An External Current Representation of the Quiet Nightside Geomagnetic Field Level Changes

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(Received January 15, 1984)

The annual and semiannual behavior of the local midnight field for North America, is represented as an external current system display derived from a spherical harmonic analysis. There are two vortices of this current: one is clockwise, centered in the Southern Hemisphere in the June solstitial period; the other is counter-clockwise, centered in the Northern Hemisphere in the December solstitial period. The foci of approximately 19,000 amperes are located near 8 degrees geomagnetic latitude. The seasonal change in orientation of the solar wind with respect to the Earth's geomagnetic dipole axis explains most of the current pattern appearance. The maximum amplitude of the field components reconstructed from the representation rises to about 5 to 6 gammas at the equatorial and polar latitudes and to about half that size at the middle latitudes.

1. Introduction

The nighttime field levels at a middle and low latitude observatory indicate the seasonal and activity level behavior of the Earth's magnetic field in space as it reacts to variations in the direction and composition of plasma constantly emitted from the Sun. The quiet midnight geomagnetic field measurements are used in two significant ways. They may represent "baseline" levels about which the effects of the predominantly daytime ionospheric currents are measured (cf. PRICE and WILKINS, 1963; MIZUNO, 1968; MALIN, 1969; MATSUSHITA and CAMPBELL, 1972; MALIN and ISHIKARA, 1976; CAMPBELL, 1983). They are used for the determinations of geomagnetic secular changes and for improving the evaluation of local crustal field contributions in regional mapping (cf. CAMPBELL, 1980; WALKER, 1982).

Often for geomagnetic studies it has been found valuable to represent surface observations of large scale field changes by currents flowing in a thin shell concentric with the Earth. Such a procedure is especially valuable when it is recognized that the principal source of a field change is external to the Earth itself, when there is reason to believe that such current approximates a physical existence at some fixed altitude above the Earth, or when such external representation simplifies the description and allows a better understanding of the observed spatial or temporal field change. The purpose of this paper is to provide a current representation of the yearly nightside field changes during selected quiet

days of an especially quiet year, 1965. Such representation will be shown to satisfy the first and last of the above conditions and, in that way, it can be an aid both to the understanding of magnetospheric behavior and to the prediction of nighttime field levels.

The year, 1965, is important for geomagnetic studies because an international cooperation in that year made available a large number of high quality geomagnetic records and because the geomagnetic activity was at its lowest levels since 1934 (MEYERS and ALLEN, 1977). By the selection of special quiet days within 1965 for analysis, the variance in the determinations of annual and semiannual field changes may be reduced sufficiently to improve the accuracy of secular variation values and magnetic mapping resolution.

2. Analysis Method

A latitude representation of the dominating annual and semiannual periodicity in midnight field changes at North American locations during 1965 was published earlier (CAMPBELL, 1980, 1981). For those studies the local midnight fields were taken to be the mean hourly values of the orthogonal field components for the UT hour containing the local midnight meridian at each observatory. Thirty quiet days had been selected to represent 1965 by a choice of conditions giving minimum values of the Dst and AE geomagnetic activity indices (CAMPBELL, 1979). Such a selection emphasized times when the magnetosphere was least compressed by the solar wind, had the smallest field-aligned and auroral electrojet currents, and supported a minimum of equatorial magnetospheric ring current. A special function containing a constant, a linear change, and the sine and cosine Fourier coefficients for annual and semiannual variations had been fitted to the year's 30 quietest midnight values. By smoothing the station Fourier coefficients over all northern latitudes it was then possible to reconstruct the seasonal changes of the three orthogonal components of the quiet nighttime field at all latitudes in the North American region (cf. Fig. 7 in CAMPBELL, 1982). The Fourier coefficients from this representation are the data values for the spherical harmonic analysis (SHA) discussed below.

SHA is similar, in a way, to a Fourier analysis expanded in a three-dimensional sphere. SHA is a method whereby one may fit analytical measurements of field over a sphere (of radius r) using two converging series of spherical harmonic oscillations (CHAPMAN and BARTELS, 1940). Given the condition that no currents flow across the analyzed region, these series also allow a separation of the external and internal current contributions to the observations by a separation of the one series, with terms that increase directly with powers of r , from the other series, with terms that increase with reciprocal powers of r .

The sphere of the analysis may be a realistic one of the type used for fitting the global main-field measurements (BARRACLOUGH, 1978). Alternatively, it may be a partially hypothetical one such as that employed in zonal quiet daily variation, Sq, analysis (MATSUSHITA, 1967; CAMPBELL, 1983). In these latter cases

the field variation from one zone of the Earth and/or one hemisphere was appropriately expanded to represent a full sphere of observations for the analysis; then the final results were restricted in meaning to only the more limited, original-sample region.

In the present analysis the Southern Hemisphere, from which no data were available, is accommodated by special symmetry requirements on the analysis polynomials. The calculation assumes a model for which the 12-month change of midnight field equals 360° in longitude; the model is equivalent to describing a midnight-field pattern that surrounds an Earth having an annual rotation. Although the model is unrealistic, the current derived from the SHA such a field can represent, in a simple way, the complex latitude and time changes of the observed midnight data.

