Holocene East Asian monsoon variability: Links to solar and tropical Pacific forcing

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[1] Sedimentary geochemical records from subalpine Retreat Lake, subtropical Taiwan, document the unstable East Asian monsoon (EAM) climate over the past ~10,300 years, with a weak EAM between ~10.3 and 8.6 ky B.P., EAM intensity peaks between 8.6 and 7.7 ky B.P., and then gradually decrease in response to summer insolation, heat and moisture transport. Our proxy record reveals several weak monsoon intervals that correlate to low sea surface temperatures in the western tropical Pacific and cold events in the North Atlantic, linking the tropical Pacific, North Atlantic, and Polar climates because weak EAM events at ~8.2, 5.4 and 4.5–2.1 ky B.P. also correspond to low values of atmospheric methane and periods of reduced North Atlantic Deep Water formation. We therefore suggest that centennial to millennial scale monsoon variability during the Holocene in the northern subtropics is globally-mediated via a sun-ocean-monsoon-North Atlantic linkage. Citation: Selvaraj, K., C. T. A. Chen, and J.-Y. Lou (2007), Holocene East Asian monsoon variability: Links to solar and tropical Pacific forcing, Geophys. Res. Lett., 34, L01703, doi:10.1029/2006GL028155.

1. Introduction

[2] Marine sedimentary records from the North Atlantic demonstrate that the Holocene was interrupted by a series of quasi-periodic (~1000–1500 yr) cold, dry events [deMenocal et al., 2000a; Bond et al., 2001]. Such climate instabilities are also apparent in high-resolution marine [Gupta et al., 2005] and speleothem-based Asian monsoon (AM) records [Fleitmann et al., 2003; Wang et al., 2005], suggesting that centennial to millennial scale monsoon events were caused by solar and glacial boundary forcing. High-resolution records from the tropical Pacific [Lea et al., 2000; Stott et al., 2004] show evidence for internal forcing on decadal to millennial scale monsoon variability though the importance of internal forcing remains ambiguous [Wang et al., 2005]. This warrants additional data to evaluate the combined sun-monsoon link and the role of tropical climate dynamics on a global scale, especially within the AM system. One ideal location for such study is the subtropical East Asian island of Taiwan, well known for its vigorous tropical and extra-tropical land-ocean-atmosphere interactions.

[3] Taiwan’s weather and climate are primarily controlled by the East Asian monsoon (EAM). The EAM is the result of thermal contrast between the Asian landmass and the tropical Pacific with an additional thermal and dynamic trigger of the Tibetan Plateau [An, 2000]. The EAM is extremely important because it regulates global atmospheric circulation through heat and moisture transport from the warmest part of the tropical ocean, the West Pacific Warm Pool (WPWP), to higher latitudes [Wang et al., 2001]. Since Taiwan has the world’s highest physical weathering rate (1365 mg/cm²/yr) [Li, 1976], terrestrial vegetation and weathering are highly dependent on the intensity of the EAM. Here we report the results of geochemical analyses (for further details, see auxiliary material1) performed on sediments from a small (~10⁴ m²), hydrologically closed, subalpine Retreat Lake (24°29′30″N, 121°26′15″E; 2230 m) in NE Taiwan. The lake lies directly in the path of the moisture-laden, southeasterly down-winds of the EAM from the western tropical Pacific (WTP), and close to the main axis of the Kuroshio Current, a major boundary current that transports a large volume (18–25 Sverdrup = 10⁶ m³ s⁻¹) of warm, salty seawater from the WTP to the North Pacific. The modern lake catchments have two different seasons: a warm, wet season during Northern Hemisphere (NH) summer when the intertropical convergence zone (ITCZ) shifts northward (Figure 1s) and EAM reaches its maximum and a cool, dry season during the boreal winter when the Siberian high establishes a strong anticyclone on the Tibetan Plateau and ITCZ migrates to a southern position that is associated with the stronger winter monsoon. The lake is surrounded by ~60 m high mountains comprised of Tertiary metamorphic rocks (slate, phyllite and argillite). Lake level is primarily controlled by precipitation and evaporation as there are no in- and out-flow. The combination of mild mean annual temperature (12°C) and high precipitation (~3000 mm) results in thick vegetation in the catchments of Retreat Lake.

