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The Plio-Pleistocene development of Atlantic deep-water circulation and its influence on climate trends

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A R T I C L E I N F O

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A B S T R A C T

Using benthic stable isotope records from 10 sites in the Atlantic Ocean, including two new records from Walvis Ridge in the Southeast Atlantic (Sites 1264 and 1267), we review changes in Atlantic deep-water circulation in the context of Plio-Pleistocene climate. Overall, we find non-linear responses of Atlantic deep-water circulation to a cooling climate, with differently evolving glacial and interglacial states. Our main conclusion is that peak North Atlantic Deep Water (NADW) production was reached between ~2.0 and 1.5 Ma, most prominently seen by a maximum in ventilated (high $\delta^{13}C$) conditions in the mid-depth Southeast Atlantic (Site 1264). We infer that a major source of NADW at this time was the export of dense overflow water from the Nordic Seas into the abyssal East Atlantic. Sea surface temperature records from the North and South Atlantic support this notion and indicate that the peak NADW production between ~2.0 and 1.5 Ma was compensated by a stronger warm surface-water return flow (i.e. Atlantic Meridional Overturning Circulation (AMOC) was enhanced), causing long-term (>10^5 year) heat piracy from the South to the North Atlantic. In the wider picture of Plio-Pleistocene climate evolution, we find that a long-term enhancement in the average state of AMOC (~2.4–1.3 Ma) coincides with the "41-kyr world". Hence, we speculate that the transitory negative feedback response of enhanced AMOC to a cooling climate supplied heat to key areas of ice-sheet growth, acting to limit their size and maintain the "41-kyr world". Once a threshold in global cooling was reached, the strength of AMOC lessened, providing a positive feedback for the Early-Middle Pleistocene Transition and the associated build-up of northern hemisphere ice-sheets.

1. Introduction

The average state of Atlantic deep-water circulation is a key feature of the climate system, acting to influence climate through two primary means: the meridional redistribution of heat and changes to the partial pressure of carbon dioxide in the atmosphere (pCO_2). As deep water is formed in the high-latitude North Atlantic and exported southward at depth, it is compensated by a net northward flow of warm upper ocean water across the equator. Accordingly, this heat piracy results in relative warming in the North Atlantic and cooling in the South (Crowley, 1992). In addition, the amount and temperature of North Atlantic Deep Water (NADW) upwelling around Antarctica has an influence on the mass balance of marine based ice-sheets there, and influences the salinity of Antarctic Bottom Water (AABW), thereby affecting deep-ocean stratification (Adkins, 2013). The extent to which the ocean is filled by deep-waters last ventilated in the North Atlantic versus the Southern Ocean also affects stratification and plays an important role in the efficiency of the 'biological carbon pump', both of which contribute significantly to the exchange of CO_2 between the deep-ocean and the atmosphere (Sigman and Haug, 2003; Sigman et al., 2010). Changes in this 'conveyor belt' circulation – known as Atlantic Meridional Overturning Circulation (AMOC) – can be monitored from key regions in the deep-Atlantic Ocean, the records of which have proved central to our understanding of recent changes in climate over 10^2–10^5 year timescales (Bond et al., 1993; Clark et al., 2002; Imbrie et al., 1993, 1992).

On >10^5 year timescales, the development of Plio-Pleistocene climate has been in the direction of colder temperatures and increasingly severe fluctuations of continental ice volume (Fig. 1). Superimposed on this trend, climate evolved regionally and in steps, with significant global transitions occurring at ~2.72 Ma and between ~1.2 and 0.7 Ma – the Plio-Pleistocene Transition (PPT)