An order 2 degree 12 spherical harmonic analysis was used. With 360 degrees of longitude representing one year, the polynomial order (m) equals 1 for the annual and equals 2 for the semiannual changes. The maximum degree, $n=12$, was selected for the analysis to limit the shorter, low amplitude wavelengths along a circle of longitude to a spatial size of about $360/(n-m+1)=30$ degrees. The absence of Southern Hemisphere data was accommodated through setting certain of the SHA coefficients to 0 as required by the symmetry properties. That is, when $m=1$ the coefficients with $n-m=(\text{odd})$ were set equal to 0, and when $m=2$ the coefficients with $n-m=(\text{even})$ were set equal to 0. For the annual (semiannual) change this symmetry step is equivalent to requiring that the field component H is of the opposite (same) sign in opposite hemispheres and both the D and Z field components are of the same (opposite) sign in the opposite hemispheres.

Before analysis the data were additionally smoothed in the two following ways. First, in the equatorial region the values of annual H -component changes and the values of semiannual D - and Z -component changes were set to zero amplitude at the Equator then linearly increased with latitude to the observed values at 7.5 degrees, with unchanged phase. This step modified the observations only slightly but avoided an equatorial discontinuity for Southern Hemisphere matching. Second, all three components of field representation at 77.5 degrees latitude were extended linearly (with unchanged phase) to zero amplitude at the geomagnetic pole. This step permitted the analysis to exclude the high-latitude, quiet-level, auroral-oval field contributions and to avoid analysis irregularities at the pole. Tests showed that no fundamental change in the results occurred if the high latitude adjustment started at 65 degrees or if it were omitted entirely.

The SHA analysis techniques that I followed for the present study have been described by CHAPMAN and BARTELS (1940) and MATSUSHITA (1967). I used a Schmidt normalization of the Legendre polynomials and carried out numerical integrations at every 2.5 degrees latitude with the midnight field values of the North (H), East (D), and downward (Z) orthogonal geomagnetic component directions determined by the annual and semiannual Fourier coefficients for 1965 (CAMPBELL, 1980, 1981).

3. Results

The contour plot displayed in Fig. 1 illustrates the pattern of equivalent external currents that were obtained from an order (*m*) 2, degree (*n*) 12 spherical harmonic analysis of the midnight field levels (Table 1). An induced internal current representation showed a similar behavior with contour amplitudes about 0.7 of those for the external current. The Southern Hemisphere contours were obtained from an appropriate latitude mirroring of the Northern Hemisphere results shifted by six months. The zero contour here represents the mean level of the annual and semiannual variations; some other arbitrary selection of the zero level would leave the contour distribution unchanged, merely sliding the scale of amplitudes.

Figure 1 contours have a number of dominant features. The two simple vortices centered at approximately 8 degrees north and south latitude appear with maximum foci currents of 19.2×10^3 amperes at the solstices. The current

Table 1. Spherical harmonic coefficients for midnight field representation.

External		<i>a</i> (cos)	<i>b</i> (sin)
<i>n</i>	<i>m</i>		
1	1	−2.076	−0.114
3	1	0.188	−0.240
5	1	−0.057	−0.210
7	1	0.160	0.061
9	1	−0.048	−0.076
11	1	0.020	−0.090
3	2	−0.339	−0.329
5	2	0.113	0.257
7	2	−0.139	0.152
9	2	0.025	0.159
11	2	−0.057	0.035

Internal		<i>a</i> (cos)	<i>b</i> (sin)
<i>n</i>	<i>m</i>		
1	1	0.555	0.212
3	1	−0.433	−0.379
5	1	0.069	−0.146
7	1	−0.048	−0.105
9	1	0.064	−0.102
11	1	−0.028	0.042
3	2	−0.241	0.192
5	2	−0.074	−0.070
7	2	−0.031	0.140
9	2	−0.168	−0.030
11	2	−0.070	0.076

flow is clockwise about the June solstitial period and counter clockwise about the December solstitial period. The current directions are predominantly northward in February, March, and April and predominantly southward in August, September, and October. The zero-level contour is near the equinoxes for regions below the auroral zone. The current contours are shifted to later months at high latitudes.

Figure 2 illustrates the seasonal variation in the nighttime geomagnetic field on quiet days for 5-degree latitude increments. These plots were obtained from a summation of the external and internal fields described by the order 2, degree 12, SHA. The field components horizontal to the Earth are largest at the higher latitudes; the vertical field component is largest at the lower latitudes. Near the equator a semiannual variation dominates H , whereas an annual variations dominates D and Z . A phase shift to later months with increasing latitude is seen in H above 40 degrees latitude.

