RECENT SECULAR VARIATION OF THE GEOMAGNETIC FIELD. NEW INSIGHTS FROM LONG SERIES OF OBSERVATORY DATA

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La variation séculaire récente du champ géomagnétique. Nouveaux aperçus à partir de longues séries de données des observatoires. L'analyse des séries longues de 100–150 années, comprenant des valeurs moyennes annuelles provenant des observatoires géomagnétiques, met en évidence la présence des composantes avec des périodes de 11, 22 et ~80 ans, superposées sur une variation stationnaire. Tandis que les deux premières sont clairement liées à l'activité solaire (le cycle des taches et, respectivement, le cycle magnétique), l'amplitude plus grande de la variation de ~80 ans (500–600 nT en comparaison avec 20–40 nT) pointe vers la source dans le noyau, possiblement contrôlée aussi par l'activité solaire (cycle de Gleissberg), mais le mécanisme de couplage n'est pas clair jusqu'a présent. Les caractéristiques de la variation de ~80 ans et de la variation stationnaire ont été présentées en termes de magnitude et de direction du champ à la surface et en termes du moment magnétique et de la direction des dipôles centrés équivalents. En termes de la présente analyse, les secousses géomagnétiques sont un résultat de la superposition de variations liées aux cycles solaires de 11 et 22 ans sur la variation de ~80 ans. Le mode dont les trois se combinent fait la différence des moments, des magnitudes et de la durée des secousses observées.

Key words: main geomagnetic field, secular variation, geomagnetic jerks.

1. INTRODUCTION

The secular variation of the main geomagnetic field is an important constraint on geodynamo models and it has been extensively studied. A first problem in such a study is to adequately separate the main field from available observatory data, which contain a rich spectrum of time variations. Generally it is agreed that variations with periods comparable to and shorter than the sunspot cycle are primarily of external origin (Bloxham, 1992). The annual means at geomagnetic observatories are supposed to be free of most of the variations with periods smaller than one year. It has long been recognized, however, that sunspot-cycle-related variations are present in the annual means at geomagnetic observatories (Chapman and Bartels, 1940; Yukutake, 1965; Bhargava and Yacob, 1969; Alldredge, 1976; Courtillot and Le Mouël, 1976; Alldredge *et al.*, 1979; Yukutake and Cain, 1979;

Demetrescu *et al.*, 1988) and in data from repeat stations (Atanasiu *et al.*, 1976; Anghel and Demetrescu, 1980; Galdeano *et al.*, 1980; Demetrescu *et al.*, 1985). The magnetic solar cycle in the solar activity, present in *aa* data (Currie, 1976), should also be present in observatory data as a consequence of the modulation of magnetospheric and ionospheric current systems by the solar activity. Bhargava and Yacob (1969) found that, in case of several observatories, the solar cycle response was higher during the maximum of odd solar cycles, indicating a 22-year variation in the field. The same authors inferred the existence of a 80 to 90 year cycle in the long data series of Colaba-Alibag observatory (ABG).

The main field evolution can be rendered evident for certain points on the Earth's surface using data time series at geomagnetic observatories, or using spherical harmonic coefficients computed for successive geomagnetic epochs. In the first case, the main field has been described (represented) in several ways, which include: (1) "normal values" obtained by averaging annual means with a 10-year running window; (2) fitted parabolas to time series of annual means (Courtillot and Le Mouël, 1976); (3) higher order polynomials fitted to longer series of annual means (Bhardwaj and Rangarajan, 1997); (4) band pass filtered series of annual means for the sunspot-cycle-related signature (Bhargava and Yacob, 1969); (5) sums of sinusoids corresponding to various long periods found by spectral analysis of data (Demetrescu *et al.*, 1988; Demetrescu and Andreescu, 1992). Other studies addressed the description of the main field and of its variation globally, by means of spherical harmonic analyses retaining low-order ($n<12$-14) coefficients (Langel *et al.*, 1986; Bloxham, 1992; Campbell, 2003). Periodicities between 22-23 years and 2.2 years have been found in the 2nd and 3rd degree coefficients (Langel *et al.*, 1986), due to the presence in data of the solar cyclic activity signature. In view of the much lower amplitude of these variations (20–40 nT) in comparison with the longer-term ones, it was considered that the sunspot cycle effect could be safely neglected (Yukutake, 1965). However, as regards the secular variation, the variations corresponding to solar cycles effects are of the same order of magnitude as the long-term variations of the main field, so eliminating the former becomes important. The new comprehensive model for the main field (Sabaka *et al.*, 2004), which results from data free of the 11-year cycle influence, is an improved approach from this point of view.

An important feature in the time evolution of the main field is the so called "geomagnetic impulse" or "geomagnetic jerk", expressed as a V shape graph of the secular variation (first time derivative of the field), or a step-like variation of the acceleration (second time derivative) of the field, or a Dirac distribution of the third time derivative of the field. First discovered by Courtillot *et al.* (1978), jerks have been extensively discussed as regards their internal or external origin (see for instance references in (Le Huy *et al.*, 1998; Sabaka *et al.*, 2004)). The internal origin of jerks is now generally accepted, following a demonstration by Malin and Hodder (1982).

In the present paper we isolate the main field by filtering out from data (annual means at several observatories with 100-150 years-long data series) the two known ingredients related to external sources (sunspot-cycle signal and magnetic cycle signal), and show the presence of a "~80-year variation" superimposed on a "steady variation" in the main field. Then we discuss some of the characteristic features of these two components in terms of the magnetic field vector magnitude and direction, and in terms of equivalent centered dipoles magnetic moment and direction. In the last section of the paper we show that a jerk results from the superposition of the 11- and 22-year solar-cycle-related variations on the ~80-year variation, with consequences on jerks timing, magnitude, and length.

2. DATA AND METHOD

Annual means of geomagnetic elements from 8 geomagnetic observatories (HAD, CLF, COI, VAL, ESK, BFE in Europe, FRD in North America and ABG in India) as given by http://www.geomag.bgs.ac.uk/gifs/annual_means.html have been used. Obvious jumps were corrected (e.g. HAD at 1925.5, 1957.5). The resulted time series for the 8 observatories are plotted in Fig. 1, in case of the horizontal component. Superimposed on a general trend, a variation of several hundred nT at the ~80 years scale is present. An example of the field evolution in case of the other geomagnetic elements is given in Fig. 2, for HAD. The ~80-year variation is present too.

In our approach we have chosen to filter out from data the variations related to the sunspot-cycle (Schwabe) and the variation related to the magnetic solar cycle (Hale), by averaging data with an 11-year running window followed by a 22-year running window. In Fig. 3a the sunspot-cycle-free (H11) and sunspot-cycle-free plus solar-magnetic-cycle-free data (H22) are shown by the red and blue lines, respectively. In Fig. 3b, the sunspot cycle (SC) signal (red), obtained by subtracting the filtered series from the annual mean series, and the magnetic cycle (MC) signal (blue), obtained by subtracting the 22-year averages from the 11-year averages are shown. We remind here that the signal is the sum of the field produced by the external sources related to the solar activity and the induced counterparts, by magnetic induction in the crustal rocks and by electromagnetic induction in the conductive mantle and crustal structures (Demetrescu *et al*., 1988, Demetrescu and Andreescu, 1992).

Having at this step eliminated signals related to the solar activity, we are left with what we may consider the main geomagnetic field. The blue line representing this field in Fig. 3a (H22) would, of course, be the sum of the field produced by the geodynamo process in the external core and the induced field by magnetic induction in the crustal rocks and by electromagnetic induction in the conductive mantle and crustal structures. This field can be further decomposed in what we call a "steady variation" by averaging the time series with a 78-year running window

(H78 – thick green line in Fig. 3a) and a "~80-year variation" by subtracting H78 from H22 (thick green line in Fig. 3b).

