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Notes

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ABSTRACT

Some studies indicate that the solar modulation of galactic cosmic ray (GCR) particles has profound consequences for Earth's climate system. A corollary of the GCR-climate theory involves a link between Earth's magnetic field and climate, since the geomagnetic field also modulates the GCR flux reaching Earth's atmosphere. In this study, we explore this potential geomagnetic-climate link by comparing a new reconstruction of the Holocene geomagnetic dipole moment with high-resolution speleothem data from China and Oman. The speleothem $\delta^{18}O$ data represent proxy records for past precipitation in low-latitude regions, which is a climate parameter that is likely to have been sensitive to variations in the GCR flux modulated by the dipole moment. Intriguingly, we observe a relatively good correlation between the high-resolution speleothem $\delta^{18}O$ records and the dipole moment, suggesting that Earth's magnetic field to some degree influenced low-latitude precipitation in the past. In addition to supporting the notion that variations in the geomagnetic field may have influenced Earth's climate in the past, our study also provides some degree of support for the controversial link between GCR particles, cloud formation, and climate.

INTRODUCTION

It remains difficult to capture the complexity of Earth's climate system in numerical models. A meaningful discussion of past and future climate variability cannot, therefore, rely solely on mechanistic computer models, but must, at least to some extent, be based on actual climate observations. Because the instrumental records are too short to elucidate several aspects of the climate system, new insights often have to rely on crude comparisons between climate-proxy records and potential climate-forcing factors recorded in geological archives. The controversial role of the Sun as a driver of climate change represents a good example, as geological proxy records are important for our endeavor to understand climate variability.

The role of solar variability in climate change is strongly debated, mainly because the relative importance of solar variability compared to other climate-forcing mechanisms is unclear (Bard and Frank, 2006; Courtillot et al., 2007). On the one hand, observed correlations between reconstructions of past solar activity and climate proxy records indicate that natural variations in solar activity had a significant impact on the Holocene climate (e.g., Bond et al., 2001; Neff et al., 2001; Mayewski et al., 2004; Gupta et al., 2005; Wang et al., 2005). On the other hand, past variations in solar irradiance appear to have been relatively small (Foukal et al., 2006), which, taken at face value, suggests that solar variability was less important than several other climate-forcing mechanisms. Adding to the complexity are potential indirect solar forcing mechanisms, which could have amplified the Sun's influence on climate and possibly explain the relatively strong solar forcing suggested by some geological records. The GCR-climate theory, which is arguably the most prominent of the indirect forcing mechanisms, reasons that the flux of GCR particles entering Earth's atmosphere plays a crucial role for low-altitude cloud formation, which, in turn, influences the radiative balance of Earth and, ultimately, climate (e.g., Svensmark and Friis-Christensen, 1997; Svensmark, 2000; Marsh and Svensmark, 2000, 2003; Carslaw et al., 2002; Kirkby, 2007). Since the flux of GCR particles reaching Earth's atmosphere is modulated by the solar wind, the GCR-climate theory involves a solar forcing of the climate that significantly amplifies the forcing owing to solar irradiance. An interesting aspect of the GCR-climate theory arises from the fact that the GCR flux is also modulated by Earth's magnetic field, and the theory consequently predicts a connection between Earth's magnetic field and climate (e.g., Gallet et al., 2005; Kirkby, 2007; Usoskin et al., 2008). Hence, if the GCR-climate theory is correct, one would expect not only a relatively strong solar-climate link, but also a connection between Earth's magnetic field and climate.

The potential connection between Earth's magnetic field and climate was discussed in a number of recent studies (e.g., Gallet et al., 2003, 2005; Courtillot et al., 2007; Kirkby, 2007; Usoskin et al., 2008), which have sparked a heated debate, highlighting the need for further research into this controversial topic (Bard and Delaygue, 2008; Courtillot et al., 2008). In this paper, we compare a new global reconstruction of the Holocene geomagnetic dipole moment (Knudsen et al., 2008) with proxy records for past low-latitude precipitation (Fleitmann et al., 2003; Wang et al., 2005).

