Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability

M. Staubwasser,[1] F. Sirocko,[2] P. M. Grootes,[3] and M. Segl[4]

Received 20 December 2002; revised 20 December 2002; accepted 31 January 2003; published 18 April 2003.

[1] Planktonic oxygen isotope ratios off the Indus delta reveal climate changes with a multi-centennial pacing during the last 6 ka, with the most prominent change recorded at 4.2 ka BP. Opposing isotopic trends across the northern Arabian Sea surface at that time indicate a reduction in Indus river discharge and suggest that later cycles also reflect variations in total annual rainfall over south Asia. The 4.2 ka event is coherent with the termination of urban Harappan civilization in the Indus valley. Thus, drought may have initiated southeastward habitat tracking within the Harappan cultural domain. The late Holocene drought cycles following the 4.2 ka BP event vary between 200 and 800 years and are coherent with the evolution of cosmogenic ^{14}C production rates. This suggests that solar variability is one fundamental cause behind Holocene rainfall changes over south Asia. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4267 Oceanography: General: Paleoceanography; 1620 Global Change: Climate dynamics (3309). **Citation:** Staubwasser, M., F. Sirocko, P. M. Grootes, and M. Segl, Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability, *Geophys. Res. Lett.*, *30*(8), 1425, doi:10.1029/2002GL016822, 2003.

1. Introduction

[2] Northern hemisphere records reveal millennial-scale climate changes during the Holocene, which may have been tuned to solar radiation variability [*Sirocko et al.*, 1996; *deMenocal et al.*, 2000; *Bond et al.*, 2001]. The most pronounced changes in northern Africa and western Asia occurred at the mid-late Holocene transition between 5.5 and 4.0 ka cal. BP, where one or several successive shifts towards dryer conditions are well documented [*Bar-Matthews et al.*, 1997; *deMenocal et al.*, 2000; *Gasse*, 2000]. Around 4.2 ka BP the ancient civilizations of Egypt and Mesopotamia suffered from sustained drought or even collapsed entirely [*Weiss et al.*, 1993; *Hassan*, 1997; *Cullen et al.*, 2000]. At the same time the Harappan civilization of the Indus valley (Pakistan) transformed from a highly organized urban phase to a post-urban phase of smaller settlements accompanied by a southeastward migration of the population [*Possehl*, 1997]. However, previous climate records are inconclusive on the timing of south Asian Holocene climate change, the underlying mechanisms of such change, and whether the Harappan civilization decline was the result of climate change [*Singh et al.*, 1990; *Possehl*, 1997; *Enzel et al.*, 1999; *Weiss*, 2000].

2. Regional Setting and Chronology

[3] Due to the effects of the south Asian monsoon a strong zonal precipitation gradient exists across the Arabian Sea (AS) (Figure 1a). The only significant freshwater source to the northern AS was the river Indus, until irrigation and flood control measures dramatically reduced its outflow over the last century [*Milliman et al.*, 1984]. Summer monsoon ocean upwelling, which in the western AS lowers sea surface salinity, does not affect the northern AS or the Gulf of Oman (GO), and low salinity water from the Bay of Bengal does not flow into the northern AS during winter [*Levitus et al.*, 1994]. However, a strong seasonality is imposed on northern AS and GO sea surface temperatures (SST) and mixed layer depth by the reversing monsoon winds and associated air temperatures (Figures 1b and 1c) [*Rao et al.*, 1989].

[4] Laminated sediment core 63KA was retrieved from a site on the continental margin off Pakistan at 316 m water depth off the formerly active Indus delta (Figure 1a). The chronology of the mid-late Holocene section presented here is based on 36 ^{14}C dated single species samples of planktonic foraminifera, typically *Globigerinoides sacculifer*, but *Orbulina universa* in three occasions (Figure 2). ^{14}C ages were calibrated by least-squares fitting of a ^{14}C plateau resolved between 5 and 6 ka BP to the ^{14}C calibration record (supplementary note 1)[1] [*Staubwasser et al.*, 2002]. The obtained reservoir age of 565 ^{14}C years was then used throughout the rest of the core.

