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Holocene Variations in Asian Monsoon Moisture: a Bidecadal Sediment Record from the South China Sea

Luejiang Wang[1] and Michael Sarnthein
Institut fuer Geowissenschaften, University of Kiel, D-24098 Kiel, Germany

Helmut Erlenkeuser and Pieter M. Grootes
Leibniz Labor, University of Kiel, D-24098 Kiel, Germany

Joan O. Grimalt and Carles Pelejero
Department of Environmental Chemistry (C.I.D.-C.S.I.C.), 08034 Barcelona, Catalonia, Spain

Gudula Linck
Institut für Orientalistik, University of Kiel, D-24098 Kiel, Germany

Abstract. The East Asian monsoon system involves extensive transport of sensible/latent heat between land and sea and from low to high latitudes. Our high resolution, bidecadal marine records present a first detailed history of monsoon climate change over the Holocene. The high-amplitude perturbation in monsoon moisture centered at 8,150 years ago and the monsoon maximum in the Early Holocene show inter-hemispheric teleconnections to both a cool episode in Greenland and to the Indian monsoon monitored in the Arabian Sea. Periodicities of 84, 102 and, especially, near 775 years in monsoon variation suggest a climatic forcing both by long-term oscillations in thermohaline circulation and (possibly) solar activity cycles.

Introduction

Monsoon summer rains form the main source of moisture in southern Asia being crucial for sustaining life in this densely populated region. Previous studies have shown that some dry phases with enhanced monsoon dust discharge during winter were mainly linked to glacial/cold stages, short-term Heinrich events, and the Younger Dryas (Kudrass et al. 1991), whereas interglacials led to wet climate and soil formation in China (Porter and An 1995). One may expect that events of enhanced precipitation and fluvial runoff in South China lead to an enlarged plume of low sea-surface salinity (SSS) offshore Hong Kong (Fig. 1). In this study, we present a new time series of SSS with bidecadal resolution, which was reconstructed from hemipelagic sediments at the continental margin of South China for the last 10,000 years. During this time, sea level had almost reached its modern level, hence lateral shifts of the coastline were insignificant, unable to influence the salinity variations recorded at our continental-margin site 17940 (Fig. 1). Like in the Arabian Sea (Sirocko et al. 1993), the results show an early Holocene (Preboreal) extreme in runoff that ended with a salinity maximum at about 8300 calendar yr BP. Thus, a hemisphere-wide synchroneity of long-term changes in monsoon precipitation is established.

[1]Now at Department of Geoscience, Graduate School of Environmental Earth Science, Hokkaido University, Sapporo, Japan.

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Samples and methods

Gravity core 17940 (20°07'N, 117°23'E; 1727 m water depth; 13.30 m long) was obtained on SONNE cruise 95 (Sarnthein et al. 1994) from the South China continental margin, 400 km southeast of Hong Kong (Fig. 1). This location lies close to a prominent freshwater plume from the Pearl River mouth, which has the second largest water discharge of China. *Parasound* sub-bottom profiles showed that the hemipelagic sediments at core location 17940 are undisturbed (Sarnthein et al. 1994).

The sediment records were dated by 40 AMS-radiocarbon ages on *Globigerinoides ruber* (white) and/or *G. sacculifer* (Fig. 2a). In the last 11 ka, the calendar age model developed for this core was based on date-by-date comparison with the age conversion scheme of Stuiver and Braziunas (1993) after application of a smooth-spline and an estimated reservoir age for the western Pacific of 540 y (Wang et al., 1998). Beyond the calibration age of dendrochronology, ^{14}C years were corrected by 2000-3500 years using calibration schemes based on rare U/Th ages and varves. Sedimentation rates of 40-85 cm per 1,000 yr and a $\delta^{18}O$ sampling distance of 1 to 2 cm provided a time resolution of 15-25 years over the last 10,000 years B.P., with each sample averaging 1 cm in diameter. The fairly constant sedimentation rates (about 50-80 cm ka) over the last 8500 years suggest that the sediments were laid down in a continuous regular manner. The bioturbational mixing

