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Geomagnetic jerks and seismic activity

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Abstract
By means of a Monte Carlo simulation, we explored the extent to which large earthquakes may induce fluctuations on the secular variation of the Earth's magnetic field. We speculate that the energy released by large earthquakes may perturb the dynamical interaction between the outer core and the lower mantle, and consequently give rise to rapid variations of the main field detectable on the Earth's surface (geomagnetic jerks). In order to test the existence of a possible correlation between the seismic activity and the occurrence of magnetic jerks, we examined both the number of earthquakes and the total moment released in a lapse of time preceding the known geomagnetic jerks of this century. Our results are compatible with the hypothesis of a causal relationship between periods of time characterized by an anomalous global seismic activity and rapid changes of the main magnetic field. Several possible mechanisms accounting for such a correlation are discussed.

Key words *geomagnetic jerks – earthquakes – CMB*

1. Introduction

The geomagnetic field observed on the Earth's surface is not a steady feature but is characterized by time variations ranging from milliseconds to millions of years. It is commonly recognized that variations occurring on time scales of ten years or longer («Secular Variations», SV) are related to internal processes, whereas on shorter time-scales an external origin is usually invoked.

In recent decades, several papers reported on the existence of anomalous short changes in the SV (called jerks), lasting less than a few years (*e.g.*, Courtillot *et al.*, 1978; Ducruix *et al.*, 1980; Nevanlinna and Sucksdorff, 1981; Malin *et al.*, 1983; Courtillot and Le Mouël, 1984; McLeod, 1985). This discovery gave rise to an interesting debate on the origin of this impulsive phenomenon. According to recent studies, these impulsive changes in the main field SV may have occurred a few times during this century, although it is now almost accepted that only the 1910 and 1969 jerks are related with a world-wide synchronous break of the main field SV.

Length of Day (LOD) fluctuations can be considered evidence of differential rotation between the outer core and the mantle (*e.g.*, Lambeck, 1980). Such a relative motion may generate the westward drift of the non-dipole field, provided that some electromagnetic coupling exists between the fluid core and the mantle (Bullard *et al.*, 1950). Therefore, one may argue that LOD changes are related to fluctuations of the main geomagnetic field. This has basically been confirmed by Courtillot and Le Mouël (1984), who have shown that extrema in the LOD are correlated with periods of intense secular acceleration changes. If this holds true, a problem arises about the physical mechanism driving fluctuations of the differential rotation between the core and the mantle.

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In this paper, we pursue the idea that very large earthquakes could induce abrupt differential rotation variations and/or topographic effects at the Core-Mantle Boundary (CMB), with subsequent geomagnetic impulsive variations diffusing through the mantle (Florindo and Alfonsi, 1995).

Before attempting any forward modeling approach, we made an exhaustive analysis based on a Monte Carlo simulation (Metropolis and Ulam, 1949) whose aim is to enlighten a possible correlation between global seismic activity and geomagnetic jerks.

2. Geomagnetic jerks

A sudden change in the slope of the annual secular variation curve is defined as a geomagnetic jerk. It corresponds to a step function increase in the second differences (secular acceleration) (Nevanlinna, 1985), occurring on a time-scale of 1.5-2 years (Golovkov *et al.*, 1989).

The first report of a jerk, observed in all European observatories in 1969, was given by Courtillot *et al.* (1978). Further analyses of geomagnetic data have shown that the 1969 jerk was indeed visible over much of the northern hemisphere (Courtillot *et al.*, 1978; Ducruix *et al.*, 1980). Another occurrence was found around 1910, comparable for geographical impact and intensity with the 1969 acceleration (*e.g.*, Gire *et al.*, 1984). Recently, other jerks were identified in 1913, 1925, 1969 and 1978 (Alexandresku *et al.*, 1995). The existence of other two singularities respectively in 1947 and 1958, was proposed by Golovkov *et al.* (1989, 1995). Recently Cafarella and Meloni (1995) consider the possibility of a 1990 geomagnetic jerk, visible at a selection of European observatories. The occurrence of jerks before 1900 is also reported (*e.g.*, Ducruix *et al.*, 1980; Le Mouël and Courtillot, 1981), but the limited number of observations available does not permit a detailed investigation of their geographical extent.

