GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L20707, doi:10.1029/2009GL039687, 2009

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Extratropical forcing of Sahel aridity during Heinrich stadials

E. M. Niedermeyer,[1] Matthias Prange,[1,2] Stefan Mulitza,[1] Gesine Mollenhauer,[1,2,3] Enno Schefuß,[1] and Michael Schulz[1,2]

Received 19 June 2009; revised 5 September 2009; accepted 23 September 2009; published 28 October 2009.

[1] In order to investigate a possible link between tropical Northeast (NE) Atlantic sea-surface temperature (SST), Atlantic meridional overturning circulation (AMOC), and drought in the Sahel during the past 44 thousand years (kyr) we used alkenone paleothermometry and $\delta^{13}C$ of *C. wuellerstorfi* of a marine sediment core from the continental slope off Senegal. Our data show periods of low SST and reduced AMOC that coincided with drought in the Sahel during North Atlantic Heinrich stadials (HS). The coldest period was HS1 (ca. 15–18 kyr before present, BP) when SST decreased by more than 2°C. Moreover, the SST off Senegal lagged variations in Sahel aridity, which is in agreement with results from a freshwater hosing experiment. We conclude that variations in tropical NE Atlantic SST were not the initial trigger of millennial-scale Sahel droughts of the past 44 kyr. Instead, it is thought that these droughts were induced by substantial coolings of the extratropical North Atlantic. **Citation:** Niedermeyer, E. M., M. Prange, S. Mulitza, G. Mollenhauer, E. Schefuß, and M. Schulz (2009), Extratropical forcing of Sahel aridity during Heinrich stadials, *Geophys. Res. Lett.*, *36*, L20707, doi:10.1029/2009GL039687.

1. Introduction

[2] It is generally accepted that the distribution pattern of SSTs of the Atlantic and the Indian Oceans is critical for interannual and interdecadal Sahel rainfall variability [e.g., *Folland et al.*, 1986; *Fontaine and Bigot*, 1993; *Giannini et al.*, 2003; *Lu and Delworth*, 2005]. Using an atmosphere general circulation model, *Sutton and Hodson* [2005] investigated the role of the Atlantic SST pattern in forcing Northern Hemisphere summer climate. In particular, their model predicted that an anomalously warm tropical North Atlantic (0°N to 30°N, excluding the Gulf of Guinea; their Figure S1B) leads to a substantial increase in rainfall over the West African Sahel [*Sutton and Hodson*, 2005, Figure 3B], whereas SST anomalies in the extratropical North Atlantic (>30°N) were inferred to have no significant effect on Sahel climate. Particularly cold tropical SSTs along the West African coast between Mauritania and Guinea (i.e., ~20°N to 10°N) associated with Sahel droughts were identified by *Hastenrath* [1984] and *Druyan* [1991]. On longer timescales, *Mulitza et al.* [2008] argued that millennial-scale Sahel "mega-droughts" during the past 50 kyr were primarily triggered by strong coolings of the extratropical North Atlantic during HS which, in turn, were induced by perturbations of the AMOC and its associated northward heat transport.

[3] In this study, we examine a possible link between tropical NE Atlantic SST and AMOC and further investigate the potential role of tropical NE Atlantic SST in triggering drought in the Sahel through the past 44 kyr. For this purpose, we analyzed a gravity core from the continental slope off Senegal. This site allows reconstructing SST through alkenone paleothermometry, deep ocean ventilation through benthic carbon isotopes, and direct comparison to a continental aridity record from the same core as depicted by changes in XRF elemental ratios [*Mulitza et al.*, 2008]. Our data show that tropical NE Atlantic SST lags Sahel aridity and therefore likely is not the initial trigger for the onset of millennial-scale Sahel drought.

2. Material and Environmental Setting

[4] Marine sediment core GeoB9508-5 was retrieved from the continental slope off Senegal during RV Meteor cruise M65/1 about 160 km southwest (15°29.90′N 17°56.88′W) of the Senegal River mouth at a water depth of 2,384 m (Figure 1).