Due to the averaging with running windows of 11, 22, and 78 years, the successive filtered time series are shorter than the original time series by 10, 31, and 108 years, respectively. One can obtain a time series longer by 31 years in case of the steady and of the ~80-year variation by 78-year smoothing directly on measured data (H78*). These averages and the corresponding ~80-year variation will include, of course, the 11- and 22-year signals. Having in view the large differences between the magnitude of the steady and the ~80-year variations and of the 11- and 22-year variations, this could be a useful approach when large scale characteristics of the steady and ~80-year variations are discussed. The black dash-dot lines in Figs. 3a and b represent the H78* values and, respectively, the corresponding ~80-year variation. Fitting a straight line to H78* would allow obtaining an even longer information on the ~80-year variation (dashed green line in Fig. 3b), if the straight line is extrapolated to the entire time interval with H22 data or with measured data (see Fig. 4b).

The same treatment was applied to other geomagnetic elements, in order to get a complete image of the field.

3. RESULTS

The *~80-year variation* in H data, referred to H78*, is shown in Fig. 4a. This variation is similar in case of European observatories. Amplitude differences can however be noticed. In phase with these, the ~80-year variation at FRD has a much larger amplitude. At ABG the ~80-year variation shows a different phase than at the European and the North American observatories. The amplitude of this variation in the horizontal component is of about 400 nT (peak to trough) in Europe, 900 nT in India and about 1600 in North America. The gross features of the ~80-year variation for the entire study interval (1860–2004) can better be seen in Fig. 4b, where time series obtained using as a reference the extrapolated linear fit on H78* are plotted. These series contain, of course, the much smaller amplitude SC and MC signals.

The extracted *steady variation* carries the largest part of the field. It shows a significant lateral variation at regional scale of the annual rate (Table 1). For instance, in Western Europe a N-S lateral variation in the positive trend of the field from HAD and ESK, in Great Britain, to COI in Portugal can be seen. In case of BFE data the steady variation has a negative trend in the study time interval. The negative trend seems to characterize also the Eastern Europe (Demetrescu and Dobrica, in preparation) as it appears from repeat station data in Romania published by Atanasiu (1968) and Soare *et al.* (1999).

Table 1

The annual rate of the extracted *steady variation* at observatories of the present study

Observatory	Annual rate (nT/y)
HAD	7
ESK	7.2
CLF	10.8
VAL	16.3
COI	22.1
BFE	-3.2
FRD	11.5
ABG	18.1

4. THE GEOMAGNETIC FIELD VECTOR AND EQUIVALENT CENTERED DIPOLES

So far, we have discussed the various components of the measured field in terms of time series of geomagnetic elements. In the following we shall discuss the two components of the main field, namely the steady variation and the ~80-year variation, in terms of the vector representing the geomagnetic field and in terms of equivalent centered dipoles producing this field.

In Fig. 5 the magnitude of the main field vector and of its two components is shown in the left column, in the Z-H plane, and the direction of the vector is shown in the right column, in the I-D plane.

One can notice, in case of the steady variation at HAD, that the field strength decreased since 1900 to about 1940 and increased in the interval 1940–1965. In the same time interval the direction of the magnetic vector steadily moved eastward (diminishing western declination by ~5 degrees) and toward the horizontal plane (diminishing inclination by ~ 0.3 degrees). The strength of the ~80-year variation described a loop in the Z–H plane between 1900 and 1965. The plot of the direction of the ~80-year variation vector suggests an oscillatory orientation of the vector, toward west and down between 1900 and 1915, east and up between 1915 and 1947 and again west and down between 1947 and 1965. This oscillation is within 1.2 degrees in declination and 0.4 degrees in inclination.

Perhaps a better perception of the two components of the main field is achieved when looking at data in terms of equivalent centered dipoles. Their magnetic moments and direction can be computed from the magnetic field at the Earth surface. According to Butler (1998), the magnetic moment is given by:

$$M = \frac{Fr^3}{\sqrt{1+3\sin^2\varphi_s}} \tag{1}$$

and the coordinates of the corresponding pole on the Earth surface can be obtained from:

$$\varphi_p = \sin^{-1}(\sin\varphi_s \cos p + \cos\varphi_s \sin p \cos D), \tag{2}$$

with

$$p = \cot^{-1}\left(\frac{\tan I}{2}\right). \tag{3}$$

If

$$\cos p \geq \sin\varphi_s \sin\varphi_p \tag{4}$$

then

$$\lambda_p = \lambda_s + \beta \tag{5}$$

and if

$$\cos p < \sin\varphi_s \sin\varphi_p \tag{6}$$

then

$$\lambda_p = \lambda_s + 180° - \beta, \tag{7}$$

where

$$\beta = \sin^{-1}\left(\frac{\sin p \sin D}{\cos\varphi_p}\right) \tag{8}$$

In the above equations, M is the magnetic moment of the centered dipole, F the total intensity of the field at Earth surface, r the Earth's radius, λ_s and φ_s the geographical coordinates (longitude and latitude, respectively) of the observing point, λ_p and φ_p the geographical coordinates of the North magnetic pole of the equivalent centred dipole, D the declination, I the inclination, and p is the angular distance between the observing point and the pole of the equivalent centered dipole.

In Fig. 6 the evolution of the magnetic moments of the two equivalent dipoles for observatory data series long enough to allow the computation of representative time series are presented (upper panel – the results for the steady dipole, lower panel – the results for the ~80-year dipole). The steady dipole is constant or slightly increasing between 1900 and 1965 in case of European data, except COI where the steady dipole is slightly decreasing. The ABG data show an increasing trend. Higher values characterize the magnetic moment of the steady dipole derived for ABG and FRD in comparison with the European observatories ($9 \times 10^{24} - 1 \times 10^{25}$ nT m^3 as compared to about 7.4×10^{24} nT m^3).

The ~80-year variation dipole from the European observatories shows an oscillatory evolution, with a minimum value around 1935 – 1940 ranging between about -8×10^{22} nT m^3 and about -4×10^{22} nT m^3; it went through zero twice in the study time interval, around 1915 and 1965. A maximum value of about 4×10^{22} nT m^3 seems to occur around 1900. As it could be expected from the field values, the variation range in case of ABG and FRD is about two times larger than in case of European observatories and there are phase differences between the variation of the ~80-year dipole characterizing the three regions on the Globe sampled by the present study. Generally, the magnetic moment of the ~80-year variation dipole is about 100 times smaller than that of the steady variation.

As regards the orientation of the two dipoles contributing the main field, results are presented in Figs. 7 and 8 in form of the pole position for the study time interval. Temporal marks are given as well. The pole path in case of the steady dipole (Fig. 7) shows a north-westward movement of the North Pole for data from all observatories except ABG. Between 1947 and 1961, the time interval with data for all six European observatories (thick black line), the direction of the dipole was drifting north-westward by 2 (latitude)/5 (longitude) degrees (full circles in Fig. 7).

The direction of the ~80-year variation dipole shows a NW-SE oscillation with a few tenths of a degree in latitude and around 1 degree in longitude (Fig. 8). This is better visible in Fig. 9 where the pole path for HAD is based on the longer time series obtained by 78-year smoothing on annual mean data; the 11 and 22-year effects cannot be seen at this scale. Between 1882 and 1914 (years labeled in black) the direction shifted south-eastward, between 1914-1950 (red labels) north-westward, and between 1950-1982 (blue labels) again south-eastward.

5. GEOMAGNETIC JERKS

The time derivative of the declination (Y in many published analyses) is used to show the presence of jerks in the variation of the geomagnetic field (Courtillot and Le Mouël, 1984). Annual means and components of the main field in case of declination at CLF are presented in Fig. 10. The colour code is the same as in case of the field plots (Fig. 3). First differences of annual means are plotted in Fig. 11 (black line) and jerks are shown by arrows. Superimposed are first differences of successive averages with 11-, 22- and 78-year running windows. The time derivative of the three components of the declination, in terms of the present analysis, is plotted as well, in the lower part of the figure. The jerks appear to result from the superposition of the 11-year and 22-year solar-cycle-related variations on the ~80-year variation. The time of occurrence, the duration and the amplitude of the jerk depend on how the three types of variation combine to give the observed one. While the first two components are clearly related to the solar activity (the sunspot and, respectively, the magnetic cycles), the larger amplitude of the ~80-year variation (several hundred nT in H, peak to valley, as compared to 20–40 nT) points out to a core source. The latter might possibly be controlled, however, by the solar activity too (the Gleissberg cycle), but the coupling mechanism is unclear as yet. The core sources and the induced counterparts for the steady and for the ~80-year variations plus the induced counterparts of the external 11- and 22-year variations would make the internal contribution to jerks, noticed by Malin and Hodder (1982). It is obvious that the long term evolution of the first time derivative is given by the ~80-year variation. It is interesting to note that Alexandrescu *et al.*, (1997) remarked that filtering out from data the sunspot cycle signal leaves one with a smoother variation, in which the jerk would be produced in a longer time than 1–2 years but did not further explore the consequences of this observation. However, the external contribution is decisive in establishing the very short time scale characterizing jerks, and to some extent also the amplitude and timing of the jerk. Our results give credit to Alldredge's (1984; 1985) arguments against the jerk concept. Recently, Sabaka *et al*. (2004) detected an external component in jerks in their comprehensive model CM4.

