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Astronomically paced changes in deep-water circulation in the western North Atlantic during the middle Eocene

Maximilian Vahlenkamp[a,*], Igor Niezgodzki[b,c], David De Vleeschouwer[a], Torsten Bickert[a], Dustin Harper[d], Sandra Kirtland Turner[e], Gerrit Lohmann[b], Philip Sexton[f], James Zachos[d], Heiko Pälike[a]

[a] MARUM - Center for Marine Environmental Sciences, University of Bremen, Leobener Str. 8, 28359 Bremen, Germany
[b] Alfred Wegener Institute - Helmholtz Centre for Polar and Marine Research, Bussestr. 24, 27570 Bremerhaven, Germany
[c] ING PAN - Institute of Geological Sciences, Polish Academy of Sciences, Research Center in Kraków, Biogeosystem Modelling Laboratory, Kraków, Poland
[d] Department of Earth & Planetary Science, University of California, Santa Cruz, CA 95064, USA
[e] Department of Earth Sciences, University of California, Riverside, CA 92521, USA
[f] School of Environment, Earth & Ecosystem Sciences, The Open University, Milton Keynes MK7 6AA, UK

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ABSTRACT

North Atlantic Deep Water (NADW) currently redistributes heat and salt between Earth's ocean basins, and plays a vital role in the ocean-atmosphere CO_2 exchange. Despite its crucial role in today's climate system, vigorous debate remains as to when deep-water formation in the North Atlantic started. Here, we present datasets from carbonate-rich middle Eocene sediments from the Newfoundland Ridge, revealing a unique archive of paleoceanographic change from the progressively cooling climate of the middle Eocene. Well-defined lithologic alternations between calcareous ooze and clay-rich intervals occur at the ~41-kyr beat of axial obliquity. Hence, we identify obliquity as the driver of middle Eocene (43.5–46 Ma) Northern Component Water (NCW, the predecessor of modern NADW) variability. High-resolution benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ suggest that obliquity minima correspond to cold, nutrient-depleted, western North Atlantic deep waters. We thus link stronger NCW formation with obliquity minima. In contrast, during obliquity maxima, Deep Western Boundary Currents were weaker and warmer, while abyssal nutrients were more abundant. These aspects reflect a more sluggish NCW formation. This obliquity-paced paleoceanographic regime is in excellent agreement with results from an Earth system model, in which obliquity minima configurations enhance NCW formation.

1. Introduction

Modern North Atlantic Deep Water (NADW) production accounts for ~40 to 50% of Atlantic Meridional Overturning Circulation (AMOC) (Broecker, 1998). As an important part of global thermohaline circulation, the AMOC helps regulate global climate in three primary ways: i) through the zonal and latitudinal redistribution of heat, salt, and nutrients (Broecker and Peng, 1982), ii) via the carbon cycle, by AMOC's dominant role in moderating oceanic CO_2 uptake (Zickfeld et al., 2008) and iii) by its effect on atmospheric circulation through modulation of global sea surface temperatures (SST) (Mulitza et al., 2008). Accordingly, variations in AMOC intensity can cause large-scale perturbations to global and regional climates.

Ocean circulation has evolved in response to changes in paleogeographic configurations over time. During the early Paleocene, the oceanic connection between the Greenland-Norwegian Sea and the North Atlantic was not yet established and the Atlantic was a much narrower elongated basin with extended adjacent shallow shelf areas (Scotese et al., 1988). Overturning principally occurred in the Southern Ocean during the late Paleocene to early Eocene (Pak and Miller, 1992; Thomas et al., 2003), with possible contribution of deep-water sources in the North Pacific (Thomas, 2004) and warm saline deep water originating in the Tethys (Scher and Martin, 2004). Extremely high deep ocean temperatures (up to 12 °C higher than modern) (Cramer et al., 2011; Sexton et al., 2006a; Zachos et al., 2001) and elevated atmospheric CO_2 (Anagnostou et al., 2016) were associated with decreased latitudinal temperature gradients (Tripati and Elderfield, 2005) and an enhanced hydrological cycle (Barron et al., 1989) that freshened the surface ocean at high latitudes. During the early Eocene, rifting in the Greenland-Norwegian Sea (Mosar et al., 2002) created the

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[*] Corresponding author.
E-mail address: mvahlenkamp@marum.de (M. Vahlenkamp).