[5] Surface waters at the site are indirectly influenced by the southward flowing Canary Current. At about 21°N, the Canary Current detaches from the continental margin and turns westward into the North Equatorial Current. South of 20°N, the cool southward African Coastal Current flows along the West African shoreline in winter and spring. During summer and fall, a northward flow, the Mauritania Current, exists along the coast [e.g., *Stramma and Schott*, 1999], transporting warm surface waters influenced by the North Equatorial Countercurrent and the Guinea Dome.

[6] The area of our study site experiences weak upwelling in winter and spring and no upwelling throughout the rest of the year [*Mittelstaedt*, 1991]. Seasonally averaged SSTs range from 19°C during winter to 28°C during summer (National Virtual Ocean Data System, http://ferret.pmel.noaa.gov/NVODS). Alkenone derived SST estimates off NW Africa represent the yearly average of the mixed layer temperature [*Müller and Fischer*, 2001].

[7] At present, the core site is bathed by North Atlantic Deep Water (NADW) [*Sarnthein et al.*, 1994]. During glacial times the core site was most likely located close to the boundary between the glacial North Atlantic Deepwater and Antarctic Bottom Water [*Sarnthein et al.*, 1994, *Lynch-Stieglitz et al.*, 2007], which makes the core a sensitive recorder of vertical changes in the distribution of both water masses.

3. Methods

[8] Alkenones were extracted as described by *Müller and Fischer* [2001] on 73 samples from the upper 692 cm of the

[1]Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany.
[2]Department of Geosciences, University of Bremen, Bremen, Germany.
[3]Alfred Wegener Institute, Bremerhaven, Germany.

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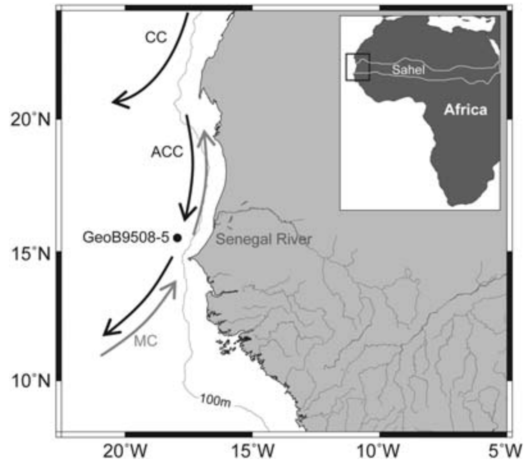

Figure 1. Position of marine gravity core GeoB9508-5 in the tropical NE Atlantic off Senegal. Black curved arrows indicate surface currents during winter and spring, and gray curved arrows indicate surface currents in summer and fall: CC, Canary Current (winter and spring); ACC, African coastal current (winter and spring); and MC, Mauritania current (summer and fall). A detailed map of tropical Atlantic currents systems is given by *Stramma and Schott* [1999].

core. $U^{K'}_{37}$ was calculated as described by *Prahl and Wakeham* [1987] and SST was estimated according to *Prahl et al.* [1988]. The analytical precision was determined by co-extracting and analyzing a reference sediment every 11 samples, revealing a standard deviation (1σ) of 0.7°C.

[9] Changes in the stable carbon isotopic composition ($\delta^{13}C$) of bottom water total dissolved inorganic carbon (ΣCO_2) were traced by measuring $\delta^{13}C$ of the benthic foraminifer *Cibicidoides wuellerstorfi*. Sample preparation and analytical procedures for isotopic and XRF data are described by *Mulitza et al.* [2008].

[10] The age model of the core is based on 12 AMS radiocarbon dates on planktic foraminifera and a correlation of the benthic $\delta^{18}O$ record with core MD95-2042 [*Shackleton et al.*, 2004; *Mulitza et al.*, 2008]. The resulting average sampling interval is ~600 years.

[11] A freshwater-hosing experiment with the NCAR (National Center for Atmospheric Research) coupled climate model CCSM2/T31x3a [*Prange*, 2008] was performed as described by *Mulitza et al.* [2008] to obtain further insight into physical mechanisms that lead to tropical and extratropical NE Atlantic SST changes and Sahel aridity in response to a slowdown of the AMOC. In this experiment, a present-day control run was perturbed by a freshwater flux of 0.1 Sv into the northern North Atlantic. The continuously perturbed model was integrated for ~400 years.

