Dear Editor,

Thank you for the letter regarding the paper SE-2017-119. We revised our manuscript taking into account your observations, as follows.

Sincerely,

Venera Dobrica, Crisan Demetrescu, Mioara Mandea

1) Part of the literature that cannot be ignored. For instance in the abstract you assume that decadal changes are « supposed to be related to external variations and called '11-year constituent' ». This is part of your background hypothesis, but you must recognize that this point of view cannot entirely be correct. Of course there exist an external signal at such periods; however, internal signals are of primary importance at these very periods, in link with the red spectrum of the internal field (Lesur et al, PEPI 2017).
Furthermore, the ambiguity in the internal/external sources separation being much reduced with satellite data, the community is pretty confident in a large signal from the core at periods around 11 yrs (see e.g. the global models such as CHAOS-6, Finlay et al, EPS 2016).

We agree that our point of view regarding the signal at frequencies related to the solar activity as an external one might not be correct. We tend to attribute the 11-year signal to the external sources (our background hypothesis) based on a long list of papers referenced by Demetrescu and Dobrica (PEPI 2014) and on the demonstrations by Verbanac et al. (EPS 2007) and Wardinski and Holme (GJI 2011), to cite a few. The former showed that the residual signal after removing the CM4 core field contribution from the annual averages of the European observatories has a clear solar-cycle signature and can be modeled down to ±2 nT using magnetospheric ring current data (Dst) and an ionospheric field proxy (Ap). The latter characterizes the external effects stochastically, analyzing the correlated so-called 'noise' in the time series of X, Y, and Z at observatories world-wide and the Dst index, in a first step, and residuals at Niemegk instead of Ap, in a second step. Moreover, there is no published information on the amplitude (or spectral power density) of the internal 11-year signal that we could mention here, as a possible alternative of our working hypothesis.

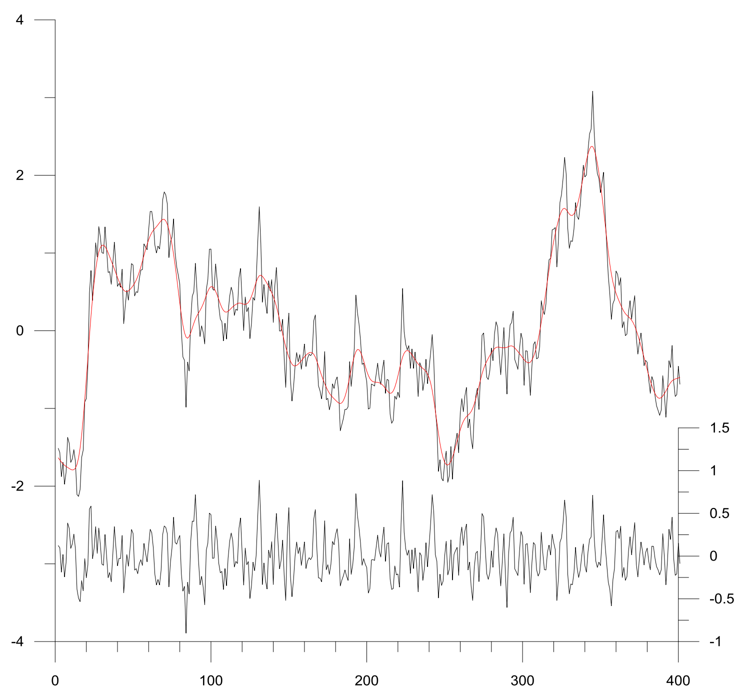
We agree that models based on satellite data succeeded in drastically reducing the ambiguity in the external/internal sources separation. However, the information from double logarithmic plots of FFT spectra of, e.g. Lesur et al. (2017), only shows that there is an 11-year signal in the **core field of the model**, but cannot decide on the origin. The same has been noted by De Santis et al. (PEPI 2003): "The observational spectrum follows the predicted linear behaviour relatively well down to periods of about 7 years; we do not know whether this is simply fortuitous or whether it depends on possible external contamination to annual means at the shortest periods or it has some other physical meaning". A paragraph mentioning the above studies have been included in Introduction (page 2, lines 33-34, page 3, lines 1-3) of the revised manuscript.

Perhaps information on the amplitude (or spectral power density) of the internal 11-year signal, which is not discussed in the currently published papers, would give a definitive answer. For the moment we added in the revised manuscript **(**Page 6, lines 20-22; page 13, lines 11-12) that we are aware that our point of view regarding the signal at frequencies related to solar activity as an external one might not entirely be correct.

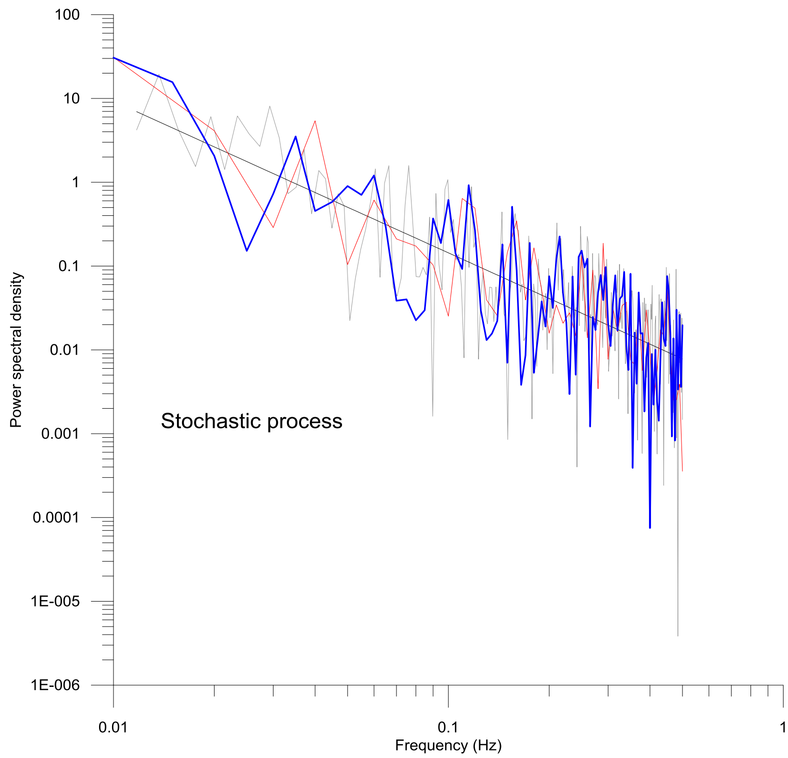
2) You should explain how your results (the existence of "cyclic constituents") is compatible or at odds with the approximately -4 slope found in the PSD of ground observatory series (de Santis et al, PEPI 2003; Lesur et al 2017). Indeed, series characterized by such a PSD slope in the considered frequency range do not contain any specific spectral line. Can you prove that the cyclic behavior you see (in particular towards long periods) do not come from the restricted time-span of the series ?
Said differently, you should apply your signal analysis tool to short segments of stochastic series presenting a PSD with a -4 slope over the considered frequency range ; if there you find cyclic constituents, it means they are possibly due to the limited duration of geophysical series. My concern is motivated by the fact that apparent periodicities are often wrongly put forward when too short series are considered.

1. Our filtering is based on well documented findings of a long line of preceding researchers, listed in the references, that previously studied periodical signals in geomagnetic data (we added several lines (23-26) at page 4 concerning the paper by Jackson and Mound (2010) who showed by EMD periods that are in line with ours). We do not use filtering to find periodicities, but rely on already found ones.

2. The figure below shows a 400 points (=years) stochastic time series with the approximartely -4 slope of its PSD plus the corresponding spectrum in log-log form. Also spectra for shorter time series (200 –blue, 100 years –red) cut from the initial one are superimposed. We do not see spurious lines at low frequencies in case of shorter time series.

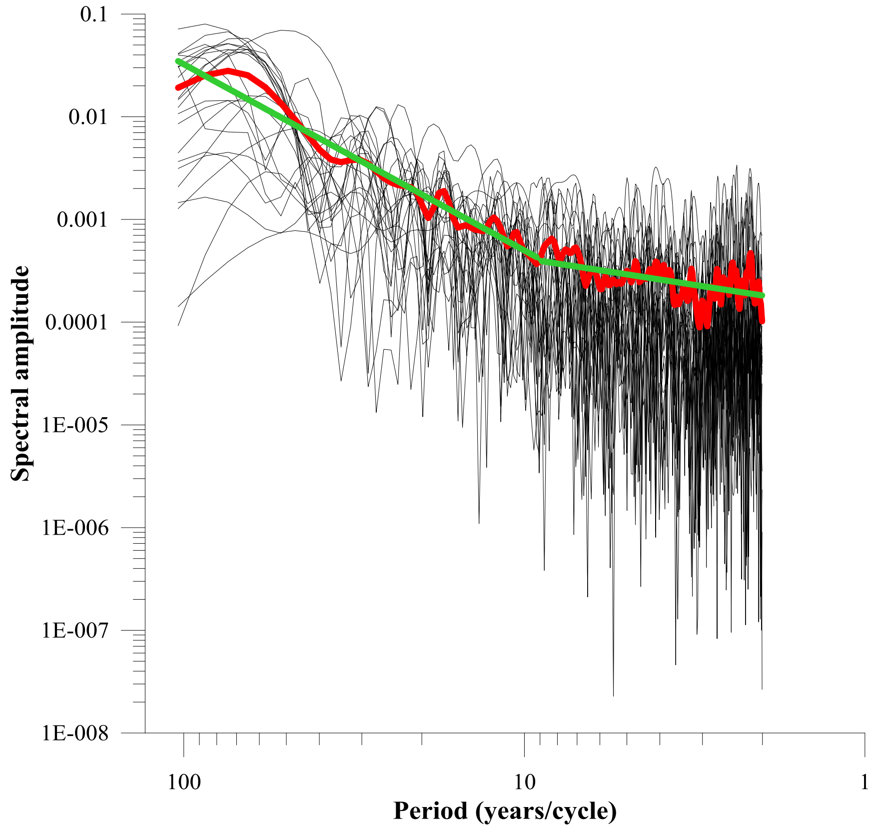


Stochastic time series (black, upper panel), trend get by HP filtering (red, upper panel) and cyclic constituent (black, lower panel)



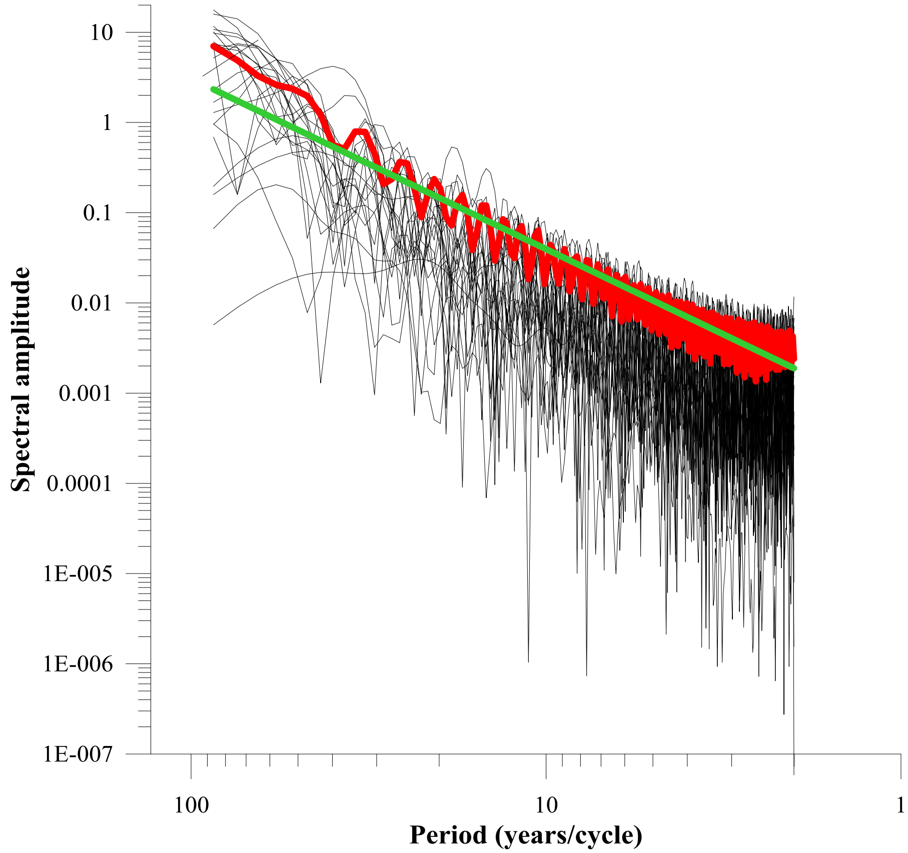
FFT power spectra in log-log representation for 400- (black), 200- (blue) and 100-years (red) stochastic time series

3. The superimposed power spectra of our 24 declination time series of secular variation (dD/dt) are shown in the figure below, together with the mean spectrum (red) and two straight line segments (green) illustrating the power law that characterize the mean spectrum; a slope change occurs at a period of about 10 years. The power-law exponent is -1.81, similar to the figure found by Lesur et al. (2017) for individual observatories.



