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Tracking geomagnetic impulses at the core–mantle boundary

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Abstract

The main magnetic field of the Earth is generated and maintained by convective motions in the fluid outer core. Temporal field variations occur on an impressive variety of scales, ranging from months to millions of years. Among these, the most intriguing features are geomagnetic "impulses" or "jerks" [V. Courtillot, J. Ducruix and J.L. Le Mouël, Sur une accélération récente de la variation séculaire du champ magnétique terrestre, Acad. Sci. Paris C.R., D287, (1978) 1095–1098., J.L. Le Mouël, J. Ducruix and C. Ha Duyen, Geophys. Res. Lett., 5, (1983) 369. [1,2]]. Here, we investigate these very rapid events at the surface of the Earth's core using a global model, designed for use at this depth. We identify two regions of very active variations, where wave-like structures propagate. The geometrical characteristics of these wave-like motions provide new constraints on the intricate dynamics of the core.

Keywords: Geomagnetism; Geodynamo; Secular variation

1. Introduction

There are generally three sources of the magnetic fields surrounding the Earth: (1) the main component of the field, originating in the Earth's fluid core, (2) the crustal field, originating in the Earth's crust from remanent and induced magnetization of the material in the upper layers of the Earth, (3) the field from ionospheric and magnetospheric currents generated by the interaction with the solar wind. The temporal variations of these contributions have a broad spectrum, from millions of years (magnetic reversals) to seconds (magnetic storms). Long-term variation is mainly due to the dynamo process, and is known as secular variation.

Repeated surveys of the geomagnetic field are highly desirable due to the fact that internal field gradually changes in the course of the years in a way which at our present knowledge is not predictable. In fact, unexplained abrupt changes have occurred in the magnetic field variations on the time

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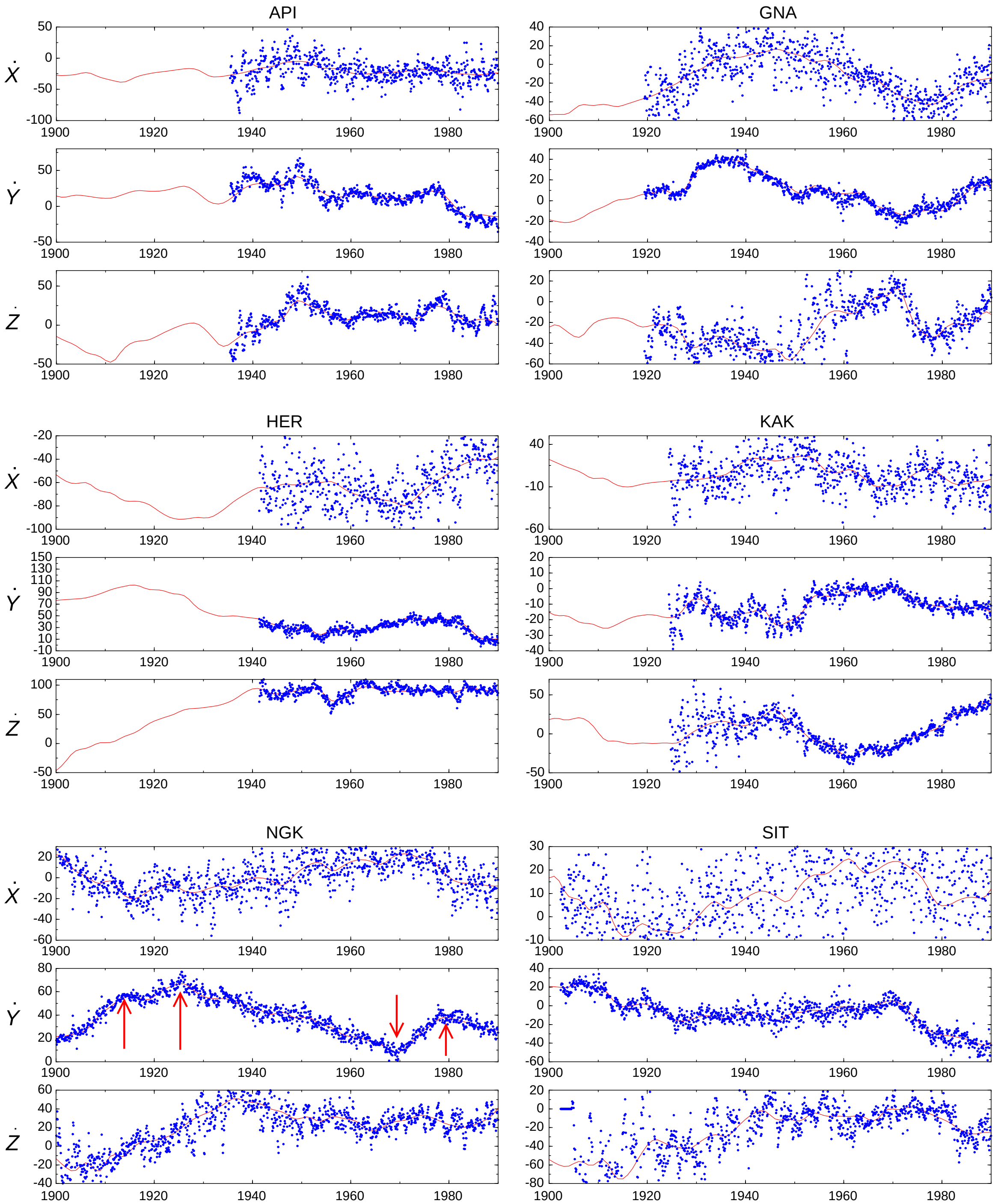

