Global and Planetary Change 106 (2013) 64–76

Contents lists available at SciVerse ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Low- to high-productivity pattern within Heinrich Stadial 1: Inferences from dinoflagellate cyst records off Senegal

Ilham Bouimetarhan [a,*], Jeroen Groeneveld [a,b], Lydie Dupont [a], Karin Zonneveld [a]

[a] MARUM — Centre for Marine Environmental Sciences and Department of Geosciences, University of Bremen, PO Box 330 440, D-28334, Bremen, Germany
[b] Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

ARTICLE INFO

Article history:
Received 3 January 2013
Accepted 16 March 2013
Available online 26 March 2013

Keywords:
Heinrich Stadial 1
Senegal
Marine productivity
Dinoflagellate cysts
Upwelling
Two-phase pattern
NE trade winds

ABSTRACT

In order to investigate a possible connection between tropical northeast (NE) Atlantic primary productivity, Atlantic meridional overturning circulation (AMOC), and drought in the Sahel region during Heinrich Stadial 1 (HS1), we used dinoflagellate cyst (dinocyst) assemblages, Mg/Ca based reconstructed temperatures, stable carbon isotopes ($\delta^{13}C$) and geochemical parameters of a marine sediment core (GeoB 9508-5) from the continental slope offshore Senegal. Our results show a two-phase productivity pattern within HS1 that progressed from an interval of low marine productivity between ~19 and 16 kyr BP to a phase with an abrupt and large productivity increase from ~16 to 15 kyr BP. The second phase is characterized by distinct heavy planktonic $\delta^{13}C$ values and high concentrations of heterotrophic dinocysts in addition to a significant cooling signal based on the reconstructions of past sea surface temperatures (SSTs). We conclude that productivity variations within HS1 can be attributed to a substantial shift of West African atmospheric processes. Taken together our results indicate a significant intensification of the North East (NE) trade winds over West Africa leading to more intense upwelling during the last millennium of HS1 between ~16 and 15 kyr BP, thus leaving a strong imprint on the dinocyst assemblages and sea surface conditions. Therefore, the two-phase productivity pattern indicates a complex hydrographic setting suggesting that HS1 cannot be regarded as uniform as previously thought.

1. Introduction

The western Sahel has experienced pronounced climatic variability in response to Northern Hemisphere high-latitude climatic fluctuations during the last glacial period (e.g. Street-Perrott and Perrott, 1990; Gasse, 2000; Jullien et al., 2007; Mulitza et al., 2008; Romero et al., 2008; Itambi et al., 2009). Therefore, it is an ideal region to conduct late Quaternary paleoceanographic and paleohydrologic studies and to improve the understanding of the interaction of the low-latitude African monsoon system with high-latitude climate variability. The Sahel response to high latitude climate variability is likely linked through atmospheric processes involving the latitudinal migration of the Intertropical Convergence Zone (ITCZ) associated with changes in the intensity of the northeasterly (NE) trade winds (Dahl et al., 2005; Stouffer et al., 2006; Mulitza et al., 2008; Tjallingii et al., 2008; Itambi et al., 2009; Penaud et al., 2010). Changes in atmospheric circulation are well reflected in sea surface temperatures (SSTs) and productivity through changes in the upwelling dynamics, particularly in the Eastern Boundary Current system that is mainly controlled by the NE trade winds (Pearce, 1991; Hagen, 2001; Nave et al., 2001; Romero et al., 2008; McGregor et al., 2007). A number of studies using marine sediment cores off NW Africa have suggested large-scale changes in marine productivity during glacial periods with abrupt variations related to the last deglaciation (Marret and Turon, 1994; Zhao et al., 2000; Nave et al., 2001; Kulmann et al., 2004; Romero et al., 2008; Holzwarth et al., 2010; Penaud et al., 2010). However, most of these records derive from regions extending from the southern Saharan boundary to the Moroccan margin (between ~21°N and 34°N) where perennial upwelling prevails. Furthermore, except for core GeoB7926-2 off Mauritania (Romero et al., 2008; Filipsson et al., 2011), high resolution records to define hydrographic and productivity variations during the last deglaciation, especially during Heinrich Stadial 1 (HS1), are still lacking. This ~4000 year interval is shown to be a period of vigorous atmospheric circulation and extreme aridity over the western Sahel (Mulitza et al., 2008) that displayed a succession of three major phases indicating a complex atmospheric pattern during HS1 (Bouimetarhan et al., 2012). The last phase covers the extremely dry part of HS1 when NE trade winds were strongest as revealed by the expansion of desert vegetation (Bouimetarhan et al., 2012). In the present study, we investigate the response of surface and deep-water environments to past rapid climate events associated with HS1, using organic-walled dinoflagellate cyst (dinocyst) associations, pollen/spores and Ti/Ca records. This multi-proxy approach is used to infer past changes in surface water productivity and to describe variations in past wind intensity and land aridity/humidity variations. We couple these qualitative data with quantitative information on past hydrography and productivity changes from foraminiferal carbon isotopes and Mg/Ca-based temperature records. Using terrestrial and marine proxies from the same marine

