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The quiet daily variation in the total magnetic field: global curves

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Abstract. Most magnetic mapping exercises involve measuring the amplitude, or total-field component, of Earth's magnetic field. Removing the time-varying part of the field is a task of data reduction, and the most common time variation is the quiet daily variation, S_q . It is thus valuable to have for reference type curves of the quiet daily variation in the total field. To meet this need, global data obtained during the 1965 International Year of the Quiet Sun have been used to derive type curves describing the S_q variation of the total magnetic field, in addition to the traditional field components. As for the traditional components, the total-field curves show significant seasonal and latitudinal variability in amplitude and phase. The effect of the equatorial electrojet is clearly evident. In both hemispheres of the globe there are bands of reduced amplitude in total-field signal between the equator and the path of the S_q focus. These bands, here termed the total-field "doldrums", persist throughout the year.

Introduction

The geomagnetic field has a number of sources, both internal and external to Earth. The fields these sources produce are generally time dependent, with time-scales ranging from seconds to thousands of years. Usually, magnetic surveys focus on the crustal field, which varies with long time-scales. Significant effort is expended in removing the effects of external origin, with short time-scales, from magnetic survey data.

One of the earliest time-varying fields recognised in magnetic records was the daily variation [*Chapman and Bartels*, 1940; *Malin*, 1987], associated with the apparent movement of the sun across the sky. At times of low magnetic disturbance the quiet daily variation exhibits a repeatability. In an analysis of a series of quiet days the 24, 12, 8 and 6 hour harmonics are prevalent, due to the effects of Earth's rotation rather than the characteristics of the signal which occurs during any particular day [*Lilley*, 1975]. In addition to its solar components the quiet variation also comprises lesser components of lunar origin [*Malin*, 1970; *Winch*, 1981], which arise due to ionospheric bulges associated with lunar tides. This paper is restricted to the solar quiet variation, often denoted S_q .

Observatory records, and magnetic field models based on them, indicate that the form of S_q field variations has a spatial dependence primarily related to geographic latitude, with dependence also on geomagnetic latitude [*Campbell*, 1997]. Geomagnetism texts commonly include figures which compare variations of the components of the magnetic field at different locations on the globe [*Chapman and Bartels*, 1940; *Matsushita*, 1967, for example], without including the total field. A number of more recent analyses of the geomagnetic daily variation have been conducted, including *Parkinson* [1977], who used data collected during the magnetically active International Geophysical Year.

In the present paper, curves for S_q total-field variations are derived from a global model based on an analysis of observatory data recorded during a year with very low levels of solar activity [*Campbell et al.*, 1989]. Such total-field curves are particularly relevant to magnetic mapping, in which the parameter measured is generally the total field, containing a daily- variation signal.

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S_q variations

As described in *Campbell* [1997], the daily variation of the geomagnetic field, as typically observed at mid-latitude stations during quiet periods, originates in the ionosphere some 100 km above Earth's surface. The solar component of the quiet daily variation, S_q, is the result of enhancement of the conductivity of the E region of the ionosphere, induced by solar radiation. Current vortices above both the northern and southern hemispheres are formed as thermotidal and thermospheric forces cause electrically charged ions to move through Earth's magnetic field.

These currents are of global scale, and the contribution they make to magnetic survey measurements is strongly dependent on where the survey is located. There are other factors which contribute to the character of S_q variations, particularly in amplitude and phase (phase reflects the time at which the daily maximum amplitude occurs). These other factors include time of year, level of solar activity and, to a lesser extent, longitude of the survey.

Also, because Earth is a conductor of electricity, and senses the magnetic fields associated with the ionospheric electric currents as changing magnetic fields, major induced electric currents flow in the solid body of Earth (and its oceans), approximately mirroring the electric current flow in the ionosphere [*Hobbs*, 1992, for example].