Fig. 1. Comparison of secular variation for $\dot{X}$, $\dot{Y}$, $\dot{Z}$ components (in nT/yr) over 1900–1990, obtained from monthly means provided by magnetic observatories (blue dots), and computed at the surface of the Earth from *gufm1* model (red lines). The chosen observatories, indicated by their IAGA code, are world wide distributed: API (Pacific zone), GNA (Australia), HER (South Africa), KAK (Japan), NGK (Germany), SIT (United States).

scale of 1 yr ("geomagnetic jerks" or "geomagnetic impulses"). This calls for regular measurements of the geomagnetic field, but also for new approaches in understanding these internal variations, produced in the Earth's core.

The Earth's outer core is a conducting fluid where convection takes place with characteristic velocities of a few tens of kilometers per year [3,4]. Dramatic advances have recently been made in describing dynamo action, thanks to numerical simulations [5,6] and experiments [7,8]. Observational studies remain essential to guide further developments. Among the most puzzling issues are the geomagnetic impulses so far detected and characterized from observatory data [1,2,9]. None of these events have occurred during the recent satellite missions [10].

In this paper we investigate how geomagnetic models can be used to characterize the geomagnetic jerks. First, we show that using a global model makes it possible to track the geomagnetic jerks at the core surface. Then, we study the evolution of the secular variation and identify two regions of very active variations. Finally, we propose an interpretation in terms of wave-like structures responsible for the observed jerks.

2. Jerks in geomagnetic models

Important efforts in modeling the core field [11,12] yield new opportunities to obtain a complete picture of the field evolution. Based on such a recent model [12], we investigate changes in the geomagnetic field from 1900 to 1990. The time-dependent field model is parameterised spatially and temporally. This field model, known as *gufm1* is built in terms of spherical harmonics, with truncation at degree 14, (because higher order harmonics of the core field in the power spectrum are overwhelmed by the crustal field). The model is also parameterised temporally using fourth order B-splines as basis functions for expanding the Gauss coefficients, and is designed for use at the core–mantle boundary (CMB).

We focus on the clearly well defined geomagnetic impulses detected over the time span 1900–1990, i.e. those occurring in 1913, 1925, 1969, and 1978 [9]. Comparing synthetic data obtained from the *gufm1* model with magnetic data from observatory measurements, we verify that the *gufm1* model properly fits data from magnetic observatories, as had been done for previous models [13]. Fig. 1 illustrates a typical comparison of data from a set of six observatories situated in very different parts of the world. In this paper, we refer to the times at which geomagnetic jerks are observed as "epochs" rather than "years" since the same event was often detected in various observatory data with significant time lags of up to 3 yr [9]. Data dispersion is largest for the northern component of secular variation ($\dot{X}$), the effects of the external field being most significant in this direction. Geomagnetic impulses are most clearly seen in the eastern component ($\dot{Y}$), and are well captured by the *gufm1* model. They are slightly less singular than in real data, due to the model temporal smoothing (see Fig. 1). In the vertical component secular variation ($\dot{Z}$) the geomagnetic jerks can be perceived only in some regions of the world (see Fig. 1). Nevertheless, the *gufm1* model offers an excellent representation of secular variation including impulses. We use this property to perform a direct and global high-resolution investigation of geomagnetic impulses at the surface of the Earth's core.