4. Results

[12] Alkenone-based SST estimates at the study site (Figure 2b) generally decrease during North Atlantic Heinrich stadials (HS) 1–4. The most prominent coolings occur during HS1 (>2°C) and HS4 (1.5°C). Despite the different minimum SST during HS, the decrease (except for HS2) generally takes place with a cooling rate between 0.1 and 0.2°C per 100 years.

[13] The $\delta^{13}C$ of *C. wuellerstorfi* (Figure 2c) shows more depleted values during HS1 and 4. These excursions toward lower values parallel the decreases in SST. Moreover, during HS1 both records show a gradual decline followed by an abrupt increase. From the beginning of the Holocene to 5.5 kyr BP, the $\delta^{13}C$ increases from 0.6‰ up to 0.9‰ is followed by a decrease to 0.7‰, closely matching the temporal evolution of the SST record.

[14] The Fe/K ratios (Figure 2a) show a similar pattern as the SST estimates. Minimum Fe/K ratios coincide with lower SST during HS1-4 (Figure 2b). A closer inspection of the records, however, reveals that the transitions of the Fe/K ratios to lower values during the onset of HS (indicated by the gray bars in Figure 2) are completed (HS1 and 4) or have already started (HS3), when SST still shows relatively high values. For HS2, however, it is not possible to properly define the onset of the SST decrease given the very small total variation. For the other HS, the decrease of SST lags the abrupt transitions seen in the Fe/K record by ~400 years during HS1 and 3, and even by 1,000 years during HS4. We note that these estimates are limited by the sampling frequency and that the real time lag might be smaller.

5. Discussion

[15] Our data show coolings of tropical NE Atlantic SST during HS1-4 that coincide with decreased Fe/K ratios. As *Mulitza et al.* [2008] demonstrated, variations of Fe/K within sediment core GeoB9508-5 can be used to trace climatic conditions over the western Sahel. Lower Fe/K ratios correspond to decreased riverine input and enhanced dust supply, suggesting drier conditions during these intervals.

[16] The variation in $\delta^{13}C$ recorded by *C. wuellerstorfi* can be used to monitor bottom water $\delta^{13}C$ ΣCO_2 and water

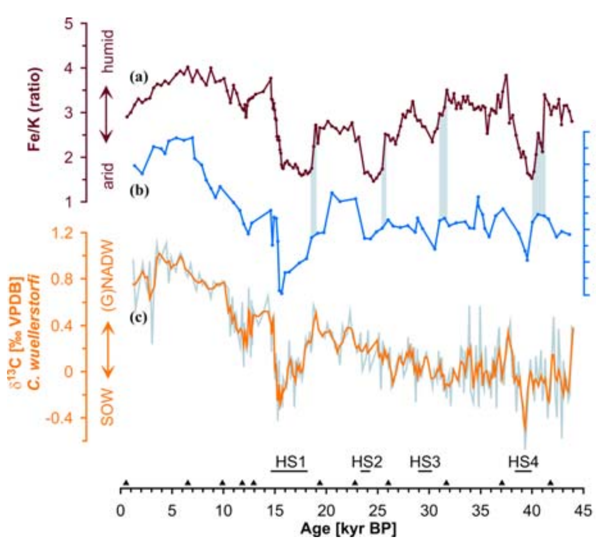

Figure 2. Records of GeoB9508-5: (c) $\delta^{13}C$ of *C. wuellerstorfi* and (b) SST plotted together with (a) Fe/K ratios from *Mulitza et al.* [2008]. Gray bars indicate intervals of abrupt transitions toward lower values seen in the Fe/K record. Ages of North Atlantic HS after *Sarnthein et al.* [2001]. Triangles indicate AMS radiocarbon datings. (G)NADW, (glacial) North Atlantic Deepwater; and SOW, deep Southern Ocean Water.

