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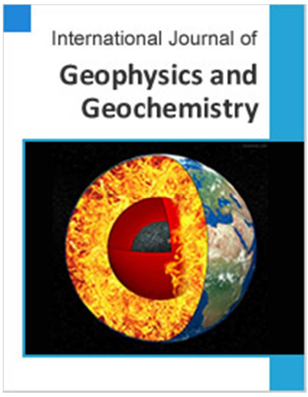

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Relation between Differential Delay Times of Geomagnetic Jerks and Lateral Variations in Mantle Heat Flow

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Abstract
An analysis of available data derived from ground based geomagnetic observatories and satellites have been carried out with the purpose of investigating the characteristics of differential time delays of abrupt changes (jerks) in secular variations of the geomagnetic field. The results obtained, confirm the conclusions of recent studies that geomagnetic jerks are not worldwide in occurrence and that the arrival times of jerks over the last four decades are not simultaneous, but situated around the years of 1971, 1980 and 1991. Empirical relations derived from best fit curves to data sets indicate that the time scales for growth and propagation of magnetic disturbances in toroidal ring currents are of the order of 2.4 to 3.0 years. A similar time scale is also observed for time delays associated with transmission of geomagnetic disturbances within the deeper parts of the toroidal ring current systems. In the present work we have extended this conventional approach and attempted a joint interpretation of global data sets on mantle heat flux with those of the Comprehensive Mapping – CM4 models. The results obtained point to a significant correlation between the differential delay times of jerks and mantle heat flux. The optimal solution for the best fitting correlation has a value of 2.6 years for intra ring growth time, 3.0 years for inter-ring propagation time and 265 for the exponential scale factor. This value of intra ring growth time is comparable with that proposed in the recent literature for the reorganization time of flow pattern in loop systems of the outer core. Clearly, the attenuation effects of sub-lithospheric thermal field must be taken into consideration in assessment of jerk delay times. The correlation has been interpreted as providing new insights into processes occurring in the toroidal ring currents in the outer core and also into propagation through the deeper parts of the ring currents. It provides a better understanding of short-term fluctuations of the core magnetic field and in development of numerical models of core dynamics.

1. Introduction

According to consensus in modern geomagnetic research large parts of the Earth's magnetic field are generated by fluid motions in the molten outer core [1, 2, 3]. Data acquired at ground based observatories over the last centuries and results of continuous satellite measurements since 1999, have allowed detailed space-time descriptions of the Earth's magnetic field and its variations. These data have recently been used to investigate small-scale core flow but only a few efforts has yet been made of the improved temporal resolution, partly because the filtering effect of the electrically conducting mantle mask short-period magnetic variations.

It has been observed that the rate of secular variation of geomagnetic field occasionally undergoes rather abrupt changes, referred to as Jerks. Such events have been detected in geomagnetic time series, centered approximately on the calendar years of 1971, 1980, 1991, and 1999. Others have been inferred from historical records. The geomagnetic secular variations are believed to represent a reorganization of deep seated field components and imply an internal origin, as established through spherical harmonic and wavelet analysis [4, 5].

Nevertheless, some characteristics of abrupt changes in secular variations (ACSV), such as differential time delays in the records of geomagnetic observatories, are not well understood. Apparently, part of the problem stems from limited knowledge of attenuation of magnetic disturbances in the mantle overlying the core. In the present work, we have attempted a joint interpretation of results of the Comprehensive Mapping – CM4 model [6] of geomagnetic field as well as global data sets on mantle heat flux. Here we show that additional insights into the nature of this problem can be obtained by studying the correlations between differential time delays of jerks and sub-lithospheric mantle heat flux.

2. Geomagnetic Data Used in the Present Work

The geomagnetic data sets available at the web site INTERMAGNET (International Real-Time Magnetic Observatory Network), established by the British Geological Survey in common agreement with the International Association of Geomagnetism and Aeronomy - IAGA, has been the main source of information used in the present work. Currently 108 observatories situated in 42 countries take part in the joint activities of the INTERMAGNET. Most of the data are acquired in intervals of one minute and has a resolution of 0.1 nanotesla (nT). Fig. 1. indicates the locations of ground based geomagnetic observatories considered in the present work.