3. The 4.2 ka BP drought Event

[5] The $\delta^{18}O$ record of surface dwelling planktonic foraminifer *Globigerinoides ruber* shows little change in the mid-Holocene, but enhanced variability in the late Holocene with $\delta^{18}O$ values between $-1.7‰$ to $-2.1‰$ (Figure 2). Between $\sim$1.0 ka BP and $\sim$0.4 ka BP detailed observations are somewhat compromised by intermittent absence of *G. ruber* in the core. The relatively variable late Holocene appears to begin with a (positive) shift to heavier $\delta^{18}O$ at 4.2 ka BP. This shift in *G. ruber* $\delta^{18}O$ may reflect any combination of cooler sea surface temperatures (SST) and heavier $\delta^{18}O$ of the

[1]Department of Earth Sciences, University of Oxford, Oxford, UK.
[2]Institute für Geowissenschaften, Universität Mainz, Mainz, Germany.
[3]Leibniz Labor, Universität Kiel, Kiel, Germany.
[4]Geowissenschaften, Universität Bremen, Bremen, Germany.

0094-8276/03/2002GL016822

[1] Auxiliary notes and tables are available via Web browser or via Anonymous FTP from ftp://ftp.agu.org, directory "apend" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about.html.

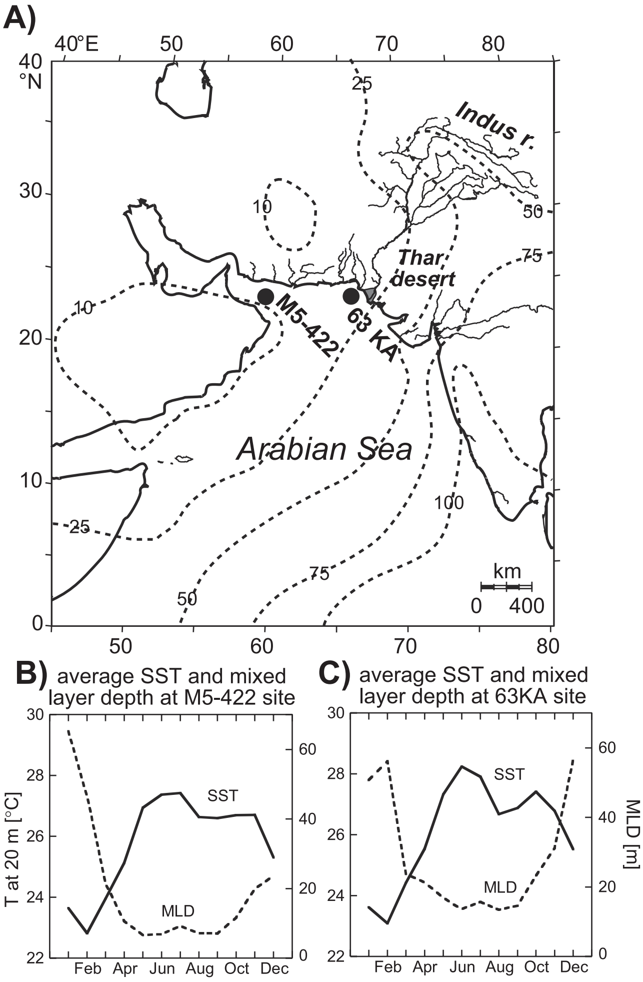

Figure 1. (a) Arabian Sea region with core sites and continental watersheds. The Harappan cultural domain prior to 4.2 ka BP encompassed the Indus valley and the Thar desert [*Possehl*, 1997]. Contours show average annual rainfall in mm/month [*GPCC*, 1998]. (b) Annual evolution of sea surface temperature and mixed layer depth for the Gulf of Oman and, (c) for the northeastern Arabian Sea [*Levitus and Boyer*, 1994].

