Geophys. J. R. astr. Soc. (1982) **69**, 101–111

An investigation of the causes of abnormal quiet days in *Sq* (*H*)

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Received 1981 August 6; in original form 1981 April 3

Summary. From a study of 'abnormal quiet days' (AQDs) along the 0° meridian between 14 and 60° N, it was found (Butcher & Brown) that the minimum in H at stations on the poleward side of the $Sq\,(H)$ focus was formed by a small negative substorm event when the normal $Sq\,(H)$ amplitude was reduced by a superposed northward field.

In this paper we consider both the AQD event and the superposed northward field as a function of longitude and also consider in more detail the latitude variation of the superposed northward field. From such a study it is concluded that: (1) the AQD event is definitely due to a small magnetospheric substorm event; (2) the superposed northward field varies smoothly with longitude falling to zero some 110° from the longitude of its maximum amplitude; (3) the superposed northward field has a variation with geomagnetic latitude tending to zero near 20° and 70°N with a maximum near 55° N in summer and 35° N in winter; (4) there is some evidence that the effect of the IMF penetrates into the mid-latitude E-region and its effect is latitude-dependent. Although the evidence supports the suggestion that the currents responsible for the superposed northward field flow in the E-region no suggestion as to the origin of the driving force of the currents is forthcoming.

1 Introduction

It is well known that the phase of $Sq\,(H)$ shows considerable variability from day to day. Brown & Williams (1969) used this property to define arbitrarily classes of quiet days and defined an 'abnormal quiet day' (AQD) as a day when, for a mid-latitude station like Hartland, situated poleward of the focus, a minimum in H occurs outside the range 0830–1330 LT. A day where the minimum occurs within the range 0830–1330 LT is termed a 'normal quiet day' or NQD. The properties of AQDs have been well documented by Brown & Williams (1969) and Brown (1975). Subsequently using hourly values of the magnetic H-data for the years 1963–64 from eight magnetic observatories situated between the latitudes of 14° and 60° geographical, and aligned approximately along the 0° longitude meridian, Butcher & Brown (1981) have attempted to explain the nature of AQDs and how their occurrence properties arise. The years 1963–64 were used since the occurrence of AQDs is highest in sunspot number minimum years (Brown & Williams 1969). It was found that for an AQD: (1) the amplitude of the normal $Sq(H)$ variation (i.e. between 0830 and 1330 LT) at stations like Hartland was reduced, and (2) a small negative 'bay-like' magnetic event occurred outside the 0830–1330 LT time range that lasted 3–4 hr which, because of the reduced amplitude of the normal $Sq(H)$, formed the new minimum in $Sq(H)$.

The reduction in the normal $Sq(H)$ amplitude at Hartland was such that at all latitudes considered, irrespective of the phase of $Sq(H)$, it was equivalent to the addition of a northward field to H, i.e. for stations on the poleward side of the focus the amplitude of the normal $Sq(H)$ was decreased whereas for those stations on the equatorward side of the focus the amplitude of the normal $Sq(H)$ was increased. The magnitude of this northward field was found to depend on the direction of the interplanetary magnetic field (IMF) it being greater on days when the azimuthal component of the IMF, B_y, was 'away' from the Sun (A-days, B_y positive) than when the IMF was 'towards' the Sun (T-days, B_y negative). It is seen that the sense of this added field is such as to cause an apparent poleward motion of the $Sq(H)$ focus on AQDs, this movement being greater on A-days than on T-days (Butcher & Brown 1980).

Over the latitude range considered it was found that the bay-like event was always negative, and for a given AQD had an approximately constant amplitude with latitude. This event was found to be correlated with the component of the IMF perpendicular to the plane of the ecliptic, B_z, which reached a maximum negative value approximately 1 hr prior to the attainment of the maximum negative value of the event. Such a correlation is similar to that obtained between magnetic substorms or bays and B_z and hence this AQD event has similar characteristics to a mid-latitude bay but has a much smaller latitude. For the period 1963–64 the most likely value of this amplitude was found to be about -6 nT, but, by considering AQDs in the sunspot minimum years of solar cycles 16–20 it was found that this amplitude varied considerably from one cycle to the next and appeared to be related to the annual sunspot number of the following sunspot maximum (Brown & Butcher 1981). It was tentatively suggested that this variation in event amplitude could be related to the magnitude of the negative change in B_z hence giving a physical meaning to the relationship of AQD occurrence in sunspot minimum years to the average annual sunspot number of the following sunspot maximum found by Brown (1974) and used in sunspot number predictions (Brown 1980).