The log-log power spectra (black) and the mean spectrum (red) of declination secular variation with the power-law fit (green)

4. The same analysis on declination time series (D) results in almost the same exponent (-1.89) – see figure below, but not close to -4 as got by De Santis et al. (2003).



The log-log power spectra (black) and the mean spectrum (red) of declination with the power-law fit (green)

4. Our dD/dt log-log plot shows „lines”, or rather, periods grouped in three time-scales, namely 60-90, 20-35, and 8-15 years, exactly those we considered for our filtering approach. The actual figure we use for filtering window or cutoff does not alter the frequency content of the filtered time series (Demetrescu and Dobrica, PEPI 2014, Appendix). A spectral density power versus frequency or period plot is able to comparatively show the magnitude of various oscillations present in the time series, and it is only to be expected that a log-log plot smoothes the spectral lines, resulting in the power law one finds.

We added a new figure in the Supplementary material (FIG. S2) to show how our results are compatible or at odds with the approximately -4 exponent of the power-law fitted to spectra and a paragraph in the revised manuscript (page 4 at lines 26-30 and page 5, lines 1-5).

3) Below is a list of comments on your responses to the referees (in blue the referees points, in red your response or modified text, in black my comments) on comments by Susan Macmillan

3.1- More detail is needed on how the 30-year and 73-year spectral lines are identified in Figure 2 because these values are then used (at least initially) in some of the subsequent filter design...

Most observatories indicate these figures for the spectral line corresponding period… the filtered time series do not lose the information related to actual periods involved, no matter what figure is used in filtering.

You do not answer the question : how do you estimate the periods ? Is it by applying an average over the several spectra ? Could you provide errorbars on the obtained period? Behind the question of the referee, I understand that the periods are not obvious from fig. 2.

Indeed, we applied an average over the 24 spectra, as De Silva et al. (JGRB 2012, Fig. 2), Demetrescu and Dobrica (PEPI 2014, Fig.3), and Ou et al. (JGRA 2017, Fig. 3) proceeded with their data. What is important, however, is that no matter what figure was used in our filter design (except the actual period in data), the filtered time series would show the actual oscillations hidden in the unfiltered time series (Demetrescu and Dobrica, PEPI 2014, Appendix). We added that in the 2nd round revised manuscript (Page 5, lines 28-31).

3.2- What is the reason for the split in the 3rd panel of Figure 3? NGK runs continuously through this time. (a point also raised by J. Mound)

… We treated separately the two parts of the signal (1890-1960 and 1961-2014) because the plot suggests a change in frequency that contribute to the signal…

This affirmation is not obvious at all to me, as in both parts of the series it only concerns a few periods.

Furthermore, the accuracy you give for the periods seems illusory to me. I do not think any conclusion such as “beatings between the sunspot (so-called 11-year) and magnetic (~22-year) solar cycles” can be drawn.

Indeed, there are only a few periods in each of the two parts of the series. We agree with your comment regarding the accuracy we gave for the periods and about our conclusion. We removed that part of the manuscript (including the plot in question). As a matter of fact, external variation in D is rather different when compared to H and Z, due perhaps to additional sources that contribute, beside the symmetric ring current. We leave this matter for a next study.

Here analyses of synthetic series (see point 2) would be useful. Indeed, stochastic series often show natural modulations that look like changes in apparent periods (although no period line actually exists).

We do not consider our time series as stochastic but rather a result of turbulent flow in the outer core. We had already stated in the manuscript (page 9, line 32-35, pag. 10, lines 1-2 in the revised one): “That the flow in the core is turbulent became common consideration with many studies on geodynamo and core flow modelling from secular variation data (see the review by Holme (2015) on the latter). The turbulent flow, as inferred by De Santis et al. (2003) by looking at the power spectra of X, Y, Z annual means time-series, does not exclude but, on the contrary implies the existence of vortices with various time and space scales.”

3.3- How can you be sure that the big jerks are not influencing the results of the filtering in Figure 6?… an important conclusion potentially.

The results of filtering are not influenced by the position of the big jerks.

This is not an answer. Could you detail a bit ? Again you could illustrate this with synthetic tests.

We give here a more detailed and convincing answer. We were missled by the term ‘big jerk’, as successive jerks have about the same magnitude.

We have previously noticed that dominating powerful signals at larger time-scales in data tend to contaminate the filtered time-series meant to show quasi-periodic variations at smaller time-scales, when using running window and Butterworth filtering (as stated in the present revised manuscript at page 5, lines 9-10). This was the reason for which we adopted the HP filtering, to avoid this happening in case of the 11-year variation. In Fig. 6 there is an obvious effect of the variation at the 60-90 year scale on the inter-decadal variation. It is the result of using Butterworth filtering on trend time series to get the inter-decadal and the sub-centennial constituents. The position in time of maxima and minima of the inter-decadal constituent can, however, stand for jerk moments, as the filtering does not influence the jerks timing.

On comments by Jon Mound:

3.4- in your modifications following the comment “… could be noted that there is a corresponding six year signal în length-of-day that cannot be explained by known external sources and thus has been linked to processes in the core… ” you refer to Cox et al (2016) saying “… shows, however, that a 6-year wave in the core cannot give the estimated effects at Earth’s surface, placing the problem of internal high-frequency signals under debate.”

This is not correct. Indeed, what Cox et al show is that the 6 yr signal from synthetic geostrophic waves (with amplitude that found by Gillet et al 2010) is tiny, comparable with the uncertainty level in observatory series. However, around 6 yr periods, core flows inverted from magnetic data are dominated by more intense non-geostrophic motions that are able to explain the resolved signal at such periods (i.e. there is no problem for interannual magnetic signals to be explained by core motions). Furthermore, because there are about 100 independent observatories to constrain the secular variation, the uncertainty level on core motions is much reduced. This explains why such small geostrophic motions can be retrieved even if they are only responsible for a tiny signal.

We considered your comment. In our reasoning we were led by our background hypothesis that the 11-year signal, and consequently other, higher frequency signals are of external origin, as has been demonstrated by Ou et al. (2017) for the case of QBO-related variations. In the present revised manuscript we removed our comment on the Cox et al. paper.

3.5- You do not modify the text in response to “… I don’t see any easy resolution to this problem through pure time series analysis, comparison to external field models or proxies (e.g. indices of solar activity) seem necessary to unravel the origin of the high frequency content within the geomagnetic observatory time series.”. You write “Once the external contributions to the first differences of the observatory annual means – of comparable amplitude with the inter-decadal and sub-centennial constituents – are minimized, the observed secular variation no longer exhibits a clear V-shape at time of geomagnetic jerks.”

Following point 1 above, how can you be sure you have only removed external signals ? In your conclusion you should acknowledge that you have most probably also removed some important internal signal. This may be part of the reason why the correlation of the 11 yr constituent with the solar cycle is not so clear. You should also mention somewhere the attempts at extracting external contributions through global models on long periods (McLeod et al, JGR 1996; Langel et al, PEPI 1996; Gillet et al, G3 2013), who give an idea of what wan be achieved on the basis of spherical harmonics decomposition, and of the expected respective amplitudes of internal and external signals.

Of course separation between internal and external sources is far to be perfect. We made the suggested changes in the 2nd round revised manuscript: page 6, lines 12-23 and pag.13, lines 11-12.

3.6- … Therefore I might be cautious about claiming that the sub-centennial signal is really traced all the way back to 1600. … As the sub-centennial variation in *gufm1* closely follow the observed time series in the last ~200 years of the time series depicted in Fig. 10, there is ground to give credit to the entire time series.
I don't see the logic of your response. The point of the referee remains valid, and should be explicitly acknowledged.

We added comments in the revised text, arguing for the presence of the sub-centennial variation back to 1600 (page 11, lines 2-7 and lines 18-19).

We state that the sub-centennial variation can be traced back to 1600, meaning that the corresponding wave was singled out in the reconstructed and *gufm1* time series by the filtering procedure used, as shown in Fig. 10 (Fig. 9 shows, in red, time series of observed data, that are indeed noisy in the first 100 years). The sub-centennial signal is noisier at the beginning of the five time series and mismatches to *gufm1* are evident at 1650 and 1700 for Munich and Rome. However, the *gufm1* time series are consistent with each other. On the oher hand, *gufm1* is not based only on the five time series, but on a much larger number of measurements and the SH analysis distributes errors over the entire spherical surface, so perhaps *gufm1* is able to satisfactory represent the sub-centennial variation at the beginning of the time series. We remind that the sub-centennial variation is the outcome of the filtering **only if** the time series subjected to filtering contains that variation.

Geomagnetic field declination: from decadal to centennial scales

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Abstract. Declination annual means time-series longer than a century provided by 24 geomagnetic observatories worldwide, together with 5 Western European reconstructed declination series over the last four centuries have been analyzed in terms of frequency constituents of the secular variation at inter-decadal and sub-centennial time-scales of 20-35 and, respectively, 70-90 years. Observatory and reconstructed time-series have been processed by several types of filtering, namely Hodrick-Prescott, running averages, and Butterworth. The Hodrick-Prescott filtering allows to separate a quasi-oscillation at decadal time scale, supposed to be related to external variations and called '11-year constituent', from a long-term trend. The latter has been decomposed in two other oscillations, called 'inter-decadal' and 'sub-centennial' constituents by applying a Butterworth filtering with cutoffs at 30 and 73 years, respectively. The analysis shows that the generally accepted geomagnetic jerks occur around extrema in the time derivative of the trend and coincide with extrema in the time derivative of the 11-year constituent. The sub-centennial constituent is traced back to 1600, in the five 400-year long time-series, and shows to be a major constituent of the secular variation, geomagnetic jerks included.

1 Introduction

The temporal variation of the geomagnetic field has been monitored for decades mainly by continuous recordings in geomagnetic observatories. In spite of the growing number, their geographical coverage is highly uneven. Since the longest recorded series of observations at geomagnetic observatories do not exceed some 150 years, research has seen increasing interest in historical spot measurements to construct as long as possible time-series of geomagnetic elements (declination and inclination) going back over some centuries (Malin and Bullard, 1981 for London area; Cafarella et al., 1992 a, b for Rome; Barraclough, 1995 for Edinburgh; Alexandrescu et al., 1996, 1997 and Mandea and Le Mouël, 2016 for Paris area; Korte et al., 2009 for the Munich area). Korte et al. (2009) also included archeomagnetic data, in order to infer information going back to 1400 AD. Such an interest has also been present in Eastern Europe (Bucha, 1959 for the Czech and Slovak territories; Valach et al., 2004 for Slovakia; Atanasiu, 1968; Constantinescu, 1979; Soare et al., 1998 for Romania), reconstructions go back to 1850 and included intensity elements of the geomagnetic field. Let us also note the collection of declination and inclination data from sea voyages over the 15-18th centuries by Jonkers et al. (2003), and the spherical harmonics (SH) model by Jackson et al. (2000). This model includes these data and describes the geomagnetic field evolution since 1590, for all geomagnetic elements (the intensity values are based on an assumed uniform dipole decay rate before 1850).

The last four decades – since the finding by Courtillot et al. (1978) of 'geomagnetic jerks' – have seen a focus of research on the features of the time evolution of the geomagnetic field originating in the Earth's core (main field). Geomagnetic jerks are viewed phenomenologically as sharp changes, within one year or so, in the temporal variation of the main field (secular variation), expressed as the first time derivative of the geomagnetic field time-series, or steps in the secular acceleration expressed as the second time derivative. The definition of geomagnetic jerks is usually illustrated by declination (D) or by the eastward horizontal component of the field (Y) thought to be the least influenced by external variations. Alexandrescu et al. (1997) and Korte et al. (2009) explored the possibility that jerks also occurred before the modern era for which they were evidenced. A review on the subject has been published by Mandea et al. (2010). The geomagnetic jerks have been treated as chaotic fluctuations of the field by Qamili et al. (2013). Brown et al. (2013) have been interested in the sharp time changes in the secular variation, using an improved method to account for the external variations in data (Wardinski and Holme, 2011) and for a jerk identification (Pinheiro et al., 2011); they find by far more events than had previously been determined, with a general trend of increased number of identified jerks towards the end of the 20th century and beginning of the 21st century. The new satellite era offers high resolution magnetic data and the possibility to deeply investigate these events. Indeed, Finlay et al. (2015) and Chulliat et al. (2015) indicate the occurrence, in 2006, 2009 and 2012, of geomagnetic secular acceleration pulses at the core surface. We can note as dates of these new events 2003 (Olsen and Mandea, 2007), 2007 (Olsen et al., 2009; Chulliat et al., 2010), 2011 (Chulliat and Maus, 2014), 2014 (Torta et al., 2015; Kotze, 2017).