6. CONCLUSIONS

Data from 8 observatories with 100–150 years long time series of annual means have been processed to show the main field evolution, by averaging out effects of the 11- and 22-year solar-cycle-related variations. The existence of a *~80-year variation* superimposed on a *steady variation* has been rendered evident in the evolution of the main field. Some of their characteristics have been described in terms of the geomagnetic field vector intensity and direction and in terms of centered dipoles producing the observed surface field.

The *steady variation* carries the largest part of the main field. It shows a significant lateral variation at regional scale of the annual rate. The magnetic moment of the *steady variation* dipole is of about 7.4×10^{24} nT m^3, constant or slightly increasing in case of European observatories. Larger values, of 9×10^{24} nT m^3 characterize the non-European ones. The direction of the dipole was drifting northwestward by 2(latitude)/5(longitude) degrees between 1947 and 1961.

The amplitude of the ~80-year variation in the horizontal component is of about 400 nT (peak to trough) in Europe, 900 nT in India and about 1600 in North America. The *~80-year variation* dipole shows an ENE-WSW oscillation within a few tenths of a degree in latitude and around 1 degree in longitude, combined with a variation of its magnetic moment between -8×10^{22} nT m^3 and about -4×10^{22} nT m^3 at minimum (1935–1940) and around 4×10^{22} nT m^3 at maximum (1900), in case of European observatories. Variations twice as large and phase differences characterize the Indian and North-American observatories of this study.

All variations discussed contain the response of the Earth by magnetic induction in the crustal rocks and by electromagnetic induction in the conductive mantle and crustal structures.

In terms of the present analysis, the geomagnetic jerks seem to be merely a result of the superposition of the 11- and 22-year solar-cycle-related variations on the ~80-year variation. The way the three combine makes the difference in timing, magnitude, and length of jerks as observed. The internal origin of jerks seems to be warranted by the existence of the ~80-year variation. However, the external contribution is decisive in establishing the very short time scale characterizing jerks, and, to some extent, also the amplitude and timing of the jerk.

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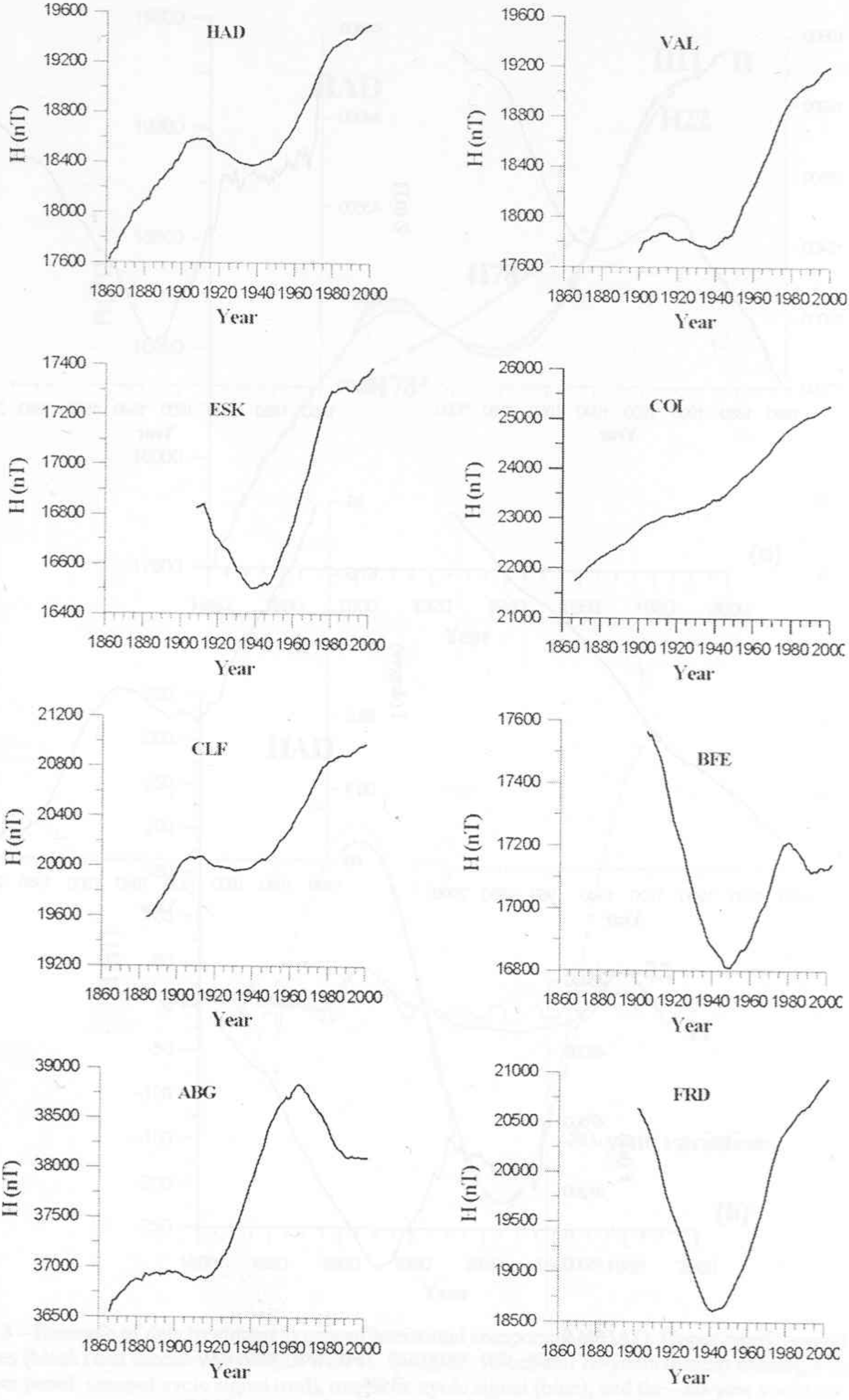


Fig. 1 – Evolution of the horizontal component at observatories.