In view of the interesting properties of AQDs particularly with respect to their relationship to sunspot number prediction (Brown 1975; Brown & Butcher 1981) and their effect on the apparent position of the $Sq(H)$ focus it would seem appropriate to consider further the properties of both the event and the additional northward field associated with AQDs. In this paper we therefore consider both these properties, in order to determine both the longitudinal and latitudinal extent of their influence.

2 Determination of event amplitude and superposed northward field associated with AQDs

Hourly values of the magnetic H-component for the observatories shown in Table 1 for the years 1963–65 were used since they covered a fairly wide range of longitudes over a relatively narrow range of latitudes. The event amplitude was determined in the same way as described previously (Butcher & Brown 1981), i.e. using the Hartland data to select the AQDs, the average quiet day variation of $Sq(H)$ at each station was obtained by taking the average of those NQDs in the month in which the AQD occurred together with those NQDs in the preceding and following month (giving a maximum of fourteen possible days in the average) and this average was then subtracted from the H-variation for the AQD. The event

Table 1.

Station	Geographical Latitude	 Longitude
Hartland	51° 00 N	4° 29'W
Surlari	44° 40'N	26° 15'E
Svendlovsk	56° 44'N	61° 04'E
Irkutsk	52° 10'N	104° 27'E
Memambetsu	43° 55'N	144° 12'E

amplitude was then determined by measuring the maximum deviation from the average trend each side of the AQD event.

Now all the observatories used in this analysis were to the east of Hartland and their normal minimum in *Sq* (*H*) occurred mostly between 0030 and 1130 UT hours. Hence, since both the event amplitude and the magnitude of the superimposed northward field were to be determined, only AQDs were considered where the event occurred in the period 1330–2230 UT such that the normal *Sq* (*H*) minimum could also be observed at all stations. Such a restriction limited the number of suitable AQDs to eight. The longitudinal variation of the amplitude of the event was found to vary from event to event, but overall there was a tendency for the negative magnitude of the amplitude to decrease the further east of longitude of the station, and in some cases the amplitude even went positive. This is shown in Fig. 1 where we have plotted for the eight days the amplitude obtained at the five stations.

In order to determine the amplitude of the superposed northward field at each station, the amplitude of the average quiet day variation of *Sq* (*H*) and the amplitude of the 'normal' *Sq* (*H*) variation on AQDs were obtained by determining the maximum deviation of *Sq* (*H*) from the average night-time *H*, i.e. the average of the *H*-variation at 0030, 0130, 2230, 2330, LT at each station was assumed to indicate the zero level of *H* for that station. The amplitude of the superposed northward field was then considered as the difference between the two amplitudes thus determined.

In Fig. 2(a) we have plotted the average amplitude of this variation and it may be seen that there is a tendency for this amplitude to be a maximum near the longitude of Hartland and it decreases as one progresses east, and may even become negative (corresponding to a superposed southward field).

3 The AQD event amplitude

In a previous paper (Butcher & Brown 1981) evidence was presented that strongly suggested that the AQD events were bay-like perturbations of small amplitude and hence were associated with magnetospheric substorms. If they are indeed related to substorms then we must consider whether the longitude variations of amplitude shown in Fig. 1 are consistent with the effects we might expect to observe in mid-latitudes. Rostoker *et al.* (1980) have discussed the signatures expected to be observed in the *H*-variation in mid-latitudes associated with substorm events. Energy appears to be transferred from the solar wind into the nightside magnetosphere, via a mechanism that is not completely understood, when changes in the IMF occur which are usually, but not always, associated with the B_z component of the IMF turning southward (i.e. B_z negative). A substorm is triggered (releasing an amount of energy that depends on both the solar wind velocity and on the direction and magnitude of the IMF) and a current flows down into the auroral regions as a field aligned