The origin of the geomagnetic jerks is the subject of ongoing debate, mainly regarding their internal or external origin (Nevanlinna and Sucksdorff, 1981; Alldredge, 1985; Backus *et al.*, 1987; Stewart and Whaler, 1992) and their geographical impact (Chau *et al.*, 1981; Le Mouël *et al.*, 1982, McLeod, 1992). It should be noted that Alldredge (1979, 1985) gave a reasonable explanation of the jerks in terms of external sources related with the sunspot cycle. Spherical harmonic analyses allowed a separation within the internal and external parts of the geomagnetic jerk (Malin and Hodder, 1982; Gubbins, 1984; McLeod, 1992). These studies concerned in particular the 1969 impulse and revealed that most of the jerk was of internal origin (Malin and Hodder, 1982). Kerridge and Barraclough (1985) repeated the analysis of Malin and Hodder at two year intervals from 1931.5 to 1971.5, concluding that within that period the only well-resolved singularity was the jerk of 1969. Nevanlinna (1985) carefully calculated the magnitude of the external part in the all-day annual mean for the geomagnetic impulsive event of 1969, finding that it was negligible, and concluded that changes in the external sources contributed slightly to the variation of the eastern component of the geomagnetic field, observed in North Europe. Nevanlinna (1985) also pointed out that the solar activity and the energy input into the Earth's magnetosphere were roughly 30% lower in the year around 1970 (coinciding with sunspot maximum year) than during the adjacent sunspot maxima.

Even though the origin of the jerk is still disputed, a series of explanations have been provided in terms of internal sources. Among others, Courtillot *et al.* (1978) pointed out a possible correlation between periods of intense secular acceleration changes since 1800 and extrema in the Earth's rotation rate; Mörner (1989) associated the occurrence of jerks to interchange of angular momentum between the solid Earth and the hydrosphere, suggesting that the redistribution of masses due to ocean circulation could trigger a geomagnetic impulse.

Under the hypothesis that the jerks are of internal origin, the detection of such magnetic signals, generated in the Earth's core and diffused through the mantle, may provide constraints on the mantle electrical conductivity (see *e.g.*, Stewart *et al.*, 1995 for a review).

3. Data analysis

In the following, we employ a Monte Carlo technique in order to establish the potential relationship between the occurrence of jerks and the energy release by large earthquakes. Our study is based on two distinct approaches. First, the impact of the number of earthquakes per year on the occurrence of geomagnetic jerks is studied. For this purpose, we employed the earthquake data set provided by the National Earthquake Information Centre (NEIC) of the USGS, which includes the earthquakes with known magnitude $M_s \geq 7$ which have occurred since the beginning of this century.

A subsequent analysis is performed in order to test the relevance of the seismic moment release. This is accomplished by means of the catalogue compiled by Pacheco and Sykes (1992), which provides the moment estimates for the large shallow earthquakes of this century. Data pertaining to large, intermediate and deep focus earthquakes are taken from Abe (1981, 1984). We translated the broadband body wave magnitudes listed by Abe in terms of seismic moment by using the results provided by Purcaru and Berckhemer (1982). The seismic moment time series which results from the combination of these two data sets is referred as to MOM data set in the following.

According to Courtillot and Le Mouël (1984), the 1910 and 1969 magnetic jerks (unbroken lines in fig. 1a-c) are to be considered the most certain in view of their intensity and world-wide detectability. We therefore consider simulations based on both a set of jerks including all of six events reported in the literature (hereafter referred as to set J6) and on the narrow set which only includes the two reported by Courtillot and Le Mouël (set J2). Figure 1a-c presents the basic data employed in this study. In fig. 1a the NEIC time series of earthquakes with $M_s \geq 7$ is compared with both the J6 and the J2 set. The NEIC time series for magnitude $M_s \geq 8$ is shown in fig. 1b, whereas fig. 1c displays the seismic moment release as a function of time according to the MOM data set (see above).

