Paleoceanography and Paleoclimatology

> Supporting Information for

# A systematic role for extreme ocean-atmosphere oscillations in the development of glacial conditions since the Mid Pleistocene Transition 

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Table S1; Figures S1 to S10

| Greenland/North Atlantic |  | Approximate Antarctic equivalent |  |
| :---: | :---: | :---: | :---: |
| INTIMATE event | This paper |  |  |
| GS-1 | YD |  |  |
| GI-1 | B/A | AIM1 |  |
| GS-2.1a | $\sim \mathrm{HS1}$ |  |  |
| GI-2 | DO2 | AIM2 |  |
| GS-3 | HS2 |  |  |
| GI-3 | DO3 | AIM3/4 |  |
| GI-4 | DO4 |  |  |
| GS-5.1 | HS3 |  |  |
| GI-8 | DO8 | A1 AIM8 |  |
| GS-9 | HS4 |  |  |
| GI-12 | DO12 | A2 AIM12 |  |
| GS-13 | HS5 |  |  |
| GI-14 | DO14 | A3 AIM14 |  |
| GS15/16 | HS5a |  |  |
| GI-17 | DO17 | A4 AIM17 |  |
| GS-18 | HS6 |  |  |
| GI-19.2 | DO19 | A5 AIM19 |  |
| GS-20 | C19 |  |  |
| GI-20 | DO20 | A6 AIM20 |  |
| GS-21 | C20 |  |  |
| GI-21 | DO21 |  | $7 \quad$ AIM21 |
| GS-22 | C21 | A7 |  |

Table S1. Conversion between nomenclatures used in this study and previous publications. INTIMATE events are taken from Rasmussen et al. (2014). Gl-1 etc = Greenland Interstadial, GS1 etc $=$ Greenland Stadial; YD $=$ Younger Dryas, B/A = Bølling Allerød, DO2 etc $=$ DansgaardOeschger event, HS1 etc = Heinrich Stadial event, C19 etc = cold (stadial) event, A1 etc = Antarctic warming event (Blunier \& Brook, 2001), AIM1 etc = Antarctic Isotope Maximum (EPICA, 2006; Svensson et al., 2012).



1st differential



Figure S1. Individual records used for quantifying the abrupt transitions from stadial to interstadial conditions (see also Fig. 2). From top to bottom: NGRIP temperature (Kindler et al., 2014)[Kindler et al., 2014], GISP2 [Ca] (Mayewski et al., 1997), GISP2 Base/Acid balance (Barker, 2005), Iberian Margin SST (Davtian \& Bard, 2023), Composite Chinese speleothem $\delta^{18} \mathrm{O}$ (Cheng
et al., 2016), GISP2[Ca]/[SO4] (Mayewski et al., 1997). In each case the dark blue curve is the smoothed record (underlying raw data are light blue hollow symbols), which is differentiated to give the red curve. Minimum and Maximum values for each transition are indicated by dark blue and red symbols respectively. Light blue solid symbols and curves are calculated delta values.

Smoothing window $=0.3 \mathrm{kyr}$


Figure S2. Quantifying the magnitude and rate of Antarctic cooling during Greenland interstadials. See full description in Methods. The AAT stack (Parrenin et al., 2013) (orange symbols) is smoothed (upper red curve in each panel) before differentiating to identify minima (red curve with blue fill) that are taken to represent interstadial periods in Greenland (light blue curve). The duration of each minimum (while the rate of change is less than zero) is used to define the start and end of cooling and the temperature difference between these points gives the magnitude ( $\Delta \mathrm{T}$ ). The cooling rate (yellow symbols over lower curve) is then calculated as $\Delta \mathrm{T} /$ duration. As can be seen, the smoothing window applied ( $0.3,0.4$ or 0.7 kyr in this case) before differentiating strongly affects the calculated duration of cooling, with a longer window resulting in overestimation of duration and underestimation of rate for shorter events. On the other hand, a shorter smoothing window (which produces a noisier differential) results in an unrealistically short duration of some longer cooling intervals (e.g. DO21, 8580ka). However, we note that the overall negative relationship between duration and rate is observed for a range of smoothing and the individual cooling rates for DO19 and 20 lie consistently above a linear trend through all data points (blue dashed line). A linear fit to all events $\leq 1.3 \mathrm{kyr}$ (grey line) is included to highlight the negative relationship between duration and rate of cooling for shorter events.

Smoothing window $=0.3 \mathrm{kyr}$








Smoothing window $=0.7 \mathrm{kyr}$







Figure S3. Quantifying the magnitude and rate of Antarctic cooling after removing orbital timescale variability (subtraction of a 7 kyr smooth). See full description in Methods. Panels are the same as in Fig. S2 (except that the records of AAT have had their orbital component removed to give AAT_hi) and the results are consistent with those without removal of orbital timescale variability i.e. DO19 and 20 display rates that are faster than might be predicted from their duration alone (in common with DO8 and 12, which follow Heinrich events). Note when using a 300 yr smooth (top panel) the duration of DO20 is too short i.e. the period of cooling does not encompass the entire interval associated with DO20.


Figure S4. Extreme millennial-scale cooling precedes onset of glacial stability. Results for a range of values of AATstdevMax. See annotation of Figure 3 for a fuller explanation.