ambient water due to enhanced salinity [*Bemis et al.*, 1998]. A comparison with the $\delta^{18}O$ record (*G. ruber*) of core M5-422 from the GO shows opposing $\delta^{18}O$ trends across the northern AS at the 4.2 ka BP event (Figure 3). Under the dominant monsoon forcing of AS surface temperature (Figures 1b and 1c), opposing $\delta^{18}O$ trends across the northern AS are difficult to explain in terms of SST changes. In addition, a late – mid-Holocene alkenone record from the northeastern AS does not indicate significant SST change between 4.5–3.5 ka BP [*Doose-Rolinski et al.*, 2001]. Because of the strong zonal precipitation gradient over the northern AS and the proximity of core 63KA to the Indus delta, an alternative explanation for this contrast is a change in the annual northern AS evaporation - precipitation budget and Indus river discharge. The 0.3‰ heavier $\delta^{18}O$ in 63KA after 4.2 ka BP (0.4‰ if the change to more negative, i.e. lighter, values in core M5-422 reflects a warming throughout the northern AS) would amount to a 1.0–1.2‰ higher surface salinity (1.3–1.6‰ accounting for sea surface warming), depending whether linear mixing between the very light Indus water (average $\delta^{18}O \sim -10$‰) and AS surface water ($\delta^{18}O \sim 0.8$‰) is assumed or the $\delta^{18}O$ - salinity relation for the open AS is used [*Mook*, 1983; *Delaygue et al.*, 2001].

[6] Around the 4.2 ka BP shift in 63 KA $\delta^{18}O$ the Harappan civilization in the Indus valley transformed from a highly urban urban phase to a rural post urban phase [*Possehl*, 1997]. In particular, cultural centers, such as the large cities of Mohenjo-Daro and Harappa, were almost completely abandoned while locations in northern India grew in population. The concordance of Harappan habitat tracking with the 4.2 ka Indus discharge event suggests a causal relationship. A possible explanation is that a reduction of the average annual rainfall over the Indus river watershed restricted Harappan farming in the Indus valley and left large city populations unsustainable.

4. Causes of Holocene Monsoon Change

[7] A reduction in annual rainfall over the Indus watershed must not necessarily be the result of a change in the amount of summer monsoon rain alone. Although Indus discharge is extremely biased towards the summer monsoon season [*Milliman et al.*, 1984], the $\delta^{18}O$ of Indus water is lighter than monsoon rainwater and significantly affected by melt water from glaciers and snowfields in the Karakoram and western Himalayas, which are largely fed by winter and

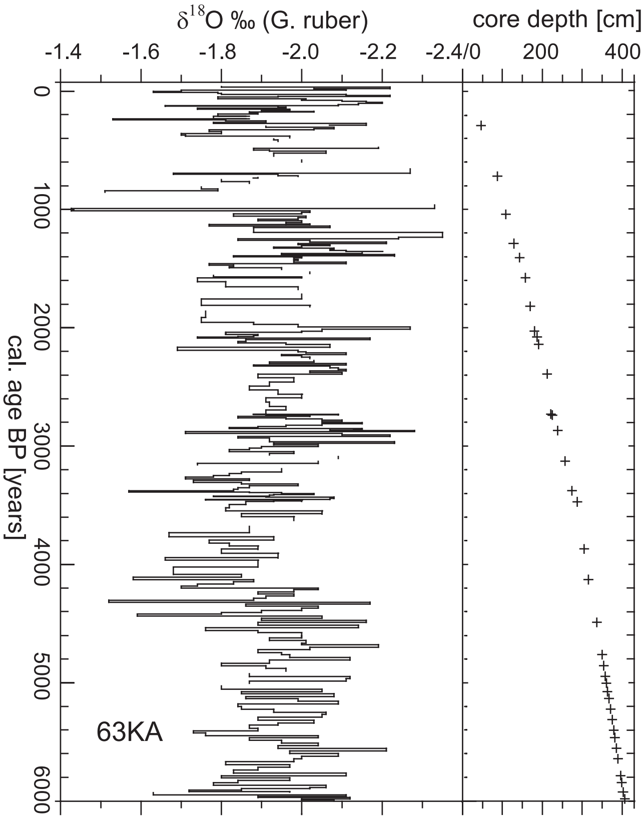

Figure 2. Core 63KA (sedimentation rate 65 cm/ka, see supplementary note 1) was sampled for *Globigerinoides ruber* in continuous 1 cm intervals (typically 15–30 individuals) with a few intermittent sections of coarser sampling. Gaps in the record are due to absent *G. ruber*.

