Decadal-centennial scale monsoon variations in the Arabian Sea during the Early Holocene

Citation for published version:
Jung, SJA, Davies, GR, Ganssen, G & Kroon, D 2002, 'Decadal-centennial scale monsoon variations in the Arabian Sea during the Early Holocene', Geochemistry, Geophysics, Geosystems, vol. 3, no. 10, pp. 1-10. https://doi.org/10.1029/2002GC00348

Digital Object Identifier (DOI):
10.1029/2002GC00348

Published In:
Geochemistry, Geophysics, Geosystems

Geochemistry Geophysics Geosystems G3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Research Letter
Volume 3, Number 10
24 October 2002
1060, doi:10.1029/2002GC000348
ISSN: 1525-2027

Decadal-centennial scale monsoon variations in the Arabian Sea during the Early Holocene

S. J. A. Jung, G. R. Davies, G. Ganssen, and D. Kroon
Institute for Earth Sciences, Free University, De Boelelaan 1085, 1081 HV Amsterdam, Netherlands (jung@geo.vu.nl; davg@geo.vu.nl; gang@geo.vu.nl; kroo@geo.vu.nl)

[1] An essential prerequisite for the prediction of future climate change due to anthropogenic input is an understanding of the natural processes that control Earth's climate on timescales comparable to human-lifespan. The Early Holocene period was chosen to study the natural climate variability in a warm interval when solar insolation was at its maximum. The monsoonal system of the Tropics is highly sensitive to seasonal variations in solar insolation, and consequently marine sediments from the region are a potential monitor of past climate change. Here we show that during the Early Holocene period rapid δ^{18}O-changes of the summer (upwelling) dwelling foraminifer *G. bulloides* of up to ~0.6% in Core 905 from the Arabian Sea occurred on decadal-centennial timescales. This δ^{18}O-change predominantly translates into summer temperature variations of roughly 2–3°C. Within the resolution of the AMS^{14}C-dating, the isotope changes occur in phase with precipitation-induced δ^{18}O-variations recorded in a stalagmite in the Hoti Cave in Oman [*Neff et al.*, 2001]. From this relationship we conclude that solar insolation affecting the monsoonal system not only induced the precipitation changes as recorded in Oman (in the sense of *Neff et al.* [2001]) but also controlled temperature variations in the upwelled waters found off Somalia. The present study demonstrates that decadal-scale climate records can be obtained from nonlaminated ocean sediment records and that coherent rapid high-amplitude climate change is recorded in the Arabian Sea on a regional scale of >2000 km.

Components: 4684 words, 4 figures, 1 table.

Keywords: Holocene; Arabian Sea; decadal-scale; monsoon; climate change.

Index Terms: 4267 Oceanography: General: Paleoceanography; 1620 Global Change: Climate dynamics (3309); 1699 Global Change: General or miscellaneous.

Received 22 March 2002; **Revised** 22 May 2002; **Accepted** 16 July 2002; **Published** 24 October 2002.

Jung, S. J. A., G. R. Davies, G. Ganssen, and D. Kroon, Decadal-centennial scale monsoon variations in the Arabian Sea during the Early Holocene, *Geochem. Geophys. Geosyst.*, *3*(10), 1060, doi:10.1029/2002GC000348, 2002.

1. Introduction

[2] In order to fully resolve the potential impact of man-made CO_2 emission on the Earth's climate, it is crucial to improve our understanding of the natural climate variability on decadal-centennial timescales. In addition, it is particularly important to obtain a detailed knowledge of the link between terrestrial and marine climate change in order to determine the climatic coupling between the oceans and atmosphere. Over the last two decades researchers have presented extensive evidence of long-term climate change on millennial timescales during both glacial and

interglacial time periods all over the globe [e.g., *Imbrie et al.*, 1992; *Anderson and Prell*, 1993; *Tiedemann et al.*, 1994; *Clemens and Tiedemann*, 1997; *Schneider et al.*, 1997]. Natural climate change on timescales relevant to human life times (decadal-centennial), however, has received comparably little attention. Using deep sea sediments from the Arabian Sea, this study concentrates on the Early Holocene time interval, which is a predestine time period in which to assess the natural variability of Earth's climate because it was a warmer period than today.

[3] High-resolution studies from the Early Holocene period are rare in the Arabian Sea area. *Neff et al.* [2001], using a stalagmite record from the Hoti Cave (Oman), attributed decadal-centennial scale climate variations in the monsoonal system to changes in solar insolation. On a regional scale, however, there are no records that assess the link between climate records from the ocean and the continent. Such records are important to help fully understand the coupled oceanic-atmospheric processes that control the regional monsoonal system, which is one of the most vulnerable parts of Earth's climate. Here we present a decadal-centennial scale climate history recorded in sediments from the Arabian Sea off Somalia in order to assess the natural variability of the West-Asian monsoon system. A comparison of the present results with a nearby terrestrial climate record implies regional coherent monsoon variations on a decadal-centennial timescale.

