Running Title: Late Quaternary East Asian Summer Monsoons

History of East Asian Summer Monsoon Climates During the Late Quaternary: Land-Sea Connection

Kuo-Yen Wei, Tzu-Chien Chiu, and Yue-Gau Chen

Institute of Geosciences, National Taiwan University, Taipei, Taiwan 10617, ROC

Correspondence should be addressed to K.Y.W. (e-mail: weiky@ms.cc.ntu.edu.tw).

ABSTRACT

The East Asian monsoon is a system in which seasonality of wind directions, temperature and precipitation show strong linkage between low and middle latitudes, as well as between land and sea. The magnetic susceptibility of the paleosol-loess sequence of Louchuan in the central Chinese Plateau fluctuates in concert with a newly-derived maritime summer monsoon index of the last 870-kyrs from the South China Sea, attesting that continental wet periods are associated with stronger summer monsoons during the interglacial stages. Notably, paleosol units S3 and S5 spanned longer in time than the conventionally defined marine oxygen isotope stages (MIS) 9 and 15, respectively. High values of maritime summer monsoon index during MIS 9 – 8.5 (340-280 ka) and MIS 15-13 (620-480 ka) can account for the development of thick paleosols of S3 and S5.

INTRODUCTION

Analogous to the global salinity convey belt in the ocean, the Asian monsoon system in the atmosphere plays an important role in transporting moisture and heat from low to middle latitudes (Webster, 1987; Webster et al., 1998). The East Asian monsoon, as the eastern component of the Asian monsoon, is driven mainly by the differential heating of the ocean and Asian landmass (Li and Yanai, 1996), and conceivably, a system in which strong seasonality of wind directions, temperature and precipitation show close relationship between low and middle latitudes, between land and sea. However, a direct link between the Chinese loess records with marine records from the nearby source area of heat and moisture, the South China Sea, is yet to be demonstrated and examined.

EAST ASIAN MONSOON RECORDS OF THE CHINESE LOESS PLATEAU

Paleosol-loess sequences in north China have provided long-term records of East Asian monsoons over the Chinese Loess Plateau during the Quaternary (An et al., 1990, 1991; Banerjee, 1995; Ding et al, 1995; Kukla and An, 1989; Heller and Liu, 1982; Kukla et al., 1988; Liu et al., 1991). Such records have been correlated to deep-sea oxygen isotope stratigraphy (Heller and Liu, 1984, 1986; Kukla, 1987;. Kukla et al., 1988; Ding et al., 1994; Bloemendal et al., 1995; Tauxe et al., 1996; Zhou and Shackleton, 1999; Heslop et al., 2000), mostly for establishing a chronology for the terrestrial records. Such exercises have suggested that both summer (Lu et al., 1999) and winter (Ding et al., 1995) monsoon variations are dominated by ice-volume forcing throughout the past 800,000 years. A direct correlation of the loess records with nearby marine records is only available for short time interval (the last ~20,000 years, see An et al., 1993), partly because long-term marine records of Quaternary have become available only most recently (Shyu et al., 2001; Wang et al., 2001).

OXYGEN ISOTOPE STRATIGRAPHY FROM THE SOUTH CHINA SEA

Herein, we present a high-resolution oxygen isotopic record for the past 870 kyrs from Core MD972142 (12°41.33'N, 119°27.90'E) in the southeast South China Sea and compare it with an astronomically tuned record from the classical Louchuan Section (35 ° 45'N, 109 ° 25'E) (Heslop et al., 2000) in central Chinese Loess Plateau (Fig. 1). The deep-sea sedimentary core was retrieved from the continental slope off Palawan Island at a water depth of 1557 m during the 1997 IMAGES-III-IPHIS Cruise (Chen et al., 1998). The well-preserved foraminifers in this 35.9m-long sequence allowed us to establish a continuous record of the past 870 kyrs. About 8 specimens of planktic foraminifer *Globigerinoides ruber* in the size range of 250-300 μm were picked from each sample and processed for isotopic analyses. With the confirmation of two independent chronostratigraphic markers, namely, the last appearance of pink-pigmented *G. ruber* (~125ka) (Thompson et al, 1979; Lee et al., 1999) at 910cm, and the Matuyama/Brunhes (M/B) geomagnetic boundary at 3370 cm (Lee, 2000), the resulted δ^{18}O time-series can be well correlated with the low-latitude stack (Bassinot et al., 1994) down to marine oxygen isotopic stage 21 (Fig. 2c). We further tuned the record against two astronomical target curves made of insolation variation caused by obliquity and precession at 15 ° N to get an astronomical time scale following the method outlined by von Grafenstein et al (1999). The tuning established an independent astronomical timescale for site MD972142 pertinent to tropical variation in the marine monsoonal realm of the East Asia.