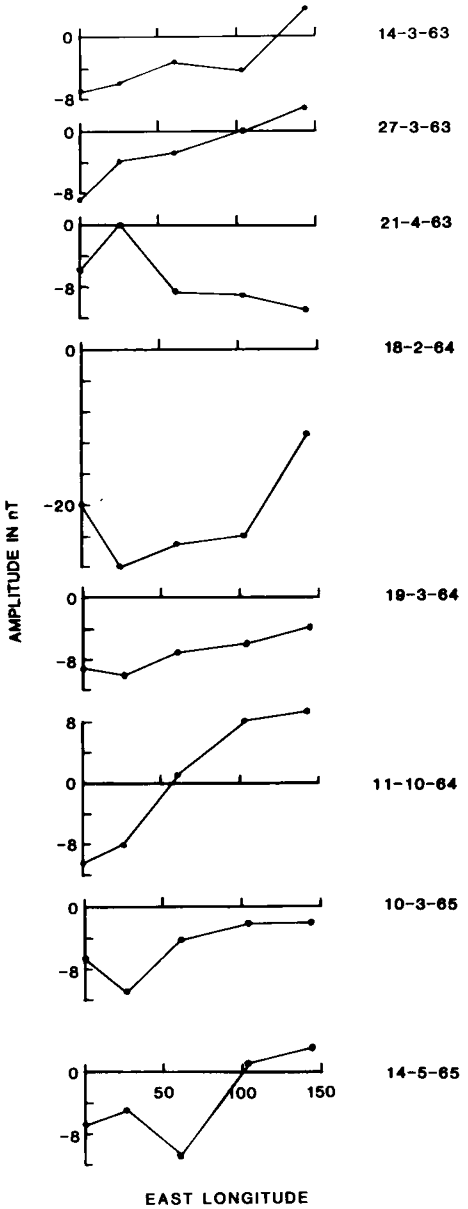
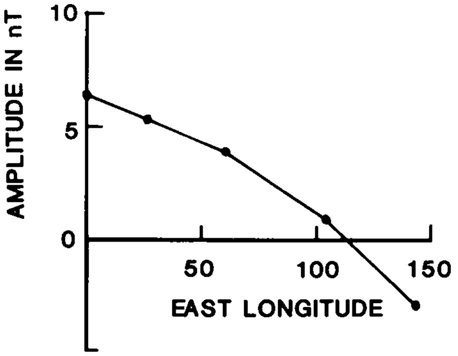
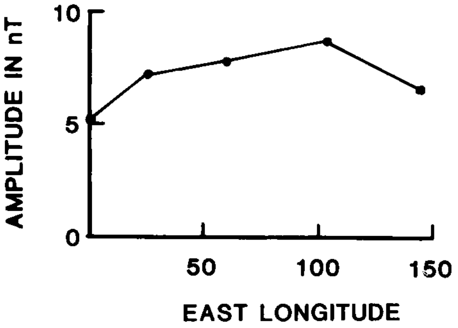


Figure 1. AQD event amplitude as a function of longitude.

current, westward as an electrojet in the ionosphere and back out into the magnetosphere as a field-aligned current. We may obtain some idea of the magnetic variation expected in this situation by considering initially only the outgoing field-aligned current (i.e. at the westward edge of the auroral electrojet) and constraining ourselves to a latitude below the auroral electrojet region but above the equatorial region. Then at an observatory to the west of the western edge of the electrojet the magnetic effect will be a negative depression whereas for an observatory to the east of the western edge of the electrojet the magnetic effect will be a positive change. An estimate of the expected longitude variation along a line of latitude may



(a)



(b)

Figure 2. Average amplitude of the superposed northward field as a function of longitude: (a) for eight AQDs determined at Hartland, (b) for six AQDs determined at Sverdlovsk.

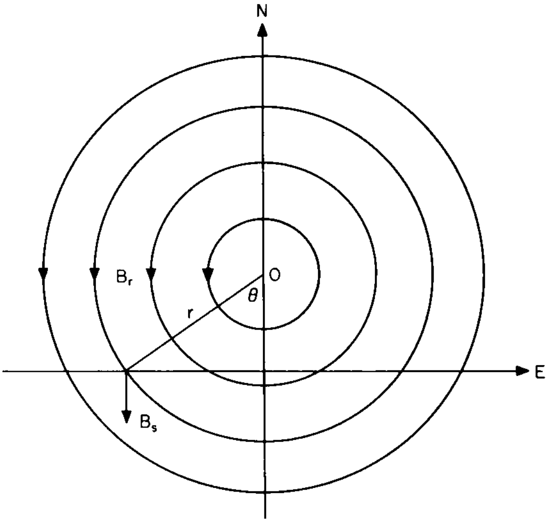


Figure 3. Assumed magnetic field contours due to a field-aligned current situated at 0 and directed out of the plane of the figure.

