The geomagnetic jerk of 2003.5-characterisation with regional observatory secular variation data

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Abstract

The 2003.5 geomagnetic jerk was identified in geomagnetic records from satellite data, and a matching feature reported in variations in length-of-day (ΔLOD), but detailed study has been hampered by lack of geomagnetic observatory data where it appears strongest. Here we examine secular variation (annual differences of monthly means) based on a new resource of 43 Chinese observatory records for 1998 until the present, focusing on 10 series of particularly high quality and consistency. To obtain a clean series, we calculate the covariance matrix of residuals between measurements and a state-of-the-art field model, CHAOS-6, and use eigenvalue analysis to remove noisy contributions from the uncorrected data. The magnitude of the most significant eigenvector correlates well with Dcx (corrected, extended Dst), suggesting the noise originates from unmodelled external magnetic field. Removal of this noise eliminates much coherent misfit around 2003—2005; nevertheless, the 2003.5 jerk is seen clearly in the first time derivative of the East component in Chinese data, and is also seen in the first time derivative of the vertical component in European data. Estimates of the jerk time are centred on 2003.5, but with some spatial variation; this variation can be eliminated if we allow a discontinuity in the secular variation as well as its temporal gradient. Both regions also provide evidence for a jerk around 2014, although less clearly than 2003.5. We create a new field model based on new data and CHAOS-6 to further examine the regional signals. The new model is close to CHAOS-6, but better fits Chinese data, although modelling also identifies some data features as unphysical.

Keywords: Geomagnetic field, Secular variation, Jerk, CHAOS-6, Length of day

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1. Background

The observed geomagnetic field originates from field sources both internal and external to the Earth, varying on time scales of milliseconds to billions of years. Largely, short time scales (a year or less) are the result of external variations (changes in the magnetosphere or ionosphere associated with solar field variations), while variations on longer time scales originate from the internal field generated in the Earth's core by the magnetohydrodynamic dynamo. The shortest observed changes that have been attributed to internal variations are the so-called geomagnetic jerks, first defined by Courtillot et al. (1978) as a sudden change in the slope of the geomagnetic secular variation (SV, the first time derivative of the Earth's magnetic field), or equivalently an abrupt (step-like) change in the secular acceleration (SA, the second time derivative). The most widely discussed jerk is in 1969 (Malin and

Hodder, 1982), but many others have been identified (e.g., 1978, 1991, 1999 and 2003) in time series of geomagnetic observatory data, or geomagnetic models (Mandea et al., 2010), most recently from 2011 (Chulliat and Maus, 2014) and 2014 (Torta et al., 2015). A feature of recent interest has been an approximately 6-year cycle in SV linking to jerks (Chulliat and Maus, 2014), and also seen strongly in variations in Earth rotation (length-of-day, LOD) (Gillet et al., 2010; Holme and De Viron, 2013). These observations support an association with possible torsional oscillations in the outer core (Bloxham et al., 2002), linked to either inner-core rotation and coupling (Mound and Buffett, 2003) or an intrinsic flow mode (Gillet et al., 2010). However, there remains considerable debate as to the nature of jerks . Are they a global or localised feature (Mandea et al., 2010; Torta et al., 2015)? Is the discontinuity in the second derivative the best way to characterise them (Alexandrescu et al., 1996)? Do external field features (Alldredge, 1984; Demetrescu and Dobrica, 2014) cause or contribute to some jerks? Are all jerks similar, or are there a variety of different types, and potentially causes (Mandea et al., 2010)?

Most studies on geomagnetic jerks focus on magnetic observatory data, because of their long-time stability, and high temporal resolution to define the secular variation. However, (Mandea and Olsen, 2006) developed a complementary study tool deriving “virtual observatories” using data from magnetic satellites, by stacking the data in time for a limited geographical region. The derived individual secular variation estimates are of lower quality than those from ground based observatories, but provide global data availability rather than depending on the sparse and uneven geomagnetic observatory network.

Using this method, Olsen and Mandea (2007) identified several jerks, including one centred on 2003.5. This feature is of particular interest because it is not aligned with the approximately 6-year variation, but nevertheless correlates with a jerk-like feature in variations in Earth rotation or length of day ΔLOD (Holme and De Viron, 2013), also separate from the 6-year variation. Inference from the rotational record suggests a possible discontinuity in not just the rate of secular variation, but the secular variation itself, changing the range of possible physical mechanisms that could give rise to it. The similarity in timing of the two records also constrains other geophysical properties, particularly deep-mantle electrical conductivity (Holme and De Viron, 2013).