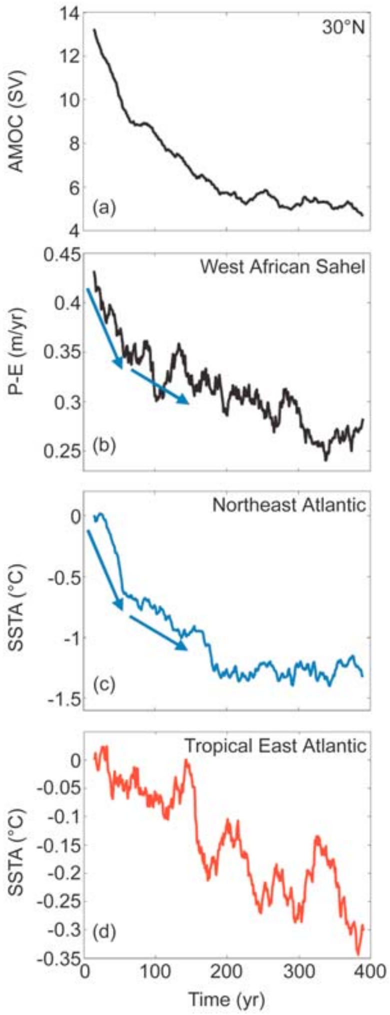

Figure 3. Simulated climate response to a North Atlantic freshwater perturbation (all time series are smoothed by a 30-yr boxcar average and start from the equilibrium climate of the control run). (a) Temporal evolution of the AMOC at 30°N given as the streamfunction maximum below 800 m, (b) summer (July–September) precipitation minus evapotranspiration (i.e., runoff) averaged over the West African Sahel (15°W–10°E, 10–20°N), (c) mid-latitude NE Atlantic SST anomaly (SSTA, average over 30–50°N, east of 40°W) relative to the control run climatology, and (d) tropical NE Atlantic SSTA (average over 10–20°N, east of 25°W, i.e., around core location). Arrows are drawn as a visual guide and highlight synchronous rapid drops in Sahel runoff and mid-latitude NE Atlantic SST directly after the beginning of the freshwater injection.

mass structure, based on the link between biological productivity at the surface and deep-water δ^{13}C ΣCO_2 that leads to relatively low δ^{13}C ΣCO_2 of the 'old' southern component water as compared to the better ventilated northern component water [*Duplessy et al.*, 1988; *Sarnthein et al.*, 1994]. The δ^{13}C signature of deep Southern Ocean Water has been found extending to 60°N at water depths as shallow as 2000 m during the last glaciation [*Sarnthein et al.*, 1994; *Elliot et al.*, 2002; *Lynch-Stieglitz et al.*, 2007]. We interpret the decrease in δ^{13}C during HS4 and HS1 to represent a retreat of glacial North Atlantic Deepwater in favour of an expansion of deep Southern Ocean Water to the core location, associated with a reduction in the AMOC [e.g., *Sarnthein et al.*, 1994; *McManus et al.*, 2004].

[17] Climatic variations over the western Sahel are marked by abrupt transitions with the decrease of SST lagging the onset of drought during HS1, HS3 and HS4 by some centuries. The tight coupling of δ^{13}C and SST variation argues for a link between glacial North Atlantic Deepwater formation and tropical NE Atlantic SST. These findings are consistent with our model results. A slowdown of the AMOC (Figure 3a) reduces the northward transport of warm tropical surface waters within the western branches of the subtropical North Atlantic Gyre, leading to a temperature drop by ~0.7°C in the mid-latitude North Atlantic within ~60 years (Figure 3c). After 200 years, mid-latitude SST is virtually equilibrated. By contrast, SST in the tropical NE Atlantic (Figure 3d) decreases at a slower rate and lags the extratropical temperature evolution possibly even beyond the 400 years of the model run. The modelled temperature decrease in the tropical NE Atlantic is partly attributable to a cooling and strengthening of the Canary Current which delivers extratropical waters towards the tropical region. Such a cooling and strengthening of the Canary Current in response to AMOC weakening has already been described in previous model studies [*Schiller et al.*, 1997; *Prange et al.*, 2004]. Further, an anomalous supply of relatively warm waters from the South (not shown) counteracts the cooling of the tropical NE Atlantic, leading to delayed SST decrease. The time series of Sahel runoff (precipitation minus evapotranspiration; Figure 3b) follows the abrupt SST drop in the mid-latitude NE Atlantic (Figure 3c) during the first ~150 years of the experiment (arrows in Figure 3) when SST anomalies in the tropical NE Atlantic are still negligible (Figure 3d). After 400 years, runoff in the western Sahel is almost 50% lower than at the beginning of the experiment. About 75% of this drying takes place within the first ~150 years and is associated with the rapid SST drop in the extratropical NE Atlantic.