be obtained since the lines of constant magnetic field at the ground for such a current will be approximately circular. Hence, the amplitude of the southward component, B_s, of this field B_r at radius r (see Fig. 3) is $B_r \sin\theta$ and since $B_r \propto 1/r$ then for a constant latitude $B_s \propto \sin 2\theta$. Thus in moving westward from the western edge of the electrojet along a line of constant latitude we would expect the (negative) amplitude of the event to increase, reach a maximum, and then decrease. The effect of the westward current flow of the electrojet would be to add an additional negative field at all longitudes to that due to the field-aligned current (its magnitude decreasing as the observer moves west away from the electrojet) causing the amplitude of the magnetic substorm event to go through zero somewhere near, but probably to the east of the outgoing field aligned current. In Fig. 1 we see that all the AQD events, except that which occurred on 1963.4.21, give a longitude variation of the amplitude consistent with what might be expected on the above argument.

Differences in the longitudinal variation of the event amplitude observed in Fig. 1 from one AQD to another arise, on the above argument, from quite significant differences in the (inferred) longitude of the outgoing field aligned current. It is seen that this longitude may vary between 60° and 160° east. (Deviations from its expected variation occur due to the fact that all the stations are not located along the same latitude and so at Surlari and Memambetsu, which are at slightly lower latitudes, the amplitudes would be smaller than that expected. However, this effect is likely to be small.) A crude estimate using Ampère's Law and taking a field aligned current of 2×10^5 amp located at 90° E and 80° N gives about 4 nT for the expected amplitude at Hartland which is of the order observed.

The results presented here, taken together with the previously reported correlations of the AQD event with B_z therefore appear to confirm that the AQD events are associated with magnetic substorms and are most probably negative mid-latitude bays of small amplitude.

4 The magnitude of the superposed northward magnetic field

In Fig. 1 we plotted the amplitude of each AQD event with longitude without giving an average variation for the eight events. From the discussion of Section 3 this was justified since for each event the form of the variation depends on the longitude of the western edge of the electrojet. Previously it was pointed out (Butcher & Brown 1981) that the magnitude of the superposed northward field had a diurnal variation which appeared to be related to the ionospheric conductivity but it was established that the field did appear to be present throughout the whole day. It was suggested that this northward magnetic field might be caused by an electric field that drives a west–east ionospheric current on both sides of the *Sq* (*H*) focus. Thus it seems reasonable to take an average value of the superposed northward field at each station which would then at least represent the average change in its magnitude with longitude. Hence, if this additional magnetic field were caused by an electric field driving a west–east current such an average would give some indication as to the extent of the average *E*-field since one would not expect the ionospheric conductivities to change drastically over the range of stations involved. It is seen from Fig. 2(a) that the northward magnetic field (or alternatively the inferred *E*-field) falls to zero about 110° to the east of Hartland and there is some indication that the direction might then reverse. No information is available as to what happens to the west of Hartland since for such observations the AQD event and the normal *Sq* (*H*) minimum would tend to occur in the same time range making it impossible to separate the two effects. However, in order to investigate this further, measurements of this effect have been made on AQDs that were determined from the Sverdlovsk data rather than the Hartland data. Since the reduction in the normal *Sq* (*H*) amplitude appears to be the most important parameter in determining whether a day is an AQD it was hoped that when an AQD occurred at Sverdlovsk this might indicate that the northward field was a maximum near that station. Again, only AQDs were considered where the minimum in H occurred between 1330 and 2230 UT and the result for the average of six such AQDs is shown in Fig. 2(b). It is seen that there is some indication that a maximum in the northward field occurs near the longitude of Sverdlovsk indicating the northward field is probably only present over a limited longitude range.

5 Latitude variations associated with AQDs

It has been shown previously (Butcher & Brown 1980) that the amplitude of the AQD event is approximately constant over the geographic latitude range 14°–60° N. On the arguments presented in Section 3 it would be expected that the event amplitude would decrease with decreasing latitude. However, since the longitude of the outgoing field-aligned current is far removed from the 0° longitude meridian such a decrease might be expected to be small. The latitude variation of the magnitude of the northward field has not been discussed previously although it may be seen from figs 2–5 of Butcher & Brown (1980) that it does vary with latitude and the variation is different on A-days than T-days and is also different in summer than winter. Not enough data were available of the longitude variation to allow a separation on a seasonal basis or on IMF polarity, but that restriction is not present for the latitude variation and in Fig. 4 is shown the magnitude of the northward field as a function of latitude separated by seasons and IMF polarity. Of the 80 quiet days in the two-year period considered, 32 were found to be AQDs, 15 occurred in the May–August period of which nine were A-days and six T-days and 17 occurred in the November–February period of which 10 were A-days and seven T-days. For the NQDs 25 occurred in the May–August period of which 16 were A-days and nine were T-days and 23 occurred in the November–February period of which 13 were A-days and 10 were T-days. Since each point in Fig. 4 is determined from the difference between the average AQD and NQD amplitude the statistical significance of this difference has been determined using the Student t-test and the percentage level at which it is significant is shown alongside each point in Fig. 4. Points whose