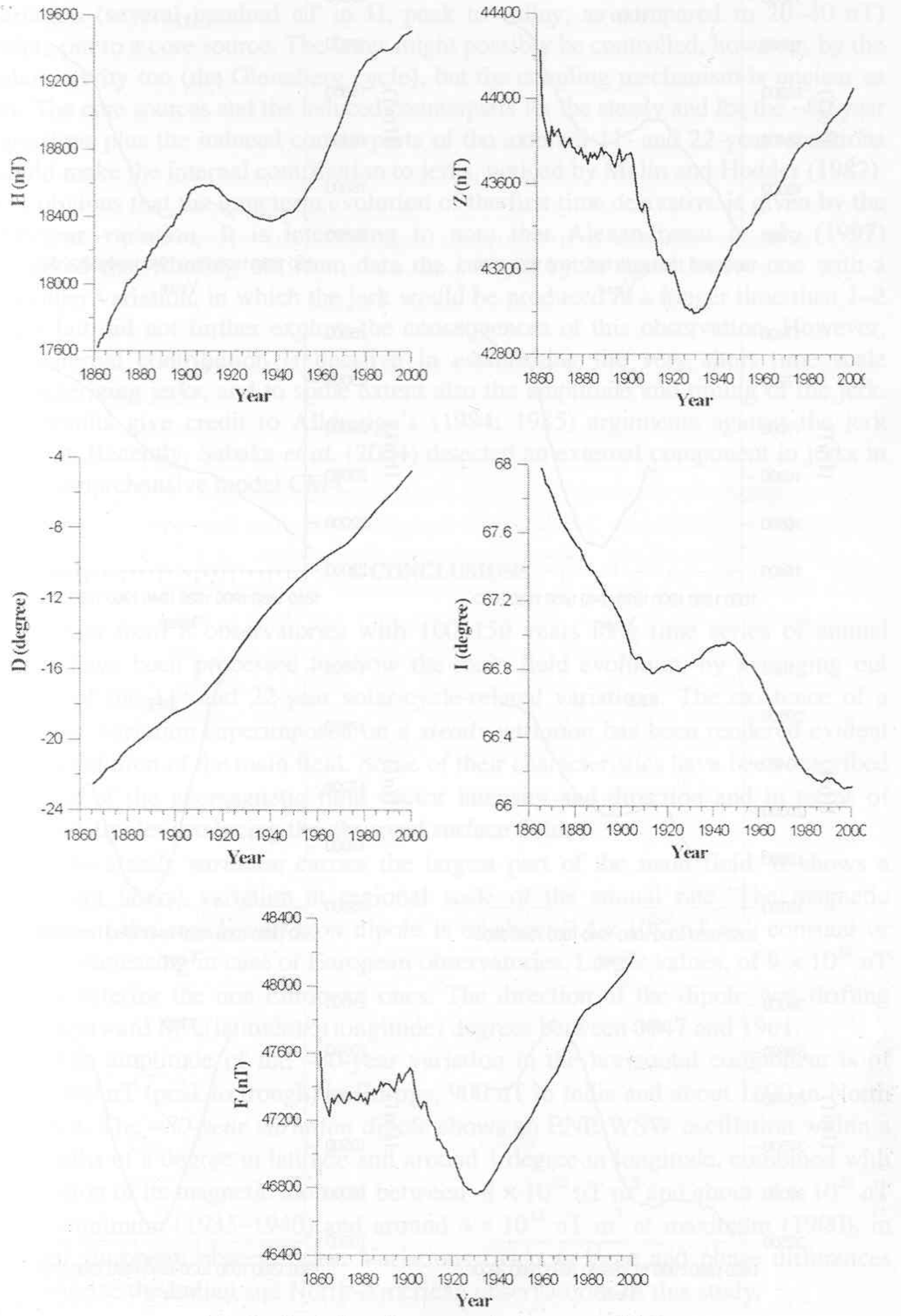


Fig. 2 – Evolution of geomagnetic elements at HAD.

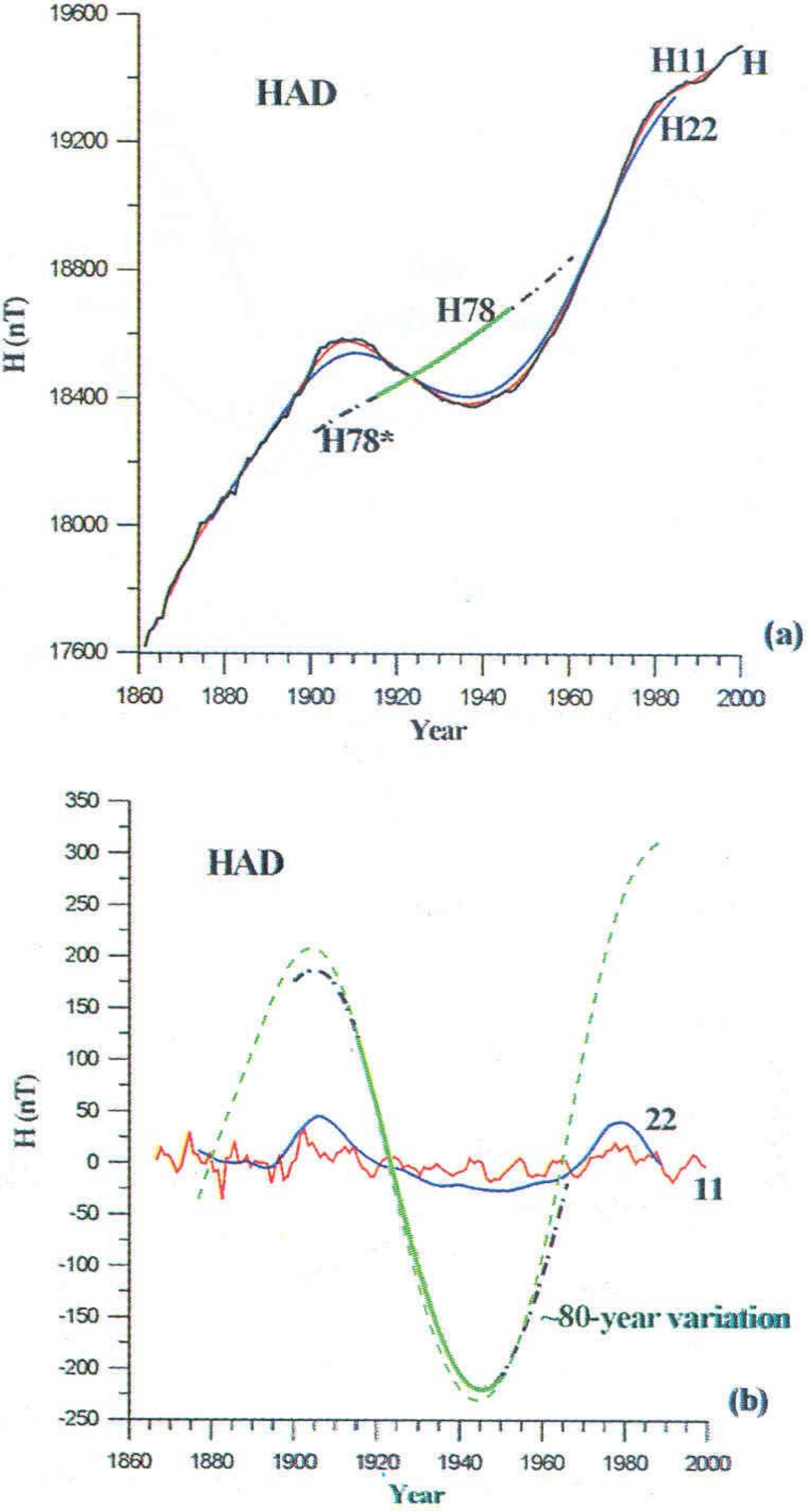


Fig. 3 – Example of data treatment in case of horizontal component at HAD. Upper panel: annual mean values (black) and succesive averages with 11- (red), 22- (blue) and 78-years (green) running windows. Lower panel: sunspot cycle signal (red), magnetic cycle signal (blue), and the ~80-year variation signal (green). For details see text.

