PROBLEMS IN GEOPHYSICS FOR THE NEW MILLENNIUM
Eds. Enzo Boschi, Göran Ekström and Andrea Morelli

Geomagnetic jerks: impulses of secular variation in geophysics

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Abstract - Geomagnetic records from some observatories give a strong indication that there was a rapid, impulsive change in geomagnetic secular acceleration around 1990. Using data coming from about 80 observatories widely distributed all over the world, the structure of the secular variation for the *X*, *Y* and *Z* magnetic field intensities around 1990 was investigated. Evidence of a new recent jerk in 1991 was found. The 1991 geomagnetic jerk features (worldwide character of the *Y* second time derivative jump intensity and of the occurrence time) are compared with the character of the previous well known jerk events of 1969 and 1978.

1 Introduction

In the nineteenth century Gauss recognized that the magnetic field at the surface of the Earth could be approximated well by a magnetic dipole placed at the Earth's center and tilted about 11° with respect to the axis of rotation. Such a dipole accounts for roughly 90% of the Earth's magnetic field at the surface. The remaining part of the field is referred to as a non-dipole field. The most important and commonly used method of describing the Earth's magnetic field quantitatively is through Spherical Harmonic Analysis (SHA). SHA creates a mathematical representation of the Earth's magnetic field and its secular variation using various combinations of global observatory, satellite, and magnetic field survey data. Essentially, this method divides the field into separate components that decrease at different rates with increasing distance from the center of the Earth. A considerable amount of information concerning the Earth's magnetic field and its variation in time is contained in the spherical harmonic coefficients (Gauss coefficients). In particular, the SHA is used to prove that the main field of the Earth originates mostly from processes taking place in the Earth's interior and that only a minor proportion of the field arises from currents in the external environment of the Earth. The analysis of the Gauss coefficients and the wavelengths of features of the non-dipole field indicate that the main field is produced in the fluid outer core of the Earth while the interaction of the Earth's global field with the solar wind and the dynamics of the ionosphere give rise to secondary magnetic fields called "external fields". The fluctuations of these external fields induce currents in the upper Earth which result in tertiary fields called "induced fields".

At any particular place on the Earth the magnetic field is not constant in time. Variations of the geomagnetic field observed at the Earth's surface occur on time scales ranging from milliseconds to millions of years. The variations on timescales shorter than 5 years arise mostly from electrical currents flowing in the ionosphere and magnetosphere, while variations over longer time scales, with periods of years to millions of years, are thought to be due to dynamo processes acting within the Earth's fluid core. These slower changes are generally referred to as the geomagnetic Secular Variation (SV). The study of the secular variation is of particular interest for theoretical development of geomagnetism as well as for the investigation of the Earth's core and the processes taking place there. The geomagnetic field is due to a complex system of motions within the core, and changes in the geomagnetic field on a certain time scale as revealed by the secular variation, may reflect dynamic features of fluid core motion. Consequently the study and the characterization of the secular variation allows us to probe various physical properties of the Earth's deep interior. For instance, the secular variation provides an image of the motion pattern in the fluid core, at least close to its surface, and constrains models of field generation by dynamo action. Furthermore, the secular variation appears to be correlated with other global geophysical parameters, such as the rotation velocity of the Earth's mantle, thereby providing information on the couplings between the core and mantle. The variations of the field are also being used to model deep Earth conductivity structures. The study of the secular variation is thus inextricably linked with studies of the dynamics of the Earth's deep interior and in particular with dynamical processes occurring in the liquid metallic core of the Earth.

The boundary between external and internal sources for the production of the geomagnetic field is still not accurately known. Formerly it was believed that a separation could be made in the frequency domain, with a cut-off period of approximately four years. Below this value core variations are screened out by an electrically conducting mantle and are consequently unable to penetrate its full thickness. However, the quasi-cyclic nature of solar activity, together with seasonal effects, leads to the modulation of the external and therefore the induced fields on time-scales of up to a decade or so. Therefore, even accepting this cut-off period of about 4 years, there is an overlap of external field time scales with those of the core field variation. This overlap became more evident after the recognition of the internal nature of the geomagnetic jerks that occur on time-scales of a year or two.

2 Geomagnetic jerks

A "geomagnetic jerk" or "secular variation impulse" can be defined as a rapid change, taking place in a year or two, in the slope of the secular variation of a field component. This would appear as a spike in the third time derivative of the field, or as a step-function in the second derivative (see Figure 1).

The first jerk was identified in 1978 by Courtillot *et al.* (1978), who discovered that a rapid change in the secular acceleration of the geomagnetic field had occurred nine years earlier at the French observatories. Subsequently, Le Mouël *et al.* (1982) and Malin *et al.* (1983), studying an extensive set of observatory records, showed that this event was observed worldwide, though it was not evident in all magnetic field components, depending on geographical location.

Similar rapid fluctuations in the measured magnetic field were well known. Many sources outside of the Earth, such as magnetospheric and ionospheric currents, were known to generate magnetic fields and to induce electric currents to flow in the mantle and, consequently, to modify the magnetic fields generated in the Earth's core. The geomagnetic jerk, however, seemed to be something new. This fluctuation was not generated by external sources but clearly originated in the Earth's core. Malin and Hodder (1982), using the spherical harmonic analysis, separated the internal and external contributions to the field and concluded that most of the jerk was created within the Earth. The internal nature of the geomagnetic jerk has made this event a key factor in understanding the Earth's internal dynamics. An understanding of the jerk and its space-time distribution is, indeed, directly associated with the solution of the main problem of geomagnetism *i.e.*, the origin of the magnetic field and its variations and with the evaluation of the electrical conductivity of the lower mantle and the verification of hypotheses regarding the internal nature of the Earth.