Periodicities have been found in the evolution of the geomagnetic field. Fourier spectral analysis (e.g. Currie, 1973; Alldredge, 1977; Langel et al., 1986), but also the Maximum Entropy Method (Jin and Thomas, 1977), the Empirical Mode Decomposition (Roberts et al., 2007; Jackson and Mound, 2010), as well as calculations of torsional waves in the Earth's core (Zatman and Bloxham, 1997; Dickey and de Viron, 2009; Buffett et al., 2009), pointed to periodicities at several time-scales, such as ~11, 13-30, 50-60, and 60-90 years. Buffett (2014) explores the MAC (Magnetic, Archimedes, Coriolis forces) waves and their role in generating long-period variations (60 years) of the field. Periods shorter than the solar cycle time-scale have also been detected, both in some geomagnetic field models (Silva et al., 2012) and in observatory data (e.g. Ou et al., 2017). These studies revealed periodicities in the time domain of about 4-7 years and, respectively 2-3 years. The latter was considered of external origin, while the former has been used as an argument in favour of a six-year internal variation. Recent studies by Gillet et al. (2010, 2015) and Holme and de Viron (2013) point to a ~6 year variation originating in the core that is also observable in length-of-day data. The signal was also discussed by Abarca del Rio et al. (2000), Mound and Buffet (2006), Cox et al. (2016), Duan et al. (2018). We note, however, that both periodicities are very close to the harmonics of the solar cycle, inducing the idea of a possible external origin.

By analysing the frequency content of the geomagnetic field variability, De Santis et al. (2003) and Lesur et al. (2017) have been able to reveal the behaviour of the geomagnetic field as either chaotic or stochastic. They showed that the temporal spectra of the geomagnetic field at the Earth's surface and of the core field spherical harmonic coefficients could be approximated by a power law with a negative slope of about -4 (in the frequency range corresponding to periods from 7 to 64 years), and of about -2, respectively. The latter succeeded to reach periods down to 1 or 2 years.

Demetrescu and Dobrica (2014) demonstrate the presence, in 24 observatory time-series (annual means of the D, H, Z components over some 100-150 years) of constituents of secular variation at time-scales of 22- and ~80-year, superimposed on a so-called steady variation. A slightly different time scale, of 70-75 years, not of ~80 years as seen in H and Z data, is characteristic of declination. They also show that these constituents are seen in the first time derivative of the field, too. The episodes of increasing and decreasing secular variation that result from the superposition of the two constituents are separated by a smooth transition that lasts several years; the sharpness of a geomagnetic jerk is decided by the external effects still existing in data. Indeed, the external effects, mainly controlled by the 11-year solar cycle, are still present when averaging available data to obtain the annual means. These remaining external contributions are present mostly in the intensity elements of the recorded field (H, Z), and affect less the declination (e. g., Olsen and Mandea, 2007). The effects of external contributions in studying the secular variation have been emphasized and quantitatively shown for the European observatories by Verbanac et al. (2007), in terms of correcting annual means using information on external sources, by Wardinski and Holme (2011), in terms of a stochastic (covariant) modeling method, and by Dobrica et al. (2013), in terms of secular variation maps. Demetrescu and Dobrica (2014) tentatively show that the ~80-year variation can be traced back to the 15th century, using three long time-series of declination, of London (Malin and Bullard, 1981), Rome (Cafarella et. al., 1992 a, b), and Munich (Korte et al., 2009).

In the present paper we focus on declination data and revisit 24 time-series of observatory data, updating the available measurements with additional ones since 2007, the last year included in a previous analysis (Demetrescu and Dobrica, 2014). Additional data allow us to better constrain the 1999 (Mandea et al., 2000) and 2007 (Chulliat et al., 2010) events and to infer a possible external contribution to the 2003 geomagnetic jerk (Olsen and Mandea, 2007). Here, new methods are applied in filtering the time-series and novel approaches regarding the quasi-periodicities of the constituents at longer time-scales are considered (Hodrick and Prescott (1997)). Additionally, a special attention is given to the 11-year solar-cycle-related constituent, present in the declination annual means. Finally, we elaborate on our previous analysis of three very long declination time-series, by *i)* including in the analysis two more: Paris (Alexandrescu et al., 1996, 1997; Mandea and Le Mouël, 2016) and Edinburgh (Barraclough, 1995), *ii)* discussing the first time derivative of the five time-series, *iii)* comparing in detail our analysis on jerk occurrence to the Alexandrescu et al. (1997) and Korte et al. (2009) ones, and *iv)* comparing with time-series provided by the *gufm1* main field model by Jackson et al. (2000).

2 Data

2.1 Observatory data

Annual means of declination as given by http://www.geomag.bgs.ac.uk/data_service/data/annual_means.shtml have been used. The locations of the 24 observatories with 100-150 years long time-series, labelled with their IAGA codes are shown in Fig. S1 (Supplementary material), superimposed on the WMM2010 declination map at the geomagnetic epoch 2010.0 (http://www.ngdc.noaa.gov/geomag/WMM/data/WMM2010/WMM2010_D_MERC.pdf). In Fig. 1 we show, as an example, time-series of declination and of its first time derivative at Niemegk (Germany) observatory (IAGA code NGK).

2.2 Historical data

Five long time-series referenced above, for Edinburgh, London, Paris, Munich, and Rome have been considered in the present study. Data used, in the order of decreasing latitude of the location, are as follows:

- Edinburgh: raw data published by Barraclough (1995), adjusted to Eskdalemuir observatory (ESK);
- London: raw data published by Malin and Bullard (1981), adjusted to Hartland observatory (HAD);
- Paris: raw data published by Alexandrescu et al. (1996, 1997) and reviewed recently by Mandea and Le Mouël (2016), adjusted to Chambon la Foret observatory (CLF);
- Munich: 11-year filtered smoothing spline fitted to raw data, as published by Korte et al. (2009), adjusted to Furstenfeldbruck observatory (FUR);
- Rome: assembled time-series using data published by Cafarella et al. (1992 b) for Rome area and for three successively operating Italian observatories (Pola, 1881-1922; Castellaccio, 1933-1962; L'Aquila, 1960-2011), adjusted to L'Aquila observatory (AQU).

These time-series are used in Section 4.

3 Method

A Fourier spectral analysis (FFT) on the 24 declination time-series (Fig. 2a) and of their time derivative (Fig. 2b) shows a broad spectral peak at around 73 years (60-100) that dominates by far other (broad) peaks at ~30, ~22, and ~17 years. It is worth mentioning that these periods are in good agreement with those found by Jackson and Mound (2010) using a different approach, the Empirical Mode Decomposition, on declination and inclination time series from 48 geomagnetic observatories (the periods found by these authors being 11.5, 30.5, 62 and 81 years). We show the power spectra of declination and of its secular variation in a log-log scale too, following De Santis et al. (2003) and Lesur et al (2017), in Fig. S2a,b (Supplementary material). While the average power spectrum of declination time series might be represented by a power law with an exponent of -1.89 in the frequency range corresponding to all periods less than 100 years, the average power spectrum of secular variation shows a slope change occurring at a period of about 10 years. The power law exponent for the interval 100-10 years is -1.81, similar to the figure found by Lesur et al. (2017) for individual observatories. Fig. S2b indicates „lines", or rather, periods grouped at three time-scales, namely 60-90, 20-35, and 8-15 years, exactly those we considered for our filtering approach. At odds with the log-log plot, which is expected to smooth the spectral lines, the power spectral density versus frequency or period in a semi-log scale plot is able to comparatively show the magnitude of various oscillations present in the time series.

At this stage we also remark differences between observatories regarding frequencies corresponding to these lines, which are commented upon below. Some of these differences could arise from the different lengths of the time-series, as some tests (not shown here) of repeating the FFT for the same time-series truncated to different lengths seems to indicate. Demetrescu and Dobrica (2014) notice that dominating powerful signals at larger time-scales in data tend to contaminate the filtered time-series meant to show quasi-periodic variations at smaller time-scales. That is why in the present paper we apply a Hodrick and Prescott (1997) (HP) type analysis, which is able to separate oscillatory features at smaller (e. g. decadal) time-scales from trends representing variations at larger (e. g. centennial) time-scales.

The HP filter separates a time-series y_t into a trend component T_t and a cyclical component C_t such that $y_t = T_t + C_t$. The function for the filter has the form

$$\sum_{t=1}^{m} C_t^2 + \lambda \sum_{t=1}^{m} \left[(T_t - T_{t-1}) - (T_{t-1} - T_{t-2}) \right]^2$$

where m is the number of samples and λ is the smoothing parameter. The first sum minimizes the difference between the time-series and its trend component (which is its cyclical component). The second sum minimizes the second-order difference of the trend component (which is analogous to minimization of the second derivative of the trend component). If the smoothing parameter is 0, no smoothing takes place. As the smoothing parameter increases in value, the smoothed series becomes more linear. Appropriate values of the smoothing parameter depend upon the data sampling. In our case data being yearly sampled we apply a smoothing parameter of 100, recommended by Hodrick and Prescott (1997) and checked by us after a few tests with λ varying between 10 and 1600 with a step of 50 (not shown here). Actually, according to Paige and Trindade (2010), the HP filter is a special case of a linear penalized spline model with knots placed at all observed time points.

Variations at larger time-scales seen in the trend given by HP filtering have been further decomposed in two other oscillations, by applying a Butterworth (1930) filtering with certain cutoffs corresponding to periods of ~73 and 30 years, as indicated by two broad peaks in the superimposed FFT spectra of the trend for all 24 observatories shown in Fig. S3 (Supplementary material). Actually, the above cutoffs are derived as averages over the 24 FFT spectral lines, as De Silva et al. (2012), Demetrescu and Dobrica (2014), and Ou et al. (2017) proceeded with their data. It is important to note that no matter what figure was used in our filter design (except the actual period in data), the filtered time series would show the actual oscillations hidden in the unfiltered time series (Demetrescu and Dobrica, PEPI 2014, Appendix).

3.1 Observatory data

We have applied the described methods on observatory and historical data. With respect of observatory data, firstly we show in Fig. 3, as an example of data processing, results for Niemegk. The first time derivative of declination (the first differences of annual means) is shown in the first panel of the figure, together with the trend given by the HP filter. The cyclic component is also plotted (second panel). No difference exists when the latter is compared to the superimposed time-series obtained as residuals of filtering the original time-series with an 11-year running average window or with a high-pass 11-year cutoff Butterworth (1930) filter. Verbanac et al. (2007) show that the residual signal after removing CM4 core field model from the annual averages of European observatories has a clear solar-cycle signature and can be modeled down to ± 2 nT, using magnetospheric ring current data (Dst) and an ionospheric field proxy (Ap). Wardinski and Holme (2011) characterize the external effects stochastically, analyzing the correlated so-called 'noise' in the time-series of X, Y, and Z components at world-wide distributed observatories and the Dst index in a first step and residuals at Niemegk instead of Ap, in a second step. Here, we also mention attempts at extracting external contributions through global models on long periods (Yukutake and Cain, 1979; McLeod et al, 1996; Langel et al, 1996; Gillet et al, 2013), who give an idea of what can be achieved on the basis of spherical harmonics decomposition, and of the expected respective amplitudes of internal and external signals. We tend to attribute the 11-year signal to external sources, based on a long list of papers referenced by Demetrescu and Dobrica (2014). In the third panel of Fig. 3, the sunspot number time series have been plotted as an independent indication of the external origin of the cyclic component. It might be seen that the cyclic component is almost in opposite phase with the 11-year solar cycle, but more detailed aspects will be addressed in a future study. In a recent review (Finlay et al., 2017), it is one more underlined that the external field characterisation is a challenge for the main geomagnetic field modeling. We are aware, however, that our point of view regarding the signal at these frequencies as an external one could be considered as partially correct, as new models, based on satellite data, succeed to reduce the ambiguity in the internal/external sources separation. We note that core sources could also contribute to the high-frequency 11-year signal and its constituents, for instance by the 6-year signal discussed by Gillet et al. (2010, 2015) and Holme and de Viron (2013).

Since the HP filtering applied to the trend is not able to further separate it in constituents, we appeal (a) to running averages (Demetrescu and Dobrica, 2014) and (b) Butterworth (1930) filtering to get the time-series corresponding to the ~73 and at 25-35 years time-scales. In Fig. 4 we show, again as an example, the results for NGK. In the first case, the constituents of the trend are obtained by successively smoothing the trend time-series with 30- and 73-year running average and subtracting them from the trend time-series and, respectively, from the 30-year average time-series. A similar result is obtained in the second case, of using 30- and, respectively, 73-year cutoff Butterworth filtering. Both methods have advantages and disadvantages. As one can notice in Fig. 4, the running average filtering produces time-series that include the full information from the unfiltered data on a certain central portion, but no information for both ends of time-series (the 30- and the 73-year smoothed time-series are shorter by 15 and 36 years respectively, at each end), while the Butterworth filter produces time-series of the same length as unfiltered data, but with distorted amplitudes at ends. The dates of maxima and minima in the filtered time-series are, however, correctly retrieved, allowing conclusions on (quasi)periodicities in data to be drawn for the entire time interval covered by data. Let us note that if we have used instead of 30- and 73-year filtering on trend values the 22- and 80-year filtering by Demetrescu and Dobrica (2014), we would have obtained similar results (extrema at the same moments, but slightly different amplitudes), as one can see in Fig. 4. Of course, any pair of constituents one chooses, 30- and 73- or 22- and 80-year ones, the sum of the two constituents is the same, namely the trend plotted in the top panel of Fig. 3.