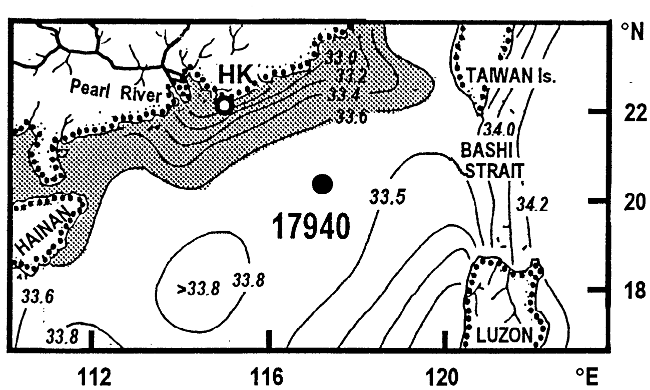

Figure 1. The northern South China Sea, with the modern plume of low sea-surface salinity in front of the Pearl River mouth near Hong Kong (HK) during summer and the position of core 17940 (Sarnthein et al. 1994).

depth (Trauth et al. 1997) amounts to 6.0-7.5 cm during the Holocene.

The molecular tracer $U^{k'}_{37}$ was measured at spacings of 4-10 cm in 1-cm intervals and converted into SST values using an empirical equation (Pelejero and Grimalt 1997) for annual average and 0-30 m water depth. The SST estimate from the undisturbed sediment surface (0-1 cm depth) approximately matched the modern SST value measured in this region (Fig. 2a). After correcting the $\delta^{18}O$ values for minor Holocene variations in global ice volume (Fairbanks 1989), paleosalinities were calculated from planktonic $\delta^{18}O$ values and SST, based on the equation of Wang et al. (1995). The SST estimates were interpolated to match in age the more narrowly spaced $\delta^{18}O$ data and were smoothed by a spline fit to avoid spurious frequency signals generated by different measurement spacings. The smoothing procedure retained significant changes (*e.g.* Younger Dryas) and fell within the analytical error of the $U^{k'}_{37}$ SST (±0.7°C).

Spectral analysis was performed using standard time-series procedures. The SSS record was linearly interpolated on equidistant steps of 30 yr. The method calculates the Fourier transform of the autocovariance function (Nyquist frequency of 1/64 yr^{-1}).

The modern SSS value (33.9‰) deviates from our SSS estimate from the core top by about −1.2‰, a systematic deviation which is related to a problem of choosing annual-

