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The observational signature of modelled torsional waves and comparison to geomagnetic jerks

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ABSTRACT

Torsional Alfvén waves involve the interaction of zonal fluid flow and the ambient magnetic field in the core. Consequently, they perturb the background magnetic field and induce a secondary magnetic field. Using a steady background magnetic field from observationally constrained field models and azimuthal velocities from torsional wave forward models, we solve an induction equation for the wave-induced secular variation (SV). We construct time series and maps of wave-induced SV and investigate how previously identified propagation characteristics manifest in the magnetic signals, and whether our modelled travelling torsional waves are capable of producing signals that resemble jerks in terms of amplitude and timescale. Fast torsional waves with amplitudes and timescales consistent with a recent study of the 6 yr ΔLOD signal induce very rapid, small (maximum ~2 nT/yr at Earth's surface) SV signals that would likely be difficult to be resolve in observations of Earth's SV. Slow torsional waves with amplitudes and timescales consistent with other studies produce larger SV signals that reach amplitudes of ~20 nT/yr at Earth's surface. We applied a two-part linear regression jerk detection method to the SV induced by slow torsional waves, using the same parameters as used on real SV, which identified several synthetic jerk events. As the local magnetic field morphology dictates which regions are sensitive to zonal core flow, and not all regions are sensitive at the same time, the modelled waves generally produce synthetic jerks that are observed on regional scales and occur in a single SV component. However, high wave amplitudes during reflection from the stress-free CMB induce large-scale SV signals in all components, which results in a global contemporaneous jerk event such as that observed in 1969. In general, the identified events are periodic due to waves passing beneath locations at fixed intervals and the SV signals are smoothly varying. These smooth signals are more consistent with the geomagnetic jerks envisaged by Demetrescu and Dobrica than the sharp 'V' shapes that are typically associated with geomagnetic jerks.

1. Introduction

Satellite and ground-based observations show that temporal fluctuations in the geomagnetic field occur on a wide range of time scales, from daily interactions with the ionosphere to the millions of years between polarity reversals. Most changes at approximately annual to centennial timescales, called secular variation (SV), is associated with the geodynamo, the process that generates a large-scale self-sustaining magnetic field from fluid motion inside Earth's outer core (Larmor, 1919; Elsasser, 1946). However, progress in understanding the dynamics of Earth's core, and the associated signals in the geomagnetic field, is hindered by the fact that the core is too remote to be probed directly and that numerical dynamo simulations are unable to reach the relevant parameter regime due to computational limitations (Davies et al., 2011; King and Buffett, 2013). The most rapid observed feature of the core-generated magnetic field are geomagnetic jerks. These are abrupt jumps in the second time-derivative (secular acceleration, SA) of Earth's magnetic field, which correspond to sharp changes in the trend of the first time-derivative of the magnetic field (SV) (Courtillot et al., 1978; Mandea et al., 2010). Jerks separate periods of almost steady SA so that the SV appears as a series of straight-line segments separated by the jerk itself, see Fig. 1 for several examples of jerks in the East (Y) component of SV at four European observatories. Several jerks are known to have occurred in the twentieth and twenty first centuries, including those in 1969 (Courtillot et al., 1978; Malin et al., 1983; Whaler, 1987), 1978 (Gubbins and Tomlinson, 1986; Davis and Whaler, 1997), 1991 (Macmillan, 1996), 1999 (Mandea et al., 2000) and 2003 (Olsen

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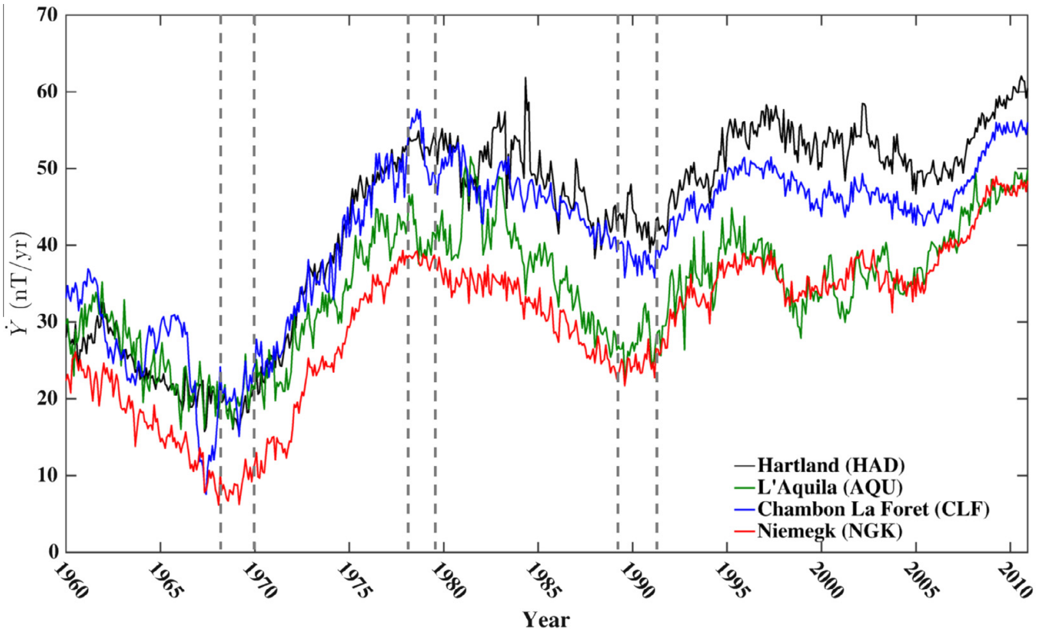

