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The CM4 model prediction of ground variation of the geomagnetic diurnal field away from quiet time

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ABSTRACT

We analyse the geomagnetic diurnal variation for days away from quiet time to see how well the comprehensive model (CM4) can reasonably predict ground variation of the diurnal field. To do this, we compared ground observatory hourly means to predictions given by the CM4 model for days away from quiet time. Our results show that, away from quiet time, the CM4 model is producing more reasonable predictions than expected, despite the lack of active data in the original model dataset. However, the CM4 model is not doing so well predicting short term features during period of rapid variations, especially for the X component of the geomagnetic diurnal variation field. When comparing the different modelled diurnal variation field maps of the CM4 model and the observatory data, our results show that the model to data fitness increases as we increase the spherical harmonic degrees. From our results we could see that the inability of the CM4 model to accurately predict the geomagnetic diurnal field for days away from quiet time, during time of rapid variations, may be due to the fact that the external field descriptions included in the CM4 model could not sufficiently explain the field contributions for days away from quiet time. This is seen in the low coherence, agreement and correlation in the comparison and cross correlation coefficient between the X component of the observatory data and the D_{st} index (which allows CM4 model to respond to active conditions outside of the original geomagnetic activity remit).

1. Introduction

The Earth's magnetic field shows regular variations having periods of submultiples of a solar day. The quiet-time diurnal variation is one of the most consistent components of the time-varying part of the Earth's magnetic field (Kane, 1976; Lilley et al., 1999). It originates primarily due to electric currents generated within the ionosphere, although components have long been proposed, and have more recently been identified as originating from the Earth's magnetosphere (Maus and Luhr, 2005). Diurnal variations are further influenced by the effects of induction in the solid Earth and oceans (Kuvshinov, 2008), with strong signals particularly seen in equatorial regions, associated with a current running along the dip equator particularly near noon, local time, the equatorial electrojet (EEJ).

The Solar quiet (Sq) diurnal variation is seen in most quiet-time diurnal geomagnetic records. It can be masked or obscured away from quiet time by irregular disturbance variation originating in the outer ionosphere or well outside the ionosphere – the magnetosphere. Measurement of the geomagnetic field taken at the Earth's surface contains superposition of field contributions of different origins – the internal (core, lithosphere) and the external (ionosphere, magnetosphere). Separating these various contributions and the accurate determination of their spatial and temporal structures based on field observations is a significant challenge which requires geomagnetic field modelling techniques. The regular diurnal variations are of external origins and separating them from the internal contributions requires the use of the comprehensive model of Sabaka et al. (2004) or other appropriate models. The basic idea behind the comprehensive model is to co-estimate the major field sources using many different datasets. It uses the 'comprehensive approach' in a joint inversion of ground based and satellite field measurements to co-estimate and describe field contributions from core, lithosphere and external (ionosphere and magnetosphere) fields, along with their associated Earth-induced signals. One strength of the comprehensive model approach is the ability to properly divide the signal among the contributions. CM4 gives a global description of the geomagnetic

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field during quiet time conditions, which it is primarily made for. But due to the regularity of the ionospheric field and the tracking of the ring current and ionospheric amplification by D_{st} and F10.7 respectively, there is a possibility that CM4 may be able to predict diurnal variations and variations with magnetic activity in the external and induced fields.

Over the years, a lot have been learned about many components of the geomagnetic field, particularly the geomagnetic quiet-time (Sq) diurnal variation (Campbell, 1997, 1989), but the diurnal variation for days away from quiet time have not received as much attention. In this paper, we look at the geomagnetic diurnal variation for days away from quiet time. We use spherical harmonic modelling of geomagnetic ground observatory data, with the well-characterised internal and magnetospheric components subtracted from the data, to generate global maps of the residual field at different hours of the day. Lead by the CM4 model, we compared global maps produced by the CM4 model with geomagnetic ground observatory station data to see how well the CM4 can predict the ground variation of the geomagnetic diurnal field. Can the CM4 model reasonably predict ground variation of the diurnal field, or do the data themselves provide real-time constraint?

2. Data and method

The main body of data for this paper consist of hourly mean values in computer reader form from INTERMAGNET database. We use data for moderately magnetic disturbed day (away from quiet time). This is defined as days when the Kp index (used for measuring magnetic activity level) reads Kp $\leqslant$ 5-. Data were taken from over 85 geomagnetic ground observatory stations scattered around the globe. At ground observatory stations, external field variation such as diurnal variation can, to some extent, be argued to average over time. They provide excellent temporal coverage and because recordings are made at a single location, averaging can reduce greatly any zero mean noise (Wardinski and Holme, 2006). The geographical distribution of the data is shown in Fig. 1. As we can see their coverage is far from uniform over the globe. This is inevitable with studies based on geomagnetic ground observatory data, as the Southern hemisphere and the oceans are poorly covered, while there is great density in Europe, and to an extent, North America.