To better examine this feature in the geomagnetic data, a study of ground observatory data is clearly highly advantageous. Brown et al. (2013) provide such a study, but Olsen and Mandea (2007) localise the event as around the 90° E meridian, a geographic region for which easily available data from world geomagnetic data centre holdings are sparse. Here we investigate previously unutilised data from 43 Chinese observatories covering the period 1998 to 2016. These data provide a particular tool for studying this jerk, but also a potential homogeneous database for future high resolution regional studies of secular variation, to compare with other densely instrumented areas such as Europe. We compare these data with the European data, focusing particularly on the 2003.5 jerk to determine whether there exist linked changes in Asia and Europe, which therefore could provide a global constraint on secular variation, and a direct observational constraint on the rapid variation of the geodynamo. We characterize the short-period variation in the time series as being related to external field, and by subtracting this influence, strengthen the interpretation and better constrain the timing of the 2003.5 jerk. To explore the content of the new data, we create a new global, time-dependent model which is both close to the field predicted by the CHAOS-6 model and also better fits the newly available Chinese data. We will use this tool to better characterize all rapid variations in secular variation.

2. Data

There are currently 43 operational Chinese observatories (Figure 1) providing good spatial coverage throughout the Chinese mainland, with records broadly available from 1998 to the present day, and many extending earlier. Available observatories were established and are maintained by the Geomagnetic Network of China, Chinese Earthquake Administration, which has provided hourly mean data; many of these data are not as yet held by the World Data Centers. To compare with and verify our results, 7 European observatories (figure 2) are also studied. The codes of all 43 Chinese observatories are listed in the appendix.

Figure 1

Figure 2

As we are interested primarily in internal field variations, from all available hourly data we calculated monthly means of the three components (northward X, eastward Y and vertically downward Z) of the magnetic field of each observatory, thereby eliminating high-frequency external variations. We estimated SV determining annual differences of monthly means, for example for Y as:

$$\left.\frac{dY}{dt}\right|_t = Y_{(t+6)} - Y_{(t-6)} \tag{1}$$

where t denotes time in months. By taking differences, we eliminate constant crustal field offsets (Bloxham and Jackson, 1992). By taking annual differences, we reduce the influence of external noise, e.g. magnetospheric ring currents, particularly those components with annual cycles. This method is equivalent to the approach of Mandea et al. (2000), who took monthly differences, but then applied a 12-month running mean. There are generally two problems when dealing with the data: baseline jumps (or erroneous data) and data gaps, resulting from many possible causes (e.g., instrument error, power failure, station relocation, anthropogenic current disturbance, etc). We have applied all documented baseline corrections, and have identified and corrected for some additional jumps (see appendix). Data gaps are more difficult, and unfortunately many of the Chinese data series are discontinuous. Brown et al. (2013) treated a gap shorter than 6 months by interpolating, while if longer than 6 months the data were split into separate time series. We choose to use the data "as is", and will consider data gaps by comparison with the CHAOS-6 field model and covariance modelling, described below. Our primary focus is on 10 Chinese observatories with the most continuous records (THJ, JIH, QIX, GLM, TSY, COM, YON, WMQ, DLG and CHL, see figure 1). To compare the results, monthly mean data of 7 European observatories (BEL, CLF, DOU, FUR, HLP, HRB and NGK, see figure 2) are adopted from the Bureau Central de Magntisme Terrestre (BCMT), World Monthly Means Database Project, which provides monthly averages of components $\mathrm{d}X/\mathrm{d}t$, $\mathrm{d}Y/\mathrm{d}t$ and $\mathrm{d}Z/\mathrm{d}t$ at 118 observatories worldwide) calculated from hourly means held by the World Data Centre (WDC) for Geomagnetism at the British Geological Survey, Edinburgh (Chulliat and Telali, 2007).

3. Jerk-like features

In figures 3-5, we plot the secular variation estimates for both arrays of observatories. For the $\mathrm{d}Z/\mathrm{d}t$ component, the plot of variation for the Chinese data is dominated by a linear secular trend. To bring out the rapid changes, we provide an subfigure (middle figure of fig 5) in which this trend is removed.