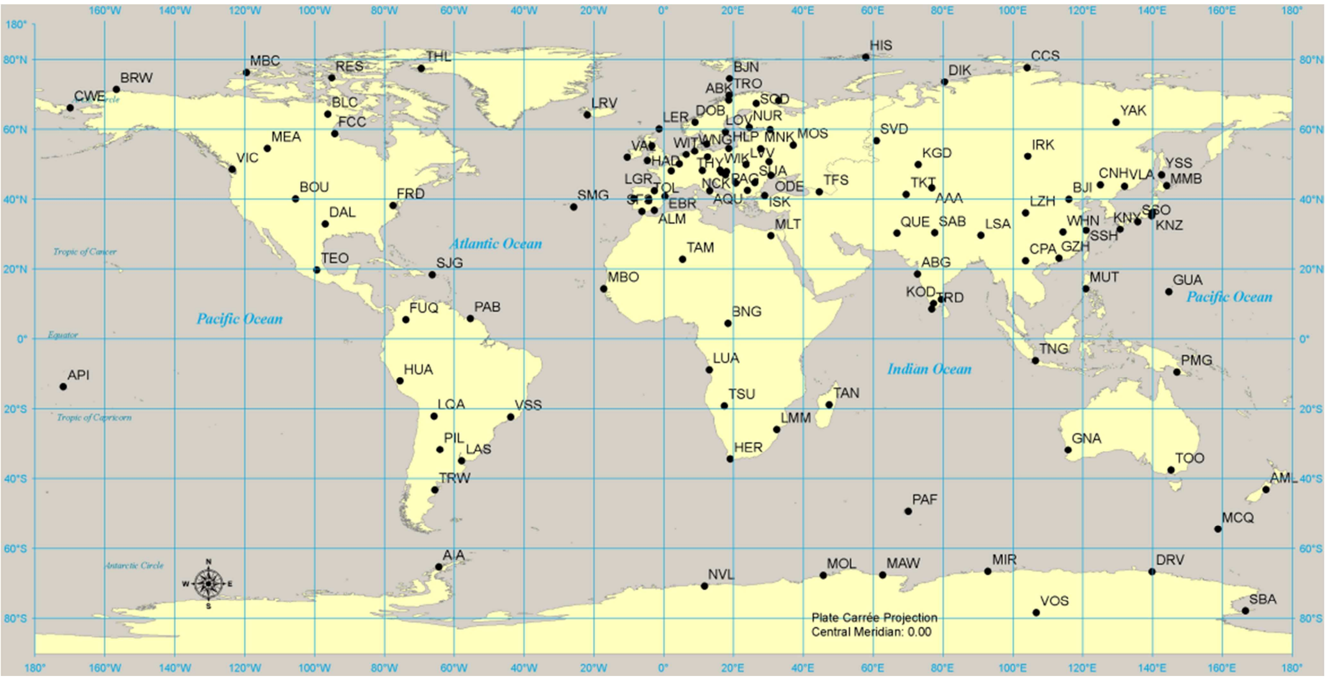

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Fig. 1. *Locations of 108 ground based geomagnetic observatories considered in the present work.*

Most of the primary analysis of the geomagnetic data in the present work has been carried out using the Comprehensive Mapping Model – CM4 [6]. This model make use of annual differences of ground observatory monthly means (from the years 1970 to 2006) as well as data acquired by the satellites Ørsted, CHAMP and SAC-C to derive a model of the Earth's magnetic field. It provides a satisfactory description of more than 95% of the temporal variance in the Earth's magnetic field. It is therefore reasonable to consider CM4 model as a suitable tool to investigate rapid changes in magnetic field of internal origin, and examine its implications for short-period core motions. In particular the ability of this model to explain the temporal changes of the core field on millennium time scales (known as secular variation) are well known. In the present work we make use of this data set in examining the characteristics of abrupt changes in secular variation (ACSV) of the magnetic field recorded in 108 0bservatories.

3. Abrupt Changes in Secular Variations (ACSV)

Secular variation is often described as a relatively slow but significant change in the declination of the Earth's magnetic field. It is considered as related to changes occurring in the convective cells in the outer shell of the liquid core. Observational data acquired in geomagnetic observatories point to occurrence of relatively occasional abrupt changes in secular variations (ACSV), designated also as Jerks. Fig. 2. illustrates examples of ACSV observed in the Y component of the geomagnetic field observed in 1969 and 1978 at the Vassouras Observatory (VSS-BR) in Brazil. In this figure the black lines indicates the best fit and the dotted lines indicate fits for earlier and later dates. Similar events have been observed in records of the year 1990.

The identification of ACSV is made by linear least square fits to first differences in mean annual B field. The amplitudes of ACSV are evaluated by considering the differences in the inclinations of consecutive linear segments. Obviously, the identification of ACSV depends to a large extent on the method used for selection of the data segments. A summary of the methods used in analysis of ACSV is presented in Table (1), where the method used in the present work is highlighted in yellow color.