There is still some controversy in the scientific community concerning the jerk especially in terms of the time duration of the impulse and whether this phenomenon is worldwide or local. Some of the scientific controversy concerning the jerk is perhaps a result of the difficulty in distinguishing between fields of internal and external origin in the data as well as difficulty in distinguishing between these fields and noise. Noise in this case is defined as errors due to instrument drift and malfunction, calibration errors, manmade magnetic signals, and possible errors in the data processing that leads to annual means.

Today there is evidence in the magnetic record that jerks have occurred several times this century. Alexandrescu *et al.* (1996), using a wavelet analysis technique for the detection of the geomagnetic jerks, concluded that seven events (in 1901, 1913, 1925, 1932, 1949, 1969, and 1978, respectively) apparently occurred throughout the world during the present century. Golovkov *et al.* (1989), using a different method of analysis, listed two more jerks, one in 1958, the existence of which seems also to be supported by the study of Jackson (1997), and another between 1938 and 1940, confirmed by McLeod (1989) and Jackson (1997). Finally, we must take into account also the most recently discovered jerk: the 1991 event (Cafarella and Meloni, 1995; Macmillan, 1996; De Michelis *et al.*, 1998). Figure 2 shows the trend of the Y component secular variation (Y') as recorded at two different observatories (Hartland (HAD): lat. 50.995°, long. 355.517°; Honolulu (HON): lat. 21.32°, long. 201.998°) in which are clearly evidenced all the jerks of this century.

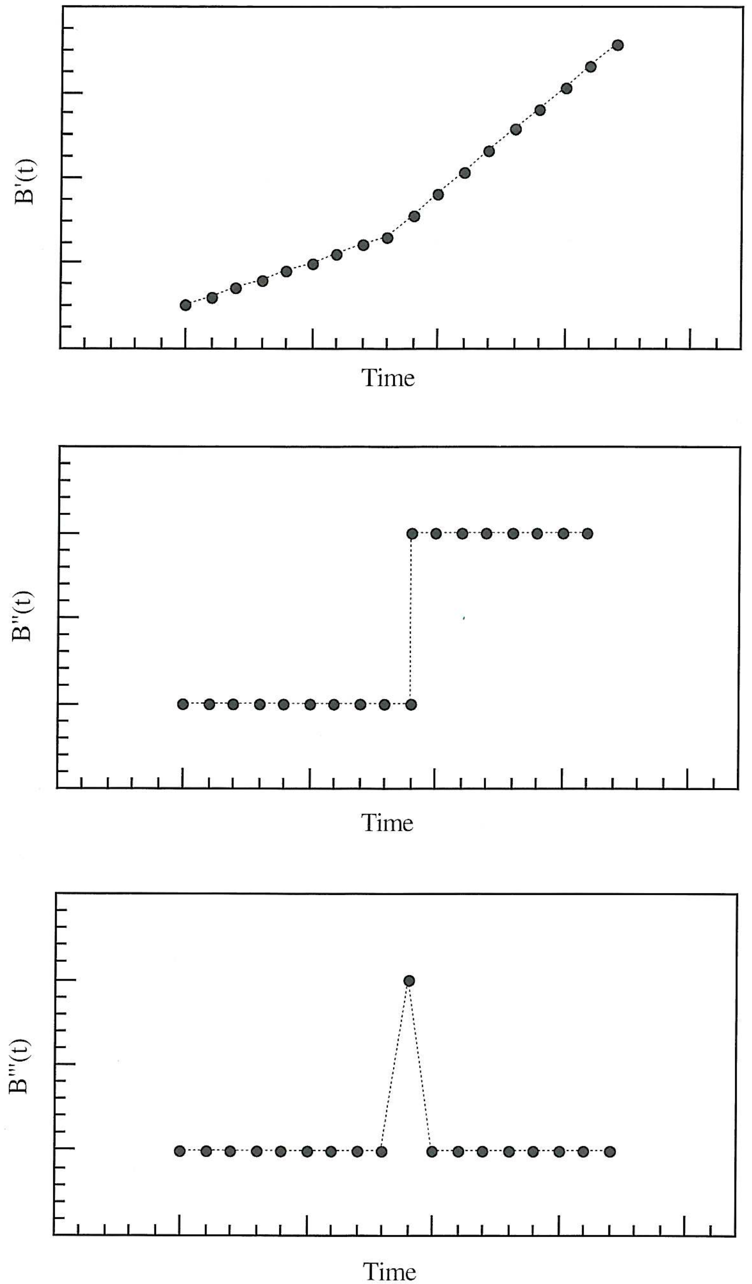
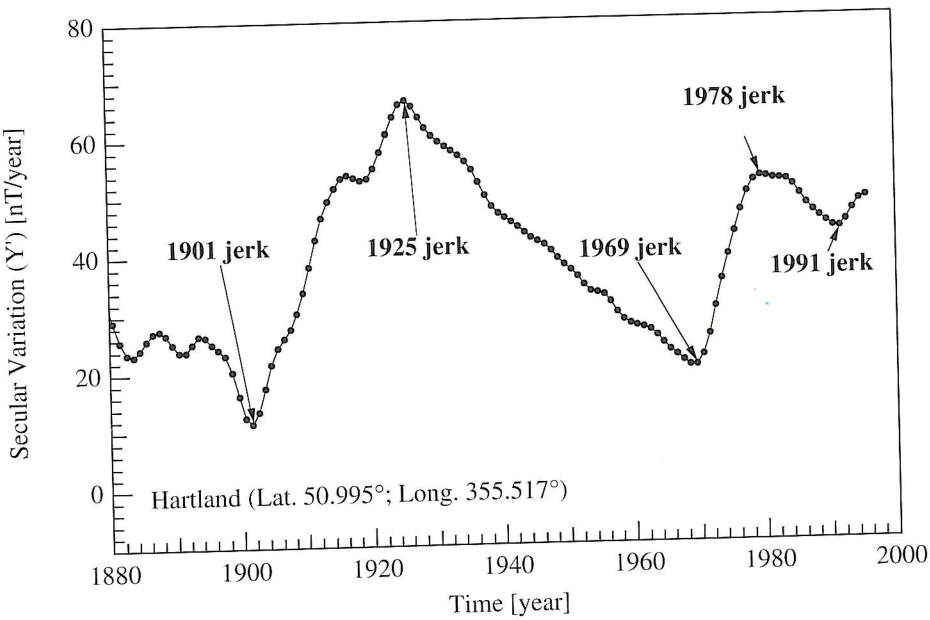


