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Increased magnetic storm activity from 1868 to 1995

M. A. Clilverd[a,*], T. D. G. Clark[b], E. Clarke[b], H. Rishbeth[c]

[a] *British Antarctic Survey (NERC), Madingley Road, Cambridge, CB3 0ET, U.K.*
[b] *British Geological Survey (NERC), West Mains Road, Edinburgh, U.K.*
[c] *Dept. of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, U.K.*

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Abstract

The *aa* index provides the longest continuous data set which can be used in the analysis of magnetospheric and ionospheric phenomenology. All phases of the solar cycle show increases in activity since cycle 14. The activity increase does not appear to be associated with any instrumental, ionospheric or magnetospheric effects. Barely significant effects (in terms of the results presented in this paper) have been identified in the long-term change in magnetic latitude of the observatory sites, the positions of high-latitude ionospheric features such as the cusp, and ionospheric Pedersen and Hall conductivities due to changing magnetic field orientation and strength. The prime cause of the change in geomagnetic activity is an increase in solar activity. The number of storms at solar minimum has typically increased by 40% more than the other phases. This is principally due to increased recurrent storm activity to such an extent that conditions at minimum in recent cycles could be thought of as being more representative of the declining phase. © 1998 Elsevier Science Ltd. All rights reserved.

1. Introduction

Previous workers have pointed out an increasing trend in the *aa* index with time (Feynman and Crooker, 1978). This paper describes an increase with time in the number of magnetic storms as defined by $aa^* \geqslant 40$ nT, particularly during periods of solar minimum activity. An analysis of the occurrence rate of magnetic storms is undertaken for the whole data set (125 years). Possible causes of the increase in magnetic activity are discussed in terms of observational, solar, ionospheric, and magnetospheric changes.

Measurements of geomagnetic variation have been undertaken since 1840. The measurements help to quantify the influence of solar disturbances on the Earth's magnetic field. One index of geomagnetic disturbance is the *aa*, which uses data from antipodal magnetic observatories to describe the level of geomagnetic activity. Values of the index are typically 2–200 with $\geqslant 40$ indicative of disturbed conditions. The *aa* index has been retrospectively calculated from 1868 (Mayaud, 1972) and provides one of the longest continuous data sets which can be used in the analysis of magnetospheric and ionospheric phenomenology. In comparison, routine ionospheric soundings have only been in operation since 1931 and satellite measurements only since 1957. Other long term data sets include sunspot number and also the occurrence of aurora. These long term data sets can be useful in describing geomagnetic changes since the *aa* index started in 1868.

The sunspot number is well known to vary with a period that is on average 11 years. The length of this cycle varies typically by ± 1 year. Currently solar cycle lengths are shortening, with a maximum length having been observed in about 1900 (cycle 13). Variations much longer than 11 years have also been reported, with well-defined 80 and 200 year periods observed (Hughes, 1977). Long-term smoothed sunspot numbers are now observed to be increasing after passing through a minimum in about 1910–1915 (cycle 14).

Observations of aurorae have been noted for more than two millennia. Mid- and low-latitude aurora triggered the interest of the Chinese and more recent observations have taken place at higher latitudes. The occurrence of aurorae shows a 200-year cycle as well as the 11-year one (Lassen and Friis-Christensen, 1993). The

* Corresponding author. Tel.: 0044 223 251541; fax: 0044 223 221226; e-mail: m.clilverd@bas.ac.uk

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activity minimum of the current 200-year cycle occurred in 1905. An important limitation of this data set can be indicated by the observation that the number of aurorae detected after 1715 was much higher than before. This sudden change apparently coincides with a well-recorded display towards the end of the 70-year Maunder minimum which produced much interest in the phenomenon and hence more observations (Halley, 1716; Hughes, 1977).

Another change that has occurred during the lifetime of the *Aa* index is the slow decrease in the Earth's dipole field strength (*B*), where a change of -10% in the first three terms of spherical harmonic magnetic field models (e.g. IGRF) has been observed in the last 150 years. This may produce decreases in magnetotail loading as given by with the Akasofu (1980) loading factor and hence corresponding changes in the substorm occurrence rate. Additionally, the decrease in *B* may be expected to produce changes in the ionospheric response to magnetic disturbance by changing the Hall and Pedersen conductivities influence.

2. The *aa* index

In producing an index of magnetic activity two systematic variations have to be taken into account: the local time variation, which is related to the nighttime maximum of substorm activity; and the annual variation that has a maximum in each hemisphere during the summer solstice. By using two geomagnetically near-antipodal observatories both of these variations should be approximately cancelled and as a result only random planetary activity would have any effect on the index. However, it should be noted that the semiannual variation in activity is not affected by the use of near-antipodal observatories. At each observatory, *K* indices are produced and scaled to be equivalent to a mid-latitude station. The *aa* index is defined by the average, for each 3 h period, of the *K* indices from two near-antipodal stations after the transformation of *K* into amplitudes (nT). The magnetic field variations observed at the ground, from which the activity index is calculated, depend on the E-region Pedersen and Hall conductivities in the local ionosphere. Mayaud (1971) showed that the cancellation of the local time dependence of storm activity is efficient when four or more 3 h values are averaged and that averaging over 24 h (denoted by *Aa*) gives an excellent correlation with other planetary indices. For these reasons this paper used 8-point running means to generate 24 h average values of *aa*, denoted by aa^*. A geomagnetic storm is counted when $aa^* \geqslant 40$ nT and considered to be over when aa^* drops below 40 nT for two consecutive 3 h periods.