2. Materials, Methods, and Proxies

[4] Total organic carbon (TOC), total nitrogen and magnetic susceptibility (MS) were measured in 1.7 m long sediment core collected from the lake that was continuously sub-sampled at 1 cm interval, which is equivalent to a temporal resolution of 45 years. Selected major and trace elements were analyzed from samples of coarse intervals (2–4 cm) to provide additional constraints of EAM variability on subtropical weathering. Chronology is based on 8 accelerator mass spectrometry (AMS) and 2 conventional ¹³C dates of bulk organic matter (Table S1)1, all uncorrected dates (see auxiliary material and Figure S2) converted to

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0094-8276/07/2006GL028155. Other auxiliary material files are in the HTML.
Figure 1. Sedimentary geochemical proxy records of Retreat Lake depicting Holocene East Asian monsoon variability in subtropical Taiwan. (a) Age model and a hiatus between ~2.1 and 4.5 ky B.P. (35–38 cm), (b) total organic carbon and $\delta^{13}$C values, (c) carbon$_{\text{org}}$/nitrogen$_{\text{total}}$ ratio, (d) magnetic susceptibility, (e) chemical index of alteration, (f) Rb/Sr ratio, and (g) K/Rb ratio. Cross bars in Figures 1e–1g represent non-orbital weak monsoon intervals.

calendar years using the calibration [Stuiver and Reimer, 1993]. The linearly interpolated calendar age-depth model (Figure 1a) indicates that sedimentation was variable with a mean sedimentation rate of 16.8 cm/ky spanning the last ca. 10.3 calendar kilo years before the present (ky B.P., where the “present” is defined as the year 1950 A.D.). A hiatus with extremely slow sedimentation (1 cm/∼790 years) between 38 and 35 cm was, however, demarcated by 2 closely-spaced dates (4.5 ± 0.03 and 2.12 ± 0.04 ky B.P.; Figure 1a) perhaps in large part because of desiccation. To interpret the Holocene’s EAM variability, we used characteristic sedimentary geochemical proxies namely TOC, carbon$_{\text{org}}$/nitrogen$_{\text{total}}$ (C/N ratio), MS, the chemical index of alteration (CIA), a proxy for terrestrial weathering calculated as in work by Selvaraj and Chen [2006], as well as the Rb/Sr and K/Rb ratios. An increase or decrease in the proxies is more closely related to the strength of the EAM than to any other climatic variable in the study area. High TOC value and C/N ratio, and associated higher negative carbon isotope ($\delta^{13}$C) values, for example, are interpreted to reflect vascular plant (C$_3$) dominance due to increased monsoon precipitation during periods of warm/wet climate. Conversely, high MS and CIA values, and high Rb/Sr but low K/Rb ratios reflect intense chemical weathering and a drastic reduction in detrital input into the lake as a result of reduced erosion due to thick C$_3$ vegetation. [Third, a dry climate with weak monsoon precipitation since ca. 4.5 ky B.P. is revealed by low contents of TOC and low C/N ratios, relative to sediments deposited in the “Holocene optimum” interval, as well as higher values of MS and CIA, and the high Rb/Sr but lower K/Rb ratios. A driest interval at ~4.5 to 2.1 ky B.P. is indicated by acute starvation of organic-inorganic materials input into the lake, suggesting a significant drop, perhaps failure, in EAM precipitation which probably brought the lake into a desiccation stage; an inference very consistent with an arid period (~4.4–2.1 ky B.P.) shown in speleothem $\delta^{18}$O record from central China [Shao et al., 2006]. Typical lacustrine detrital records such as those for Ti, Zr, and Ti-based detrital percentage, and molar SiO$_2$/Al$_2$O$_3$ - a grain size proxy, all (auxiliary Figure S3) corroborate the above inferred EAM fluctuations.

