GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 6, 1280, doi:10.1029/2002GL016570, 2003

Arctic/North Atlantic Oscillation signature in Holocene sea surface temperature trends as obtained from alkenone data

N. Rimbu, G. Lohmann, J.-H. Kim, H. W. Arz, and R. Schneider

Department of Geosciences, Bremen University, Bremen, Germany

Received 6 November 2002; revised 23 December 2002; accepted 10 January 2003; published 19 March 2003.

[1] The variability in alkenone-derived sea surface temperatures (SSTs) in the North Atlantic realm shows that a continuous SST decrease in the northeast Atlantic from the early to the late Holocene was accompanied by a persistent warming over the western subtropical Atlantic, the eastern Mediterranean Sea and the northern Red Sea. Based on the analysis of the instrumental data and of atmospheric general circulation model experiments, we show that this variation in SSTs during the Holocene can be attributed to a continuous weakening of a Northern Hemisphere atmospheric circulation pattern similar to that of the Arctic/North Atlantic Oscillation. *INDEX TERMS:* 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3319 Meteorology and Atmospheric Dynamics: General circulation; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3399 Meteorology and Atmospheric Dynamics: General or miscellaneous. **Citation:** Rimbu, N., G. Lohmann, J.-H. Kim, H. W. Arz, and R. Schneider, Arctic/North Atlantic Oscillation signature in Holocene sea surface temperature trends as obtained from alkenone data, *Geophys. Res. Lett.*, *30*(6), 1280, doi:10.1029/2002GL016570, 2003.

1. Introduction

[2] Global surface air temperature increases in the past 25 years with about 0.5°C, and in the past century with about 0.75°C [*Hansen et al.*, 2001]. On the longer perspective, the 20th century warming is likely to be the largest during any century over the past 1000 years for the Northern Hemisphere, with the 1990s the warmest decade and 1998 the warmest year of the millennium [*Mann et al.*, 1998]. A recent study [*Thompson et al.*, 2000] reveals a remarkable similarity between recent climate trends and the structure of the Arctic Oscillation (AO) pattern, defined as the first empirical orthogonal function (EOF) of 20th-century sea level pressure (SLP) [*Thompson et al.*, 2000]. The index of this Northern Hemisphere annular mode has exhibited a trend toward the high index polarity over the past few decades, corresponding to a decrease in SLP over the pole and increase in the subtropics. The AO pattern contains the North Atlantic Oscillation (NAO), which may be considered a different view of the same phenomenon [*Thompson et al.*, 2000].

[3] One can ask whether these modes may have played a significant role for the Holocene (the last 10 thousand years before present, 10 kyr BP) climate variability. *Keigwin and Pickart* [1999] find the AO/NAO signature in the North Atlantic centennial SST variability and suggest a possible role of AO/NAO in generating millennial time scale variability.

[4] Here, we provide a set of North Atlantic, Mediterranean Sea and northern Red Sea sea SST records based on the alkenone method from the beginning of the Holocene to modern conditions. The information in this data set is combined with data analysis of the instrumental period and atmospheric general circulation model simulations. In particular, we want to address the question of opposite trends of warming and cooling between certain sites in the North Atlantic realm during the Holocene. With the combination of the above mentioned methods, we are able to construct a consistent physical picture of the underlying mechanisms for the long-term opposite SST trends during the Holocene and the role of AO/NAO.

2. Holocene Trends and Related Patterns

[5] The SST records examined in this paper come from twelve sediment cores raised from the North Atlantic, the Mediterranean Sea and the northern Red Sea (Figure 1). The paleotemperature estimates of all sediment cores were based on the alkenone methods [e.g., *Brassell et al.*, 1986]. The 12 alkenone SST records were published by *Cacho et al.* [1999, 2001], *Rühlemann et al.* [1999], *Bard et al.* [2000], *Emeis et al.* [2000], *Herbert and Schuffert* [2000], *Marchal et al.* [2002], and *Calvo et al.* [2002]. For the northern Red Sea (GeoB 5844-2), a new paleotemperature record is included which is part of a multiproxy study (H. W. Arz et al., Mediterranean moisture source for early to mid-Holocene humid period in the northern Red Sea, *Science*, 2003, in press).