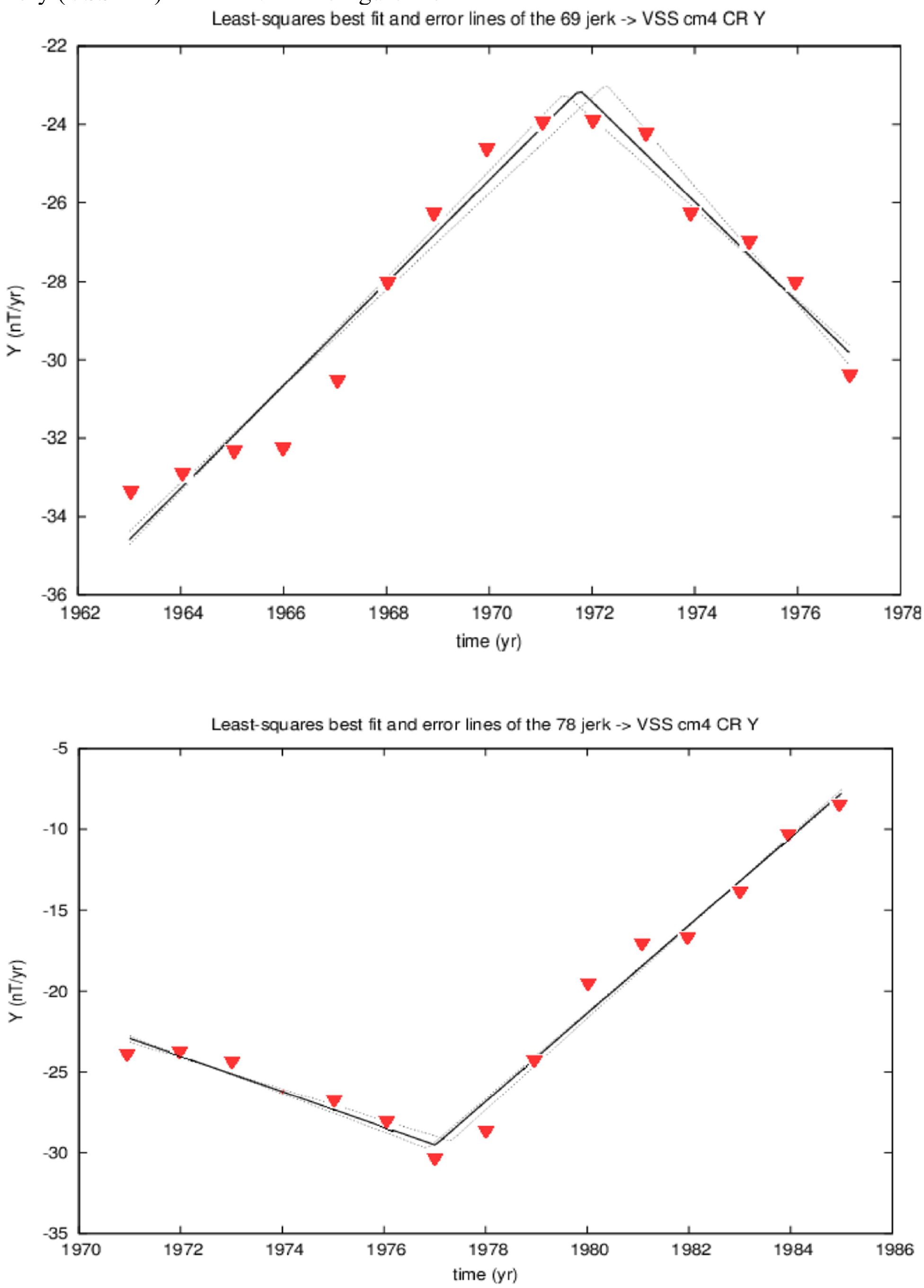

Fig. 2. The Y component of ACSV, calculated from data records for the years 1969 and 1978, at the observatory in Vassouras, Brazil (VSS-BR).

Table. 1. *Methods employed in analysis of abrupt changes in secular variations (ACSV) of the geomagnetic field.*

Method	Data Type	Year of ACSV	Reference
Least squares	Annual Means (X, Y, Z)	1969	[7]
Least squares	Annual Means	1969, 1978, 1991 global	[8]
Wavelet analysis	Monthly means: Linear combination of *X* and *Y*	1901, 1913, 1925, 1932, 1949, 1969, 1978	[5]
Least squares	Annual Means (*X, Y, Z*)	1991 global	[9]
Visual	Monthly means (*Y*)	1999	[10]
Statistical model Least squares	Monthly means (*X, Y, Z*)	1969, 1978, 1991 global	[11]
Wavelets; Least squares	Monthly means (*Y*) and CM 4 data	1969, 1978, 1991 global (?)	[12]
Wavelet analysis	Monthly means	1978, 1991, 1999 global, 1986 local	[13]
Har. Expansion – Least squares	Satellite, Monthly means	2003	[14]
Least squares	Annual and Monthly Means and CM4 data	1969, 1978, 1991 global	[15]
Least trimmed squares	Annual means	1969, 1978, 1991 global	[16]

Table 2. *Number of records of X, Y and Z components of jerks commonly identified as associated with the 1969, 1978 and 1991 events.*

"1969" Event				"1978" Event				"1991" Event			
Calendar	Components			Calendar	Components			Calendar	Components		
Year	X	Y	Z	Year	X	Y	Z	Year	X	Y	Z
1964	0	2	0	1973	0	1	0	1987	6	0	4
1965	1	4	3	1974	14	0	8	1988	9	7	4
1966	6	2	2	1975	20	6	13	1989	7	10	1
1967	6	3	4	1976	12	13	17	1990	3	11	6
1968	8	19	1	1977	17	49	15	1991	7	16	10
1969	7	47	16	1978	6	21	7	1992	10	19	6
1970	22	22	25	1979	3	7	8	1993	8	14	15
1971	9	10	17	1980	4	3	14	1994	22	7	18
1972	10	3	15	1981	2	13	8	1995	14	9	11
1973	4	3	11	1982	5	7	6	1996	9	5	10
1974			8	1983	5		7	1997		1	2
1975			3	1984	1		1				
Total	73	115	105	Total	89	120	104	Total	95	99	87

In the present work we employed the LTS (Least Trimmed Squares) method, in which points with large residuals are removed following a criteria based on the Spearman coefficient (ρ):

$$\rho = 1 - 6\frac{\sum_i d_i^2}{n(n^2-1)} \quad (1)$$

In the above equation d_i refer to the difference between the mean and observational values and n the number of data.

In the present work, this procedure was adopted to identify occurrences of ACSV in records of 116 geomagnetic observatories. Table (2) provide numbers of observatories which have recorded X, Y and Z components of jerks usually identified as associated with the "1969", "1978" and "1991" events. Note that the times of occurrences of these events span over several years.

4. Delay Times of Jerks

Examination of records of geomagnetic observatories reveals that not all jerks are recorded globally. A well-known case is the jerk recorded in 1932 in many observatories of the southern hemisphere, but absent in records of the northern hemisphere. On the other hand, the best-studied jerks of global extension, occurred around the years 1969, 1978 and 1991, are recorded in many observatories of the southern hemisphere with delay times of 2 to 3 years, relative to those of the northern hemisphere. It has been proposed that the non-simultaneous behavior is a consequence of differences in arrival times of the jerks [12, 17]. The analysis of delay-times of jerks has been considered important in studies of constraints of the electrical conductivity of the lower mantle [18, 19, 20, 21].

In the present work, we report progress obtained in analysis of delay times of jerks occurred in 1969, 1978 e 1991. The delay times are defined as the difference between the time of occurrence of any specific jerk event and the global mean value of the selected event. The calculations were carried out by direct analysis of observational data sets and the series constructed using spherical harmonic model CM4 [6, 12]. A closer examination of the results of differential time delays, derived from the CM4 model, reveals that the magnitudes of time delays vary not only with the components (X, Y and Z) of the geomagnetic field but also with the origin of the source (Following standard convention internal source is designated as CR; and external source is designated as II). In addition, the characteristics of jerks vary from one event to another. Such complexities make analysis of data sets a difficult task.

