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

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[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.

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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 Δage. The Δage

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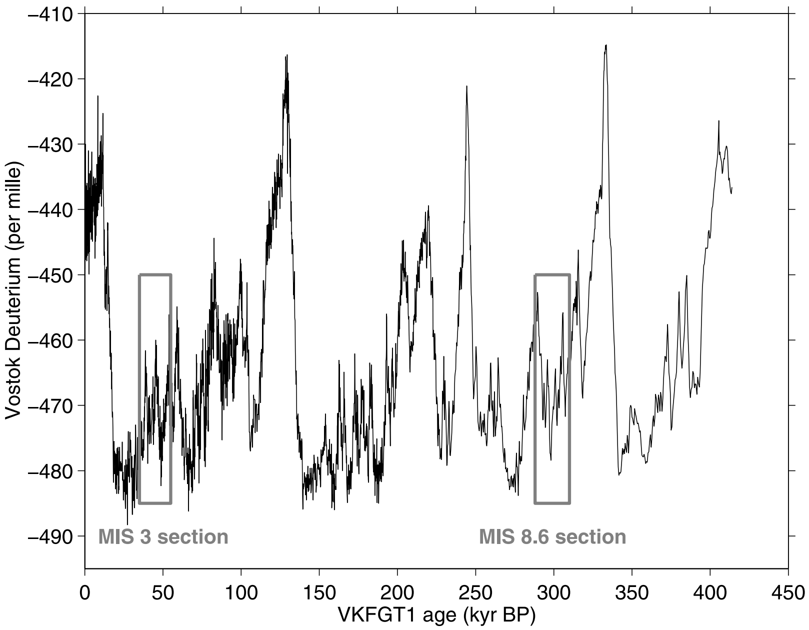

Figure 1. Vostok deuterium record [*Petit et al.*, 1999] on a VKFGT1 age scale. Grey boxes illustrate the sections of the record discussed in the text [*Parrenin et al.*, 2004].

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 (∼ 2°C) or a reduced accumulation rate (∼ 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

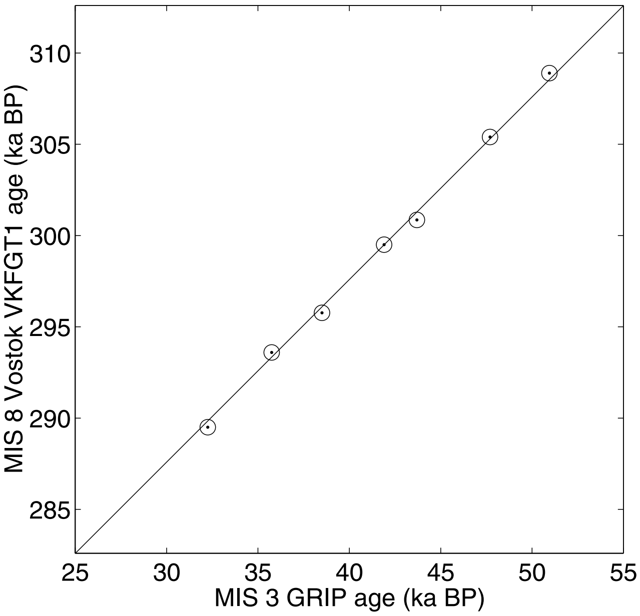

Figure 2. A plot of the age comparison model tie points as displayed on Figure 1 in the text. The tie points are illustrated by circled points and have a mean deviation from the 1:1 relationship of 200 years and a maximum deviation of 300 years.

