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Can downwelling at the top of the Earth's core be detected in the geomagnetic secular variation?

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ABSTRACT

It has been argued based on recent seismic and mineral physics studies that the top of Earth's liquid outer core is stably stratified. Here I analyze persistent geomagnetic secular variation features on the core–mantle boundary to examine whether a kinematic signature of core fluid upwelling/downwelling can be detected. I focus on regions of intense high-latitude geomagnetic flux patches that may be maintained by fluid downwelling. In order to identify persistent patterns, the radial field and its secular variation are stacked in the flux patch moving reference frame. These stacked images are compared with forward solutions to the radial induction equation based on idealized field-flow models. Clear advective secular variation signature below North America indicates that these intense flux patches may exhibit significant mobility. Stretching signature in the form of persistent positive secular variation correlated with the intense flux patch below the Southern Indian Ocean may be considered as regional scale geomagnetic evidence for whole core convection, although pure toroidal flow cannot be outruled.

1. Introduction

The geomagnetic field is generated by dynamo action driven by convection in Earth's liquid metallic outer core. The style of convection is in general thermochemical - secular cooling drives thermal convection, whereas light element release by the freezing inner core drives compositional convection (e.g. Olson, 2007). Uncertainties in the precise adiabatic temperature profile in the outer core and in the magnitude of the heat flux across the core–mantle boundary (CMB) pose uncertainty on whether the present day convection in the outer core has any significant thermal contribution, in particular at the top of the core (e.g. Lay et al., 2008). Recent seismic studies (Helffrich and Kaneshima, 2010) and new estimates of large core thermal and electrical conductivities from mineral physics calculations (Pozzo et al., 2012; Vlcek et al., 2012) indeed suggest that the top of the core is stably stratified (Gubbins and Davies, 2013).

Can time-dependent geomagnetic field models help elucidate whether upwelling/downwelling prevail at the top of the core? Two approaches have been employed so far to address this question. On global scale, core flow inversions may be used to reveal whether poloidal flow is required to explain the observed geomagnetic secular variation (SV). Pure toroidal core flow models consistent with stable stratification at the top of the core (Gubbins, 1982; Bloxham, 1989, 1992; Holme and Olsen, 2006; Olsen and Mandea, 2008) showed that it is possible to fit (to a certain level) the observed SV without magnetic field stretching. However, because of the severe non-uniqueness associated with core flow inversions (Bloxham and Jackson, 1991; Holme, 2007), explaining the SV with pure toroidal flow cannot be considered as a proof for the non-existence of upwelling. For example, Rau et al. (2000) have demonstrated using synthetic data from numerical dynamos that both pure toroidal and tangential geostrophic flows may explain the SV. Even if upwelling is permitted, most core flow models are dominantly toroidal (see Finlay and Amit, 2011, and references therein). Nevertheless, Whaler, 1986 argued that a poloidal flow contribution is needed to adequately explain the SV, and moreover, it is even possible to recover the observed SV with a pure poloidal flow (Beggan and Whaler, 2008). Overall, the observed SV may constrain the dominant toroidal core flow component, while the coupling between toroidal and poloidal flows, and hence the upwelling existence and pattern, largely depend on the apriori physical assumption that is incorporated in the inversions.

Another approach to examine the existence of upwelling just below the CMB is pointwise, i.e. to evaluate the geomagnetic SV at radial field extreme points. At these special points the radial field horizontal gradient is zero, so no SV is generated by advection. Under the frozen-flux approximation (Roberts and Scott, 1965), the only remaining effect that may produce SV at these points is magnetic field stretching by upwelling. Whaler (1980) argued that

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relatively weak SV at extreme points suggests no upwelling and stable stratification at the top of the core. However, uncertainties in the precise locations of these extreme points render such an analysis unreliable (Whaler and Holme, 2007).

Here I propose to analyze geomagnetic SV on a regional scale rather than global (core flow inversions) or pointwise (extreme radial field points). In particular, I focus on regions of intense geomagnetic flux patches. These robust features are present in geomagnetic field models spanning various timescales (Kelly and Gubbins, 1997; Jackson et al., 2000; Korte et al., 2009). Numerical dynamos reproduce well the observed high-latitude intense flux patches (e.g. Christensen et al., 2010). In these simulations the origin of intense flux patches on the outer boundary is fluid downwelling at the top of the core that concentrates field lines (Christensen et al., 1998; Olson and Christensen, 2002; Amit et al., 2010). The time-average locations of these correlated fluid downwelling and magnetic flux patches are prescribed by lower mantle thermal heterogeneity (e.g. Gubbins, 2003) although on a snapshot the patches may be found elsewhere (Bloxham, 2002; Amit et al., 2010). Directly related to a thermal mantle anomaly or not, the kinematic relation between concentrated flux and fluid downwelling is expected from the stretching term in the radial magnetic induction equation.