In the present work the data sets employed for correlation studies refer to jerk events occurred in the years 1970, 1979 and 1992. Unambiguous identification of jerks has been possible for 17 data sets. The maximum, minimum and mean values of delay times in years calculated for the 1969. 1978 and 1991 events are presented in Table (3). The data listed in this table refer to the components of the main (X, Y and Z), core (crX, crY, crZ) and external (iiX, iiY and iiZ) fields.

The spatial distribution of delay times for the Y component of internal origin of the recorded magnetic field are presented in the bar maps of Fig. 3. In this figure the top, middle and bottom panels correspond to the events of 1969, 1978 and 1991. The bars in red color correspond to events with early arrival times while the bars in green color indicate events with late arrival times. The heights of the bars correspond to the value of the jerk delay time in years.

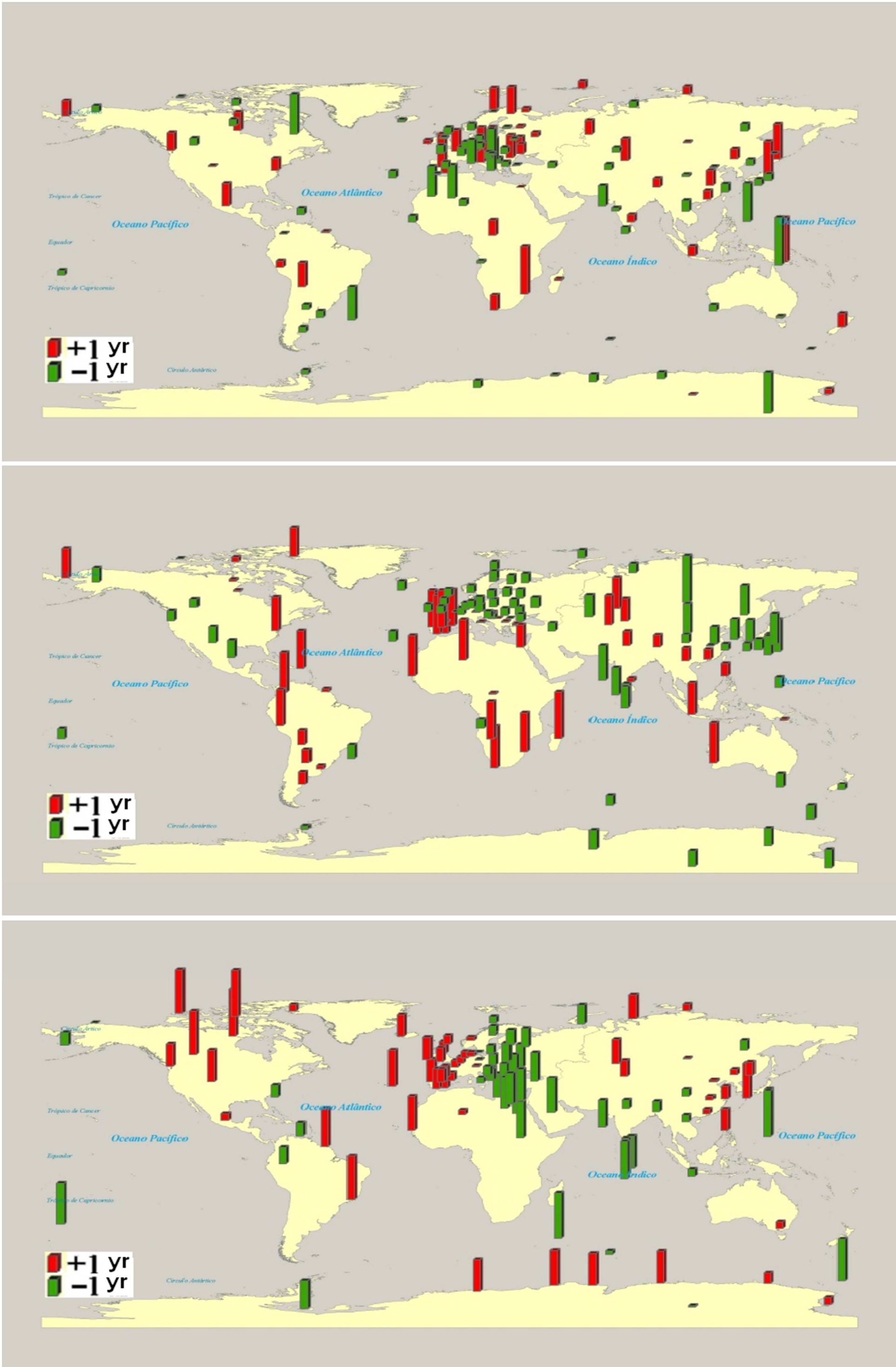

Fig. 3. *Illustrations of differential time delays of the Y component of the internal field for the events of 1969 (top), 1978 (middle) and 1991 (bottom). Bars in red color indicate early events while those in green color indicate later events.*

Table 3. *Numbers (N) and delay times (DT) of jerks occurred in 1969, 1978 and 1991.*