Despite its inherent simplicity the index is a meaningful measure of global geomagnetic activity. The antipodal observatories used in forming the index were initially Greenwich (1868–1926) and Melbourne (1868–1926). In the northern hemisphere these were superseded first by Abinger (1926–1957), and later by Hartland (1957–). In the South, Toolangi (1926–1980) and Canberra (1980–) have been used to continue the series. At each observatory change a correction was made for changes in geomagnetic latitude and local induction effects.

3. Results

Figure 1 shows the solar cycles in *Aa* by Bartels solar rotation format. The panels increase in year from left to right and top to bottom. For each solar cycle the minimum (as defined by smoothed sunspot numbers) occurs on the leftmost edge of the plot, while solar maximum occurs near the middle of each panel. In the first few cycles solar minimum coincides with an extended period of relatively quiet magnetic activity. However, in the more recent solar cycles the period of quiet magnetic activity is much less apparent, suggesting that solar minimum conditions have changed significantly in the last 125 years. The following figures show this in more detail.

Figure 1 shows recurrent solar activity with periods of about 27 days as patches that extend over a number of rotations (e.g. day 6 of the later half of cycle 19). Typically this type of activity is associated with the declining phase of the solar cycle, although there is some suggestion from this plot that recurrent activity during solar minimum has become more common during recent cycles. This hypothesis is considered in more detail later in the paper.

Figure 2 s a plot of the number of magnetic storms with $aa^* \geqslant 40$ nT as a function of year since 1868. Superposed on the figure is the variation in smoothed sunspot numbers which is used to define solar minimum conditions and a vertical dashed line is plotted to indicate when this occurs. The plot suggests that the rate of occurrence of magnetic storms has increased during most solar conditions, but particularly during the minimum. The first four cycles show almost no significant solar activity at solar minimum whereas the later cycles have activity levels which are similar to early solar maximum conditions. Similarly, smoothed sunspot numbers are also non-zero in the most recent cycles.

By breaking the solar cycle down into four well defined periods: maximum (± 1 year), declining, minimum (± 1 year) and ascending, we can determine the change in storm occurrence for each phase during solar cycles 11–22. To effectively compare the numbers of storms in each phase of the solar cycle the rate of storm occurrence was calculated for each phase and then normalised such that each phase is of equivalent length (36 months) whatever the length of the cycle. Figure 3 is such a plot and shows that all the phases exhibit an upward trend in activity since cycle 14. A least squares linear fit to the data since