3. Investigation of jerks at the CMB

Using the *gufm1* model, we compute the secular variation ($\dot{X}$, $\dot{Y}$, $\dot{Z}$) at the basis of the mantle, under the approximation of a perfectly insulating mantle. Note that secular variation at the base of the mantle only reflects accurately the secular variation at the top of the core for the vertical ($\dot{Z}$) component. All three components in the mantle derive from a single scalar and therefore contain the same information, but the emphasis can be placed on particular structure by choosing a particular component (as will be discussed later).

This procedure is standard as far as the core field is concerned [12,14]. Investigating secular variation naturally highlights rapid events such as geomagnetic impulses. A natural approach is to investigate secular variation right under observatories. One could then have expected this procedure to yield a similar behaviour. Such is not the case. In fact the signal is then very difficult to interpret. No clear slope discontinuities can be reported, and while jerks were clearly visible on the Earth surface at NGK, the corresponding secular variation at the CMB is rather low compared to that at HER (see Fig. 2). This highlights the need for a global representation for the secular variation and its impulses at the top of the core.

Fig. 3 presents the $\dot{X}$, $\dot{Y}$, $\dot{Z}$ maps for the 1913, 1925, 1969, and 1978 epochs (animations based on yearly maps for the whole 1900–1990 period are available on the website http://www.ipgp.jussieu.fr/~dormy/impulses). It is worth noting that, while impulses are present in the model, secular variation at the core surface does not exhibit such temporally sharp events. It is striking, and was previously reported [4,14], that secular variation has a non-uniform behaviour all over the world: the Pacific hemisphere is characterized by very low variation, while most changes occur in the Atlantic hemisphere. In fact, two regions of intense variation can be identified: one in the Northern Hemisphere, roughly under North America (hereafter referred to as NA), and the other one in the Southern Hemisphere, under South Africa (hereafter referred to as SA). Fig. 3 as well as the animations, clearly reveal areas of traveling features, that we will refer to as “patches of intense secular variation” (PISV). Because extrapolation of the field downward from the Earth’s surface to the core surface becomes progressively more inaccurate (increasing errors on higher degrees), it is important to check the influence of the truncation degree on the follow-up patches. Fig. 4 shows that structures we are interested in are well captured by models truncated at all degrees/orders 10–14. Moreover, Fig. 5 demonstrates that the energy spectrum obtained from *gufm1* model and that of a recent model based on the Oersted satellite data are similar up to degree 11.

Let us focus in more detail on the PISV, well localised in the above mentioned regions. Surprisingly they appear (see animations) to have a preferred traveling direction, almost northward in both regions: in the NA-region, PISV exhibit a motion from the equator to the pole, and in the SA-region from the pole to the equator (let us note that this direction is consistent with many of the flow models at the CMB obtained by inversions, which show large steady flow gyres in that region of the CMB). The direction of motion of PISV is not exactly oriented along meridians, but these provide a good first approximation. A departure from this northward direction to the west should be reported in the SA-region: patches emerge around (60° S, 45° E) and seem to meet the equator roughly at (0°, 0°). The PISV path in the NA-region is more closely aligned with meridians. Both regions are connected at the equator, and the trace of PISV on the equator appears directly related to recently reported equatorial traveling features [14].

The equatorial region is particularly important for these patches, as their trajectories are strongly altered near the equator. Interestingly, the NA-region is not strictly restricted to the Northern Hemisphere, extend-