Figure 3

Figure 4

Figure 5

For $\mathrm{d}X/\mathrm{d}t$, the rapid variation shows strong correlation (correlation coefficient r=0.77) between China and Europe, with many oscillations in common during 1998-2015. Focusing on 2003.5 and 2014, changes in slope ($\vee$ and $\wedge$ shapes) are present simultaneously in both data sets. For $\mathrm{d}Y/\mathrm{d}t$, a longer term $\vee$ shape also can be clearly recognized in 2003.5 in China, but not clearly in 2014. In contrast, European data express clear jerk like shape in 2014 but not in 2003.5. For $\mathrm{d}Z/\mathrm{d}t$, comparing the detrended Chinese data we find good agreement between two regions around 2003.5 (r=0.91) and 2014 (r=0.83). To summarise, 2003.5's jerk could be clearly identified in China among $\mathrm{d}X/\mathrm{d}t$, $\mathrm{d}Y/\ \mathrm{d}t$ and $\mathrm{d}Z/\mathrm{d}t$, consistent with Olsen and Mandea (2007), and 2014's jerk can be located as Torta et al. (2015). 2014's jerk can also be distinguished in Australia, central Pacific and Europe through models including CHAOS-6 (Finlay et al., 2016; Brown et al., 2016). To other jerks (Mandea et al., 2010), 1999 and 2011's jerks can be found in $\mathrm{d}X/\mathrm{d}t$ in two regions. It is easy to find 2009's jerk in $\mathrm{d}Y/\mathrm{d}t$ and $\mathrm{d}Z/\mathrm{d}t$ in Europe but not in China. Finally, a jerk-like feature may be emerging around 2015.

4. External fields

The data contain a strong component that is related to external and induced fields, in particular from the large-scale magnetospheric ring currents and associated induced signals due to ground electrical conductivity. Strong correlation between variations of different components (particularly $\mathrm{d}X/\mathrm{d}t$ and $\mathrm{d}Z/\mathrm{d}t$) are particularly indicative of this. Magnetic field models such as CHAOS-6 and CM4 (Finlay et al., 2016; Sabaka et al., 2004) are constructed to co-estimate the external field, with some allowance for the induced field. This external effect is parameterized by an a priori geomagnetic index, e.g. RC or Dst. However, the global model of the ring current does not include the influence of possible local conductivity structure on induced fields. As an alternative, Wardinski and Holme (2006) showed that the residual between observation and model can replace the Dst index in their calculations as a proxy for unmodelled external signals. Removal of such signals substantially reduces the standard deviation of the data, therefore improving the resolution of internal features such as jerks (Brown et al., 2013).

We follow Wardinski and Holme (2006) to create the covariance matrix of residuals of observatory monthly mean annual differences and CHAOS-6 model secular variation prediction. We assume that the residuals are zeromean, so we can define the elements of the covariance matrix

$$cov(p,q) = \frac{\sum_{i=1}^{n} P_i Q_i}{n}, \tag{2}$$

where P, Q are residuals of the secular variation estimates of particular components from one or two observatories, with the sum over n observations. For n observatories each with 3 component data $\mathrm{d}X/\mathrm{d}t$, $\mathrm{d}Y/\mathrm{d}t$ and $\mathrm{d}Z/\mathrm{d}t$, the covariance matrix is of order $3n$; the eigenvalues and eigenvectors of the matrix are then determined. We calculate the covariance matrices separately for groups of 10 Chinese and 7 European sites, yielding 30 and 21 eigenvalues, respectively, plotted in figure 6.

Figure 6

In both data sets, there is a clear sharp decrease between the first and second eigenvalues, after which the values decrease gradually. As a result, the first eigenvector makes a dominant contribution to the misfit. In figure 7, we plot the contributions to this eigenvector for the 10 Chinese observatories.

Figure 7

The spatial structure of this eigenvector is indicative of its origin from the ring current, which produces a field dominantly in $\mathrm{d}X/\mathrm{d}t$ and $\mathrm{d}Z/\mathrm{d}t$ directions, with the relative values depending on the observatory's location. Here, $\mathrm{d}X/\mathrm{d}t$ dominates because the Chinese observatories are at low magnetic latitude. The quietest component as seen in this figure is $\mathrm{d}Y/\mathrm{d}t$, which is perpendicular to the ring current field (Pinheiro et al., 2011). Note that we did not initially obtain this result, but instead determined an eigenvector dominated by one particular observatory; this turned out to be an unmodelled baseline shift, and the ring current structure only became clear when such data artefacts were removed. As a result, the method also acts as a sensitive test of data quality.

We examine the spatial structure of this noisiest (largest eigenvalue) eigenvector in more detail in Figure 8. For the 10 observatories already considered, we extracted the ($\mathrm{d}X/\mathrm{d}t$, $\mathrm{d}Y/\mathrm{d}t$, $\mathrm{d}Z/\mathrm{d}t$) components for each observatory, and normalized each 3 vector to unit length. The other 33 observatories have data of lower quality; to consider these observatories as well, we repeat the covariance/eigenanalysis by adding one of those observatories to the 10 good observatories sequentially (making each eigenanalysis of 11 observatories (33 data series)), and each time calculated the normalized components for the additional observatory. We plot the $\mathrm{d}X/\mathrm{d}t$ and $\mathrm{d}Y/\mathrm{d}t$ components; an observatory with only a $\mathrm{d}Z/\mathrm{d}t$ component would plot at the origin.

