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Long-term trends in geomagnetic daily variation

Susan Macmillan and Anna Droujinina*

British Geological Survey, West Mains Road, Edinburgh, EH9 3LS, U.K.

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Long-term changes in the magnetic environment of the Earth are of interest to those studying space weather and climate change, particularly in the upper atmosphere. In this paper we examine long-term changes in daily variation as derived from hourly mean values from 14 geomagnetic observatories around the world. Their time series date back to the beginning of the 20th century. We find that there are similar features in all the records, with peaks in the amplitudes of the daily variation occurring in the 1950s and 1980s, and a small upward trend of 1.3 nT/century corresponding to an increase of over 10%. The extrema coincide with those seen in solar irradiance proxy data, in particular the F10.7 flux density dataset which starts in 1947.

Key words: Geomagnetism, daily variations.

1. Introduction

The geomagnetic field has a regular variation with a fundamental period of 24 hours. This regular variation is dependent on local time, latitude, season and solar cycle. It is caused mainly by electrical currents in the upper atmosphere, peaking at altitudes around 110 km above the Earth's surface. Current systems in the distant magnetosphere, in particular the magnetotail, also contribute to the daily variation but their magnetic signatures on the ground are relatively small. The upper atmosphere is ionised by the Sun's ultraviolet and X-radiation to create the ionosphere, and the free ions and electrons are moved by winds arising from the heating effects of the Sun. This creates the required conditions for a dynamo to operate, i.e. motion of a conductor in a magnetic field, and current gyres are formed, with one in the sun-lit northern hemisphere in an anti-clockwise direction, the other in the sun-lit southern hemisphere in a clockwise direction (looking from above the ionosphere) (see for example, Chapman and Bartels, 1940). The magnetic effect of these current systems is observed on the ground at observatories at mid-latitudes as solar quiet-day variation, or Sq.

The variation of Sq range with sunspot number has been known for some time (e.g. Olsen, 1993 and references therein) but what is less well known is any variation at periods longer than the 11-year solar cycle. Le Mouël *et al.* (2005) observed long-term trends in new magnetic indices derived from daily ranges of hourly mean values of magnetic field components at individual observatories and concluded that after 1990 the correlation between these indices and global mean temperature deteriorates. This led to the conjecture that the anthropogenic component to the observed change of climate is not necessarily the dominant effect. However their indices include the effects of magnetic storms and sub-storms which are related to solar wind variations, as well as the effects of electromagnetic radiation. In this paper we also look for trends in magnetic data at periods longer than the solar cycle, but this time concentrating on the regular variation which is related to, though not exclusively, the electromagnetic radiation from the Sun. We also include data from other observatories and in recent years.

2. Data Selection

We select observatories which are currently operating and have time series of hourly mean values longer than 70 years. The corrected geomagnetic latitude (Gustafsson *et al.*, 1992) of the selected 14 observatories is less than 60° so the effects of the ever-present high latitude current systems on the results should be small. These high latitude systems are connected to the magnetosphere and are therefore more influenced by any long-term changes in the solar wind.

We select days when there is low magnetic activity. On disturbed days variations in the solar wind has a considerable effect on the coupled magnetosphere-ionosphere system and as a result all currents are energized, especially those at high latitudes. We are more interested in the quiet times than the disturbed times because they occur more frequently and are more predictable, and any long-term trends should be easier to detect. As some of the hourly mean series start before the series of planetary disturbance index Kp in 1932, from which the International Quiet Days are derived, we choose to use another 3-hourly magnetic activity index, the aa index, to select quiet days. For each month we select the five days which have the lowest daily average of the aa index. The aa index is derived from observatory K indices, as is the Kp index, but uses only two observatories instead of thirteen. In cases where there are more than five candidate days in a month, we also use the range of aa during the day to make the selection, choosing the day with

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[*] Now at Shell E&P Int., Kesslerpark 1, 2880 AB Rijswijk, Netherlands.

Table 1. Observatories and time spans used in analysis, ordered by corrected geomagnetic latitude (CGM).