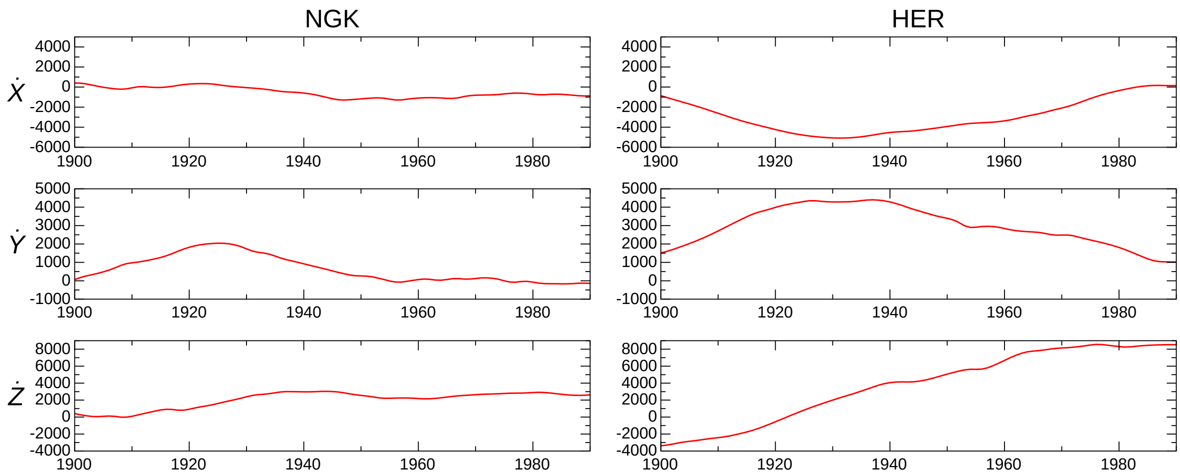

Fig. 2. Downward continuation of the secular variation at the core-mantle boundary for the same position (latitudes and longitudes) as the NGK and HER observatories (i.e. just under these observatories).