Figure 8

The more consistent the data series for different observatories, the closer the points for the different observatories should be. In figure 8, the left hand figure shows broad consistency between the observatories. The right hand figure provides more details, with 8 observatories separated from the majority; examining the series shows that they contain large misfits likely resulting from uncorrected artefacts. For the 35 consistent series, many have large data gaps, leading to our decision to concentrate analysis on only 10 good observatories with broadly continuous records.

To support our hypothesis that this largest noise source is related to the ring current, we compare the component of this eigenvector in the residuals at each time (the dot product of the residual vector with this unit eigenvector) with an index of ring-current activity. We use an corrected, extended

Dst index, Dcx, which is achieved selecting 17 stations and correcting for the quiet-time seasonal variation (Mursula et al., 2008). (The index is provisional from non-definitive data for 14 stations for 2012-2016.) We calculate the annual differences of Dcx and compared to the noisy contributions from Chinese and European observations (figure 9).

Figure 9

Figure 9 shows a good agreement between the annual differences in variations of Dcx and noisy contributions from both China and Europe, particularly in the active periods 2003-2006 and 2014 onwards, when Dcx significantly oscillates and their trends look highly consistent. This situation implies that the jerk signature around 2003.5 and 2014 could be seriously influenced by external fields. The correlation coefficient between Chinese magnetic observatories and Dcx is 0.70, and that between European observatories and Dcx is 0.68. Note also that the eigenvectors for the separate analyses for China and Europe have correlation coefficient 0.96, confirming the conjecture of Wardinski and Holme (2011) that the dominant eigenvector and its magnitude may be a better correction method than scaling with Dcx.

5. Cleaned data

We have shown that the largest eigenvalue/eigenvector of the misfit of the data to the field model is not random, but arises from a specific source, likely dominated by variations in the magnetospheric ring current. Therefore, to clean the data for better analysis of possible internal signals, we remove the contribution of the highest (noisiest) eigenvalue, which we believe strongly reduces the influence of magnetospheric ring-current variation. We subtract the noisy contributions corresponding to the largest eigenvalue/eigenvector as follows:

$$\mathbf{r}' = \mathbf{r} - (\mathbf{r} \cdot \mathbf{v})\mathbf{v}, \tag{3}$$

where $\mathbf{r}$ is residual vectors at a particular time, $\mathbf{v}$ is the unit normalized eigenvectors corresponding to the largest eigenvalue. The clean (denoised) data have the influence of the largest eigenvalue removed, plotted in Figures 10-12.

Figure 10

Figure 11

Figure 12

Much of the apparent jerk signal is eliminated, suggesting that much of the sharp change in $\mathrm{d}X/\mathrm{d}t$ and $\mathrm{d}Z/\mathrm{d}t$ around 2003.5 is of external origin, especially from the magnetospheric ring current. This is of particular significance, as the original identification of the jerk by Olsen and Mandea (2007) was from analysis of the $\mathrm{d}Z/\mathrm{d}t$, which might therefore also have been contaminated by external field structure. The similar timings also support and explain earlier discussions of jerk signals from in part external sources (Alldredge, 1984; Demetrescu and Dobrica, 2014). Comparing with figure 7, $\mathrm{d}X/\mathrm{d}t$ is most changed with $\mathrm{d}Z/\mathrm{d}t$ less; $\mathrm{d}Y/\mathrm{d}t$ is little changed. In figure 10, $\mathrm{d}X/\mathrm{d}t$ is much changed with fewer oscillations both in China and Europe compared with uncorrected variation. The 2014 jerk can be roughly distinguished while 2003.5 is not clear. Figure 11 shows little change in $\mathrm{d}Y/\mathrm{d}t$ due to this direction being perpendicular to the magnetic field of the ring current; the 2003.5 jerk can still be clearly identified in China. For $\mathrm{d}Z/\mathrm{d}t$, we again linearly detrend the Chinese data for clarity. No clear jerk is seen in the Chinese data, but a jerk signal remains in the European data.

To highlight the suggested jerks, we replot the figures for $\mathrm{d}Y/\mathrm{d}t$ for China (Figure 13) and $\mathrm{d}Z/\mathrm{d}t$ for Europe (Figure 14).

Figure 13

Figure 14

A jerk is present in both regions at around 2003.5, both records show some evidence of a jerk in 2014, and overall the two signals show broad anti-correlation throughout the interval. Therefore the two jerks are global signals, albeit seen most clearly in different components in different geographic regions, and therefore in a field model will be dominated by spherical harmonic field components of low degree. We further examined the SV of the 33 less good Chinese observatories in 2003.5 and 2014 in the same way; these two jerks are reflected particularly cleanly at 18 and 6 of these observatories respectively, where the limited numbers are due to lack of data rather than evidence that the jerk is *not* present.