Figure 1 A schematic picture of the occurrence of a jerk event in the secular variation and in its derivatives.



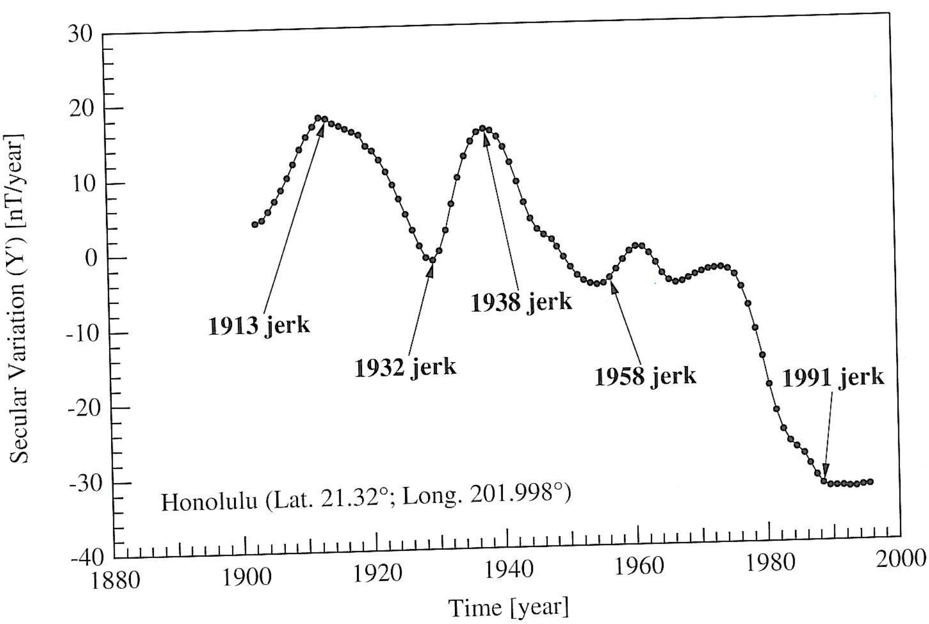


Figure 2 Temporal trend of the *Y* component secular variation (*Y'*) as recorded at two different observatories (Hartland (HAD): lat. 50.995°, long. 355.517°; Honolulu (HON): lat. 21.32°, long. 201.998°). In these trends are clearly evidenced all the jerks of this century.