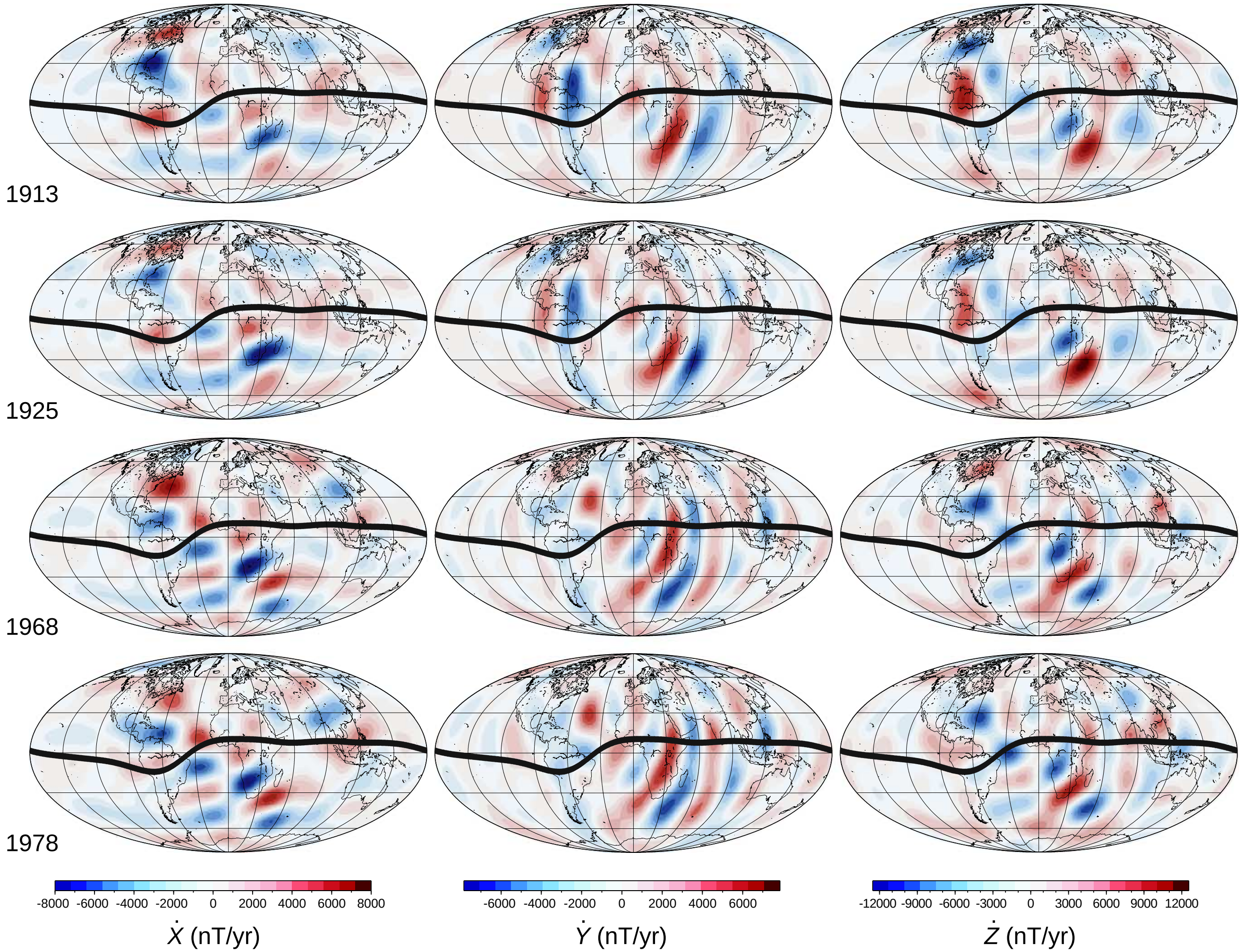

Fig. 3. Maps showing the three components of the secular variation and the potential V from which they derive. Reconstruction at the core–mantle boundary, from the *gufm1* model at four given years (1913, 1925, 1968, 1978). The geomagnetic equator at the Earth's surface for each corresponding year is also represented.

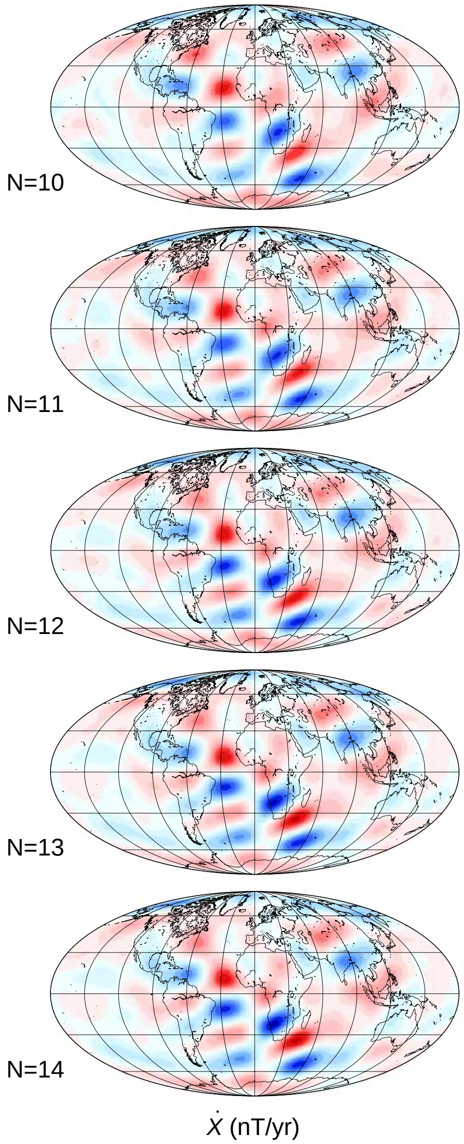

Fig. 4. Secular variation of the $\dot{X}$ component, for different truncation degrees N: patches of intense secular variation (PISV) are already well described with 10 harmonics.

ing in fact some 15° into the Southern Hemisphere. However, this region stays well confined to the north of the dip equator (the dip equator only forms a connected set at the surface of the Earth, filtering out small scale variations existing at the core surface, this equator is based on the *gufm1* model and reflects the field of internal origin). Indeed, the shape of the dip equator itself appears directly related to the positions of these two intriguing regions of active secular variation. The noticeable kink in the equator at the level of the central Atlantic Ocean precisely indicates the boundary between south of the NA-region and north of the SA-region.