2. Modern Monsoon Dynamics in the Arabian Sea: The Hemispheric Control

[4] Today the monsoon circulation in the Arabian Sea at the site of Core 905 is controlled by the seasonally varying insolation distribution, which affects the key atmospheric pressure elements in the region. The position of the Inter Tropical Convergence Zone (ITCZ) causes a "hemispheric" impact on the climate in the western Arabian Sea. During northern hemisphere winter the ITCZ is located around the equator, and the major climate elements are shifted far southward. Hence northern hemisphere components dominate during this season. The atmospheric pressure difference between high-pressure polar air masses over the Eurasian continent and the low pressure ITCZ results in the NE-monsoon winds. In contrast, during summer all major pressure systems are shifted northward into the Arabian Sea, and accordingly southern hemisphere components dominate the climate. The atmospheric pressure gradient between the high-pressure cell over the southern Indian Ocean and the low-pressure zones in the northern Arabian Sea (ITCZ) and over the Indian subcontinent results in the summer SW-monsoon winds (Figure 1). Off Somalia these winds induce intense ocean upwelling of nutrient-rich subsurface water masses from $\sim$200 to 250 m depth [*Wyrtki et al.*, 1988]. The SW-monsoon-driven air masses were also the sources for the Early Holocene precipitation over the Arabian Peninsula recorded in the Hoti Cave [*Neff et al.*, 2001]. Hence the upwelling history off Somalia and the precipitation variation over Oman both reflect climate variations controlled by the monsoon in the Arabian Sea region. Given the delicate balance of the airflow in the monsoonal system, past climate variations may have been sensitively recorded in sediments from this area.

3. Methods

[5] Piston Core 905 was retrieved from a water depth of 1580 m offshore Somalia during the Netherlands Indian Ocean Program (NIOP) in 1993 (Figure 1). On the basis of an initial age model [*Jung et al.*, 2001] the Early Holocene section was sampled at 0.5 cm steps. Because of the very high Early Holocene sedimentation rate of roughly 30 cm ka^{-1}, this sampling strategy resulted in an age difference between neighboring samples of roughly 20 years. Subsequent to standard sample preparation (washing, sieving) four specimens of the planktic foraminifer *G. bulloides* species were picked for stable O-isotope analysis. Two to five replicate analyses (average $\sim$3) per sample were performed. The replicate analysis strategy was designed to minimize any noise introduced by natural variation within a

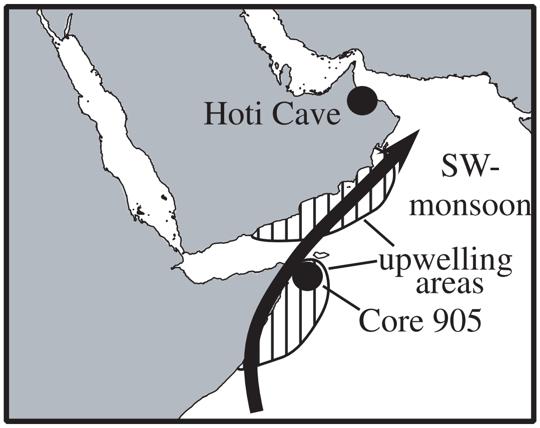

Figure 1. Location of Core 905 and Hoti Cave [*Neff et al.*, 2001]. Black arrow illustrates the path of the summer SW-monsoon. Hatched areas delimit regions of summer upwelling.

sample due to short-term oceanographic variations and the effect of bioturbation.

4. Quality Assessment of the δ^{18}O-Record of Core 905

[6] The δ^{18}O-data record rapid high-amplitude variations of up to 0.6‰ (Figure 2). Bioturbation within sediments could disturb the archived climate record. In the extremely densely sampled Core 905, however, bioturbation actually acts as a low-pass filter controlled by sedimentation rate [e.g., *Trauth et al.*, 1997]. In general, higher sedimentation rates will improve the preservation potential of high-frequency climate signals. Given the high sedimentation rate of up to 36 cm ka^{-1} in Core 905, the influence of bioturbation is predicted to have been minor. In order to assess the variability in δ^{18}O recorded by each sample population, 1-sigma errors of the mean were calculated and are presented in Figure 2 (A conservative error of ±0.1‰ was assumed for each single analysis). Figure 2 shows that although some of the δ^{18}O-variations are within error, there is significant variation. In particular, all the large amplitude variation of >0.5‰ are significant, but so are some of the smaller δ^{18}O-variations. This finding suggests that a substantial part of the isotopic variation shown reflects the natural variability within the time period covered by each sample. Accordingly, we assume that the small δ^{18}O-variations in the δ^{18}O-record of the planktic foraminifer *G. bulloides*, although sometimes close to the detection limit of the method, reflect the natural variability off Somalia.