[18] The modelled cooling rate of the tropical NE Atlantic is about 0.1°C per 100 years and is consistent with the alkenone-derived cooling rates for HS1, HS3, and HS4. The strong cooling associated with HS1 (>2°C), however, is exceptional among the HS and cannot be simulated by the model. As *Bard et al.* [2000] point out, HS1 is marked by two subsequent events of ice rafting. Indeed, the existence of two distinct events during HS1 is indicated in the δ^{13}C record (Figure 2c). The seemingly gradual decrease of SST during HS1 might represent two subsequent cooling events that are not resolved by the sampling frequency of the record. We further surmise that enhanced coastal upwelling (a process not properly resolved in the coarse-resolution ocean component of the climate model) influenced the core site during HS1, when due to a low sea-level (ca. 120–110 m lower than today [*Lambeck and Chappell*, 2001]) the core location was closer to the shoreline and anomalous southward winds along the West African coast (simulated in our freshwater hosing experiment; not shown) resulted in stronger Ekman pumping. Lowering of surface solar radiation by Saharan dust (not included in the climate model) might have further contributed to the observed sea-surface cooling [*Lau and Kim*, 2007; *Evan et al.*, 2009].

[19] However, one might argue that for HS1 tropical SST does not lag but precede Sahel aridity if the decrease in SST between 20.5 and 19.7 kyr BP is taken into account. This would imply that the onset of Sahel aridity during HS1 would lag the decrease of SST (which is as large as 1°C) by 1.5 kyr, which we do not consider physically reasonable and therefore unlikely to have occurred.

[20] Taken together, our study indicates that the tropical North Atlantic SST is not the initial trigger for abrupt Sahel climate change during HS, corroborating the conclusion of *Mulitza et al.* [2008] that millennial-scale Sahel aridity was induced by an abrupt drop in extratropical NE Atlantic SST. This cooling created a positive sea-level pressure anomaly over northern North Africa and hence led to a southward shift of the monsoon trough. The Sahel drying was further amplified by an intensification of the African Easterly Jet.

[21] In contrast to this study, *Sutton and Hodson* [2005] did not find a significant influence of extratropical North Atlantic SST on Sahel rainfall in their model. We suspect that this discrepancy is due to the different SST forcing amplitudes, i.e., northern North Atlantic SST anomalies during HS were much larger than the anomalies considered by *Sutton and Hodson* [2005]. This suggests that extratropical North Atlantic SST anomalies have to exceed a certain threshold value in order to exert a significant influence on West African climate.

6. Conclusions

[22] Our data show that millennial-scale sea-surface cooling off Senegal largely concurs with decreased bottom water $\delta^{13}C$ ΣCO_2 that coincide with drying events in the western Sahel during HS1-4. We suggest that the SST decrease results from a reduced northward heat transport within the subtropical North Atlantic Gyre due to a reduced AMOC. Our data indicate that tropical NE Atlantic surface cooling lags the onset of Sahel aridity during HS. A freshwater hosing experiment supports the conclusion that the tropical NE Atlantic SST off Senegal is not the initial trigger of millennial-scale Sahel aridity. Glacial Sahel droughts were most likely induced by extratropical coolings in the North Atlantic.

[23] **Acknowledgments.** This work was funded by the DFG through the Research Center/Excellence Cluster "The Ocean in the Earth System" at MARUM, through GLOMAR (EMN), and through project SCHE903/8 (ES). The climate model experiments were performed on the IBM pSeries 690 Supercomputer of the HLRN. We are grateful for the comments of two anonymous reviewers that greatly improved this study. We thank James Collins for linguistic support.

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G. Mollenhauer, S. Mulitza, E. M. Niedermeyer, M. Prange, E. Schefuß, and M. Schulz, Center for Marine Environmental Sciences, University of Bremen, PO Box 330 440, D-28334 Bremen, Germany. (eniedermeyer@marum.de)