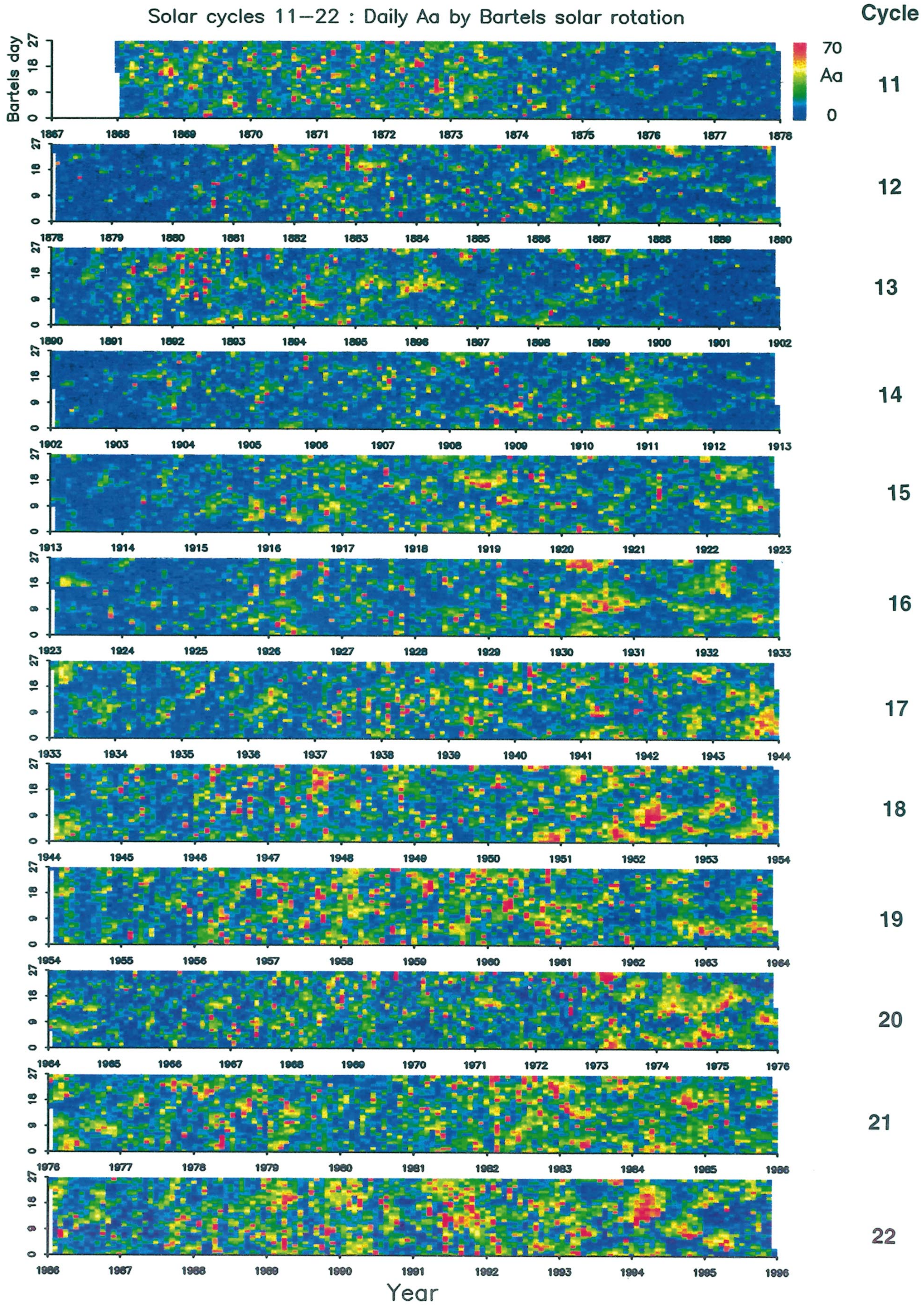

Fig. 1. Daily mean values of the *aa* index (*Aa*) for 1870–1996, arranged by 27-day solar rotations. Red represents the most disturbed days and blue represents the quietest days. The horizontal panels represent a complete solar cycle from minimum to minimum. In this plot recurring geomagnetic activity appears as horizontal patches of red and green.

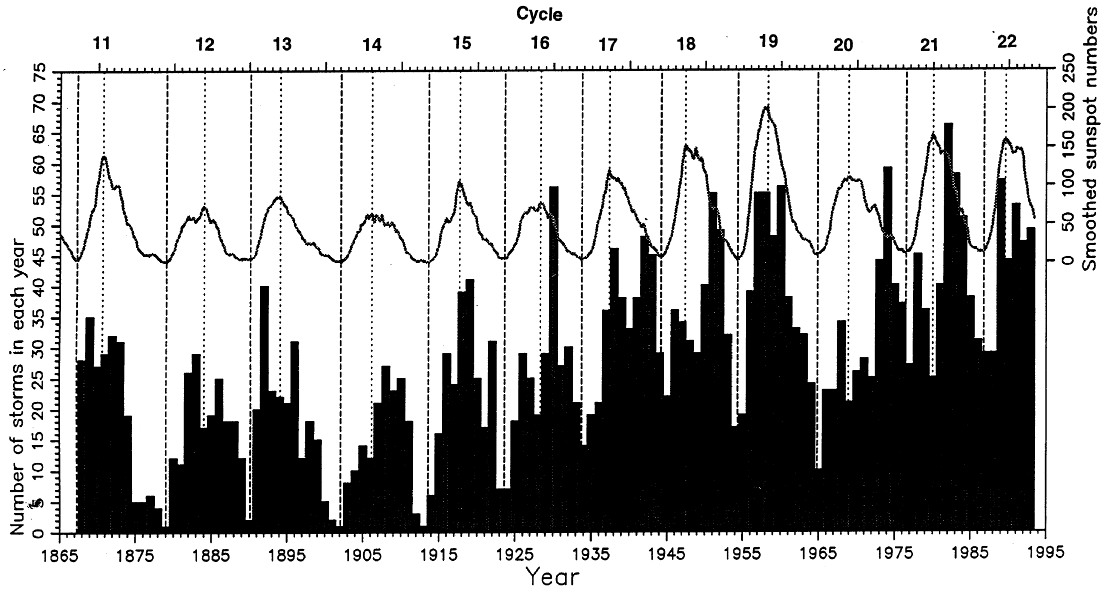

Fig. 2. Histogram showing the annual number of magnetic storms with $aa^* \geqslant 40$ nT. Superposed is the smoothed sunspot number. The dashed lines indicate solar minimum and the dotted lines indicate solar maximum. The lowest levels of storm activity occur at solar minimum.

cycle 14 indicates that the phases Min:Asc:Max:Dec have increasing gradients of 10:8:7:5 storms/cycle respectively. The confidence levels in the correlation coefficients exceed 97.5% for all phases apart from the maximum, which has greater than 90% confidence. This analysis suggests that conditions during solar minimum are changing more than at other phases.

As already mentioned, Fig. 1 suggests an increasing prevalence of recurrent magnetic activity at solar minimum, i.e. increasing recurrent features. Figure 4 is a plot of the percentage number of recurrent storms (i.e. $aa^* \geqslant 40$ nT with a 27 ± 2 day repetition period) that occurred during the combined declining and minimum phase of each solar cycle. Although the proportions vary from one cycle to another, the minimum phase contributes a greater proportion of recurrent activity in more recent cycles (17–22) than in most of the earlier ones

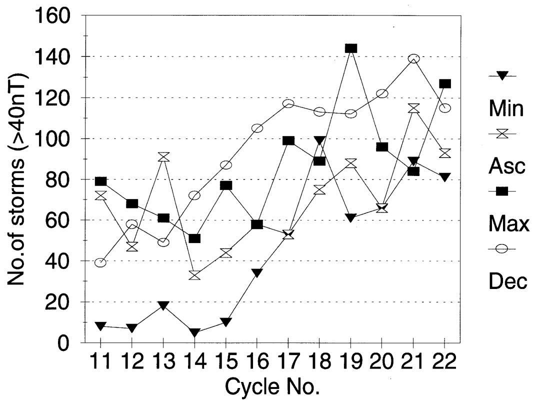

Fig. 3. The variation of the number of storms ($aa^* \geqslant 40$) with each phase of the solar cycle. The plot shows that storm occurrence in solar minimum has undergone a marked change since cycle 15.