Fig. 1. The *Y* component of SV, calculated as annual differences of monthly means, at four different observatories in Europe. The black line is Hartland (HAD), the green line is L'Aquila (AQU), the blue line is Chambon La Forêt (CLF) and the red line is Niemegk (NGK). The vertical dashed lines (grey) indicate approximate timings of three observed geomagnetic jerks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and Mandea, 2007). According to Alexandrescu et al. (1996), who used wavelet analysis to detect and characterise worldwide jerk occurrences, some are observed globally and others only regionally.

Despite many attempts, the physical origin of geomagnetic jerks is yet to be established, see Mandea et al. (2010) for a thorough review of this topic. Malin and Hodder (1982) used spherical harmonic analysis to establish that jerks are of internal origin, but none of the subsequently proposed generating mechanisms has proved completely successful. The previous interpretations of jerks include core flows (e.g., Le Huy et al. (1998), Wardinski et al. (2008), and Silva and Hulot (2012)), torsional oscillations (Bloxham et al., 2002) and instability of an Ekman–Hartman boundary layer at the CMB (Desjardins et al., 2001). Of particular interest to this work are those interpretations that rely upon zonal core flows and/or torsional Alfvén waves, a type of magnetohydrodynamic wave that is predicted to exist in Earth's core on decadal timescales (Braginsky, 1970, 1984), identified in dynamo models (Wicht and Christensen, 2010; Teed et al., 2013, 2015), and inferred from various geophysical datasets (e.g., Hide et al., 2000; Zatman and Bloxham, 1997, 1999; Buffett et al., 2009; Gillet et al., 2010).

Several authors (Waddington et al., 1995; Bloxham et al., 2002; Olsen and Mandea, 2008) have shown that no steady flow can produce jerk-like features, nor can a steady flow in a drifting frame (Holme and Whaler, 2001). This implies that a steady flow of the magnitude typically assumed for core flow, $\mathcal{O}(10^{-4})$ m/s, is not able to produce the strong SA associated with jerks and that flow acceleration is likely an important contribution to jerks (Waddington et al., 1995). Bloxham et al. (2002) relaxed the steady flow constraint and showed that some jerks can be explained by the combination of a steady flow and a simple time-varying, axisymmetric, equatorially symmetric, toroidal zonal flow. Such flows are consistent with torsional oscillations (torsional wave normal modes) and give an excellent fit to many jerk features, particularly in Europe, though the predicted SV was notably smoother than the observations. The authors also noted that the SV generated by simple core flows depends on the local morphology of the ambient magnetic field. This is a crucial point because it means that large-scale core flow can produce localised signals at magnetic observatories and thus there is no need to invoke a small-scale core flow to explain those jerk events that are observed on a regional scale. However, whilst the simple zonal flows consistent with torsional waves are likely an important contribution, a radial component to flow is required to explain jerks (Lesur et al., 2015). Less restrictive flows, such as toroidal or tangentially geostrophic flows, are needed to reproduce all of the observed features of SV (e.g., Wardinski et al., 2008; Silva and Hulot, 2012). Toroidal flows have no radial (poloidal) component and are consistent with a stratified layer at the top of the outer core, which was proposed by, among others, Whaler (1980) and Braginsky (1999). More recently, various authors (e.g., Helffrich and Kaneshima (2013), Gubbins and Davies (2013), and Buffett (2014)) have advocated a stratified layer in the outer core using seismological evidence, geomagnetic observations, and material properties of liquid iron at high temperature and pressure. Tangentially geostrophic flows neglect the Lorentz term in the force balance at the top of the core, implying a zeroth order balance between the horizontal components of the pressure gradient and the Coriolis force (Le Mouël, 1984). This flow is also consistent with a stratified layer beneath the CMB (Jault and Le Mouël, 1991), though this constraint is less restrictive than the purely toroidal case because it allows a poloidal component. An intermediary flow that is more general than pure torsional oscillations but more restrictive than tangential geostrophy is also able to explain observed SV, including geomagnetic jerks. These are called quasi-geostrophic flows (Gillet et al., 2009) and are almost invariant along the rotation axis. See Holme (2015) for a recent review of fluid motions in the outer core and previous core flow modelling attempts.

The aim of this paper is to use the forward models of Cox et al. (2014, hereafter CLM) to establish the nature of torsional wave-induced SV at the core–mantle-boundary and at the Earth's surface. Of particular interest to this work are the effects of the background magnetic field morphology on sensitivity to zonal core flows, and the influence of wave propagation speeds and amplitude scalings on the characteristics of the modelled SV. The wave propagation velocity is determined by the strength of the ambient mag-