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Mark Siddall, Thomas F. Stocker, Thomas Blunier, Renato Spahni, Jakob Schwander, et al.. Marine Isotope Stage (MIS) 8 millennial variability stratigraphically identical to MIS 3. *Paleoceanography*, 2007, 22 (PA1208), 1 à 4 p. 10.1029/2006PA001345 . insu-00377274

HAL Id: insu-00377274

<https://insu.hal.science/insu-00377274>

Submitted on 12 Mar 2021

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Marine Isotope Stage (MIS) 8 millennial variability stratigraphically identical to MIS 3

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Received 13 July 2006; revised 19 September 2006; accepted 26 October 2006; published 21 February 2007.

[1] The Marine Isotope Stage (MIS) 3 stratigraphy is highly robust and was reproduced during another period: MIS 8.6 global ice volume was similar during MIS 8.6 to MIS 3 (60 to 90 m sea level equivalent), but the Milankovitch insolation forcing was different, implying that Earth's predisposition to millennial internal variability is controlled by the configuration of the major ice sheets. The involvement of additional factors cannot be ruled out but by identifying several such periods using new deep ice cores from Dome Concordia and Dome Fuji (Antarctica) as well as the marine record we may isolate the factors predisposing Earth to these highly significant modes of climate variability.

Citation: Siddall, M., T. F. Stocker, T. Blunier, R. Spahni, J. Schwander, J.-M. Barnola, and J. Chappellaz (2007), Marine Isotope Stage (MIS) 8 millennial variability stratigraphically identical to MIS 3, *Paleoceanography*, 22, PA1208, doi:10.1029/2006PA001345.

1. Introduction

[2] Northern high-latitude Marine Isotope Stage (MIS) 3 variability consists of Dansgaard-Oeschger (D-O) events, decadal warmings of 8–15°C [Alley *et al.*, 2003; Huber *et al.*, 2006]. D-O events are often clustered in “Bond cycles,” groups of four with a longer warm period followed by three shorter warm periods, interspersed with cold periods [Bond and Lotti, 1995].

[3] D-O events correspond to slower, smaller changes in Antarctica [Stocker and Johnsen, 2003]; Bond cycles correspond with the largest variations in Antarctic temperature (A1 to A4) followed by more subdued variability [Stocker and Johnsen, 2003]. This north-south relationship between high-latitude ice cores is mirrored in a surface deep relationship between planktonic (D-O like variability) and benthonic oxygen isotopes (Antarctic-like variability) in a Portuguese margin marine core [Shackleton *et al.*, 2000], implying that the Atlantic Meridional Overturning Circulation (MOC) is linked to this bipolar behavior. The physical mechanism responsible for this “bipolar seesaw” is linked to the fact that an active meridional overturning circulation in the Atlantic transports heat northward at all latitudes heating the north and cooling the south [Crowley, 1992]. If the MOC shuts down, heat is no longer drawn to the north from the southern reservoirs (South Atlantic and parts of the Southern Ocean), causing rapid cooling in Greenland and gradual warming in Antarctica. Models of various complexity exhibit this behavior [Stocker *et al.*, 1992; Knutti *et al.*,

2004; Stouffer *et al.*, 2006]. Stocker and Johnsen [2003] describe one such simple model of the thermal bipolar seesaw in the MOC, which has successfully described the relationship between Antarctic and Greenland temperature during MIS 3. The thermal bipolar seesaw assumes that Antarctic temperature responds in a damped way and opposite to changes in Greenland temperature with a characteristic response time of the order of 1000 years; in response to rapid warmings in Greenland Antarctica starts to gradually cool and in response to rapid coolings in Greenland Antarctica starts to gradually warm.

[4] We address whether or not this dynamical linkage is a universal characteristic of ice ages. General similarities between MIS 3 variability and variability in the more distant past have been noted [Oppo *et al.*, 1998; McManus *et al.*, 1999] and a study of millennial events recorded in the Vostok ice core has suggested broadly similar north-south phase relationships over the last four climatic cycles [Delmotte *et al.*, 2004]. We use this recent data set combined with an inverted version of the thermal bipolar seesaw model [Siddall *et al.*, 2007] to compare in unprecedented detail the stratigraphy and timing of millennial-scale events during MIS 8.6 and MIS 3.

