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Late Pliocene changes in the North Atlantic Current

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ABSTRACT

During the late Pliocene global climate changed drastically as the Northern Hemisphere glaciation (NHG) intensified. It remains poorly understood how the North Atlantic Current (NAC) changed in strength and position during this time interval. Such changes may alter the amount of northward heat transport and therefore have a large impact on climate in the circum-North Atlantic region and the growth of Northern Hemisphere ice sheets. Using the alkenone biomarker we reconstructed orbitally resolved sea surface temperature (SST) and productivity records at Integrated Ocean Drilling Project (IODP) Expedition 306 Site U1313 during the late Pliocene and early Pleistocene, 3.68–2.45 million years ago (Ma). Before 3.1 Ma, SSTs in the mid-latitude North Atlantic were up to 6 °C higher than the present and surface water productivity was low, indicating that an intense NAC transported warm, nutrient-poor surface waters northwards. Starting at 3.1 Ma, surface water characteristics changed drastically as the NHG intensified. During glacial periods at the end of the late Pliocene and beginning of the Pleistocene, SSTs decreased and surface water productivity in the mid-latitude North Atlantic increased, reflecting a weakened influence of the NAC at our site. At the same time the increase in surface productivity suggests that the Arctic Front (AF) reached down into the mid-latitudes. We propose that during the intensification of the NHG the NAC had an almost pure west to east flow direction in glacials and did not penetrate into the higher latitudes. The diminished northward heat transport would have led to a cooling of the higher latitudes, which may have encouraged the growth of large continental ice sheets in the Northern Hemisphere.

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1. Introduction

The Pliocene epoch[1] is the most recent period in geological history when global temperatures were several degrees higher than today (e.g., Dowsett et al., 2009; Haywood et al., 2009). Atmospheric pCO_2 was approximately 100 ppm higher than pre-industrial levels (Pagani et al., 2010) and ice sheets in the Northern Hemisphere were relatively small. The general surface current system was similar to the present one (Dowsett et al., 2009), but sea surface temperatures (SSTs) in the North Atlantic Ocean were up to 10 °C warmer compared to the present as an intense North Atlantic Current (NAC) led to a reduced meridional SST gradient (e.g., Cronin, 1991; Dowsett et al., 1992; Robinson, 2009).

During the late Pliocene these warm conditions terminated as the Northern Hemisphere glaciation (NHG) intensified and the Quaternary-style climate that characterizes the Pleistocene epoch developed. The exact timing of the intensification of NHG is not well constrained and differs between studies and site locations. In benthic foraminiferal $\delta^{18}O$ records, a measure for high latitude temperature and continental ice volume, the increase started around 3.6 Ma, indicating the built-up of continental ice sheets in the Northern Hemisphere (Mudelsee and Raymo, 2005). However, the threshold towards full glacial/interglacial conditions is located near 2.7 Ma during the Marine Isotope Stage (MIS) G6 when the amplitude of the 41-ka component increased (Ruggieri et al., 2009). Around the same time ice-rafted debris (IRD) became widespread in sediments from the higher latitudes (e.g., Kleiven et al., 2002; Maslin et al., 1998; Shackleton et al., 1984). MIS G6 is therefore considered as the first intense glacial period with large Northern Hemisphere ice sheets.

Various hypotheses such as a change in orbital configuration, a decrease in atmospheric pCO_2 via polar ocean stratification, and/or changes in oceanic and atmospheric heat transport, possibly related to the closing of the Central American Seaways (CAS), have been proposed as cause for the intensification of the NHG (Bartoli et al., 2005; Driscoll and Haug, 1998; Haug and Tiedemann, 1998; Haug et al.,

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[1] Please note we use the updated definitions of the early Pliocene (5.332–3.6 Ma), late Pliocene (3.6–2.588 Ma), and early Pleistocene (2.588–0.781 Ma) (Gibbard et al., 2009).

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1999, 2005; Haywood et al., 2000; Lawrence et al., 2009; Maslin et al., 1998; Mudelsee and Raymo, 2005; Ravelo et al., 2004; Sarnthein et al., 2009; Seki et al., 2010). So far, none of these have given a complete satisfactory explanation and the ultimate cause remains an enigma. Nevertheless, recent studies suggest that cooling of the higher latitudes and increase in meridional SST gradient were crucial for the intensification of NHG (Berger and Wefer, 1996; Brierley and Fedorov, 2010; De Schepper et al., 2009; Lunt et al., 2008). This means that the NAC, by which the excess in heat from the tropics was transported northwards during the Pliocene, had to weaken and/or change its path during the intensification of the NHG in order to allow the higher latitudes to cool and the meridional SST gradient to increase. This contradicts other hypotheses in which an increase in northward heat transport, related to closure of the CAS, and associated feedback mechanisms are suggested as the main cause for the intensification of the NHG (e.g., Bartoli et al., 2005; Driscoll and Haug, 1998; Haug and Tiedemann, 1998).

Therefore reconstructing the influence of the NAC on the North Atlantic during the late Pliocene is crucial for a better understanding of the mechanisms behind the intensification of the NHG. At present, only one study discussing variations in northward heat transport is available for the complete late Pliocene (Lawrence et al., 2009). However, that study used samples from Ocean Drilling Project (ODP) Site 982. This site is located at the northern end of the NAC and probably does not reflect major variations in the position and strength of the main branch of the NAC. This is obvious in view of the high-amplitude SST variability, which is most likely related to short-term variability in the most northern position of the NAC (Lawrence et al., 2009). More important, the age model of Site 982 for the late Pliocene might require revision (Khélifi and Sarnthein, 2010). Therefore, this study is based on sediment samples from the more southerly located Integrated Ocean Drilling Project (IODP) Expedition 306 Site U1313. The main objective of this paper is to reconstruct variations in the NAC and the subsequent change in northward heat transport during the late Pliocene, when the NHG intensified.

