Pulses and decays of the dipole field during the Holocene

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1. INTRODUCTION

One of the most important characteristics of the geomagnetic field is its secular variation. Nowadays, it can be observed a decreasing of the dominant axial component of the dipole field of 16 nT/yr at least since 1840 AD (Finlay et al., 2016). For earlier times the paleomagnetic and archeomagnetic reconstructions are a very useful tool for investigating the past of the geomagnetic field.

In this work, we focus our study on the last 10 kyr, covering almost the entire Holocene, analyzing in detail the increases and decreases of the dipole field energy. For this purpose, we have selected four representative paleomagnetic reconstructions: SHA.DIF.14k (Pavón-Carrasco et al., 2014), CALS10k.2 (Constable et al., 2016), BIGMUDI4k (Arneitz et al., 2019) and SHAWQ2k (Campuzano et al., 2019).

2. RESULTS

Dipole energy (Fig. 1) at the Earth's surface is calculated following Lowes (1974) decomposing the spatial power spectra at each epoch and taking degree 1. We study the characteristic periods using the Fourier Transform (Fig. 2), the Empirical Mode Decomposition, EMD (Fig. 3) and the wavelet analysis (only the short-term is presented in Fig. 4). A decomposition into short- and long-terms is carried out based on the results of the EMD which allow us to divide each dipole curve into different zero-mean Intrinsic Mode Functions (IMF) with characteristic time periods (Fig. 3). For the longest paleoreconstructions that cover the 10 kyr, i.e. SHA.DIF.14k and CALS10k.2, the long-term is defined by the IMF with the largest period (around 7 kyr, see Fig. 3) plus the residual, while the short-term is the sum of the rest IMFs with lower periods. The shortest models, BIGMUDI4k and SHAWQ2k (that cover 4 kyr and 2 kyr, respectively) are not able to detect this large period, therefore, the EMD approach directly provides the short-term as the sum of all the IMFs.

The most remarkable period in the short-term is found between 600-800 years, which is observed in all reconstructions, marked by a shaded area in Fig. 2. Furthermore, Fig. 4 shows that this period is present almost the whole time window, especially in SHA.DIF.14k (Fig. 4a) and SHAWQ2k (Fig 4d) models. In CALS10k.2 (Fig. 4b) this period seems to be present intermittently with lower power than in SHA.DIF.14k. In addition, CALS10k.2 and BIGMUDI4k (Fig. 4c) share a remarkable period of around 1400 years. BIGMUDI4k (Fig. 4c) and SHAWQ2k (Fig 4d) show common periods of around 200-300 years, as well.

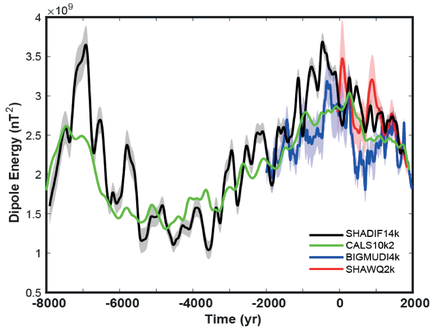

Figure 1. Dipole energy for each selected paleoreconstruction following Lowes (1974)

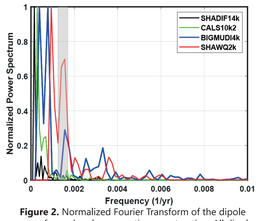

Figure 2. Normalized Fourier Transform of the dipole energy for each paleomagnetic reconstruction. All dipole energy curves were previously standardized (zero mean and standard deviation one) in

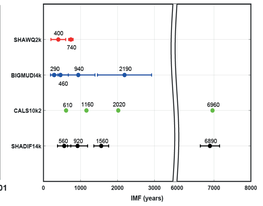

Figure 3. Intrinsic Mode Functions (IMF) obtained by the EMD for each paleoreconstruction.

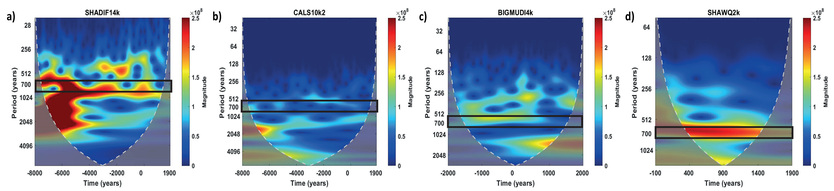

Figure 4. Wavelet analysis of the short-wavelength term of the dipole field for each paleomagnetic reconstruction: a) SHA.DIF.14k; b) CALS10k.2; c) BIGMUDI4k; d) SHAWQ2k

3. DISCUSSION

Focusing on SHA.DIF.14k and CALS10k.2 paleoreconstructions, since they are the ones that cover the entire 10 kyr, we study the long-term over the last 10 kyr. Analyzing the dipole Gauss coefficients (Fig. 5) we can assure that the long-term behavior is observed only in the axial dipole. We take the long-term of the $|g_1^0|$ (Fig. 6) and analyze the increasing and decreasing time intervals. There are two decreasing times: from 7000 BC to 4500 BC and between around 100 BC and present time; and only one increase is registered in the $|g_1^0|$ which occurs between 4500 BC and around 100 BC in both models.