To facilitate a comparison of the MD972142 record with a comparable record obtained from the ODP Site 769 (Linsley and Dunbar, 1994) in the neighboring Sulu Sea (Fig. 1), the Sulu Sea record was re-calibrated against the time-scale of MD972142 by curve matching (Fig. 2c). Both records were re-sampled at every 4,000 years through the past 800,000 and the difference between the two newly interpolated time-series were calculated as shown in Fig. 2b. Separated only by a shallow sill at 420 m of the Mindoro Strait, the Sulu Sea is situated in similar latitudes with the

South China Sea and therefore shares with similar climatic conditions except that Sulu Sea has slightly higher sea-surface salinity (by 0.5‰) (Levitus et al., 1994) and temperature (~0.5 °C) (Levitus and Boyer, 1994). Given the fact that the oxygen isotopic profiles of MD972142 and ODP769 were generated from the same foraminifer species, *G. ruber*, at comparable size range, the two records were expected to yield similar values and pattern over time while the effects caused by the slight difference in temperature and salinity should cancel each other out. Nevertheless, MD972142 tends to show more negative δ^{18}O values than ODP769, especially during the interglacial stages (the odd-numbered stages in Fig. 2c). Larger gradients (up to 1 – 1.5 ‰) exist for most parts of the interglacial stages whereas small difference (0 – 0.5 ‰) for the glacial stages (Fig. 2b). Furthermore, the amplitude of the glacial-interglacial fluctuation in MD972142 profile also is larger, attesting an amplified effect of the South China Sea.

While the foraminifers used by both studies were well preserved and there was no inter-laboratory difference in oxygen isotopic measurements (personal communication with Linsley, 1998) the ever-lasting and repeated deviation pattern in δ^{18}O between the South China Sea and Sulu Sea must result from a significant difference in hydrographic condition between the two basins through the past 870 kyrs. The relatively more negative δ^{18}O values in MD972142 can only be accounted by higher temperature or lower salinity, or a combination of both. However, the former factor — higher sea-surface temperatures (SSTs) in the South China Sea — is less likely because the Sulu Sea is located closer to the core of the west Pacific Warm Pool (WPWP) and has remained to be warmer; in fact, the SSTs in the core area of WPWP has not varied much (less than 2 °C from the present) (Thunell et al. 1994; Ohkouchi et al., 1994). In contrast, SSTs in the South China Sea dropped by as much as 2 – 6 °C (Wang and Wang, 1990; Miao et al., 1994; Wang et al., 1995; Chen and

Huang, 1998; Wei et al., 1998; Pelejero et al., 1999; Wang et al., 1999; Steinke et al., 2001) (equivalent to ~0.5 – 1.5 ‰ increase in δ^{18}O signal) from the interglacial to glacial intervals. The SSTs of the South China Sea seldom exceeded the modern temperature in the past, for instance, the increase in SST during the warmest period, the substage 5.5 (~125 ka) in the last interglacial, was less than 1^{o} C than the Holocene (Wang et al., 1999). Therefore temperature variation (mostly becoming cold) alone in the South China Sea would likely have caused the δ^{18}O values to be more positive, opposing to the observed negative tendency. The only appropriate explanation for the light oxygen isotope composition is that over most part of the past 870 kyrs, the sea-surface salinities (SSSs) of the South China Sea were lower than that in the Sulu Sea, especially during the interglacial periods. Nowadays, rivers in Indochina Peninsula, Borneo and Sumatra serve as major sources of fresh water to the South China Sea. It is reasonable to argue that during past interglacial stages, intensification of the summer southwesterly monsoon would have brought in more moisture and precipitation over the SCS and the surrounding land masses. Enhanced precipitation and thus the increased runoff would result in a much lower salinity, particularly for the southern part of the SCS. On the other hand, the Sulu Sea was more or less immune from the influence of the increased fresh-water runoff.

MARITIME PROXY OF EAST ASIAN MONSOON

The strongest convective precipitation in the South China Sea and over the Indochina Peninsula is in association with the Inter-Tropical Convergence Zone (ITCZ) (Lau and Li, 1984; Hoffman and Heimann, 1997); the position of ITCZ, in turn, is controlled by the north-south thermal gradient through the troposphere. Furthermore, in convectively active regions, such as the tropical islands and monsoon prevailing areas, the amount effect of precipitation on δ^{18}O is significant. This is exemplified by the significant drop of δ^{18}O from $0^{0}/_{00}$ to $7^{0}/_{00}$ when precipitation increases from 0 to 350 mm/month (Hoffman and Heimann, 1997). We examined the precipitation data collected by IAEA at Bangkok for Year 1968-1998 and found indeed that precipitation has been concentrated in the summer-early autumn and the δ^{18}O values dropped to as low as $-10^{0}/_{00}$ when the monthly precipitation exceeded 400 mm/month (Fig. 3). The amount effect is estimated as $-1.4^{0}/_{00}$ every increase of 100mm/month in precipitation.

Based upon the above reasoning, the negative excursion in δ^{18}O of Site MD972142 from that of ODP769 (Fig. 2b) indicates an excessive input of freshwater/precipitation to the South China Sea, and thus a proxy of summer monsoon intensity. The increase of the excursion (Δ^{18}O in Fig. 2b) during the interglacial periods is consistent with most previous inferences about the East Asian monsoon variation in the South China Sea, that the summer monsoon was stronger during the interglacial periods with a concomitant weakening of winter monsoon (Wang and Wang, 1990; Huang et al., 1997; Wang et al., 1999; Jian et al., 2001). The variation pattern of this summer monsoon index (Fig. 2b) shows several important features: (1) Precipitation (summer monsoon) was strengthened generally during the interglacial stages; (2) peak precipitation took place usually in the middle part of interglacial; (3) the oxygen isotopic stage 14 is peculiar in showing heavy precipitation and strong summer monsoon, which is at odds with other glacial stages. The way this time series was derived made it inherit much uncertainty both in timing and magnitude of the signal, and therefore it should be viewed merely a semi-quantitative expression of the past changes of the summer monsoons. Quite strikingly, nevertheless, this “maritime summer monsoon” index agrees very well with the magnetic susceptibility record of Louchuan, central Chinese Loess Plateau (Heslop et al., 2000) (Fig. 2a).

