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A simple model for geomagnetic field excursions and inferences for palaeomagnetic observations

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ABSTRACT

We explore simple excursion scenarios by imposing changes on the axial dipole component of the Holocene geomagnetic field model CALS10k.2 and investigate implications for our understanding of palaeomagnetic observations of excursions. Our findings indicate that globally observed directions of fully opposing polarity are only possible when the axial dipole reverses: linearly decaying the axial dipole to zero and then reestablishing it with the same sign produces a global intensity minimum, but does not produce fully reversed directions globally. Reversing the axial dipole term increases the intensity of the geomagnetic field observed at Earth's surface across the mid-point of the excursion, which results in a double-dip intensity structure during the excursion. Only a limited number of palaeomagnetic records of excursions contain such a double-dip intensity structure. Rather, the maximum directional change is coeval with a geomagnetic field intensity minimum.

1. Introduction

Geomagnetic field excursions have occurred numerous times in the geological past (see Laj and Channell, 2007; Roberts, 2008; Singer, 2014). A greater understanding of the range of geomagnetic field behavior exhibited during excursions is essential to a fuller understanding of geodynamo processes and the applicability of excursions as global or regional stratigraphic markers (Merrill and McFadden, 2005). In addition, the strength of the geomagnetic field and its global morphology are important components in the interaction between the geomagnetic field, the palaeomagnetosphere and space climate (Constable and Korte, 2006; Vogt et al., 2007; Stadelmann et al., 2010), the production of cosmogenic radionuclides (e.g., Baumgartner et al., 1998; Wagner et al., 2000; McCracken, 2004; Muscheler et al., 2005) and may influence atmospheric chemistry and dynamics (Suter et al., 2014).

A combination of palaeomagnetic observations, empirical modeling and numerical dynamo simulations are bringing us closer to understanding the possible range of excursion characteristics and their underlying physical mechanisms. Despite this progress, the surface field morphology and the physical origin of excursions remain unclear. Although significant advances have been made in determining the age, duration and global character of excursions from volcanic rocks (e.g., Jicha et al., 2011; Laj et al., 2014; Singer, 2014) and sediments (e.g., Laj et al., 2006; Channell et al., 2012; Channell, 2014; Nowaczyk et al., 2012, 2013), sparse spatial coverage, age uncertainties, and the fidelity of palaeomagnetic records hinder our understanding of the global behavior of excursions.

Recently, progress has been made in empirical modeling of the global geomagnetic field at the core-mantle boundary during specific excursions (Lanci et al., 2008; Leonhardt et al., 2009); however, the low number of high-resolution sediment records available at the time of model construction restricted firm conclusions on geodynamo processes that may generate excursions. Numerical dynamo simulations allow the physical mechanisms behind excursions to be explored (e.g., Coe et al., 2000; Busse and Smitiev, 2008; Wicht, 2005; Wicht and Meduri, 2015) and a variety of scenarios for excursion initiation have been proposed (see reviews by Coe et al., 2000; Wicht et al., 2009; Amit et al., 2010); however, it is unclear which parameters are of direct relevance to Earth.

Following from earlier work (Brown et al., 2007; Valet and Plenier, 2008; Valet et al., 2008), we take a complementary approach and generate 'toy' excursions by manipulating the axial dipole term within a model of the Holocene geomagnetic field (CALS10k.2, see Appendix A). The justification and assumptions of this approach are discussed in Brown et al. (2007) and Valet and Plenier (2008). Here we highlight certain characteristics of the global geomagnetic field that may occur during excursions

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and that should be considered when interpreting the global uniformity and timing of excursional field structures. Compared with Brown et al. (2007) we focus solely on excursions and use a set of geometrically simple scenarios (Section 2) to assess the complexity of field variations produced at Earth's surface. The results of the excursion scenarios are described in Section 3 and are compared with palaeomagnetic observations in Section 4.

2. Method

Excursions were generated by manipulating the axial dipole coefficient (g_1^0) of CALS10k.2 (see Appendix A); a time-varying global spherical harmonic model of secular variation for the past 10 ka. Compared with Brown et al. (2007), where the character of excursions was explored by scaling g_1^0 by a constant for the duration of the model, here we scale g_1^0 linearly through time to investigate the possible influence of large changes in g_1^0 on the surface field morphology during excursions. This approach is akin to Valet et al. (2008).

From 8000 BC ($t_1 = -8000$) to 3005 BC ($t_2 = -3005$)

$$g_1^0(t)_{scaled} = g_1^0(t)\left(1 - (1-\alpha)\left(\frac{t-t_1}{t_2-t_1}\right)\right), \tag{1}$$

and between 3005 BC (t_2) and 1990 AD ($t_3 = 1990$)

$$g_1^0(t)_{scaled} = \alpha g_1^0(t_2) + g_1^0(t)(1-\alpha)\left(\frac{t-t_2}{t_3-t_2}\right), \tag{2}$$

where t is time and α sets the scaling value at 3005 BC (the midpoint of the excursion). We primarily consider four scenarios where α is 0.5, 0, −0.5, −1.0 (Fig. 1a). When $\alpha = 0$ there is no axial dipole at the midpoint of the excursion and when $\alpha = -1.0$ the axial dipole is fully reversed at the midpoint of the excursion. In addition, to test the sensitivity of the surface field morphology to small reversed g_1^0 contributions we consider three cases from Valet et al. (2008), where α is −0.1, −0.15, −0.2, with an extra case, $\alpha = -0.05$. In reality the axial dipole component may be more variable during an excursion than our linear scaling produces (Fig. 1b); however, the above scenarios will highlight complex temporal and spatial geomagnetic field variations for even simple variations in g_1^0.