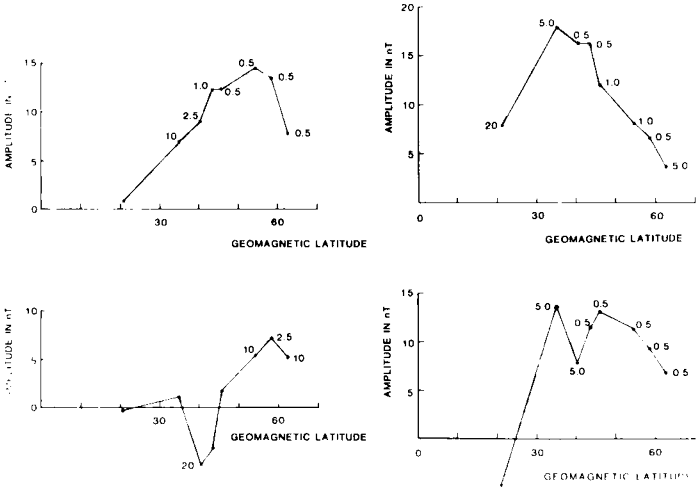


Figure 4. Average variation of the superposed northward field (1963–64) with geomagnetic latitude. Top: A-days; left summer, right winter. Bottom: T-days; left summer, right winter. The numbers alongside each point indicate the level of significance of the point determined using the Student t-test. Points with no number alongside them are not significant below the 30 per cent level.

significance is below the 30 per cent level are considered not to be significant and no level has been included in Fig. 4 for these points. It is seen that there is a variation with latitude which may be considered to be significant in all cases, the magnitude reaching a maximum in mid-latitudes that is more equatorward in winter than in summer. The magnitude is greater on A-days than T-days, is more regular on A-days and on both A- and T-days there is an equatorward shift of about 20° in the geomagnetic latitude of the maximum magnitude from summer to winter.

6 Discussion

From the results presented previously (Butcher & Brown 1980) and here, there seems little doubt that the AQD event is associated with a magnetospheric substorm which manifests itself in mid-latitudes as a small amplitude negative bay. This bay then forms the minimum in H at stations on the poleward side of the $Sq(H)$ focus if there is a sufficient reduction in the normal $Sq(H)$ amplitude. This reduction is accomplished by the presence of a superposed northward field which is present over a limited range of latitudes and longitudes and, over the latitude range 14°–60° N (geographic) is larger on A-days than on T-days. Its magnitude peaks in mid-latitudes and moves equatorward some 20° from summer to winter.

In order to attempt to explain the source of the superposed northward field let us first consider the effect of the IMF. The IMF is carried by the solar wind with a velocity component V_x and induces a dynamo electric field component $\mathbf{E}_\mathrm{I} = \pm V_x B_y \hat{\mathbf{k}}$ where the + or – sign corresponds to A- or T-days respectively indicating a north to south (+) or south to north (–) field. If the Earth were surrounded by a vacuum the electrostatic field $\mathbf{E}_\mathrm{s} = -\mathbf{V} \wedge \mathbf{B} = -\mathbf{E}_\mathrm{I}$ would appear across the Earth. However, since the solar wind flows around the magnetosphere then $\mathbf{E}_\mathrm{s}$ should be excluded from the near Earth environment. However, there is some evidence that $\mathbf{E}_\mathrm{s}$ does penetrate down to ionospheric levels, particularly in the polar cap regions (i.e. Jorgensen, Friis–Christensen & Wilhjelm 1972) where high latitude magnetograms may be used to infer IMF polarity (Svalgaard 1972). Let us assume here then that some effect of $\mathbf{E}_\mathrm{s}$ reaches the mid-latitude E-region. Since in the northern hemisphere the geomagnetic field, B_G, is towards the Earth ($(B_\mathrm{G})_z$ negative), $\mathbf{E}_\mathrm{s}$ would cause an east–west current in the ionosphere on A-days and hence an additional southward magnetic field. However, on T-days, $\mathbf{E}_\mathrm{s}$ will be north–south and would cause an additional northward magnetic field, i.e. opposite to that in A-days. The observations indicate that the superposed field is northward on both A- and T-days, but larger on A-days. Therefore if we assume that on AQDs a west–east current flows at all latitudes in the northern hemisphere (which is responsible for most of the superposed northward field) then the Hall currents driven by $\mathbf{E}_\mathrm{s}$ would either add (T-days) or subtract (A-days) from this current. This is the opposite of the effect observed. Thus we see that the difference in the amplitude of $Sq(H)$ on AQDs for A-days and T-days is not due to the effect of the interplanetary electrostatic field, $\mathbf{E}_\mathrm{s}$, penetrating directly into the mid-latitudes E-region. However, some parameter related to the IMF does affect the amplitude and it is interesting to note that the dynamo electric field, $\mathbf{E}_\mathrm{I}$, is of the correct polarity to explain the observations but it is difficult to see a physical mechanism involving $\mathbf{E}_\mathrm{I}$ directly.