Since PISV appear to evolve in the latitudinal direction, we choose to focus our discussion only on the latitudinal component of the core field secular variation ($\dot{X}$). Again the information content of all three component is equivalent since they derive from a single potential. Although this choice may not intuitively appear as the most appealing one (geomagnetic jerks are clearly detected in $\dot{Y}$ component at the Earth's surface, and the $\dot{Z}$ component is the only continuous component through the core–mantle boundary [15,16]), this latitudinal component accentuates short wavelengths in that direction (in the same way as considering secular variation allowed us to point out rapid changes). The features we describe below are present in all three components, yet these are more clearly identified on $\dot{X}$. Because PISV are very small scale, their intensity is significantly reduced from the core surface to the Earth's surface. Indeed, individual patches vanish at the surface, while regions of strong activity (NA and SA) remain well defined. As these two regions are confined to very

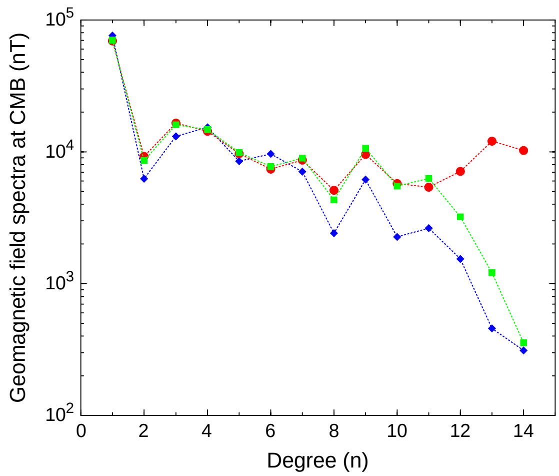

Fig. 5. Geomagnetic field spectra at the core–mantle boundary: for epoch 2002, derived from a model based on Oersted satellite data (red); averaged *gufm1* model over the period 1900–1990 (blue); *gufm1* model for epoch 1990 (green). The very good resemblance has to be noted between the spectra corresponding to models for 1990 and 2002, up to degree 11.

distinct longitudinal areas (some 120° apart), the east–west gradient becomes larger, making impulses most clearly detectable on the $\dot{Y}$ component when analysing observatory series [1,2]. Moreover, the $\dot{X}$ component of the field in observatory data is noisy due to external field contributions.

To illustrate the evolution of these patches, latitudinal cross sections of both regions are considered. As discussed above, the identified directions do not perfectly follow the direction of propagation (which is slightly tilted). We chose longitudes of 50° E (for the SA-region) and 290° E (for the NA-region), which lie approximately at the center of the active regions. These are represented as a function of time in Fig. 6. Wave-like motions of PISV are particularly clear from the chosen cross sections. More interestingly, the variation of intensity of PISV can be investigated on such cross sections. It is remarkable that the peaks of intensity on these graphs correspond to the epochs of the observed geomagnetic impulses. In the Northern Hemisphere, one extremum of variation occurs around 1913 and another one around 1968, while in the Southern Hemisphere one extremum occurs around 1925, and a double one, having an elongated shape, around 1968–1978. These PISV constitute the first representation at the core–mantle boundary of internal events whose

