Does Antarctic glaciation force migration of the tropical rain belt?

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ABSTRACT

High-resolution (~3–6 k.y.) upper ocean temperature and salinity estimates derived from planktic foraminiferal δ18O and Mg/Ca in Ocean Drilling Program (ODP) Site 1146 reveal stepwise changes in the precipitation-evaporation balance of the subtropical northwestern Pacific during the Middle Miocene (15.7 to 12.7 Ma). We attribute the punctuated pattern of surface warming and freshening following Antarctic ice growth episodes at 14.6, 14.2, 13.9, and 13.1 Ma to successive northward movements of the Intertropical Convergence Zone, implying high sensitivity of tropical rain belts to the interhemispheric temperature gradient driven by high-latitude climate. This dynamic interaction has implications for future warmer climate regimes with differential warming of the Northern Hemisphere, as it may lead to changes in the latitudinal penetration of tropical Pacific moisture over Southeast Asia.

INTRODUCTION

Tropical-subtropical precipitation patterns track seasonal migration of the Intertropical Convergence Zone (ITCZ), a narrow latitudinal zone of wind convergence that oscillates across the equator. Today, the maximum amplitude in the seasonal shift of the ITCZ occurs between southern China and northern Australia with a latitudinal displacement of ~35° (Fig. 1), though this may have differed substantially in the past. Precipitation, continental runoff, and marine salinity proxies have shown that marked variations in the ITCZ position occurred during the late Pleistocene and Holocene, variations that appear to be linked to Northern Hemisphere climate variability, net heat transports associated with thermohaline circulation, and differential hemispheric heating due to changes in the Earth’s radiation budget (Haug et al., 2001; Benway et al., 2006; Leduc et al., 2007; Partin et al., 2007; Sachs et al., 2009).

The Pleistocene scenario of an extensive and strongly fluctuating Northern Hemisphere ice cap exerting a major influence on global climate is relatively unusual in Earth’s history. During warmer climate phases of the Cenozoic, characterized by predominantly unipolar glaciations in Antarctica, the dynamics of the ITCZ may have been different. Understanding the past evolution of this variable climate feature in the absence of large Northern Hemisphere ice sheets provides a perspective relevant to future variability on a warmer Earth. Of particular interest is the Middle Miocene interval of stepwise high-latitude (and likely subsurface ocean) cooling, and Antarctic ice sheet expansion, which led to the inception of continuous icehouse conditions in Antarctica (Flower and Kennett, 1993; Holbourn et al., 2005; Lewis et al., 2007; Shevenell et al., 2008). Ice expansion in the Northern Hemisphere is thought to have been small relative to Antarctica, although perhaps not negligible (DeConto et al., 2008).

Here we present upper ocean temperature and salinity records from Ocean Drilling Program (ODP) Site 1146 (19°27.40’N, 116°16.37’E) was drilled at 2092 m water depth in northern South China Sea. MSU—Microwave sounding unit.

Figure 1. Mean monthly precipitation during boreal winter (January, southernmost position of Intertropical Convergence Zone, ITCZ) and boreal summer (July, northernmost position of ITCZ). Precipitation (in mm/month) from Wallace et al. (1995). Ocean Drilling Program Site 1146 (19°27.40’N, 116°16.37’E) was drilled at 2092 m water depth in northern South China Sea. MSU—Microwave sounding unit.

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scale of 0.22‰ per °C, and assuming no changes in local surface-water δ18O related to salinity (Figs. 2C and 2D). SST varies only between ~25.5 and 30.5 °C (±1.2 °C), whereas δ18O fluctuates between ~−1.8‰ and ~−3.6‰ (standard deviation of 0.8 °C for SST equivalent to ~1.0‰ δ18O, in contrast to 0.4‰ for δ18O equivalent to ~2 °C), implying that substantial variations in salinity are also imprinted in the planktic δ18O curve.

The SST record does not reflect major increases in benthic δ18O ca. 14.6 and 13.9 Ma, interpreted as ice volume growth (Holbourn et al., 2005; Shevenell et al., 2008), and therefore appears unaffected by major transitions in Southern Hemisphere high-latitude climate. The planktic δ18O signal also differs markedly from benthic δ18O, and even shows reverse trends, although a similar ice volume component is embedded into the two signals (Figs. 2A and 2D). This is particularly evident after 14.6 Ma, when major increases in benthic δ18O ca. 14.6, 13.9, and 13.1 Ma are not imprinted in the planktic δ18O record. This divergence supports that changes in planktic δ18O after 14.6 Ma are compensated by variations in local salinity, as expressed in the ice volume corrected δ18Osw curve (Fig. 2E). Based on the long-term evolution of benthic and planktic δ18O, SST, and δ18Osw, we identify three successive patterns of climate variability between 15.7 and 12.7 Ma.