Let us discuss the differences between observatories, seen in frequencies corresponding to the broad spectral lines singled out above (Fig. 2 and Fig. S3 (Supplementary material)). The information regarding the actual periodicities at various observatories would not be lost when adopting a certain average value (e. g. 73 or 80 years) in data processing. Indeed, unless the window in the running average or the cutoff value in the Butterworth filtering is a multiple of the hidden period in data, the filtered cyclical component is itself a cyclical component of the same period as the original component (Appendix, Demetrescu and Dobrica, 2014). This can be seen in Fig. 4, where time-series obtained using values of 22 and 30 years or, respectively, 80 and 73 years for filtering data are compared. In case of H and Z (not shown) the filtered ~80-year constituent shows an oscillation of that period (actually a mean period of 78 years), but in case of D a slightly different time-scale, of 70-75 years seems to be characteristic. Since D is a non-linear function of the field vector, one should not expect that field oscillations induced by the core sources be identical in H and D (Roberts et al., 2007), so a slight difference might occur. Also, according to the same authors, one should not expect exactly the same response at all observatories to variations in the core sources changes. Consequently, in the remaining of this paper we use the terms “inter-decadal” and “sub-centennial” constituents for the ones at the 20-35 and, respectively, 70-90-year time-scales.

We remark here that, at odds with the internal inter-decadal and sub-centennial constituents, the 11-year constituent is very noisy, on one hand because errors in the annual means (measurement noise, baseline definition, changes in pillars etc.) are retained almost entirely in this time-series, and, on the other hand, as a result of the time derivative operator that enhances noise and brings forward harmonics of the 11-year constituent that are not significant in data (compare also Figs. 2a and 2b). Besides, the solar cycle length variability (between 8 and 14 years over the past 10 cycles) also contributes to the noise in the high-passed 11-year time-series. Superimposing spectra of the cyclic component for the 24 declination time-series (Fig. S4 (Supplementary material)), the noisiness is evident. However, in spite of that, some specific lines can be distinguished:

- lines in the 15-25 year interval, corresponding to the ~22-year constituent, detected in the last ~40 years of the cyclic component time-series of Fig. 3;
- lines in the 8-14 year domain, corresponding to the 11-year constituent;
- lines in the 4-7 and 2-3 year domains, corresponding to the first two harmonics of the 11-year constituent. We note that the 4-7 year signal covers the 6-year signal detected in variations of length-of-day (Holme and de Viron, 2013) and in wave processes discussed by Gillet et al. (2010, 2015), pointing to a possible core contribution to the observed variation. We also note the presence of stronger peaks in the 2-3 years period domain than those in the 4-7 years one. This observation is in line with the study by Ou et al. (2017).

We are aware of the fact that, due to noise, the separation in frequency domains is not an ideal one. For instance, there are large peaks occurring between frequencies corresponding to periods between 7 and 9 year; they characterize spectra for Hartland and, with smaller amplitude, Canberra observatories. We consider this possibly linked to the less precise values at the beginning of the time-series, noise that is retained in the 11-year signal and can significantly alter the FFT.

3.2 Historical data

The historical data have been processed as it has been done for observatory time-series. Since data are sparser and sparser before ~1800, for London, Paris, Rome, and Edinburgh a cubic B-spline interpolation of early data is used to obtain a plot with continuous annual values, after removing the evident outliers. The latter can be a result of less precise measurements and/or less precise reduction to the location of the present-day observatory, contributing with data over the most recent periods. Due to the temporal distance of several years between historical data at the beginning of the reconstructed time-series, the spline line might show artefact wiggles. For that part of time-series a linear or quadratic interpolation could be more appropriate. The Munich series has been already filtered by Korte et al. (2009).

Fig. 5 shows the time derivative of the Paris time-series together with the superimposed HP trend; the inter-decadal and sub-centennial constituents of the trend are shown too. The noise problem becomes stronger when the time derivative of the declination series is considered. The time derivative enhances, as expected, short time variations presented at decadal and shorter time-scales by less accurate historical data before ~1850, that results in higher amplitudes than for the observatory era of the two constituents of the HP trend (compare 0.12 to 0.025 and 0.05 to 0.01 in case of the inter-decadal, and respectively, sub-centennial constituents).

4 Results and discussion

4.1 Observatory data

The two constituents of the secular variation for the 24 observatories considered in this study, as obtained by a HP filtering, namely the trend and the decadal cyclic variations, are shown in Fig. 6. The trends are referred to the average value for the time interval in which they are defined. The two constituents of the trend, the inter-decadal and the sub-centennial variations, as obtained by a Butterworth filtering, are also plotted. We superimpose the time-series from the 24 observatories, corresponding to each of the time-scales, in order to emphasize common features and differences. We also indicate in Fig. 6 the accepted occurrence time of geomagnetic jerks (e.g. Mandea et al., 2010; Brown et al., 2013).

The cyclic constituent obtained from a HP filtering (second top panel in Fig. 6), supposed to show the effects of external sources in data, is very noisy and prevents in this form any interpretation regarding this constituent of the recorded secular variation. However, plotting only data from the considered European observatories (Fig. 7), emphasizes the strong presence of harmonics of the 11-year cycle, superimposed on the 11-year oscillations in the first part of the time-series and on the significant 22-year oscillation in the last ~40 years. We have chosen geographically close European observatories in order to enhance the visual effect, as they are affected by the same 22- and ~80-year variations (see Demetrescu and

Dobrica, 2014) and show similar time evolutions. The similarity of the 11-year signal in European observatories is also noticed in a previous paper (Dobrica et al., 2013).

The 2003 jerk shown in Fig. 6 has been evidenced for limited areas only ($\Delta dY^2/dt^2$ slightly negative over Central and Eastern Europe and positive along the 90-100°E meridian, noted by Olsen and Mandea (2007)). From Fig. 7 it seems that the external effects might play a role in characterizing the 2003 jerk, as a 5-year running averages smoothing, meant to get rid of variations related to the first harmonic of the 11-year variation, attenuates the sharp variation of the declination time derivative seen in the raw data (upper plot). We note that the smoothing would attenuate also the 6-year component discussed by Gillet et al. (2010, 2015) and Holme and de Viron (2013), if present in data. According to the same figure, other recent European geomagnetic jerk occurrence dates should be slightly shifted by one year, from 1999 and 2007, to 1998 and 2006 respectively, when extrema actually occur in the 11-year variation. However, due to the filtering procedure and the annual means sampling of data, the events by the end of series might not be so well described. It is worth to note that in terms of analysis shown in Figs. 6 and 7, the very recent geomagnetic jerks occurred in 2011 and 2014, evidenced for limited areas by Chulliat and Maus (2014) and Torta et al. (2015) in Atlantic sector and Atlantic and European sectors, respectively, reveal a strong influence of the decadal constituent at those dates. A more detailed analysis of the 11-year constituent of the secular variation is beyond the scope of this paper.

In Figs. 6 and 7 the vertical lines mark epochs of accepted geomagnetic jerks; they occurred around extrema in the time derivative of the trend variation, produced by a combination of the two constituents, at ~30 and ~73-year timescales, and coincide with extrema in the time derivative of the external variation (with the above observation, regarding the 1999 and 2007 events). Phase differences between individual time-series explain differences in the occurrence time and geographical distribution of geomagnetic jerks. Once the external contributions to the first differences of the observatory annual means, of comparable amplitude with the trend variations are minimized, the core contribution to the observed secular variation no longer exhibits the very sharp appearance of geomagnetic jerks. According to our quantitative analysis of recorded data presented in Figs. 6 and 7 (see also Demetrescu and Dobrica (2014)), the geomagnetic jerk might be seen as a result of a more general phenomenon, namely the evolution of the secular variation as a result of a superposition of two (or several) waves describing effects of processes in the Earth's core at two (or several) time-scales. This is in line with Bloxham et al. (2002) and Alldredge (1984; 1985) who have advanced this possibility, based on core flow modeling arguments and, respectively, on geometric arguments. Finlay and Jackson (2003) and Jackson and Finlay (2007) have identified core surface equatorial westward moving magnetic flux patches that can be either a result of core flow vortices entrained by a larger scale westward flow, or Alfvén waves excited in the core. That the flow in the core is turbulent became common consideration with many studies on geodynamo and core flow modelling from secular variation data (see the review by Holme (2015) on the latter). The turbulent flow, as inferred by De Santis et al. (2003) by looking at the power spectra of X, Y, Z annual means time-series, does not exclude but, on the contrary implies the existence of vortices with various time and space scales. The "waves" we speak of above could be in fact surface manifestations of core surface vortices that move around and survive for a given timespan, as shown by Demetrescu and Dobrica (2014). The latter discussed the map appearance of their steady, 22-year and ~80-year variations, pointing to the different space scales of the three ingredients that manifest themselves at the three timescales. As noted by Holme (2015), the core flow models existing to date, including those of higher resolution based on satellite models of the field and secular variation, are not able to predict small scale features, as field models cannot resolve details in the core field smaller than the spherical harmonic degree 13.

4.2 Historical data

Demetrescu and Dobrica (2014) have previously analyzed three of the long time-series of historical magnetic declination data (London, Munich, Rome) and showed that the sub-centennial variation is present back in time to the 15th century. Here, we define and characterize the sub-centennial variation in case of the secular variation of declination for five available time-series.

The time-series showing the declination at the five locations are plotted in Fig. 8. We also superimpose time-series obtained from *gufm1* (Jackson et al., 2000) for the corresponding location. The spot measurements before observatory era are affected by much larger errors than observatory measurements, due, on one hand, to the equipment accuracy, and on the other to the non-corrected external variations and/or reduction to the location of the present-day observatory. As mentioned in Section 2, for London, Paris, Rome, and Edinburgh a cubic B-spline interpolation of early data is used to obtain a plot with continuous annual values. The spline curve shows artefact wiggles before ~1700. For that part of time-series a linear or quadratic interpolation could be more appropriate to describe the long-term evolution. The Munich time-series, published by Korte et al. (2009), had been smoothed with an 11-year filter and a 2.5-year knot space spline. Fig. 9 shows, for the five locations, only the first time derivative of the HP trend, together with the corresponding HP trend time derivative in *gufm1* values.

In the following, only the sub-centennial constituent, less affected by noise than the decadal and inter-decadal constituents, is discussed. The five curves in Fig. 10, showing the sub-centennial constituent of the trend plotted in Fig. 9, demonstrate that the latter is not restricted to the last 150 years. So does also the sub-centennial constituent derived from *gufm1*. The same conclusion, based on Empirical Mode Decomposition applied to Munich data, has been invoked by Jackson and Mound (2010). The latter also found a longer period, of 160 years. Referring to the appearance of the curves in Figs. 8 and 9, a variation at a much larger timescale, of 400 years or longer, could, however, be present in data.

Several maxima and minima are evident in the sub-centennial constituent time derivative plots (Fig. 10) before 1900, besides the known ones over the 20th century. Comparing the five time-series of the sub-centennial constituent time derivative with each other and with the corresponding *gufm1* model, a few interesting observations could be emphasized:

- Firstly, all curves as derived from data and/or model show the same maxima and minima of the sub-centennial constituent after 1850, namely maxima at 1850-1880, 1920-1930, and minima at around 1900 and 1960; however, the sub-centennial signal is noisier at the beginning of the five time series and mismatches to *gufm1* are evident at 1650 and 1700 for Munich and Rome, while the *gufm1* time series are consistent with each other. Taken into account the noise in the historical data (Fig.9) and the fact that *gufm1* is based on a much larger number of measurements, not only on the five time series considered here, the *gufm1* is conceivably able to satisfactory represent the sub-centennial variation at the beginning of the time series;

- Secondly, the amplitude of the sub-centennial constituent before and after 1900 seems to be comparable, in spite of the lower quality of data for the first 300 years of the time-series. Larger amplitude variations at the start of the time-series stem probably from the poorly constrained data in that time interval;

- Finally, before 1850 the noise in data is more evident in case of London time-series. However, a synchronous maximum around 1800 and a minimum around 1820 can be seen in London, Paris, and Rome curves, but not in the Munich and in the *gufm1* ones, that show only an inflexion at 1790-1800 and at ~1820 (change to a lower secular acceleration – the second time derivative of the field – and then change again to a higher secular acceleration). Another maximum, well developed around 1750 in Paris, Munich, and Rome plots, as well as in all *gufm1* ones, is not seen in the London curve. Back toward 1650, another maximum seems to be present in London and Paris curves, but not in the Munich one, while the *gufm1* plots indicate its presence. We might account this behavior on the temporally less dense data before 1780 and on the spline smoothing. Again, *gufm1*, which is based on a much larger set of measurements, shows consistent behavior among the five locations considered, and could support the existence of the sub-centennial variation all the way back to 1600.