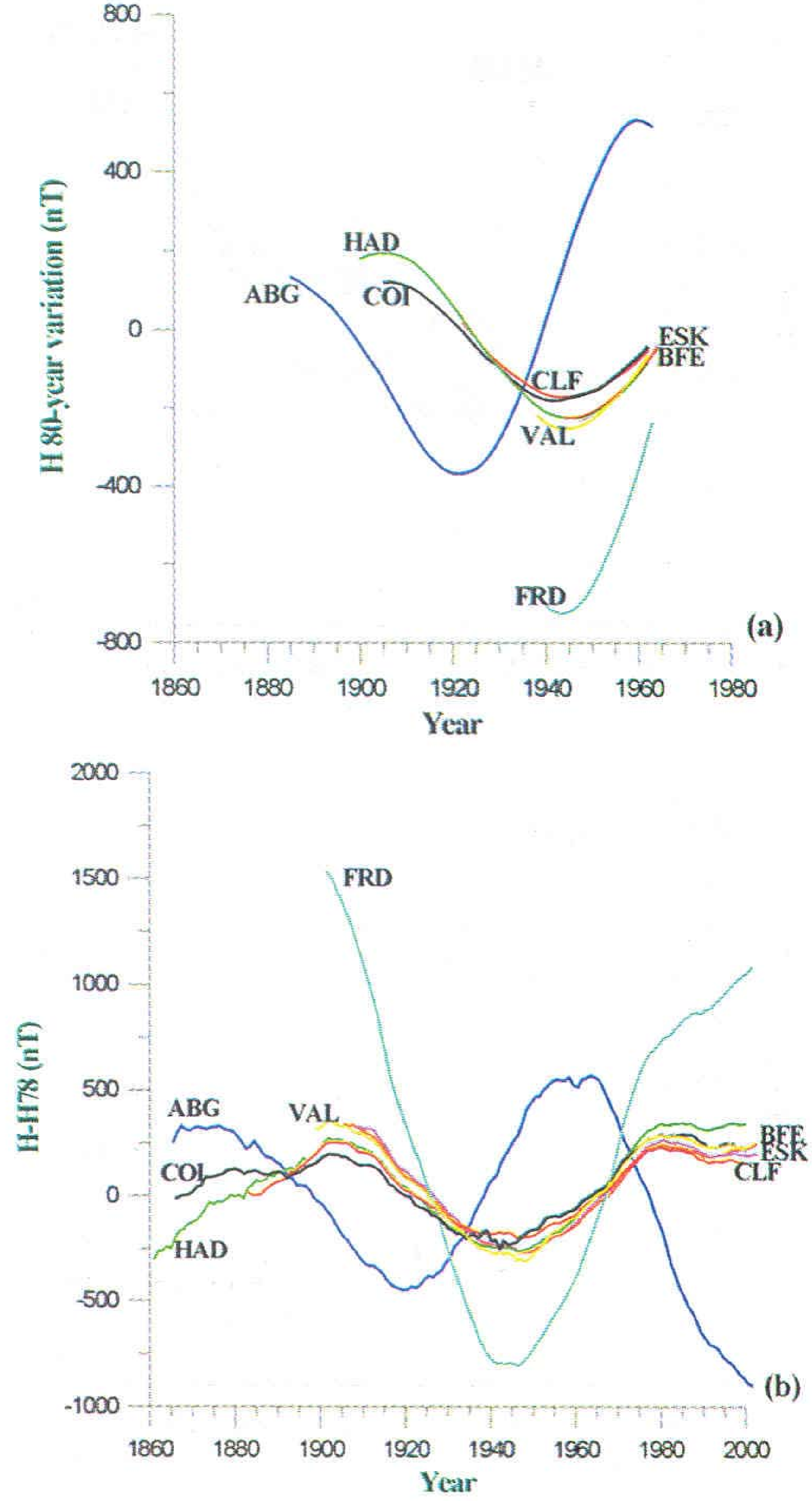


Fig. 4 – The ~80-year variation in H for observatories of the study **(a)**. The same, but in case of 78-year smoothing on measured values and extrapolation by a fitted straight line **(b)**.

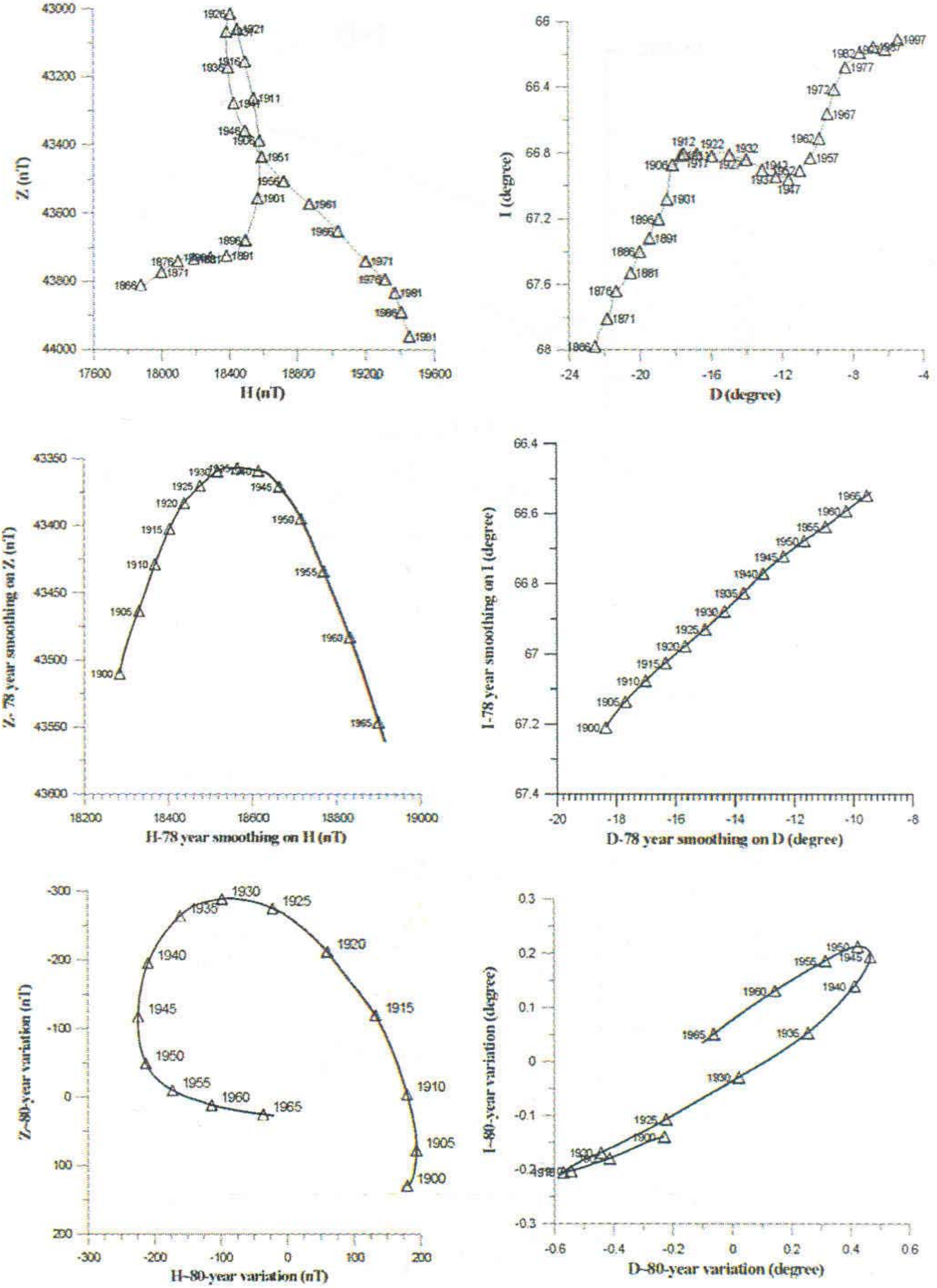


Fig. 5 – The evolution of the main filed and of its two components at HAD, in terms of magnitude (left column) and direction (right column) of the field vector. Upper panels – main field; center – steady field; bottom – the ~80-year variation.