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necessary paleogeographic preconditions for the onset of a deep-water source in the North Atlantic. In addition, global cooling increased the importance of sea surface salinity relative to sea surface temperature in the formation of deep water (De Boer et al., 2007), thus accentuating the potential for deep-water formation in the North Atlantic (De Boer et al., 2008). The input of mechanical energy triggered by winds, tides and eddies induces diapycnal mixing (Kuhlbrodt et al., 2007), adding to the buoyancy forcing, which results from differences in water temperature and salinity. This mixing drives the exchange between the surface ocean and deeper layers through overturning and upwelling of deep-water masses around the Antarctic Circumpolar Current (Toggweiler and Bjornsson, 2000; Toggweiler and Samuels, 1998). The modern four layer ocean structure and increased export of Northern Component Water to the South Atlantic has been related to the development of the Antarctic Circumpolar Current during the late Eocene to early Oligocene when the Drake and Tasman Passages began to open (Cramer et al., 2009; Katz et al., 2011; Scher and Martin, 2008). Davies et al. (2001) proposed an onset of NCW at 35 Ma based on the identification and dating of the at this time oldest known North Atlantic Drift Sediments. Nd isotopes from the South Atlantic and the Southern Ocean have later been used to verify this age (Via and Thomas, 2006). However, the South Atlantic was less radiogenic (as characteristic of NCW) during the middle Eocene than during the Oligocene (Scher and Martin, 2008; Via and Thomas, 2006). Hohbein et al. (2012) pushed back the date of the onset of NCW based on the onset of sediment drift deposits within a restricted sedimentary basin at the Greenland–Scotland Ridge, a key gateway for modern NADW outflow into the North Atlantic. This age close to the early-middle Eocene boundary is supported by the onset of the Newfoundland Drifts (Boyle et al., 2017) and winnowing at Blake Nose as indicated by the deposition of foraminiferal sands which have been deposited across the early–middle Eocene boundary disconformity (Norris et al., 2001). The proposed timing of first NCW at the early-middle Eocene boundary coincides with the invigoration of bottom currents inferred by large scale erosion in the North Atlantic (Berggren and Hollister, 1974), the onset of the Cenozoic global deep-water cooling trend (Zachos et al., 2001), major changes in deep-sea circulation as evident through changes in the global inter-basinal δ^{13}C gradient (Sexton et al., 2006a) warming of the Atlantic relative to Pacific bottom waters (Cramer et al., 2009) and enhanced global productivity (Nielsen et al., 2009).

Most attempts to characterize the oceanic response to astronomical forcing under greenhouse conditions during the Cenozoic have focused on the early Eocene greenhouse, before the onset of NCW formation (e.g. Lunt et al., 2011; Sloan and Huber, 2001). Here, we particularly focus on the response to changes in obliquity (i.e. the tilt of Earth's rotational axis) after the onset of NCW (Boyle et al., 2017; Hohbein et al., 2012).

The effect of obliquity is largest at high latitudes, where the climate response to obliquity forcing is enhanced by various feedback mechanisms (Mantsis et al., 2011). Several mechanisms including atmospheric and ocean circulation are known to transfer high latitude insolation forcing into mid or low latitudinal climate signals (Liu and Herbert, 2004). During the Pleistocene, overturning in the North Atlantic was hampered by freshwater release from ice sheet collapse during intervals with unusually warm summers caused by maxima in obliquity (Sigman et al., 2007). Furthermore, in pre-Pleistocene times when Northern Hemisphere ice sheets were absent or smaller, cooler global temperatures are usually associated with minima in obliquity (De Vleeschouwer et al., 2017; Hays et al., 1976) facilitating sea ice formation and thus stimulating NCW formation. This is consistent with strong NADW formation during early Pliocene (4.7–4.2 Ma) obliquity minima (Billups et al., 1997). In the absence of continental ice sheets, obliquity can regulate the strength of the thermohaline circulation via its influence on temperature and density gradients, the hydrological cycle, the extent of sea ice, and possibly via the carbon cycle (Kuhlbrodt et al., 2009; Rahmstorf, 1995).