In terms of geomagnetic jerks, Alexandrescu et al. (1997), based on a synthetic declination curve for Paris inferred from Paris and London series, recognized one event around 1870 in annual and monthly means time-series, also detected in Helsinki, Furstenfeldbruck and Oslo data. Other possible events are noted around 1700, 1730, 1750, 1770 and 1785. These dates correspond, within a decade, with maxima and minima of the sub-centennial variation time derivative plotted in Fig. 10 (1690, 1740, 1780, 1800, 1850-1860, 1900), which is satisfactory given the uncertainty on both sides of this comparison. Data prior to 1870 were considered by Alexandrescu et al. (1997) too noisy or unreliable to clearly reveal geomagnetic jerks, at least of comparable amplitude with the 1870, 1901, 1925, 1969, and 1978 jerks. However, as mentioned above, the amplitude of the sub-centennial variation before and after 1900 is comparable. Korte et al. (2009) compared the Munich smoothed secular variation time-series with a time-series of the same length (1400-2000) for Paris, containing archeomagnetic and other measured data prior to 1700, adjusted to CLF, spline-smoothed in the same way as the Munich time-series. A good agreement characterizes the time interval 1770-2000 and, as the authors stated, surprisingly consistent secular variation and acceleration between the smoothed curves from the two locations is found for the time span 1400-1580, in spite of the rather low quality of data over this time-span. Significant differences between the two locations exist however between 1580 and 1770. Korte et al. (2009) also note that in both curves the time interval 1765-1865 seems to be devoid of strong rapid secular changes.

When comparing the possible geomagnetic jerks (called “events” by Korte et al. (2009)) in the Munich curve, with the maxima and minima of the first time derivative of the sub-centennial constituent for the same location, plotted in Fig. 10, we find that most of them (1448, 1508, 1558, 1693, 1741, 1861, 1889, 1932) coincide within 0-3 years with maxima and minima of our sub-centennial constituent (1460, 1510, 1560, 1690, 1740, 1780, 1800, 1850-1860, 1900). In the time interval

1765-1865, considered to be devoid of strong rapid secular changes by Korte et al. (2009), our analysis detects, as mentioned above, inflections at 1790-1800 and at ~1820, which are close to the 1790-1810 maximum and, respectively, to the 1818-1828 minimum seen in the London, Paris, and Rome curves.

We note that the similar variability shown by the field at the five European locations is not surprising, as, on one hand, a core source with Earth's surface effects on a large area acted the whole timespan of the model (Stefan et al., 2017). On the other hand, the spatial resolution of the *gufm1*, which decreases significantly towards the start of the model, could also contribute.

Considering these results we can suggest that geomagnetic jerks are only a part of a variation at a much longer timescale, the sub-centennial constituent. A certain contribution, most visible over the last 40 years, comes also from the 20-30-year inter-decadal constituent. The larger noise in data before 1900 prevents a possible identification of the latter at earlier times, the only variation that could be observed being the sub-centennial one.

5 Conclusions

Our results underline the importance of the time perspective one has on geomagnetic data: besides the contribution of the sub-centennial constituent in defining geomagnetic jerks, what we called 'steady variation', based on 150 years of observatory data (Demetrescu and Dobrica, 2014), proves to be only a part of a larger timescale variation, when 400 years of data are available.

Declination annual means time-series longer than a century provided by 24 geomagnetic observatories world-wide, together with 5 reconstructed declination series over the last four centuries in the Western Europe have been analyzed in terms of frequency constituents of the secular variation at inter-decadal and sub-centennial time-scales of 20-35 and, respectively, 70-80 years. Observatory time-series until 2015 have been processed by several types of filtering, namely Hodrick-Prescott, running averages and Butterworth. Average windows of, and respectively cutoffs at 11, 30, and 73 years have been used to account for broad lines in the FFT spectra corresponding to (a) the external solar-cycle-related contamination in the annual averages, the so-called 11-year or *decadal* constituent, to (b) a 20-35-year constituent, named *inter-decadal*, and, respectively, to (c) a broad intense spectral line (60-100 years) present in data, the so-called *sub-centennial* constituent, singled out by the HP filtering and FFT analysis of the constituents. The average values used in filtering to obtain the variations of the three constituents of the observed time derivative of declination have no consequences on the evolution and dominant period of the retrieved constituents at individual observatories. This is expected, as any filtered cyclical component is itself a cyclical component of the same period as the original one. Also, a slight difference between average sub-centennial timescales in declination and in the vector components of the field could be noticed (73 years compared to 78 years). These results confirm the conclusion by Demetrescu and Dobrica (2014), based on shorter sub-centennial and inter-decadal time-series.

The accepted geomagnetic jerks occur around more pronounced extrema in the time derivative of inter-decadal constituent and coincide with extrema in the time derivative of the 11-year constituent (except the '1999' and the '2007' events). Around 1925, 1969, and in 2006 the extrema in the sub-centennial constituent coincide in time or is close to the extrema in the inter-decadal constituent, leading to more pronounced geomagnetic jerks. Phase differences between individual time-series explain differences in the occurrence time, geographical distribution and magnitude of geomagnetic jerks. Once the external contributions to the first differences of the observatory annual means – of comparable amplitude with the inter-decadal and sub-centennial constituents – are minimized, the observed secular variation no longer exhibits a clear V-shape at time of geomagnetic jerks. We are aware, however, that in doing so, some possibly important internal signal would have been removed too, and further work is necessary to elucidate this problem.

The detected extrema in the historical data have been compared with events interpreted in terms of geomagnetic jerk occurrence dates proposed by other authors (Alexandrescu et al., 1997; Korte et al., 2009). It appears that possible "events" in jerk terms, at 1700, 1730, 1750, 1770, 1785, considered with a question mark by Alexandrescu et al. (1997) because of too noisy or unreliable data, are occurring close to maxima and minima of the sub-centennial constituent. The sub-centennial constituent has comparable amplitudes before and after 1900, in spite of lower quality of data in the first 300 years of the analyzed time-series, making it a reliable tracer of geomagnetic jerks in the past. Unfortunately, because of noise in the reconstructed time-series, the inter-decadal variation, a constituent of the secular variation, could not be recovered and complete information on these phenomena occurrence is limited.

According to our results, epochs of geomagnetic jerks may vary as much as a couple of years from one series to another. Over the investigated period, some very clear long periods exist between two successive and well-defined jerks. Over this long-term tendency, less well-defined events can be observed, as the many noted since magnetic satellite data are available (e.g. Torta et al., 2015). We suggest that the geomagnetic jerk concept should be considered as a more general notion, namely the evolution of the secular variation as a result of superposition of two (or more) constituents describing effects of processes in the Earth's core at two (or more) time-scales. Revealing the causes of these variations from the point of view of mechanisms in the core is beyond the scope of this work.

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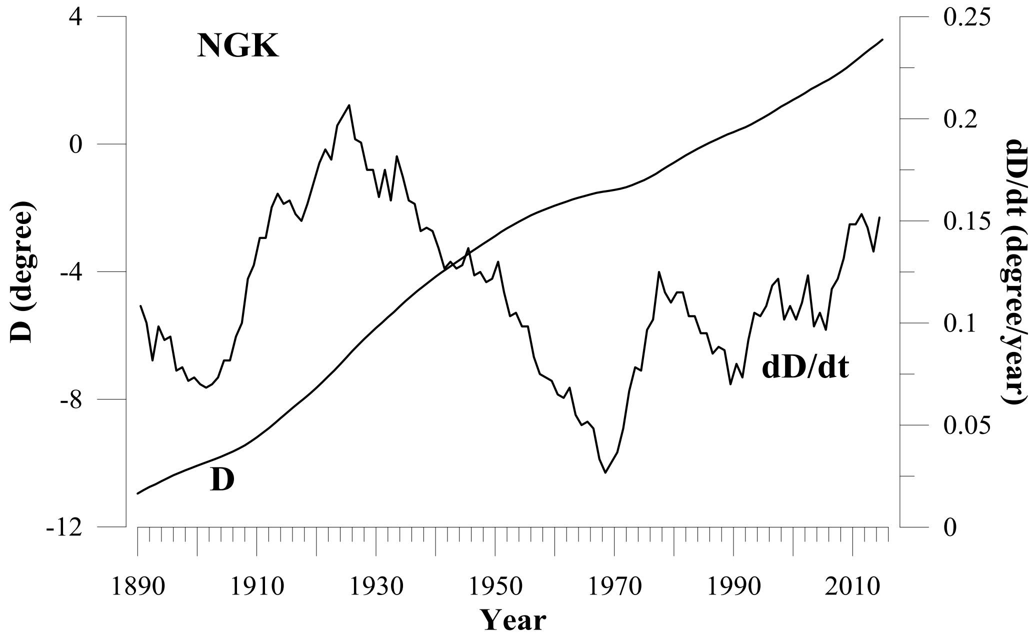
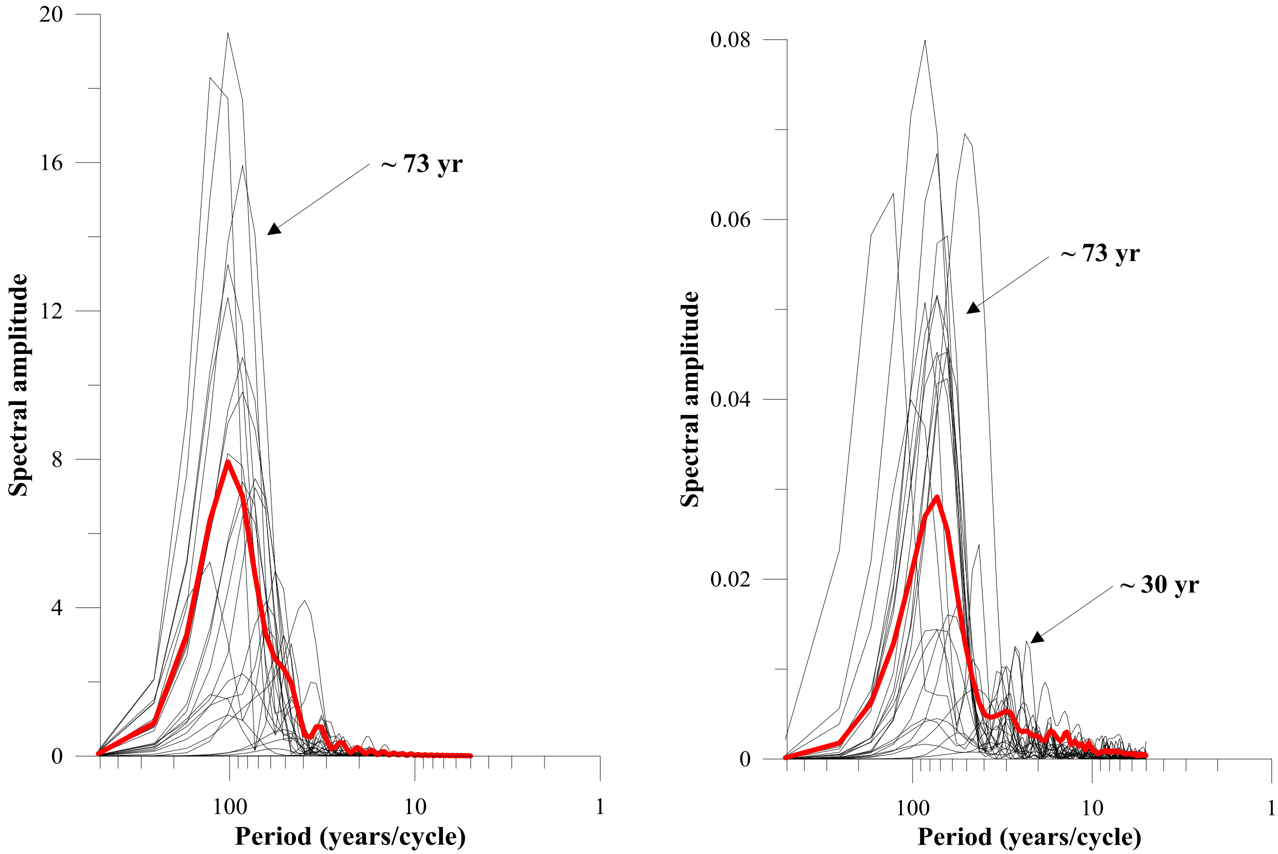


Figure 1: Declination and its first time derivative time-series. Example for a high-standards geomagnetic observatory (Niemegk, NGK).



(a) (b)

Figure 2: FFT power spectrum: observatory declination time-series (a); time derivative of declination time-series (b). The average power spectrum (red).