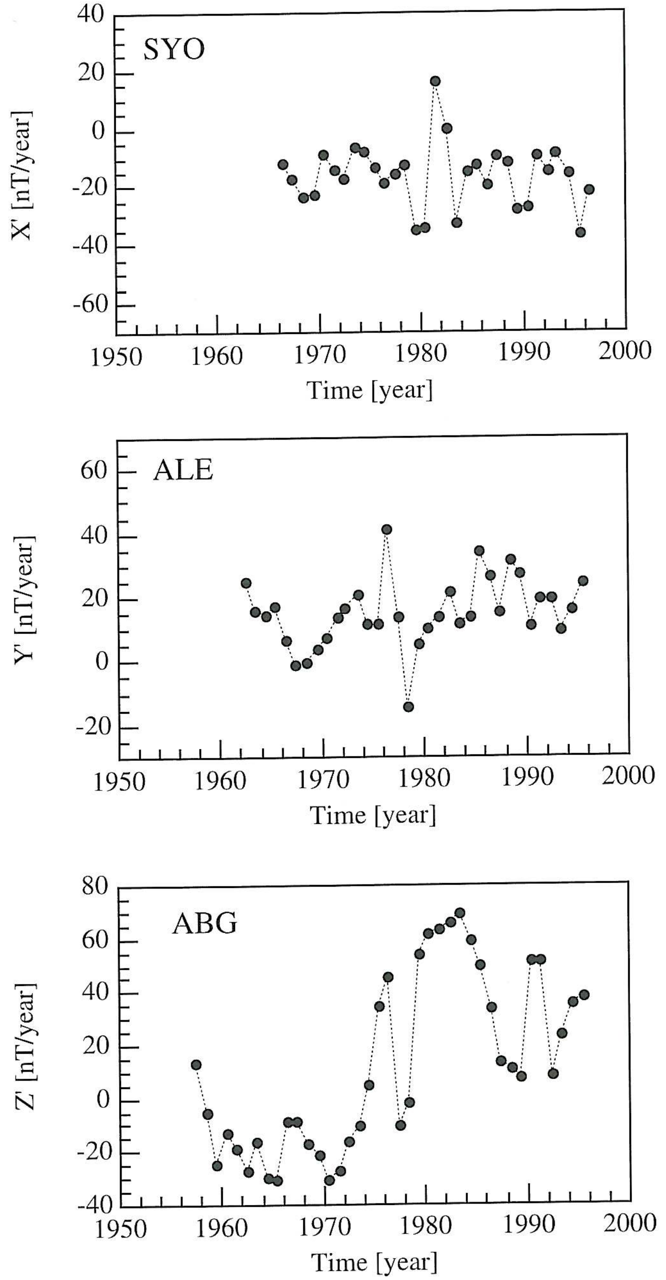


Figure 3 Plots of the first time derivatives of magnetic field components showing some examples of observatories with problems in base-line control (Syowa Base (SYO): lat. –69.007°, long. 39.59°; Albert (ALE): lat. 82.497°, long. 297.647°; Alibag (ABG): lat. 18.638°, long. 72.872°).

3 Data analysis and results

Data for analysis of the jerk phenomenon come from the National Geophysical Data Center in Boulder, CO. This database contains annual means based on daily measurements for more than 197 observatories worldwide. However, for the purpose of this study, important criteria in data selection are the length, continuity and quality of the magnetic field records. This means that it is necessary, for example, to remove from the database all those time series for which the annual mean values around the jerk years are not available or for which only absolute values are reported. All those observatories with problems in base-line control were also discarded. This defective base-line control generates sharp, erratic fluctuations in the secular variation curves that are often numerous and large and consequently prevent a good analysis of the signal (Figure 3). To analyze simultaneously the last three geomagnetic jerks (1969-1978-1991) it is also important to use the same data set for each jerk and therefore to select only those observatories having three-component vector data during the interval from 1960 to at least 1994. Applying these criteria reduced to about 80 the number of observatories available (Figure 4). An inspection of their geographical locations reveals that they are widely, although not uniformly, distributed throughout the world. The number of observatories which are located in the Southern Hemisphere is very low and there are certain areas with very poor coverage.

To study the jerk phenomenon it is necessary first to remove the effects of external fields such as that due to the interaction between the solar wind and the Earth's magnetosphere from the data. To do this, different methods have been

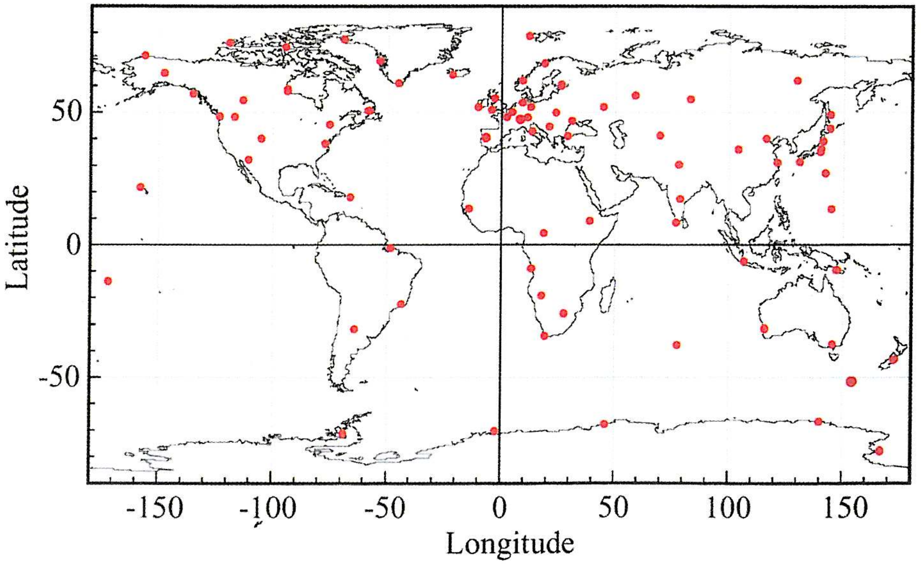


Figure 4 Map of the locations of the selected observatories used in our study.

proposed (see, for example, Walker, 1982; Gavoret *et al.*, 1986; McLeod, 1992; Stewart and Whaler, 1995). We have decided to construct a deterministic model of geomagnetic time series, incorporating an *a priori* characterization of the average effect of the external fields. The external part of this model can then be subtracted from the observed field and what is left can be considered a better estimate of the time varying core field. The external signal is identified by comparing the long-term variations of the components of the geomagnetic field at different observatories with the long-term variations of some geomagnetic indices devised to characterize the different external source fields. In particular we have used the geomagnetic indices *Dst* and *aa*, which are correlated with transient and recurrent phenomena of solar activity in different ways, and the Wolf number *R* which takes into account the modulation of the amplitude of the solar daily variation (see Figure 5).

Figure 6 shows the results of our method as applied on three magnetic field components and the corresponding secular variation at Niemegk (NGK) observatory. This figure shows a change of slope in the secular variation in all the three magnetic field components around 1969, 1978 and 1991. A preliminary examination of the secular variation trends at the observatories reveals that this behavior is present in many of them. This change of slope occurs in different years depending both on the geographic location of each observatory and the magnetic field component.