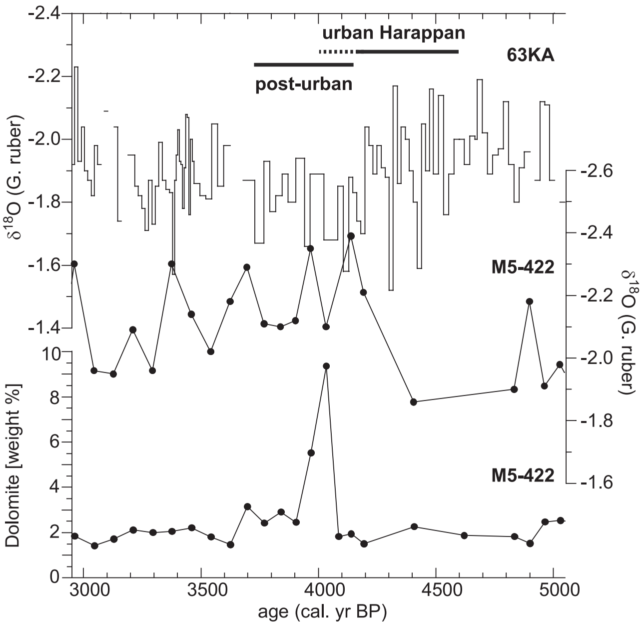

Figure 3. Core 63KA (northeastern Arabian Sea) δ^{18}O of *Globigerinoides ruber* compared to core M5-422 (Gulf of Oman) δ^{18}O (*G. ruber*) and dolomite concentration [*Sirocko*, 1995; *Cullen et al.*, 2000]. Dolomite is a proxy for dust flux from a northern Arabian source. The same ^{14}C reservoir correction was used in both cores. Harappan and Akkadian cultural phases are given for comparison.

spring precipitation [*Mook*, 1983; *Wake*, 1989; also The Global Precipitation Climatology Centre, available at http://www.dwd.de/research/gpcc, 1998, hereinafter referred to as GPCC, 1998]. Advanced glaciers in the Karakoram mountains as well as pollen assemblages and lake-levels in the Thar desert suggest that winter/spring rain was also higher than today during the mid Holocene and extended further southwards than at present [*Singh et al.*, 1990; *Enzel et al.*, 1999; *Phillips et al.*, 2000]. It is therefore likely, that Indus discharge was then distributed more evenly over the year, and that an enhanced annual Indus discharge rate led to lighter δ^{18}O values in the northeastern AS. At the time of the Indus discharge reduction at 4.2 ka BP, dust flux from northern Arabia and Mesopotamia also increased (Figure 3), and rainfall in the Eastern Mediterranean was reduced [*Bar-Matthews et al.*, 1997; *Cullen et al.*, 2000]. This regional pattern suggests a significance of the 4.2 ka BP drought event beyond the south Asian summer monsoon regime into the winter rain dominated extra tropics of the northern hemisphere. It is likely, that the drought induced decline of ancient civilizations in Mesopotamia and south Asia at ~4.2 ka BP is the consequence of altered extra tropical airflow during winter and a change in monsoon seasonality.