5. Age Model

[7] In order to assess the realistic error in the age determination, multiple AMS^{14}C-analyses on three planktic foraminifer species (*G. ruber, G. bulloides, N. dutertrei*) were performed on 7 individual samples (Table 1). The 7 samples included 3 pairs from adjacent sampling intervals. A crucial element in transferring conventional radiocarbon ages into calendar ages is the reser-

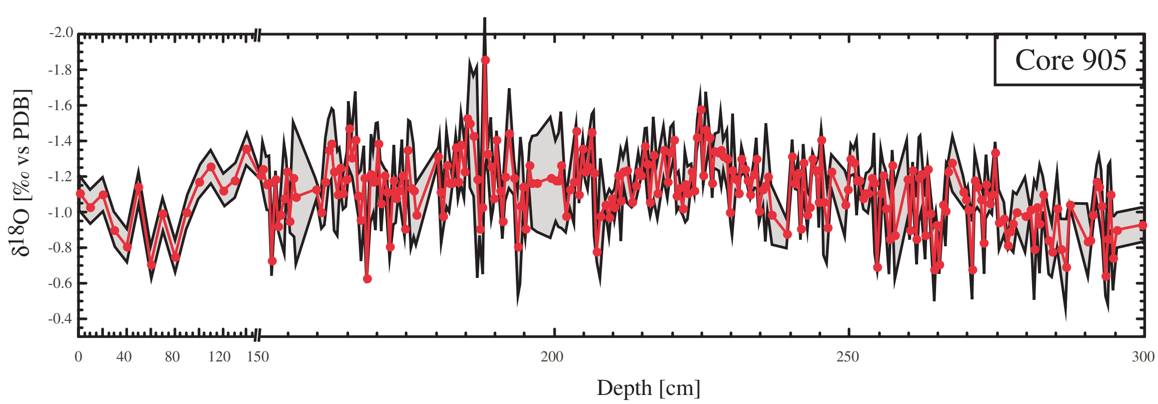

Figure 2. Stable O-isotope record of the planktic foraminifera *G. bulloides* from Core 905 off Somalia versus depth including 1-sigma error bars.

Table 1. Summary of AMS14C-Results for Core 905[a]

Depth in Core 905, cm	Foraminifera Species	Conventional Age	Analytical Error	2-Sigma Ranges of Calibrated Ages of Individual Analysis	Depth in Core 905, cm	Mean Conventional Age	Mean Calibrated Calendar Age	2-Sigma Range
165–166.5	*G.ruber/G. sacculifer*	6710	45	7191–6840				
	G. bulloides	6740	40	7209–6877				
	N. dutertrei	6780	40	7241–6927				
					167–167.5	6653	6931	7147–6745
168.5–170	*G.ruber/G. sacculifer*	6480	40	6877–6592				
	G. bulloides	6500	35	6889–6621				
	N. dutertrei	6710	40	7183–6846				
181.5–183	*G.ruber/G. sacculifer*	6935	40	7399–7150				
	G. bulloides	7295	45	7673–7444				
	N. dutertrei	7200	50	7604–7382				
					183–183.5	7125	7422	7557–7229
184.5–186	*G.ruber/G. sacculifer*	6970	40	7414–7178				
	G. bulloides	7235	45	7634–7413				
	N. dutertrei	7115	45	7550–7295				
249.5–251	*G.ruber/G. sacculifer*	8540	45	9264–8673				
	G. bulloides	8815	45	9736–8913	249.5–251	8620	8919	9278–8800
	N. dutertrei	8505	50	9261–8603				
290–291.5	*G.ruber/G. sacculifer*	9795	45	11,103–9886				
	G. bulloides	9855	50	11,114–10,102				
	N. dutertrei	9730	50	10,582–9826				
					291–291.5	9748	10287	11,090–9865
291.5–293	*G.ruber/G. sacculifer*	9800	45	11,104–9889				
	G. bulloides	9790	50	11,102–9882				
	N. dutertrei	9735	55	10,584–9828				

[a] The mean and the two-sigma ranges of the calibrated ages were calculated using revision 4.3 of the software program CALIB. CALIB 4.3 uses the marine98 data set [Stuiver et al., 1998]. In order to account for a higher reservoir age, a dR (difference between regional and world ocean reservoir age) of 200±50 years was used. For further explanation see text.