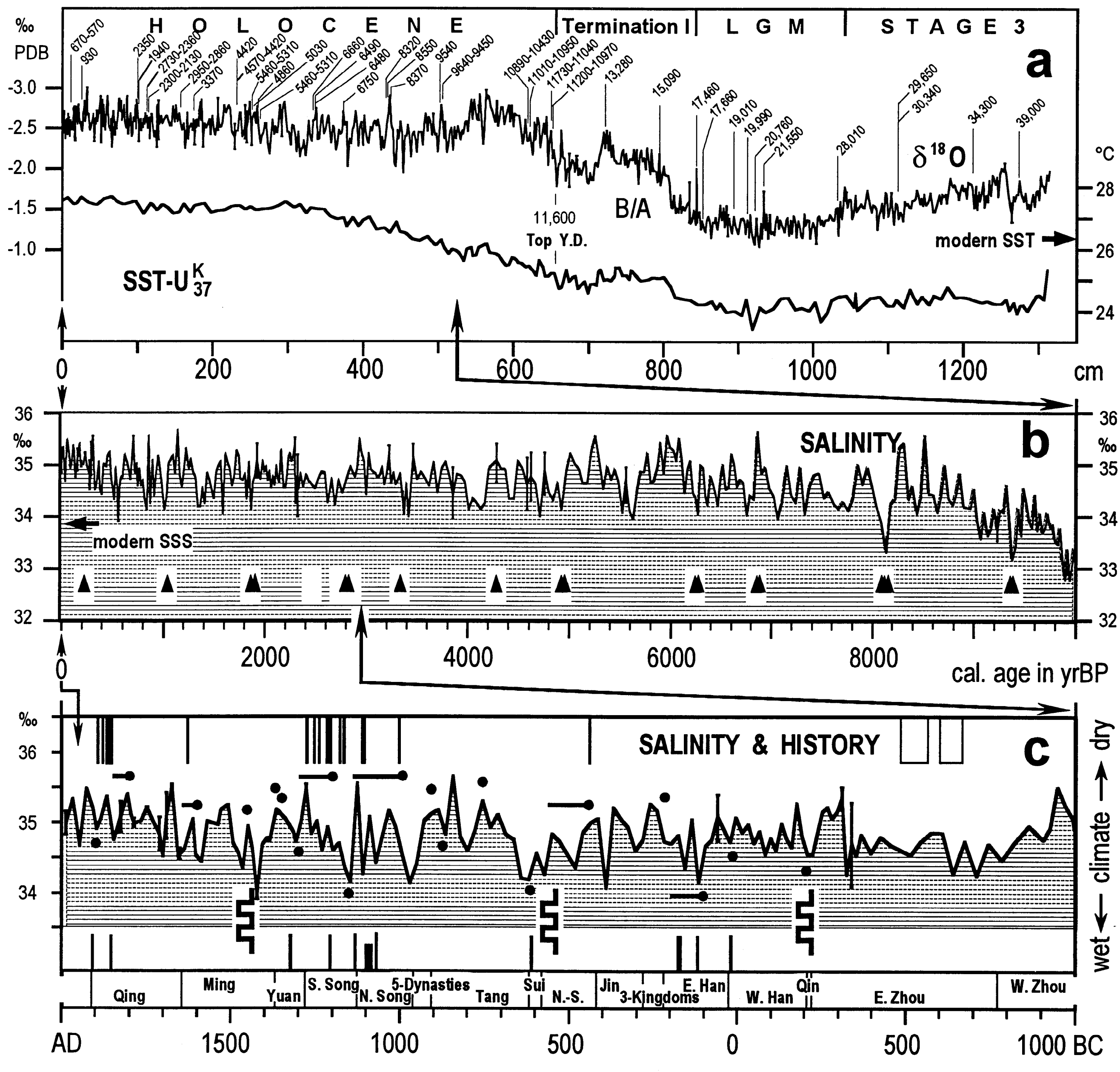

Figure 2. (a) Calendar ages (cal. yr BP) of core 17940-1/2 and planktonic $\delta^{18}O$ values of *G. ruber* (white), diameter: 315-400 μm, 15-20 specimens. Numerous duplicate $\delta^{18}O$ analyses indicated by error bars confirm the oscillations of the record. Annual sea surface temperatures (SST) at 0-30 m water depth are based on C_{37} alkenones. Arrow at right margin shows annual average modern seasonal SST (Levitus 1982). LGM = last glacial maximum. Y.D. = Younger Dryas. B/A = Bølling-Allerød (b) Close-up of summer sea surface salinity (SSS) at 0-50 m water depth over the last 10,000 yr. Arrow at left margin shows modern annual SSS range (Japan Hydrographic Association 1978); triangles indicate age control points. (c) Close-up of SSS over the last 3,000 yr. Bars on the upper and lower margins identify droughts and floods, respectively, as recorded in Chinese historiography; bullets indicate major peasant uprisings, in part extending over >100 years; crenellated lines show main construction phases of the Great Wall (Gernet 1979). A Chinese dynasty sequence is added at the bottom of this panel.

average SST values for 0-30 m water depth (Pelejero and Grimalt, 1997). If we choose SST values for 0-50 m, obviously a closer approximation to the local habitat depth of *G. Ruber*, the difference between estimated and measured SSS sinks to –0.5‰ and less.