EAM variability is influenced by different factors, whereas NH summer insolation, the oceanographic characteristics of the WPWP, the strength of the North Equatorial Current (NEC) in the western Pacific, and the El Niño Southern Oscillation (ENSO) in the tropical Pacific are the most important ones. In subtropical Taiwan, the rapid increase and peak EAM precipitation between ~8.6 and 7.7 ky B.P. (Figures 1 and 2a) indicate a rapid northward migration of the ITCZ and is in phase with time lag of ~2.4 ky to the NH summer insolation anomaly at 11–12 ky B.P. [Berger and Loutre, 1991]. During this interval, a marked change from organic-poor to -rich, peaty sediments and a concomitant negative excursion of $\delta^{13}$C values (from ~27‰ to ~30.6‰) (Figure 1b) indicating the sudden expansion of C$_3$ biomass favoring warm, humid conditions. This increase in EAM intensity in subtropical Taiwan is consistent with the onset of climatic optimum in the Loess Plateau [An et al., 2000] and corresponds to the highest growth rate (as high as 500 μm/yr) between 8.5 and 7.5 ky B.P. in Chinese stalagmite [Dykoski et al., 2005]. The strong, negative relationship between TOC, an

3. Results and Discussion

The geochemical records for Retreat Lake (Figure 1), consistent with sediment lithology (auxiliary Figure S2), show three distinct climatic episodes. First, a cold, dry period with low precipitation between ca. 10.3 and 8.6 ky B.P. is indicated by the lowest TOC value and low C/N ratios. This interpretation is substantiated by high values of MS, CIA, and high Rb/Sr but low K/Rb ratios indicate strong erosion in lake catchments due to less dense vegetation cover. Second, a warm and wet interval with strong EAM precipitation during the “Holocene optimum” between ~8.6 and 4.5 ky B.P. is indicated by organic-rich, peaty sediments with high contents of TOC and a high C/N ratios. In this interval, negative MS and low CIA values along with low Rb/Sr and high K/Rb ratios indicate intense chemical weathering and a drastic reduction in detrital input into the lake as a result of reduced erosion due to thick C$_3$ vegetation. [Third, a dry climate with weak monsoon precipitation since ca. 4.5 ky B.P. is revealed by low contents of TOC and low C/N ratios, relative to sediments deposited in the “Holocene optimum” interval, as well as higher values of MS and CIA, and the high Rb/Sr but lower K/Rb ratios. A driest interval at ~4.5 to 2.1 ky B.P. is indicated by acute starvation of organic-inorganic materials input into the lake, suggesting a significant drop, perhaps failure, in EAM precipitation which probably brought the lake into a desiccation stage; an inference very consistent with an arid period (~4.4–2.1 ky B.P.) shown in speleothem $\delta^{18}$O record from central China [Shao et al., 2006]. Typical lacustrine detrital records such as those for Ti, Zr, and Ti-based detrital percentage, and molar SiO$_2$/Al$_2$O$_3$ - a grain size proxy, all (auxiliary Figure S3) corroborate the above inferred EAM fluctuations.

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ideal proxy for EAM variations, and summer (JJA) insolation evident between \( \sim 10.3 \) and 8.6 ky B.P. (Figure 2a) reveals that the EAM intensity during the early Holocene was largely controlled by glacial boundary forcing (e.g., Tibetan Plateau snow cover and North Atlantic SSTs). Although decadal to centennial variations in Indian Ocean monsoon (IOM) precipitation between \( \sim 10.3 \) and 8 ky B.P. indicates an analogous relationship with Greenland temperatures [Fleitmann et al., 2003], the delayed strengthening of EAM in Taiwan could also be related to the tropical Pacific SSTs which attained its Holocene average at \( \sim 8.5 \) ky B.P. in the WPWP, where EAM prevails [Gagan et al., 2004]. This, however, contradicts speleothem- [e.g., Dykoski et al., 2005] and pollen-based [Liew et al., 2006] monsoon reconstructions which all show evidence for an enhanced monsoon during the early Holocene.

Nevertheless, our EAM record shows a strong visible coincidence with insolation from 8.6 ky B.P. onward (Figure 2a), indicating that long-term changes in EAM intensity depend on summer insolation. Importantly, the gradual long-term decrease in monsoon precipitation in subtropical Taiwan resembles speleothem-based AM [Wang et al., 2005], IOM [Fleitmann et al., 2003] records from China and Oman, faunal-based southwest AM record from the Arabian Sea [Gupta et al., 2005], and sedimentary bulk Ti record from the Cariaco Basin, tropical Atlantic [Haug et al., 2001] (Figure 2). Accordingly, during the “Holocene optimum”, our TOC record, consistent with the Ti record of the Cariaco Basin, shows increased precipitation and thus supports a more northerly mean position of the Pacific ITCZ. Conversely, during the late Holocene, the southward migration of ITCZ owing to less seasonal NH insolation would have reduced the strength of summer monsoon in Taiwan as well as the entire northern subtropics. Equally important, this low-latitude, wide monsoon similitude indicates that the broad temporal pattern of postglacial to modern precipitation in the subtropics are controlled, probably on a global scale, by the continuous southward migration of the mean summer ITCZ and a gradual weakening of the monsoon intensity in response to orbital- induced declining summer insolation; an interpretation consistent with modeling study [Kutzbach and Otto-Bliesner, 1982].