[6] The alkenone SST records considered show trends in opposite directions (Figure 1). Negative trends are recorded in the northeast Atlantic and the western Mediterranean Sea, and positive trends characterize the SST records from the eastern Mediterranean Sea and the northern Red Sea.

[7] In order to better asses and confirm the opposite trends of SST anomalies in the regions mentioned above, we perform an EOF analysis to the Holocene SST records. This method requires that the SST values from different records are available for identical time intervals. Here, mean SST values in the 100 yr time intervals are derived using linear interpolation. The SST anomalies against the SST mean over the considered period are calculated for each record and normalized with the corresponding temporal standard deviation. In order to remove the high frequency noise variability, the normalized time series are smoothed with a 2 kyr running mean filter.

0094-8276/03/2002GL016570$05.00

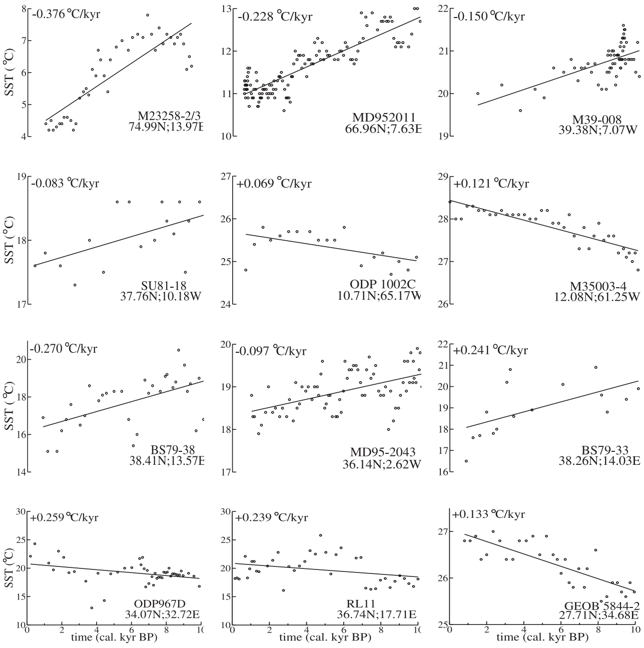

Figure 1. The time series of Holocene SST reconstructions (dot). The value of linear trend (solid) is indicated in the upper left corner while the name of the core as well as the coordinates are indicated in lower right corner of each panel. All SST reconstructions are based on the alkenone method.

[8] The leading EOF of Holocene SST variability (Figure 2a), which describes 69% of the field variance, indicates a spatial pattern similar to that of linear trend coefficients (Figure 1). The associated principal component (PC1) emphasizes a strong linear trend (Figure 2b) during the Holocene.

3. Analogy to the Instrumental Period

[9] In order to find the atmospheric circulation related to the Holocene SST trend pattern, we look for an analogous situation during the instrumental period. Based on the spatial pattern of Holocene SST trends (Figure 2), we define an SST index by subtracting the averaged SST anomalies over the region dominated by positive Holocene SST linear trend [(5°N–20°N;70°W–60°W) and (20°N–40°N;20°E–40°E)] from the averaged SST anomalies over the region dominated by negative Holocene SST linear trend [(30°N–75°N;10°W–20°E)]. The corresponding regression map of annual mean SST [*Rayner et al.*, 1996] and 850 hPa wind [*Kalnay et al.*, 1996] for the period 1950–1997 are shown in Figure 3a. A very similar pattern is obtained for the winter data (not shown). The pattern is similar to that associated with AO/NAO [*Hurrell*, 1995]. This is consistent with high correlation between the SST variations from these regions and the AO/NAO index [*Cullen et al.*, 2002].

[10] In order to further evaluate the hemispheric picture, we extended the SST index defined above for the period 1899–1997, using the Kaplan SST data [*Kaplan et al.*, 1998]. The corresponding regression map of Northern Hemisphere SLP [*Trenberth and Paolino*, 1980] indicates an annular Northern Hemisphere pattern with highest SLP anomalies in the North Atlantic realm (Figure 3b). The regional wind and SST patterns (Figure 3a) fit well with this large scale atmospheric circulation pattern.