Type	Field			CM4 Core			CM4 External		
	Id	Max	Min.	Id	Max	Min.	Id	Max	Min.
Comp.	69x			69crx			69iix		
Nº	73			112			85		
DT	1,28	3,44	-4,86	1,77	3,75	-4,64	1,44	4,16	-4,25
Comp.	69y			69cry			69iiy		
Nº	95			120			118		
DT	0,57	3,42	-6,11	1,32	4,46	-4,77	1,29	4,46	-4,30
Comp.	69z			69crz			69iiz		
Nº	68			117			105		
DT	2,22	4,95	-4,79	1,49	3,86	-5,08	1,32	3,51	-4,32
Comp.	78x			78crx			78iix		
Nº	57			123			72		
DT	0,79	7,71	-2,41	1,54	6,27	-2,46	0,12	5,54	-2,20
Comp.	78y			78cry			78iiy		
Nº	105			123			117		
DT	1,16	4,97	-3,30	0,36	4,23	-4,56	0,36	3,96	-4,66
Comp.	78z			78crz			78iiz		
Nº	46			113			59		
DT	-0,59	6,49	-3,52	0,32	5,06	-4,35	0,44	3,79	-3,93
Comp.	91x			91crx			91iix		
Nº	35			98			50		
DT	1,78	4,65	-4,91	1,00	3,45	-5,04	0,51	3,32	-3,51
Comp.	91y			91cry			91iiy		
Nº	93			102			96		
DT	1,27	5,74	-3,10	0,40	4,39	-3,93	0,39	4,20	-3,97
Comp.	91z			91crz			91iiz		
Nº	82			92			90		
DT	2,27	4,96	-5,03	1,36	3,33	-5,30	0,03	3,97	-3,78

5. Processes Responsible for Differential Time Delays

Examination of processes responsible for time delays of jerks have been the focus of investigations during last few decades. Foremost among these are the effects of mantle filtering associated with vertical and lateral variations in its electrical conductivity. The relation between mantle's electrical conductivity and characteristics of changes in secular variation was examined by [21]. He presented a model in which mantle is considered as a linear, causal and time invariant filter of field changes occurring in the core. According to this model the input signal is represented by abrupt changes in geomagnetic field at the core-mantle boundary (CMB). Its propagation to the surface is influenced by electrical properties of mantle, which acts as a filter. The output values are the records made at the observatories.

According to the mathematical description of the mantle filter presented by [21] the poloidal scalar coefficient of the magnetic field, in regions external to the core, $P_l^m(a,t)$ may be considered as convolution of the field generated at the core-mantle interphase $p_l^m(c,t)$ with the mantle filter F (l, t) and the geometric filter g (l):

$$P_l^m(a,t) = g(l)\int_{-\infty}^{\infty} F(l,t-t')\, p_l^m(c,t')\, dt' \tag{2}$$

In the above equation l and m are the degree and order of harmonic expansion, a is the Earth radius and c the core radius. The relation for geometric filter is:

$$g(l) = (c/a)^{l+1} \tag{3}$$

The effect of the mantle filter is to delay and smooth the original signal generated in the core. A low frequency approximation was used by [21], which admits a linear relation between electrical conductivity (σ) of the mantle and transit time (τ) for the propagating impulse. According to model results high values of electrical conductivity imply large propagation times and vice versa, in cases where harmonic mixing is not significant [22].

It is clear that the field variations recorded in geomagnetic observatories needs to be corrected for the filtering effects of mantle, in reconstructing the original field generated in the core of the Earth. Temperature plays a major role in determining electrical conductivity and hence it is natural to expect that the effects of mantle filtering be influenced by lateral variations in the mantle thermal field. In the present work, we examine the nature of correlation between jerk delay times and global distribution of mantle heat flux.

6. Combined Effects of Jerk Generation Process and Mantle Filtering

According to recent studies [23, 24] geomagnetic disturbances responsible for secular variations are generated in a system of loop currents the top part of the outer core. Models of time-independent flow in the top parts of the outer core provide satisfactory descriptions of the general features of secular variation, but fail to provide a reasonable account of short-term fluctuations. A combination of steady flow and torsional oscillations (that consist of time-dependent axisymmetric and equatorial symmetric zonal flows) is also unable to explain the short-term fluctuations. Such flows roughly account for field changes at some observatories, but fails at others. In the present work we adopt the general framework of the models [23] that allow us to take into account for the specific features in delay times of jerks. The proposed models are based on the following assumptions:

a) The perturbations responsible for jerks in secular variations get initiated in the current loops in the outer parts of the core. Obviously the location of the loop system is not fixed, different jerk events having specific loops of its own. Though very little information is available on processes operating within such loops it seems reasonable to postulate that the intra-loop growth of this perturbation take place in a time interval (t_G) that is characteristic of the loop convection system. Also, since such perturbations are expected to take place in loop systems operating over large areas of the outer core the overall effect of the growth process may be expected to manifest itself as an initial offset effect on differential time delays of jerks; and

b) The perturbations of the magnetic field in the initial loop system induce related perturbations in the neighbouring loops. Very little information is available on processes responsible for propagation of magnetic disturbances operating between such loops, but it seems reasonable to assume that the intensity of perturbation transmitted from one loop to another decrease with distance from the initial loop. An immediate consequence of this inter-loop propagation of magnetic field disturbances is that the area of jerk producing mechanism spreads out over a large zone in the upper parts of the outer core. The surface projection of this zone determine the areas where jerks would be observed. More importantly, the time for inter-loop transmission (t_P) leads to lateral variations in the origin time of jerks, as recorded at the observatories.

A schematic illustration of the loop system proposed in the present work is provided in Fig. 4. In this figure the loops without color represent those that have not been affected by magnetic perturbations. This zone is described as the shadow zone, the space – time characteristics of which vary with the event under consideration. The surface projection of the shadow zone would determine the areas where jerks are not observed in any particular event.

According to this model the major processes that can potentially contribute to differential time delays of jerks are the characteristic time for growth of magnetic perturbation in the interior of the initial loops (t_G), time for propagation of perturbation between nearby loops (t_P) and the differential effects of velocity changes in propagation induced by lateral variations in the electrical conductivity of the mantle.