The behavior of the long-term can be seen as a succession of decays and 'pulses'. For evaluating these processes we assumed that the decreasing intervals are dominated by the diffusion following an exponential decay (Merrill et al., 1998). We can compute a characteristic time, τ, by fitting the long-term of $|g_1^0|$ to a decreasing exponential function ($|g_1^0| = a_0 e^{-t/\tau}$). The results for SHA.DIF.14k are τ = 7600 ± 1200 years for the first decay and τ = 15300 ± 1800 years for the present decay. Meanwhile, in CALS10k.2 the values obtained are τ = 25700 ± 2600 years and τ = 13600 ± 1600 years for the first and second decays, respectively. There is a great difference in the characteristic times in the 7000 BC to 4500 BC decay that may be attributed to the lack of data at the earliest times since the results for the present decay of the $|g_1^0|$ are closer. These results for diffusion times are the same order of magnitude for the diffusion of the dipole field used in the geodynamo model, around 20 kyr (e.g. Terra-Nova et al., 2016).

If we now consider that the diffusion is always present, the increasing interval of $|g_1^0|$ between 4500 BC and 100 BC is affected by it. In order to get the 'real' increase of the $|g_1^0|$ we eliminate the correspondent diffusion in each time point as the exponential decay fitted in the previous decay (7000 BC - 4500 BC). The hypothesis we make is this 'pulse', i.e. the 'real' increase of $|g_1^0|$, is comparable with the charge of a capacitor, since we have fitted the decay interval as its discharge ($|g_1^0| = a_0[1-e^{-t/\tau}]$) This simple model allows us to obtain characteristic times of 'charge' of the axial field of 19100 ± 500 years and 16000 ± 3000 years in SHA.DIF.14k and CALS10k.2, respectively. We can also compute a maximum theoretical value of $|g_1^0|$ which would be reached if the charge is completed. However, this does not occur and the observed maximum value before the present decay is around 24% in SHA.DIF.14k and 64% in CALS10k.2 of the theoretical value obtained with the fit.

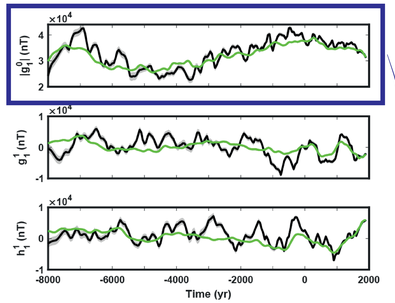

Figure 5. Temporal evolution of the dipole Gauss coefficients: $|g_1^0|$ (top), g_1^1 (middle), h_1^1 (bottom) for the SHA.DIF.14k (black) and CALS10k.2 (green) reconstructions.

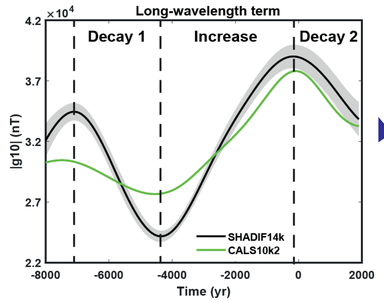

Figure 6. Long-wavelength term obtained by the EMD over $|g_1^0|$ (blue frame in Fig.5) as explained in Results for SHA.DIF.14k and CALS10k.2 reconstructions.

4. CONCLUSIONS

In this work, we analyzed the secular variation of the dipole field during the Holocene. We have performed a detailed frequency analysis using three different techniques, Fourier Transform, Empirical Mode Decomposition and wavelet analysis that allow us to determine the following characteristic periods:

- A period of around 1400 years observed especially in CALS10k.2 and BIGMUDI4k, and with lower power in SHA.DIF.14k that could be related to the 1350 year cycle observed by Nilsson et al. (2011).
- Between 600 - 800 years which is observed in the four selected paleoreconstructions during the whole time window.
- The shortest period is observed around 200 – 300 years, especially in BIGMUDI4k and SHAWQ2k.

For the long-term, we hypothesize that it is controlled by a succession of 'pulses' and decays and we modeled them as the charge and discharge of a capacitor. We obtained coherent results for the characteristic times of diffusion of $|g_1^0|$ for the present day decay in SHA.DIF.14k and CALS10k.2 with values between 13 - 15 kyr. This simple model results in characteristic times of the same order of magnitude as the diffusion times for the dipole field in the geodynamo theories.

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Acknowledgements

This work has been possible thanks to FPU grants (FPU17/036035) financed by the Spanish Ministry of Education and the projects CGL2017-92285-EXP and CGL2017-87015-P financed by the Spanish Ministry of Science and Innovation. SAC thanks to Juan de la Cierva Formación Program (FJC2018-037643-I). AMC acknowledges the contract funding from CGL2017-87015-P project (FEDER/Ministerio de Ciencia, Innovación y Universidades – Agencia Estatal de Investigación)