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

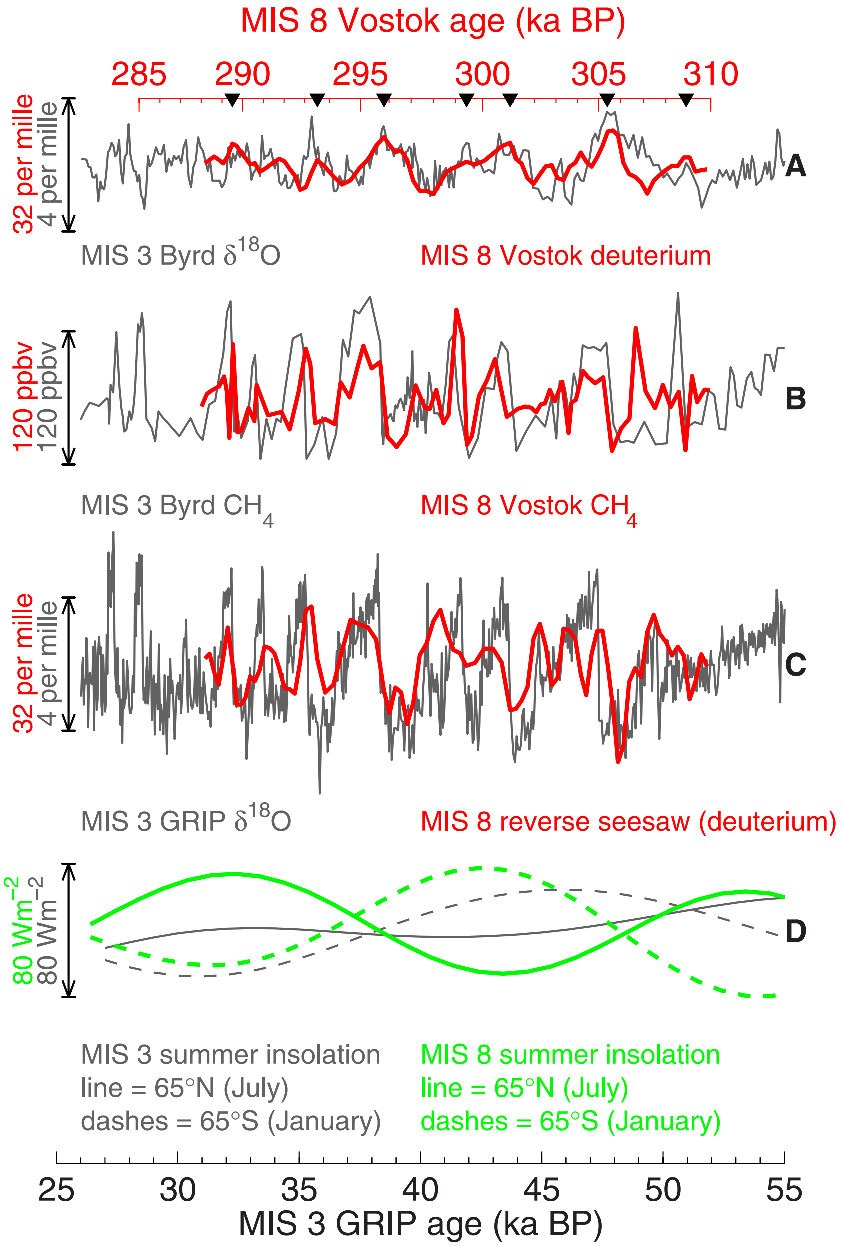

Figure 3. Comparisons between MIS 8.6 (red) and MIS 3 (grey) proxy records for high-latitude climate treated with a high-pass, 8 kyr Gaussian filter. (a) Deuterium and $\delta^{18}O$ are proxies for high-latitude temperature, shown here are the Vostok Antarctic deuterium record for MIS 8.6 [*Petit et al.*, 1999] and the Byrd Antarctic $\delta^{18}O$ 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 $\delta^{18}O$ 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.

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References

Alley, R., et al. (2003), Abrupt climate change, *Science*, *299*, 2005–2010.

Blunier, T., and E. Brook (2001), Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period, *Science*, *291*, 109–112.

Bond, G. C., and R. Lotti (1995), Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation, *Science*, *267*, 1005–1010.

Crowley, T. J. (1992), North Atlantic deep water cools the Southern Hemisphere, *Paleoceanography*, *7*, 489–497.

Delmotte, M., J. Chappellaz, E. Brook, P. Yiou, J. M. Barnola, C. Goujon, D. Raynaud, and V. I. Lipenkov (2004), Atmospheric methane during the last four glacial-interglacial cycles: Rapid changes and their link with Antarctic temperature, *J. Geophys. Res.*, *109*, D12104, doi:10.1029/2003JD004417.

Goujon, C., J.-M. Barnola, and C. Ritz (2003), Modeling the densification of polar firn including heat diffusion: Application to close-off characteristics and gas isotopic fractionation for Antarctica and Greenland sites, *J. Geophys. Res.*, *108*(D24), 4792, doi:10.1029/2002JD003319.

Huber, C., M. Leuenberger, R. Spahni, J. Flückiger, J. Schwander, T. F. Stocker, S. J. Johnsen, A. Landais, and J. Jouzel (2006), Isotope calibrated Greenland temperature record over Marine Isotope Stage 3 and its relation to CH_4, *Earth Planet. Sci. Lett.*, *243*, 504–519.