In order to analyze the geographic extent of the V-shaped pattern in the signal and to evaluate the intensity of the corresponding discontinuity in the secular acceleration, the secular variation time series are fit using a bilinear functional form

$$\begin{cases} a_1(t - t_j) + d & t < t_j \\ a_2(t - t_j) + d & t > t_j \end{cases}$$

where a_1 and a_2 are the average slopes of the secular variation before and after the jerk event respectively, while t_j is the time of the jerk event. In this first order approximation we can express the intensity of the secular acceleration discontinuity as the difference between the average slope of the secular variation before and after the jerk event.

Figure 7 shows the maps for $\Delta Y''$ values expressed in (nT/year^2) for the 1969, 1978 and 1991 jerks. In order to compute these maps, $\Delta Y''$ data have been firstly reduced on a regular grid using a weighted four most nearby points interpolation scheme with constrain of a spherical harmonic symmetry. Successively the resolution was enhanced by means of a bilinear interpolation. The resulting plates were also filtered using a 3×3 Gaussian filter to remove local spikes. The 1969 $\Delta Y''$ worldwide distribution is very similar to that obtained both by Le Mouël *et al.* (1982) and by Malin *et al.* (1983) for the same event. The simultaneous analysis of the maps in Figure 7 shows the existence of some common and interesting features. All maps show the existence of areas with positive and negative values of the $\Delta Y''$ in which there is never found a value of different sign. The distribution of

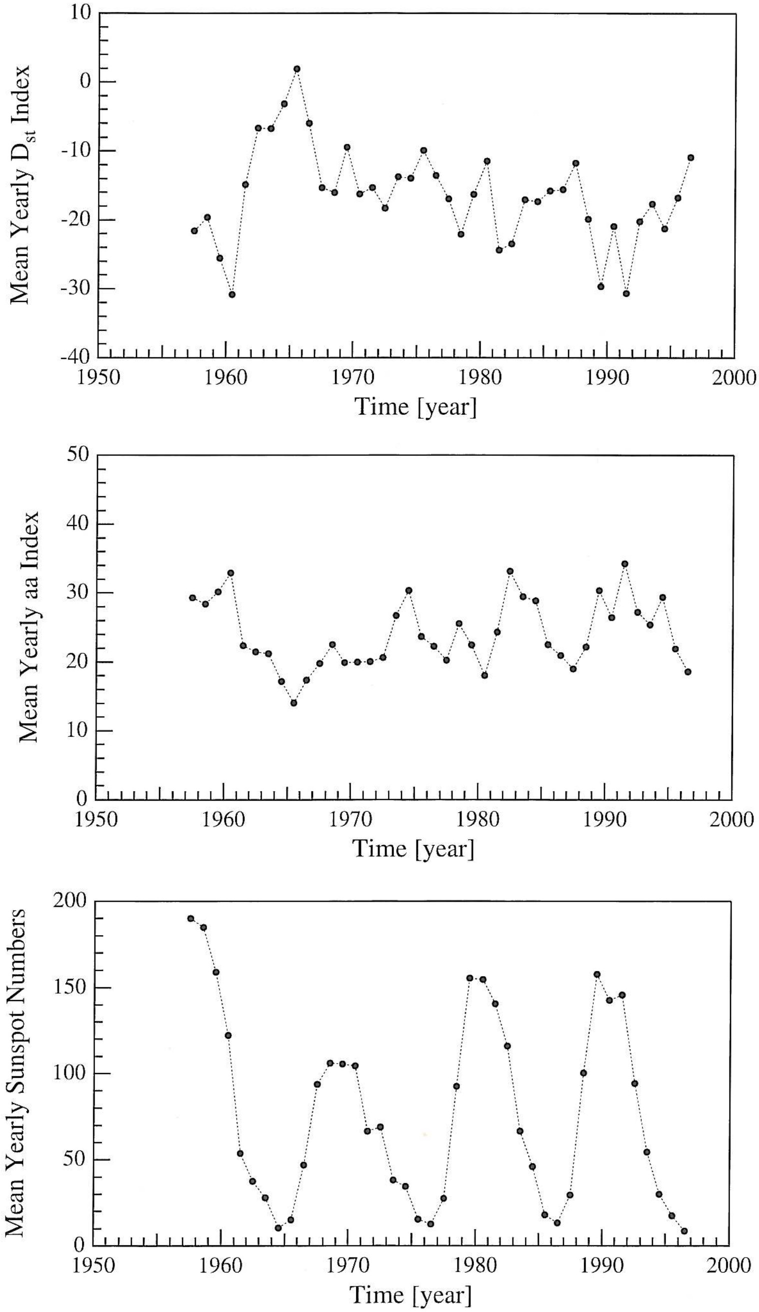


Figure 5 Temporal trend of the geomagnetic indices that we used to characterize the different external source fields.