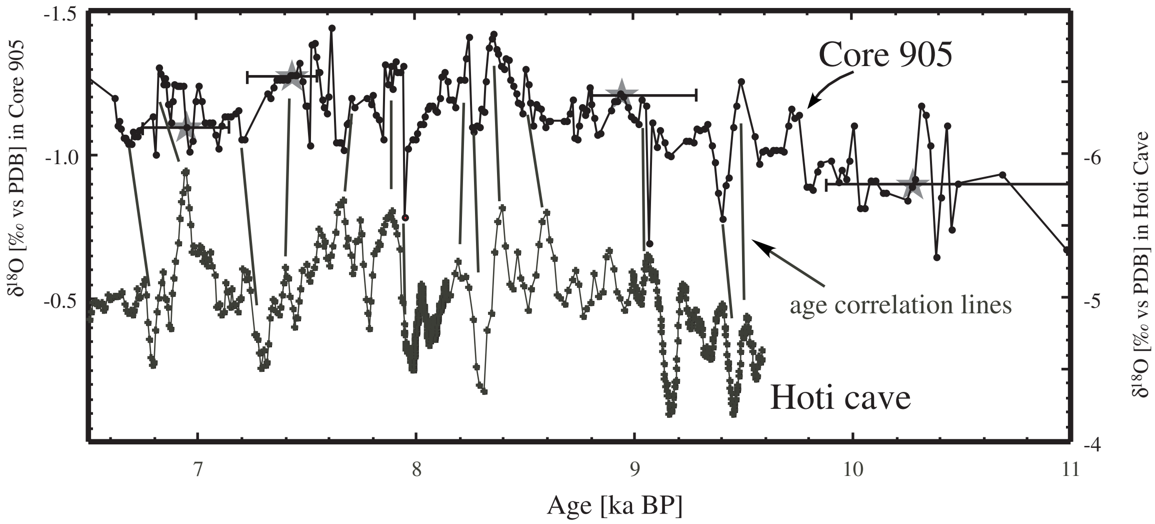

Figure 3. Stable O-isotope records of *G. bulloides* from Core 905 off Somalia and from a stalagmite from Hoti Cave [*Neff et al.*, 2001] based on their individual age models. Correlation lines show the main tie points used to adjust the age model of Core 905 to that of Hoti Cave. A 40-year moving averaging filter was applied to both records. Asterisks mark AMS^{14}C-dates including two sigma uncertainty ranges (see Table 1).

voir age of the ambient seawater. Conventionally a reservoir age of 400 years is assumed for most marine carbonate samples in the tropical-subtropical area. A recent study from the Arabian Sea, however, has shown that the reservoir age in surface waters varied and may have been 600 years during the Early Mid Holocene [*von Rad et al.*, 1999]. We therefore apply a reservoir age of 600 years to convert the AMS^{14}C-dates with an assumed uncertainty of ±50 years. Given the variation in reservoir age within the Arabian Sea and an offset in reservoir age of 200 years between the Arabian Sea and other ocean regions [*von Rad et al.*, 1999], this is a conservative assumption. Using the latest revision of the standard radiocarbon-calendar year calibration software (CALIB 4.3; details in table heading) [*Stuiver et al.*, 1998] yields 2-sigma uncertainties of up to 1000 years in the calibrated calendar ages. Given these uncertainties, the resulting calibrated calendar ages for adjacent sample pairs are not significantly different (Table 1). Although variable, there is no systematic offset of the AMS^{14}C-dates in individual samples between the different foraminifera species (Table 1) as may have been expected if they were derived from different water masses or seasons. Sediment traps and net haul studies at and close to Site 905 show, however, that the three species predominantly reflect property variations at the sea surface above 50 m depth [*Conan and Brummer*, 2000; *Peeters*, 2000], implying little expected difference in recorded AMS^{14}C-ages. The variability of the conventional AMS^{14}C-dates in Table 1 is therefore an unexpected result. The age variation may record factors such as differences in the timing of the calcification throughout the year (or season) or slight differences in calcification depth within the top 50 m of the water column. Given these uncertainties, we choose to improve the robustness of the dates by averaging the original individual conventional radiocarbon ages and assigning those to the midpoints of the respective depth intervals. Assuming an error of ±50 years for both the analytical determination and the reservoir age of the seawater leads to the 2-sigma uncertainties displayed in Figure 3 and Table 1. If we had used more realistic (larger) uncertainties for both the AMS^{14}C-measurement and the variation of the reservoir age, the 2-sigma levels would be much larger. None of the conclusions drawn below, however, would be affected by this alternative strategy. This treatment of the radiocarbon data is designed to stress the extreme difficulties