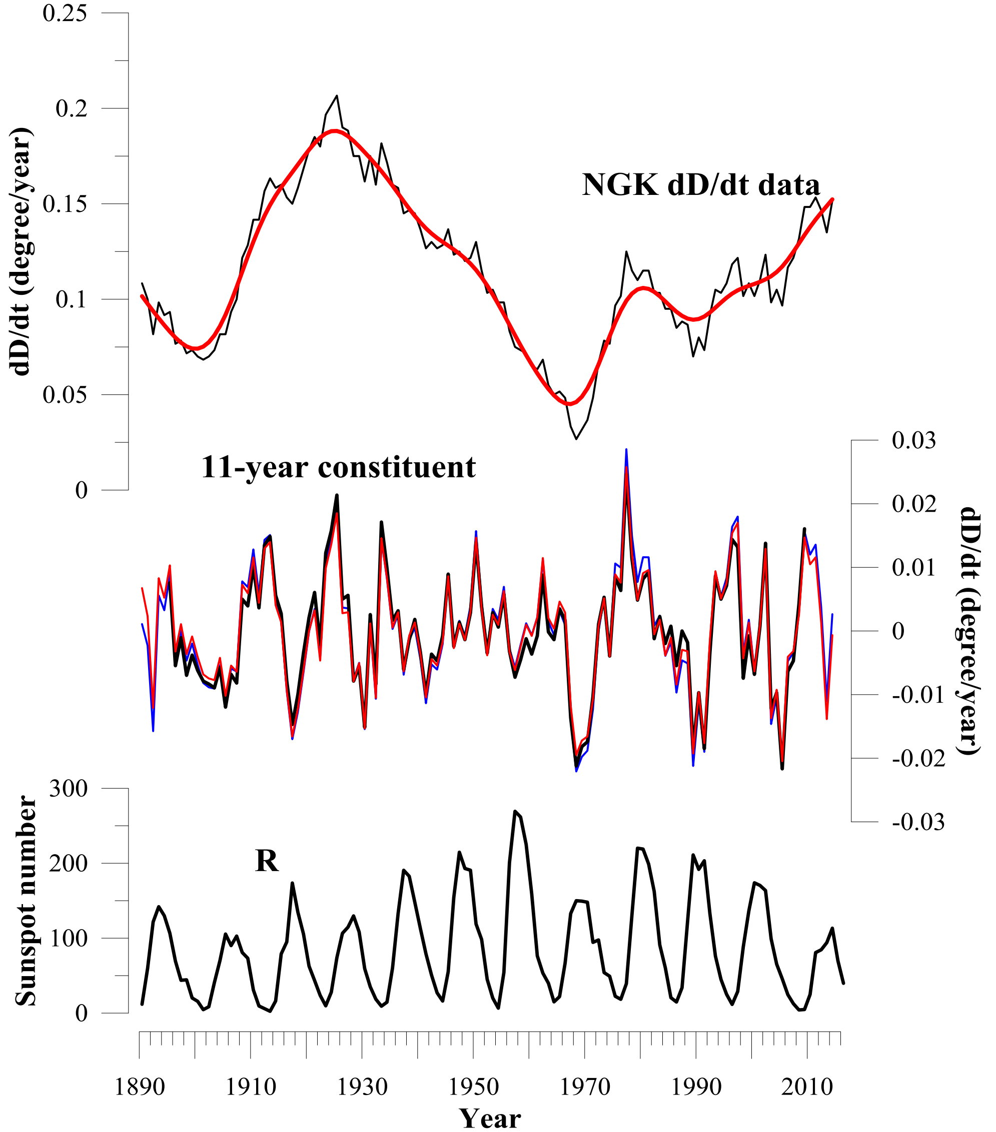


Figure 3: Constituents of the first time derivative of the declination at Niemegk observatory. First panel: first differences of annual means (thin black curve) and the trend from a HP filtering (thick red curve). Second panel: cyclic constituent from a HP filtering (red), the 11-year signal from filtered first differences by an 11-year cutoff high-pass Butterworth filtering (blue), and the 11-year signal obtained as a residual after the removal of an 11-year running average from the dD/dt time-series (black). Third panel: the sunspot number time series (R).

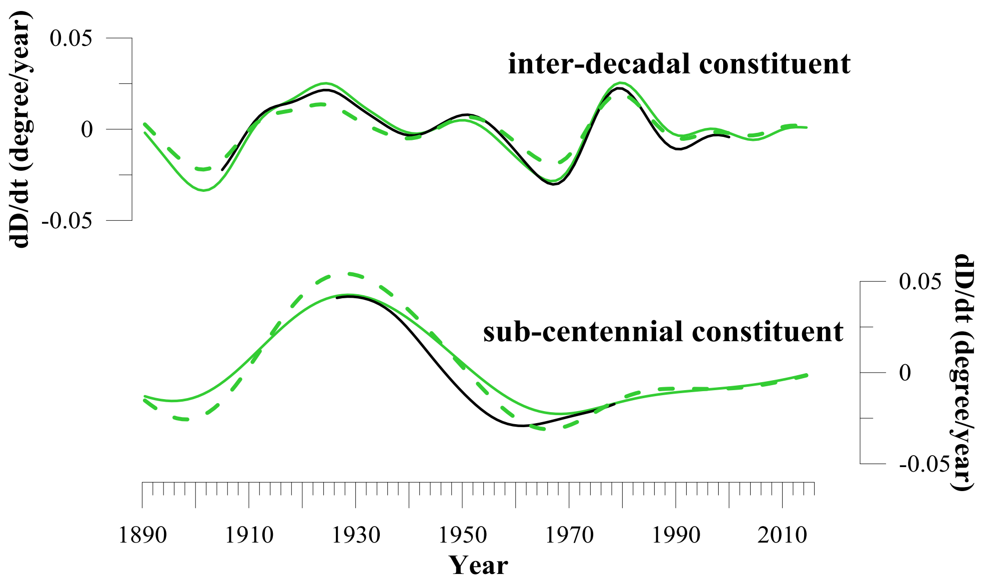


Figure 4: Constituents of the first time derivative trend of declination at Niemegk observatory (the red curve in upper plot, Fig. 3). Top: the inter-decadal constituent of the trend as a 30-year cutoff high-pass Butterworth filtering (green) and as a residual after removal of a 30-year running average filtering (black) from the trend, the '~22-year' constituent from a 22-year cutoff high-pass Butterworth filtering (dashed green). Bottom: the sub-centennial constituent of the trend as a 73-year cutoff Butterworth filtering (green), and as a residual after removal of a 73-year running average filtering from the 30-year smoothed trend (black), the '~80-year' constituent from a 78-year cutoff Butterworth filtering (dashed green).

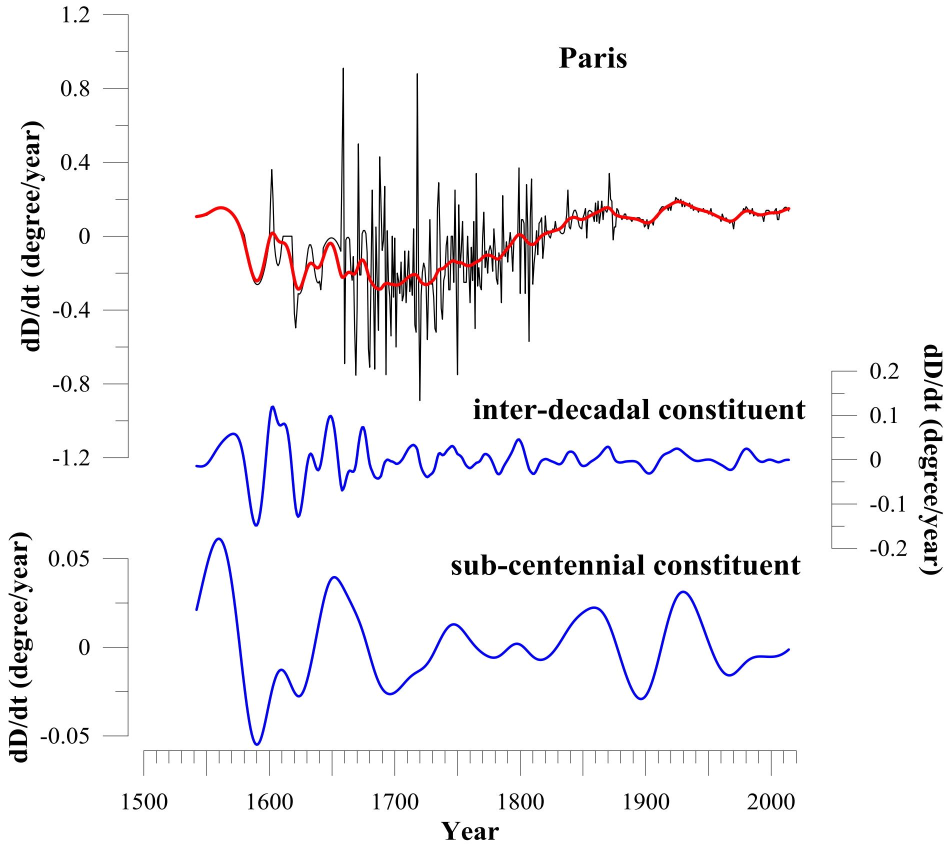


Figure 5: The first time derivative of the Paris declination time-series (black) and the HP trend (red) (top panel); the inter-decadal (middle panel) and the sub-centennial (bottom panel) constituents of the trend from a Butterwoth filtering.

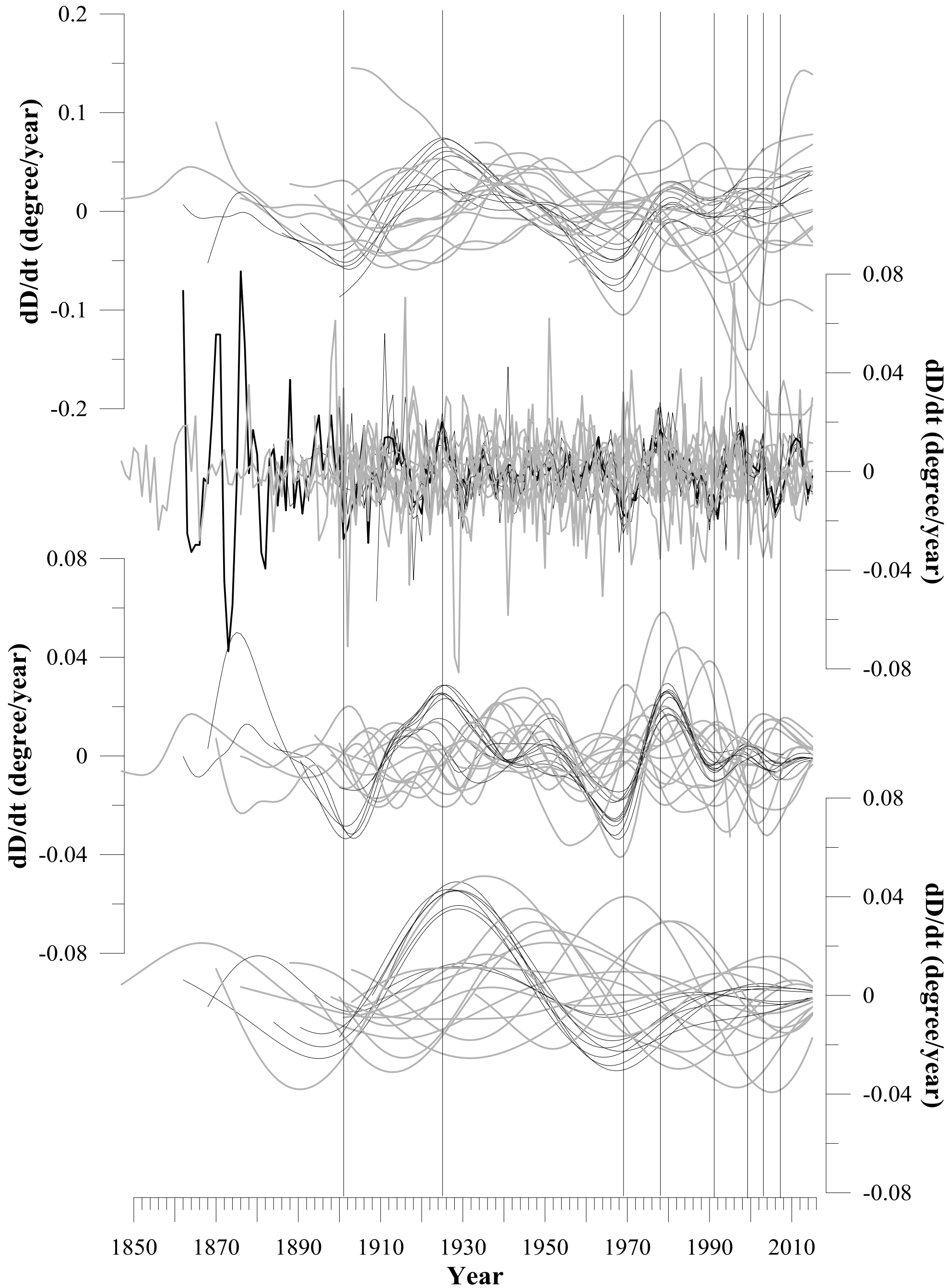


Figure 6: Constituents of the first time derivative of the declination at all analyzed observatories (European (black) and non-European (gray) time-series). From top to bottom: the trend from a HP filtering, the cyclical constituent from a HP filtering, the inter-decadal constituent of the trend, the sub-centennial constituent of the trend. Vertical lines mark the generally accepted 20th century geomagnetic jerks.