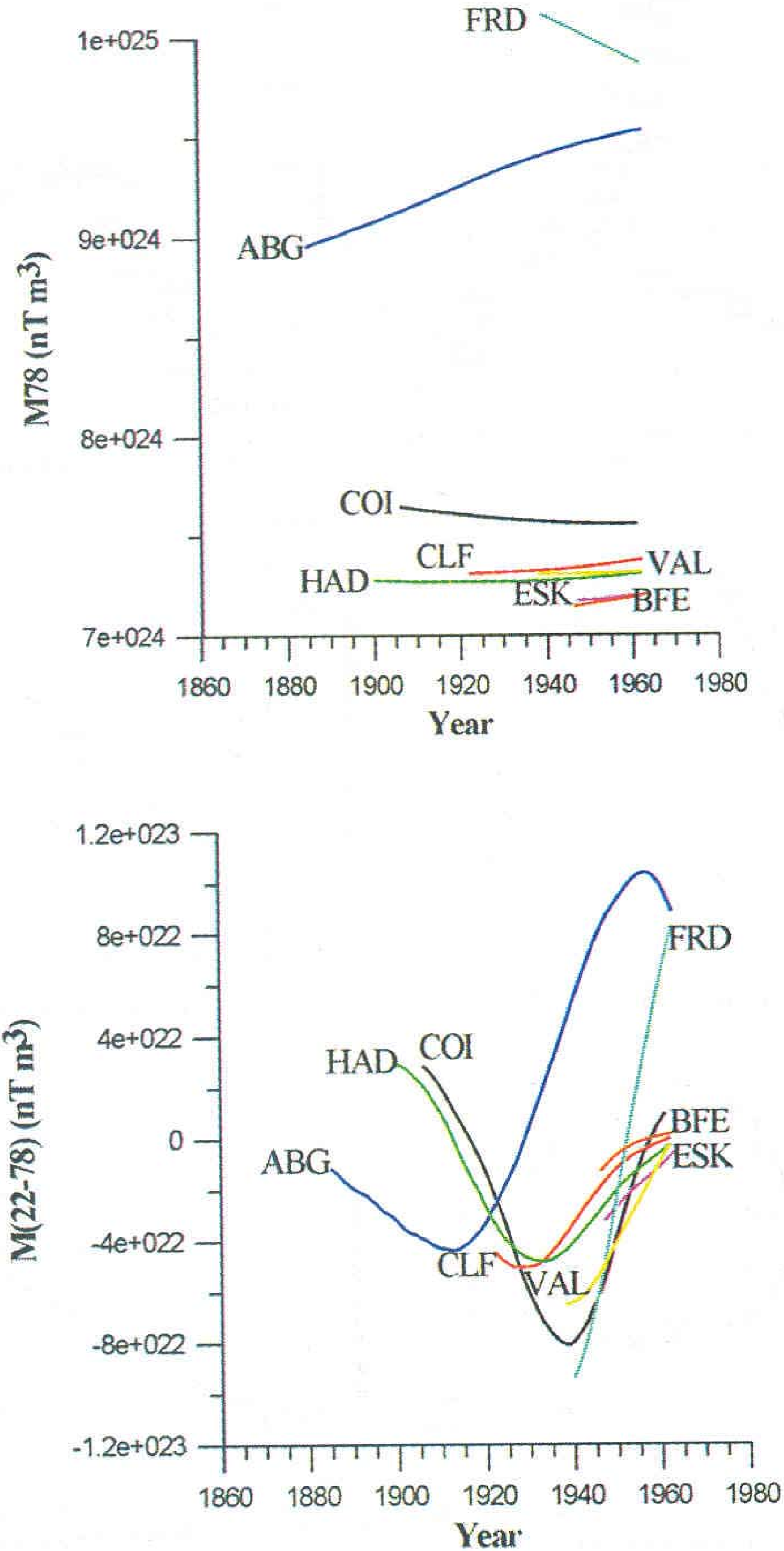


Fig. 6 – The evolution of the magnetic moment of equivalent centered dipoles for the observatories of the study. Upper panel – steady variation; bottom panel – the ~80-year variation.

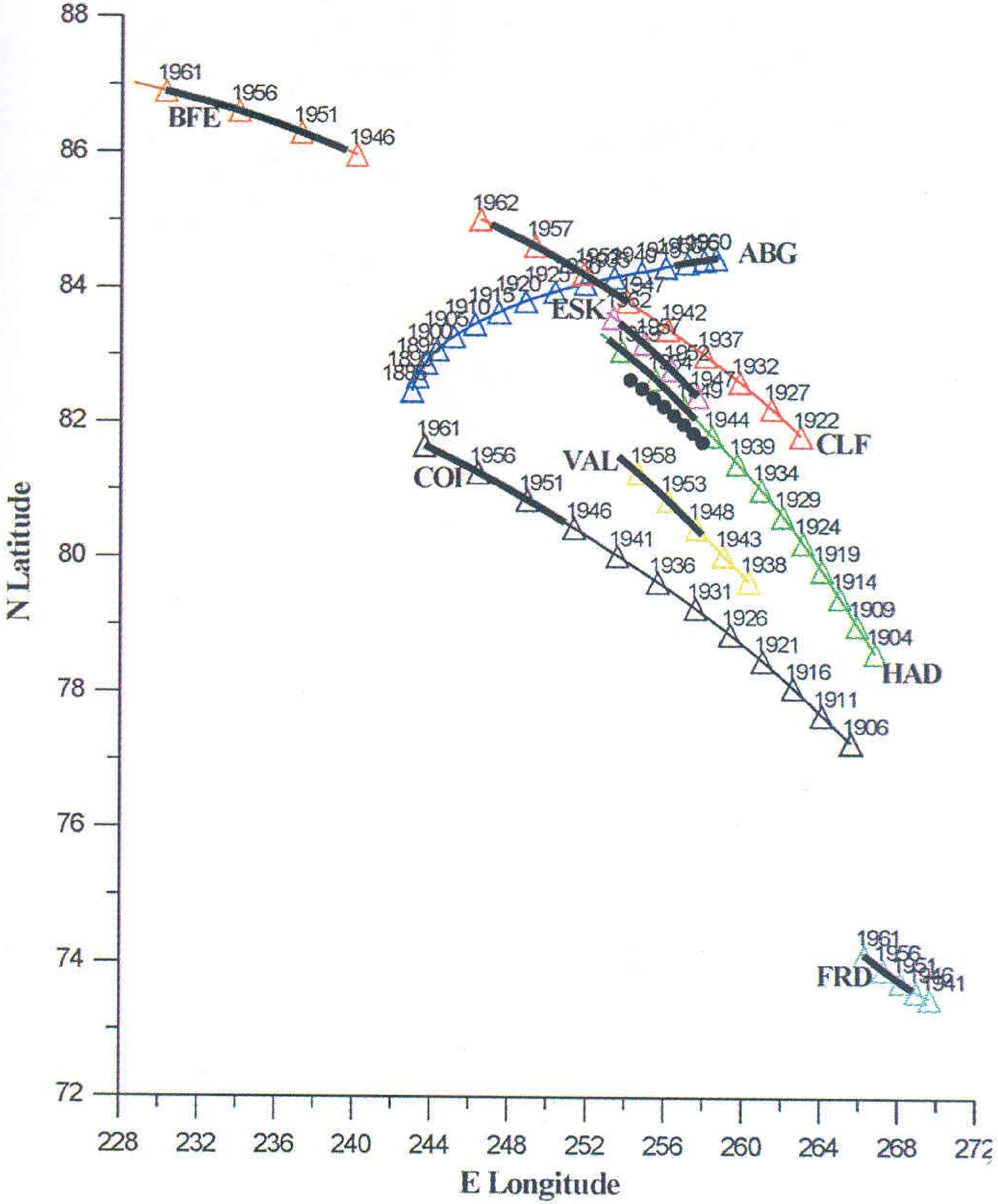


Fig. 7 – The evolution of the North pole corresponding to the steady variation. Thick black superimposed lines – common time interval for the 8 observatories (1946–1961). Full circles – mean pole path between 1946–1961.