* Corresponding author. Tel.: +49 421 218 65138; fax: +49 421 218 65159.
E-mail address: bouimetarhan@uni-bremen.de (I. Bouimetarhan).

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http://dx.doi.org/10.1016/j.gloplacha.2013.03.007

archive enables the reconstruction of concerted changes in both terrestrial and oceanic conditions. This provides the opportunity to establish direct land–sea correlations and delivers a more detailed and reliable picture of the interaction between different processes. The quantitative and qualitative data both suggest an internally complex pattern of productivity dynamics within HS 1 where it was previously considered to be an interval with overall continuously high productivity.

2. Regional setting and background

2.1. Oceanography

The surface water circulation in the research area is dominated by the Canary Current (CC), which is the easternmost branch of the Azores Current. The CC flows southwestward along the NW African coast. It moves away from the continental margin at ~21°N when it turns westward to join the Atlantic North Equatorial Current (NEC) (Mittelstaedt, 1991). South of 20°N, the cool African Coastal Current flows southward along the West African shoreline in winter and spring. The northward flowing Mauritania Current prevails along the coast during summer and fall (e.g., Stramma and Siedler, 1988), and transports warm surface waters influenced by the North Equatorial Countercurrent and the Guinea Dome (Fig. 1).

The alongshore flow is associated with upwelling when the position of the subtropical high pressure system strengthens the NE trade winds in boreal winter (Nykjaer and Van Camp, 1994). Satellite images of the chlorophyll-*a* concentrations at the sea surface show a general maximum of about 2.5 to 10 mg/m^3 on the shelf (http://reason.gsfc.nasa.gov) with the highest values during boreal winter and a decreasing trend from the coastal sea to open ocean (Fig. 2). Present upwelling source waters off NW Africa consist of the salty and relatively nutrient-poor North Atlantic Central Water (NACW) at latitudes down to ~22–23°N and the less saline and nutrient-rich South Atlantic Central Water (SACW) south of ~20–21°N.

Filaments and eddies entrain cool, upwelled nutrient-rich water at the coast (Johnson and Stevens, 2000) and extend up to several hundred kilometers offshore into the open ocean (Mittelstaedt, 1991) as a result of offshore export of upwelled nutrients (Van Camp et al., 1991). These nutrient-rich waters are characterized by the enhanced biological productivity of, notably, diatoms (Romero et al., 2008), coccolithophores (Nave et al., 2001; Romero et al., 2008), dinocysts (Margalef, 1973), and planktonic foraminifera (Meggers et al., 2002).

