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Insights from geodynamo simulations into long-term geomagnetic field behaviour

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ABSTRACT

Detailed knowledge of the long-term spatial configuration and temporal variability of the geomagnetic field is lacking because of insufficient data for times prior to 10 ka. We use realisations from suitable numerical simulations to investigate three important questions about stability of the geodynamo process: is the present field representative of the past field; does a time-averaged field actually exist; and, supposing it exists, how long is needed to define such a field. Numerical geodynamo simulations are initially selected to meet existing criteria for morphological similarity to the observed magnetic field. A further criterion is introduced to evaluate similarity of long-term temporal variations. Allowing for reasonable uncertainties in the observations, observed and synthetic axial dipole moment frequency spectra for time series of order a million years in length should be fit by the same power law model. This leads us to identify diffusion time as the appropriate time scaling for such comparisons. In almost all simulations, intervals considered to have good morphological agreement between synthetic and observed field are shorter than those of poor agreement. The time needed to obtain a converged estimate of the time-averaged field was found to be comparable to the length of the simulation, even in non-reversing models, suggesting that periods of stable polarity spanning many magnetic diffusion times are needed to obtain robust estimates of the mean dipole field. Long term field variations are almost entirely attributable to the axial dipole; nonzonal components converge to long-term average values on relatively short timescales (15–20 kyr). In all simulations, the time-averaged spatial power spectrum is characterised by a zigzag pattern as a function of spherical harmonic degree, with relatively higher power in odd degrees than in even degrees. We suggest that long-term spatial characteristics of the observed field may emerge on averaging times that are within reach for the next generation of global time-varying paleomagnetic field models.

1. Introduction

Earth's magnetic field of internal origin displays temporal variations spanning a vast range of frequencies (Constable and Johnson, 2005; Korte and Constable, 2006). The field can change quickly as evidenced by so-called geomagnetic jerks, abrupt changes manifest on <1 yr timescales (Malin and Hodder, 1982; Alexandrescu et al., 1995), and the more moderate but still rather rapid archeomagnetic jerks seen on centennial timescales (Gallet et al., 2009). At the other extreme, changes associated with geomagnetic excursions and polarity reversals generally occur a few times every million years (Cande and Kent, 1992, 1995; Glatzmaier and Coe, 2007), but the time taken for such changes (hundreds to thousands of years) remain a matter of some debate. Global time-dependent models of the magnetic field at the core–mantle boundary (CMB) now span the past 10 yr (e.g. Olsen et al., 2010), 400 yr (Jackson et al., 2000), 3 kyr (Korte and Constable, 2011), 7 kyr (Korte and Constable, 2005), and 10 kyr (Korte et al., 2011) and display common features such as a predominantly dipolar field, weak flux near the geographic poles, and intense patches of magnetic flux at high latitudes. These models have enabled significant advances in understanding the geodynamo process.

On timescales longer than 10 kyr there are not yet any time-varying global models of the same quality as for the Holocene time interval, although there is some progress in this area. High-quality data have generally been confined to the dipole moment (Valet et al., 2005; Ziegler et al., 2011), with time-series spanning the past 2 Myr, and detailed well-dated directional data at a few sparse locations such as Hawaii and Réunion Island (e.g. Laj et al., 2011); for the longest periods, only the geomagnetic polarity timescale

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(Cande and Kent, 1992, 1995) is well documented. As a consequence, fundamental questions about the long-term behaviour of the geomagnetic field remain unanswered. For example, it is not yet known if the modern field is representative of the past field, which is important for elucidating the role of external forcings on the geodynamo (Biggin et al., 2012), or how the field structure changes as it is averaged over successively longer periods. Does a time-averaged field exist, such that when averaged over sufficient time there are no significant changes upon further temporal averaging? If so, what is the structure of this field and how long a time-series is needed to observe it? Additional information is needed to answer these questions. This paper explores them using numerical geodynamo simulations and comparisons with available paleofield models.

We consider geodynamo simulations as useful tools for investigating long-term field behaviour for three reasons. Firstly, they have recovered prominent features of the modern and paleomagnetic fields (e.g. Olson and Christensen, 2002; Coe and Glatzmaier, 2006; Gubbins et al., 2007; Bloxham, 2000; Christensen and Olson, 2003; McMillan et al., 2001; Davies et al., 2008). Secondly, they provide a global representation of the magnetic field at each time point, achieving a spatial resolution that is much higher than in observational field models. Finally, high resolution simulations can be run on long timescales, providing a detailed picture of long-term processes. However, simulations cannot yet be run with the rapid rotation rates and low diffusivities associated with Earth's core, and reaching this goal in the near future seems unlikely (Glatzmaier, 2002; Davies et al., 2011). These parameters determine the balance of forces, affecting the dynamics in the simulation and the spatio-temporal characteristics of the generated magnetic fields. Indeed, a variety of field morphologies have been obtained (Kutzner and Christensen, 2002; Olson and Christensen, 2006), which raises the question of how to decide if a given simulation exhibits "Earth-like" behaviour.