4. Model Simulations

[11] In order to understand the physical mechanisms behind the SST trend pattern from the North Atlantic realm during the Holocene, we analyze the differences between atmospheric circulation in the Northern Hemisphere for modern conditions and the Climate Optimum (6 kyr BP). We use the data from the atmospheric general circulation model ECHAM3 simulations for the present day and 6 kyr BP. These simulations are described in detail by *Lorenz et al.* [1996] and *Lohmann and Lorenz* [2000]. Prescribed sea surface temperature, orography, ice sheet distribution, insolation, and CO_2 concentration were applied for the modern and 6 kyr BP simulations.

[12] The solar radiation at the time of the Climatic Optimum was enhanced over the Northern Hemisphere during May to September causing a temperature increase over land up to 3 °C and increase in Indian summer monsoon [e.g., *Lorenz et al.*, 1996]. During December to April, the precession cycle accounts for a reduced tropical insolation of about 20 Wm^{-2}.

[13] In these climate simulations, the tropical cooling during winter induces a weaker Aleutian Low and a north-

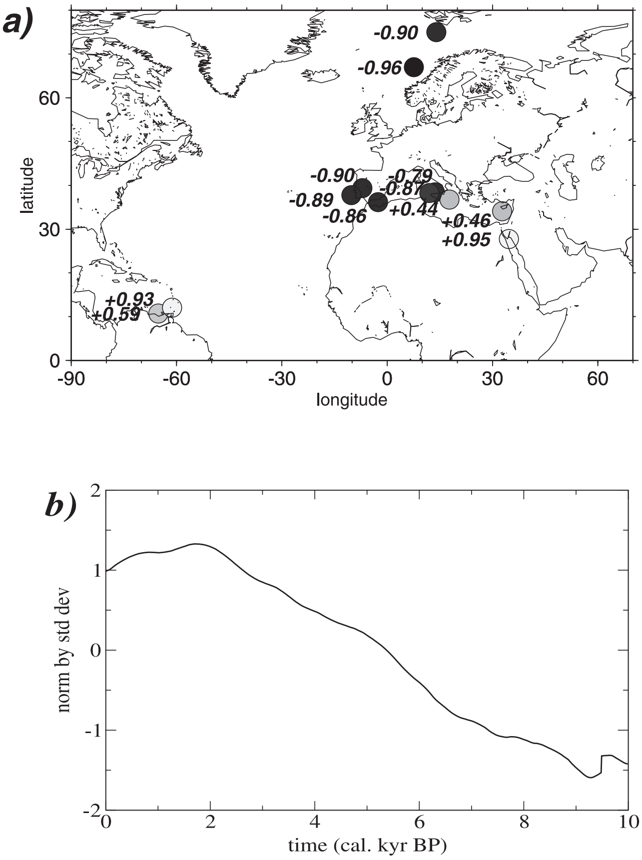

Figure 2. The leading mode of SST variations (a) and its corresponding expansion coefficient time series (PC1) (b). The values on the EOF map represent the correlation coefficient between PC1 and smoothed and normalized SST field.