Further mechanisms make substantial contributions to the quiet daily variation at both low and high latitudes, by superimposing additional fields on those arising from the S_q current vortices. In equatorial regions the equatorial electrojet, which flows in a more highly conductive ionospheric

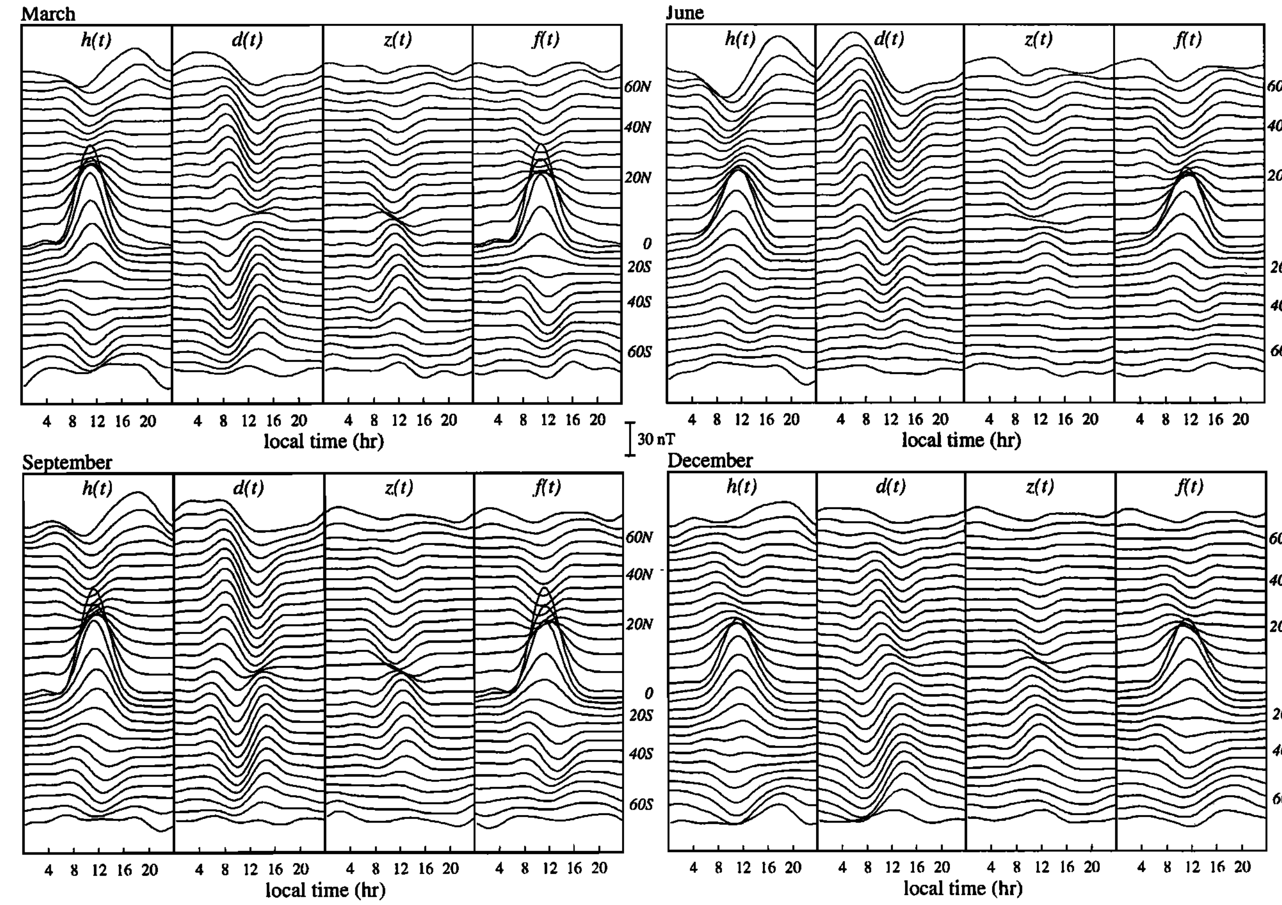

Figure 1. Global S_q curves for the seasons of the year. The curves are obtained by averaging variations in latitudinal bands (geomagnetic) around the globe. They should be understood as indicative of S_q behavior at these latitudes, and do not take into account possible regional and local effects.