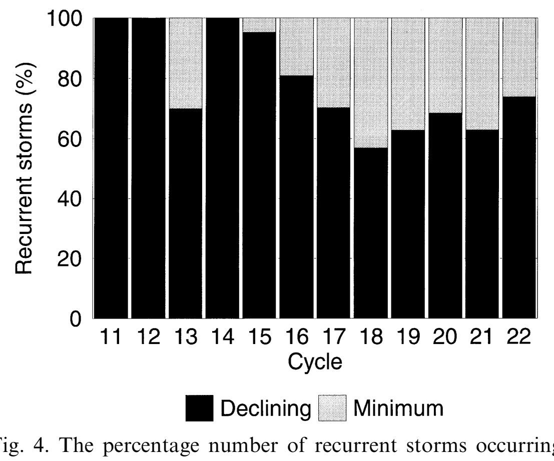

Fig. 4. The percentage number of recurrent storms occurring during the declining and minimum phases of the solar cycle. From cycle 11 to cycle 15 the vast majority of recurrent activity occurred during the declining phase, but, later cycles show an enhanced contribution from the minimum phase.

(11–14). The increase in recurrent storm activity at solar minimum can also be observed in Fig. 1. Typically the recurrent activity lasts for more solar rotations in recent solar minima than in past ones, i.e. about 5 rotations in cycles 11–15 and about 9 rotations in cycles 18–22. There are about the same number of active groups in each minimum phase, i.e. approximately 4, but the most recent cycles have shown an increase from 2 to 5 days in the number of days that each recurrent storm lasts. In summary the observed increase in geomagnetic activity in the declining and minimum phase of the solar cycle result from a doubling both of the number of recurrent storms and their duration.

A comparison of the average sunspot number (*R*) and the average *Aa* index during the solar minimum phase is shown in Fig. 5. The plot indicates that both *R* and *Aa* vary in a similar fashion, and this suggests a link between solar activity and the trend in the *Aa* index. However, by using a threshold (i.e. $aa^* \geqslant 40$ nT) in the analysis it is possible that some of the long-term changes reported in this section could be due to instrumental effects, such as changing sensitivity. Figure 6 is a plot of yearly mean of the lowest *Aa* value observed in each month. Even the most disturbed part of the solar cycle tends to have periods of quiet activity and thus it would be expected that the lowest *Aa* values recorded each month would remain constant. This assumption is supported by the monthly minimum sunspot number superposed on the plot which shows that during every solar minimum phase there are occasions when no sunspots are observed. Figure 6 shows an upwards trend in quietest *Aa* in the last 100 years but only about 3–4 nT. The corresponding rise at sunspot maximum is rather similar in magnitude. This could be caused by a subtle instrumental effect or possibly by local ionospheric current/conductivity effects. Both of these effects will be discussed in the next section.

Figure 7 shows the effect of having a threshold value other than 40 nT on the storm numbers detected during the solar minimum phase of solar cycles 12–22. A similar trend is seen for all four threshold values.

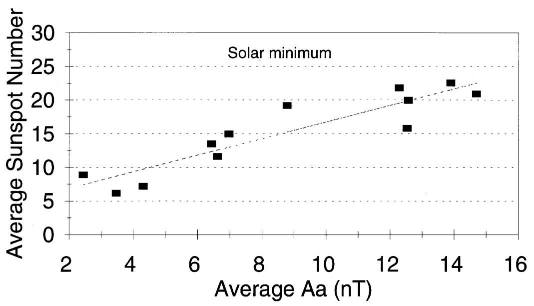

Fig. 5. Average sunspot number (*R*) versus average *Aa* index during the solar minimum phase. The confidence level in the correlation coefficient exceeds 99.9%.

4. Discussion

We have shown that the occurrence of high geomagnetic activity has changed markedly since the beginning of the *Aa* index in 1868. The number of storms at solar minimum has increased by a factor of about 2 in 11 solar cycles compared with the declining phase, with the most significant increase being observed in recurrent storm activity. In this next section we discuss possible mechanisms through which this change may have occurred.

4.1. *Observational changes*

Although offset corrections have been made for changes in observatory site, no long term corrections have been made for the slow change in geomagnetic latitude of the observatories because of the secular change of the geomagnetic field. Figure 8 shows how the corrected geomagnetic latitudes of Hartland and Canberra have altered since 1870. In the northern hemisphere an equatorward drift of about 4° has occurred, while in the South there has been a drift of about 2° polewards. The scale used at each observatory to convert the 3 h ranges into *K* index depends on the angular distance from the observatory to the band of maximum auroral activity (Mayaud, 1980) which is defined to be at a corrected geomagnetic latitude (c.g.l.) of 69°. Note that the angular distance between the observatory and the auroral oval is not simply the difference between the c.g.l. of the two because of the distortion of the corrected geomagnetic coordinate system.