2. Regional setting

The North Atlantic is characterized by a continuous northward flow of warm and salty surface water that constitutes the upper part of the meridional overturning circulation (Fig. 1). At the origin of the surface current system is the Gulf Stream, which continues as the North Atlantic Current (NAC) and finally the North Atlantic Drift Current in the northeast North Atlantic. We use the term NAC to refer to the whole warm surface current that continues after the Gulf Stream into the northeast North Atlantic. The NAC forms the transition zone between the two different regimes: in the higher latitudes the cold and productive Arctic waters, in the subtropics the warm and oligotrophic waters from the subtropical gyre (Fig. 1). The region of high surface water productivity just north of the NAC is associated with the location of the Artic Front (AF), which is characterized by high eddy activity that promotes surface water productivity.

Various studies showed that surface water characteristics in the (mid-latitude) North Atlantic mainly depend on the strength and position of the NAC, which in turn determines the position of oceanic fronts (e.g., Calvo et al., 2001; Lawrence et al., 2009; Robinson, 2009; Stein et al., 2009; Versteegh et al., 1996; Villanueva et al., 2001). High SSTs indicate an intense NAC transporting warm surface waters northwards across the mid-latitude North Atlantic, whereas cooler SSTs reflect a weakened influence of the NAC.

Alkenone ARs provide a second measure of variability in the NAC. Both coccolith carbonate and alkenone abundance have been used to track the movement of the high productivity zone associated with the AF during the middle and late Pleistocene (e.g., McIntyre et al., 1972; Stein et al., 2009; Villanueva et al., 2001). These studies showed that during glacials the productivity maximum moved southwards as the AF shifted into the mid-latitude North Atlantic, cold polar waters expanded to lower latitudes, and the NAC did not influence the higher latitudes in the northeast Atlantic. A reconstruction of SSTs for the Last Glacial Maximum depicts this almost purely west to east flow

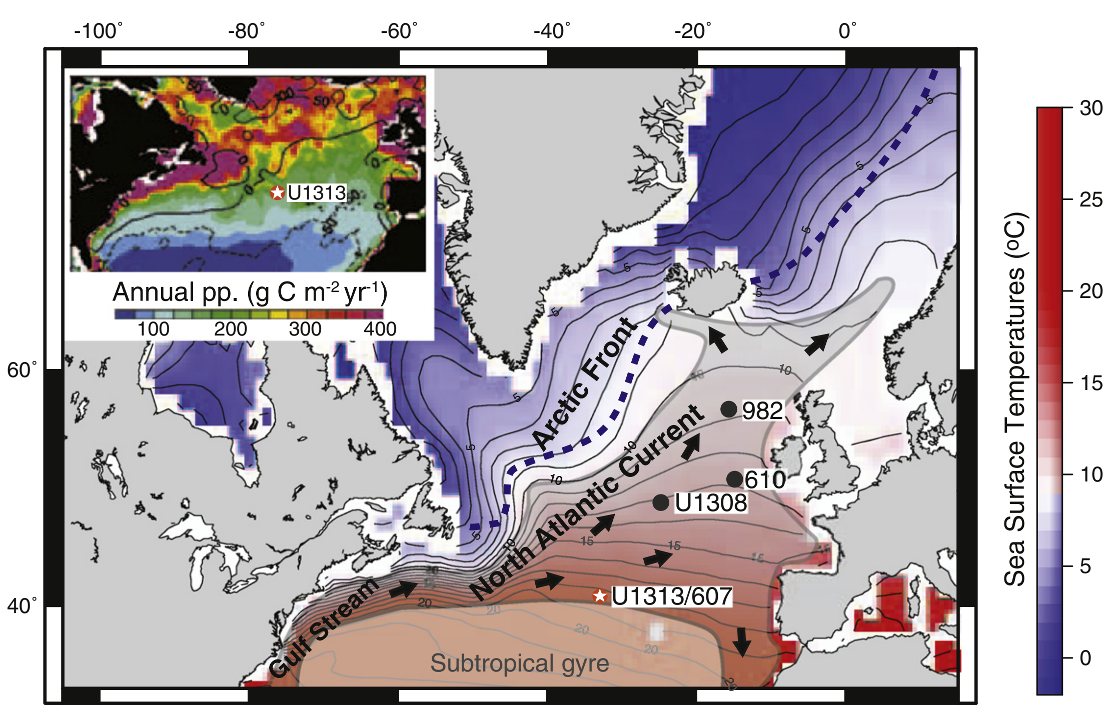

Fig. 1. Map of the North Atlantic Ocean showing modern mean annual SSTs at the surface (Locarnini et al., 2006) together with the position of the Gulf Stream and North Atlantic Current (NAC). Dashed line shows the position of the Arctic Front (AF), which separates warm Atlantic waters in the mid-latitudes from cold subpolar waters in the higher latitudes (Pflaumann et al., 2003; Swift, 1986). Insert shows annual primary productivity (pp.) in the North Atlantic (modified from Williams and Follows, 1998). The NAC forms the transition zone between warm and oligotrophic waters of the subtropical gyre to the south and cold and productive Arctic waters associated with the AF in the north. In this study we used samples from IODP Site U1313, a re-drill of DSDP Site 607, which at present is located under the direct influence of the NAC. Other sites discussed in the text are also shown.

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