E region, contributes an additional component to quiet daily variations. Field aligned currents and magnetospheric electric fields are present in auroral regions.

In addition, the amplitudes of the components of S_q variations are enhanced at times of high sunspot activity in the solar cycle; mid-latitude stations tend to have maximum S_q amplitudes (and advanced phase) during summer while amplitudes at equatorial stations are enhanced at equinoctial times.

Global S_q model and total-field variations

During the International Year of the Quiet Sun (IYQS, 1965) levels of solar activity were exceedingly low; 46 % of days had all K_p indices ≤ 3 [*Campbell,* 1997, p. 65]. Data obtained from a global network of magnetic observatories during the IYQS have been analysed by *Campbell et al.* [1989], and a model developed by those authors which describes S_q variations of the field components at any location on the globe. Algorithms for generating the S_q variations in H, D, X, Y and Z are available at http://www.ngdc.noaa.gov/seg/potfld/utilw hc.html.

The S_q variations in H, D and Z generated by the model are here represented by the time series $h(t)$, $d(t)$ and $z(t)$ respectively, which describe the departures of each component from epoch field values. Total-field variations, $f(t)$, as would be observed by a scalar instrument, have been determined on a 5° × 5° global grid (geographic) from $h(t)$ and $z(t)$ using

$$f(t) = h(t)\cos\mathcal{I} + z(t)\sin\mathcal{I} \tag{1}$$

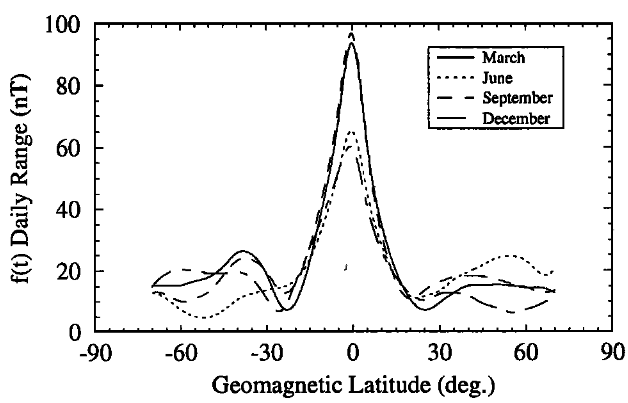

Figure 2. The amplitude range in the average total-field variations for each geomagnetic latitude, derived from the global S_q model.