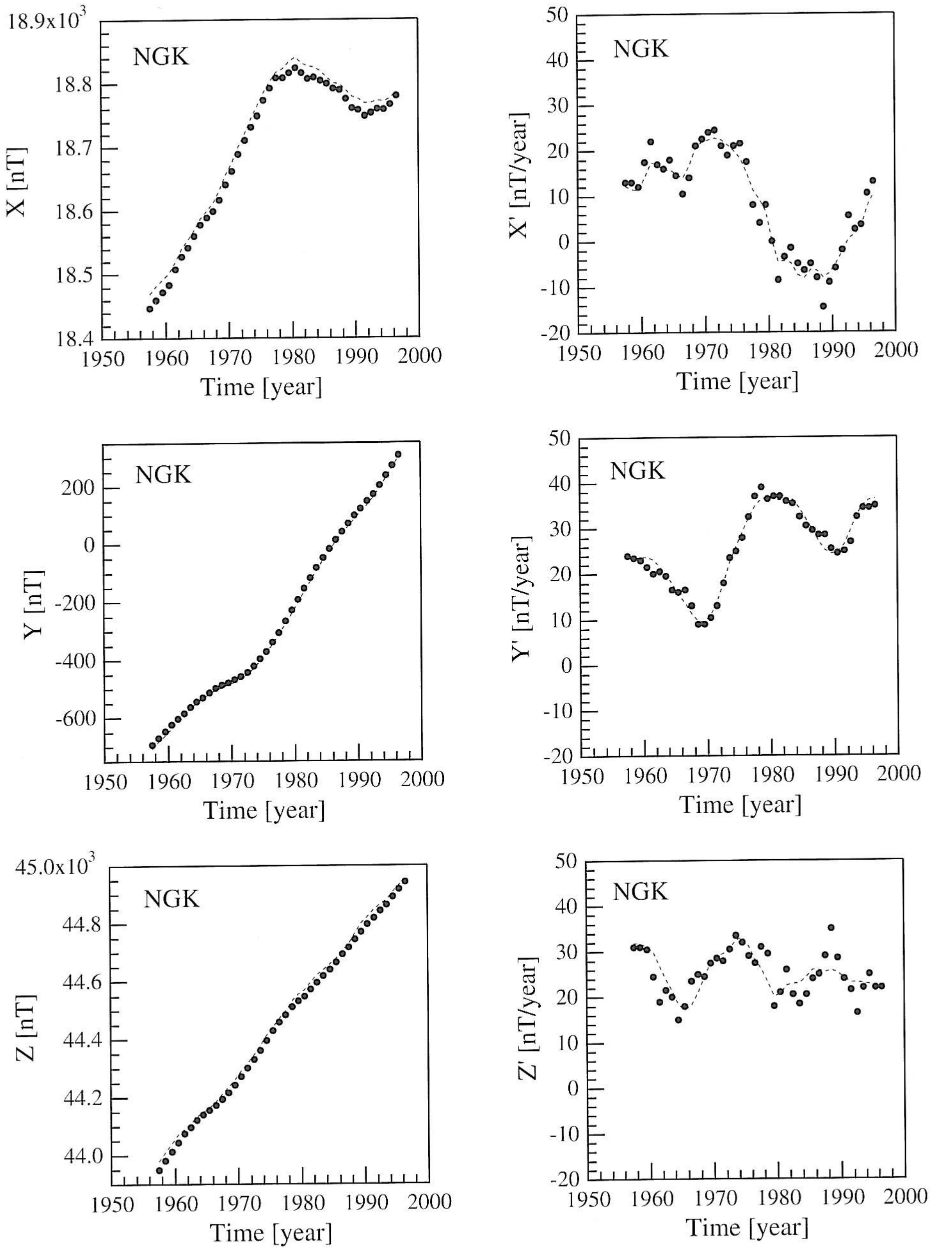


Figure 6 On the left side a comparison between the three magnetic field components recorded at Niemegh (NGK: lat. 52.072°, long. 12.675°) observatory represented by dots and the same components, represented by a dashed line, obtained using our method of external effects de-noising, is reported. On the right side the same comparison is reported for the secular variation.

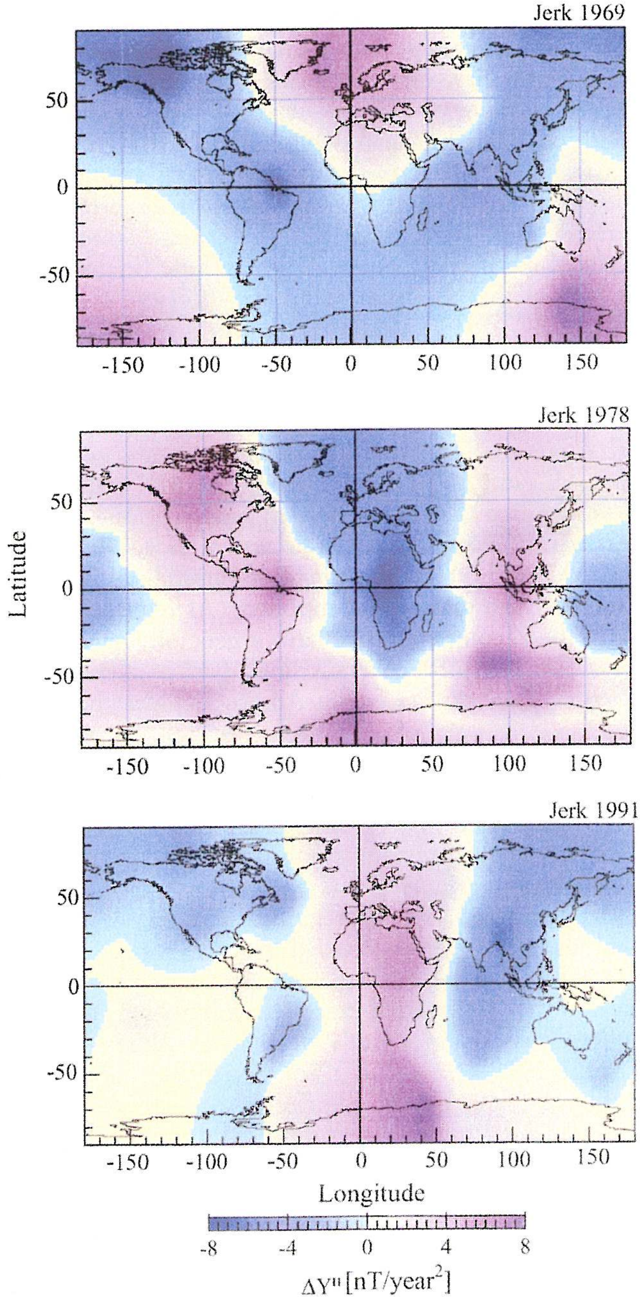


Figure 7 Maps of $\Delta Y'''$ values for 1969, 1978 and 1991 geomagnetic jerks.