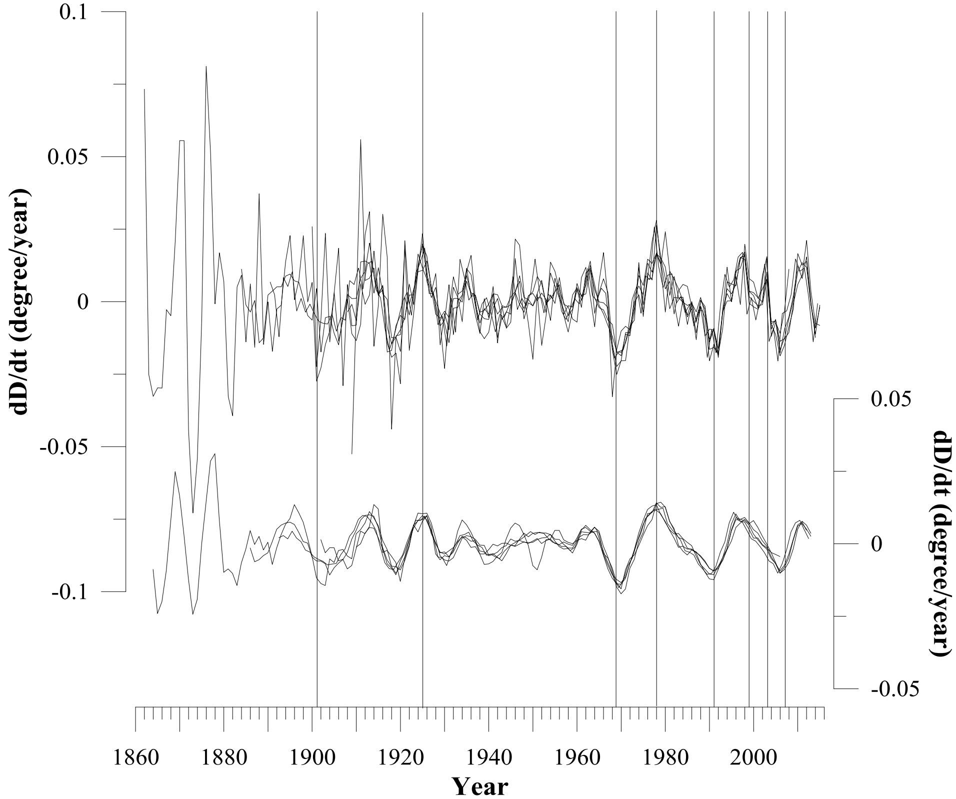


Figure 7: Upper panel: the decadal variation of the first time derivative of declination at the European observatories (cyclical constituent from a HP filtering). Lower panel: the 5-year running averages smoothing of time-series plotted in the upper panel. Vertical lines mark the generally accepted 20th century geomagnetic jerks.

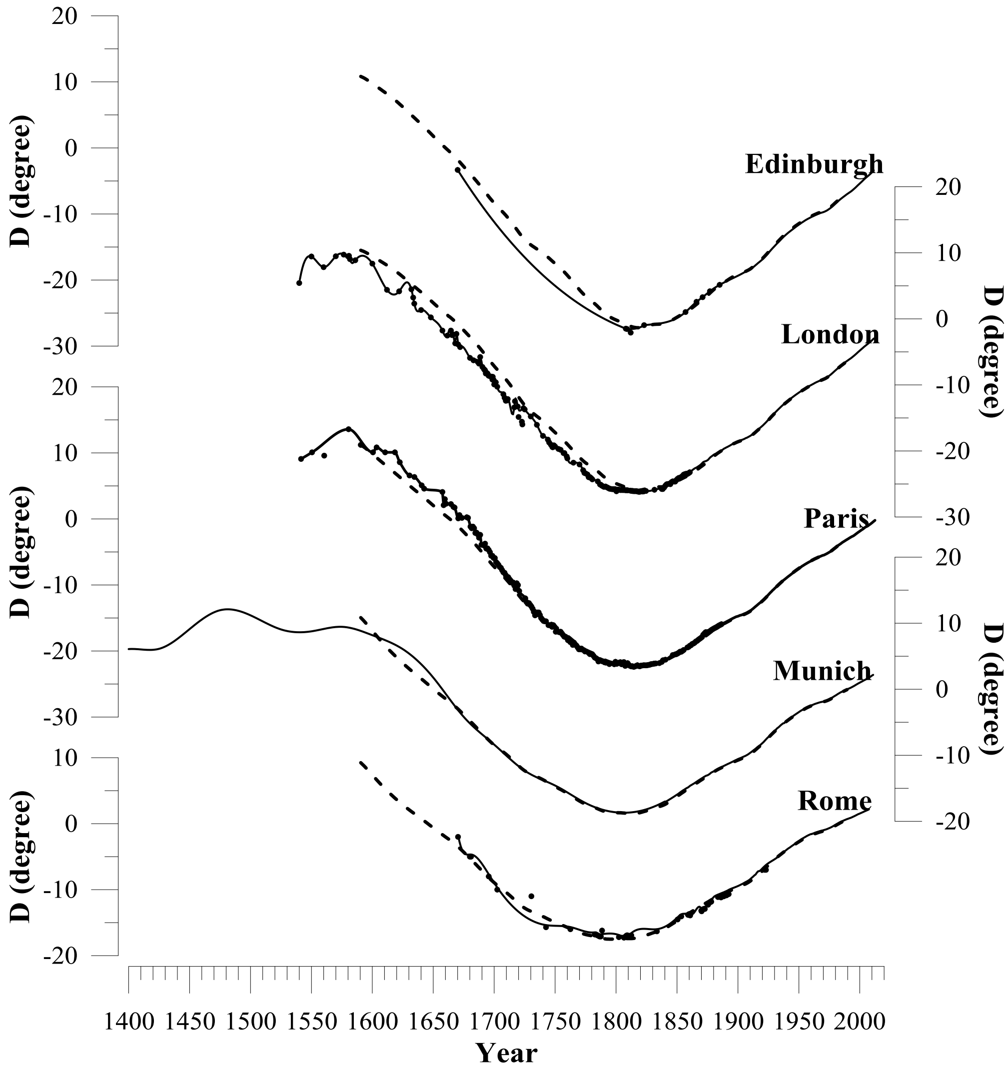


Figure 8: The declination evolution since 1400 AD at five locations in Europe. Annual values as obtained by a cubic B-spline interpolation on historical observations and observatory data (full black curve); and as obtained from the *gufm1* time-series (dashed curve).

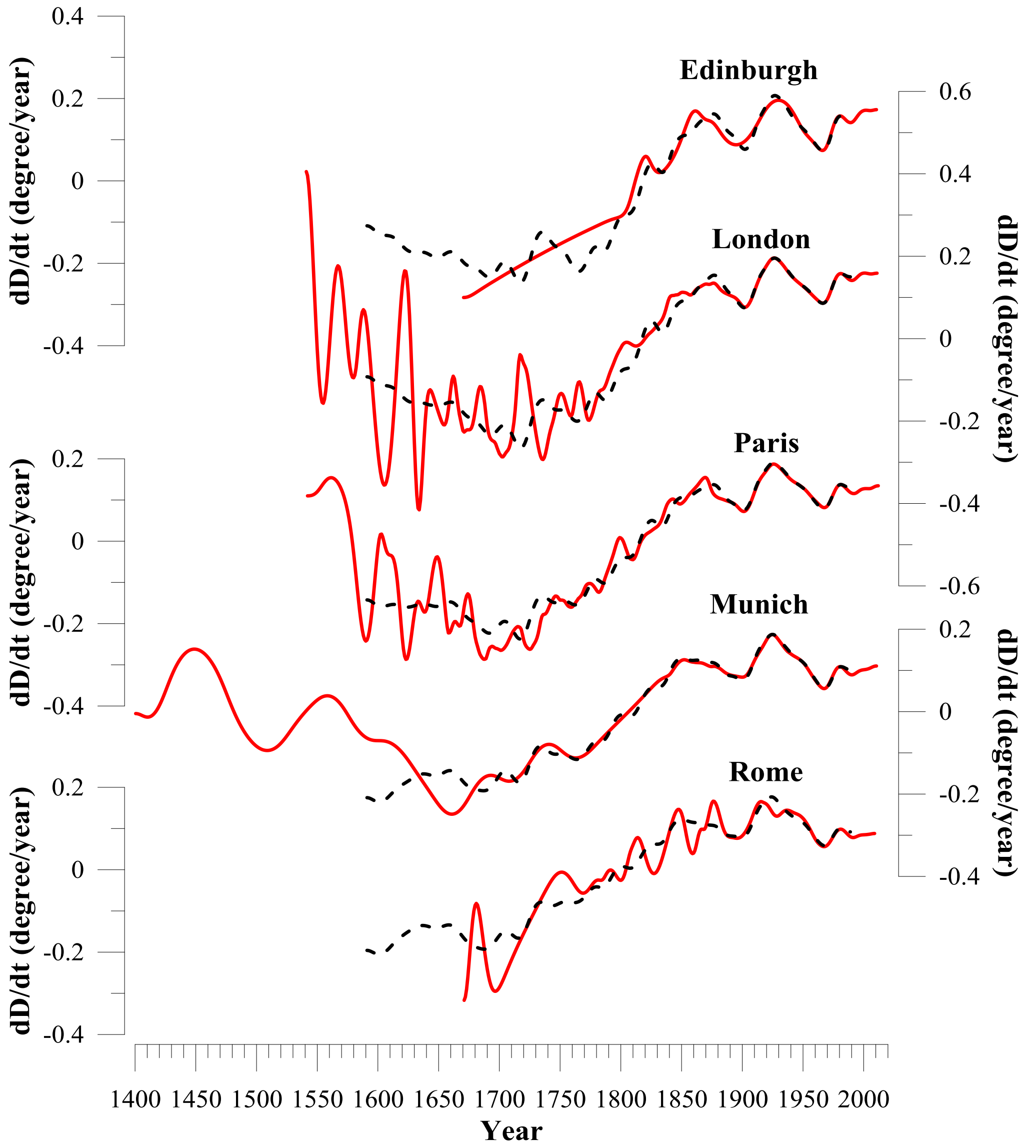


Figure 9: The first time derivative of the HP trend in data (red) and in the *gufm1* (dashed black) for the five locations in Europe.

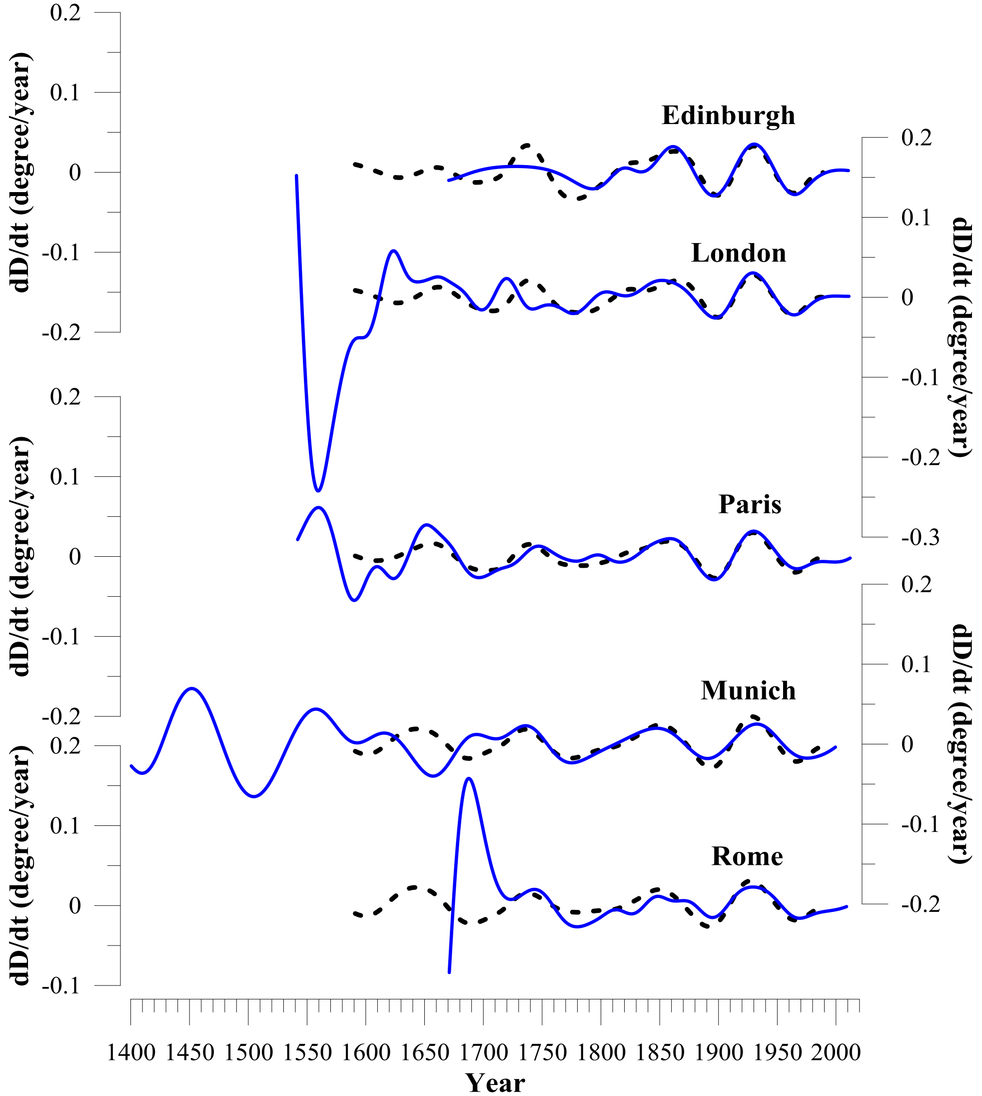


Figure 10: The first time derivative of the sub-centennial constituent at the five locations, from the trend of observed data (blue) and of *gufm1* (dashed black); a high-pass 73-year cutoff Butterworth filtering on time-series of Fig. 9 is applied.