IAGA code	Name	Geographic latitude	Geographic longitude	CGM (1980.0)	Time span	Notes
SIT	Sitka	56.87	224.67	59.64	1902–2004	
LER	Lerwick	59.97	358.82	58.04	1926–2004	
LOV	Lovo	59.18	17.83	55.55	1929–2004	
ESK	Eskdalemuir	55.32	356.80	52.86	1911–2004	
BFE	Brorfelde	55.45	11.67	51.85	1927–2004	<1981 RSV
HAD	Hartland	51.00	355.52	47.93	1926–2004	<1957 ABN
NGK	Niemegk	52.07	12.68	47.72	1890–2003	<1932 SED/POT
CLF	Chambon La Fôret	48.02	2.27	43.56	1923–2003	<1936 VLJ
TUC	Tucson	32.17	249.27	39.68	1910–2003	
SJG	San Juan	18.10	293.85	29.87	1926–2003	
KAK	Kakioka	36.23	140.18	28.58	1914–2003	
HON	Honolulu	21.19	202.00	21.76	1905–2003	
HER	Hermanus	−34.24	19.23	−41.93	1932–2004	<1940 CTO
GNA	Gnangara	−31.61	115.95	−44.18	1919–2003	<1958 WAT

the lower range. By using five days per month we ensure the sample size is constant with time. The observatories used and the time spans of their hourly mean series, are listed in Table 1.

3. Derivation of amplitude of solar quiet daily variation

For each set of hourly mean values from the 5 quiet days per month Fourier functions of the form

$$B_k(t) = a_0 + \sum_{n=1}^{3} (a_n \cos nt + b_n \sin nt)$$

were fitted, where $B_k(t)$ is the magnetic field k component at time t in radians ($2\pi = 24$ hours). Harmonics with periods 24, 12 and 8 hours correspond to values of $n = 1, 2$ and 3.

The coefficient a_0 is the monthly mean of the component in question—this represents the main field and crustal field to a first approximation. The other coefficients are used to find the amplitude and phase of the corresponding periodicity. This simple model results in a mean root mean square misfit of 2.7 nT, 2.8 nT and 1.4 nT for X, Y and Z respectively.

We consider only the amplitudes of the 24-hour periodicities, i.e.

$$A_k = \sqrt{a_1^2 + b_1^2}$$

and derive monthly values for these for each of the magnetic components at the selected observatories. The semi-annual, annual and solar cycle effects are removed from these amplitudes by application of an 11-year running mean. The resulting smoothed amplitudes are shown in Fig. 1. Although the solar cycle length is, on average, less than 11 years for the period covered by the data (1890 onwards), by taking a complete number of years, the annual and semi-annual variations are also removed. It is noted that the solar cycle length varies from just under 10 years to almost 12 years during this period.

The amplitudes for the Y component are nearly always higher than those for the X component, and are always higher than the Z component. This is likely to be linked to the geometry of the main field, which is predominantly north-south, and its effect on the movement of electrons and ions in the ionosphere. The Z amplitude is usually lower than the other components because the source, large-scale horizontal current gyres at ∼110 km altitude, can be modelled by planar current systems which, for the extent of their coverage, will not produce a Z component. However, as the Earth and the geomagnetic observatories rotate underneath them, a diurnal signal in the Z component will be observed at the "limbs" of the current gyres. Induction is also likely to have the most affect on the amplitudes of the Z component, especially for observatories located near the coast. The amplitudes agree with those found by others, for example Chulliat *et al.* (2005).

Maxima in the 1950s and 1980s occur for all observatories in Fig. 1. This result is very similar to that found by Le Mouël *et al.* (2005) where they computed daily ranges using hourly means from all days. These extrema are also observed in other observatories which have shorter time series or are at higher latitude. An extremum at around 1930 for the observatories with sufficiently long time series may also be visible. There also appears to be small upward trend in the daily variation amplitudes. First of all let us investigate the possibility of the Sun being one cause for these features.