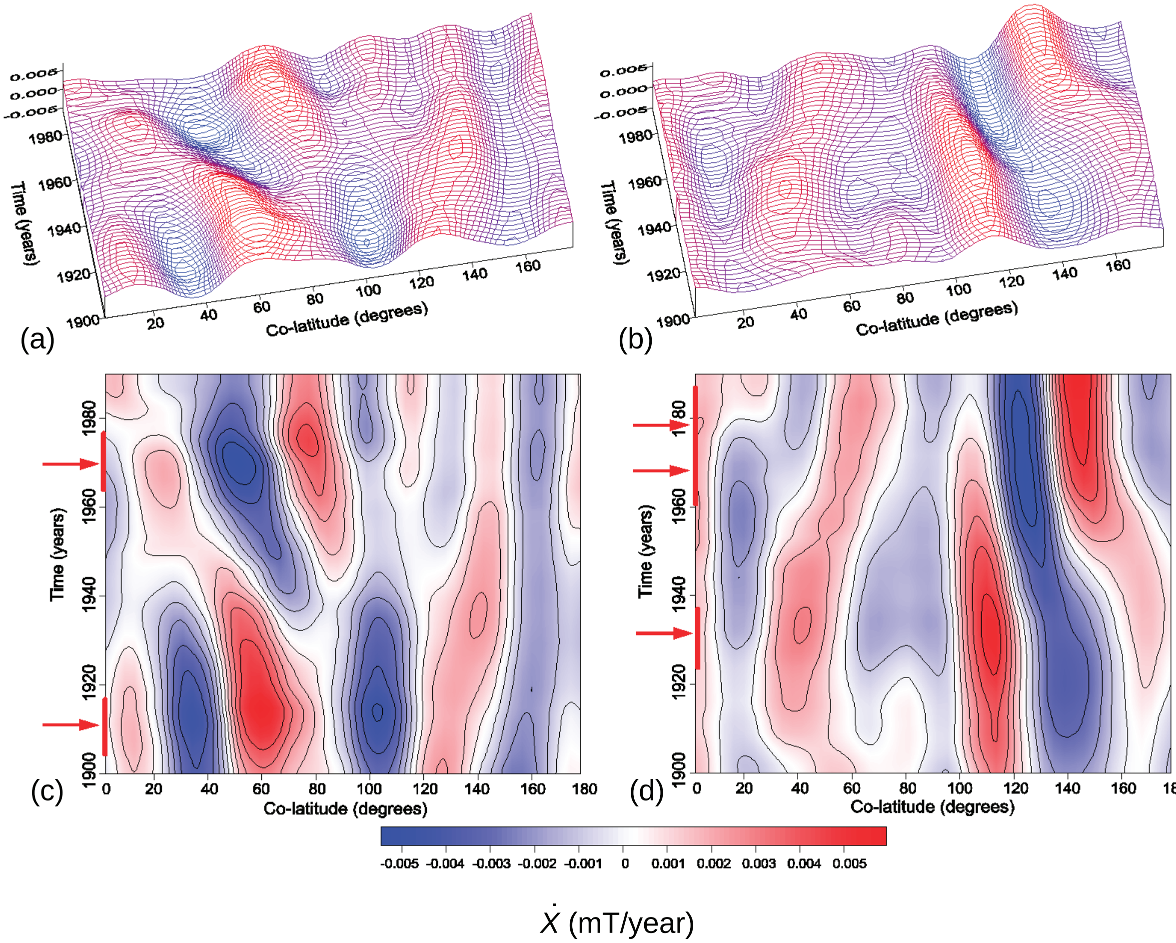

Fig. 6. Temporal evolution of the secular variation for $\dot{X}$ component along latitude for two given longitudes, 290° E on the left panel and 50° E on the right panel, sampling both area of active variation (North America on the left, and South Africa on the rigth). Impulses in 1913, 1925 and 1968 correspond to extrema of variation alternately in NA- and SA-regions. The 1978 event appears to correspond to two consecutive extrema in the SA-region extending over a longer period of time.

signatures have been noted in the observatory data, at the Earth's surface as geomagnetic impulses (Fig. 1).

4. Physical interpretation

It is important to ponder the origin of the reported PISV and their temporal evolution. The dominant northward motion in active regions is evident in both cross sections (see Fig. 6). One can however note in Fig. 6.c and 6.d that motions in the less active hemisphere (i.e. southern for Fig. 6.c and northern for Fig. 6.d) are opposite in direction, i.e. southward. Although their velocity is not steady in time, the traveling nature of these patches is revealed by Fig. 6.c and 6.d. This could result either from the presence of some traveling waves in the core or from advection of the magnetic field by the fluid flow. A rapid estimate, based on Fig. 6, reveals that the typical "velocity" of a PISV is on the order of 35 km yr^{-1}, which is twice the standard estimate for the core flow [4]. The wave origin of these variations is therefore much more realistic. Traveling waves have recently been proposed in the core [14,17]. As many kinds of waves can propagate in the Earth's liquid core, it is not straightforward to distinguish which type might be connected to the observations we report. Fig. 6.c and 6.d show that periods of most active variations coincide with the occurrence dates of jerks. This is perhaps even more clearly visible on the root–mean–square of $\dot{X}$ computed on both meridians (see Fig. 7).

The motion of patches is not steady, and extrema in Fig. 6.c and 6.d seem to correlate with variations in patch velocities. Moreover, extrema do not occur at the same time for all latitudes, and they appear to propagate in a direction opposite to the wave, i.e. southward (this is particularly clear in Fig. 6.c). From a physical point of view, this suggests that the phase velocity is opposite to the group velocity.