TERRESTRIAL SUMMER MONSOON RECORD OF LOUCHUAN SECTION, CHINESE LOESS PLATEAU

It has been documented for years that the magnetic susceptibility (MS) is generally high in paleosol units and low in loess. The MS of surface sediments on the Chinese Loess Plateau has been demonstrated to correlate well with mean annual temperature and annual precipitation (Porter et al., 2001). This acutualistic study supports the conventional interpretation that the magnetic susceptibility variation records the fluctuation of summer monsoons through time (An et al., 1990, 1991).

Setting an appropriate timescale for the Louchuan sequence has been the main aim for many studies since the 80's. Correlation of the record with marine oxygen isotope stratigraphy either by conducting astronomical tuning (Lu et al., 1999), or simply interpolating ages between fixed tie-points of known ages (e.g., Liu et al., 1985), one of the pivotal problems is where the "genuine" location of the Matuyama/Brunhes geomagnetic boundary is. As illustrated by Zhou and Shackleton (1999) that different assessments of the "lock-in depth" of delayed acquisition of natural remanent magnetization below the surface contemporaneous with the M/B reversal has complicated the age correlation matter. Fortunately, the widespread Austraslasian microtektites caused by asteroid impact on the Indochina Peninsula slightly before the M/B boundary serves an independent isochronous marker. All the three sedimentary sequences under scrutiny contain discrete layer of Austrslasian microtektites: within the oxygen isotope stage 20 in Core MD972142 (Lee and Wei, 2000) and in ODP769 (Schnieder et al., 1992; Kent and Schnieder, 1995), and within the loess unit L8 in the Louchuan section (Zhou and Shackleton, 1999). Using the microtektite layer as a reference point, the perfect line-up of the three timescales attests good chronologies attained (Fig. 2).

CORRESPONDENCE BETWEEN TERRESTRIAL AND MARITIME SUMMER MONSOON INDICES

At a coarse scale, the magnetic susceptibility shows high values for paleosol units S1 – S8 formed during the interglacial periods (Fig. 2a). Similarly, the maritime index of summer monsoon also tends to show peak values during the interglacial intervals, particularly in the middle part of each interglacial. At a closer examination, except for the younger part of the S2 paleosol (S2-I, 195 – 225 ka), both indices vary in good concert throughout the records. It is worthwhile to note that the paleosol unit S3 was prolonged, extending into the first part of the glacial stage 8 (285 – 300 ka). This can be well explained by the relatively negative δ^{18}O values in MD972142 and the high values of maritime summer monsoon index during the period (Fig. 2).

The paleosol S5 is the thickest and the most mature soil complex developed in the whole sequence of Chinese loess sequences (An and Wu, 1980), A long-lasting perplexing problem for correlating the Louchuan sequence to marine isotopic stratigraphy has been that the paleosol S5 appears to be too long, straddling marine oxygen isotopic stages 13-15. In light of our new results of this study, the “glacial” MIS 14 is significantly subdued in the South China Sea (Fig. 2c), conceivably ascribed to the occurrence of stronger summer monsoons relative to other glacial stages (Fig. 2b). Furthermore, the maritime index (Fig. 2a) shows continuously high values for the entire MIS 13-15, reflecting a prolonged period of intensified summer monsoons in the Southeast Asia.

In conclusion, the newly derived maritime summer monsoon index derived from the South China Sea and Sulu Sea varies in concert with the magnetic susceptibility pattern documented from the Louchuan Section of the central Chinese Loess Plateau. The correlation attests the long-term land-sea linkage in the East Asian monsoon system between the South China Sea and the Chinese Loess Plateau during the late

Quaternary.

ACKNOWLEDGMENTS

We thank Drs. Z.S. An, H, Lu and D. Heslop for providing us the MS data of Louchuan and inspiring discussions. The study was supported by the National Science Council of the ROC through IMAGES Grant NSC89-2611-M-002 and the APEC program of the Academia Sinica. The precipitation data at the Bangkok Station of IAEA were downloaded from the website of the Global Network for Isotopes in Precipitation (GNIP) managed by the Isotope Hydrology Information System (ISOHIS) (http://isohis.iaea.org).

REFERENCES CITED

An, Z. S., Kukla, G. J., Porter, S. C., Xiao, J. L. 1991. Magnetic susceptibility evidence of monsoon variation of the Loess Plateau of central China during the last 130,000 years. Quat. Res. 36: 29-36.

An, Z. S., Liu, T. S., Lu, Y. C., Porter, S. C., Kukla, G. J., Wu, X. H., Hua, Y. M. 1990. The long-term paleomonsoon variation recorded by the loess-paleosol sequence in central China. Quat. Int. 7/8: 91-95.