The observatories in the northern hemisphere have used the same *K* scale throughout the whole timespan of the *aa* index, but the c.g.l. of the observatories have decreased during this time, so it may be expected that, given a constant level of global geomagnetic activity, more quiet intervals ($K = 0$ or 1) would be scaled in the later years than the earlier years. We would expect to see the opposite trend in the southern hemisphere. However an examination of the annual occurrence of intervals of $K = 0$ and 1 at the northern and southern observatories indicates that the occurrence of $K = 1$ has remained fairly constant throughout the timespan of the *aa* index (cycle 22 has 95% $K = 1$ occurrence compared with previous cycles). The occurrence of $K = 0$ has decreased in both hemispheres (cycle 22 has 30% $K = 0$ occurrence compared with previous cycles), although it appears to have decreased more in the northern hemisphere (Clark et al., 1997). Figure 6 indicates some increase in the amplitude of *Aa* during the quietest magnetic periods, which would have the effect of decreasing the occurrence of $K = 0$. This is discussed in detail by Clark et al. (1997) who concluded that the scaling of the quietest activity is a very sensitive process (because of the logarithmic scale of *K* indices) and even the component of the rise since 1985

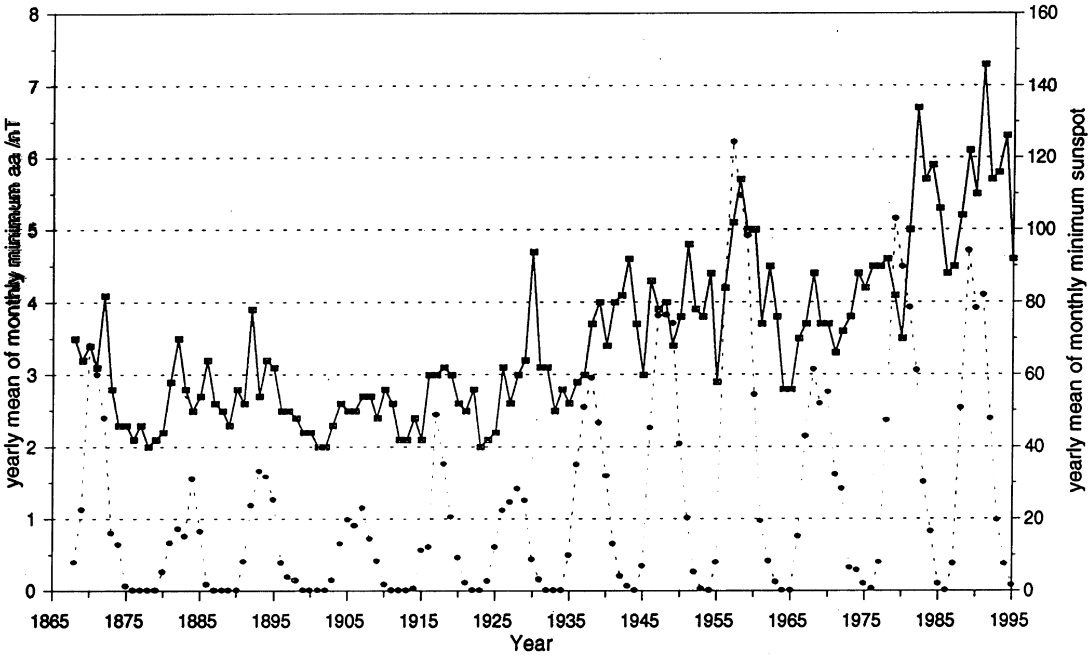

Fig. 6. The variation in the yearly mean of the lowest *Aa* values observed in each month (squares) and sunspot numbers (circles).