2. Method

[5] Identifying periods equivalent to the marine isotope stages in ice cores is potentially difficult. We use the SPECMAP nomenclature [Imbrie *et al.*, 1984] which puts MIS 8.6 at 299 ka BP. Figure 1 gives the context for these isotope stages from the Vostok deuterium record.

[6] Changes in methane concentration mimic the timing and structure of northern high-latitude temperature reconstructions during MIS 3 [Blunier and Brook, 2001]. The model-estimated Greenland temperature has a temporal offset from the methane record; atmospheric gas is occluded roughly 100 m below the surface and is significantly younger than the surrounding ice by Δ age. The Δ age

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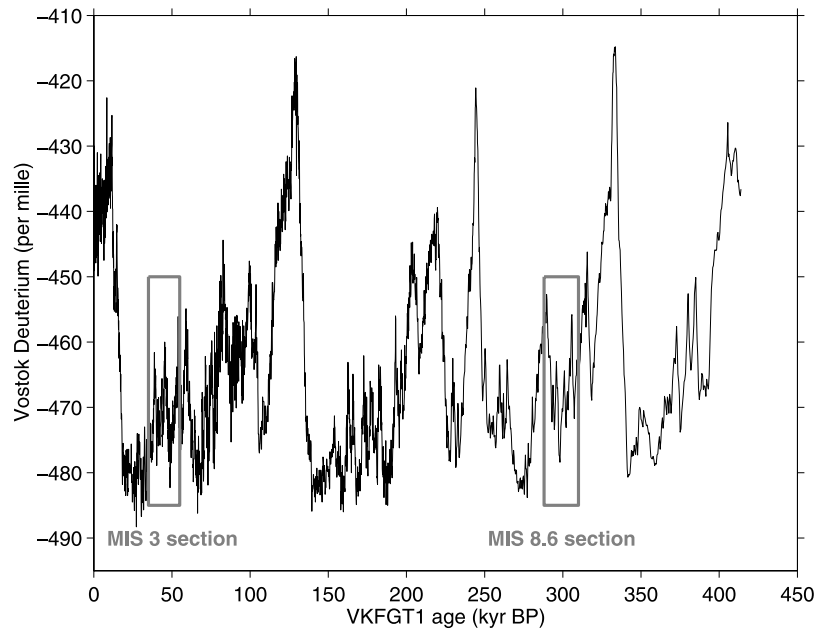


Figure 1. Vostok deuterium record [Petit *et al.*, 1999] on a VKFGT1 age scale. Grey boxes illustrate the sections of the record discussed in the text [Parrenin *et al.*, 2004].

model [Goujon *et al.* 2003] calculates Δage about 600 ± 100 years smaller than the shift we observe between modeled high-latitude temperature and methane during MIS 8. This difference can be explained by a reduced temperature ($\sim 2^\circ\text{C}$) or a reduced accumulation rate ($\sim 10\%$). This is within the uncertainty of these input parameters to the Δage model so we adjust the Δage -corrected Vostok methane age scale accordingly.

[7] MIS 8.6 to MIS 3 comparison is facilitated by linear interpolation between several tie points to create a “comparison age model.” Following Shackleton *et al.* [2000], we select a minimum number of points based on D-O transitions. The relationship between the MIS 8.6 and MIS 3 ages used as tie points is shown in Figures 1 and 2. The maximum difference in age between the comparison age model and ages derived using a single tie point (with no other distortion) is only 300 years so the comparison age model does not significantly distort the Vostok age scale (see also auxiliary material).¹ The comparison age model is expressly for this comparison and is not an alternative Vostok age model.

3. Results

[8] Strong similarities exist between MIS 8.6 and MIS 3 in the phasing, magnitude and duration of millennial events (Figure 3). In particular the duration and magnitude of “A events” are markedly similar, relating to Bond cycles during MIS 8.

[9] Global ice volume during MIS 8.6 was similar to MIS 3 (60 to 90 m sea level equivalent [Siddall *et al.*, 2003; Waelbroeck *et al.*, 2002; Shackleton, 2000; Lea *et al.*, 2002;

Labeyrie *et al.*, 1987]). However, the Milankovitch insolation forcing was different. We conclude that planet Earth’s predisposition to millennial internal variability is controlled by the configuration of the major ice sheets. Milankovitch insolation forcing is a key driver in ice sheet growth on

