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Detecting thermal boundary control in surface flows from numerical dynamos

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Abstract

The geomagnetic field and secular variation exhibit asymmetrical spatial features which are possibly originating from an heterogeneous thermal control of the Earth's lower mantle on the core. The identification of this control in magnetic data is subject to several difficulties, some of which can be alleviated by the use of core surface flow models. Using numerical dynamos driven by heterogeneous boundary heat flux, we confirm that within the parameter space accessible to simulations, time average surface flows obey a simple thermal wind equilibrium between the Coriolis and buoyancy forces, the Lorentz, inertial and viscous forces playing only a secondary role, even for Elsasser numbers significantly larger than 1. Furthermore, we average the models over the duration of three vortex turnovers, and correlate them with a longer time average which fully reveals the signature of boundary heterogeneity. This allows us to quantify the possibility of observing mantle control in core surface flows averaged over a short time period. A scaling analysis is performed in order to apply the results to the Earth's core. We find that three vortex turnovers could represent between 100 and 360 years of Earth time, and that the heat flux heterogeneity at the core-mantle boundary could be large enough to yield an observable signature of thermal mantle control in a time average core surface flow within reach of the available geomagnetic data.

Keywords: Earth; Core; Dynamo; Geodynamo; Flows; Geomagnetism; Mantle; Thermal; Control; Coupling

1. Introduction

Over the last two decades many studies have been carried out to investigate possible intrinsically asymmetric spatial properties within the Earth's magnetic field. On the historical time scale, the secular variation (SV) of this field is quite heterogeneous (e.g. Bloxham and Gubbins, 1985; Jackson et al., 2000; Hulot et al., 2002), with a more active Atlantic hemisphere and a quieter Pacific hemisphere, and magnetic flux patches seemingly locked at remarkably stable spatial positions (Bloxham, 2002). It has also been suggested that the time average paleomagnetic (Gubbins and Kelly, 1993; Johnson and Constable, 1995) and archeomagnetic (Constable et al., 2000; Korte et al., 2005) fields show similar departures from axisymmetry as the modern historical field, although the robustness of such conclusions has been questioned by several authors (McElhinny et al., 1996; Carlut and Courtillot, 1998; Hongre et al., 1998) and is indeed difficult to assess without appropriate statistical tools (Hulot and Bouligand, 2005; Bouligand et al., 2005; Khokhlov et al., 2006).

The physical properties of the Earth's liquid core are however spatially homogeneous, and were the

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core-mantle boundary to impose homogeneous boundary conditions, no symmetry-breaking properties should arise in the time average behavior of the magnetic field created by the geodynamo, except possibly equatorial symmetry breaking properties which may arise spontaneously (Hulot and Bouligand, 2005; Bouligand et al., 2005). It is, therefore, generally thought that a longitudinal asymmetric signature within the geomagnetic field should reflect some spatially heterogeneous coupling at the CMB. Various coupling mechanisms have been proposed. Thermal control by the mantle, however, remains the most obvious and has indeed received much attention in the last decades (see for instance Hide, 1970; Jones, 1977; Bloxham and Gubbins, 1987). Given typical fluid velocities and heat diffusion constants at the base of the mantle, local temperature heterogeneities are likely to remain for millions of years, i.e. much longer than any time scale of core dynamics. Seen from the mantle, the rapidly mixed core is an isothermal boundary. Temperature anomalies in the mantle therefore translate into heat-flow anomalies (a colder mantle extracting more heat from the isothermal core). Since heat flow is continuous at the CMB, the core then "sees" the mantle as prescribing a steady and heterogeneous heat flow boundary condition.

Several difficulties hamper the identification of thermal mantle control in geomagnetic data. First, the signature of boundary heterogeneity is best seen when considering time averages (for instance Olson and Christensen, 2002; Bouligand et al., 2005) because transients usually mask the signal. Unfortunately, the needed averaging time is likely longer than the available geomagnetic time series. Autocorrelation functions of the geomagnetic field (Hulot and Le Mouël, 1994; Le Huy et al., 2000) indicate indeed that the signal loses memory of itself (a necessary condition for the removal of transients) on times of the order of several hundreds of years. A second difficulty is associated with the magnetic signature of thermal mantle control itself. Numerical dynamo models with heterogeneous heat flow at the outer boundary have shown that departures from the geocentric axial dipole are weak (Olson and Christensen, 2002) and difficult to distinguish from the statistical noise (Bouligand et al., 2005). The secular variation provides a clearer signature (Christensen and Olson, 2003) but it is difficult to formulate a simple theoretical link with the structure of boundary heterogeneity.

Core flows can be inverted at the core-mantle boundary (CMB) of the Earth from the historical magnetic field and SV observations (recently Hulot et al., 2002; Amit and Olson, 2004). Summarizing all the available information into a fluid dynamical framework, they tend to suffer less from the difficulties mentioned above. Their autocorrelation time is shorter (Le Huy et al., 2000), because the advection of momentum is much more turbulent than the advection of the magnetic field, as a result of the large ratio of magnetic diffusivity to viscosity in the Earth's core. Furthermore, a simple thermal wind theory is expected to connect them with CMB heat flow heterogeneities (Bloxham and Gubbins, 1987; Bloxham and Jackson, 1990), although questions remain concerning the role of the Lorentz force, which will be addressed in the present study. Finally, they preserve the spatial asymmetry of the original data (Amit and Olson, 2006): the Atlantic/Pacific dichotomy, as well as stable vortices (specifically in the southern hemisphere). In addition heterogeneity is also present between the northern and southern hemispheres, with significant westward drift at mid-latitude of the southern hemisphere but nearly no drift at mid-latitude of the northern hemisphere (Pais and Hulot, 2000; Amit and Olson, 2006). In this line of work, several studies compared core flows models with the time average outcome of numerical convection models driven by heterogeneous thermal boundary conditions, especially focusing on the interaction of convection structures with the boundary heat flow pattern (Zhang and Gubbins, 1992, 1993; Gibbons and Gubbins, 2000).

Previous studies have shown that core flows also need time-averaging to reveal the mantle signature. A central question remains: how long should the time-average be in order to remove enough of the transients? We anticipate that this should be shorter than for the magnetic field, and the first goal of the present study is precisely to assess this. Amit and Olson (2006) used the historical geomagnetic SV data to infer a time-average flow model for the period 1840–1990. Is such an averaging interval enough to reveal the core flow driven by boundary heterogeneity? To address this question we focus on self-consistent numerical models of convective dynamo action with heterogeneous boundary heat flow, and produce two types of flows: snapshots, and averages over intermediate intervals which we argue would cover 100–360 years of real Earth time once properly rescaled. These flows are compared to the actual steady flow computed by averaging over the entire simulation time. A statistical analysis of the correlation coefficient between the intermediate flows and the steady flow then provides us with a quantitative way to assess the likeliness of revealing mantle control in time-average core surface flows. This study also provides an opportunity to investigate core surface fluid flows, in very much the same way as Olson and Christensen (2002) investigated the magnetic field. Finally it makes it possible to discuss more quantitatively the possibility that certain robust fea-