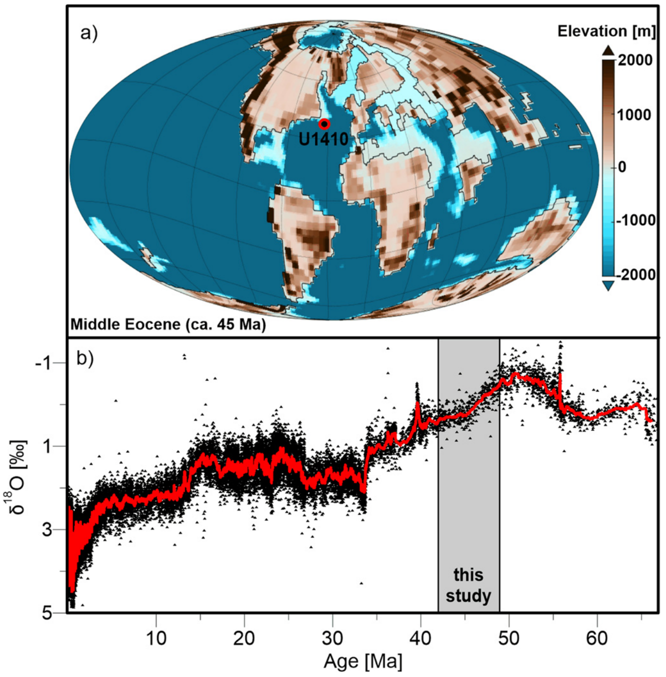

Fig. 1. Paleoclimate setting of the middle Eocene (45 Ma). a) Global topography and bathymetry used for middle Eocene model simulations in this study (modified after Lunt et al., 2016). b) The middle Eocene is characterized by the long-term cooling after the warmest climates of the Cenozoic, as indicated by a global compilation of Cenozoic $\delta^{18}O_{benthic}$ records (Cramer et al., 2009).

Sediments at Site U1410, drilled during IODP Expedition 342 at the Newfoundland Ridge (Norris et al., 2014) provide a unique opportunity to study middle Eocene deep ocean circulation in the western North Atlantic on orbital timescales. Here, we use the X-ray fluorescence (XRF) derived ratio of Ca/Fe in bulk sediment and benthic foraminiferal stable carbon and oxygen isotopes to constrain the intensity of the Deep Western Boundary Currents as well as deep-water nutrient availability and paleotemperature. Together, these allow us to infer orbital-scale variations in deep ocean circulation in the western North Atlantic during an interval of middle Eocene cooling. We establish the deep-water response to astronomical parameters and complement our observations with simulations using the coupled Earth system model *COSMOS*.

2. Material and methods

Site U1410 (41°19.6993′N, 49°10.1847′W; ∼3387.5 m water depth) (Fig. 1) was drilled during Integrated Ocean Drilling Program (IODP) Expedition 342 – Paleogene Newfoundland Sediment Drifts (Norris et al., 2014). Middle Eocene sedimentation at this site occurred at a paleodepth of ∼2950 m at ∼50 Ma (Norris et al., 2012; Tucholke and Vogt, 1979). The recovered middle Eocene sediments hold a record of carbonate-rich, cyclic sequences. Moreover, relatively high sedimentation rates (2–4 cm/kyr) (Norris et al., 2014) characterize these sediments, allowing for a high-resolution reconstruction of oceanographic and climatic change.

2.1. XRF data

X-ray fluorescence measurements in the studied intervals were carried out on the Avaatech XRF Core Scanner at Scripps Institution of Oceanography Geological Collections, U.C. San Diego. Elemental