After 8.6 ky B.P., the long-term monsoon trend is punctuated by eight discrete intervals of weak EAM (low TOC values; vertical grey bars in Figure 2) that, within dating error, can be correlated with other monsoon records and the low values of faunal Mg/Ca-derived SST record from the WTP [Stott et al., 2004] (Figure 2f), indicating the influence of tropical SSTs on the EAM and, in turn, the low-latitude monsoon patterns. Among these intervals, 6 coincide to the timings of millennial-scale events (cold spells numbered 0–5; Figure 2g) in the North Atlantic [Bond et al., 2001] (plotted such that cooling and monsoon weakening are downward), suggesting the influence of variable solar activity on the EAM. Three weak EAM events of relatively longer in duration and larger in amplitude at around 8.3–8, 5.7–5.1 and 4.5–2.1 ky B.P can be correlated to the low values of atmospheric CH\(_4\) recorded in the GRIP ice core, central Greenland [Blunier et al., 1995] (Figure 3). Furthermore, these events coincide with reduced formation of North Atlantic Deep Water (NADW).
as demonstrated by $\delta^{13}$C values of benthic foraminifera, *Cibicidoides wuellerstorfi*, an established proxy for deep water variability (Figure 3), from the sediments of the subpolar northeastern Atlantic [Oppo et al., 2003]. These high-latitude cooling-reduced NADW formation and low tropical SSTs-weak EAM couples suggest that the reduced heat and moisture export during these times may reduce the global wetlands and contributed to decreased atmospheric methane, exactly as noted [Blunier et al., 1995; Alley et al., 1997]. The event centered at ~8.17 ky B.P. closely correlates with the ~3.2 ky event’ recorded in Greenland ice cores [e.g., Alley et al., 1997], probably related to a catastrophic outburst of freshwater from ice-margin lakes to Hudson Bay. A prominent, weak EAM centered at ~5.4 ky B.P. is consistent with the termination timing (5.5 ky B.P.) of the African humid period [deMenocal et al., 2000b] and slightly leads the onset (~5 ky B.P.) of modern frequencies of the ENSO [Moy et al., 2002]. A wide interval of weak EAM and consequent lake desiccation at 4.5 to ~2.1 ky B.P. are possibly linked to cold events 1, 2, and 3 (Figures 2a and 2g). This deterioration is widely represented by lower lake levels in China, India, and Africa, as well as widespread cultural collapse in low-latitude regions, including the Neolithic cultural collapse in China [Wang et al., 2005] (NCC in Figure 2b).