[8] Recently, a relationship between global climate change during the Holocene and the variation in solar radiation has been demonstrated [*Neff et al.*, 2001; *Bond et al.*, 2001]. Solar radiation variability is generally inferred from cosmogenic ^{14}C production records, where enhanced production rates are attributed to lower solar radiation intensity and a reduced shielding of the earth from cosmic particles by the solar magnetic field [*Stuiver and Braziunas*, 1993]. The coherent quasi-periodic pacing of Indus discharge and ^{14}C production on the multi-centennial band (630–780 years) during the late Holocene following the 4.2 ka BP event suggests a link between solar variability and south Asian climate change (Figure 4, see also supplementary note 2). Minima in the bi-centennially averaged record of ^{14}C production rate (enhanced solar radiation) correspond to heavier δ^{18}O values (reduced Indus discharge/drier conditions over the NW Indian subcontinent), and ^{14}C production maxima (reduced solar radiation) correspond to lighter δ^{18}O (higher discharge/wetter conditions) after the 4.2 ka BP event. Across the 4.2 ka BP event a similar reduction in the ^{14}C production rate can be observed, but there is no apparent similarity between the two records prior to that event between ~4.5 and 7 ka BP. As such, no full cycle is observable across the event, and the contribution of solar forcing to the Indus discharge reduction at 4.2 ka BP in particular remains somewhat uncertain. However, a well-dated dry spell has been observed in the Thar desert around 4.7 ka cal BP [*Enzel et al.*, 1999], which coincides with a ^{14}C production minimum. Therefore, we cannot rule out that the absence of coherency between solar variability and Indus discharge between ~4.5 and 7 ka BP may be due to either a sampling artifact or a different δ^{18}O - salinity - SST relationship. Because of a potential inaccuracy of the AS surface ^{14}C reservoir correction of up to 150 years prior to 7 ka [*Staubwasser et al.*, 2002], chronological uncertainty may obscure any present coherency in the early Holocene. However, spectral analysis of the AS 63KA and Oman stalagmite δ^{18}O records suggests a significant contribution of solar forcing to early Holocene south Asian climate variability [*Neff et al.*, 2001; *Staubwasser et al.*, 2002].

[9] Climate cycles in the ~700 years band are inherent in other Holocene records from south Asia, but have hitherto

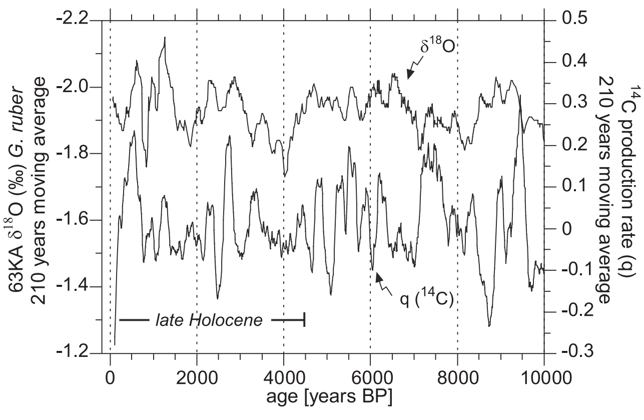

Figure 4. Comparison of the detrented global ^{14}C production rate [*Stuiver and Braziunas*, 1993] with the δ^{18}O (*G. ruber*) record of core 63KA. The late Holocene section of 63KA is from [*Staubwasser et al.*, 2002]. Both records have been smoothed by a 210 years moving average. After 4.2 ka BP the two records show a similar pacing of change, which is significantly coherent in the 630–780, and 250–280 years frequency band (see supplementary note 2). Superimposed millennial scale variability can be observed throughout the Holocene with clusters of multi-centennial cycles spaced ~1500–2000 years apart. The millennial cycles are recurrent in lower resolution Arabian Sea cores [*Sirocko et al.*, 1996].