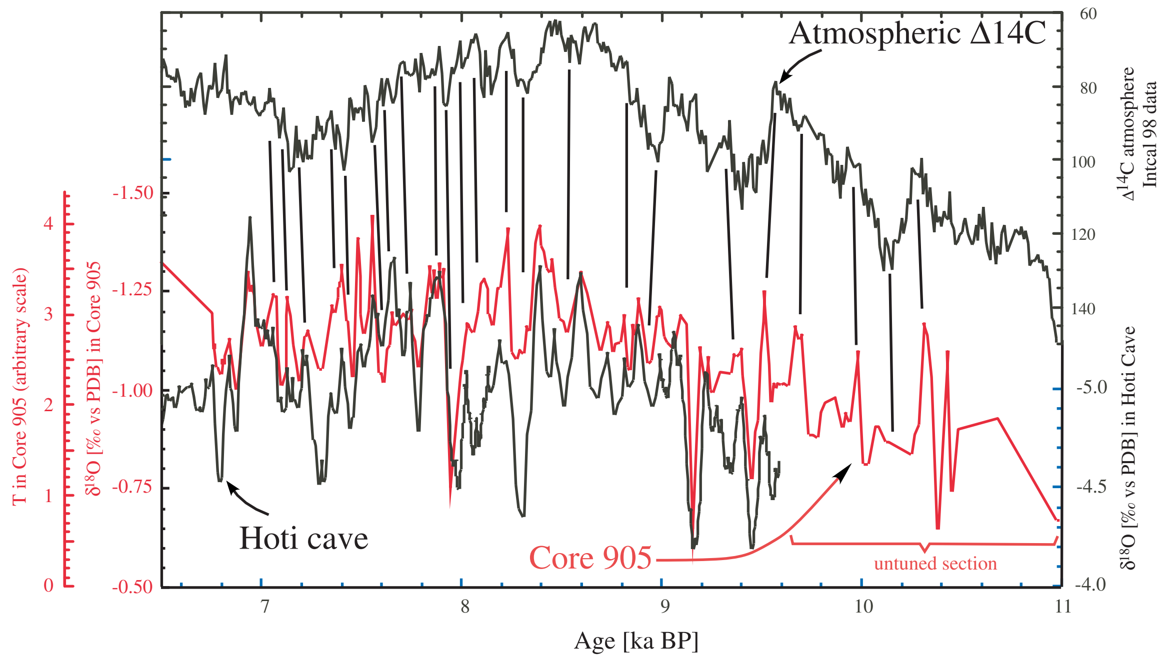

Figure 4. The stable O-isotope record of *G. bulloides* from Core 905 and from a stalagmite from Hoti Cave [*Neff et al.*, 2001] based on the age model used for the Hoti Cave record. A 40-year moving averaging filter was applied to both records in order to improve visual comparison. The tree ring-derived atmospheric $\Delta^{14}C$-record (Intcal 98 data set) [*Stuiver et al.*, 1998] illustrates the close correlation between variations in solar radiation and the terrestrial and marine monsoon records. The potential temperature variation implied by the $\delta^{18}O$-record of Core 905 was calculated assuming a ratio of 0.23%/°C [*Erez and Luz*, 1983].

in obtaining radiocarbon dates from oceanic sediments to a precision better than several hundred years, even for the Early Holocene.

6. Linking Continental and Oceanic Climate Records in the Arabian Sea Area

[8] A linear interpolation between the resulting ages was used to calculate a provisional age model for Core 905 and to compare the $\delta^{18}O$-record of Core 905 with the $\delta^{18}O$-record of a stalagmite from the Hoti Cave in Oman [*Neff et al.*, 2001, Figure 3]. In order to allow a better visual comparison, a 40 year running mean filter was applied to both records. The most obvious result in Figure 3 is that both records show highly similar patterns with only minor offsets. In order to fully assess the similarity between both records, the age model of Core 905 was graphically adjusted to that of the Hoti Cave (U-Th based) [*Neff et al.*, 2001]. A graphical correlation of the two records is presented in Figure 3 and Figure 4. Figure 3 shows the main correlation lines used to construct a revised tuned age model for Core 905 based on the Hoti Cave record. After tuning the age model of Core 905, all AMS^{14}C-dated samples remain within error of the calibrated calendar ages. The maximum temporal offset between both records was ~150 years. Figure 4 shows the resulting age model and compares the $\delta^{18}O$-record of Core 905 with that of Hoti Cave. The records are strikingly similar with a correlation coefficient of r = 0.67 and demonstrate that the Early Holocene terrestrial and marine climate records in the Arabian Sea region vary in phase (Figure 4). Given that each data point is determined on average in triplicate (compare 1 sigma levels in Figure 2) and that smoothing has been applied, the similarity of the $\delta^{18}O$-variabilities shown by Core 905 and Hoti Cave [*Neff et al.*, 2001] in Figure 4 is highly significant.

[9] The $\delta^{18}O$-record of *G. bulloides* potentially reflects a combination of several factors. The temperature and the stable O-isotope composition