Previous studies have quantified the level of agreement between synthetic and observed fields using measures based on properties of the observed field (Dormy et al., 2000; Kono and Roberts, 2002). Christensen et al. (2010) made significant progress in this regard by defining "Earth-like" behaviour based on four quantities, derived from global field models, that characterise the spatial structure of the field. The defined criteria require that the misfits between synthetic and observed values of the four quantities fall below given tolerances; a simulation that meets the criteria is considered to be morphologically similar to the observed field. We use these definitions to select dynamo simulations that are suitable for further study.

For the long (>10 kyr) timescales of interest in this paper we require one further criterion that measures the agreement between temporal variations in synthetic and observed fields. We use the axial dipole moment as a measure of global changes in the field and do not include further complexities. Several time-dependent models are available (Constable and Johnson, 2005; Valet et al., 2005; Ziegler et al., 2011), but we focus on the more recent 2 Myr model PADM2M of Ziegler et al. (2011). Ziegler et al. (2011) have already established that the power spectral density for PADM2M is compatible with that from Sint-2000 (Valet et al., 2005), and Ziegler and Constable (2011) indicate that the spectrum falls off at a rate of about $f^{-7/3}$, where f is frequency, for PADM2M above a corner frequency of about 10 Myr^{-1} in agreement with falloff rate observed in some dynamo simulations. We build a power law fit to the frequency spectrum of PADM2M and require that observed and synthetic axial dipole moment spectra can be fit by the same power law model, within appropriate uncertainty levels for the observations. Simulations that meet this criterion are considered to exhibit temporal variations similar to the PADM2M model.

This paper is organised as follows. In Section 2 we describe the observational and numerical models used in this study. In Section 3 we first discuss the problem of scaling dimensionless model time into dimensional units and select two plausible time scalings based on intrinsic timescales of the magnetic field. We then compare morphological properties of the simulations with global field models using the criteria of Christensen et al. (2010) in Section 3.1, and temporal variations exhibited by the simulations with the observed axial dipole moment variation in Section 3.2. In Section 4 we use simulations that meet all criteria to investigate the length of time required to obtain the mean observed and synthetic axial dipole fields. We also investigate how the synthetic fields change when averaged over successively longer periods. Discussion and conclusions are presented in Section 5.

2. Models

2.1. Global field models

We use three time-varying representations of the geomagnetic field: the 400 yr historical model gufm1 (Jackson et al., 2000), the 3 kyr model CALS3k.4b (Korte and Constable, 2011), and the 2 Myr model for axial dipole moment variations PADM2M (Ziegler et al., 2011). gufm1 and CALS3k.4b are constructed by expanding the spatial dependence of the magnetic field **B** in spherical harmonics and the temporal dependence of **B** in cubic B-splines. These models are regularised in space and time and for the most recent portion of CALS3k.4b departures from the gufm1 model are penalised. It should be noted that the quality of the paleomagnetic models derived for millennial time scales is vastly inferior to that of gufm1. This is a direct consequence of poor data coverage in the southern hemisphere, and lower accuracy in the data. Detailed descriptions of the methods and inversion strategy used to construct the global models are given in Bloxham and Jackson (1992), Jackson et al. (2000), Korte and Constable (2003, 2008, 2011) and Constable (2011). For longer time periods we use PADM2M which again uses cubic B-splines for temporal dependence but only aims to model variations in axial dipole moment. A complete description of PADM2M is given in Ziegler et al. (2011).

2.2. Geodynamo models

The model setup and solution method for our convection-driven dynamo models is standard and only a brief description is given here. An incompressible, electrically conducting Boussinesq fluid with constant thermal diffusivity κ, constant coefficient of thermal expansion α, constant viscosity ν, and constant magnetic diffusivity η is contained in a spherical shell of thickness $d = r_o - r_i$ and aspect ratio $r_i/r_o = 0.35$ rotating at a rate Ω. Here, r_i corresponds to the inner boundary and r_o to the outer boundary. The nondimensional parameters are the Ekman number E, the Prandtl number Pr, the magnetic Prandtl number Pm, and the Rayleigh number Ra given by

$$E = \frac{\nu}{2\Omega d^2}, \qquad Pr = \frac{\nu}{\kappa}, \qquad Pm = \frac{\nu}{\eta}, \qquad Ra = \frac{\alpha g \beta d^4}{\nu\kappa}, \qquad (1)$$

where g is gravity and β is the temperature gradient at the outer boundary.

The parameter values used in this study are summarised in Table 1. Some of these models have been reported before (Davies et al., 2008; Davies and Gubbins, 2011) and some are new. All simulations employ a no-slip outer boundary that is electrically insulating with the heat-flux fixed. On the inner boundary a no-slip condition is imposed in all models, while both conducting and insulating magnetic boundary conditions and temperature and