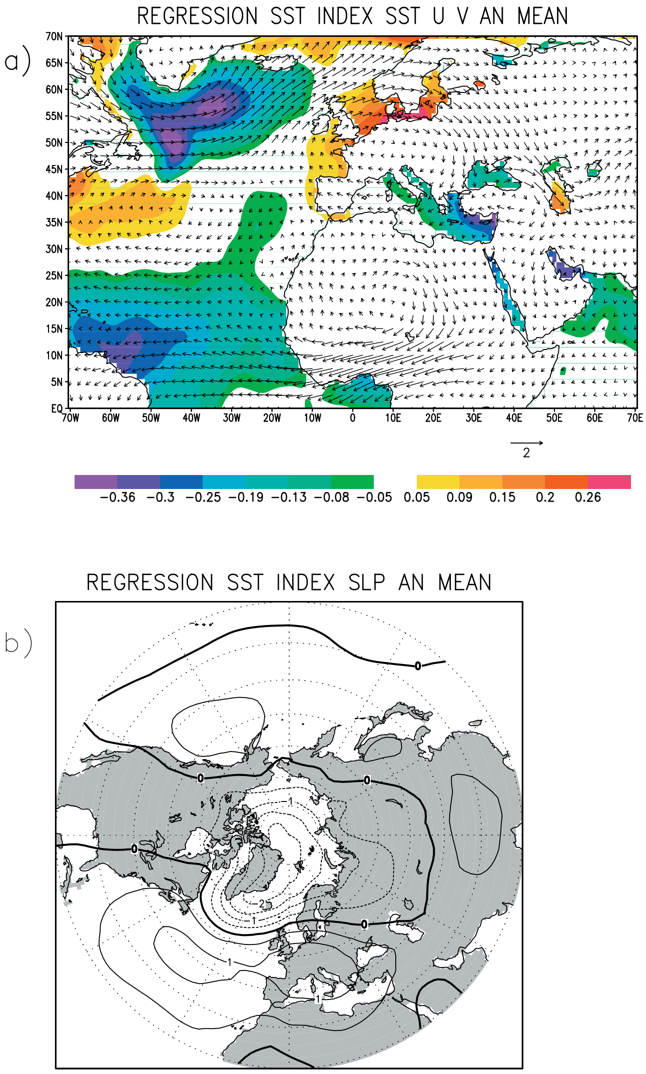

Figure 3. The regression maps of the SST index and (a) SST (shaded) and 850 hPa wind (vector) and (b) sea level pressure. The SST index is defined according to the Holocene SST trend pattern (see text for details). Units are °C, m s^{-1} and hPa.

ward shift of the Northern Hemisphere jet. During the Climatic Optimum, the Pacific North American pattern [*Thompson et al.*, 2000] is shifted toward its negative phase which goes along with an increased Azoric High and enhanced trade winds. These surface conditions are represented by an anomalous annual Northern Hemisphere SLP pattern similar to AO/NAO (Figure 4). The corresponding 2 meter temperature and 850 hPa wind anomaly patterns from the North Atlantic realm (not shown) are very similar to those represented in Figure 3a.

5. Discussion and Conclusions

[14] Analysis of observational [*Hurrell*, 1995], historical and proxy data [*Appenzeller et al.*, 1998; *Mann et al.*, 1998; *Rimbu et al.*, 2001; *Luterbacher et al.*, 2002] shows that AO/NAO signal is detectable at time scale from interannual to multi-centennial. Our study suggests a possible role of AO/NAO in generating millennial-scale SST trends. The positive AO/NAO phase is accompanied by a relatively mild winter over northern Europe and a relatively cold climate in the eastern Mediterranean and Middle East regions. A reverse situation occurs in the negative phase of AO/NAO [*Hurrell*, 1995]. The negative SST trends in the northeast Atlantic and western Mediterranean and the positive SST trends in the eastern Mediterranean, northern Red Sea and western subtropical Atlantic, as detected in the Holocene SST records analyzed here suggest a continuous weakening of AO/NAO pattern from the early to late Holocene.

[15] Detailed comparison studies of different SST reconstructions during the Holocene [*Bard*, 2001] show that proxies can suffer from bias due to alternation and perturbation by environmental variables other than temperature. Such problems are inherent to the nature of marine sediments and to the fact that all SST proxies are linked to complex biological processes. Our analysis suggests that the trends in the alkenone derived SST records are related to winter circulation changes during the Holocene. The winter temperature signal has a long-term memory through the oceans. Therefore, the trend from the positive toward the negative phase of the AO/NAO phenomenon during the Holocene is monitored by the alkenone data analyzed here. Some other SST reconstructions which are not based on the alkenone method [e.g. *Marchal et al.*, 2002] indicate trends consistent with the SST trend pattern obtained from the alkenone derived SST records (Figure 2).