of the ambient seawater ($\delta^{18}O_{water}$) during calcification, the chemistry of seawater (alkalinity), and the long-term ice effect are important primary factors. In addition, variations in the seasonal abundance of the measured planktic foraminifer species would change the recorded $\delta^{18}O$ and represent a secondary factor. Present-day variations in $\delta^{18}O_{water}$ offshore Somalia, however, are small because there are no major rivers flowing into the area and there is no significant correlation between $\delta^{18}O_{water}$ and salinity [*Delaygue et al.*, 2001; *Jung et al.*, 2001]. Even if we were to assume an unlikely scenario with an enhanced precipitation and runoff from NE-Africa during the Early Holocene affecting the surface water properties at Site 905, the potentially induced change in $\delta^{18}O$ would be small. In order to assess the impact for a change between extreme boundary conditions, we assume that the maximum change in salinity would be ~1.3 PSU (practical salinity unit), that is, the suggested change in salinity due to variations in the evaporation-precipitation balance between the last Glacial and the Holocene [*Rostek et al.*, 1997]. In such a scenario a lowering of the present-day salinity of ~36 PSU by 1.3 PSU is assumed to result from fluvial runoff. The $\delta^{18}O_{water}$ value in modern NE-African rain is approximately −3‰ [GNIP data set]. A potential runoff derived from this rain implies a change in the $\delta^{18}O_{water}$ in the surface waters of −0.12‰ (Modern $\delta^{18}O_{water}$ in surface water from the region is 0.3‰) [*Jung et al.*, 2001]. This potential change in $\delta^{18}O$ is significantly smaller than the observed down core variation in Core 905. We assume that the modern $\delta^{18}O_{water}$ characteristics in rain from NE-Africa prevailed during the entire Holocene period. This implies that any Holocene variations in ocean salinity induced by changes in the evaporation-precipitation balance do not significantly affect the $\delta^{18}O_{water}$ [*Jung et al.*, 2001] and hence the $\delta^{18}O$-record of *G. bulloides* in Core 905.

[10] Variations in alkalinity of seawater may also have a subtle effect on the $\delta^{18}O$-values of tests of foraminifera on glacial-interglacial timescales [*Spero et al.*, 1997]. The present study, however, covers a short time period within the Holocene. Accordingly, the effect of variations in alkalinity on the decadal-centennial timescale pertinent to the $\delta^{18}O$-record of Core 905 is negligible.

[11] Another long-term control of $\delta^{18}O$ in the ocean is the waxing and waning of continental ice sheets that preferentially store the light ^{16}O isotope. The vast majority of the ice shields formed during the last glaciation melted during the transition to the Holocene [*Bard et al.*, 1996]. Minor melting, however, continued up into the Early Holocene [*Bard et al.*, 1996, and references therein]. The general gradual decrease in the $\delta^{18}O$-record of Core 905 between 11 and ~8.4 ka BP is considered to be a consequence of such melting. There are no direct surface/subsurface currents that connect the regions of meltwater drainage with the Arabian Sea, and the overturning time of the oceans is between several hundred to >1000 years. Consequently, any $\delta^{18}O$-variation caused by ice sheet decay cannot be "mixed" into the Arabian Sea on decadal-centennial timescales. Ice sheet melting can therefore be excluded as an explanation of the abrupt $\delta^{18}O$-variations in Core 905. Accordingly, variations in the primary factors controlling O-isotope values in foraminifera cannot explain the $\delta^{18}O$-record of *G. bulloides* from Core 905. Hence the latter predominantly reflects variability in surface water temperature.

[12] Sediment trap data from the same location as Core 905 show that *G. bulloides* almost exclusively reproduces during the SW-monsoon-induced upwelling season [*Conan and Brummer*, 2000]. Vertical net haul data from this area indicate that *G. bulloides* calcifies within the top 50 m of the water column [*Peeters et al.*, 2002]. Consequently, the $\delta^{18}O$-record of *G. bulloides* from Core 905 predominantly reflects summer temperature variations in the matured upwelling cells at the sea surface [*Kroon and Ganssen*, 1989; *Peeters et al.*, 2002]. Figure 4 shows the temperature variations implied by the $\delta^{18}O$-record of Core 905. The most striking result is that the Early Holocene surface ocean temperature off Somalia rapidly varied by up to 2–3°C during the upwelling season. These data reinforce the conclusion made from other high-resolution studies [*Bond et al.*, 2001; *Haug et al.*, 2001] that the

Early Holocene climate was locally highly variable. The almost perfect match between the δ^{18}O-records of Core 905 and from Hoti Cave, however, establishes that coherent climate variability on a decadal-centennial scale was at least a regional phenomenon.

[13] The close similarity of the δ^{18}O-records from Core 905 and from Hoti Cave implies that the temperature variation recorded during the upwelling season in Core 905 and the variation in precipitation over Oman responded to the same forcing mechanism. Figure 4 shows a peak-to-peak correlation between the atmospheric ^{14}C concentration [*Stuiver et al.*, 1998; *Neff et al.*, 2001] (as a first order proxy for variations in solar insolation) and the δ^{18}O-records from Core 905 and Hoti Cave. The excellent correlation between these records also implies a linkage between changes in solar insolation and temperature variations in the surface ocean off Somalia. Given the dynamics of the monsoon system, it is difficult to discriminate between potential processes involved in coupling the observed decadal scale climate records. Stalagmite evidence from Oman suggests a more northerly position of the ITCZ during insolation maxima [*Neff et al.*, 2001]. The results of the present research links these variations to higher temperatures in upwelling waters off Somalia. Potential explanations may involve a direct heating of the ocean, a change in atmospheric circulation that interacts with the ocean, or a combination of both. In a scenario with solely insolation-induced heating of parts of the ocean, the δ^{18}O-record in Core 905 may reflect straightforward temperature variations in the source region of the upwelled subsurface waters. In such a scenario (and potential others of this type) it is, however, difficult to explain the large temperature variation recorded off Somalia by the rather subtle variations in solar insolation. The large heat capacity of the ocean would also tend to dampen the temperature change induced by insolation changes rather than amplify it.