An, Z. S., Porter, S. C., Zhou, W.J, Lu, Y. H., Donahue, D. J., Head, M. J., Wu. X. H., Ren, J.Z and Zheng, H.B. (1993) Episode of strengthened summer monsoon climate of Younger Dryas age on the Loess Plateau of Central China. Quat. Res., 39: 45-54.

An, Z. S. and Wu, L. Y. (1980) The fifth paleosol in the Lishi Loess and its paleoclimatic significance (in Chinese). Acta Pedol. Sin., 17: 1-10.

Banerjee, S. K. 1995. Chasing the paleomonsoon over China: its magnetic record. GSA Today, 5: 93-97.

Bassinot, F. C., Labeyrie, L. D., Vincent, E., Quidelleur, X., Shackleton, N. J. and Lancelot, Y. (1994) The astronomical theory of climate and the age of the Brunhes-Matuyama magnetic reversal: *Earth and Planetary Science Letters*, 126, 91-108.

Bloemendal, J., Liu, X.M., and Rolph, T. C. 1995. Correlation of the magnetic susceptibility stratigraphy of Chinese loess and the marine oxygen isotope record, chronological and paleoclimatic implications. Earth Planet. Sci. Lett. 131: 371-380.

Chen, M.-T. and Huang, C.-Y. 1998. Ice-volume forcing of winter monsoon climate in the South China Sea. *Paleoceanography*, 13(6): 622-633.

Chen, M-T., Beaufort, L. and the Shipboard Scientific Party of the IMAGES III/MD106-IPHIS Cruise (Leg II) (1998) Exploring Quaternary variability of the East Asian monsoon, Kuroshio Current, and the Western Pacific warm pool systems: high-resolution investigations of paleoceanography from the IMAGES III/MD106 – IPHIS cruise: *TAO*, *Terrestrial, Atmospheric and Oceanic Sciences*, 9: 129-142.

Ding, Z. L., Liu, T.S., and Rutter, N. W., Yu, Z.W., Guo, Z.T., Zhu, R.X. 1995. Ice-volume forcing of East Asian winter monsoon variation in the past 800,000 years. Quat. Res., 44: 140-159.

Ding, Z.L., Yu, Z.W., Rutter, N.W., Kiu, T.S., 1994. Towards an orbital time scale for Chinese loess deposits. Quaternary Science Reviews, 13: 39-70.

Heller, F. and Liu, T. S. 1982. Magnetostratigraphical dating of loess deposits in China. Nature 300, 431-433.

Heller, F. and Liu, T. S. 1984. Magnetism of Chinese loess deposits. Geophys. J. R. Astron. Soc., 77: 125-141.

Heller, F. and Liu, T.S. 1986. Paleoclimatic and sedimentary history from magnetic susceptibility of loess in China. Geophys. Res. Lett. 13: 1169-1172.

Heslop, D., Langereis, C. G. and Dekkers, M. J. 2000. A new astronomical timescale for the loess deposits of Northern China. Earth and Planet. Science Letters 184: 125-139.Heslop et al., 2000

Hoffmann, G. and Heimann, M. (1997) Water isotope modeling in the Asian monsoon region. Quaternary International, 37: 115-128.

Huang, C.-Y., Liew, P.-M., Zhao, M., Chang, T.-C., Kuo, C.-M., Chen, M.-T., Wang, C.-H. and Zheng, L.-F. 1997. Deep sea and lake records of the southeast Asian paleomonsoons for the last 35 thousand years. *Earth and Planetary Science Letters* 146: 59-72.

Jian, Z., Huang, B., Kuhnt, W. and Lin, H.-L. (2001) Late Quaternary upwelling intensity and East Asian monsoon forcing in the South China Sea. Quat. Res., 55: 363-370.

Kent, D.V., and Schneider, D.A. 1995. Correlation of paleointensity variation records in the Brunhes/Matuyama polarity transition interval, Earth Planet. Sci. Lett. 129, 135-144, 1995.

Kukla, G. 1987. Loess stratigraphy in central China. Quaternary Science Reviews 6, 191-219.

Kukla, G. and An, Z. S. 1989. Loess stratigraphy in central China. Palaeogeography, Palaeoclimatology, Palaeoecology 72: 203-225.

Kukla, G., Heller, F., Liu, X.-M., Chun, X.-T., Liu, T.-S. and An, Z. S. 1988. Pleistocene climates in China dated by magnetic susceptibility. Geology, 16: 811-814.

Lau, K.-M. and Li, T. 1984. The monsoon of East Asia and its global associations – a survey. Bull. Amer. Meteor. Soc., 65: 114-125.

Lee, M.-Y. and Wei, K.-Y. 2000. Australasian microtektites in the South China Sea and the West Philippine Sea: Implications for age, size, and location of the impact crater. Meteoritics and Planetary Sciences 35: 1151-1155.

Lee, M.-Y., Wei, K.-Y. and Chen, Y.-G. (1999) High resolution oxygen isotope stratigraphy for the last 150,000 years in the southern South China Sea: core MD972151: *TAO, Terrestrial, Atmospheric and Oceanic Sciences*, 10, 239-254.