2.2. Continental climate and modern atmospheric circulation

Climate conditions on the continental slope off northern Senegal are mainly controlled by the West African monsoon system. The monsoon system controls the amount and distribution of rainfall over West Africa with intense precipitation in summer and dry conditions in winter as a result of the seasonal migration of the Intertropical Convergence Zone (ITCZ) (Hsu and Wallace, 1976) and the tropical rainbelt (some 10° of latitudes south of the ITCZ) (Nicholson and Grist, 2003). The modern atmospheric circulation pattern over NW Africa is dominated by two main wind systems primarily controlled by the ITCZ seasonal shift. During the boreal summer, the ITCZ reaches its northernmost position. The tropical rainbelt delivers precipitation into the Sahel that generates monsoonal rainfall over NW Africa and increased river discharge into the Atlantic Ocean (Nicholson and Grist, 2003; Nicholson, 2009). At

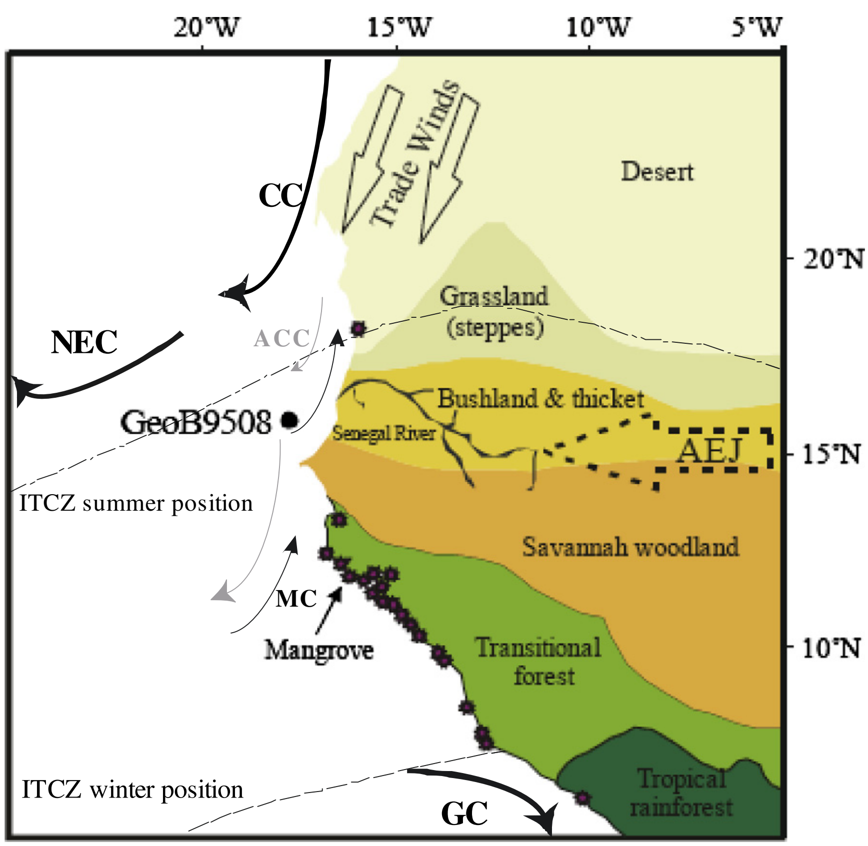

Fig. 1. Map of the study area showing the location of marine core GeoB 9508-5 (black dot) with major surface oceanic currents: CC: Canary Current, NEC: North Equatorial Current, GC: Guinea Current (after Sarnthein et al., 1982; Mittelstaedt, 1991), ACC: African Coastal Current (gray arrows) (winter and spring), MC: Mauritania Current (summer and fall) (after Stramma and Schott, 1999). Simplified phytogeography and biomes are also denoted after White (1983). Main wind belts: AEJ, African Easterly Jet, and NE trade winds. The dashed lines indicate the boundaries of the yearly migration of the Intertropical Convergence Zone (ITCZ) from present day boreal summer position (dash-dotted line) to boreal winter position (dashed line) after Leroux (2001).