For the field modelling, three components of the magnetic elements, northward (X), eastward (Y) and vertically downward (Z) were compiled for each observatory station data. The method is based on the 'comprehensive approach' in which the major field sources are parameterized and then co-estimated in order to achieve optimal separation of the fields (Sabaka et al., 2002, 2004). We apply version two code of the fourth generation of the

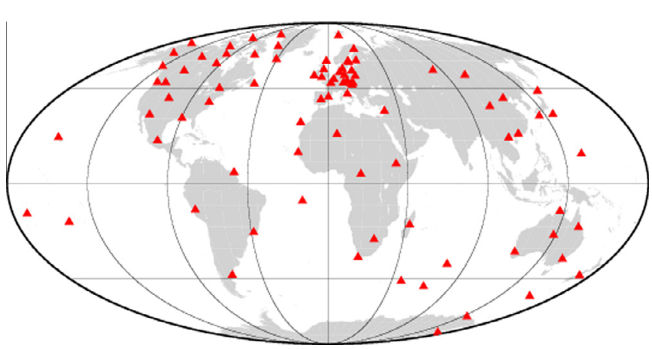

Fig. 1. Locations (red triangles) of the 85 magnetic observatory stations that provided the minutes and hourly-mean measurements used in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

comprehensive model (CM4) (Sabaka et al., 2004) of the geomagnetic field, which helps to separate the field sources into internal and external parts. Since our interest is in the geomagnetic diurnal variations, which primarily originate from external sources, we used CM4 to subtract well characterised internal and magnetospheric components from the data. We then generate signature plots of the data and CM4 model for the different geomagnetic observatory stations, and compared how well CM4 is able to predict the geomagnetic diurnal variation for days away from quiet time.

In an attempt to further investigate and see how well CM4 perform globally, we generated global maps of the diurnal field from the available observatory station data using the CM4 model at different times and spherical harmonic degrees. The CM4 code allows us to generate these models by applying spherical harmonic inverse modelling of the full dataset from all the observatory station data globally inputted. In its simplest form, the CM4 model does the modelling through a three-route process (input, filter and output). The inputs are the time, position and magnetic indices such as D_{st} and F10.7. The outputs are the model predictions to the observatory magnetic field data, and it does the filtering by solving a series of spherical harmonic as in the equation below, using over 16000 such parameters in describing the input data:

$$V(r,\theta,\emptyset) = a\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\tfrac{a}{r}\right)^{n+1}[g_n^m\cos(m\emptyset) + h_n^m\sin(m\emptyset)]\mathrm{P}_n^m(\cos\theta) + a\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\tfrac{r}{a}\right)^{n}[q_n^m\cos(m\emptyset) + s_n^m\sin(m\emptyset)]\mathrm{P}_n^m(\cos\theta) \quad (1)$$

where a = 6371.2 km is a reference radius, P_n^m (cosθ) are the Schmidt semi-normalized associated Legendre functions, g_n^m and h_n^m, and q_n^m and s_n^m are the Gauss spherical harmonic coefficients describing the internal and external sources respectively of degree n and order m.

Below is an itemised summation of the CM4 model approach:

- Inputs – Filter – Output 

- Inputs: time, position, D_{st}, F10.7.
- Output: model prediction to magnetic field data.
- Filter: a series of spherical harmonics

$$\phi = a\sum_{l=1}^{\infty}\left(\frac{a}{r}\right)^{l+1}\sum_{m=0}^{l}P_l^m(\cos\theta)\cdot[g_l^m\cos(m\phi)+h_l^m\sin(m\phi)] \quad \text{— Internal Field}$$
$$+a\sum_{l=1}^{\infty}\left(\frac{r}{a}\right)^{l}\sum_{m=0}^{l}P_l^m(\cos\theta)\cdot[q_l^m\cos(m\phi)+s_l^m\sin(m\phi)] \quad \text{— External Field}$$

- CM4 code uses over 16,000 such parameters to describe the input data.

In the CM4 model, terms in the first part of Eq. (1) (internal) have been retained only up to a degree truncation level, N_{max}, that is justified by the data, or in the case of satellite, up to the degree at which it is believed that the lithospheric field begins to dominate the series (the Main field) taken to be 13 (Langel and Estes, 1982; Sabaka et al., 2002). Spherical harmonic models of the lithospheric fields derived from data with estimates of the main, magnetospheric and ionospheric fields removed, indicates that noise becomes dominant somewhere between N_{max} = 60 and 70 (Ravat et al., 1995). The degree truncation level for the lithospheric field for the CM4 is set at N_{max} = 65 (Sabaka et al., 2002, 2004). For the external field sources, no specific or definite truncation levels were set for the CM4 model. The external field sources, particularly the ionospheric, depend upon solar activity. The influence of solar activity is represented by an amplification factor, assumed to be