[14] The atmosphere may respond more directly to changes in solar insolation. For example, a relationship between solar wind-magnetosphere-ionosphere-atmosphere could potentially lead to climate changes in the tropics (For a recent discussion see *van Geel et al.*, 1999). If we assume that changes in atmospheric circulation would have resulted in the variations observed in Core 905, (at least) two different scenarios may be possible. A more northerly position of the ITCZ during insolation maxima may imply a larger distance between low and high-pressure cells, more widely spaced isobars, and accordingly a weaker SW-monsoon. A weaker SW-monsoon would, in turn, reduce the upwelling velocity (nutrient supply) and prolong the time period between initial water upwelling and the growth period of *G. bulloides*. Consequently, an enhanced warming of the upwelled waters would be recorded in minima of the δ^{18}O-record of *G. bulloides*. Alternatively, an insolation maximum may have induced a more vigorous SW-monsoon that, in turn, may have resulted in a stronger mixing between the pristine upwelled cold water and the surrounding warm surface waters. An enhanced admixture of these warm waters would equally result in enhanced temperatures in the matured upwelling cells and in minima in the δ^{18}O-record of *G. bulloides*. Currently it is not possible to unambiguously relate the observed correlation between solar insolation and climate to a specific process. On the basis of its more dynamic nature, we speculate that the atmosphere would more rapidly respond to variations in solar insolation, but a (superimposed) direct effect on the ocean cannot be excluded.

[15] The scenarios discussed above involve monsoon variations occurring during summer when the climate in the Arabian Sea is controlled by the atmospheric flow between the southern and the northern hemisphere. This hemispheric link by itself suggests that at least the tropical and subtropical parts of the southern hemisphere sensitively responded to variations in solar insolation. A similar solar-forcing mechanism has been discussed in recent studies to explain the short-term variation in sediments from the N-Atlantic [*Bond et al.*, 2001] and from South America [*Lamy et al.*, 2001]. Together these data suggest that short-term solar insolation variations may have a global impact on Earth's climate, although locally differ-

ent feedback mechanisms may result in different climate records.

7. Conclusions

[16] This study shows that suitable nonlaminated sediment cores with a high sedimentation rate record the oceanic climate history at a similar time resolution as high-quality terrestrial sites. The δ^{18}O-record of Core 905 shows rapid variations in δ^{18}O interpreted as temperature fluctuations of up to roughly 2–3°C that, within the resolution of the AMS^{14}C-dating, occur in phase with the precipitation controlled δ^{18}O-variations in the Hoti Cave section (Figure 1; Oman) [*Neff et al.*, 2001]. These findings demonstrate that Early Holocene climate change in and around the Arabian Sea was simultaneously recorded in marine and terrestrial climate records. More research reconstructing the short-term climate history in the Arabian Sea and other regions is needed, aided by process-oriented computer simulations, to improve our understanding of the controls of short-term climate change in the region and on a global scale, respectively.

Acknowledgments

[17] This study is part of the EU-TMR network ERBFMRXC-T960046 "The marine record of continental tectonics and erosion" and is NSG publication number 20020903. We also thank two anonymous reviewers for their constructive criticisms that greatly improved the clarity of the manuscript.

References

Anderson, D. M., and W. L. Prell, A 300 kyr record of upwelling off Oman during the late Quaternary: Evidence of the Asian southwest monsoon, *Paleoceanography*, *8*, 193–208, 1993.

Bard, E., B. Hamelin, M. Arnold, L. Montaggloni, G. Cabioch, G. Faure, and A. Rougerie, Deglacial sea level record from Tahiti corals and the timing of global meltwater discharge, *Nature*, *382*, 241–244, 1996.

Bond, G., B. Kromer, J. Beer, R. Muscheler, M. N. Evans, W. Showers, S. Hoffmann, R. Lotti-Bond, I. Hajdas, and G. Bonani, Persistent solar influence on North Atlantic climate during the Holocene, *Science*, *294*, 2130–2136, 2001.

Clemens, S. C., and R. Tiedemann, Eccentricity forcing of Pliocene-early Pleistocene climate revealed in a marine oxygen-isotope record, *Nature (London)*, *385*, 801–804, 1997.

Conan, S. M. H., and G.-J. Brummer, Fluxes of planktonic Foraminifera in response to monsoonal upwelling on the Somalia Basin margin, *Deep Sea Res., Part II*, *47*, 2207–2227, 2000.