not been matched with solar radiation [*Wang et al.*, 1999; *Sarkar et al.*, 2000]. The large-scale significance of this cycle suggests that subtropical Asian climate in general is relatively sensitive to changes in solar radiation. Climate modeling has demonstrated a non-uniform global response of annual surface temperatures to changes in solar radiation, with a relative warming of the east African tropics and the Tibetan Plateau occurring at high solar radiation [*Cubasch et al.*, 1997]. This would have a direct effect on the fundamental cause of the south Asian summer monsoon, i.e. the heat gradient between the warm Tibetan Plateau and the cool southern Indian Ocean. However, a mismatch of amplitudes in the monsoon and solar radiation records (Figure 4) suggests that any such link would be complex. On inter-annual time-scales, changes in boundary conditions due to non-solar causes result in large amplitude variations of the monsoon [*Webster et al.*, 1998]. There is a tendency of a strong south Asian monsoon to be followed by a relatively weak one [*Meehl*, 1994]. This is part of the large scale tropospheric biennial oscillation, in which tropical/subtropical summer convection over east Africa, south Asia and the Indo-Pacific Ocean is coupled with extra tropical atmospheric flow over Asia in a way that modulates air flow direction, temperature and precipitation over south and central Asia in winter. It is possible that higher levels of solar energy output during the Holocene may have enhanced inter-annual summer monsoon variability, altered winter airflow over south Asia, and changed total annual precipitation over the Indus watershed.

[10] **Acknowledgments.** We thank J. Negendank (GFZ, Potsdam) for additional funding within the KIHZ project of the Helmholtz Gemeinschaft (HGF), and G. Henderson (Oxford) for support. MS was funded by an EC Marie Curie Fellowship.