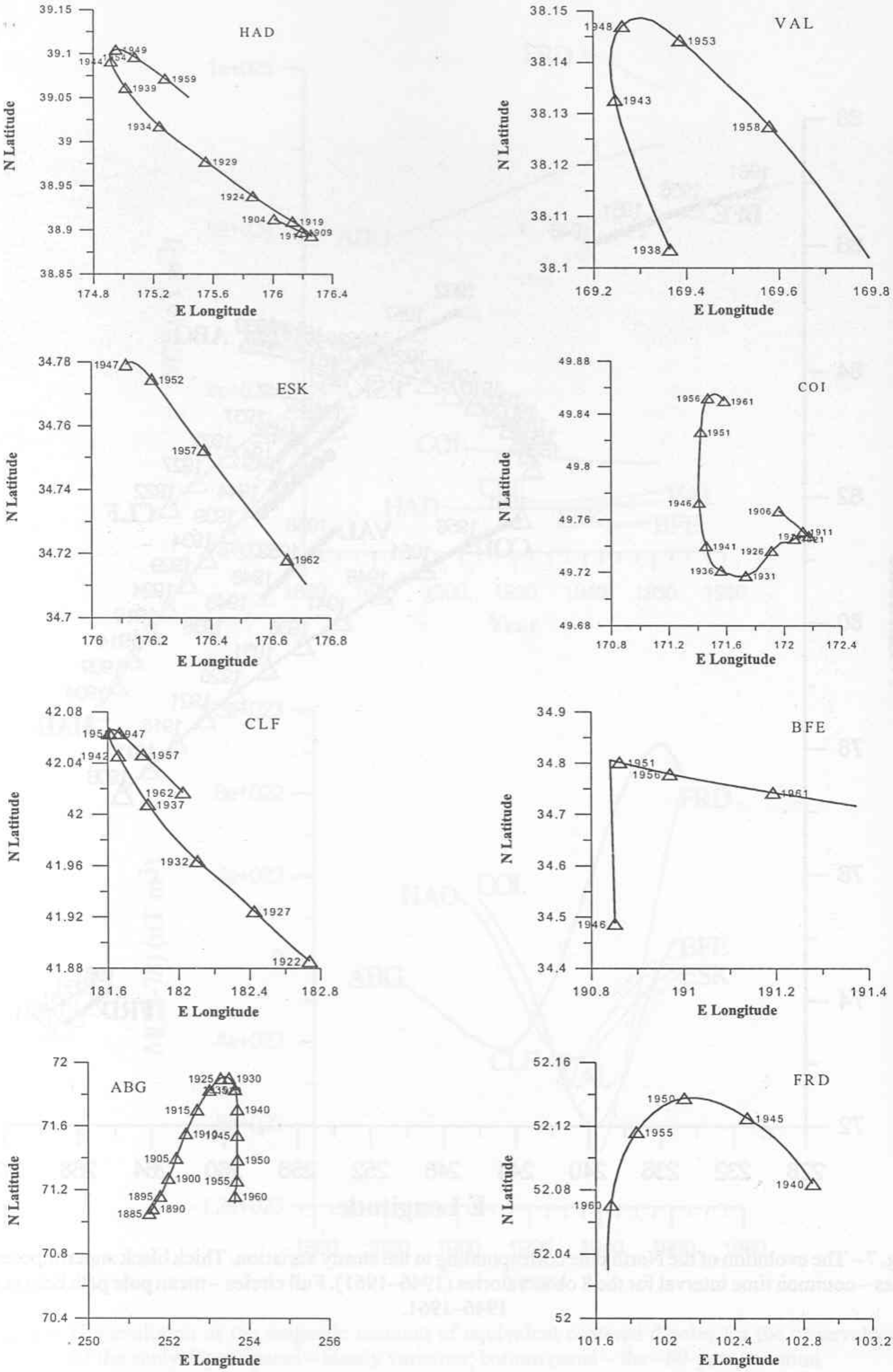


Fig. 8 – Pole path for the ~80-year variation equivalent centered dipole.

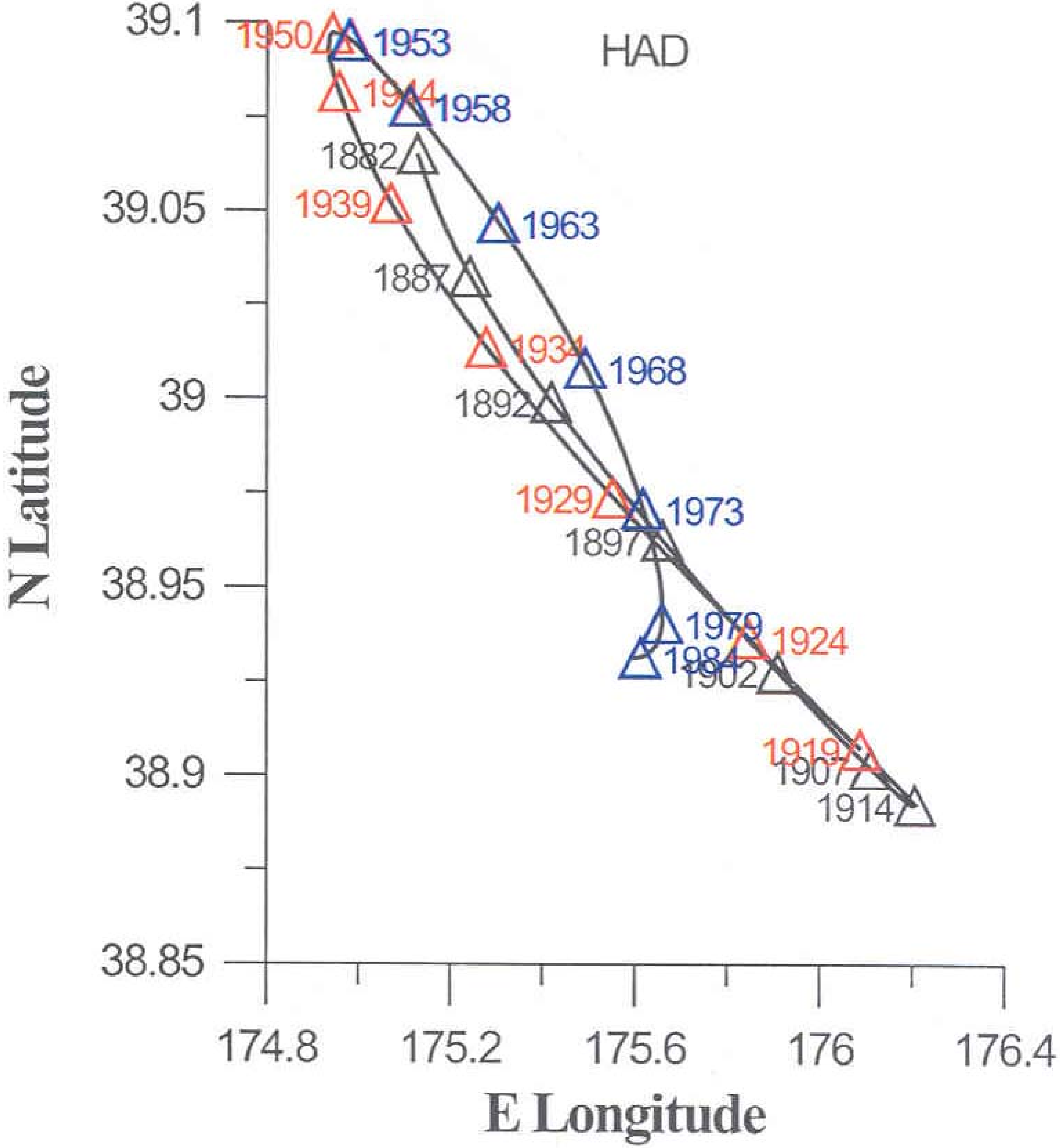
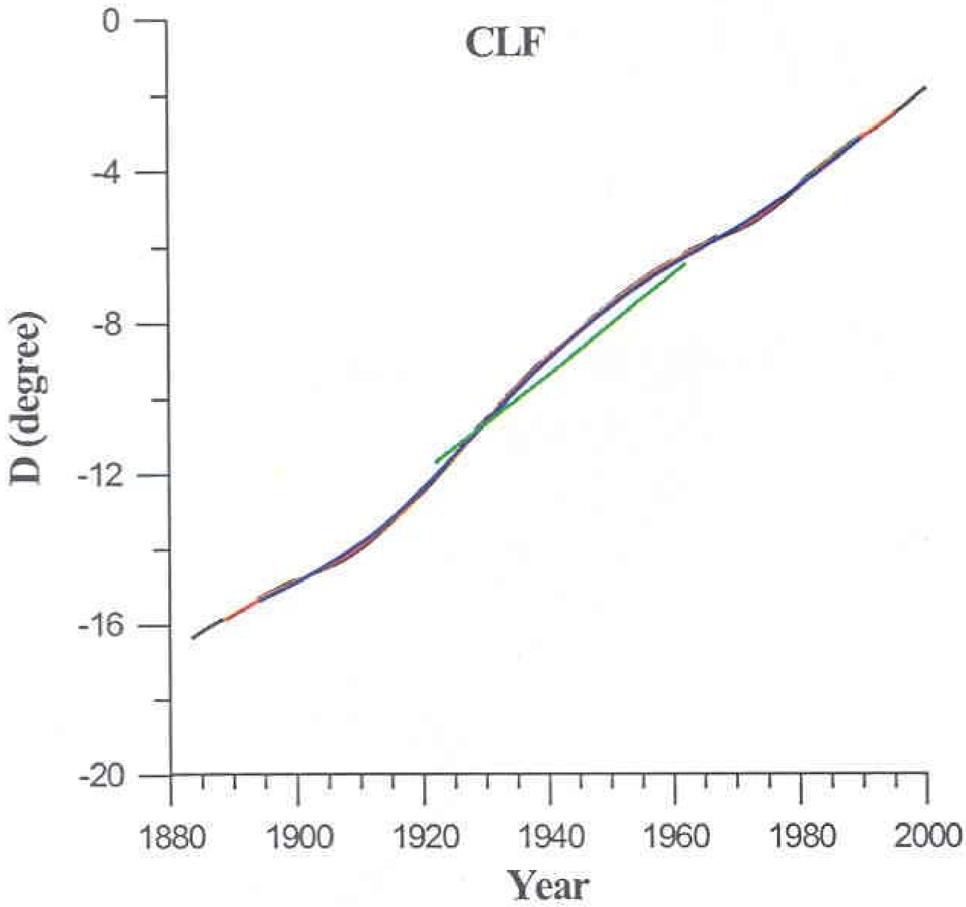


Fig. 9 – Pole path of the ~80-year variation equivalent centered dipole at HAD. The variation is defined with respect to an extrapolated steady variation.