The longest continuous series of data derived from direct observations of the Sun's energy output is the F10.7 flux density dataset. This dataset is based on daily measurements at Penticton, Canada of the integrated emission from the solar disk at 10.7 cm wavelength and is available for 1947 and onwards. We use here the "observed flux" which includes effects of the variation of the Sun-Earth distance. Whilst this is a proxy for only part of the spectrum of the Sun's energy output, it is the part that affects the ionosphere. We also use E10.7, a new proxy for the Extreme

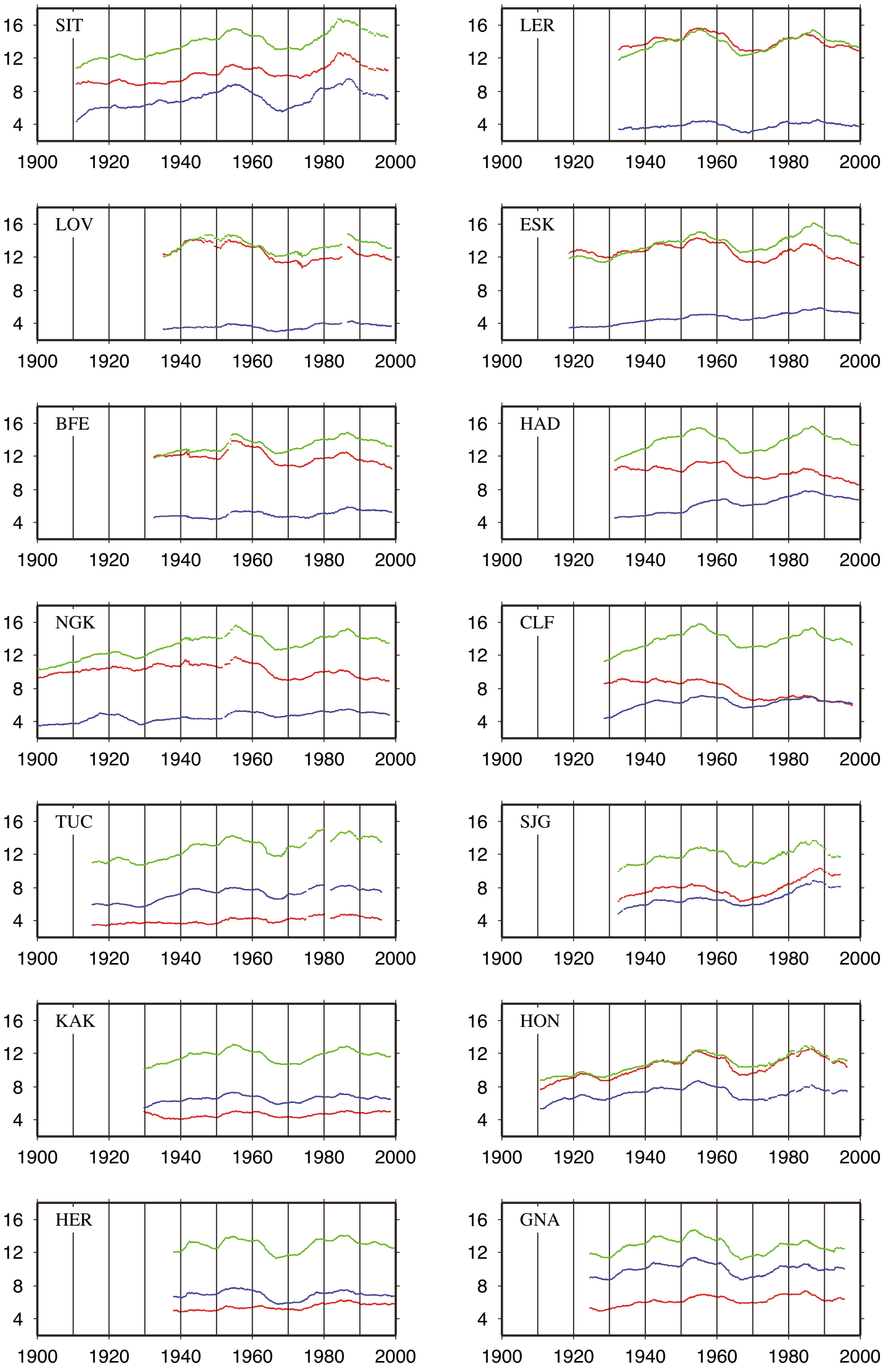

Fig. 1. Eleven-year running means of monthly estimates of amplitudes (nT) of geomagnetic daily variations in X (red), Y (green) and Z (blue) at geomagnetic observatories ordered by corrected geomagnetic latitude from left to right, top to bottom.