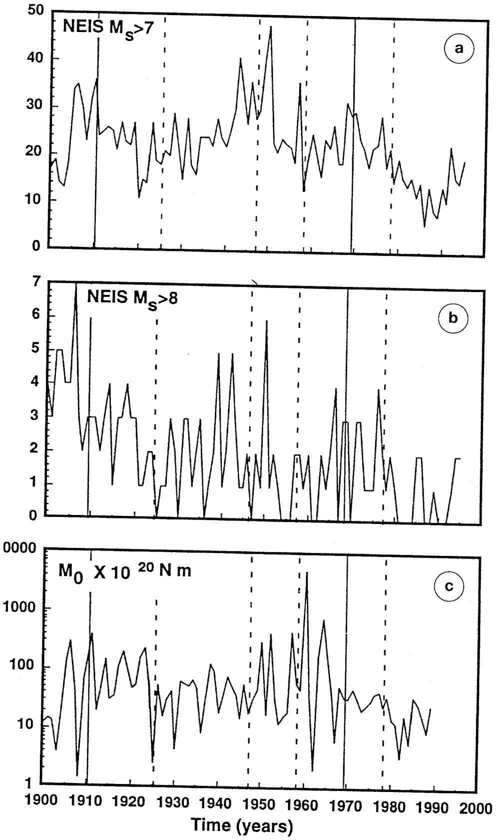

Fig. 1a-c. Time series of the NEIC earthquakes with $M_s \geq 7$ (a) and $M_s \geq 8$ (b). The two unbroken lines refer to the 1910 and 1969 magnetic impulses, respectively. c) Displays the seismic moment M_0 released as a function of time according to the catalogs of Pacheco and Sykes (1992) and Abe (1981, 1984). The jerks are marked by vertical lines.

Under the hypothesis that the jerks are of internal origin, they are clearly the surface manifestation of some perturbation affecting the fluid core. The time τ required for this perturbation to be propagated at the Earth's surface is basically determined by s_m, the electric conductivity of the mantle. The observations providing information on s_m were reviewed by Lambeck (1980) and are open to large uncertainties. According to the various estimates of s_m, we may safely assume that s_m ranges between 10^{-10} and 10^{-9} e.m.u. within the mantle. As shown for instance by Lambeck (1980), the time for a magnetic field to diffuse through a layer of thickness L is of the order of $4\pi s_m L^2$. Accordingly, assuming $L \sim 3000$ km, the time lag may vary between ~ 3 and 30 years. It should be noted that recent estimates of lower mantle conductance (Stewart *et al.*, 1995) suggest a time lag ranging between 3 and 7.5 years.

Our aim here is to the test the possibility that a jerk may occur subsequently to a lapse of time characterized by an anomalously large number of great earthquakes. From an overall visual inspection of the data displayed in fig. 1a-c, this correlation is not clearly detectable. However, from fig. 1b we may notice that the 1910 magnetic impulse effectively occurred after a decade of extremely intense activity with $M_s \geq 8$. This is not the case for the 1969 jerk, but it should be noted that the total seismic momentum released between 1960 and 1970 was in fact exceptionally large, due to the occurrence of the Chilean (1960) and Alaskan (1964) earthquakes. This motivates our choice to take into account both the number of earthquakes and the energy released during a certain epoch.

For a given jerk data set, we define N^o as the total number of large earthquakes which effectively took place in a lapse of time of length T (expressed in years) preceding the magnetic jerk. According to the previous discussion on the time delay of geomagnetic signals, we positioned the right edge of this time interval at $t_j - 3$ years, where t_j denotes the time of occurrence of a jerk. In spite of the fact that the diffusion time τ may amount even to several decades (see above), the left edge of our time interval was located at $t_j - 7$ years in order to ensure that the width of the time-window (5 years) is considerably smaller than the length of the time-series under study (95 years). The choice of the length of the time-window is of course largely subjective, but in any case a wrong choice cannot artificially introduce a significant correlation between the two time-series under study. Since the larger the time-window is, the larger the blurring effect on the time-series, in this study we limited the width of the time-window to $T = 5$ years. However, in order to test the stability of the results, we also performed our simulations in the case of a slightly larger window with $T = 8$ years.

In a second step, we repeated the above operation on a large number (ranging between $M = 10^3$ and 10^4) of randomly generated time sequences of jerks, keeping their total number fixed. With N^s we indicate the «synthetic» N^o pertaining to the sequence s. If we denote with M' the number of simulations characterized by $N^s \geq N^o$, $\xi = M'/M$ provides a measure of the probability that the apparent relation between jerks occurrence and periods of enhanced global seismic activity is due to chance.