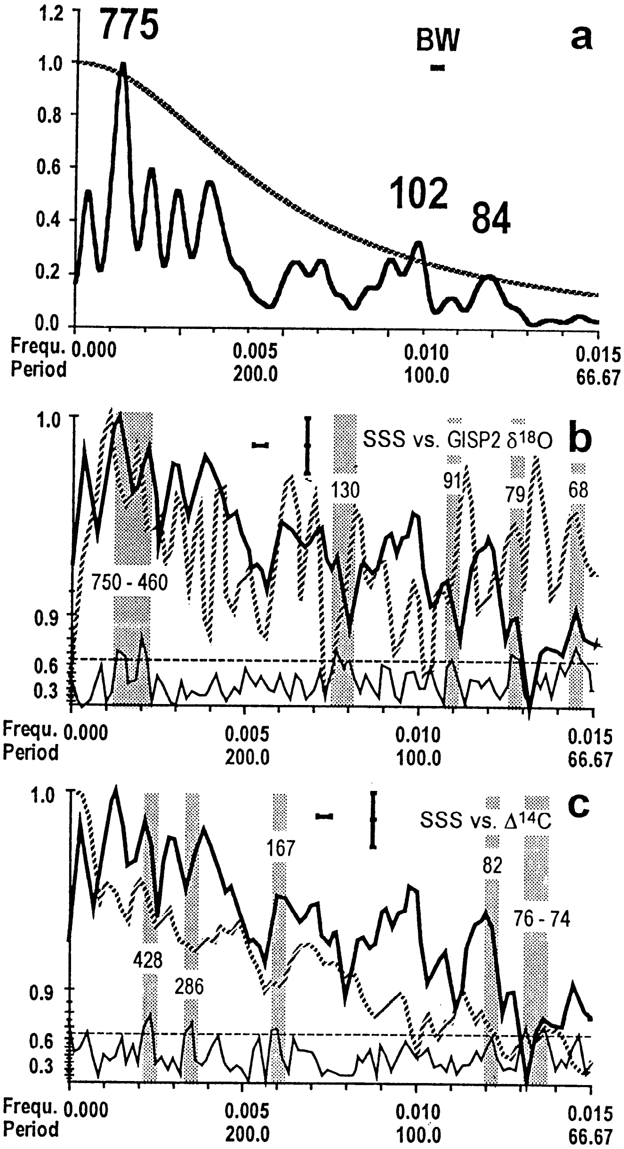

Figure 3. (a) Frequency spectra of sea surface salinity (SSS) variations in sediment core 17940-1/2 over the last 10,000 yr. Numbers indicate periods in years. Vertical axis is the normalized spectral density; the upper limit of red noise at 80% confidence level is shown by stippled line. (b) Cross spectra (lower thin line) between SSS record in core 17940 (thick solid line) and the $\delta^{18}O$ record in the GISP2 ice core (Stuiver et al. 1995; stippled line), the data spacings are linearly interpolated to an equidistance of 30 years. A significant coherency (above the non-zero coherency 80% level (= dashed line) and with a coherency confidence interval (vertical bar) at the 80 % level) occurs near periods of 750, 460, 130, 91, and 77-79 years (c) Cross spectra (lower thin line) between SSS record in core 17940 (thick solid line) and the tree-ring $\delta^{14}C$ record (stippled line; Stuiver and Braziunas 1993). The data spacing are linearly interpolated to an equidistance of 30 years. A significant coherency (above the non-zero coherency 80% level (= dashed line) and with a coherency confidence interval (vertical bar) at the 80% level) is only found at periods of 428, 286, 167 and 82/76 years. Horizontal and vertical bars in b) and c) indicate the bandwidth at 30% lag numbers and the coherency confidence interval at 80% level, respectively.