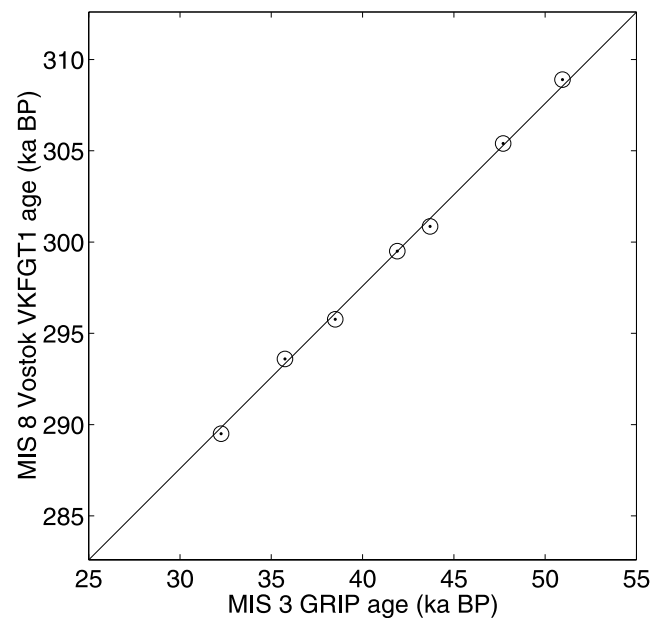


Figure 2. A plot of the age comparison model tie points as displayed on Figure 1 in the text. The tie points are illustrated by circled points and have a mean deviation from the 1:1 relationship of 200 years and a maximum deviation of 300 years.

¹Auxiliary materials are available in the HTML. doi:10.1029/2006PA001345.