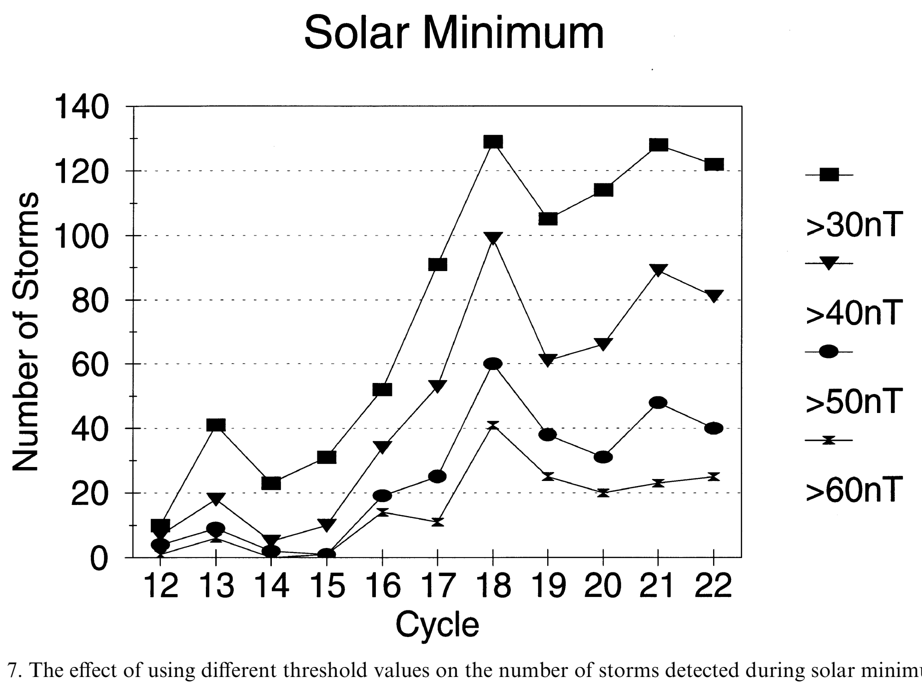

Fig. 7. The effect of using different threshold values on the number of storms detected during solar minimum.

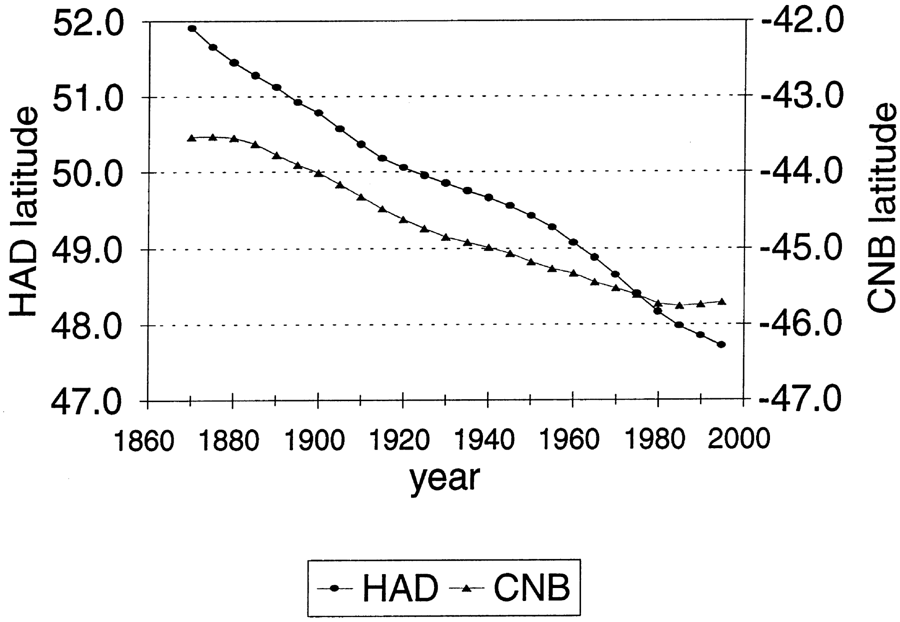

Fig. 8. The variation in corrected geomagnetic latitude of the Hartland and Canberra observatories since 1870.

associated with changing to digital instrumentation does not influence the scaling of higher index values in any significant way.

4.2. *Ionospheric changes*

Secular changes in the strength of the Earth's main field will influence the electric currents in the ionosphere, which will in turn affect the magnetic signature at the ground. Rishbeth (1985, 1997) suggests that progressive weakening of the dipole field is causing a gradual increase in height of the ionospheric dynamo layer.

As mentioned in section 2, the geomagnetic activity observed at a station depends mainly on currents flowing locally in the ionosphere. The ionospheric currents depend on the e.m.f.s that drive them and the electrical conductivity. The currents associated with magnetic activity probably originate from magnetospheric processes. Roughly speaking, the e.m.f. generated in the magnetosphere should be proportional to (solar wind speed) × (magnetic field strength), at least on time scales much longer than those of reconnection events, i.e. minutes. Although this idea may be too simple as regards the currents that produce magnetic activity, we see no reason to expect the e.m.f.s to change greatly as a result of secular decrease of the geomagnetic field.

For a given e.m.f. the ionospheric current, which mainly flows in the E-layer, depends on the Pedersen and Hall components of conductivity given by:

$$\sigma_P = \frac{Ne}{B}\left(\frac{\omega_e \nu_e}{\omega_e^2+\nu_e^2} + \frac{\omega_i \nu_i}{\nu_i^2+\omega_i^2}\right) \tag{1}$$

$$\sigma_H = \frac{Ne}{B}\left(\frac{\omega_e^2}{\omega_e^2+\nu_e^2} - \frac{\omega_i^2}{\nu_i^2+\omega_i^2}\right) \tag{2}$$

where N is the electron/ion concentration, $-e$ is the charge on an electron, and m, ω, ν (respectively) represent mass, angular gyrofrequency Be/m, and collision frequency with neutral particles. Subscripts e and i apply to electrons and ions respectively. For simplicity, we assume there is a single ion species with positive charge $+e$. It seems most unlikely that our conclusions would be altered by taking account of multiple ion species.