jerk intensity is not homogeneous: there are regions where the gradient is not very large while in others the sign change over a small distance occurs. The zero isoline shows similar trends in the three different cases. The zero isolines of the 1969 jerk are remarkably similar to those of 1978 event as if the two events tend to balance each other, as already noted by Steward (1991) on the basis of an entirely different analysis. In contrast, the zero isolines of the 1991 event are quite different from the patterns of the other two jerks; this is particularly true in the Southern Hemisphere. This difference could be connected to the values recorded at the available Antarctic observatories whose data often present erratic fluctuations. However it is important to point out that the zero isolines of the 1991 event are remarkably similar to those of the 1912-1913 event (see Ducruix *et al.*, 1983).

For the 1991 geomagnetic jerk we have extended the analysis of the spatial distribution of the jerk intensity to the other two magnetic field components (X and Z). We used a scalar approach to analyze the three magnetic field components, meaning that we analyzed these three components separately. Figure 8 shows the maps for $\Delta X''$ and $\Delta Y''$ values. The map of $\Delta X''$ values shows the presence of a large positive area that joins the two polar regions, passing essentially over Northern America, Greenland, Europe and Africa. The only analogy between the maps of $\Delta X''$ and $\Delta Y''$ is the range of variability of the jump intensity that is generally smaller than that of Z component. As regards the map of the intensity of the jerk in the Z component we have a generally negative intensity with four positive lobes. The first lobe covers a small part of North America and all Greenland, the second lobe covers South America, while the others reach the equatorial region.

Figure 9 shows the contour maps of the distribution of the time occurrence for the Y component of the last three jerks of this century. These maps computed using the same procedure as in the jerk maps (Figures 7 and 8). The white region represents the mean time of occurrence of the examined event. With respect to this white region, the blue regions represent regions where the jerk has been observed in advance while the red ones the regions where the jerk has been recorded later. From the analysis of these time occurrence distributions it is possible to note that the 1969 and 1978 global events display a particular spatio-temporal behavior with an early arrival in the Northern Hemisphere followed by a later arrival in the Southern Hemisphere (time lag of about 2 or 3 years). As regards the map of the time occurrence of the 1991 jerk on the Y component, we have always a bimodal character but in this case it is due to a different occurrence time primarily between European, Asian and African observatories and the others.

4 Summary

The analysis of the temporal behavior of the secular variation in the last thirty years, carried out on about 80 observatories widely distributed all over the world, clearly shows the existence of three geomagnetic jerks around 1969, 1978 and 1991, respectively.