Delaygue, G., E. Bard, C. Rollion, J. Jouzel, M. Stievenard, J.-C. Duplessy, and G. Ganssen, Oxygen isotope/salinity relationship in the northern Indian Ocean, *J. Geophys. Res.*, *106*, 4565–4574, 2001.

Erez, J., and B. Luz, Experimental paleotemperature equation for planktonic foraminifera, *Geochim. Cosmochim. Acta*, *47*, 1025–1031, 1983.

Haug, G., K. A. Hughen, D. M. Sigman, L. C. Peterson, and U. Röhl, Southward migration of the Intertropical Convergence Zone through the Holocene, *Science*, *293*, 1304–1308, 2001.

Imbrie, J., E. A. Boyle, S. C. Clemens, A. Duffy, W. R. Howard, G. Kukla, J. Kutzbach, D. G. Martinson, A. McIntyre, A. C. Mix, B. Molfino, J. J. Morley, L. C. Peterson, N. G. Pisias, W. L. Prell, M. E. Raymo, N. J. Shackleton, and J. R. Toggweiler, On the structure and origin of major glaciation cycles, 1, Linear responses to Milankovitch forcing, *Paleoceanography*, *7*, 701–738, 1992.

Jung, S. J. A., G. Ganssen, and G. R. Davies, Multidecadal variations in the Early Holocene outflow of Red Sea Water into the Arabian Sea, *Paleoceanography*, *16*, 658–668, 2001.

Kroon, D., and G. Ganssen, Northern Indian Ocean upwelling cells and the stable isotope composition of living planktonic foraminifers, *Deep Sea Res.*, *36*, 1219–1236, 1989.

Lamy, F., D. Hebblen, U. Roehl, and G. Wefer, Holocene rainfall variabiltiy in southern Chile: A marine record of latitudinal shifts of the Southern Westerlies, *Earth Planet. Sci.*, *185*, 369–382, 2001.

Neff, U., S. J. Burns, A. Mangini, M. Mudelsee, D. Fleitmann, and A. Matter, Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago, *Nature*, *411*, 290–293, 2001.

Peeters, F., The distribution and stable isotope composition of living planktic formaminifera in relation to seasonal changes in the Arabian Sea, Ph.D. thesis, 184 pp., Free Univ., Amsterdam, Netherlands, 2000.

Peeters, F. J. C., G.-J. A. Brummer, and G. Ganssen, The effect of upwelling on the distribution and stable isotope composition of *Globigerina bulloides* and *Globigerinoides ruber* (planktic foraminifera) in modern surface waters of the NW Arabian Sea, *Global Planet. Change*, in press, 2002.

Rostek, F., E. Bard, L. Beaufort, C. Sonzogni, and G. Ganssen, Sea surface temperature and productivity records for the past 240 kyr in the Arabian Sea, *Deep Sea Res., Part II*, *44*, 1461–1480, 1997.

Schneider, R. R., B. Price, P. J. Mueller, D. Kroon, and I. Alexander, Monsoon-related variations in Zaire (Congo) sediment load and influence of fluvial silicate supply on marine productivity in the East Equatorial Atlantic during the last 200,000 years, *Paleoceanography*, *12*, 463–481, 1997.

Spero, H. J., J. Bijma, D. Lea, and E. B. Bemis, Effect of seawater carbonate concentration on foraminiferal carbon and oxygen isotopes, *Nature*, *390*, 497–500, 1997.

Stuiver, M., P. J. Reimer, E. Bard, J. W. Beck, K. A. Burr,

K. A. Hughen, B. Kromer, J. McCormac, J. van der Plicht, and M. Spurk, INTCAL98 Radiocarbon age calibration, *Radiocarbon*, *40*, 1041–1083, 1998.

Tiedemann, R., M. Sarnthein, and N. J. Shackleton, Astronomic timescale for the Pliocene Atlantic d^{18}O and dust flux records of Ocean Drilling Program site 659, *Paleoceanography*, *9*, 619–638, 1994.

Trauth, M. H., M. Sarnthein, and M. Arnold, Bioturbational mixing depth and carbon flux at the sea floor, *Paleoceanography*, *12*, 517–526, 1997.

van Geel, B., O. M. Raspopov, H. Renssen, J. van der Plicht, V. A. Dergachev, and H. A. J. Meijer, The role of solar forcing upon climate change, *Quat. Sci. Rev.*, *18*, 331–338, 1999.

von Rad, U., M. Schaaf, K. H. Michels, H. Schulz, W. H. Berger, and F. Sirocko, A 5000-yr record of climate change in varved sediments from the oxygen minimum zone off Pakistan, northeastern Arabian Sea, *Quat. Res. (New York)*, *51*, 39–53, 1999.

Wyrtki, K., E. B. Bennett, and D. J. Rochford, *Oceanographic Atlas of the International Indian Ocean Expedition*, 531 pp., The Natl. Sci. Found., Washington D. C., 1988.