One of the convenient forms of considering the influences of such different processes on the differential time delays of jerks (A_{tD}) is through the use of a relation of the type:

$$A_{tD} = t_G \; e^{q t_P / \lambda_l} \tag{4}$$

in which t_G is characteristic time for initial intra-loop growth, t_P is the characteristic time for inter-loop propagation and q is mantle heat flux. The term λ_l is a suitable scale factor that controls the exponential term in equation (4):

$$\lambda_{tl} = \tau_l \, \Phi \tag{5}$$

Note that λ_l has dimensions of J/m^2 and may be considered as the product of reorganization time (τ) and a term (φ) with dimensions of rate of flow of energy density per unit area.

Since sub-lithospheric heat flux is a good indicator of lateral variations in mantle temperatures, attention in the present work is focussed on examination of global data on mantle heat flux and its correlation with delay times of jerks.

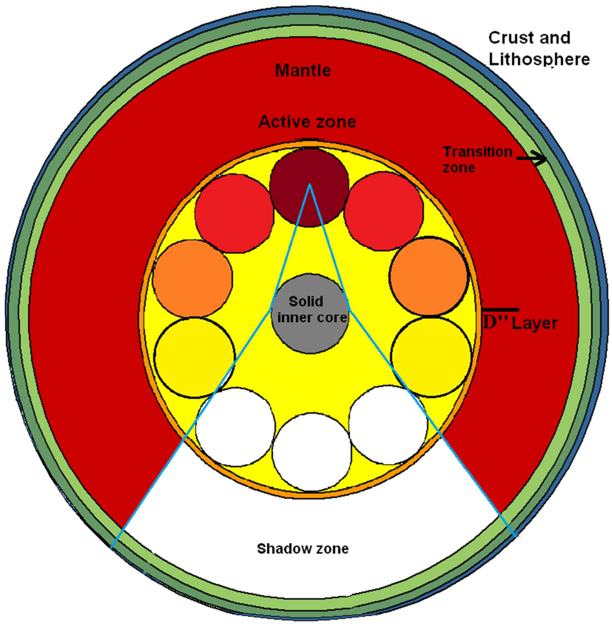

Fig. 4. Schematic representation of current loops in the outer core and appearance of shadow zone in records of geomagnetic jerks. Loops affected by magnetic perturbations are in color, while the ones in white color have not been affected.

7. Mantle Heat Flux

Examination of possible correlations between jerk delay times and mantle heat flow require an analysis of global geothermal data. Prominent among the recent compilations of heat flow data are those reported by [25, 26]. An updated compilation is also available at the web site of the International Heat Flow Commission – IHFC. More recently, [27, 28] reported data sets for surface and mantle heat flow, this latter one derived after making detailed corrections for the varying contributions of radiogenic heat in continental and oceanic regions. Reproduced in Fig. 5. is the map of global mantle heat flow, adapted with modifications from that presented by [28]. It reveals that mantle heat flux is higher than 80mW/m^2 along most of the ocean ridge areas. The continental areas of Asia, Europe, Africa, North America, South America, Australia and Antarctica stand out in general as regions with mantle heat flow of less than 40mW/m^2. Most of the remaining areas of ocean basins and continental margins have intermediate heat flow values.