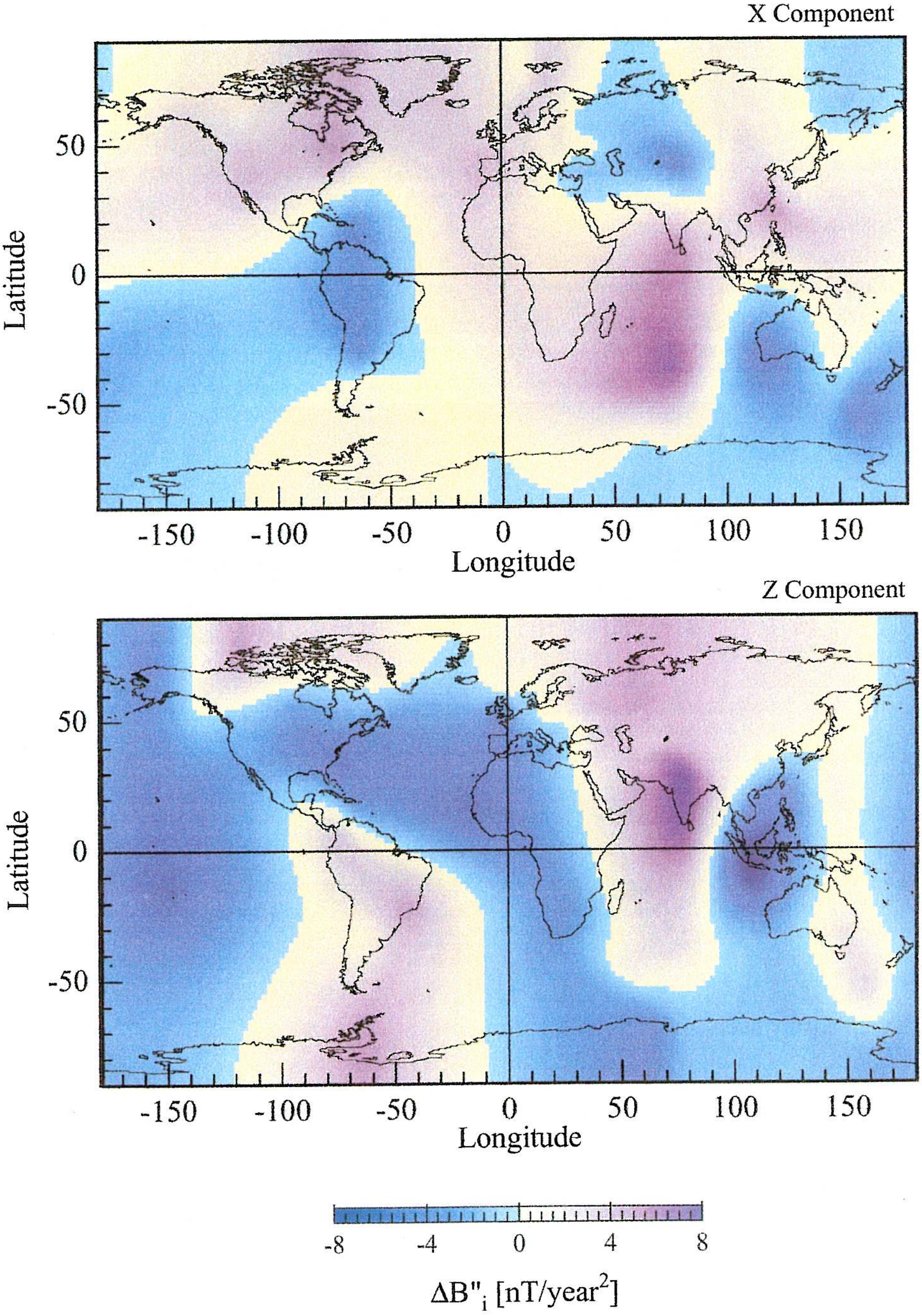


Figure 8 Maps of $\Delta X''$ and $\Delta Z''$ values for the 1991 geomagnetic jerk.

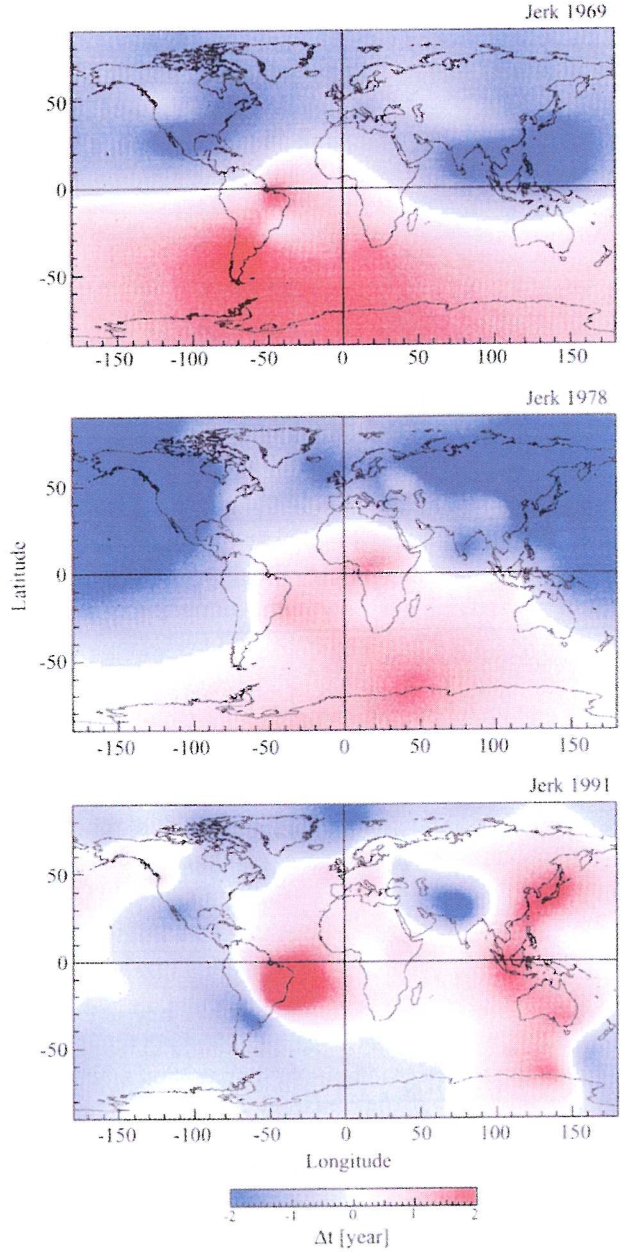


Figure 9 Map of the distributions of the time occurrences in which every single jerk is observed in the *Y* magnetic field component. The white zone represents the mean time occurrence of the examined event. With respect to this white zone the blue zones represent the regions where the jerk has been observed in advance while the red ones the regions where the jerk has been recorded later.

In order to study the jerk phenomenon and in particular to describe its morphological characteristics we studied the distributions of intensity of the secular acceleration discontinuity as well as the distributions of the time occurrence of these three jerks. As regards the maps of the distribution of the secular acceleration discontinuity intensity ($\Delta Y'''$), we noticed that the zero isoline shows similar trends in the three different jerks. It seems that, at least in the case of the Y component, the secular acceleration discontinuity intensity appears with a similar structure independent of its sign. From the analysis of the time occurrence maps we can claim that, even if the jerk appears on a global scale, its time occurrence is not simultaneous all over the world. The distribution of the years in which the last three magnetic events of this century were observed shows a bimodal character. This bimodal character of the distribution of the jerk occurrence times seems to be correlated with a different occurrence time for Northern and Southern Hemisphere in the case of 1969 and 1978 events, while for the 1991 event it seems to be correlated to a different occurrence time between the Northern and Southern America observatories and the others.

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