It can be seen from (1) and (2) that the conductivities take the form

$$\sigma_P = (Ne/B)[f_P(\omega_e/\nu_e)+f_P(\omega_i/\nu_i)] \tag{3}$$

$$\sigma_H = (Ne/B)[f_H(\omega_e/\nu_e)-f_H(\omega_i/\nu_i)] \tag{4}$$

where, f_P, f_H are dimensionless algebraic functions. The heights at which Pedersen and Hall conductivities are largest are determined by the heights at which $\omega_e/\nu_e = 1$ and $\omega_i/\nu_i = 1$. These heights are affected by changes in geomagnetic field intensity B. If B undergoes a long-term secular decrease then: (a) the multiplying factor (Ne/B) increases; and (b) the height profiles of σ_P and σ_H move upwards, because the resulting change in the ratios (ω_e/ν_e) and (ω_i/ν_i) which are in proportion to B.

These changes are not very significant for the 126 year period considered in this paper. During this time, B has decreased by approximately 10%, thereby increasing the conductivities by 10%, because of (a) above; and moving the conductivity profiles upwards by about 10% of an atmospheric scale height, i.e. by about 1 km in the E-layer, because of (b). We have no reason to believe that a change of magnetic field intensity affects the ionospheric electron concentration/height profile $N(h)$ (except possibly in the magnetic equatorial region where the well-known F-layer fountain operates), so the likely long-term change in the multiplying factor (Ne/B) is that due to the decrease of B.

These simple considerations are confirmed by detailed calculations of the height-integrated conductivities in the range 80–200 km. The height profile of N was estimated using the International Reference Ionosphere model (Rawer and Bilitza, 1989) and the height profile of v_i was estimated using the relationships given by Banks (1966). We note here the limitations of the IRI model using sunspot number as a proxy for solar UV and EUV fluxes (Donnelly et al., 1983). The height profile of B was modelled using the International Geomagnetic Reference Field (Barton et al., 1997). Figure 9 shows the variation of the local magnetic field intensity at Hartland and Canberra since 1900 modelled by the IGRF. There has been an increase of 2.8% since 1930 at Hartland and a decrease of 1.6% at Canberra since 1950. If we compute the integrated conductivities for local noon at summer solstice assuming solar minimum conditions, we find that both the height-integrated Pedersen and Hall conductivities have decreased by 3.7% since 1930 in England and increased by about 2.2% in Australia. The heights of the peaks in conductivity are estimated to have changed by amounts smaller than 1 km. If there were no other factors affecting ionospheric currents, then we would expect that magnetic variations recorded on the ground would change in amplitude by roughly the same amount. Since the upper limit for $K = 0$ at Hartland is 5 nT, and the resolution of the variometers has ranged between about 1.0–0.1 nT, any change in the amplitude of magnetic disturbances of the order of 4% would hardly affect the occurrence of $K = 0$.

Increased concentrations of greenhouse gases are expected to cause a cooling in the thermosphere (Roble and Dickinson, 1989). Rishbeth (1990) predicted a lowering of 2.5 km for the peak height of the E-layer for doubled mixing ratios of carbon dioxide and methane. This level of height change is at the limit of detectability for normal ionosonde soundings and no trends in E-layer peak height or critical frequency could be found in noon measurements from ionosonde data at Slough and Canberra. We conclude that changes in ionospheric conductivity due to changes in the local geomagnetic field intensity or greenhouse gases do not contribute significantly to the long-term change in the Aa index.

4.3. *Magnetospheric changes*

In the previous subsection we mentioned the effect of the decreasing total field intensity of the Earth. In the magnetosphere this would tend to have the effect of reducing the sunward loading area as defined by Akasofu (1980). A 10% decrease on the field strength would typically result in an Earthwards displacement of 5% in the magnetopause position and thus a consequent reduction of the sunward loading area by about 10%. However, it is not clear that such small changes in loading area would significantly alter the coupling of solar energy into the magnetosphere since the solar wind 'aspect angle' also has a significant effect on energy coupling. Several authors have addressed the problem of a large decay of the dipole component of the Earth's magnetic field during field reversals (e.g. Siscoe and Crooker, 1976; Rishbeth, 1985), but no work is known to the authors that has been undertaken on the effect of small changes. This would be an interesting area of study but one that is beyond the scope of this paper.

One possible result of a decreasing field intensity could be the relocation of the average position of high latitude ionospheric features. If the auroral oval moves closer to the observatories then the response of Aa to magnetic activity would increase. Newell and Meng (1994) showed how the dayside ionospheric features responded to changes in solar wind pressure. During a 4-fold increase in solar wind pressure (but with constant velocity) ionospheric features moved equatorward by $\leqslant 5^{\circ}$. Decreasing the field intensity would have the same sort of effect as increasing the solar wind pressure although in the case of a 10% change in field strength the ionospheric displacement would be proportionally less i.e. $\sim 1^{\circ}$ equatorwards. This is less than the drift of the observatories reported in section 4.1 and, as discussed before, is small compared with the distance to the auroral oval. It is unlikely to produce any significant change in the observed levels of magnetic activity (Mayaud, 1980).

4.4. *Solar changes*

Section 1 of this paper indicated that 80 and 200 year periods are observable in solar activity using very long data sets such as low-latitude aurorae observations and sunspot numbers. The most recent minima in the 200 year cycle occurred in the 1910–1915 or cycle 14–15. At solar minimum, even though the 80 or 200 year period minima is not clearly detectable in total number of storms, a significant change in the number of recurrent storms has occurred since cycle 14 or 15. Before that time, recurrent storms were a rare occurrence but became much more common afterwards (see Fig. 4). The apparent incursion of recurrent activity into solar minimum from the declining phase suggests a link between the two phases, or rather, that our somewhat arbitrary delineation between the two phases is no longer valid.