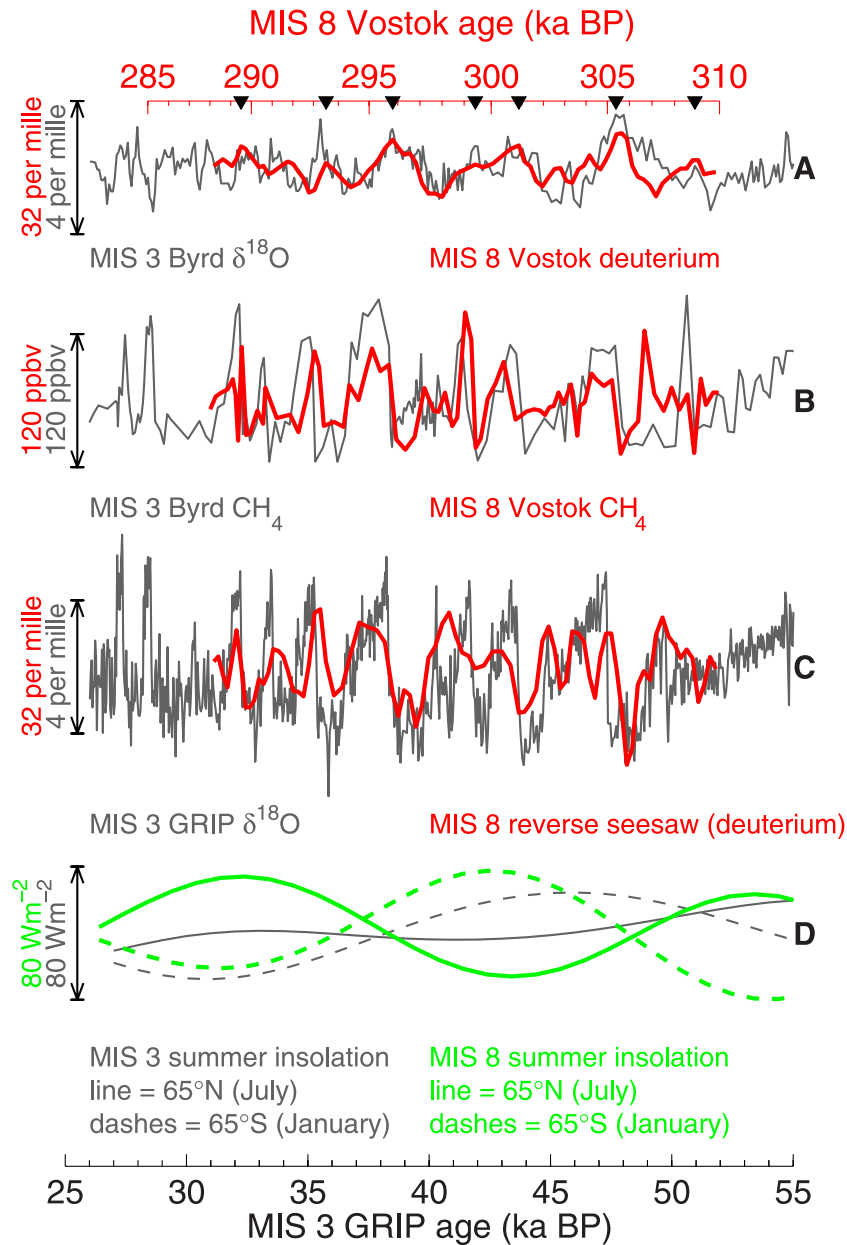


Figure 3. Comparisons between MIS 8.6 (red) and MIS 3 (grey) proxy records for high-latitude climate treated with a high-pass, 8 kyr Gaussian filter. (a) Deuterium and $\delta^{18}\text{O}$ are proxies for high-latitude temperature, shown here are the Vostok Antarctic deuterium record for MIS 8.6 [Petit *et al.*, 1999] and the Byrd Antarctic $\delta^{18}\text{O}$ record for MIS 3 [Blunier and Brook, 2001]. (b) The methane record is a proxy for high-latitude Northern Hemisphere temperature variability, and the methane record from the Byrd (MIS 3) [Blunier and Brook, 2001] and Vostok (MIS 8) [Petit *et al.*, 1999; Delmotte *et al.*, 2004] ice cores are shown (Figure 3c). (c) The reverse seesaw calculation of high-latitude Northern Hemisphere temperature is based on the MIS 8.6 Vostok deuterium temperature proxy record [Petit *et al.*, 1999], shown with the Greenland Ice Core Project MIS 3 $\delta^{18}\text{O}$ record [Blunier and Brook, 2001]. (d) Summer insolation at 65°N (July) and 70°S (January) during MIS 3 and MIS 8. All MIS 3 records shown are on the SS09 sea timescale [Johnsen *et al.*, 2001], and all MIS 8.6 records are on the VK-FGT1-G57 age scale with the gas age adjusted by 600 years (see text) [Petit *et al.*, 1999; Parrenin *et al.*, 2004; Delmotte *et al.*, 2004] in kiloyears before present (ka). Triangles on the upper (red) axis show tie points for the comparison age model. Comparisons with the available MIS 8.6 marine record are provided in the auxiliary material.

longer timescales and so Milankovitch forcing plays an indirect role in governing the ice sheet configuration [Thompson and Goldstein, 2007; Imbrie et al., 1984]. However, it is the configuration of the major ice sheets which directly preconditions the planet to D-O variability.

[10] We show here that ice volume may be a key factor to predisposition the Earth System to millennial variability but we are not in a position to conclude that ice volume is the unique factor involved. Other authors consider that the D-O variability follows an exact periodicity which they attribute to variations in solar forcing [Schulz, 2002]. However, no mechanisms for this variability are known, nor is there independent evidence for it [Stuiver and Braziunas, 1993]. Certainly an argument based on solar variability alone cannot explain the lack of significant, regular D-O variability during MIS 1, 2, 4 and 5.5. Instead the existence of floating ice shelves around the margins of the large Northern Hemisphere ice sheets could explain the link between ice sheet configuration and D-O variability. The apparent lack of D-O like millennial variability during both interglacial

(MIS 1 and MIS 5.5) and glacial (MIS 2 and MIS 4) periods could be linked to the absence of floating ice shelves over the continental shelves.

[11] By identifying as yet undiscovered periods of D-O variability using new deep ice cores from Dome Concordia and Dome Fuji (Antarctica) as well as the marine record we should be able to isolate the factors which predispose Earth to D-O variability.

[12] **Acknowledgments.** Discussions with Edouard Bard, Jerry McManus, Eelco Rohling, Marcus Leunberger, and Neil Edwards were very useful in bringing this work together, and we are grateful for their contributions. In addition, Edouard Bard and Jerry McManus kindly provided data. Funding was made available from the STOPFEN European Network research project (HPRN-CT-2002-00221). Support from the Swiss National Science Foundation and the University of Bern is acknowledged. This work is a contribution to the “European Project for Ice Coring in Antarctica” (EPICA), a joint ESF (European Science Foundation)/EC scientific program, funded by the European Commission and by national contributions from Belgium, Denmark, France, Germany, Italy, Netherlands, Norway, Sweden, Switzerland, and United Kingdom.

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