Ultra-Violet (EUV) irradiance output by the Sun from a self-consistent model of the solar spectrum, SOLAR2000 (Tobiska *et al.*, 2000). This dataset may be a better characterisation of the actual solar irradiance that deposits energy in the upper atmosphere, the main source region for Sq.

We define the root mean square amplitude at each observatory, A, as

$$A = \sqrt{(A_X^2 + A_Y^2 + A_Z^2)/3}$$

and in Fig. 2 we plot A along with F10.7 and E10.7. All datasets have been smoothed with an 11-year running mean.

The extrema in the 1950s and 1980s occur in both the magnetic and irradiance datasets, suggesting that the main cause for the patterns in the magnetic data is changes in the solar irradiance spectrum in the EUV band. This is largely as expected but is not obvious without removal, albeit incomplete, of the solar cycle effect (it is incomplete because the solar cycle length is not exactly 11 years). There is on average a 1.3 nT, which corresponds to over 10%, increase in A over one century but the irradiance datasets alone are too short to establish whether there is a similar upward trend in them.

An upward trend in the Sun's coronal magnetic field

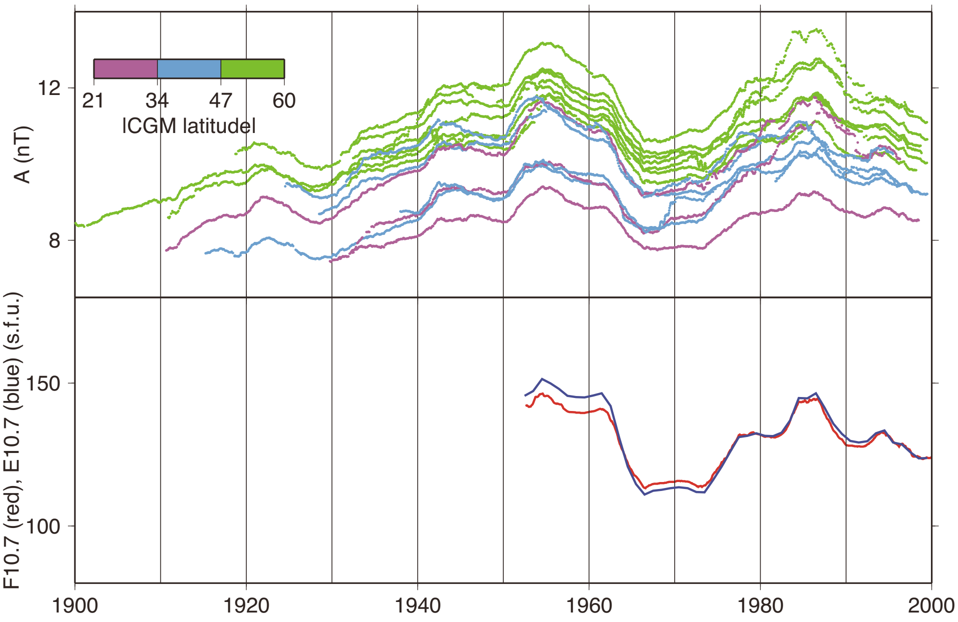

Fig. 2. Root mean square amplitude of the quiet magnetic variation at the 14 selected observatories (upper panel), colour-coded according to corrected geomagnetic latitude, and solar irradiance proxy datasets F10.7 and E10.7 in solar flux units (lower panel).

strength was found by Lockwood *et al.* (1999) from an analysis of the *aa* index (Stamper *et al.*, 1999, see also Clilverd *et al.*, 2005) and the change observed in the daily variation may be partly attributed to this. The *aa* index has the daily variation accounted for in its derivation so it therefore characterises the irregular activity which is a consequence of variations in the solar wind. Lockwood *et al.* (1999) showed that this is dependent on the Sun's coronal magnetic field strength. An increase in the numbers, and energies, of charged particles from the Sun is likely to energize current systems inside the magnetosphere and the ionospheric dynamo at mid-latitudes may be strengthened. It should be noted however that Svalgaard *et al.* (2005), from an analysis of their interdiurnal variability index, found that the interplanetary magnetic field (not the solar coronal magnetic field strength) does not show an upward trend after the 1950s.