HOLOCENE GEOMAGNETIC DIPOLE MOMENT

Variations in the Holocene geomagnetic dipole moment were recently reconstructed based on the GEOMAGIA50 database (Knudsen et al., 2008), which is a compilation of all absolute paleointensity data published in peer-reviewed journals (Donadini et al., 2007; Korhonen et al., 2008). The data derive exclusively from burned archeological materials and lava flows, and are consequently unaffected by climatic biases. In order to average out secular variation of the nondipole field and to account for large uncertainties on the ages of the paleointensity data, the data were grouped in time windows of 500 yr back to 4000 yr B.P. and 1000 yr back to 12,000 yr B.P. A running-window approach was used to determine the axial dipole moment that provided the optimal fit to the paleointensity data within the given time intervals, whereas associated error estimates were constrained using a bootstrap procedure (Knudsen et al., 2008). The axial dipole moment is well constrained back to ca. 7000 yr B.P., at which point there is a significant drop in the amount and latitudinal coverage of the paleointensity data. Although the reconstructed dipole moment effectively represents a smoothed record of the actual dipole moment, it clearly demonstrates that the Holocene dipole moment was dynamic and at times underwent dramatic changes, with rates of change similar to the historically observed 5% per century (Fig. 1).

HOLOCENE LOW-LATITUDE PRECIPITATION

In order to study the potential link between the geomagnetic dipole moment and climate, we focus our attention on Holocene low-latitude paleoprecipitation data. For this comparative study, we select two speleothem $\delta^{18}O$ records collected from caves in the vicinity of the ocean: (1) stalagmite DA from Dongge cave in southern China (25°17′N, 108°5′E; Wang et al., 2005), and (2) stalagmite Q5 from Qunf cave in southern Oman (17°10′N, 54°18′E; Fleitmann et al., 2003). Both records