Imbrie, J., J. D. Hays, D. G. Martinson, A. McIntyre, A. C. Mix, J. J. Morley, N. G. Pisias, W. L. Prell, and N. J. Shackleton (1984), The orbital theory of Pleistocene climate: Support from a revised chronology of the marine $\delta^{18}O$ record, in *Milankovitch and Climate*, edited by A. L. Berger et al., pp. 269–305, Springer, New York.

Johnsen, S. J., D. Dahl-Jensen, N. Gundestrup, J. P. Steffensen, H. B. Clausen, H. Miller, V. Masson-Delmotte, A. E. Sveinbjörnsdottir, and J. White (2001), Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP, *J. Quat. Sci.*, *16*, 299–307.

Knutti, R., J. Flückiger, T. F. Stocker, and A. Timmermann (2004), Strong hemispheric coupling of glacial climate through freshwater discharge and ocean circulation, *Nature*, *430*, 851–856.

Labeyrie, L. D., J. C. Duplessy, and P. L. Blanc (1987), Variations in mode of formation and temperature of oceanic deep waters over the past 125,000 years, *Nature*, *327*, 477–482.

Lea, D. W., P. A. Martin, D. K. Pak, and H. J. Spero (2002), Reconstructing a 350 ky history of sea level using planktonic Mg/Ca and oxygen isotope records from a Cocos Ridge core, *Quat. Sci. Rev.*, *21*, 283–293.

McManus, J. F., D. W. Oppo, and J. L. Cullen (1999), A 0.5-million-year record of millennial-scale climate variability in the North Atlantic, *Science*, *283*(5404), 971–975.

Oppo, D. W., J. F. McManus, and J. L. Cullen (1998), Abrupt climate events 500,000 to 340,000 years ago: Evidence from subpolar north Atlantic sediments, *Science*, *279*(5355), 1335–1338.

Parrenin, F., F. Rémy, C. Ritz, M. J. Siegert, and J. Jouzel (2004), New modeling of the Vostok ice flow line and implication for the glaciological chronology of the Vostok ice core, *J. Geophys. Res.*, *109*, D20102, doi:10.1029/2004JD004561.

Petit, J. R., et al. (1999), Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature*, *399*, 429–436.

Schulz, M. (2002), On the 1470-year pacing of Dansgaard-Oeschger warm events, *Paleoceanography*, *17*(2), 1014, doi:10.1029/2000PA000571.

Shackleton, N. J. (2000), The 100,000 year ice-age cycle identified and found to lag temperature, carbon dioxide and orbital eccentricity, *Science*, *289*, 1897–1902.

Shackleton, N. J., M. A. Hall, and E. Vincent (2000), Phase relationships between millennial-scale events 64,000–24,000 years ago, *Paleoceanography*, *15*, 565–569.

Siddall, M., E. J. Rohling, A. Almogi-Labin, Ch. Hemleben, D. Meischner, I. Schmelzer, and D. A. Smeed (2003), Sea-level fluctuations during the last glacial cycle, *Nature*, *423*, 853–858.

Siddall, M., T. F. Stocker, T. Blunier, R. Spahni, J. McManus, and E. Bard (2007), Using a maximum simplicity paleoclimate model to simulate millennial variability during the last four glacial periods, *Quat. Sci. Rev*, in press.

Stocker, T. F., and S. J. Johnsen (2003), A minimum thermodynamic model for the bipolar seesaw, *Paleoceanography*, *18*(4), 1087, doi:10.1029/2003PA000920.

Stocker, T. F., D. G. Wright, and W. S. Broecker (1992), The influence of high-latitude surface forcing on the global thermohaline circulation, *Paleoceanography*, *7*, 529–541.

Stouffer, R. J., et al. (2006), Investigating the causes of the response of the thermohaline circulation to past and future climate changes, *J. Clim.*, *19*, 1365–1387.

Stuiver, M., and T. F. Braziunas (1993), Sun, ocean, climate and atmospheric $^{14}CO_2$: An evaluation of causal and spectral relationships, *Holocene*, *3*, 289–305.

Thompson, W. G., and S. L. Goldstein (2007), A radiometric calibration of the SPECMAP timescale, *Quat. Sci. Rev*, in press.

Waelbroeck, C., L. Labeyrie, E. Michel, J. C. Duplessy, J. F. McManus, K. Lambeck, E. Balbon, and M. Labracherie (2002), Sea-level and deep water temperature changes derived from benthonic foraminifera isotopic records, *Quat. Sci. Rev.*, *21*, 295–305.

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