Another result which becomes apparent from Fig. 2 is that the 11-year smoothed RMS amplitude of the daily variation increases with corrected geomagnetic latitude, within the range used in this study. The long-term trends at individual observatories however do not vary with corrected geomagnetic latitude.

Thus there is a strong case for the Sun being one cause for the extrema in Figs. 1 and 2. However the argument for the long-term trend is less clear. Another possible cause for this trend is the long-term change in the internal field and it is certainly the case that there is a decrease in the total strength of this field over the last century. Using the 10th Generation International Geomagnetic Reference Field, IGRF-10 (International Association of Geomagnetism and Aeronomy (IAGA), Division V, Working Group VMOD: Geomagnetic Field Modeling, 2005), yields a 6.4% decrease in the root mean square of the magnetic field on a sphere of radius 6481 km (approximating ionosphere height). There is a similar drop in the dipole moment. During the same period the region of reversed flux at the core-mantle boundary called the South Atlantic Anomaly has been increasing in size, indicating that the internal field may be attempting to reverse—this is best seen in a model which covers more than one century and is designed for use at the core-mantle boundary (Jackson *et al.*, 2000). In short the Earth's magnetic field may be decreasing and becoming more spatially variable.

This decrease alone would result in a rise of the mean height of the ionospheric dynamo layer (Clilverd *et al.*, 1998). However, another effect is that the height-integrated Hall and Pedersen conductivities are roughly in inverse proportion to the Earth's magnetic field strength (Clilverd *et al.*, 1998) so as it decreases the conductivities increase. It is also likely that the coupling of solar energy into a dipolar magnetosphere would be reduced with a decrease in the dipole but that the increase in its variability (i.e. becoming more quadrupolar) may increase the occurrence of conditions which favour reconnection with the interplanetary magnetic field (Vogt *et al.*, 2004). The final net effect of a decrease in the Earth's internal magnetic field and an increase in its variability on Sq is not known but seems more likely to be negligible or a decrease than the increase that we observe.

Can the internal magnetic field help explain the extrema in the 1950s and 1980s? Again from IGRF-10, the maximum tilt of the dipole from the geographic axis during the 20th century occurs in 1955 (11.54°) but there is no such extrema in the 1980s. Le Mouël *et al.* (2005) allude to geomagnetic jerks being a possible cause for changes in the geometry of the Earth's magnetosphere but as these jerks are impulse-like changes in the magnetic field and for the 20th century are known to occur at 1925, 1969, 1978, 1991 and 1999 (Mandea *et al.*, 2000), it does not seem likely that they can be connected to the extrema observed in the daily variations in the 1950s and 1980s. Thus it is not clear that features in the Earth's internal field of duration shorter than one century contribute to similar short-term features in the geomagnetic daily variation.

4. Conclusions

The records of regular magnetic field variations at mid-latitudes, assumed to be generated in the ionosphere, contain features that are similar from one observatory to another, and vary in a manner similar to solar irradiance proxy data. Our analysis, based on almost century-long records from 14 observatories, shows that there are maxima in the amplitude of the solar quiet day variation in the 1950s and 1980s and that there is an overall small upward trend of 1.3 nT/century, equivalent to over 10% rise. We show that the maxima correspond to maxima in the solar irradiance proxy datasets F10.7 and E10.7. Future work should concentrate on the origin of the long-term trend. This may be partly explained by changes in the Sun and changes in the Earth's internal field but many other factors not considered here may contribute, including anthropogenic effects, for example the greenhouse effect (Laštovička *et al.*, 2006).

We have also effectively shown that geomagnetic data may be a suitable proxy for the upper atmosphere through similarities with other proxies, the F10.7 and E10.7 irradiance datasets, and as such, may be useful in understanding the influence of solar irradiance on space weather and the Earth's climate on longer timescales. Being an Earth-based proxy they may therefore be quite suitable for climate studies.

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S. Macmillan (e-mail: smac@bgs.ac.uk) and A. Droujinina