Figure 5 also suggests a link between solar activity and the reported increase in the Aa index during solar minimum conditions. Thus it appears that although there

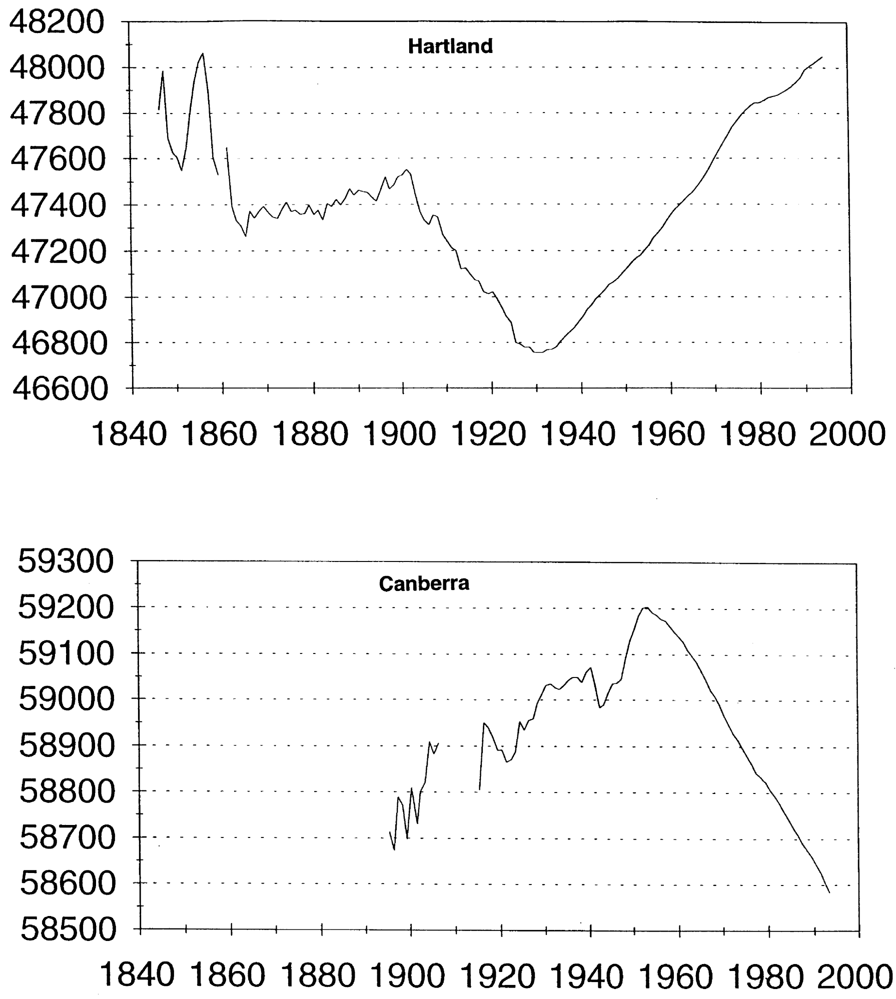

Fig. 9. The variation in local total field intensities of the Hartland and Canberra observatories since 1870. No annual mean values for Canberra are available before 1893.

is a general increase in storm activity in all phases of the solar cycle since the beginning of the *Aa* index, solar minimum has undergone the most dramatic change, with storm numbers increasing typically 40% more per cycle than the maximum phase. This change has been brought about principally through increased recurrent storm activity since cycle 15 to such an extent that conditions could be thought of as representative of the declining phase rather than minimum.

5. Conclusions

This paper reports an increase in the number of magnetic storms (defined by $aa^* \geqslant 40$) during the minimum phase of solar cycles since 1868. Although all phases show increases in activity with time since 1910–1915, solar minimum has undergone the most marked change. The number of storms at minimum has typically increased by 40% more than the other phases since cycle 14 (about 1913). The underlying cause of this increase is principally the incursion of declining phase conditions into solar minimum (defined by minima in the variation of smoothed sunspot numbers), so that 'solar minimum' is much shorter than it used to be.

We have no grounds to believe that any significant increase in activity can be due to instrumental effects (section 4.1.) or changes in ionospheric conductivity (section 4.2.). As for changes in magnetospheric configuration (section 4.3.), the decrease in the dipole field reduces the cross-section on the magnetosphere, and thus decreases the solar wind energy intercepted. As the geomagnetic field may be changing in shape as well as in strength, the 'aspect angle' at which the solar wind impinges on the magnetosphere may also change. Detailed magnetospheric modelling would be required to investigate the consequences. Small and barely significant effects may arise from secular changes in magnetic latitudes of the observatory sites, in relation to features such as the auroral ovals and dayside cusp.

Since the solar wind has been systematically measured for only 30 years, we cannot assess its possible long-term changes. Long term trends in the E-region parameters measured by ionosondes close to the location of the observatories were not observed, although this area of study continues to be a topic for future work. We are left with the increase of solar activity (section 4.4.) as the likely prime cause of the change in geomagnetic activity.

Acknowledgement

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