Lee, T.-Q. 2000. Geomagnetic secular variation of the last one million years recorded in Core MD972142 from southeast South China Sea. Jour. of the Geological Society of China 43: 423-433.

Levitus, S. and Boyer, T. P. (1994) *World Ocean Atlas, Vol. 4. Temperature*. NOAA, U.S. Dept. Commerce, Washington, DC.

Levitus, S., Burgett, R., and Boyer, T. P. (1994) *World Ocean Atlas, Vol. 3. Salinity*. NOAA, U.S. Dept. Commerce, Washington, DC.

Li, C. and Yanai, M. (1996) The onset and interannual variability of the Asian summer monsoon in relation to land-sea thermal contrast. J. Climate, 9:358-375.

Linsley, B. K. and Dunbar, R. B. (1994) The late Pleistocene history of surface water $\delta^{13}C$ in the Sulu Sea: Possible relationship to Pacific deepwater$\delta^{13}C$ changes: *Paleoceanography,* **9**, 317-340.

Liu, T.S. and 30 others, 1985. Loess and Environment. China Ocean Press, Beijing, pp. 31-67.

Liu, X. M., Liu, T.S., Shaw, J., Heller, F., Tu, T.-C., and Yuan, B.-Y. 1991. Paleomagnetic and paleoclimatic studies of Chinese loess. Pp. 61-81. In: Liu, T. S. (ed.) Loess, Environment and Global Change. Beijing, China.

Lu, H., Liu, X., Zhang, F., An, Z. and Dodson, J. 1999. Astronomical calibration of loess-paleosol deposits at Louchuan, central Chinese Loess Plateau. Palaeogeogr., Palaeoclimatol., Palaeoecol., 154: 237-246.

Miao, Q. and Thunell, R. C. (1994) Glacial-Holocene carbonate dissolution and sea surface temperature in the South China and Sulu Seas: *Paleoceanography,* **9**, 269-290.

Ohkouchi, N., Kawamura, K., Nakamura, T. and Tiara, A. 1994. Small changes in the sea surface temperature during the last 20,000 years: Molecular evidence from the western tropical Pacific. Geophys. Res. Letters, 21(20): 2207—2210.

Pelejero, C., Grimalt, J. O., Sarnthein, M., Wang, L. and Flores, J.-A. (1999) Molecular biomarker record of sea surface temperature and climatic change in the South China Sea during the last 140,000 years: *Marine Geology,* 156, 109-121.

Porter, S. C., Hallet, B., Wu. X. and An Z. 2001. Dependence of near-surface magnetic susceptibility on dust accumulation rate and precipitation on the Chinese Loess Plateau. Quaternary Research 55: 271-283.

Schneider, D. A., Kent, D. V., and Mello, G. A. 1992. A detailed chronology of the Australasian impact event, the Brunhes-Matuyama geomagnetic polarity reversal, and global climate change, Earth Planet. Sci. Lett. 111, 395-405, 1992.

Shyu, J.-P., Chen, M.-P., Shieh, Y.-T. and Hunag, C.-K. (2001) A Pleistocene paleoceanographic record from the north slope of the Spratly Islands, southern South China Sea. Mar. Micropaleont., 42: 61-93.

Steinke, S., Kienast, M., Pflaumann, U., Weinelt, M. and Stattegger, K. 2001. A high-resolution sea-surface temperature record from the tropical South China Sea (16,500-3,000 yr B.P.). Quaternary Research, 55: 352-362.

Tauxe, L., Herbert, T., Shackleton, N. J. and Kok, Y.-S. (1996) Astronomical calibration of the Matuyama-Brunhes boundary: Consequences for magnetic remanence acquisition in marine carbonates and the Asian loess sequences. *Earth Planet Sci. Lett*., 140: 133-146.

Thompson, P. R., Bé, A. W. H., Duplessy, J.-C. and Shackleton, N. J. (1979)

Disappearance of pink-pigmented *Globigerinoides ruber* at 120,000 yr BP in the Indian and Pacific Oceans: *Nature,* 280, 554-558.

Thunell, R. C., Anderson, D., Gellar, D. and Miao, Q. M. 1994. Sea-surface temperature estimates for the tropical western Pacific during the last glaciation and their implications for the Pacific warm pool. Quaternary Res., 41: 255-264.

von Grafenstein R., Zahn, R., Tiedemann, R. and Murat, A. (1999) Planktonic δ^{18}O records at Sites 976 and 977, Alboran Sea: Stratigraphy, forcing and paleoceanographic implications. In Zahn, R., Comas, M. C. and Klaus, A. (Eds.) *Proc. ODP, Sci. Results*, 161: 469-479. College Station, TX (Ocean Drilling Program).

Wang, L. and Wang, P. (1990) Late Quaternary paleoceanography of the South China Sea: glacial-interglacial contrasts in as enclosed basin: *Paleoceanography*, **5**, 77-90.

Wang, L., Sarnthein, M., Erlenkeuser, H., Grimalt, J., Groote, P., Heiling, S., Ivanova, E., Kienast, M., Pelejero, C. and Pflaumann, U. (1999) East Asian monsoon climate during the late Pleistocene: high-resolution sediment records from the South China Sea: *Marine Geology,* 156, 245-284.