From 15.7 to 14.6 Ma, planktic δ18O and SST display oscillations that are broadly in phase with benthic δ18O and follow the 100 k.y. eccentricity period (phase 1, Fig. 2). During this interval, frequently referred to as the Middle Miocene Climatic Optimum, high-amplitude fluctuations (~100 k.y. period) in benthic δ18O, and peak minimum values (0.2‰–0.4‰) suggest waxing and waxing of ephemeral high-latitude ice sheets, probably coupled with warming and cooling of deep and intermediate water. During this overall warmer climate interval, western Pacific SST generally followed global cooling and warming trends, while surface-water δ18O remained relatively high, implying that precipitation levels were relatively low over the subtropical western Pacific.

An episode of sustained ice growth ca. 14.6 Ma denotes the onset of a new pattern of climate variability with dampening of benthic δ18O variability and shortening of the dominant rhythm from ~100 to ~40 k.y. periods. This transition marked a major turning point in Middle Miocene climate evolution (phase 2, Fig. 2). In the western Pacific, a fundamental change in near-surface conditions is registered after the first glaciation event ca. 14.6 Ma (Figs. 2 and 3). SST rose abruptly by 3 ± 1.2 °C at 14.57 Ma, then oscillated around 28 ± 1.2 °C until 14.2 Ma. Surface planktic δ18O decreased by ~1‰, reaching minimum values of ~−3.4‰ at 14.5 Ma, indicating substantially fresher surface waters from 14.5 to 14.3 Ma during an interval of maximum amplitude variation in insolation over the northern subtropics. The change in surface hydrology after 14.6 Ma is also reflected by a marked intensification by ~2 ± 1.2 °C in the temperature gradient between surface and shallow subsurface planktic foraminifers at 14.57 Ma (Fig. 3). This increased stratification within the upper water column is consistent with surface freshening and warming and a decrease in mixing, perhaps as a result of a substantial rise in precipitation levels.

During the remainder of phase 2, climate exhibited high variability in the subtropical northwestern Pacific, including the δ18Osw maximum centered ca. 13.9 Ma. This period
of decreased precipitation was possibly related to high-frequency fluctuations of the Antarctic ice sheet and/or precessionally driven changes in radiative forcing affecting local moisture balance. For example, the most prominent \(\delta^{18}O\) increase ca. 13.95 Ma occurred during the benthic \(\delta^{18}O\) minimum (decreased Antarctic ice sheet) preceding the major expansion of the Antarctic ice sheet after 13.9 Ma. Although this interval coincided with high eccentricity, the amplitude variability in both planktic \(\delta^{18}O\) and SST remained low, indicating limited response to low-latitude radiative forcing.

Glaciation (benthic \(\delta^{18}O\) increase) at 13.91–13.84 Ma ultimately signaled entry into a more stable icehouse pattern (phase 3, Fig. 2). During the latter phase of ice expansion at 13.88-13.84 Ma, \(\delta^{18}O_{sw}\) values decreased by ~0.5‰, indicating a further episode of surface freshening in the subtropical northwestern Pacific. After 13.38 Ma, surface planktic \(\delta^{18}O\) and SST show an overall decline in amplitude variability, possibly as a response to a more stable Antarctic ice sheet. The ice growth event ca. 13.1 Ma ultimately ushered in a steady icehouse regime with a trend toward cooler local SST, and based on estimated \(\delta^{18}O_{sw}\) data (ice volume corrected), toward wetter conditions over the tropical western Pacific.

**INTERHEMISPHERIC TEMPERATURE CONTRAST AND ITCZ MIGRATION**

The temperature-salinity record from the northern South China Sea is currently related to the southern branch of the Southeast Asian monsoon system, which is linked to the northernmost boreal summer position of the ITCZ (Chao and Chen, 2001). Today, the southernmost extent of the Pearl River’s freshwater plume originating from continental China is at ~23°N, several hundred kilometers away from Site 1146 (Gan et al., 2009). Influence of continental runoff from the Southeast Asian continent was further reduced during the Middle Miocene, since higher sea level shifted the location of the Pearl River’s mouth further away from Site 1146. Thus, Middle Miocene salinity patterns in the northern South China Sea likely record different processes than terrestrial records of monsoonal precipitation over central China (Dettman et al., 2003; Jiang and Ding, 2008, 2009). Furthermore, the Tibetan Plateau and Himalayan range may have had a different configuration and lower elevation in Middle Miocene time, and if so they would have formed a barrier to moisture penetration into Asia, and also less of a heat source to fuel the summer monsoon, than at present (Molnar et al., 1993; Boos and Kuang, 2010).