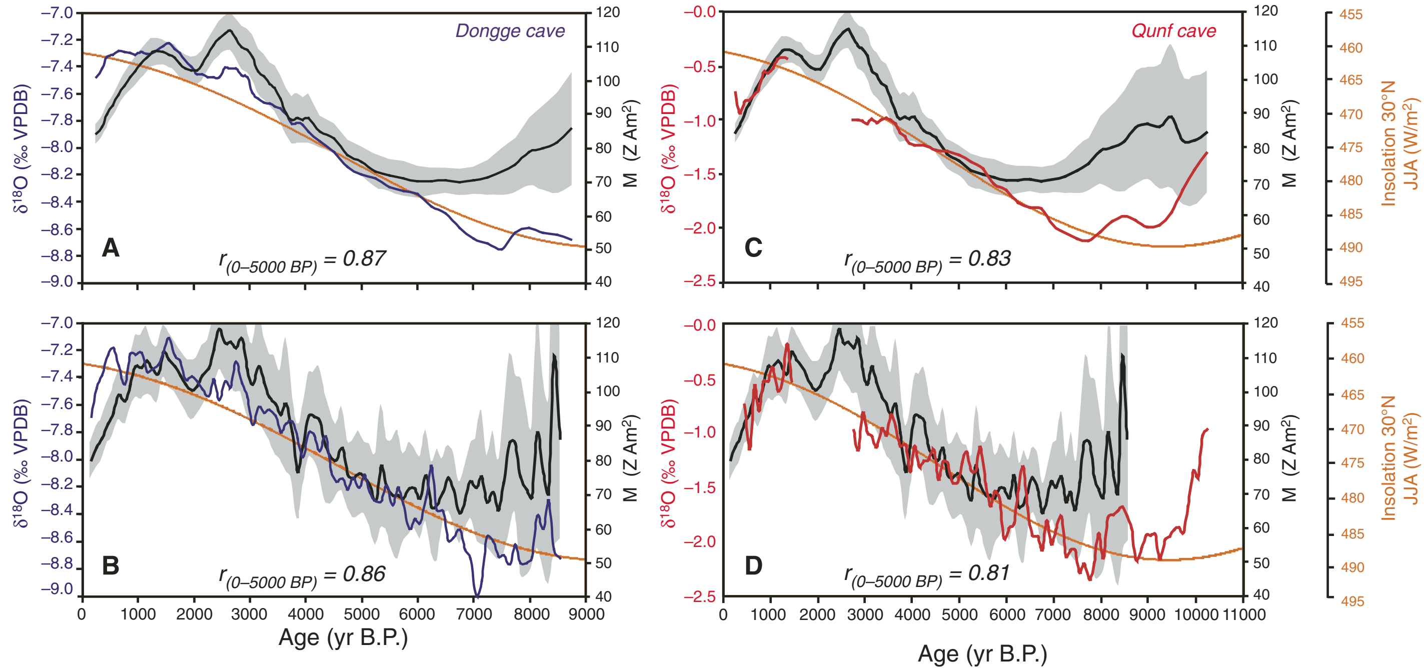

Figure 1. Comparisons between a reconstruction of the geomagnetic dipole moment, M (black), from Knudsen et al. (2008), and speleothem $\delta^{18}O$ data from Dongge cave (blue) in southern China (Wang et al., 2005) and Qunf cave (red) in Oman (Fleitmann et al., 2003). The uncertainties (2σ) associated with the dipole moments (gray-shaded areas) were obtained using a bootstrap approach. Note that Z Am² is equal to 10^{21} Am². The dipole moment and $\delta^{18}O$ data were computed at three different resolutions. A and C: Time windows of 500 yr back to 4000 yr B.P. and 1000 yr in the preceding period. B and D: A 100 yr time window throughout the period. The dipole moments can be found in the GSA Data Repository (see footnote 1). Also shown are variations in summer (June, July, August [JJA]) insolation at 30°N (orange).

are of exceptionally high resolution, and based on correlations to solar proxy data (mainly ^{14}C), they have both played an important role for the growing acceptance of solar variability as a driving mechanism for climate change during the Holocene.

Low-latitude paleoprecipitation represents a climate parameter that is likely to have been sensitive to changes in the GCR flux modulated by dipole moment changes. First of all, the experimentally observed link between GCRs and cloud cover is particularly strong at low latitudes (Marsh and Svensmark, 2000, 2003; Usoskin et al., 2004), probably reflecting the higher atmospheric water vapor concentrations and cloud-forming potential at low latitudes compared to higher latitudes. Secondly, and perhaps more importantly, changes in the geomagnetic shielding of GCR particles, resulting from changes in Earth's dipole moment, is maximum at low latitudes and disappears at higher latitudes, where the geomagnetic field is steeply inclined. Thirdly, as also noted by Usoskin et al. (2008), paleoprecipitation data represent a climate parameter that is closely linked to processes in the atmosphere, where the GCR modulation takes place, and therefore a climate parameter that is likely to have been influenced by past changes in the GCR flux.

CORRELATIONS BETWEEN DIPOLE MOMENT VARIATIONS AND LOW-LATITUDE PRECIPITATION

In order to compare the high-resolution $\delta^{18}O$ records with the paleomagnetic dipole moment estimates, we initially subjected the $\delta^{18}O$ data to the same running-window approach as the paleointensity data, i.e., the $\delta^{18}O$ data were grouped and averaged in time windows of 500 yr back to 4000 yr B.P. and 1000 yr back to 12,000 yr B.P. (Figs. 1A and 1C). The $\delta^{18}O$ record from Dongge cave is in excellent agreement with the dipole moment reconstruction from ca. 5000 yr B.P. to the present (correlation coefficient r = 0.87), whereas the two curves display a different trend for the period before 7000 yr B.P., i.e., a period when the geomagnetic dipole moment is less constrained (Fig. 1A). The same pattern is visible for the comparison between the $\delta^{18}O$ curve from Qunf cave, Oman, and the dipole moment reconstruction (Fig. 1C), although the agreement observed for the period after 5000 yr B.P. (r = 0.83) is not quite as striking as for the Dongge cave record. Unfortunately, there is a significant hiatus in the record from Qunf cave between 1360 yr B.P. and 2720 yr B.P., which is a period characterized by conspicuous changes in the dipole moment.

In order to test the correlation between changes in paleoprecipitation and the dipole moment at a centennial-scale resolution, we reconstructed the dipole moment using time windows of 100 yr, following the approach described in Knudsen et al. (2008) (see the GSA Data Repository[1]). Time windows of 100 yr may be too short to effectively average out secular variation of the nondipole field, but they should, nevertheless, provide a reasonable estimate of changes in the actual dipole moment (Valet et al., 2008). For the early time windows, the 100 yr dipole moment curve is poorly defined (Figs. 1B and 1D), and considering the scarcity of data, data noise, and dating uncertainties, the wiggles of the curve are only significant for the most recent part. In Figures 1B and 1D the 100 yr dipole moment reconstruction was compared to the speleothem $\delta^{18}O$ data after subjecting these to a 100 yr running average. Using this 100 yr running-window approach, we still observe a good correlation (r = 0.86) between the $\delta^{18}O$ record from Dongge cave and the dipole moment reconstruction for the past 5000 yr (Fig. 1B). The correlation between the Qunf cave record and the dipole moment is less striking (r = 0.81), but it is, nevertheless, still visible (Fig. 1D).