Although orbitally-induced summer insolation explains the long-term Holocene monsoon patterns in subtropical Taiwan, abrupt, short-term monsoon variations, including the weak monsoons at ~7, 6.3 and 5.4 ky B.P. (hatched bars in Figure 1 and auxiliary Figure S3) within the optimum conditions, seem to have little or no clear external forcing has drawn the tropical climate dynamics as an alternate candidate. Ocean-atmospheric interactions, particularly changes in the SST, in the tropical Pacific have always had a strong influence on the export of heat and water vapour to high-latitudes and are, therefore, thought to be an active force for global climate change [e.g., Lea et al., 2000]. The SSTs were mostly above 29°C before 5 ky B.P. which is consistent with the strong EAM during the "Holocene optimum" (Figures 2a and 2f). A remarkable increase between 9 and 7.3 ky B.P. and relative higher abundance up to 5 ky B.P. in a deep-dwelling, tropical planktonic foraminifer, *Pulvinatina obliquiloculata*, an indicator species of the Kuroshio path and intensity, in a number of marine sediment cores in the Okinawa Trough [e.g., Jian et al., 2000] and the South China Sea [e.g., Wang et al., 1999] demonstrate the enhanced meridional heat and moisture transport from the WTP to the North Pacific when the EAM reached its northernmost limit and the Loess Plateau was relatively greener than today. Conversely, reduced heat transport is unambiguous in SST record that shows less than 29°C with a clear decrease between 5 and 2 ky B.P. (arrow in Figure 2f) and corresponds to a weak EAM and lake desiccation in subtropical Taiwan. This inference is evidenced in the abrupt decrease in the abundance of *P. obliquiloculata* at 4.6 to 2.7 ky B.P. in sediment cores from the Okinawa Trough [Jian et al., 2000], at 4.9 to 2.9 ky B.P. in the South China Sea [Wang et al., 1999], and in the synchronous drop in SSTs ~5–3 ky B.P. in the latter area. The decrease in the depth of the thermocline around 4.3–2.5 ky B.P. in the Okinawa Trough further reveals the relaxation of trade winds throughout the Pacific and thus a weakened NEC and Kuroshio. Eventually, weak EAM events closely correspond to periods (~0.6, 1.7, 3.3, 4.6, 5.9, and 8.1 ky B.P.) of weakened Kuroshio found in the Okinawa Trough and periodicities (~1500 and 700–800 yr) of Kuroshio proxies [Jian et al., 2000] circuitously indicate a climatic forcing by changes in oceanic thermohaline circulation, including its subharmonic mode, on EAM variation.

[10] The climate of the WPWP is fundamentally linked to ENSO variability with relative drought and reduced SSTs as seen in Figure 2f, characterizing the El Niño phase [Tudhope et al., 2001]. Since modern AM failures and ENSO have a strong correlation [Charles et al., 1997], the drastic reduction in EAM strength and the lake desiccation were indeed a response to ENSO in the late Holocene as indicated by the increased vegetation loss across the Pacific Basin, Kalimantan, and Australia as well as composite records of charcoal abundance adjacent to the WPWP, Papua New Guinea and Indonesia; all show a high frequency of ENSO activities between 5 and 2 ky B.P. (for further details, see Gagan et al. [2004]). The enhanced run-off variability in the Ti record of the Cariaco Basin between 3.8 and 2.8 ky B.P. indicates a mean southward shift in the position of the Pacific ITCZ linked to ENSO changes in the late Holocene [Haug et al., 2001] (Figure 2e). ENSO model studies [e.g., Liu et al., 2000] and coral records [e.g., Gagan et al., 2004] display the greatest ENSO variability ca. 3.5–1.7 ky B.P. This seems to be correlated with the lowest content of TOC and C/N ratio ca. 2.0–1.6 ky B.P. in sediments of Retreat Lake and highest $\delta^{18}$O values of stalagmites (grey bar 1 in Figure 2f), indicative of weak AM signals. The Oman stalagmite shows a hiatus in precipitation between 2.7 and 1.4 ky B.P. (Figure 2c), further supporting the influence of the Indo-Pacific Warm Pool on variations in the IOM via the Indonesian Throughflow as well as EAM. Strong supports for the role of ocean-atmosphere interactions in monsoon variability come from an analogous pattern of heat transport in the North Atlantic [e.g., Poore et al., 2003] and numerous
lacustrine records of late Holocene-ENSO link in the American-side Pacific [e.g., Moy et al., 2002].

4. Conclusions

[11] Retreat Lake geochemical records invariably show an abrupt increase of EAM intensity at ~8.6 ky B.P. and since then the long-term EAM variations, similar to other AM records, were primarily controlled by the mean position of the ITCZ, which affected directly by summer insolation and indirectly through its effect on the tropical Pacific SSTs, and related meridional heat and moisture transport. The centennial to multi-decadal weak EAM intervals and their link with both the cold events in the North Atlantic and low SSTs in the tropical Pacific were at least in part ascribed to changes in solar forcing. An important observation of our study is that since ~5 ky B.P. the EAM, including IOM, variations seem to be affected by non-linear onset of ENSO due probably to the enhanced interaction between the Southern Oscillation and southwestward Pacific ITCZ. Our study underscores the importance of additional, high-resolution climate records in subtropical Taiwan and along the path of the Kuroshio Current so as to establish more precise land-sea correlation and to strengthen the monsoon-tropical Pacific-ENSO linkage.

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