Some of the smoothing that occurs in the formation of the spherical har-

Fig. 1. Contours of equivalent external midnight currents in units of one-thousand amperes. Such currents describe the changes of geomagnetic field level at the Earth's surface through the cycle of a quiet year. Values were obtained from an order 2 degree 12 spherical harmonic analysis of selected North American midnight field level observations for quiet days. Arrows show current flow directions. Geomagnetic latitudes and months of 1965 are indicated. Southern Hemisphere characteristics were inferred from the Northern Hemisphere calculations.

monic fit to the data is a beneficial feature for all observations of this analysis that spotlights the dominant global annual and semiannual characteristics of the midnight field changes. Therefore, it is difficult to access the true "error" of the SHA fitting. However, a "worst-case" analysis of the error may be easily shown by comparing the reconstructed field with the original input. For a given observatory location and date let us call ABSDIF the absolute value of the difference between the field reconstructed from the SHA coefficients (called SHAREC) and the field obtained from the original observatory annual and semiannual Fourier coefficients of the midnight changes (called OBSHDZ). The correlation coefficient between SHAREC and OBSHDZ had a mean value of 0.65 (std. dev. 0.28) for the midmonth values of H , D , and Z at the 11 observatories of the original study at latitudes less than 77.5 degrees. This correlation indicates that the shape of the midnight field reconstruction (Fig. 2) matches fairly well with the original seasonal midnight field variation shape at the observatory. The mean value of the ratios, for all observatories, of ABSDIF to the corresponding year's range of values of OBSHDZ was 0.23 (std. dev. 0.09). This result indicates that the mean SHA fitting error is typically less than one-quarter of the yearly range of a station's recorded midnight field observations.

4. Discussion

The external current patterns shown in Fig. 1 are called "hypothetical" ones for the principal reason that such currents cannot flow continuously from one midnight to the next through the year changing only in the day-to-day form indicated by the figure. The representation, however, is an effective means of identifying the quiettime midnight surface field levels through the year in a coherent fashion with a single recognizable pattern that aids both in the visualization of the surface field behavior and in the prediction of the magnetospheric contributions to the surface fields at fixed local hours throughout a quiet year.

The two vortices of the equivalent external current patterns, one clockwise and centered in the June solstitial period, the other counter-clockwise and centered in the December solstitial period, with almost 19,000 amperes near the foci, represent the hypothetical equivalent midnight current during extremely quiet times of the year. This current pattern indicates, rather simply, the annual change in position of the distortion that must be added to the Earth's main field on the night side. This annual change gives rise to both the annual and the semiannual field variations at the Earth's surface as well as the latitude shift in principal amplitude between the orthogonal field components. The original data selection of extremely quiet days of an exceptionally quiet year together with the modification of data above 77.5° mentioned earlier essentially excludes auroral electrojet and high-latitude field-aligned current contributions from this representation.

An effect of the nightside magnetosphere shift toward a location antipodal to the subsolar solstitial position is indicated by the foci location at 8 degrees north and south latitude. The Earth is small with respect to the regions of the

Fig. 2. Earth surface representation of the seasonal variation of the midnight geomagnetic field level reconstructed from an order 2 degree 12 spherical harmonic analysis of North American observations for quiet days. Five-degree geomagnetic latitude increments of the *H*, *D*, and *Z* components of field change are shown for the months of 1965. Scale to right indicates the field magnitude in gammas (nanoteslas).

magnetosphere within which the major quiet-time distortions occur. The midnight levels of the surface field receive contributions from all parts of the magnetosphere. The dayside distortions that follow the subsolar hemispheric shift with season should also contribute to the darkside Earth surface observations. However, the seasonal shift in location of the equivalent midnight current contour vortices indicates that the effects of the nightside magnetospheric changes dominate the midnight surface field patterns. Because of the strong Sq ionospheric currents in daylight hours, it is difficult to measure the equivalent dayside magnetospheric distortion effects at the observatories.

A seasonal change in the orientation of the solar wind with respect to the Earth's geomagnetic dipole axis may be represented by magnetospheric currents that explain most of the surface field pattern appearance reported here. From a model of the magnetopause currents OLSON (1970) showed that the average of the 24 hourly values of each day displays seasonal variations in the field components at the Earth's surface. His Figures 9 and 10 illustrate the seasonal field changes in H and Z values and are consistent with two vortices of the same polarization as those in my Fig. 1 but shifted into the opposite hemisphere. Such a change might be expected because his averaging of the 24 hourly values of each day weighted the seasonal change by the day-side effects. The expected full external current representation of the magnetospheric effects, therefore, is one of a dual vortex equivalent current system, such as that shown in Fig. 1 for the midnight data samples, whose foci shift gradually to the equator for the sunrise data samples, move to the opposing hemispheres nearer to the sub-solar latitude for midday data samples, and return via an equatorial crossing for sunset data samples.

If a nighttime field measurement at an observatory is to be taken as a "baseline" level of the dipole field for mapping purposes without proper adjustment for the annual and semiannual changes, an error may be introduced that could be as much 6 gammas (nateslas) at quiet times but would depend upon the component, latitude, and month of year, as indicated in Fig. 2. In more active occasions one might expect considerably larger seasonal amplitude changes in the nighttime field level because of the large enhancement of tail current at such times (CAMPBELL, 1973).

I wish to thank Dr. Robert S. Anderssen of CSIRO for helpful discussions regarding the analysis. The data in this study was generously supplied by the World Data Center A for Solar Terrestrial Physics.

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