Finally, we estimate the time of the 2003.5 jerk in the Chinese data. We determine best fit lines for the data before and after the jerk, and calculate the time of their intersection, as a classical measure of jerk timing. The results are presented in Table 1.

Table 1

The mean timing is close to 2003.5, although it is not possible to state that the jerk is simultaneous at all locations. However, this time also assumes that SV is continuous. Evidence from both ΔLOD and wavelet analysis of secular variation data (Alexandrescu et al., 1996) suggests that a jerk might involve a change not only in secular variation gradient, but also in its value.

Such a jump would be smoothed by the analysis: an annual first difference (as used to estimate the secular variation) is equivalent to a 12-month running average of secular variation, smoothing any such jump. To investigate this, we define the jerk time to be 2003.5, allowing a discontinuity in SV, and take a running average. Figure 15 provides an example for the observatory GLM. In all cases, the prediction provides an equally good fit to the data as allowing a difference in calculation of the jerk time, and as here the running averages are almost indistinguishable. We therefore claim that the data are consistent with both a variation in jerk timing over China, but also with a jerk at a common time but allowing an offset in secular variation, and may not allow these two hypotheses to be distinguished.

Figure 15

6. A perturbed field model

To this point, we have taken the CHAOS-6 model as a true representation of the field for the Chinese region, despite that model not being constrained by the new secular variation data. Some features in SV not predicted by CHAOS-6 seem coherent between several (although by no means all) of the different data series. To investigate the possible implications of these data, we seek a new global, time-dependent model which is both close to the field predicted by the CHAOS-6 model (and so assumed to match well the satellite data from which it is constructed) and also better fits the newly available Chinese data. Our methodology follows that of Lodge and Holme (2009). We expand in a spherical harmonic basis in latitude and longitude, truncated at spherical harmonic degree $l_{max} = 14$, with each coefficient further expanded on a basis of cubic B-splines, with temporarly dense knots at spacing 0.1 years. The CHAOS6 model is expanded on order 6 B-splines with half-year knot spacing; we obtain a reference model from a least-squares fit to each set of spline coefficients for each Gauss coefficient; the lower degree of the splines is countered by the higher knot density. We seek a model between times t_0 and t_1 (1997.1 and 2018.1 to match the limits of the CHAOS6 model) minimizing three properties: 1) the mean square misfit to the secular variation estimates derived from the 43 Chinese observatories; 2) the time integrated square vector misfit at Earth's surface to the CHAOS-6 model; and 3) the time integrated squared secular acceleration at the core-mantle boundary (CMB). Condition 1 requires a fit to the new data presented here, condition 2 provides a proxy to the fit to the satellite and observatory data from which CHAOS-6 was constructed (defined at Earth's surface), and condition 3 prevents unreasonably large temporal variation. Condition 1 is implemented as a fit to data, while conditions 2 and 3 are both "damping", giving the objective function Γ to be minimized as

$$\begin{aligned}\Gamma &= \sum_{i=1}^{n}\left(\dot{\mathbf{B}}(\mathbf{x}_i)-\dot{\mathbf{B}}_i\right)^2\\ &\quad+\lambda\int_{t_0}^{t_1}\sum_{l=1}^{l_{max}}(l+1)\sum_{m=0}^{l}\left((g_l^m-g_l^m{}_{\mathrm{CHAOS}})^2+(h_l^m-h_l^m{}_{\mathrm{CHAOS}})^2\right)dt\\ &\quad+\mu\int_{t_0}^{t_1}\sum_{l=1}^{l_{max}}(l+1)\left(\frac{a}{c}\right)^{(2l+4)}\sum_{m=0}^{l}\left((\ddot{g}_l^m)^2+\left(\ddot{h}_l^m\right)^2\right)dt\end{aligned} \tag{4}$$

The first term is the mean square fit to the secular variation data by the model. $\dot{\mathbf{B}}_i$ is a vector of SV data, with the difference taken to the model prediction at observatory location $\mathbf{x}_i$. The second term minimizes the mean square misfit mean field integrated over Earth's surface, radius a, given by the squared difference between the model Gauss coefficients g_l^m, h_l^m of degree l and order m and those of the CHAOS-6 model. The third term minimses the mean square secular acceleration at the core-mantle boundary, radius c. The two damping parameters λ and μ allow a range of possible solutions; we present three representative possible models, which we designate as low, medium and high damping. The low damping allows comparatively large secular acceleration, while the high damping provides a model closely constrained to match the field prediction of CHAOS-6. To illustrate the fit to the data, we plot the fit for each component to the station YON.