Wang, P., Tian, J. and Chen, X. (2001) Transition of Quaternary glacial cyclicity in deep-sea records at Nansha, the South China Sea. Science in China (Ser. D), 44 (10): 926-933.

Wang, P., Wang, L., Bian, Y., and Jian, Z. 1995. Late Quaternary paleoceanography of the South China Sea: surface circulation and carbonate cycles. Mar. Geology, 127: 145-165.

Webster, P. J. (1987) The elementary monsoon. In: Fein, J.S. and Stephens, P.L. (eds.) Monsoons. pp. 1-32. Wiley-Interscience, New York.

Webster, P. J., Magana, V. O., Palmer, T. N., Shukla, J., Tomas, R. A., Yanai, M. and

Yasunari, T. (1998) Monsoons: Processes, predictability, and the prospects for prediction. Jour. Geophys. Res., 103 (C7): 14,451-14,510.

Wei, K.-Y., Lee, M.-Y. Duan, W., Chen, C. and Wang, C.-H. (1998) Paleoceanographic change in the northeastern South China Sea during the last 15000 years: *Journal of Quaternary Science*, 13, 55-64.

Zhou, L.P. and Shackleton, N. J. (1999) Misleading positions of geomagnetic reversal boundaries in Eurasian loess and implications for correlation between continental and marine sedimentary sequences. Earth and Planet. Science Letters 168: 117-130.

Figure Captions

Figure 1. Map of East Asia and Pacific Ocean showing locations of the three studied sites: MD972142 in the South China Sea, ODP769 in Sulu Sea and Louchuan on the central Chinese Loess Plateau. Black arrows indicated wind directions of the Asian summer monsoons. The ticked line marks the current northwestern limit of the summer monsoon (modified after An et al., 1993, Fig. 5a).

Figure 2. Comparison between climatic records from the South China Sea and the central Chinese Loess Plateau for the past 870 kyrs. a. Time-series of magnetic susceptibility at Louchuan, central Chinese Loess Plateau. Shaded areas mark the paleosol units S1 – S8. The chronology and the magnetostratigrapy (shown by the top bar) are adopted from Heslop et al (2000). The ellipse denoted with “mtk” marks the occurrence of the Australasian microtektites (Zhou and Shackleton, 1999). b. The time-series of difference in δ^{18}O values between Site MD972142 and ODP Site 769. The bold line crossing through the data points

represents the long-term trend. Values above the general trend indicate conditions of enhanced freshwater input and thus stronger summer monsoons. Oxygen isotopic stages are marked by numbers on the top. c. Time-series of planktic δ^{18}O from Sites MD972142 and ODP769 from oxygen isotopic stages 1- 21. The timescale of MD972142 was obtained by astronomical tuning while that of ODP769 was obtained by calibrating to MD972142 with curve matching. Also shown are the position of the Australasian microtektites (mtk) found in both sequences (Schnieder et al., 1992; Kent and Schnieder, 1995; Lee and Wei, 2000) and magnetostratigraphy (Schnieder et al., 1992; Lee, 2000).

Figure 3. Monthly precipitation variation (a) and δ^{18}O of precipitation (b) during 1991-1997 at Bangkok Station of International Atomic Energy Agency (IAEA).

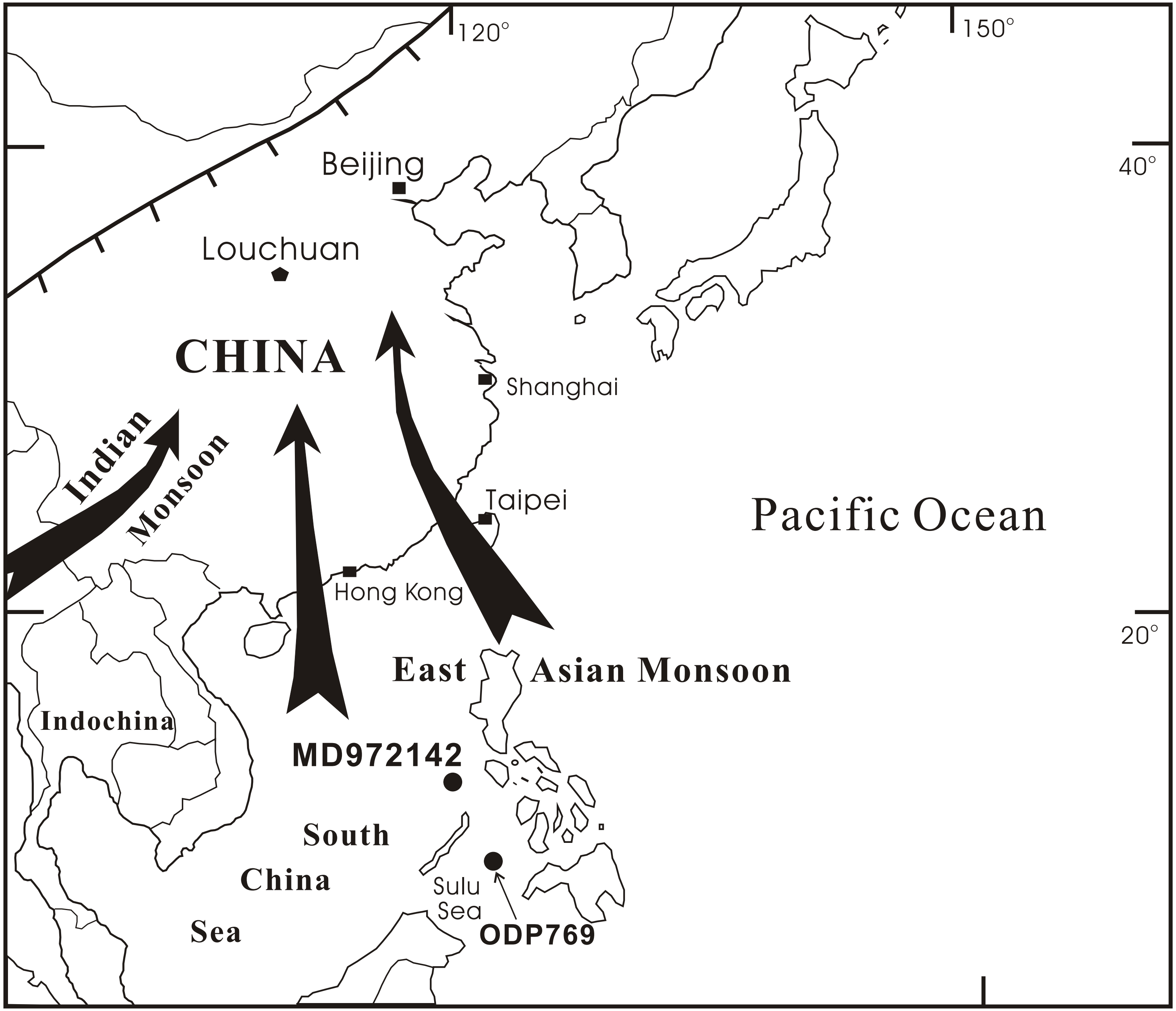
120°
150°
40°
20°
Beijing
Louchuan
CHINA
Shanghai
Indian Monsoon
Taipei
Pacific Ocean
Hong Kong
East Asian Monsoon
Indochina
MD972142
South China Sea
Sulu Sea
ODP769