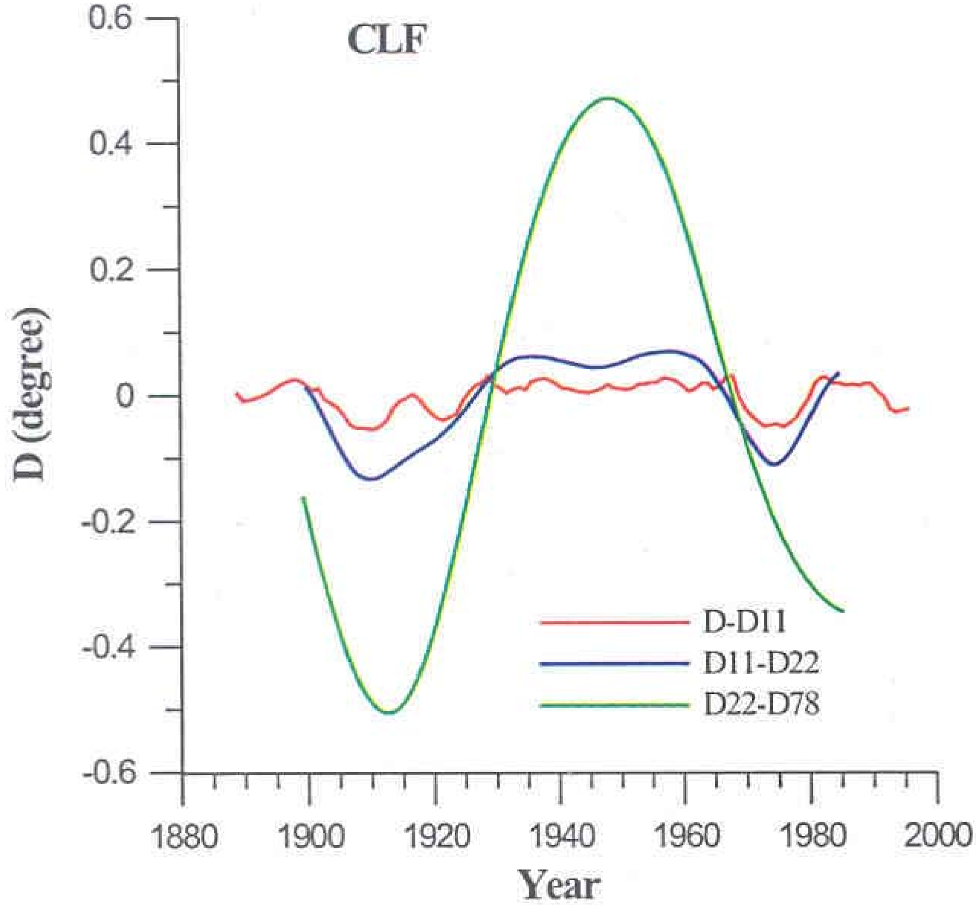


Fig. 10 – Components of the main field in case of declination at CLF. Color code as in Fig. 3.

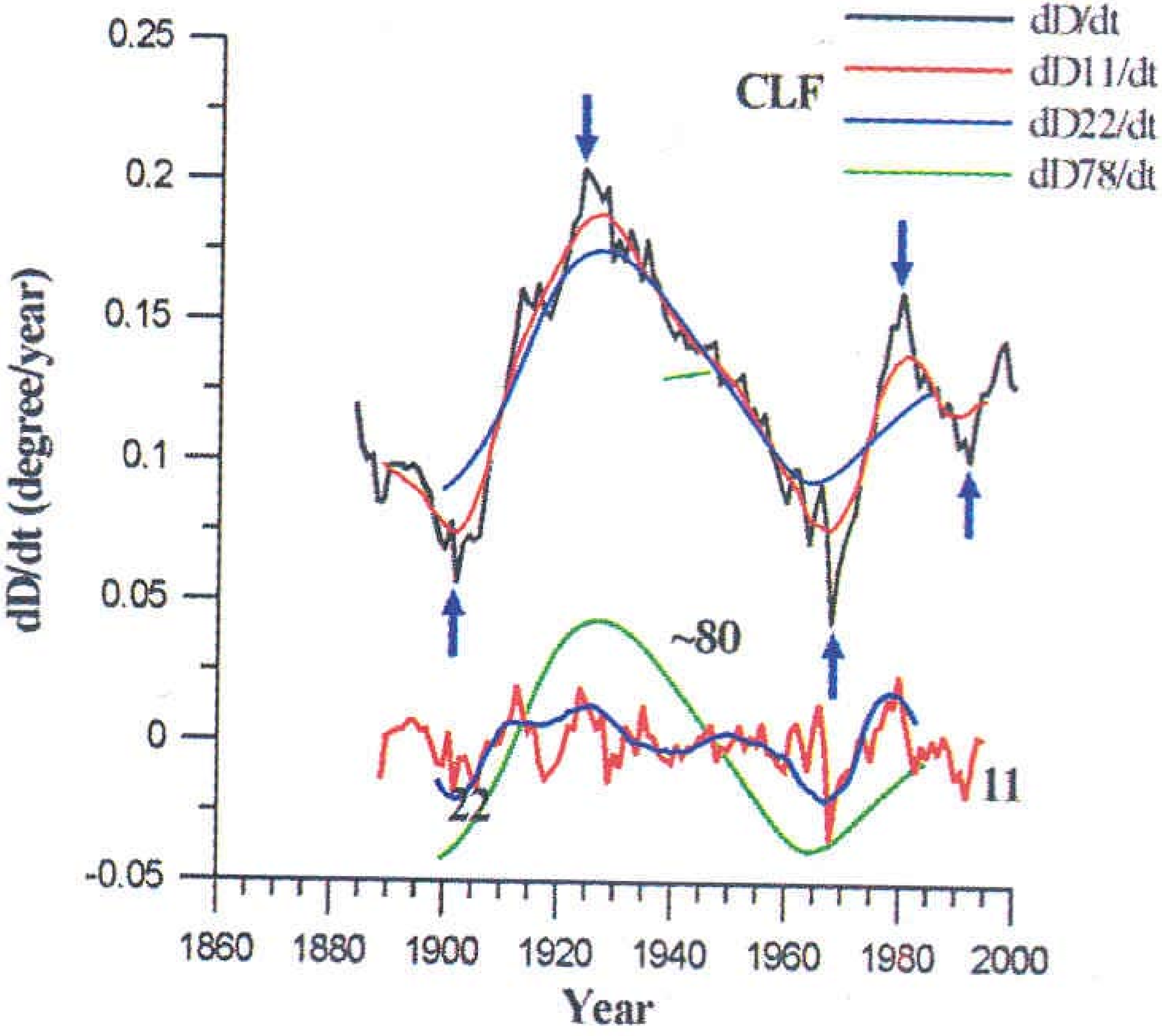


Fig. 11 – Time derivative of declination (upper panel) and of the 11-, 22-, and ~80-year components of declination at CLF. Color code as in Fig. 3. Arrows – jerks.