Figure S5. (a) Inset: Published estimates of MOT (Bereiter et al., 2018; Shackleton et al., 2020; Shackleton et al., 2021) plotted versus AAT (Parrenin et al., 2013). Lower plot: Published (blue symbols) and estimated (red curve with uncertainty envelope) MOT over last glacial cycle. See Methods. The dashed line at $-1.1^{\circ} \mathrm{C}$ is the theoretical point at which SSW reaches the freezing point of seawater $\left(\mathrm{T}_{\text {freeze }}=-2^{\circ} \mathrm{C}\right)$ assuming that all water masses cool in parallel with the mean ocean before this point (modern $\mathrm{T}_{\text {Ssw }}=-0.9^{\circ} \mathrm{C}$ ). (b) Estimated uncertainties for the calibration curve of MOT vs AAT are propagated for the calculation of density and $\Delta \rho$ to show robustness of our assertion that a density paradox occurs around 70ka, during the MIS 5/4 transition.


Figure S6. Sensitivity of the algorithm developed for multiple timeseries analysis to individual parameters. The timescale for ODP 983 can be changed from AICC2012 (Bazin et al., 2013) to U1385 (Hodell et al., 2015). Temporal bin is the bin width used for resampling raw datasets. Parameter bin is number of bins used for constructing histograms and resampling other datasets. Bin width is defined as the total range of any parameter divided by the number of bins. Sweet spot width is the threshold used to delimit the sweet spot of millennial activity, defined as a \% of the maximum mean millennial power for each parameter.

A: 983 Timescale $=$ AICC2012; Temporal Bin $=0.2 \mathrm{kyr}$; Parameter Bin $=20$; Sweet spot width $=$ 80\%. B: 983 Timescale = AICC2012; Temporal Bin = 1.0kyr; Parameter Bin = 20; Sweet spot width $=80 \%$. C: 983 Timescale $=$ AICC2012; Temporal Bin $=0.2 \mathrm{kyr}$; Parameter Bin = 10; Sweet spot width $=90 \%$. D: 983 Timescale $=$ U1385; Temporal Bin $=0.2 \mathrm{kyr}$; Parameter Bin $=20$; Sweet spot width $=80 \%$.


Figure S7. Detail of events across MIS 5/4. From top to bottom: NGRIP $\delta^{18} \mathrm{O}$ (NGRIP_members, 2004) highlights large amplitude DO events 19 and 20, Sortable Silt (SS) measurements from ODP Site 1055 from 1.8 km water depth on the Blake Outer Ridge (NW Atlantic) suggest increased velocity of bottom currents during stadial and glacial intervals, which is interpreted to reflect a net shoaling of the NW Atlantic Deep Western Boundary Current (DWBC, a key component of the modern AMOC) during these periods (Thornalley et al., 2013). Bulk sediment $\varepsilon$ Nd measurements made at the deep NW Atlantic ODP Site 1063 (Bermuda Rise, 4.6 km ) suggest a relative increase in the ratio of southern to northern deep waters during stadial periods (Böhm et al., 2015) (blue curve is a Gaussian LOESS fit with span=0.1, degree=2, points $=200$ ), benthic foraminiferal $\delta^{13} \mathrm{C}$ measurements from ODP Site 1063 (Thornalley et al., 2013) also suggest presence of more nutrient rich (possibly southern-sourced) deep waters during cold intervals. Lowermost curves highlight the decoupling of $\mathrm{CO}_{2}$ (Bereiter et al., 2015) from AAT (Parrenin et al., 2013) across DO19 and 20.


Figure S8. Deep Atlantic temperature reconstructions suggest similar magnitude of glacial cooling as inferred from MOT reconstructions. Dark blue symbols and curve is benthic $\mathrm{Mg} / \mathrm{Ca}$ results from the deep Iberian Margin (Skinner et al., 2003). Orange symbols are derived from the record of benthic foraminiferal $\delta^{18}$ O from nearby site MD95-2042 (Shackleton et al., 2000). We used the same procedure as outline by Adkins (2013) but using data only for Cibicidoides wuellerstorfi with an updated temperature calibration by Marchitto et al. (2014).


Scenario E: Fixed Vol ${ }_{\text {ssw }}$, fixed $\Delta S_{\text {ssw }}$,
$2^{*} \Delta$ salinity (NADW - rest of ocean)
$\qquad$
$\qquad$




Scenario F : Fixed $\mathrm{Vol}_{\text {ssw }}$, fixed $\Delta S_{\text {ssw }}$ $0.5^{*} \Delta$ salinity (NADW - rest of ocean)
$\underbrace{(2)}$






Scenario G: Fixed Vol ${ }_{\text {ssw, }}$, fixed $\Delta S_{\text {ssw }}$ $-1^{*} \Delta$ salinity (NADW - rest of ocean)
(2)


Figure S9. Further scenarios referred to in Section 3.3.1. In Scenarios E-G, 'rest of ocean' is dominated by the Indo-Pacific. Hence 'NADW - rest of ocean' roughly equates to NADW -Indo-Pacific'.


Figure S10. Emergence of bimodality across the MPT. (a-d) Hovmöller diagrams showing dominant modes in the LR04 benthic $\delta^{18} \mathrm{O}$ stack for various window lengths and increments (steps) in $\delta^{18} \mathrm{O}$. Each 50 kyr slice represents 800 kyr (or 200kyr) of record. Histograms on left and right illustrate the first and last windows respectively. Colours represent relative frequency $(\max =1)$ as shown in the scales for the left and righthand histograms.