[1]GSA Data Repository item 2009016, tabulation of Holocene geomagnetic dipole moments and associated uncertainties based on time windows of 1) 500 yr back to 4000 yr B.P. and 1000 yr in the preceding period, and 2) 100 yr windows throughout the period, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

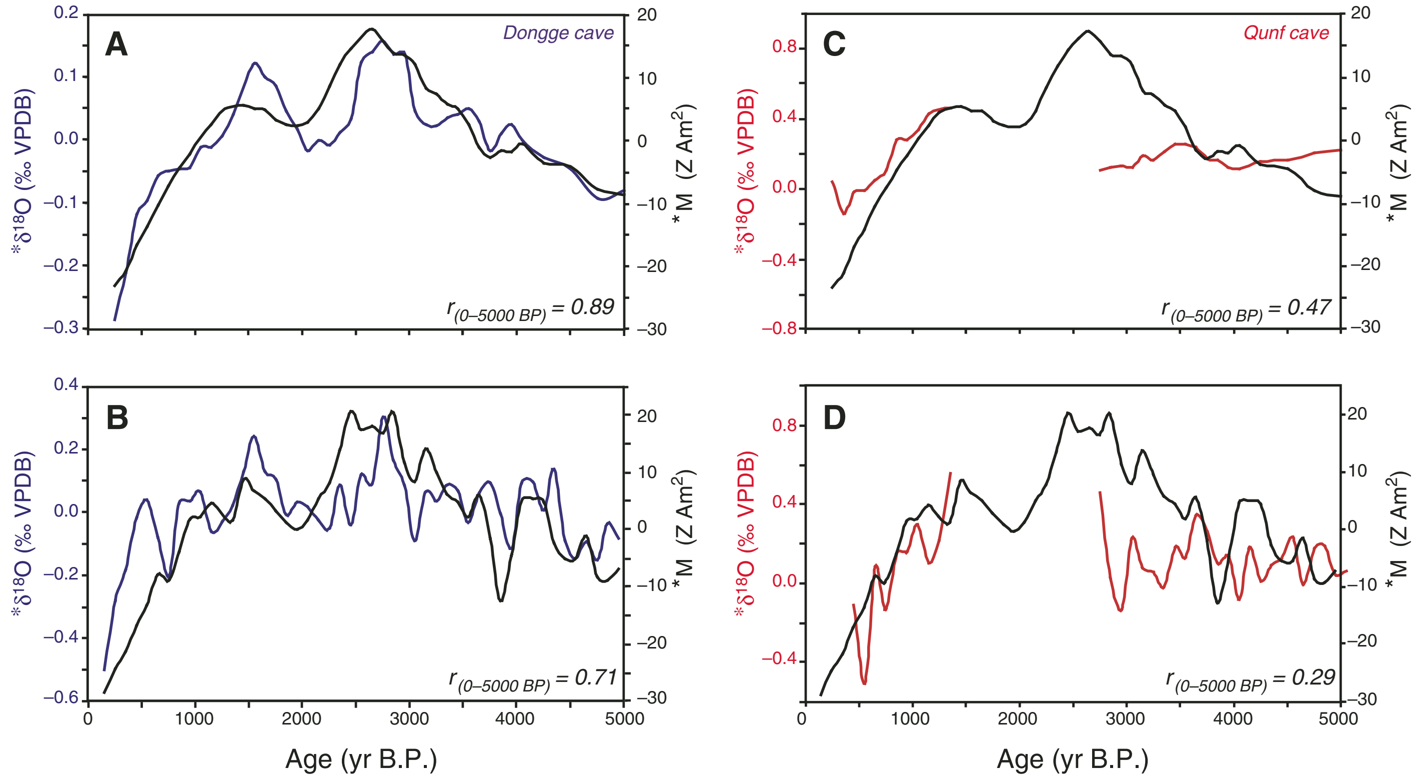

Figure 2. Comparisons between an insolation-detrended reconstruction of the geomagnetic dipole moment, *M (black), and insolation-detrended speleothem δ18O data, *δ18O, from Dongge cave in southern China (A and B) and Qunf cave in Oman (C and D). The speleothem data and the dipole moments were detrended using the 30°N summer insolation shown in Figure 1. The detrended data have been subjected to a running-window approach using the following window lengths: 500 yr back to 4000 yr B.P. and 1000 yr in the preceding period (A and C), and 100 yr windows throughout the period (B and D).