The nature of these waves is most intriguing. The typical time between events guided earlier investigations toward torsional oscillations [18]. A detailed argument was first attempted in Bloxham et al. [17]. Torsional waves can exhibit a most complex temporal behaviour [19], but they are severely constrained in their geometrical aspect: at the core–mantle boundary, the motion is east–west, constant for a given latitude (symmetrical with respect to the equator), and the wave propagates in the latitudinal direction. Bloxham et al. stressed that such global motion interacting with

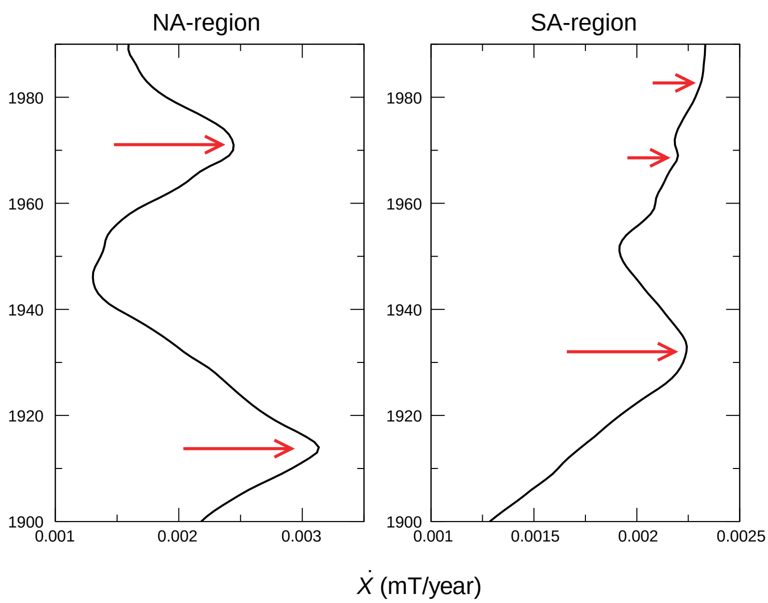

Fig. 7. Root–mean–square (RMS) of $\dot{X}$ on two meridians, for longitudes 290° E (NA-region) on the left panel, and 50° E (SA-region) on the right panel. Impulses in 1913, 1925 and 1968 are particularly clear, alternately in NA- and SA-regions. The 1978 event is not so clearly defined, and appears to correspond to two extrema in the SA-region extending over a longer period of time (see Fig. 6).

a complex field could yield localised effects [17]. The direct investigation we perform here casts serious doubts on an interpretation of impulses relying on torsional oscillations only. Indeed, such a zonal motion shearing a patch of magnetic flux would necessarily induce two patches of vertical secular variation $\dot{Z}$ opposite in sign and aligned in longitude. Such a feature is clearly absent from Fig. 3 or on the available animations. Because of their geometrical nature, torsional oscillations alone cannot account for the observed wave pattern, but they could interact with other waves and have an intricate connection with impulses. These observations suggest the presence of a wave with less constrained motion. A large variety of waves can propagate in a rotating and conducting liquid metal [20], most of them having typical time scales inconsistent with observational constraints. Moreover, the candidates must feature a sufficiently complicated dispersion relation (to allow the group velocity to be negative with respect to the phase velocity). The most plausible candidate considering these constraints appears to be MAC waves corresponding to a balance between *M*agnetic, *A*rchimedian and *C*oriolis forces. Remarkably, these waves are also expected to be directly related to dynamo action in the core [21]. This assessment indicates that geomagnetic impulses are not simply the trace of rapid events barely interacting with the main processes occurring in the Earth's core, but may instead be an essential part of the geodynamo. The interplay between MAC waves and torsional oscillations deserves further investigation.

5. Conclusion

In the present study, we have highlighted that geomagnetic models can be used to trace the secular variation at the core–mantle boundary. We have proposed an interpretation of the resulting maps in terms of traveling waves. Moreover we have shown that geomagnetic impulses, as observed at the Earth's surface, are the signatures of extrema in these waves.

Let us point out, finally, that the role of the lower mantle in controlling the dynamics of the Earth's fluid outer core is a known and controversial issue. One of the important magnetic observations in this debate is the strong asymmetry in the surface secular variation between a calm Pacific hemisphere, and an active Atlantic hemisphere. The present representation of patches of intense secular variation (PISV) at the core–mantle boundary can shed new light on the core–mantle interaction as the PISV emerge under southern Africa, precisely where tomography reveals strong heterogeneity in wave velocity [22] and the formation of a massive plume [23,24].

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2005.06.003.

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