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Millennial scale cyclicity in the geodynamo inferred from a dipole tilt reconstruction

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ABSTRACT

Constraining past changes in the strength and configuration of the geomagnetic field provides a valuable perspective on the processes that govern the geodynamo. Here we update a modelled dipole tilt reconstruction for the last 9000 years by using palaeomagnetic records that originate from globally well-distributed sites. Some features predicted by earlier dipole models become more distinct due to added data sets. We identify a dominant 1350-year cycle in the dipole tilt variations and two preferred states of the dipole axis with north geomagnetic pole longitudes confined to either c. 120° West or c. 30° East. The dipole tilt reconstruction is shown to be consistent with independent geomagnetic field intensity data from western Eurasia, which show generally higher intensities when the dipole is tilted towards this region. Our study implies that VADM reconstructions that are constrained by a biased spatial distribution of data can show variations resulting from dipole tilt instead of true dipole moment. The preferred states of the modelled dipole axis can be related to the four semi-stationary high latitude flux lobes that have been observed at the core–mantle boundary in long-term time averaged palaeomagnetic field models. The tilt episodes towards 30° East in the northern hemisphere are perhaps related to the appearance of a high intensity flux lobe beneath western Eurasia. The dipole tilt reconstruction is highly correlated to millennial scale variations in the length of day that have been reconstructed from ancient records of eclipses, which indicates that the cyclicity may constitute an important component in core flow dynamics.

1. Introduction

The current geomagnetic field measured at the Earth's surface comprises a broad spectrum of components that vary on a large range of time scales, but it is dominated by a dipole. Today, the majority of the field can be described by a dipole positioned at the Earth's centre, but tilted about 11° from the rotation axis. Geomagnetic field reconstructions for the last four centuries, which are based on magnetic observatory data and measurements from mariners and magnetic surveys in the earlier parts (Jackson et al., 2000) have provided new views of field variations on longer, decadal to centennial, time scales. According to these reconstructions the last 400 years have been characterised by a clockwise motion of the north geomagnetic pole (NGP), the point on the Earth where the dipole axis intersects the surface of the northern hemisphere, accompanied by a steadily decreasing dipole moment over the last 150 years. On longer time scales studies of the geomagnetic field have to rely on indirect palaeomagnetic data, primarily in the form of natural remanent magnetisations acquired by igneous rocks, archaeological artefacts and sediments.

The accuracy of models constrained by palaeomagnetic data is restricted by the relatively large uncertainties in the data and the limited distribution in both time and space (Donadini et al., 2009; Genevey et al., 2008; Nilsson et al., 2010) and involves some form of compromise between the complexity of the model, the quality and/or spatial and temporal resolution of the data, i.e. less complex models that require fewer records allow for the inclusion of only the highest quality data. Several attempts have been made to build spherical harmonic models constrained by palaeomagnetic data to provide comprehensive descriptions of the geomagnetic field back in time (Hongre et al., 1998; Korte and Constable, 2003, 2005; Korte et al., 2009). Such models require extensive data sets and risk shifting power to higher degree components of the field in order to accommodate for inconsistencies in lower quality data sets (Nilsson et al., 2010; Valet et al., 2008). Alternative geomagnetic field reconstructions with limited complexity (e.g. Genevey et al., 2008; Knudsen et al., 2008; Nilsson et al., 2010; Valet et al., 2008) could potentially provide better representations of the basic components (e.g. the dipole). On the other hand, simpler models conversely risk shifting power to lower degree components and only offer limited insight to the processes within the core that generate the geomagnetic field.

During the last 400 years the geomagnetic field at the core–mantle-boundary (CMB) has been characterised by the presence of four high latitude flux lobes, beneath Canada and Siberia and at approximately symmetric locations south of the equator (Jackson et al., 2000). These nearly stationary features, which are thought to form a major part of the axial dipole field (Gubbins and Bloxham, 1987) also appear in time-averaged geomagnetic field models based on palaeomagnetic data from

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the past 3000–7000 years (Korte and Constable, 2005; Korte and Holme, 2010; Korte et al., 2009) and five million years (Johnson and Constable, 1995; Kelly and Gubbins, 1997). However, in the models that extend more than 3000 years back in time the southern hemisphere flux lobes are not seen clearly, possibly due to the lack of data from the southern hemisphere. In the time averaged models based on palaeomagnetic data there is also evidence for a third, slightly weaker flux lobe in the northern hemisphere beneath Europe (e.g. Johnson and Constable, 1995). These high intensity flux lobes have been proposed to represent the ends of convection rolls into which fluid is spiralling down, dragging field lines with them (Gubbins and Bloxham, 1987). Their preferential locations have been interpreted as evidence of mantle control on the geodynamo, possibly due to lateral differences in the core–mantle heat exchange (Bloxham and Gubbins, 1987; Gubbins et al., 2007).

An independent source of information on core flow dynamics may be presented by the variations in the Earth's rotation rate, recorded as changes in the length of day (LOD). Indirect records of changes in LOD stretch back to 1620 AD and are based on historical observations of the occultation of stars by the Moon and of the transits of Mercury across the Sun's face (Stephenson et al., 1984) and even further back in time to 500 BC through documentary evidence of the location and time of solar and lunar eclipses (Morrison and Stephenson, 2001; Stephenson and Morrison, 1995). Besides long term effects (e.g. tidal dissipation slowing Earth's rotation rate) the LOD records also show decadal to millennial oscillations. These oscillations could tentatively be associated with an exchange of angular momentum between the core and the mantle. While it has been successfully shown that time-dependent azimuthal core flow inferred from historical geomagnetic secular variation can explain decadal changes in LOD (e.g. Jault et al., 1988), it has proven more difficult to explain longer term changes. Attempts have been made to link millennial changes in LOD, oscillating around a frequency of c. 1500 years, with eastward and westward drifts of magnetic field structures in the palaeomagnetic field, including the high latitude flux lobes previously mentioned. However, a detailed match between the inferred core flow models and the LOD record is yet to be achieved (Dumberry and Bloxham, 2006).