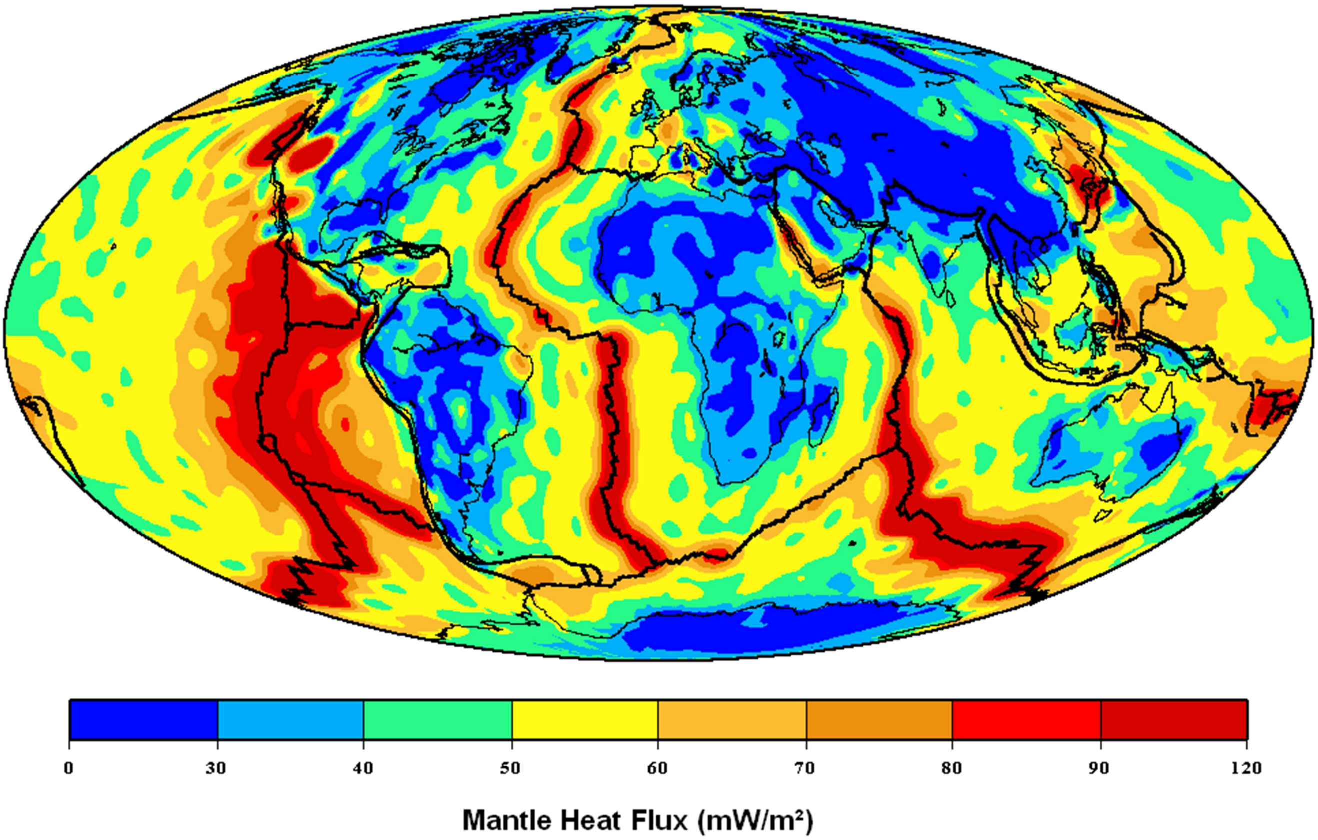

Fig. 5. *Global mantle heat flow derived from surface heat flow after corrections for the varying degrees of contributions of radiogenic heat in continental and oceanic regions (Adapted with modifications from [28]).*

8. Correlation between Delay-Times of Geomagnetic Jerks and Mantle Heat Flux

The availability of mantle heat flow values for a global grid system of 1^o x 1^o has allowed examination of correlation with delay times jerks recorded at sites of geomagnetic observatories. The relation between mantle heat flux and differential delay times has been examined on the basis of data calculated by the CM4 model. We considered five data sets for the 1969 event, six data sets for 1979 event and additional six data sets for the 1991 event. The nature of correlation between mantle heat flux (q) and differential delay times (A_{tD}) for this combined data set is illustrated in Fig. 6. Though there is considerable dispersion in the data sets the general trend of increasing delay times with increase in mantle heat flux can easily be identified. The dashed line in this figure refers to the least square fit obtained for an empirical relation (based on equation 4) with values 1.0 for t_G and 240 for λ:

$$A_{tD} = 1.0 * \exp(q\,t/240) \quad (6)$$

In equation (6) the numerical value of λ of 240 is obtained as the product of inter–loop propagation time (t_P) and energy density (Φ). For example a mean mantle heat flux of 80mW/m^2 would imply a value of three years for t_P.

Improvements in the parameter values of the best fit can be achieved through careful data selection and using least square methods with appropriate weighting schemes. However, there is a trade-off here between the improvement in the correlation coefficient and the undesirable effects of data rejection. The optimal solution, illustrated in Fig. 7. has a value of 2.6 years for t_G, 3.0 years for t_P and 265 for $\lambda_{\tau l}$. Hence the revised best fitting relation between jerk delay times and mantle heat flow is:

$$A_{tD} = 3.0 * \exp(q\,t/265) \quad (7)$$

This value of t_G is comparable with that proposed by [23, 24] for the reorganization time of flow pattern in loop systems of the outer core.

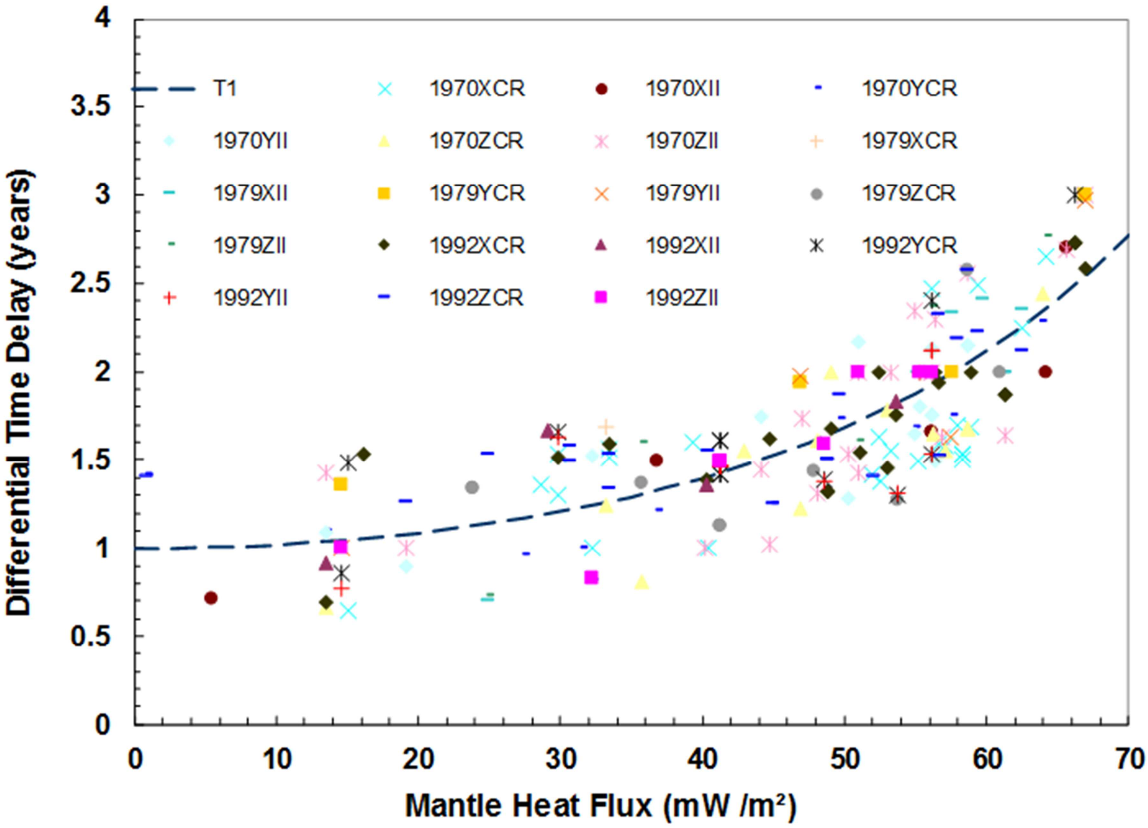

Fig. 6. Correlation between mantle heat flux and differential delay times of geomagnetic jerks for 17 data sets obtained in the present work.