If we assume that the contribution to the superposed northward field due to the IMF (whatever the mechanism), is equal and opposite on A- and T-days, then the effect of the component of the superposed field that is independent of the IMF may be determined as the mean of the A- and T-day amplitudes. In Fig. 5(b) is shown the variation of this component with geomagnetic latitude determined using the smoothed latitude variations of $Sq(H)$ amplitude observed on NQDs and AQDs for both A- and T-days for the years 1963–

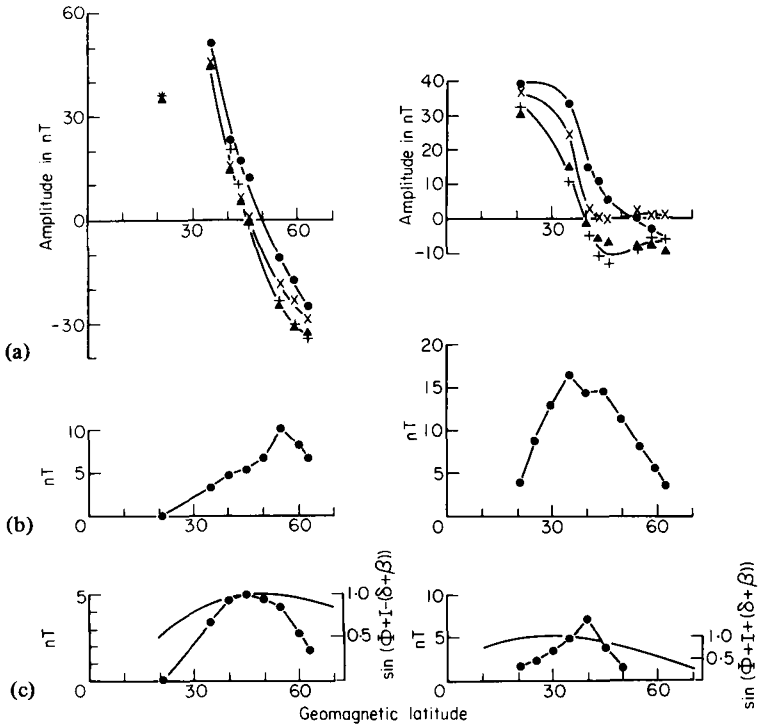


Figure 5. (a) Average amplitude of *Sq* (*H*) (1963–64) as a function of geomagnetic latitude, for NQDs and AQDs. (▲) NQD A-days, (+) NQD T-days, (●) AQD A-days, (X) AQD T-days. Left summer, right winter; (b) Variation with geomagnetic latitude of the magnetic effect of the inferred west–east current. Left summer, right winter; (c) Inferred magnetic effect on *Sq* (*H*) on AQDs due to the IMF. Left summer, right winter. The smooth curve is a plot of sin μ, where μ $(\phi + I \pm (\delta + \beta))$ is the angle between $(E_T)_Z$ and B_G and represents the theoretical contribution of the Hall currents along the 0° meridian at 1200 UT.