[16] Based on atmospheric general circulation model simulations which are solely forced by insolation and CO$_2$, we show that the weakening in the AO/NAO pattern from the early to late Holocene may be attributed to tropical warming during winter due to increasing in solar insolation associated to the Earth's precession cycle. Such a relation seems to be

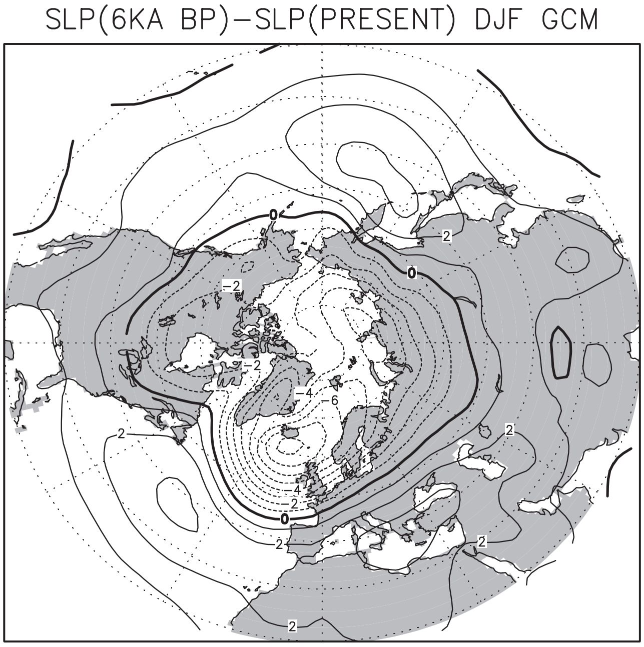

Figure 4. The difference between simulated Northern Hemisphere sea level pressure for the Climate Optimum (6 kyr BP) and present day conditions. Units are hPa.

confirmed by some recent observational studies [e.g., *Dima et al.*, 2002] which show a tendency of AO/NAO to be in its positive phase during La Niña conditions in tropical Pacific.

[17] Although the AO/NAO plays an important role, it appears that other processes should also be investigated to understand entire Holocene SST variability and its relation with solar forcing. A recent study [*Bond et al.*, 2001] shows that on multi-centennial to millennial time scales, regional coolings are discordant with the AO/NAO pattern. Instead, the temperature anomaly patterns resemble to those which accompany the variability in North Atlantic Deep Water formation with a possible link to solar forcing [*Bond et al.*, 2001]. Insights into the temporal evolution of Holocene AO/NAO climate variability are not only important for interpreting geological data, but also to bring the climate of the last centuries where instrumental and historical data are available into a longer context.

[18] **Acknowledgments.** We would like to thank I. Cacho, J. Grimalt, and K.-C. Emeis for providing their alkenone data as GHOST contributors (http://www.wdc-mare.org/Projects/GHOST). We thank the reviewers for their constructive comments. This study was funded by grants from the German Ministry of Research and Education (BMBF) through the program DEKLIM.

References

Appenzeller, C., J. Schwander, S. Sommer, and T. F. Stocker, The North Atlantic Oscillation and its imprint on precipitation and ice accumulation in Greenland, *Geophys. Res. Lett.*, *25*, 1939–1942, 1998.

Bard, E., Comparison of alkenone estimates with other paleotemperature proxies, *Geochem. Geophys. Geosyst.*, *2*, Paper number 2000GC000050, 2001.

Bard, E., F. Rostek, J.-L. Turon, and S. Gendreau, Hydrological impact of Heinrich Events in the subtropical northeast Atlantic, *Science*, *289*, 1321–1324, 2000.

Bond, G., et al., Persistent solar influence on North Atlantic climate during the Holocene, *Science*, *294*, 2130–2136, 2001.

Brassell, S. C., G. Eglinton, I. T. Marlowe, U. Pflaumann, and M. Sarnthein, Molecular stratigraphy: A new tool for climatic assessment, *Nature*, *320*, 129–133, 1986.

Cacho, I., et al., Dansgaard-Oeschger and Heinrich event imprints in Alboran Sea paleotemperatures, *Paleoceanography*, *14*, 698–705, 1999.

Cacho, I., et al., Variability of the Western Mediterranean sea surface temperatures during the last 25,000 years and its connection with the Northern Hemisphere climatic changes, *Paleoceanography*, *16*, 40–52, 2001.