Fig. 1

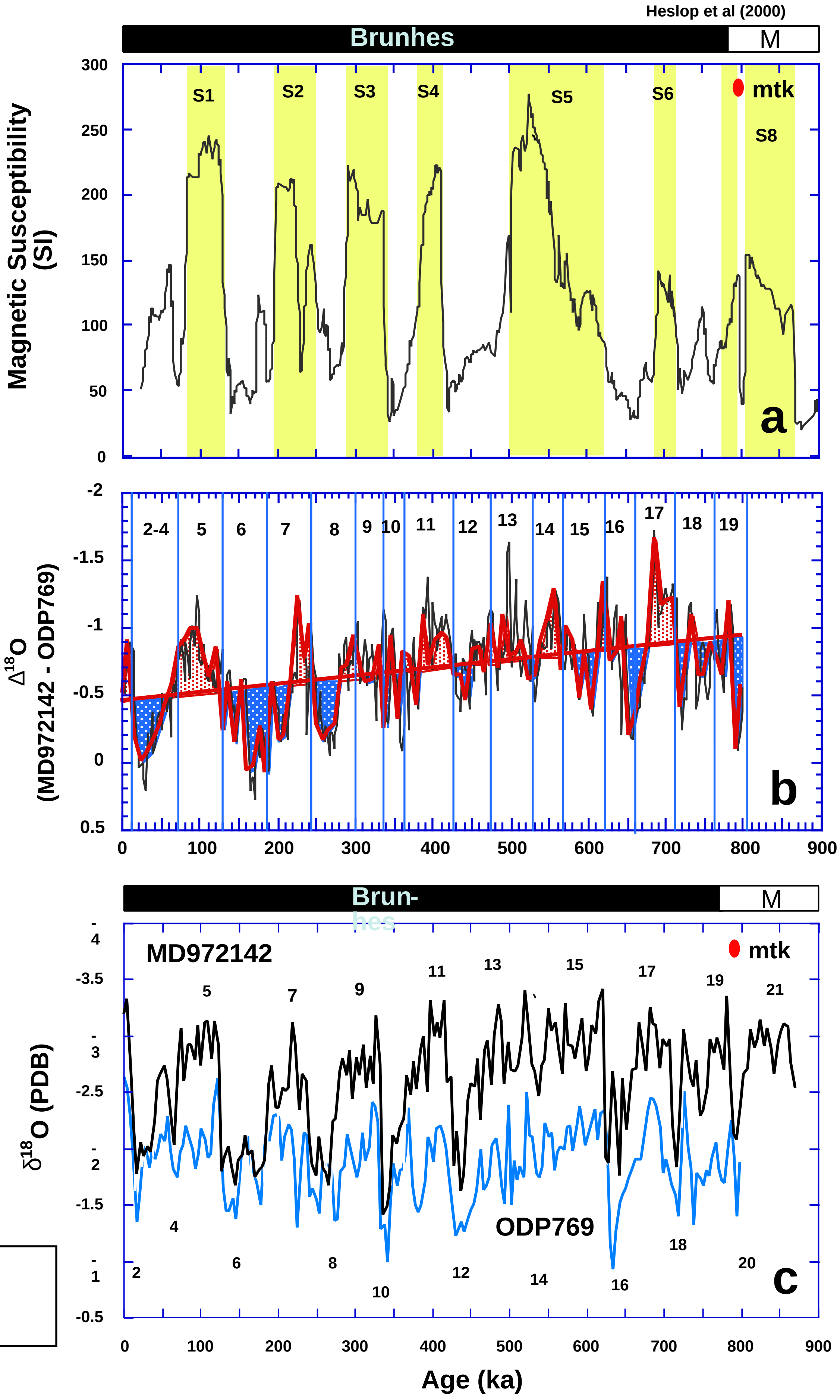
Heslop et al (2000)
Brunhes
M
Magnetic Susceptibility (SI)
300
250
200
150
100
50
0
S1
S2
S3
S4
S5
S6
mtk
S8
a
Δ18O (MD972142 - ODP769)
-2
-1.5
-1
-0.5
0
0.5
2-4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
b
0
100
200
300
400
500
600
700
800
900
Brun-hes
M
δ18O (PDB)
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
MD972142
mtk
5
7
9
11
13
15
17
19
21
4
ODP769
2
6
8
10
12
14
16
18
20
c
0
100
200
300
400
500
600
700
800
900
Age (ka)