In this paper I search for a downwelling signature in the SV at regions of intense geomagnetic flux patches. I stack SV images in the patch moving reference frame to reveal the persistent nature of the regional field variation. Stacked SV patterns are interpreted by comparison with some idealized SV patterns produced by forward solutions to the radial induction equation. These forward solutions rely on idealized field and flow models, which are based on some simple inferences from geomagnetic observations, rotating flows theory and numerical dynamo simulations.

Previous analyses of regional geomagnetic SV focused on the north polar region. Olson and Aurnou (1999) inverted the time-average radial geomagnetic field and SV at this region for the axisymmetric steady core flow. They found a persistent westward (anticyclonic) polar vortex and fluid upwelling inside the northern hemisphere tangent cylinder. Chulliat et al. (2010) observed a bipolar SV structure centered at an emerging reversed flux patch at the north polar region, which they interpreted as the signature of upwelling and magnetic flux expulsion by radial diffusion.

As mentioned above, in this study radial field and SV images are stacked to obtain time-averages in a patch moving reference frame. Stacking is common practice in seismology. Seismograms of many earthquakes are ordered in distance and plotted vs. travel-time to reduce random noise, resulting in coherent travel-time branches which represent different seismic waves traveling through the Earth's interior (e.g. Shearer, 1991; Lay and Wallace, 1995). In paleomagnetism, stacking was recently applied to find dynamic similarity of polarity reversals. By stacking the ten most detailed volcanic records and assuming same reversal duration, Valet et al. (2012) found that the reversal process includes three steps, a precursory event, the polarity transition and the rebound, each step characterized by the same time constant.

The paper is outlined as follows. In Section 2 the stacking and forward solution methods are described. The idealized field and flow models that are used to obtain forward solutions of the radial induction equation at the top of the core are introduced. In Section 3 the results of the stacked geomagnetic field and SV images are presented and compared with the idealized SV from the forward solutions. A snapshot from a recent geomagnetic field model derived from satellite and surface observatories data is also considered. In Section 4 the results are discussed, in particular their implications for the possibility of stable stratification at the top of the core.

2. Method

2.1. Stacking at regions of intense flux patches

I use the historical geomagnetic field model *gufm1* of Jackson et al. (2000) for the period 1840–1990. The centers of intense high-latitudes flux patches are taken from the timeseries obtained by Amit et al. (2011). The two northern hemisphere patches are classified as intense throughout the entire period 1840–1990, whereas in the southern hemisphere in some years only one patch is classified as intense.

At each snapshot, around a center of patch a fixed longitudinal and latitudinal range is considered. Next, a rotational transformation about the center of a patch is performed based on its orientation with respect to the center of the same patch in the previous snapshot. The pole of the initial snapshot is arbitrarily set to the north geographic pole. The rotational angle at time t_i is then defined by the angle between the centers of patches at times t_i and t_{i-1} and the westward direction. Defined this way, if a patch is only drifting without changing its shape (but in time-dependent directions), the stacked SV will show a bipolar pair oriented in the east–west direction. Any deviation from such pattern indicates the action of other kinematic processes. For more details on the rotational transformation see the Appendix.

To illustrate the importance of applying a rotational transformation, in particular for obtaining meaningful stacked SV patterns, consider a patch drifting and completing a full circle. The SV pattern at each snapshot will exhibit a bipolar structure. However, if only a translational transformation is performed, the bipolar SV will change its orientation with time encompassing all angles of

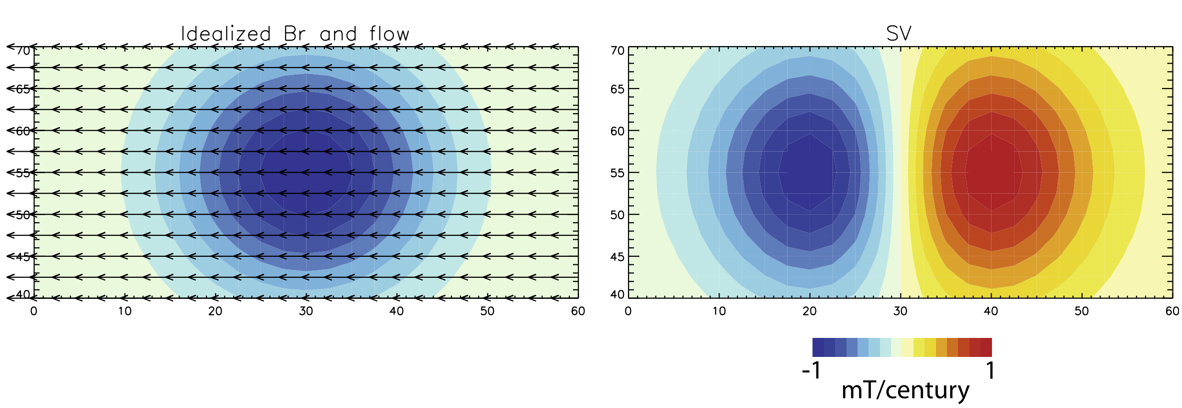

Fig. 1. Idealized translation. Left: Vertical field (colors) and horizontal flow (arrows); Right: SV. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)