References

Bar-Matthews, M., A. Ayalon, and A. Kaufman, Late Quaternary paleoclimate in the eastern Mediterranean region from stable isotope analysis of speleothems at Soreq Cave, *Israel, Quat. Res.*, *47*, 155–168, 1997.
Bemis, B. E., H. J. Spero, J. Bijma, and D. W. Lea, Reevaluation of the oxygen isotopic composition of planktonic foraminifera: Experimental results and revised paleotemperature equations, *Paleoceanography*, *13*, 150–160, 1998.
Bond, G. C., et al., Persistent solar influence on North Atlantic climate during the Holocene, *Science*, *294*, 2130–2136, 2001.
Cubasch, U., R. Voss, G. C. Hegerl, J. Waszkewitz, and T. J. Crowley, Simulation of the influence of solar radiation variations on the global climate with an ocean-atmosphere general circulation model, *Clim. Dyn.*, *13*, 757–767, 1997.
Cullen, H. M., et al., Climate change and the collapse of the Akkadian Empire; Evidence from the deep sea, *Geology*, *28*, 379–382, 2000.
Delaygue, G., et al., Oxygen isotope/salinity relationship in the northern Indian Ocean, *J. Geophys. Res.*, *106*, 4565–4574, 2001.
deMenocal, P., J. Ortiz, T. Guilderson, and M. Sarnthein, Coherent high- and low-latitude climate variability during the holocene warm period, *Science*, *288*, 2198–2202, 2000.
Doose-Rolinski, H., U. Rogalla, G. Scheeder, A. Luckge, and U. von Rad, High-resolution temperature and evaporation changes during the late Holocene in the northeastern Arabian Sea, *Paleoceanography*, *16*, 358–367, 2001.
Enzel, Y., et al., High-resolution holocene environmental changes in the Thar Desert, northwestern India, *Science*, *284*, 125–128, 1999.
Gasse, F., Hydrological changes in the African tropics since the Last Glacial Maximum, *Quat. Sci. Rev.*, *19*, 189–211, 2000.
Hassan, F. A., Nile floods and political disorder in early Egypt, in *Third Millenium BC Climate Change and Old World Collapse*, *NATO ASI Ser. 1*, vol. 49, edited by H. N. Dalfes, G. Kukla, and H. Weiss, pp. 1–24, Springer, New York, 1997.
Levitus, S., and T. P. Boyer, World Ocean Atlas 1994 Vol. 4: Temperature NOAA Atlas NESDIS 4. U.S. Department of Commerce, Washington, D.C., 117 pp., 1994.
Levitus, S., R. Burgett, and T. P. Boyer, World Ocean Atlas 1994 Vol. 3: Salinity NOAA Atlas NESDIS 3. U.S. Department of Commerce, Washington, D.C., 91 pp., 1994.
Meehl, G., Coupled land-ocean-atmosphere processes and south Asian monsoon variability, *Science*, *266*, 263–267, 1994.
Milliman, D. J., G. S. Quraishee, and M. A. A. Beg, Sediment discharge from the Indus River to the ocean: Past, present, and future, in *Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan*, edited by B. U. Haq and J. D. Milliman, pp. 65–70, Van Nostrand Reinhold, New York, 1984.
Mook, W. G., The oxygen-18 content of rivers, *Mitt. Geol. Palaeontol. Inst. Univ. Hamburg*, *52*, 565–570, 1983.
Neff, U., et al., Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago, *Nature*, *411*, 290–293, 2001.
Phillips, W. M., et al., Asynchronous glaciation at Nanga Parbat, northwestern Himalaya mountains, Pakistan, *Geology*, *28*, 431–434, 2000.
Possehl, G., Climate and the eclipse of the ancient cities of the Indus, in *Third Millenium BC Climate Change and Old World Collapse*, *NATO ASI Ser. 1*, vol. 49, edited by H. N. Dalfes, G. Kukla, and H. Weiss, pp. 193–244, Springer, New York, 1997.
Rao, R. R., R. L. Molinari, and J. F. Festa, Evolution of the climatological near-surface thermal structure of the tropical Indian Ocean, *J. Geophys. Res.*, *94*, 10,801–10,815, 1989.
Sarkar, A., et al., High resolution Holocene monsoon record from the eastern Arabian Sea, *Earth Planet. Sci. Lett.*, *177*, 209–218, 2000.
Singh, G., R. J. Wasson, and D. P. Agarwal, Vegetational and seasonal climatic changes since the last full glacial in the Thar Desert, northwestern India, *Rev. Palaeobot. Palynol.*, *64*, 351–358, 1990.
Sirocko, F., Habilitation thesis, Univ. of Kiel, Kiel, Germany, 1995.
Sirocko, F., D. Garbe-Schonberg, A. McIntyre, and B. Molfino, Teleconnections between the subtropical monsoons and high-latitude climates during the last deglaciation, *Science*, *272*, 526–529, 1996.
Staubwasser, M., F. Sirocko, P. M. Grootes, and H. Erlenkeuser, South Asian monsoon climate change and radiocarbon in the Arabian Sea during early and mid Holocene, *Paleoceanography*, *17*(4), 1063, doi:10.1029/2000PA000608, 2002.
Stuiver, M., and T. F. Braziunas, Sun, ocean, climate and atmospheric "SUP 14" CO "SUB 2": An evaluation of causal and spectral relationships, *Holocene*, *3*, 289–305, 1993.
Wake, C., Glaciochemical investigations as a tool for determining the spatial and seasonal variation of snow accumulation in the central Karakoram, northern Pakistan, *Ann. Glaciol.*, *13*, 279–284, 1989.
Wang, L., et al., Holocene variations in Asian monsoon moisture: A bidecadal sediment record from the South China Sea, *Geophys. Res. Lett.*, *26*, 2889–2892, 1999.
Webster, P., et al., Monsoons: processes, predictability, and the prospects of prediction, *J. Geophys. Res.*, *103*, 14,451–14,510, 1998.
Weiss, H., et al., The genesis and collapse of third millennium north Mesopotamian civilization, *Science*, *261*, 995–1004, 1993.
Weiss, H., Beyond the Younger Dryas: Collapse as adaptation to abrupt climate change in ancient west Asia and the eastern Mediterranean, in *Confronting Natural Disaster: Engaging the Past to Understand the Future*, edited by G. Bawden and R. Reycraft, pp. 75–98, Univ. of New Mexico Press, Albuquerque, 2000.

P. M. Grootes, Universität Kiel, Leibniz Labor, Max Eyth Str., 24118 Kiel, Germany.
M. Segl, Universität Bremen, Geowissenschaften, Klagenfurter Str., 28359 Bremen, Germany.
F. Sirocko, Institute für Geowissenschaften, Universität Mainz, Becher Weg 21, 55099 Mainz, Germany.
M. Staubwasser, Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, UK. (michael.staubwasser@earth.ox.ac.uk)