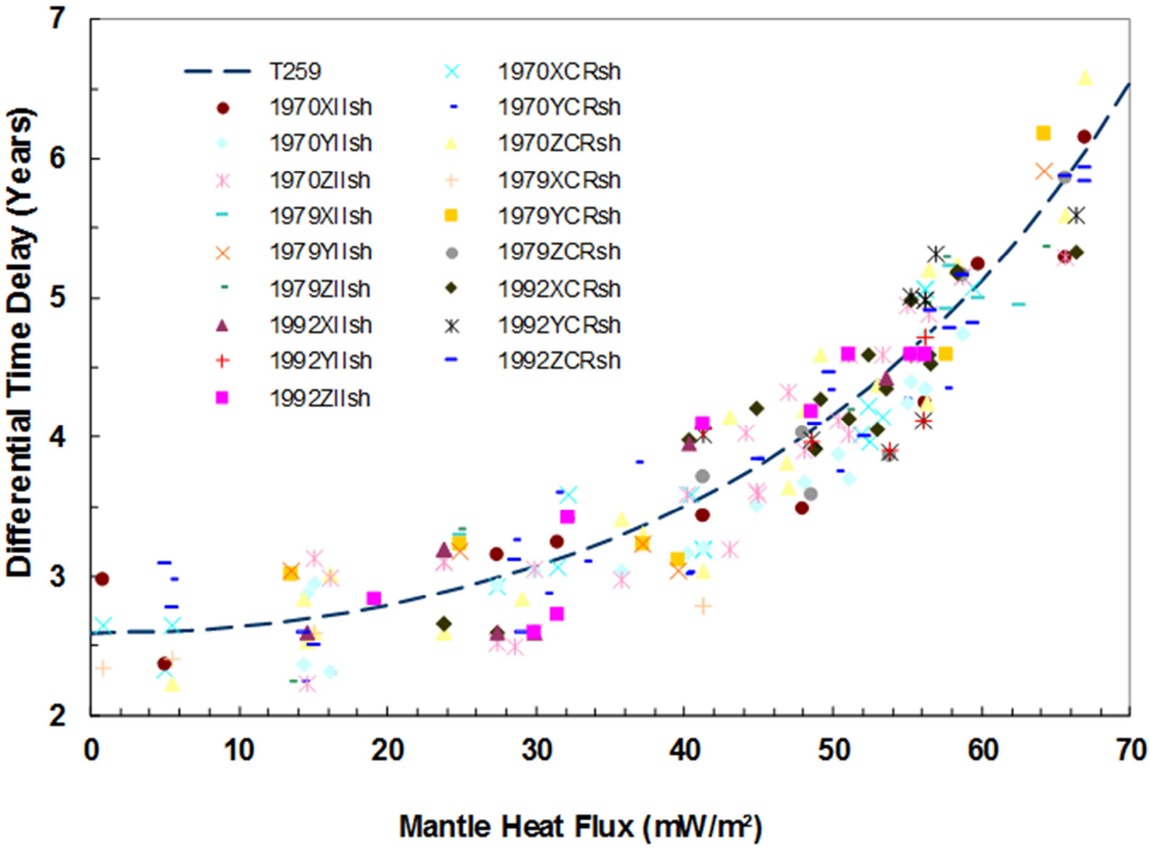

***Fig. 7.** Optimal solution obtained for the relation between mantle heat flux and differential delays of jerks. The dashed line is the fit in which the value for t_G is 2.6 years, that for is t_P 3.0 years and λ_{rl} is 265.*

9. Discussion and Conclusions

The results obtained, confirm the conclusions of recent studies that geomagnetic jerks are not worldwide in occurrence and that the arrival times of jerks over the last four decades are not simultaneous, but situated around the years of 1969, 1979 and 1991. In the present work we have extended this conventional approach and attempted a joint interpretation of results of the Comprehensive Mapping – CM4 model with global data sets on mantle heat flux. The results obtained are interpreted as indicative of the cumulative effects of three distinct processes contributing to the differential delay times of jerks observed at the surface. These include components related to processes occurring in toroidal ring currents in the outer core, propagation through the deeper parts of the ring currents and those associated with lateral variations in mantle heat flux.

Empirical relations derived from best fit curves to data sets indicate that the time scales for growth and propagation of magnetic disturbances in toroidal ring currents are of the order of 2.4 to 2.6 years. This conclusion is based on a descriptive model of generation and transmission of geomagnetic disturbances within the toroidal ring current systems at the top of the outer core. The time delays associated with transmission of geomagnetic disturbances through the deeper parts of the toroidal ring current loops is found to be three years, in reasonable agreement with the time scale for reorganization of magnetic perturbations [23, 24]. Empirical relations have also been derived that account for the remarkable correlations between jerk delay times and mantle heat flux. We conclude that attenuation effects of sub-lithospheric thermal field must be taken into consideration in assessment of short-term fluctuations of the core magnetic field and in development of future numerical models of core dynamics [29, 30].

Acknowledgments

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