In this study we update the dipole estimate constructed by Nilsson et al. (2010) by averaging virtual geomagnetic poles (VGPs) from five strategically located sites. VGPs are often presented to illustrate the position of the NGP and are determined from palaeomagnetic field directions at a given site, by assuming that the geomagnetic field in the past was purely dipolar and geocentric. By including an improved record from South America, an area previously noted for the large inconsistencies between data sets, we are able to more clearly distinguish features; in particular a dominant cyclicity in the dipole tilt, which was not investigated previously. We compare the new dipole tilt record with virtual (axial) dipole moment reconstructions (VDMs/VADMs) and discuss the global significance of these reconstructions. The dipole tilt cyclicity is compared to independent reconstructions of the LOD and the potential implications for the geodynamo are discussed.

2. Dipole tilt reconstructions

An updated dipole estimate covering the last 9000 years was constructed by averaging VGPs from continuous lake sediment palaeomagnetic records chosen according to the criteria defined by Nilsson et al. (2010). Five records were selected from strategic locations around the world: Fish Lake in Western United States (Verosub et al., 1986), Lake Nautajärvi in Finland (Ojala and Saarinen, 2002), Lake Biwa in Japan (Ali et al., 1999), Lake Keilambete in Australia (Barton and McElhinny, 1981) and Lake Escondido in Argentina (Gogorza et al., 1999, 2002). All data, including the additional data from Lake Escondido, were pre-treated in the same way as described by Nilsson et al. (2010).

In an attempt to improve the reliability of the Lake Escondido record, and to extend it back in time, the record from Gogorza et al. (1999) and used by Nilsson et al. (2010), was merged with a newer record from Gogorza et al. (2002). The record from 1999 was originally selected instead of the 2002 record due to the larger number of cores (7 compared to 4) and the continuity of the data (for more details see the Supplementary information — data treatment).

The updated dipole estimate, DE_{FNBKE}, was determined for the time period 9000–600 years BP following the methodology described by Nilsson et al. (2010) (Fig. 1). The subscript abbreviation (FNBKE) refers to the first letter of each lake included in the model. The uncertainty of the dipole estimate depends on three factors: (i) the efficiency of removing non-dipole field influences by averaging VGPs from a limited selection of data, (ii) the error of the palaeomagnetic data and (iii) the accuracy of each time scale. To assess the potential magnitude of errors introduced by the method a set of similar dipole estimates were developed for the last 400 years. We used the predicted magnetic field directions of the gufm.1 geomagnetic field model (Jackson et al., 2000) at five locations with the same coordinates as the sites in DE_{FNBKE} and the addition of a sixth site from South Africa to achieve an approximately equal spatial distribution. The results of six different solutions, removing one record at a time, produced a mean (max) error of 2.1° (4.5°) when compared to the NGPs determined directly from the model (Jackson et al., 2000). Incidentally, the solution with the same configuration as DE_{FNBKE}, shown in Fig. 1, without the data from South Africa produced the largest misfits. The errors of the palaeomagnetic data were assigned according to Donadini et al. (2009) and integrated into the dipole model uncertainty using the method described by Nilsson et al. (2010). In addition, a Jack-knife approach was used to help approximate the variance of DE_{FNBKE} results by removing one record at a time and calculating mean VGPs from the four remaining records.

The uncertainty introduced by relatively small dating errors (± 300 years) within the individual records was investigated with Monte Carlo simulations. Each record was divided into eight consecutive 1000-year time windows covering the period 8600–600 years BP. For each run, out of a total of 500, a new dipole estimate was determined based on separately time-adjusted records, where the data within each time window had been randomly stretched or compressed by up to 300 years. The stretching or compressing was partially restricted by the adjustments made to the neighbouring time-window. In this way we were able to prevent any data point from being shifted by more than 300 years and at the same time preserve a continuous record. In addition, for simplicity the start and end points were kept fixed to 600 and 8600 years BP. The maximum adjustment of ±300 years was chosen arbitrarily, but it is largely within the known uncertainties of the individual chronologies (Fig. 2).

The updated version of DE_{FNBKE} shows generally the same variations as the original (Nilsson et al., 2010) except for two maxima in colatitude (i.e. large dipole tilts) at 7900 and 6750 years BP, which are more pronounced in the new model. As shown by Nilsson et al. (2010) these two peaks also appear in dipole estimates based on data from the northern hemisphere and Australia, which suggest that they were previously smoothed out as a consequence of inconsistencies in the Lake Escondido data from 1999 (Gogorza et al., 1999). The DE_{FNBKE} results also agree fairly well with the dipole components of the CALS7K.2 (Korte and Constable, 2005) and CALS3k.3 (Korte et al., 2009) geomagnetic field models, particularly for the last 4500 years BP, with differences mostly related to the amplitudes of the colatitude variations.

Spectrum analysis of the colatitude variations shows peaks in the power spectra of DE_{FNBKE} and CALS3k.3 at c. 1/1350 years^{-1} and at half the frequency, c. 1/2700 years^{-1}, in CALS7K.2 (Fig. 1b). The apparent cyclical behaviour of the colatitude find its continuation in the colatitude variation of gufm.1 for the last 400 years, (Jackson et al., 2000), illustrated by a sine wave with a wavelength of 1350 years plotted as a dotted line in Fig. 1a. Wavelet analysis shows a strong c. 1350-year cyclicity in the colatitude variation, apart from a period between 6200 and 4400 years BP (Supplementary Fig. 2).