We attribute the punctuated pattern of surface ocean warming and freshening after ca. 14.5 Ma to successive northward incursions and retreats of the ITCZ, leading to fundamental changes in atmospheric convection and oceanic circulation in tropical and mid-latitudes in conjunction with insolation forcing. Sequential northward shifts of the ITCZ during times of Antarctic cooling likely resulted in increased seasonal precipitation over the northern South China Sea. We speculate that Southern Hemisphere cooling following Middle Miocene ice growth in Antarctica ca. 14.6 Ma initially favored displacement of the annual mean position of the ITCZ toward the warmer Northern Hemisphere. After 14.5 Ma, higher Northern Hemisphere summer insolation associated with the 19 and 23 k.y. components of precession accentuated this trend and pulled the ITCZ further northward during boreal summer. Conversely, when insolation forcing was low, the ITCZ clung closer to the equator and drier, cooler conditions prevailed in the subtropical western Pacific.

In the planktic \(\delta^{18}O\) record, high variance in the precessional band and prominence of the 29 k.y. period at 14.5–14.3 and 13.7–13.4 Ma suggest strong response to precession and obliquity forcing (Figs. 2 and 4). The 29 k.y. signal in planktic \(\delta^{18}O\) possibly results from nonlinear interaction between eccentricity and obliquity, implying combined high- and low-latitude control on subtropical precipitation patterns. After 13.38 Ma, climate variability decreased in the subtropical western Pacific, as shown by low-amplitude variations in planktic \(\delta^{18}O\) and SST (variance for planktic \(\delta^{18}O\): ~0.15 before 13.38 Ma and

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**Figure 3.** Expanded view of 14.72–14.30 Ma interval highlighting stepped increase in precipitation and upper ocean stratification following Antarctic ice expansion ca. 14.6 Ma. ITCZ—Intertropical Convergence Zone. A: Benthic foraminiferal \(\delta^{18}O\) (PDB—Peedee belemnite). B: Sea-surface and subsurface planktic foraminiferal \(\delta^{18}O\). C: Sea-surface and subsurface Mg/Ca derived temperature (T) estimates. D: Eccentricity and June 21 insolation at 30°N (from Laskar et al., 2004).

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**Figure 4.** A: Spectral analysis of planktic \(\delta^{18}O\) in Ocean Drilling Program Site 1146 exhibits significant variability at 29 and 21 k.y. and at long (>300 k.y.) periods. B: Bandpass-filtered planktic \(\delta^{18}O\) between 12.7 and 15.7 Ma (frequency: 0.034 k.y.\(^{-1}\); bandwidth: 0.005 k.y.\(^{-1}\)). Gaussian bandpass filter centered at 29.4 k.y. includes 25.6–34.5 k.y. periods.
~0.05 after 13.38 Ma; variance for SST: ~0.7 before 13.38 Ma and ~0.3 after 13.38 Ma). We infer that ice expansion ca. 13.1 Ma marked entry into a more stable icehouse mode with a fully glaciated Antarctica, and locked the ITZC into a northern position. Evidence of increased rainfall along the North African margin following Middle Miocene Antarctic cooling (John et al., 2003) suggests that the northward shift of the ITZC may have been a global event.

A close relation between the interhemispheric temperature gradient and ITZC position is supported by model simulations of Pleistocene glacial-interglacial and millennial variability that indicate that the meridional position of the ITZC is sensitive to asymmetrical polar cooling due to changes in atmospheric and oceanic heat exchange within the tropics and mid-latitudes (Chiang and Bitz, 2005; Chiang et al., 2003, 2008; Broccoli et al., 2006). In these models, a cooler Southern Hemisphere (relative to a warmer Northern Hemisphere) increased Pacific zonal SST gradients, strengthened the equatorial cold tongue annual cycle, and shifted the ITZC northward. Thus, the reorganization of atmospheric and circulation patterns in the tropical Pacific following Middle Miocene ice growth episodes in Antarctica has a similarity to present-day patterns, with preferential cooling of surface waters in the southeastern equatorial Pacific through upwelling, and displacement of SST maximum into the Northern Hemisphere (Philander et al., 1996).

CONCLUSIONS

Middle Miocene climate evolution of Southeast Asia developed in a series of steps embedded in a background of orbital-scale variability. Although drying of central China may be associated with Himalayan uplift and exhumation (Clift et al., 2008), the sequential warming and freshening of the South China Sea, illustrated here, suggest that increasing interhemispheric temperature contrast following Middle Miocene glaciation of Antarctica displaced the ITZC away from the cooler hemisphere into a more northern position. This close interaction between ice volume change, the seasonal migration of the ITZC, and shifts in the location of tropical-subtropical rain belts appears to be an enduring feature of Earth’s climate evolution, implying that future warmer climates, with predictions of differential heating of a relatively ice free Northern Hemisphere (Masson-Delmotte et al., 2006), may induce further changes in the distribution of tropical rainfall belts in the region.

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