Results and discussion

Except for the Early Holocene (650-400 cm core depth), most long-term variations of the planktonic $\delta^{18}O$ record are reflected in the SST-$U^{k'}_{37}$ signal (Fig. 2a). Low SST during late isotope stage 3 are similar to the last glacial maximum (LGM), which is followed by a two-step glacial termination I, including a pronounced Bølling-Allerød plateau at dated levels of 15,500-12,850 cal. yr B.P. and a distinct, possibly binary, Younger Dryas cold spell (ΔT up to 0.7 °C) about 12,620-11,600 cal. yr B.P. In contrast to the extreme $\delta^{18}O$ minimum right after the Younger Dryas, SST values increased only gradually by 2.5°C during Preboreal and early Holocene times, from 11,600 to 6750 yr B.P. (Fig. 2a). A constant, small range of both $\delta^{18}O$ and SST variations marks the last 6750 years.

The Holocene SSS variations mostly result from the $\delta^{18}O$ fluctuations (Figs. 2a and 2b). The small SST-$U^{k'}_{37}$ changes (±0.25°C) only exert a minor influence on the SSS estimates. From 10,000-8,500 yr BP, the global ocean $\delta^{18}O$ decreased due to melting ice sheets by less than 0.1 ‰ and by a further 0.1 ‰ until today (Fairbanks 1989), each increment corresponding to about 10 m sea-level rise. Accordingly, the Chinese coastline basically remained in place during the Holocene, because the minus-20 m isobath occurs close to the present shore of China. Hence, the broad salinity fluctuations in Fig. 2b directly record the local freshwater admixture and accordingly, the monsoon hydrological cycle.

The most prominent $\delta^{18}O$ freshwater spike of the Holocene started right after the end of the Younger Dryas and gradually ended about 9000 years ago (Fig. 2a). Both the start and the end of this freshwater event are synchronous with a similar maximum in monsoon moisture found in the Arabian Sea (Sirocko et al. 1993), pointing to a hemisphere-wide joint forcing of the long-term changes in the hydrological cycle of the Asian monsoon. Thus, higher freshwater content reflects an increased plume from the Pearl River and therefore more rain over South China because of stronger summer monsoon.

A striking but short-term (~150 years long) salinity perturbation of up to 2‰ (!) in amplitude occurred about 8100-8300 yr B.P., which is coeval with the unique short-term cooling episode in the Holocene recorded in the Greenland ice core near 8200 yr B.P. (Grootes and Stuiver, 1997). The salinity minimum represents a maximum in monsoonal runoff and precipitation/wetness right after the SSS maximum linked to the early Holocene cold event near 8250 y, which in this study is picked within the limits of dating precision with excellent accuracy. This 8150 y minimum can be interpreted as a recovery fluctuation of high (summer) monsoon intensity assuming that the observed short-term SSS excursions were governed by an internal (oceanic?) oscillation mechanism.

Later, SSS varied persistently by ±0.75 ‰, a range exceeding twice the salinity gradient of the modern freshwater plume off Hong Kong (Fig. 1). Extreme $\delta^{18}O$ -SSS excursions were corroborated by duplicate $\delta^{18}O$ data (Figs. 2a and b). Over the last 500 years the general rise in the level of salinity fluctuations by ~0.7 ‰ may present a first paleoceanographic signal of weakened monsoon rains during the Little Ice Age.

A simple visual inspection of the $\delta^{18}O$ and SSS records in Figs. 2a and b already suggests that monsoon precipitation during the Holocene was subject to ongoing regular oscillations. Fig. 3a shows three significant SSS periodicities, a more robust one at 775, two less robust ones at 102, and 84 years, accounting for 18.2, 4.1 and 3.0 % of the total variance, respectively. Subordinate cycles at 2940, 463, 342, 260, 157-141, and 110 years lie well below the noise background at the 80% confidence level.