Calvo, E., J. Grimalt, and E. Jansen, High resolution U_{37}^{K}sea surface temperature reconstruction in the Norwegian Sea during the Holocene, *Quat. Sci. Rev.*, *21*, 1385–1394, 2002.

Cullen, H. M., A. Kaplan, P. A. Arkin, and P. B. deMenocal, Impact of the North Atlantic Oscillation on Middle Eastern climate and streamflow, *Clim. Change*, *55*, 315–338, 2002.

Dima, M., N. Rimbu, and I. Dima, Arctic Oscillation variability generated through inter-ocean interactions, *Geophys. Res. Lett.*, *29*(14), 1677, doi:10.1029/2002GL014717, 2002.

Emeis, K. C., et al., Temperature and salinity variations of Mediterranean Sea surface waters over the last 16,000 years from records of planktonic stable oxygen isotopes and alkenone unsaturation ratios, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *158*, 259–280, 2000.

Hansen, J., et al., A closer look at United States and global surface temperature change, *J. Geophys. Res.*, *106*, 23,947–23,963, 2001.

Herbert, T. D., and J. D. Schufffert, 16 Alkenone unsaturation estimates of sea-surface temperatures at site 1002 over a full glacial cycle, *Proc. Ocean Drill. Program Sci. Results*, *165*, 239–247, 2000.

Hurrell, J. W., Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679, 1995.

Kalnay, E. M., et al., The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471, 1996.

Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumenthal, and B. Rajagopalan, Analyses of global sea surface temperature 1856–1991, *J. Geophys. Res.*, *103*, 18,567–18,589, 1998.

Keigwin, L. D., and R. S. Pickart, Slope water current over the Laurentian Fan on interannual to millennial time scales, *Science*, *286*, 520–523, 1999.

Lohmann, G., and S. Lorenz, On the hydrological cycle under paleoclimatic conditions as derived from AGCM simulations, *J. Geophys. Res.*, *105*, 17,417–17,436, 2000.

Lorenz, S., B. Grieger, P. Helbig, and K. Herterich, Investigating the sensitivity of the Atmospheric General Circulation Model ECHAM3 to paleoclimatic conditions, *Geol. Rundsch.*, *85*, 513–524, 1996.

Luterbacher, J., et al., Reconstruction of sea level pressure fields over the eastern North Atlantic and Europe back to 1500, *Clim. Dyn.*, *18*, 545–561, 2002.

Mann, M. E., R. S. Bradley, and M. K. Hughes, Global-scale temperature patterns and climate forcing over the past six centuries, *Nature*, *392*, 779–787, 1998.

Marchal, O., et al., Apparent long-term cooling of the sea surface in the Northeast Atlantic and Mediterranean during the Holocene, *Quat. Sci. Rev.*, *21*, 455–483, 2002.

Rayner, N. A., E. B. Horton, D. E. Parker, C. K. Folland, and R. B. Hackett, Version 2.2 of the global sea-ice and sea surface temperature data set, 1903–1994, *Tech. Rep. 74*, Hadley Cent., U.K. Meteorol. Off., Bracknell, England, 1996.

Rimbu, N., G. Lohmann, T. Felis, and J. Pätzold, Arctic Oscillation signature in a Red Sea coral, *Geophys. Res. Lett.*, *28*, 2959–2962, 2001.

Rühlemann, C., S. Mulitza, P. J. Müller, G. Wefer, and R. Zahn, Warming of the tropical Atlantic Ocean and slowdown of thermohaline circulation during the last deglaciation, *Nature*, *402*, 511–514, 1999.

Thompson, D. W. J., J. M. Wallace, and G. C. Hegerl, Annular modes in the extratropical circulation, part II, Trends, *J. Clim.*, *13*, 1018–1036, 2000.

Trenberth, K. E., and D. A. Paolino, The Northern Hemisphere sea level pressure data set: Trends, errors and discontinuities, *Mon. Weather Rev.*, *108*, 855–872, 1980.

H. Arz, J.-H. Kim, G. Lohmann, N. Rimbu, and R. Schneider, Department of Geoscience, Bremen University, P.O. Box 330 440, D-28334 Bremen, Germany. (nrim@palmod.uni-bremen.de)