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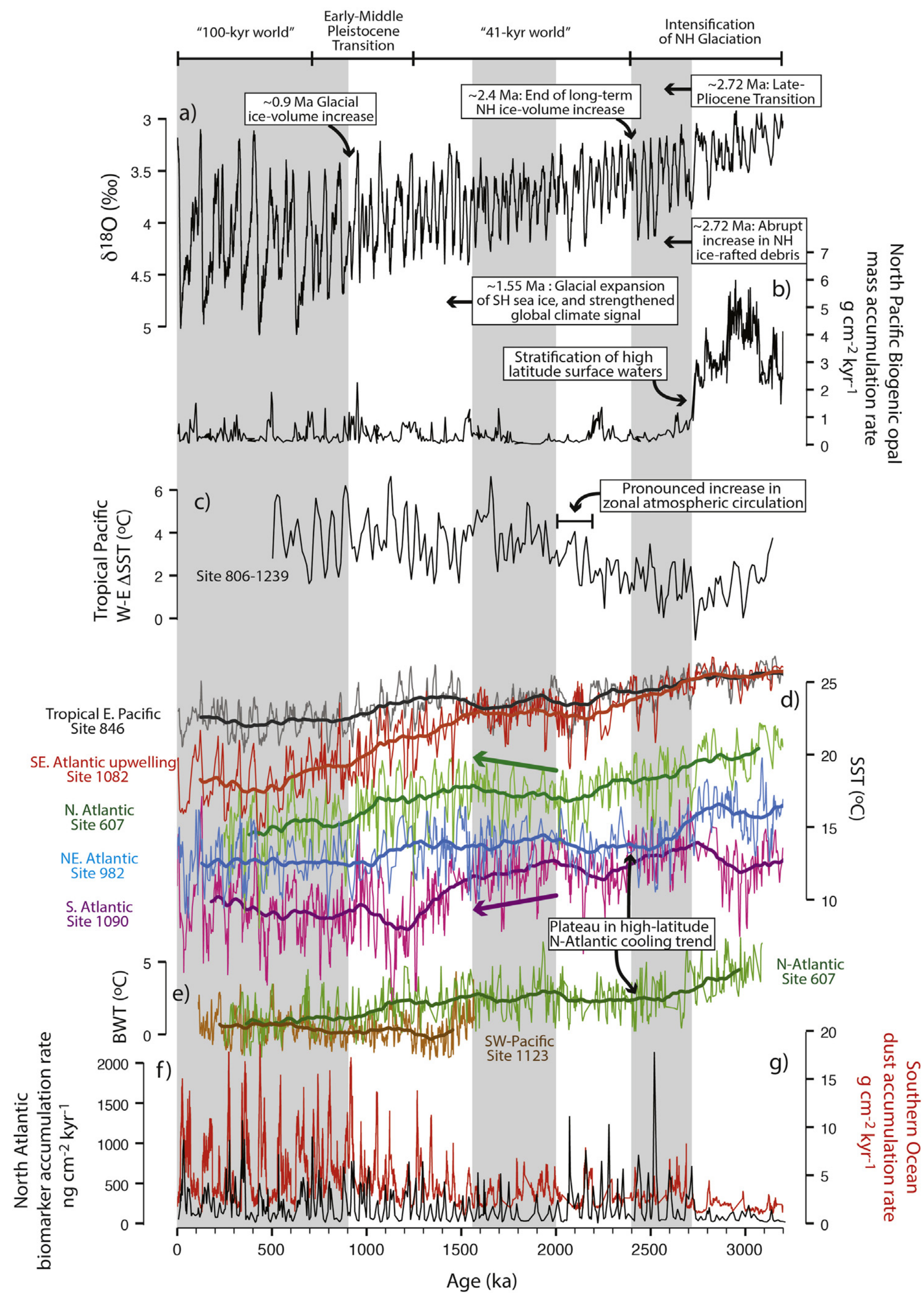

Fig. 1. Overview of climate records and events the Plio-Pleistocene: **a)** Global benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005), reflecting global changes in ice volume and deep-ocean temperature; **b)** Biogenic opal mass accumulation rate (MAR) of Site 882 in the North Pacific (Haug et al., 2005), reflecting changes in surface water productivity relating to stratification; **c)** West-East Pacific sea surface temperature gradients between Sites 806 (Medina-Elizalde et al., 2008; Wara et al., 2005) and 1239 (Etourneau et al., 2010), reflecting changes in the strength of zonal atmospheric (Walker) circulation; **d)** sea surface temperature records from Tropical Eastern Pacific Site 846 (Lawrence et al., 2006), South East Atlantic Site 1082 (Etourneau et al., 2009), North Atlantic Site 607 (Lawrence et al., 2010), North East Atlantic Site 982 (Lawrence et al., 2009), and South Atlantic Site 1090 (Martínez-Garcia et al., 2010); **e)** bottom water temperature (BWT) records for South West Pacific Site 1123 (Elderfield et al., 2012) and North Atlantic Site 607 (Sosdian and Rosenthal, 2009); **f)** North Atlantic biomarker MAR from Site U1313 (a re-drilling of Site 607) (Naafs et al., 2012), reflecting strength of dust sources; **g)** Southern Ocean dust MAR, which also matches iron MAR (Martínez-Garcia et al., 2011).

and Early-Middle Pleistocene Transition (EMPT), respectively. Widespread evidence of changes in deep-Atlantic circulation over this period indicates that AMOC played a significant role in affecting climate. In this paper, we aim to review changes in Atlantic deep-water circulation during the evolution of climate across these major global climate transitions, making use of our two newly published Walvis Ridge stable isotope records. We then evaluate these changes in the context of sea surface temperature (SST) records in order to assess the role of AMOC in the long-term (>10^5 year) evolution of Plio-Pleistocene climate.