Figure 16

Figure 17

Figure 18

The high damping model provides little departure from CHAOS-6; to obtain a closer fit to the data, more time variation is required see for example Figure 16 ($\mathrm{d}X/\mathrm{d}t$). That this variation may be unreasonably high is shown by a more detailed plot of the $\mathrm{d}Z/\mathrm{d}t$ for 2010—2012 (see more details in figure 19). The high damped model shows little change to CHAOS-6, while the intermediate and low damping models have changed to fit sharp changes in the data in 2011.3 which may well be an artifact. Only with low damping is the data fit substantially improved; compared to CHAOS-6, the misfit is reduced by 22.0%, 18.7% and 22.1% for $\mathrm{d}X/\mathrm{d}t$, $\mathrm{d}Y/\mathrm{d}t$, $\mathrm{d}Z/\mathrm{d}t$ components respectively. Even with this weakly damped model, some strong features in the data coherent between different observatories are not fit, even when the error estimate for a short period (e.g., 2002—2005) is artificially reduced.

This implies that such features cannot be represented by the components of a potential field are not likely to be a result of unmodelled internal field structure, suggesting further cleaning or selection of data to be necessary.

Figure 19

The increased temporal structure of the new models is demonstrated by considering the secular variation spectrum

$$W'(l,c) = (l+1)(\frac{a}{c})^{(2l+4)} \sum_{m=0}^{l} (\dot{g}_l^m)^2 + (\dot{h}_l^m)^2, \tag{5}$$

Here $\dot{g}_l^m, \dot{h}_l^m$ are time derivatives of the Gauss coefficients. In Figure 20, we show the power spectra at 2004.0 for our three differently damped models, also plotting $W(l,c)/(l(l+1))$, which following Mcleod (1996) and Holme et al. (2011), we might expect to be broadly independent of degree l.

Figure 20

Both the medium and low damping models show a strong rise in secular variation power above degree 10, which is unlikely to be physical. In Figure 21 we compare contour maps of SV at Earth's surface for CHAOS-6 and the weakly damped new model; the broad structure is unchanged, but the contours show small scale variations that are probably not justified.

Figure 21

A change in SV near China (better matching the data) is achieved, but only at the expense of considerably increased detail over the whole globe, which is not consistent with the original data. If plotted at the CMB, the map of the new model shows excessive small scale structure. We conclude that there is no strong evidence in the new data requiring substantial adjustment to the CHAOS-6 model – substantially improved fit to data requires unreasonably large small-scale secular variation.

7. Discussion and Conclusions

We have examined collections of spatially close geomagnetic observatory records, focusing on a new set of data from Chinese observatories, and for comparison, a set of well-studied European observatories. The Chinese data are of slightly lower quality than the European data: the data are more gappy, and require correction of undocumented baseline jumps. Nevertheless, after such corrections, the data are of high quality, and provide a close to homogenous data set for study of regional intra-decadal and longer secular variation. We have focused on one period in particular, centered around 2003.5, for which a rapid SV change (a geomagnetic jerk) had previously been reported (Olsen and Mandea, 2007). This previous identification had been based on a model constructed from satellite data using virtual observatories (averages of satellite data over a limited region); secular variation studies with observatory data will be more robust. Our data show strong features around 2003.5, particularly in the $\mathrm{d}X/\mathrm{d}t$ and $\mathrm{d}Z/\mathrm{d}t$ components for both the Chinese and European observatory arrays. However, further analysis suggests that these features result from external field variation, probably a jump in the strength of the ring current (reflected in Dcx). Removing these external fields removes much of the sharp signal in $\mathrm{d}X/\mathrm{d}t$ and $\mathrm{d}Z/\mathrm{d}t$, but a clear jerk remains in the $\mathrm{d}Y/\mathrm{d}t$ component at Chinese observatories. The jerk is also seen in $\mathrm{d}Z/\mathrm{d}t$ at European observatories, although some contamination from external sources may remain. Nevertheless, as the features form part of the long term trends in secular variation, we argue that there is a component of internal origin.

Using CHAOS-6, we plot the evolution of $\mathrm{d}Y/\mathrm{d}t$, and estimates of its first (SV) and second (SA) derivatives. The broad structure is similar for all Chinese observatories; we plot QIX, located in the middle of the observatory grouping, along with its CHAOS-6 predictions.

Figure 22

Figure 22 shows clearly the jerk in the SV around 2003.5, and allowing for the averaging of the data the SA record is consistent with a jump, perhaps overly smoothed in the CHAOS-6 model prediction. This figure does not illustrate evidence in the Chinese data of the most recently identified geomagnetic jerk in 2014 (Torta et al., 2015), this feature is only seen strongly in 6 Chinese observatories (THJ, GLM, WMQ, CDP, QGZ and HZC).