Long-term variations in the Holocene monsoon precipitation are to a large extent driven by orbitally induced summer insolation (e.g., Wang et al., 2008; Hu et al., 2008). It may therefore be argued that the excellent correspondence between variations in the dipole moment and low-latitude precipitation results from a fortuitous correlation between the summer insolation and the dipole moment, or, alternatively, that the orbital cycles driving insolation changes also influenced Earth's dipole moment (e.g., Fuller, 2006; Xuan and Channell, 2008). In order to eliminate this long-term influence, we detrended the two $\delta^{18}O$ speleothem records using the 30°N summer (June–August) insolation (Berger, 1978), and to treat all data in a consistent manner, the dipole moment reconstruction was detrended in a similar way. The detrended $\delta^{18}O$ record from Dongge cave correlates quite well with the detrended dipole moment reconstruction for 500 and 1000 yr windows (r = 0.89) (Fig. 2A) and for 100 yr windows (r = 0.71) (Fig. 2B). The correlation between the detrended dipole moment and the detrended $\delta^{18}O$ record from Qunf cave is less obvious (Figs. 2C and 2D), but the correlation is, nevertheless, noticeable for some parts of the Holocene, in particular the last ~1500 yr.

DISCUSSION

The long-term decrease in low-latitude precipitation observed in the records from southern China and Oman are in good accordance with changes in the 30°N summer insolation (Fig. 1). Superimposed on this long-term trend are short-term fluctuations, which partly have been attributed to variations in solar activity (Fleitmann et al., 2003; Wang et al., 2005). Based on similarities between the Holocene monsoon records and North Atlantic climate, it has also been suggested that ocean circulation changes in the North Atlantic influenced the Asian and Indian Ocean monsoons. However, Fleitmann et al. (2003) noted that the weak correlation between Bond events (Bond et al., 2001) and the Indian Ocean monsoon recorded during the middle to late Holocene may suggest that the North Atlantic thermohaline circulation became less important for the Indian Ocean monsoon when the Northern Hemisphere ice sheets were largely gone. This may indicate that the low-latitude monsoon precipitation responded more directly to changes in solar activity after ca. 8000 yr B.P. (Fleitmann et al., 2003).

The correlations observed in this study (Figs. 1 and 2) suggest that the Holocene low-latitude precipitation variability to some degree was influenced by changes in the geomagnetic dipole moment. This observation is underpinned by the GCR-climate theory, which provides a plausible physical mechanism by which changes in the dipole moment can affect precipitation patterns. We note that the observed correlation between the monsoon precipitation and the dipole moment seems intuitively correct in the sense that a higher dipole moment leads to a lower cosmic ray flux, resulting in reduced cloud coverage and, ultimately, lower precipitation. Centennial-scale changes in low-latitude monsoon precipitation may consequently result from a combination of different forcing mechanisms, including changes in the geomagnetic dipole moment, solar activity, and oceanic and atmospheric circulation patterns. It is notable, however, that some parts of the monsoon variability seem better accounted for by changes in the dipole moment than any other forcing mechanisms. In particular, the general increase in precipitation observed over the past ~1500 yr in both speleothem records, which cannot be readily explained by changes in summer insolation or solar activity, correlates very well with the rapid decrease in dipole moment observed during this period.

CONCLUDING REMARKS

Deciphering low-latitude precipitation proxy records is complicated by the presence of several potential climate-forcing mechanisms and the fact that proxy data from geological records by nature are noisy and imperfect representations of the actual past. The good agreement observed in this study between speleothem $\delta^{18}O$ data and the geomagnetic dipole moment suggests that dipole moment variations may have played a role in controlling past low-latitude precipitation in some regions. The physical mechanism that links dipole moment variations with low-latitude precipitation patterns is provided by the GCR-climate theory. The potential significance of the dipole moment for Holocene low-latitude precipitation probably varied considerably on a regional scale, which could explain why the dipole moment correlates better with the speleothem record from southern China compared to the record from Oman. Obviously, the potential geomagnetic influence on low-latitude precipitation outlined in the present study does not contradict the notion that long-term speleothem $\delta^{18}O$ variability in southern China and Oman was controlled by changes in summer insolation, or that the short-term variability partly was controlled by variations in solar activity and ocean-atmosphere processes.

Our study may have a more general implication, as it lends support to the notion that variations in the geomagnetic field have influenced Earth's climate in the past. If confirmed, our study also provides some support for the controversial link between cosmic ray particles, cloud formation, and climate, which is crucial to better understand how changes in solar activity impact the climate system.

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