CALS10k.2 provides a reasonable description of secular variation for a duration similar to that over which the total excursion process may occur (incorporating both directional and intensity changes). Estimates of the duration of the directional changes associated with excursions range from 300 years to 10 ka (see Roberts, 2008). Nowaczyk et al. (2012) estimated that major directional changes of the Laschamp excursion recorded in rapidly deposited sediments from the Black Sea lasted ~1200 years. However, it is important to note that intensity variations that bound the major directional changes during excursions have frequently been shown to have a longer duration (Laj and Channell, 2007). Although it is not straightforward to delimit cut-offs for the start and end of the intensity changes associated with the Laschamp excursion, the initial drop in intensity preceding the major directional change lasted ~8–10 ka, with a more rapid decrease in intensity to its minimum occurring over ~3 ka (Laj et al., 2014). These are timescales comparable with the scenarios explored here.

We note that the imperfections of CALS10k.2 will be translated into our excursion models. There are sufficient data to represent the large-scale geomagnetic field globally over the Holocene (Korte et al., 2011), but detailed features cannot be resolved. In particular, large areas of the southern hemisphere are less well constrained than the northern hemisphere as a result of sparser data coverage in the southern hemisphere (Brown et al., 2015a, b). Temporally, the resolution of CALS10k.2 is lower than for historical field models (Jackson et al., 2000) and the recent field (e.g., Lesur et al., 2010). CALS10k.2 will under-represent the temporal variability and magnitude of secular variation in our excursion scenarios. However, most data concerning temporal geomagnetic field evolution during excursions are from sediments, which smooth the geomagnetic signal to some degree depending on their sedimentation rate (e.g., Roberts and Winklhofer, 2004; Merrill and McFadden, 2005), and as sediments are used in CALS10k.2, the resolution of the excursion scenarios presented in this paper may be similar to what we can expect to recover from sediments.

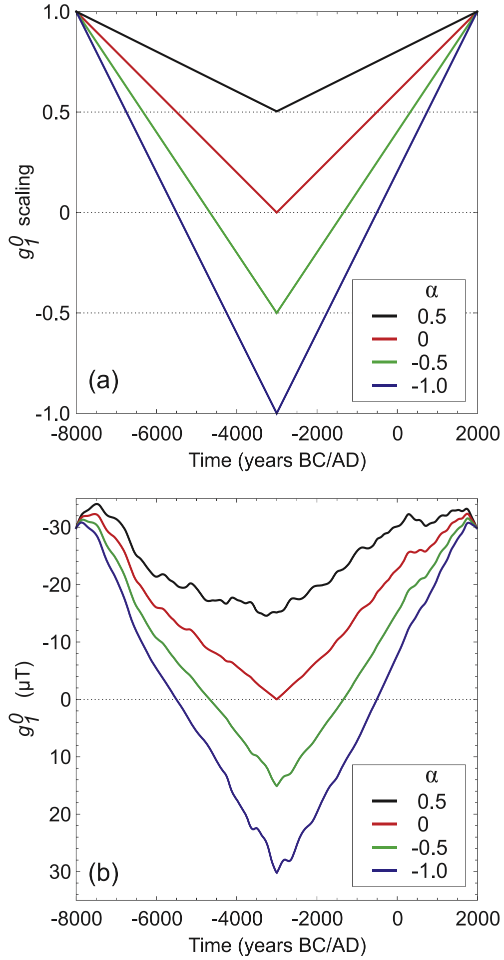

Fig. 1. (a) Scaling of g_1^0 through time for the four main excursion scenarios considered in this study, where α is the scaling of the magnitude of g_1^0 at the midpoint of the excursion. (b) Result of the scaling of (a) on the magnitude of g_1^0 from CALS10k.2.

Other time-varying Holocene geomagnetic field models have recently been developed and the outcomes of our excursion scenarios are similar when models pfm9k.1a (Nilsson et al., 2014) or HFM.OL1.A1 (Panovska et al., 2015) are considered. For simplicity we choose to show the results from CALS10k.2 only. We use the standard palaeomagnetic conventions of the virtual geomagnetic pole (VGP) latitude and the virtual axial dipole moment (VADM) to compare directional and intensity variations globally (see Tauxe, 2010).

3. Excursion model characteristics

Our excursion scenarios produce a range of spatial and temporal variability on both global and regional scales depending on the degree to which the axial dipole was reversed. We show the variability of VADM and VGP latitude through time for five globally