The exact timing of the jerk is of great interest (e.g. Pinheiro et al. (2011)); time delays have been used to propose higher electrical conductivity of the deep mantle under certain geographic regions, particularly in the Pacific. Taking the usual definition of a jerk implying continuous SV, both data and model suggest that even in the limited region covered by the Chinese data, there is some offset of jerk times with locations. All observatories show the jerk at around 2003.5, but varying between 2003 (at WMQ, the most westerly located of our 10 selected observatories) and close to 2004 (DLG, the most easterly of our observatories). The shift in jerk timing may instead result from different SV time gradients before and after 2003.5; the jerk is apparently shifted towards the less steep trending time. This is consistent with the observations above for WMQ and DLG. However, this simple analysis is complicated by the possibility of a jump in the secular variation itself, as suggested by the ΔLOD data (Holme and De Viron, 2013), but also by wavelet studies suggesting that the jerks are not exact jumps in the second derivative (Alexandrescu et al., 1996). When the effective 12 month averaging from taking annual differences of the data is allowed for, the predictions assuming continuous SV but varying jerk times, or a common time but discontinuous SV are indistinguishable. Furthermore, the data are still noisy, with features that cannot be well-fit by a model of the internal geomagnetic field, even after the removal of the largest noise eigenvector, making direct analysis of the data difficult. Further study is necessary, particularly focusing on the sources of the data, but we may conclude at least that the newly available Chinese data are consistent with a common time for the jerk of around 2003.5.

We believe our analysis shows evidence of the 2003.5 jerk appearing at widely spaced locations on the Earth, and so that the jerk is of global significance. The timing of the jerk (from the $\mathrm{d}Y/\mathrm{d}t$ in the Chinese data) is also consistent with the feature at 2003.5 reported in the variation in LOD (Holme and De Viron, 2013). LOD variation established rotational jerks, particularly of an approximately 6-year variation, which correlate well with 6 year variations in magnetic signals (Gillet et al., 2010; Chulliat and Maus, 2014). However, the 2003.5 signal is not linked with the 6 year variation; this is not surprising given its appearance in the long-term secular variation in $\mathrm{d}Y/\mathrm{d}t$ at the Chinese observatories. There may be two kinds of jerks, one associated with the 6-year oscillation, and one, such as the one presented here, of different origin, relating to longer term changes in the secular variation, shown particularly clearly by the $\mathrm{d}Y/\mathrm{d}t$ of the Chinese data. Demetrescu and Dobrica (2014) pointed out that jerk arises from the combination of the internal 22yr and 80 yr signals accoring the decomposition of the geomagnetic SV.

Perturbing the CHAOS-6 model to better fit the new data does not show evidence of missing structure in the model; large features in the data remain unfit. As they cannot be explained by a potential field of internal origin, they probably do not reflect the underlying secular variation. Our results therefore imply that CHAOS-6 model fits the reliable features in rapid field variation. To go further, careful treatment of the data, probably requiring analysis of very noisy monthly mean first differences (rather than annual differences as here) will be necessary to further constrain the origin of geomagnetic jerks. However, the new availability (and hopefully extension) of the Chinese data will provide a powerful tool for further study of this issue.

Abbreviations

SV: secular variation; SA: secular acceleration; CMB: core-mantle boundary; LOD: length of day.

Author's contributions

YF and RH initiated the study, designed the numerical experiments and wrote the manuscript. YJ provided the related calculating results, GAC supplied some beneficial suggestions. YF finalized the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests. This study does not involve humans/animals.

Appendix

The brief description of the treatment to the observatory records. Observatory data are either presented in a geographic (X, Y, Z) or geomagnetic (D, H, Z) coordinate system.

BJI-No records for 2007, 2015 and 2016, to get rid of the questionable D in 2002.

CDP-No records for 1997, Baseline correction to Z in 2003, to reduce the misfit by subtracting the difference.

CHL-No records for 2011, Baseline correction to D, H and Z in 2008, to reduce the misfit by subtracting the difference.

CNH-Baseline correction to D and H in 2007 and 2008, to reduce the misfit by subtracting the difference.

COM-Baseline correction to D in the first month in 2000, to reduce the misfit by subtracting the difference.

COQ-No records before 1998 and period 2011—2014, location had been changed since 2014.

DED-No records for 2006, 2007, 2014 and 2015.

DLG-No records for 1998, Baseline correction to D, H and Z in 2000 and 2001, to reduce the misfit by subtracting the difference.

ESH-Only has records for 2008—2016.

GLM-Baseline correction to component H in 2008, to get rid of 1 day's questionable data.

GYX-No records for 2006, 2006 and 2013 onwards.

GZH-No records for 1996—2001.

HHH-No records for 2001, 2002, 2004, 2006 and 2007, baseline correction to D in 2003, to reduce the misfit by subtracting the difference.

HZC-No records for the March, 2007.

JIH-No records for 2001. Baseline correction to D and H in 1996 and 2000, to reduce the misfit by subtracting the difference.

