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The Marine Isotope Stage 19 in the mid-latitude North Atlantic Ocean: astronomical signature and intra-interglacial variability

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ABSTRACT

Since the seminal work by Hays et al. (1976), a plethora of studies has demonstrated a correlation between orbital variations and climatic change. However, information on how changes in orbital boundary conditions affected the frequency and amplitude of millennial-scale climate variability is still fragmentary. The Marine Isotope Stage (MIS) 19, an interglacial centred at around 785 ka, provides an opportunity to pursue this question and test the hypothesis that the long-term processes set up the boundary conditions within which the short-term processes operate. Similarly to the current interglacial, MIS 19 is characterised by a minimum of the 400-kyr eccentricity cycle, subdued amplitude of precessional changes, and small amplitude variations in insolation. Here we examine the record of climatic conditions during MIS 19 using high-resolution stable isotope records from benthic and planktonic foraminifera from a sedimentary sequence in the North Atlantic (Integrated Ocean Drilling Program Expedition 306, Site U1313) in order to assess the stability and duration of this interglacial, and evaluate the climate system's response in the millennial band to known orbitally induced insolation changes. Benthic and planktonic foraminiferal $\delta^{18}O$ values indicate relatively stable conditions during the peak warmth of MIS 19, but sea-surface and deep-water reconstructions start diverging during the transition towards the glacial MIS 18, when large, cold excursions disrupt the surface waters whereas low amplitude millennial scale fluctuations persist in the deep waters as recorded by the oxygen isotope signal. The glacial inception occurred at ~779 ka, in agreement with an increased abundance of tetra-unsaturated alkenones, reflecting the influence of icebergs and associated meltwater pulses and high-latitude waters at the study site. After having combined the new results with previous data from the same site, and using a variety of time series analysis techniques, we evaluate the evolution of millennial climate variability in response to changing orbital boundary conditions during the Early–Middle Pleistocene. Suborbital variability in both surface- and deep-water records is mainly concentrated at a period of ~11 kyr and, additionally, at ~5.8 and ~3.9 kyr in the deep ocean; these periods are equal to harmonics of precession band oscillations. The fact that the response at the 11 kyr period increased over the same interval during which the amplitude of the response to the precessional cycle increased supports the notion that most of the variance in the 11 kyr band in the sedimentary record is nonlinearly transferred from precession band oscillations. Considering that these periodicities are important features in the equatorial and intertropical insolation, these observations are in line with the view that the low-latitude regions play an important role in the response of the climate system to the astronomical forcing. We conclude that the effect of the orbitally induced insolation is of fundamental importance in regulating the timing and amplitude of millennial scale climate variability.

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1. Introduction

It has long been recognised that the long-term climatic variations deduced from the geological records are driven by the insolation changes forced by variations in Earth orbital geometry

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(Adhémar, 1842; Croll, 1867a,b; Hays et al., 1976; Berger, 1988). Whether these orbitally induced insolation changes modulated or even triggered climate variability in the millennial band is still open to question. A possible feature, which has hindered the inclusion of the orbital or astronomical input as a plausible forcing for rapid climate variability, has been the difference between the primary Milankovitch periods (i.e. the shortest ~19 kyr) and the timing of abrupt climate changes (a few kyr). However, the climate system may behave as a highly nonlinear system and it is conceivable that forcing with frequencies much lower (e.g. a few kyr) than those of its own free oscillations (e.g. ~100, 41, 19–23 kyr) can influence its response.

The potential for suborbital climate variability arising as a nonlinear response to Milankovitch forcing was suggested by modelling studies (e.g., Wigley, 1976; Ghil and Le Treut, 1981; Le Treut and Ghil, 1983; Short et al., 1991; Rial and Yang, 2007) and lately observed in different palaeoclimatic spectra (Hagelberg et al., 1994; Ortiz et al., 1999; Wara et al., 2000). Oscillations at frequencies equal to precession harmonics (~11 kyr and 5.5 kyr) have been identified in different surface water records (McIntyre and Molfino, 1996; Niemitz and Billups, 2005; Weirauch et al., 2008; Billups et al., 2011; Hernández-Almeida et al., 2012) and recently we have presented evidence that not only surface- but also deep-water records vary on such timescales during the Early Pleistocene (Marine Isotope Stages (MIS) 23–20, ~910–790 ka) in the North Atlantic Ocean (Integrated Ocean Drilling Program – IODP – Expedition 306, Site U1313) (Ferretti et al., 2010). The specific mechanisms by which these orbitally induced insolation changes produced the observed climate responses are still poorly understood; however, a good correlation between our surface and deep-water hydrography reconstructions and the tropical insolation forcing have supported the hypothesis that the timing of abrupt climate changes, as well as the amplitude of millennial scale oscillations, may be strongly influenced by insolation variations at the low latitudes.

