accessible and digitally tractable. Their remarkably rich content is far from having been fully exploited. They might allow quick and easy computation of a number of characteristic indices (or proxies as climate scientists might call them), allowing to better monitor and possibly even to some extent predict solar magnetic "weather" [15,16] and Earth's magnetic "weather".

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