Supplementary material

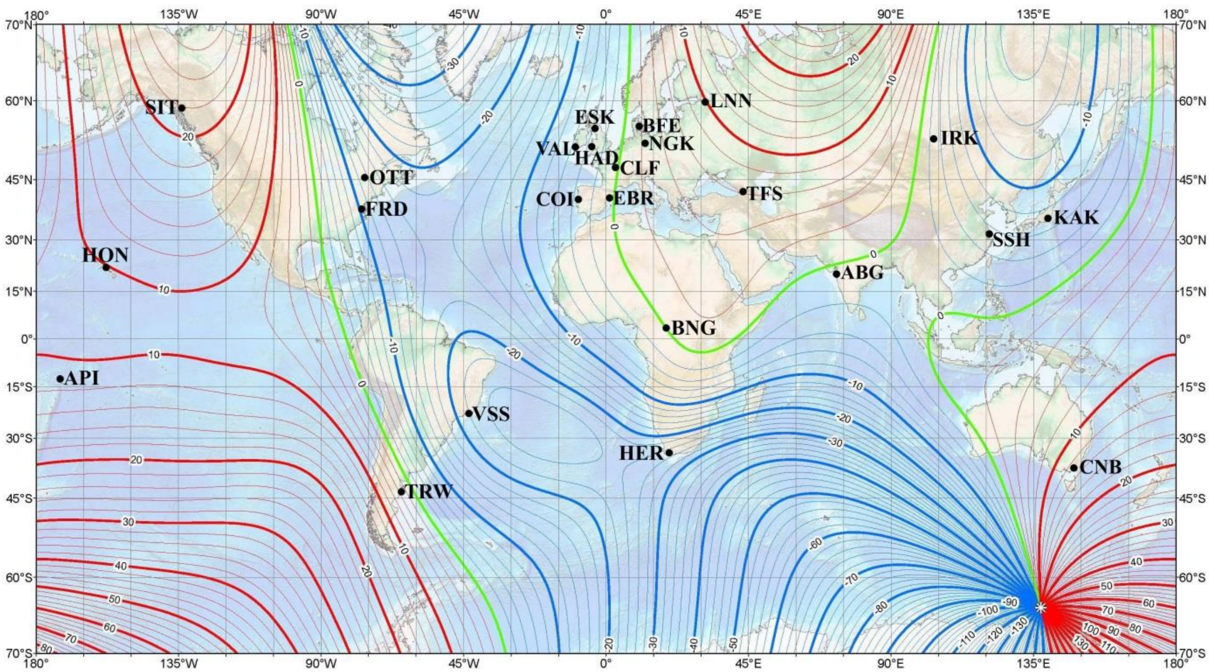
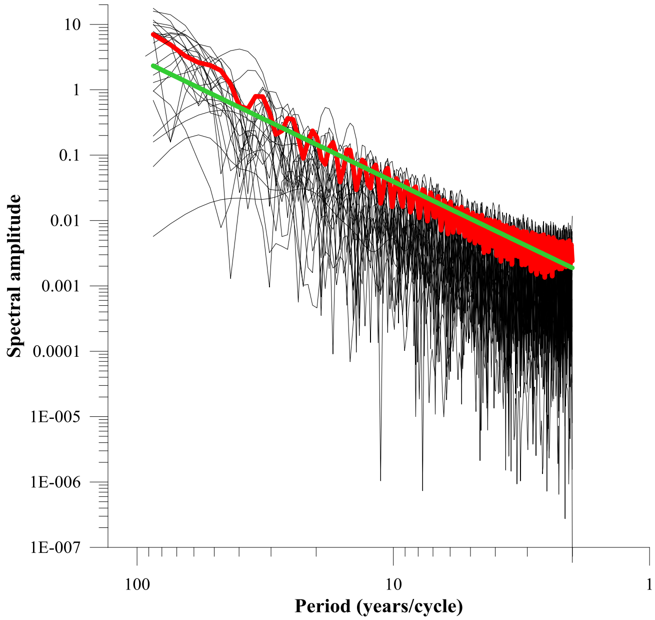
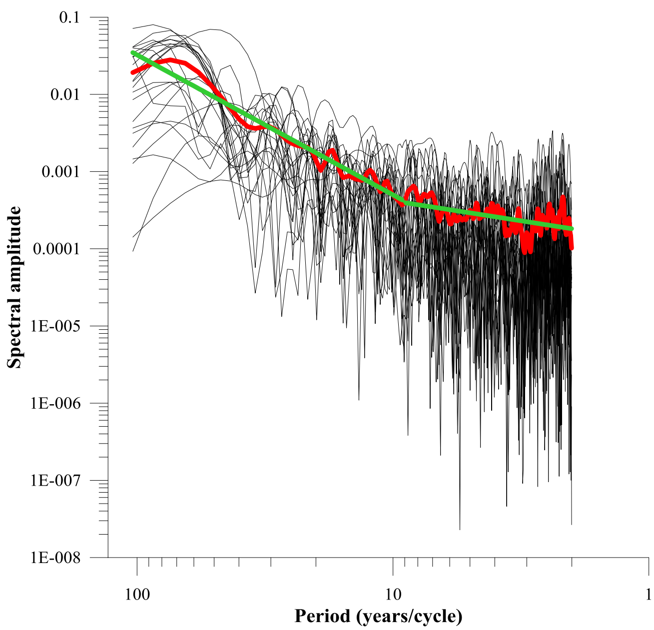


Figure S1: Geographical distribution of magnetic observatories providing recordings more than 100 years. IAGA codes are used. Background – 2010.0 declination map from http://www.ngdc.noaa.gov/geomag/WMM/data/WMM2010/WMM2010_D_MERC.pdf.



(a)



(b)

Figure S2: FFT power spectrum in a log-log representation: (a) observatory declination time series; (b) declination time derivative time series. The average power spectrum (red) and the best power-law fit (green).

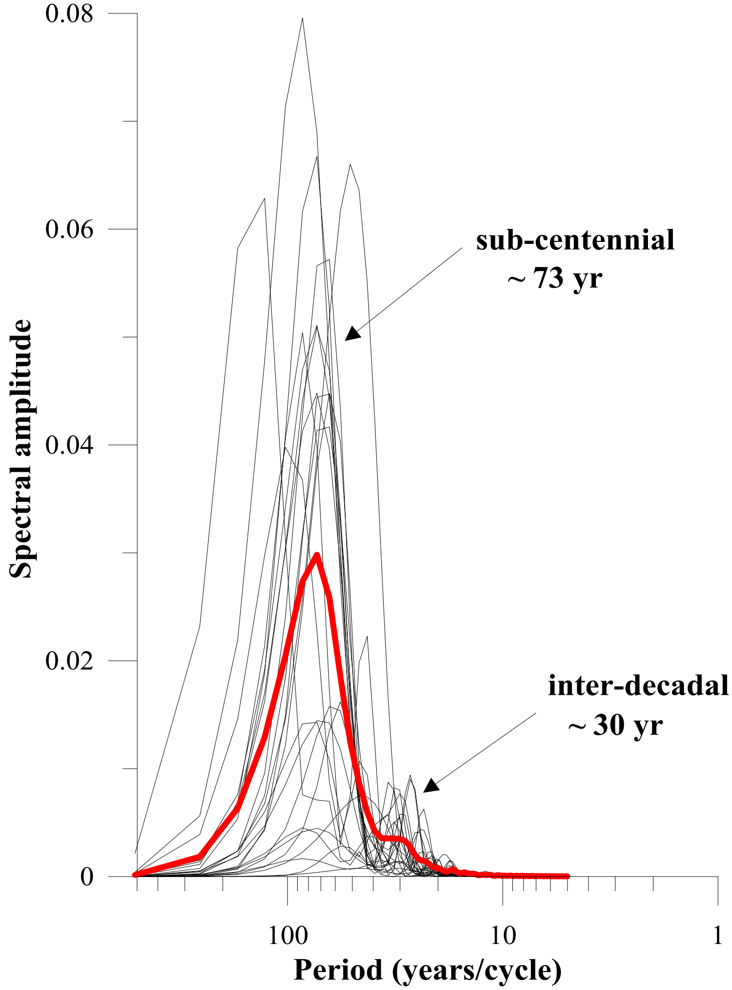


Figure S3: FFT power spectrum for the HP trend (i.e. the ~11-year variation removed) of declination first time derivative. The average power spectrum (red).

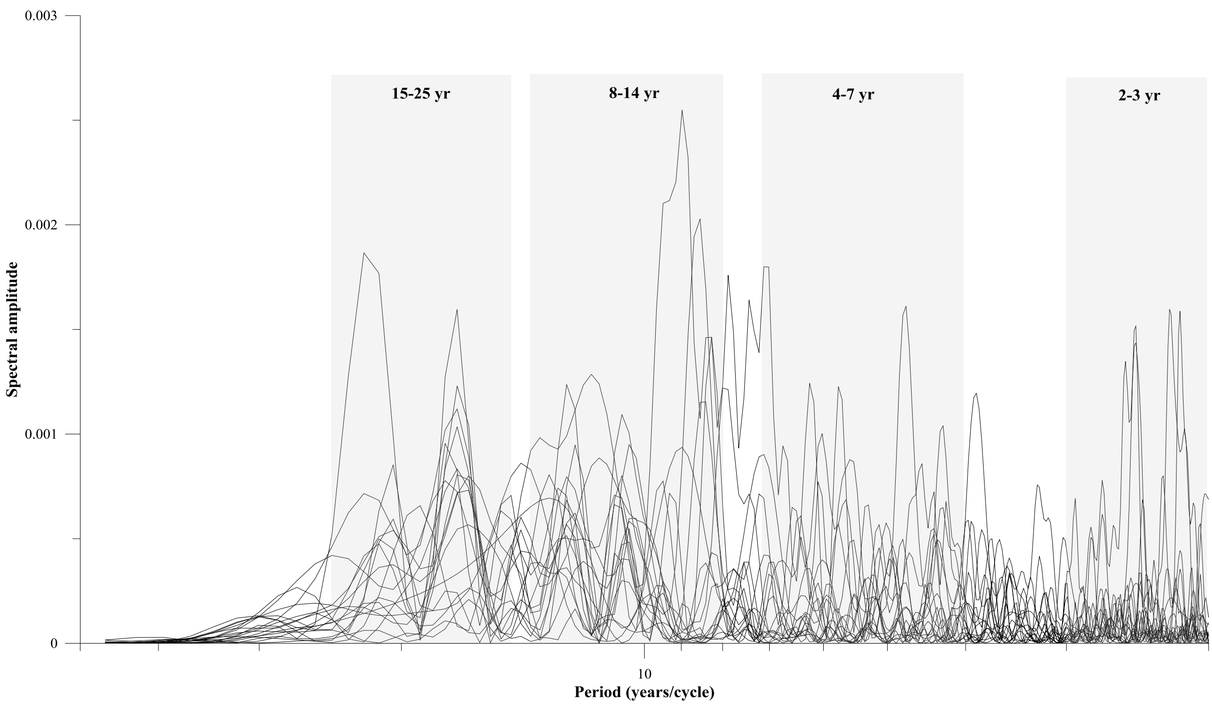


Figure S4: FFT power spectrum for the cyclic constituent from HP filtering of the first time derivative of declination. Gray background: domains of 8-14 years, 15-25 years, 4-7 years and 2-3 years.