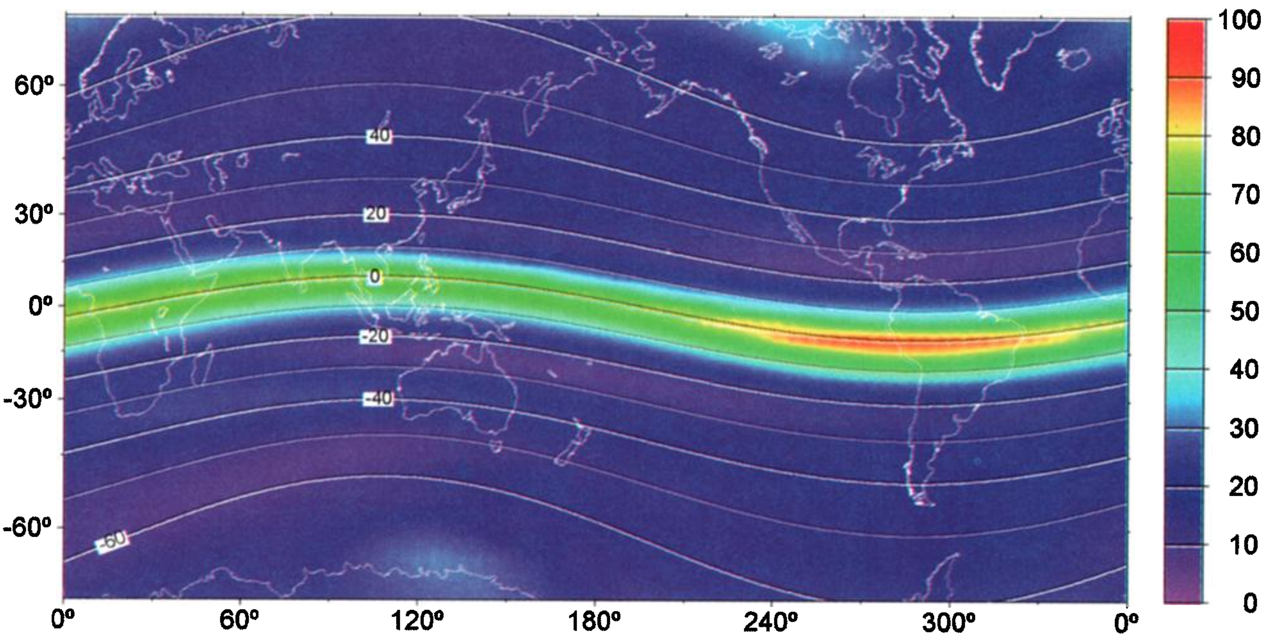

Figure 3. The global pattern of the amplitude range of total-field S_q variations (in nT). Annual average values are represented, superimposed upon contours of geomagnetic latitude.

where $\mathcal{I}$ is the inclination, obtained from the geomagnetic latitude, ϕ, at each location using the 'dipole field equation' [*Merrill et al.*, 1996, p. 94]

$$\tan \mathcal{I} = 2 \tan \phi \qquad (2)$$

Field variations obtained from the model were represented by 20 minute samples, and at each geographic location the geomagnetic latitude was determined. The average variations for each geomagnetic latitude were then obtained by, in turn, finding the mean of the variations in each geomagnetic latitude band described by $(\phi_i \pm 2.5°)$, where $70° \geq \phi_i \geq -70°$, at 5° intervals.

Figure 1 shows the type curves for S_q variations in F, in addition to H, D and Z, for the four seasons: March equinox, June solstice, September equinox and December solstice. These curves are global averages and, as such, are a general representation of the quiet total-field variation expected at a given geomagnetic latitude. Regional variability in the S_q field and local effects, such as induction in the vicinity of the oceans and conductivity anomalies [*Lilley and Parker,* 1976; *Parkinson and Hutton,* 1989], may perturb these curves at some locations.

The $f(t)$ curves in Figure 1 show the following important features.

1. As is known from studies of the equatorial electrojet phenomenon, equatorial locations experience strongly enhanced S_q signals generally. The enhancement is further amplified at equinoctial times. During summer, mid- latitude stations experience enhanced amplitude and advanced phase.
2. At low latitudes $f(t)$ follows $h(t)$ closely. At high latitudes the total field follows $z(t)$ in the northern hemisphere, and $-z(t)$ in the southern hemisphere.
3. Significant features of the $f(t)$ curves, which persist throughout the year, are the bands of low-amplitude S_q variations between about 20° and 30° (geomagnetic), in both hemispheres. Figure 2 is a plot of the amplitude range of the $f(t)$ variation against geomagnetic latitude, for each season, and shows clearly the subdued amplitude at these latitudes. The authors have found total- field "doldrums" to be a useful term for these subdued bands.

Figure 3 shows a complementary presentation of the total-field S_q results, superimposed on a map of geomagnetic latitude (obtained for the nominal day of 24 March 1997, from the DGRF and IGRF main field models for 1945 to 1985). The color pattern shows the average amplitude range for 1997, obtained by taking the mean of the four seasons. The equatorial electrojet is seen to be concentrated generally along the contour of zero magnetic latitude, and the bands of minimum $f(t)$ signal, between geomagnetic latitudes 20° and 30° in both hemispheres, are also evident.

Conclusions

Type curves of the S_q variation of the total field summarise its form over the globe, except at very high latitudes. The curves show that total-field variations have a seasonal variability and a distinct latitudinal dependence. There is a pronounced maximum in the daily variation at the equator, and, in both hemispheres on either side of this maximum, there are bands where the amplitude of total-field variations is subdued. Such characteristics are important in understanding the quiet total-field variation present in magnetic survey data, and indeed in any exercise involving the monitoring of Earth's magnetic field.

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