The periodicity of 775 years is consistent with the high-frequency SST cycle of 760 years observed at Termination II in ODP Site 658. This core is situated in the Northwest African upwelling system, which is driven by the trade winds that are inversely related to the African monsoon (Kutzbach and Guetter 1986). However, the low-frequency oscillations off Northwest Africa near 1150, 1600/1800 years, which are similar to those reported in the Arabian Sea (Sirocko et al. 1996), do not occur in the SSS record from the South China Sea.

The cycle of 84 years in the SSS record off Hong Kong precisely matches the Gleissberg sun-spot period of 84 years. This periodicity is most prominent in the $\delta^{18}O$ "temperature" record of the GISP2 ice core from Greenland over the last 10,000 years (Grootes and Stuiver 1997; Fig. 3b). Cross spectral analyses between the two records reveal various coherencies at and above the 80% non-zero coherency level near 750, 460, 130, 91 and 77-79 years (Fig. 3b). The robust 775-year periodicity in SSS comes close to a subharmonics (50%) of the outstandingly dominant 1500-year cycle in the GISP2 $\delta^{18}O$ record (Grootes and Stuiver 1997).

Comparison of core 17940 SSS variations with a bidecadal record of atmospheric $\delta^{14}C$ based on tree-ring measurements (Stuiver and Braziunas 1993) shows cross spectral coherency at periods of 428, 286, 167 and 82/76 years (Fig. 3c). The coherent cycle at 88 and 84 years again may indicate a general climatic forcing by solar activity changes linked to the Gleissberg cycle. The lack of correlation with the significant 775 and 102 year periodicities in core 17940 points to a relationship of these frequencies with the oceanic salinity conveyor belt, a subharmonics also responsible for the 1500-year cycle in the GISP2 ice core. This cycle is clearly seen in the Indian monsoon record of Siroco et al. (1996). In view of the "see-saw" mechanism between northern and southern climate in the range of the Dansgaard-Oeschger cycles (Stocker, 1998), North Atlantic heat absorption in the equator and South Atlantic (Berger and Wefer, 1996), the East Asian monsoon may be receiving a duplicate forcing from both North and South hemispheres.

Concluding remarks

The present study shows that East Asian monsoons changed synchroneously with the wind regime of the Northern Hemisphere. Moreover, the high resolution of the SSS record in core 17940 evidence that this monsoon system was possibly significantly influenced by the Gleissberg solar periodicity (84 years). The more robust longer periodicity of this SSS record at 775 is also observed in other wind driven systems (*e.g.*, African upwelling) and may represent a subharmonics of the dominant 1480-year cyclicity in the $\delta^{18}O$ record of GISP2, possibly pointing to a forcing of an internal oscillator in the global thermohaline circulation.

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H. Erlenkeuser and P.M. Grootes, Leibniz Labor, University of Kiel, Max-Eyth Str. 11, 24118 Kiel, Germany (e-mail: pgrootes@leibniz.uni-kiel.de)

J.O. Grimalt and C. Pelejero, Department of Environmental Chemistry (ICER-CSIC), Jordi Girona, 18, 08034 Barcelona, Catalonia, Spain (e-mail: jgoqam@cid.csic.es; cpbqam@cid.csic.es)

G. Linck, Department of Chinese Studies, Institute for Oriental Studies, University of Kiel, Leibnizstrasse 10, 24118 Kiel, Germany

M. Sarnthein, Institut fuer Geowissenschaften, University of Kiel, Olshausenstrassse 40, 24118 Kiel, Germany (e-mail: ms@gpi.uni-kiel.de)

L. Wang, Department of Geoscience, Graduate School of Environmental Earth Science, Hokkaido University, Sapporo, 060-0810 Japan (e-mail: ljwang@ees.hokudai.ac.jp).

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