JYG-No records for 1995—1997.

KSH-Baseline correction to three components in 2000, 2002 and 2006, to reduce the misfit by subtracting the difference.

LSA-No records for 1995.

LYH-No records for 1996—1998.

LZH-No records for 1996, 2007 and 2009.

MCH-No records for 1997, 2005—2007.

MCH-Only has records for 2009—2016.

MZL-No records for 2006.

NAJ-No records for 1998, 2002 and 2006 onwards.

QGZ-No records for 2005 and part of 2012, 2015.

QIM-Only has records for 2013—2016.

QIX-No records for part of 2007, baseline correction to D in 2015 and 2016, to reduce the misfit by subtracting the difference.

QZH-No records for 1999, 2002—2006.

SQH-Only has records for 2009—2014.

SSH-No records for 2006—2011.

SYG-No records for 1997, 2004—2007.

TAA-No records for 1995, 1996, 1998 and 2003.

TAY-No records for 1996 and 1997, to get rid of the questionable D in 2005.

THJ- Complete records.

TSY-Baseline correction to H in 2000, to reduce the misfit by subtracting the difference.

WHN-No records for 1995, and 2007.

WJH-Only has records for 2013—2016.

WMQ- No records for 1999, Baseline correction to H in 2000, to reduce the misfit by subtracting the difference.

XIC- No records for 1997, Baseline correction to H in 2007, to reduce the misfit by subtracting the difference.

YCB- No records for 1999 and 2000.

YON- No records for 1995.

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Figure 1: Locations of 43 Chinese observatories. (red squares: 10 principally investigated observatories –THJ, JIH, QIX, GLM, TSY, COM, YON, WMQ, DLG and CHL). Lambert Conformal Projection.

Figure 2: Locations of 7 European observatories (BEL, CLF, DOU, FUR, HLP, HRB and NGK). Lambert Conformal Projection.

Figure 3: Comparison of uncorrected annual differences of monthly means of X, $\mathrm{d}X/\mathrm{d}t$, between China (top) and Europe (buttom). Vertical black dash lines correspond to possible jerk times in 2003.5 and 2014.

Figure 4: Comparison of uncorrected annual differences of monthly means of Y, $\mathrm{d}Y/\mathrm{d}t$, between China (top) and Europe (buttom).

Figure 5: Comparison of uncorrected annual differences of monthly means of Z, $\mathrm{d}Z/\mathrm{d}t$, between China (top) and Europe (buttom). The Chinese $\mathrm{d}Z/\mathrm{d}t$ data are additionally linearly detrended (middle).

Figure 6: Eigenvalues of components $\mathrm{d}X/\mathrm{d}t$, $\mathrm{d}Y/\mathrm{d}t$ and $\mathrm{d}Z/\mathrm{d}t$ of 10 Chinese (red line) and 7 European (black line) observatories.

Figure 7: The components of the eigenvectors corresponding to the largest eigenvalue for the 10 Chinese observatories. Squares: $\mathrm{d}X/\mathrm{d}t$; diamonds: $\mathrm{d}Y/\mathrm{d}t$; stars: $\mathrm{d}Z/\mathrm{d}t$.

Figure 8: Normalization of the largest eigenvalue eigenvector for all 43 Chinese observatories, on full (left) and expanded (right) axes. Red squares: good observatories; black circles: less good observatories.

Figure 9: The comparison between the noisy contributions from China and Europe with annual differences of monthly means of Dcx index. Black line: Noisy contributions from China; blue line: Noisy contributions from Europe; red line: Annual differences of Dcx.

Figure 10: Comparison of denoised annual differences of monthly means of X, $\mathrm{d}X/\mathrm{d}t$, between 10 Chinese and 7 European observatories.

Figure 11: Comparison of denoised annual differences of monthly means of Y, $\mathrm{d}Y/\mathrm{d}t$, between 10 Chinese and 7 European observatories.

Figure 12: Comparison of denoised annual differences of monthly means of Z, $\mathrm{d}Z/\mathrm{d}t$, between 10 Chinese and 7 European observatories.

Figure 13: Denoised annual differences of monthly means of Y, $\mathrm{d}Y/\mathrm{d}t$, of 10 Chinese observatories.

Figure 14: Denoised annual differences of monthly means of Z, $\mathrm{d}Z/\mathrm{d}t$, of 7 European observatories.

Figure 15: The variation of $\mathrm{d}Y/\mathrm{d}t$ of GLM.

Figure 16: The variation of $\mathrm{d}X/\mathrm{d}t$ of YON under different damping parameters.

Figure 17: The variation of $\mathrm{d}Y/\mathrm{d}t$ of YON under different damping parameters.

Figure 18: The variation of $\mathrm{d}Z/\mathrm{d}t$ of YON under different damping parameters.