1964 and shown in Fig. 5(a). It has been assumed that the amplitude on NQDs at any station is the same on both A-days and T-days, an assumption which is clearly justified for the summer data but may be less justified for the winter data. From Fig. 5(b) it may be seen that its magnitude is larger in winter than in summer and the latitude where the magnitude is largest moves equatorward by about 20° geomagnetic (from 55° to 35°) from summer to winter and tends towards zero near 20° and 70° geomagnetic latitude. The magnetic effect of the component due to the IMF (assuming it is equal and opposite on A- and T-days) is shown in Fig. 5(c). These results then, taken with the results of previous work (Butcher & Brown), indicate that a west–east current, of unknown source, flows in the ionosphere on AQDs but not on NQDs. The magnetic effect of such a current is latitude dependent, its maximum effect being 10–15 nT. However, alternatively it may be that an east–west current flows on NQDs at all latitudes that is not present on AQDs thus affecting the change in the amplitude of *Sq* (*H*) and AQDs. At present we are unable to tell which mechanism operates since the origin of this source of current is unknown. Also it would appear that the results support the hypothesis that at least on AQDs the IMF may have an effect on the mid-latitude *Sq* (*H*) which is also latitude-dependent and has a maximum amplitude of about 5 nT.

Although the effect of the IMF on the *Sq* (*H*) amplitude on AQDs does not appear to be caused by E_s penetrating down to the mid-latitude E-region, the most likely cause is still likely to be some unknown electric field related to the IMF. Let us assume here that such a field exists and is directed north–south on A-days and south–north on T-days as required to explain the observations. Denoting such a field $\mathbf{E}_u$ it will drive a Hall current proportional to $\mathbf{E}_u \wedge \mathbf{B}_G$ whose magnitude will depend on the angle μ that $\mathbf{E}_u$ makes with the geomagnetic field, $\mathbf{B}_G$. μ is therefore latitude dependent and is given by

$$\mu = [\phi + I \pm (\delta + \beta)]$$

where the + or − sign applies for winter or summer respectively. ϕ is the magnetic latitude, I is the magnetic dip angle, δ is the solar declination angle, and β is the angle between the projections of the geomagnetic north–south axis on to the x–z plane (x being directed along the Sun–Earth line and z being perpendicular to the plane of the eliptic) and the geomagnetic north–south axis which varies with time of day and longitude and may be given by

$$\beta \sim \beta_0 \cos(15t - 69 + \lambda)$$

where t is the local time in hours, λ is the geographical longitude, and it has been assumed that in the northern hemisphere the geomagnetic north pole is located at 69° west longitude. The variation of $\sin\mu$ with I has been plotted in Fig. 5(c) assuming $\beta_0 = 11.3°$, $t = 1200$ hr and $\lambda = 0°$. It is seen that $\sin\mu$ shows some characteristics of the observations (e.g. maxima occur at 49.6° in summer and 26.5° in winter) but deviations would be expected since no account has been taken of the variation of $\mathbf{B}_G$ or the ionospheric electrical conductivity with latitude, both of which would affect the magnitude of the magnetic effect at each location.

A further consequence of the presence of $\mathbf{E}_u$ is that since in the southern hemisphere $\mathbf{B}_G$ is away from the Earth, the Hall currents driven by $\mathbf{E}_u$ would be east–west hence giving a superposed southward field component on AQDs for A-days and a northward component field for T-days. For a station on the poleward side of the focus we would therefore expect the *Sq* (*H*) field to be reduced more on T-days than A-days and hence more AQDs would be expected to be T-days than A-days whereas in the northern hemisphere the reverse is found to be true (Butcher & Brown 1980). For comparison, for the years 1963–64–65, at

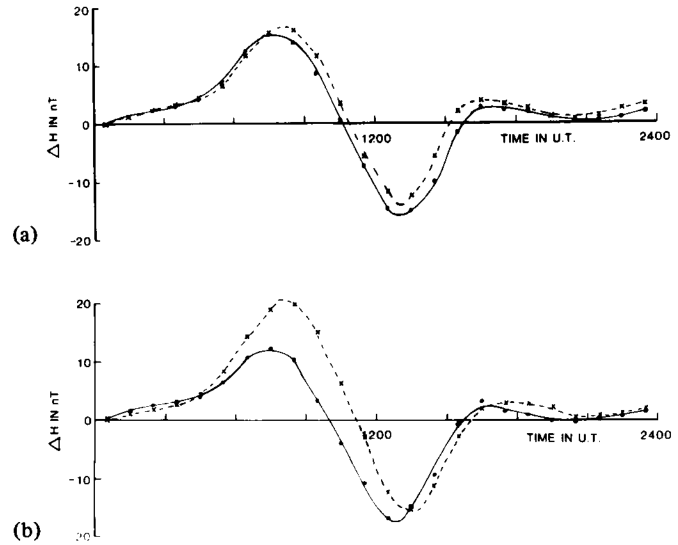


Figure 6. (a) Average variation of H at Hermanus for NQDS (×) and AQD (●) for the months of 1963–64 May, June, July and August. The AQDs were determined from the Hartland data; (b) Average variation of H at Hermanus for the AQD variation shown in (a) separated according to IMF polarity (●) A-days, (×) T-days.