Fig.2

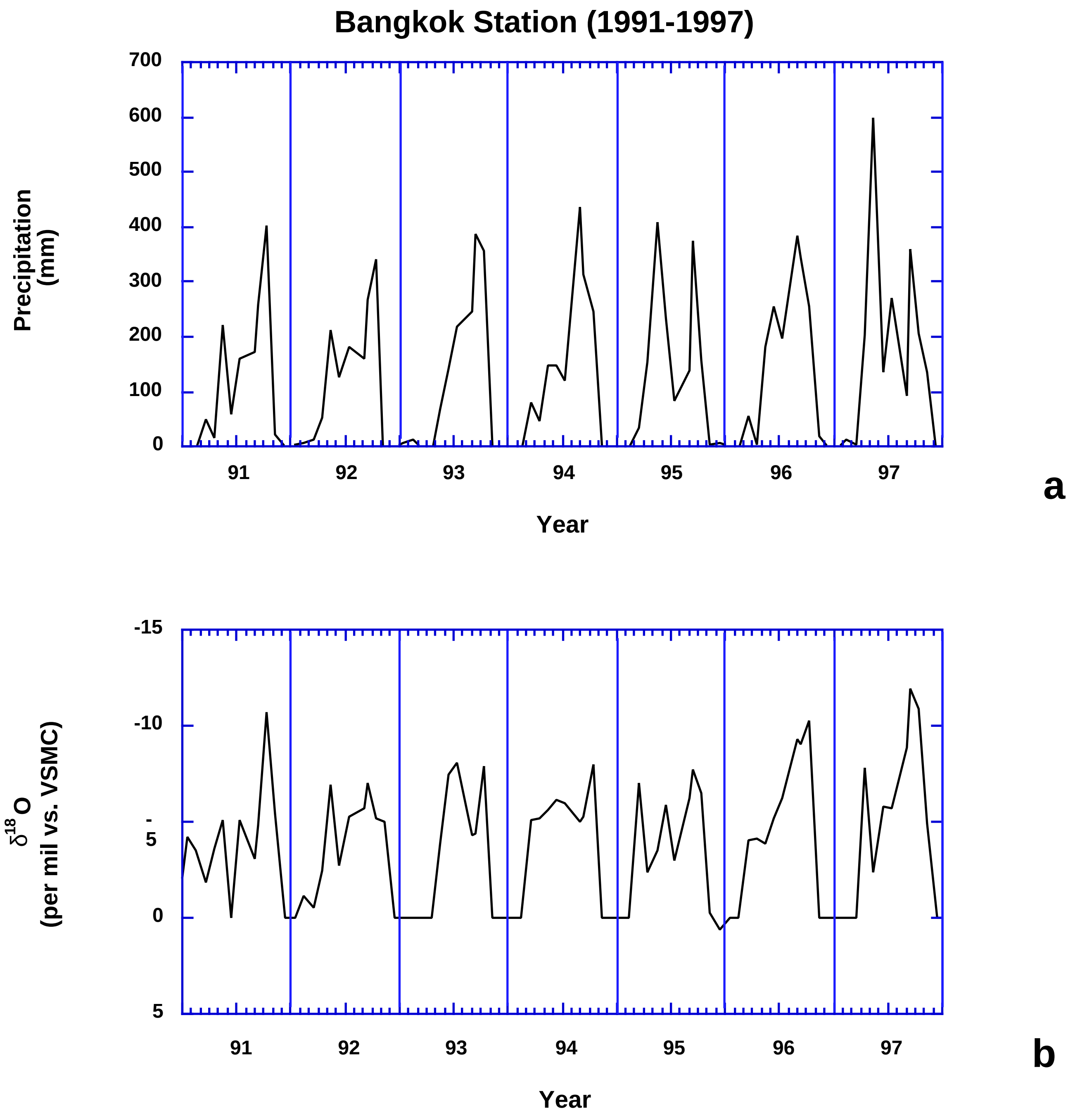
Bangkok Station (1991-1997)

Fig. 3