In order to investigate the temporal extent of these events, and verify whether the harmonics of precession were a recurring feature of the Pleistocene climatic variability, here we extend our observations at IODP Site U1313 to an interval of time characterised by different orbital configurations and place special emphasis on MIS 19. Similarly to the Holocene, MIS 19 was close to the minimum in the *c.* 400 kyr eccentricity envelope (i.e. the Earth's orbit was close to circular) thus minimising the effect of precession; this is because eccentricity modulates the climatic precession parameter which controls most of the long-term variations of the daily insolation received from the Sun (Berger et al., 1993). It follows that the major feature of the insolation over this interval is the small amplitude of its variations. We set out with the aim of investigating millennial-scale variability in North Atlantic sea surface and deep-water hydrography during MIS 19 and comparing such variations with those from our earlier study focussing on the older portion of the record (MIS 23–20). Our final objective is the assessment of the nonlinear coupling to climatic forcing recorded in the geological record via changes in orbital precession. More specifically, our working hypothesis is that if the insolation determines, in the end, the timing and amplitude of rapid climate change, during MIS 19 we would expect a weaker spectral power at periodicities associated with the harmonics of the precession band, together with relatively low amplitude oscillations aligned with intervals of low precessional forcing (i.e. periods of low eccentricity). We will see that this appears to be the case.

2. Regional setting

The sediments used for this study were recovered from Site U1313, a reoccupation of Deep Sea Drilling Project (DSDP) Leg 94 Site 607, during Expedition 306 of the Integrated Ocean Drilling Program (Expedition 306 Scientists, 2006; Stein et al., 2006). This site is located in the North Atlantic on the upper middle western flank of the Mid-Atlantic Ridge, ~400 km WNW of the Azores (41°00′N, 32°58′W) (Fig. 1). At present, Site U1313 is predominantly influenced by the surface waters of the North Atlantic Current (Fratantoni, 2001) and, at a water depth of 3426 m, is under the influence of North Atlantic Deep Water (NADW). During glacial periods however, the site became regularly influenced by high-latitude waters as evidenced by low alkenone-based sea-surface temperatures and appearance of ice-rafted debris (Naafs et al., 2011, 2013). In addition, the more negative carbon isotope values observed during glacials over the Pleistocene indicates that this location is sensitive to past changes in the relative contribution of high $\delta^{13}C$ NADW and low $\delta^{13}C$ southern source waters and to changes in the locations of these two water masses (Raymo et al., 1990, 2004; Ferretti et al., 2010; Voelker et al., 2010).

3. Materials and methods

3.1. Stable isotopes

The composite section of Site U1313 was sampled at a constant 1-cm spacing following the shipboard secondary splice between 35.94 and 38.39 m composite depth (mcd), corresponding to the interval MIS 19. The spliced stratigraphic section was refined postcruise using shipboard magnetostratigraphy, lightness and magnetic susceptibility measurements to provide more accurate correlation points, and the sampled depth-series corresponds to 36.30 and 38.40 revised metres composite depth (rmcd) (=amended metres composite depth – amcd – in Naafs et al. (2012)).

Sediment samples were processed following standard procedures that involve disaggregating the samples in reverse osmosis (RO) water overnight on an orbital shaker and washing them through a 63 μm sieve to isolate the sand size fraction. Changes in surface and deep-water hydrography were inferred from variations in stable isotopes on planktonic and benthic foraminifera, respectively. About 20 specimens of the planktonic foraminifera *Globigerina bulloides* were used for each mass spectrometric analysis to provide ample carbon dioxide; specimens were selected from the 315–355 μm size fraction to minimise noise arising from isotopic changes during ontogeny. Between 5 and 10 specimens of *Cibicidoides wuellerstorfi* were picked, mostly from the fraction >212 μm. After picking, specimens were lightly crushed and cleaned ultrasonically with methanol for a few seconds to remove fine-grained particles; excess liquid and residues were then removed with a pipette, and samples were dried under a vacuum hood. All isotope measurements were made using a ThermoFinnigan-MAT 252 isotope ratio mass spectrometer coupled with a Kiel II carbonate preparation device at the Serveis Científico-Tècnics of the University of Barcelona and are reported referenced to the Vienna Pee Dee Belemnite (VPDB) standard using NBS-19 for calibration. Analytical precision was better than 0.08 for $\delta^{18}O$ and 0.04 for $\delta^{13}C$. *C. wuellerstorfi* $\delta^{18}O$ values were adjusted for species-specific offsets relative to *Uvigerina* spp. (widely considered to precipitate its calcite in oxygen isotopic equilibrium with respect to seawater) by adding +0.64‰ VPDB (Shackleton and Opdyke, 1973).

Several duplicate measurements at the same depth were performed on *G. bulloides* between 37.15 rmcd and 38.29 rmcd; this procedure was adopted not because the results of the initial measurements were suspected to be aberrant but rather to confirm the observed pattern of higher amplitude oscillations in the planktonic $\delta^{18}O$ signal. The replicate analyses did not deviate from the original measurements and the results were then averaged.

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