The results of our analyses are summarized in table I. In the case of the J2 jerks data set, we examined $M = 10^3$ random simulations, which constitute a large fraction of the total number of possible distinct simulations. This number was raised to $M = 10^4$ in the case of the J6 set. To test the stability of our method, in the bottom part of table I we display the results obtained using a time-window of length $T = 8$ years. We first examined the correlation between the NEIC data with $M_s \geq 7$ and the occurrence of jerks (table I, top two lines). The Monte Carlo simulation indicates that this correlation is quite poor. In fact, we found that the probability ξ that a non-causal relationship exists amounts to 63% and to 41% for the jerks data sets J6 and J2, respectively. However, if one considers the earthquakes with $M_s \geq 8$ in conjunction with the J2 set (line 3), ξ only amounts to 5%. A similar figure ($\xi = 6\%$) was obtained in the case of a larger time window (see line 9), to demonstrate the stability of the estimate of ξ. The relatively large values of ξ obtained when the whole set of earthquakes with $M_s \geq 7$ were considered suggest that only very large earthquakes have some impact on the genesis of jerks. Furthermore, we notice that when the J6 data set is considered, no significant correlation is suggested by our results, regardless of the seismic data base under study and the time window employed.

In order to investigate the role played by the seismic moment release in the last century, we also show in table I some results based on the MOM time series, which incorporates the Pacheco and Sykes (1992) catalog of shallow earthquakes and the Abe (1981, 1984) data

Table I. Earthquakes and jerks data sets.

Earthquakes data set	Jerks data set	Time window, T (years)	Number of simulations, M	Ratio $M'M$ %
NEIS, $M_s > 7$	J2	5	10^3	41
NEIS, $M_s > 7$	J6	5	10^4	63
NEIS, $M_s > 8$	J2	5	10^3	5
NEIS, $M_s > 8$	J6	5	10^4	30
MOM	J2	5	10^3	14
MOM	J6	5	10^4	37
NEIS, $M_s > 7$	J2	8	10^3	61
NEIS, $M_s > 7$	J6	8	10^4	49
NEIS, $M_s > 8$	J2	8	10^3	6
NEIS, $M_s > 8$	J6	8	10^4	21
MOM	J2	8	10^3	6
MOM	J6	8	10^4	21

pertaining to large, intermediate and deep focus earthquakes. From inspection of table I (bottom), it may be noted that in the case of a relatively large time-window the results obtained coincide with those pertaining to the number of earthquakes ($\xi = 6\%$), provided that the J2 jerk data set is used. In the case of a narrower time-window (top), the estimate of ξ for J2 exceeds the result pertaining to the NEIC catalog with $M_s \geq 8$. The significance of the correlation is, in any case, strongly reduced when the simulations were carried out on J6 set.

4. Discussion and conclusions

The results presented in the above section indicate that there may be evidence that the 1910 and 1969 geomagnetic jerks are associated with epoches of enhanced seismic activity with $M_s \geq 8$. This finding remains basically unchanged when the seismic moment release is considered. The possibility that very large earthquakes may perturb the equilibrium of the CMB has been already suggested in the literature, but due to the large uncertainties on the physical parameters describing the CMB interactions, no quantitative approach to this problem has ever been accomplished.

A large earthquake may perturb the Core-Mantle System (CMB) in several ways. First, the CMB topography can abruptly change as a consequence of the seismic energy release, thus affecting the flow pattern in the outer part of the fluid core. Such fluid motions deep seated in the core are responsible for driving the dynamo, but they are also active at the top of the fluid core, where they are probably confined to the near surface layer (Gubbins, 1988). Of course, in the absence of numerical investigations of this effect, we cannot estimate the length scale of this anomalous topography. This idea, however, is supported by recent results based on forward modelling (Piersanti *et al.*, 1995), which have shown that very large earthquakes may drive coseismic deformations at very large distances from the seismic fault. The spatial scales involved are of the order of 10^3 km, comparable with the thickness of the mantle. The potential influence of large earthquakes on the CMB topography is also suggested by analyses based on the normal modes technique (Dziewonski, 1996, personal communication). In addition to topographic effects, an earthquake may also produce far-field toroidal and poloidal coseismic displacements, which may contribute to an abrupt modification of the flow pattern of the outer part of the Earth's core. The direct influence of seismic activity upon the state of the core may provide an explanation for the anomalous behavior of the main geomagnetic field over the Pacific Ocean. As pointed out by Mullan (1973), the large deep-focus seismic activity confined to the Pacific ring could affect the vectorial configuration of the velocity field of the outer fluid core layers.

Another potential physical mechanism concerns the rotational response of the Earth to large earthquakes (O'Connell and Dziewonski, 1976; Lambeck, 1980). If one assumes a certain degree of mechanical decoupling between the core and the surrounding mantle, the abrupt inertia change induced by a large earthquake may be associated with an impulsive variation of the relative angular velocities. This mechanism, which only involves long-wavelength deformations, is potentially more effective than those described above in driving global variations of the secular components of the magnetic field.

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