Hartland 62 per cent of AQDs occurred on A-days whereas at Hermanus (34° 25′ S 19° 14′ E geographical, and 33° 42′ 81° 42′ geomagnetic) only 46 per cent of the AQDs occurred on A-days lending support to the above hypothesis. (The time of occurrence of the normal minimum in *Sq* (*H*) was significantly later at Hermanus than Hartland and so for this analysis the NQD period was extended from 0830–1430 Lt for Hermanus.) In general, days that were AQDs at Hartland were not AQDs at Hermanus (unless the AQD event was large at both stations) and the reduction in the amplitude of *Sq* (*H*) that occurred at Hartland on AQDs did not occur, on the same days, at Hermanus. This may be seen from Fig. 6 where we have plotted for Hermanus the average variations of those days defined from the Hartland data as AQDs or NQDs, for the months of 1963–64 May, June, July, August. Also shown is the variation for the AQD group when separated according to IMF polarity. It is seen that the physical mechanism that causes the reduction in the normal *Sq* (*H*) amplitude on AQDs at Hartland does not appear to be operative on those days at Hermanus, although it is possible that the effects are minimal at the latitude of Hermanus but this cannot be concluded from the data. However, there is a suggestion that, at least, for part of the day (i.e. between 0600 and 1300) the northward component of *H* is greater on T-days than A-days as required. But the form of the variations is not as expected on the above arguments and obviously more analysis of southern hemisphere stations is required.

Although an explanation of how AQDs arise has been attempted, no reason can be found as to why the mechanisms only operate on certain days and not, apparently, all the time. However, if one accepts the principles of the proposals put forward here it is most likely that the mechanisms operate on a continuous basis but for some reason have a larger effect on some days than others.

Acknowledgments

The author would like to thank Professor V. A. Troitskaya of the Institute of the Physics of the Earth, Moscow, for providing the magnetic data from Irkutsk and Sverdlovsk, and Miss Kathleen Dyson of the Institute of Geological Sciences, Edinburgh for supplying the rest of the magnetic data. He also acknowledges several interesting discussions with Professor K. D. Cole and Dr G. M. Brown.

References

Brown, G. M., 1974. A new solar-terrestrial relationship, *Nature*, **251**, 592.

Brown, G. M., 1975. *Sq* variability and aeronomic structure, *J. Atmos. Terr. Phys.*, **37**, 107.

Brown, G. M., 1980. New methods of predicting the magnitude of sunspot maximum, in *Solar Predictions Proceedings* (Boulder Col.), **2**, 264.

Brown, G. M. & Butcher, E. C., 1981. The use of abnormal quiet days in *Sq* (*H*) for predicting the magnitude of sunspot maximum at the time of preceding sunspot minimum, *Planet. Space Sci.*, **29**, 73.

Brown, G. M. & Williams, W. R., 1969. Some properties of the day-to-day variability of *Sq* (*H*), *Planet. Space Sci.*, **17**, 453.

Butcher, E. C. & Brown, G. M., 1980. Abnormal quiet days and the effect of the interplanetary magnetic field on the apparent position of the *Sq* focus, *Geophys. J. R. astr. Soc.*, **63**, 783.

Butcher, E. C. & Brown, G. M., 1981. On the nature of abnormal quiet days in *Sq* (*H*), *Geophys. J. R. astr. Soc.*, **64**, 513.

Jorgensen, T. S., Friis-Christensen, E. & Wilhjelm, J., 1972. Interplanetary magnetic field direction and high latitude ionospheric currents, *J. geophys. Res.*, **77**, 1976.

Rostoker, G., Akasofu, S-I, Foster, J., Greenwald, R. A., Kamide, Y., Kawasaki, K., Lui, A. T. Y., McPherron, R. L. & Russell, C. T., 1980. Magnetospheric substorms – definitions and signatures, *J. geophys. Res.*, **85**, 1663.

Svalgaard, L., 1972. Interplanetary magnetic sector structure 1926–71, *J. geophys. Res.*, **77**, 4027.