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Orbitally-paced variations of water availability in the SE Asian Monsoon region following the Miocene Climate Transition

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ABSTRACT

Middle Miocene Earth had several boundary conditions similar to those predicted for future Earth including similar atmospheric pCO_2 and substantial Antarctic ice cover but no northern hemisphere ice sheets. We describe a 12 m outcrop of the terrestrial Yanwan Section in the Tianshui Basin, Gansu, China, following the Miocene Climate Transition (13.9–13.7 Ma). It consists of ∼25 cm thick $CaCO_3$-cemented horizons that overprint siltstones every ∼1 m. We suggest that stacked soils developed in siltstones under a seasonal climate with a fluctuating water table, evidenced by roots, clay films, mottling, presence of $CaCO_3$ nodules, and stacked carbonate nodule $\delta^{13}C$ and $\delta^{18}O$ profiles that mimic modern soils. We suggest that the $CaCO_3$-cemented horizons are capillary-fringe carbonates that formed in an arid climate with a steady water table and high potential evapotranspiration rates (PET), evidenced by sharp upper and basal contacts, micrite, sparite, and root-pore cements. The $CaCO_3$ of the cemented horizons and the carbonate nodules have similar mean $\delta^{18}O$ and $\delta^{13}C$ values but the cements have significantly smaller variance in $\delta^{13}C$ and $\delta^{18}O$ values and a different $\delta^{18}O$ versus $\delta^{13}C$ slope, supporting the conclusion that these carbonates are from different populations. The magneto-stratigraphic age model indicates obliquity pacing of the arid conditions required to form the $CaCO_3$-cemented horizons suggesting an orbital control on water availability. We suggest two possible drivers for the obliquity pacing of arid conditions: 1) variability in the cross-equatorial pressure gradient that controls summer monsoon (ASM) strength and is influenced by obliquity-paced variations of Antarctic ice volume and 2) variability in Western Pacific Ocean–East Asian continent pressure gradient controlled by the 25–45°N meridional insolation gradient. We also suggest that variations in aridity were influenced by variations in PET and sensible heating of the regional land surface which are both influenced by precession-controlled 35°N summer insolation. We then use orbital configurations to predict lithology. Coincidence of obliquity minima (strong ASM) and 35°N summer insolation maxima (strong ASM) drives strong ASM and high PET, resulting in soil formation in an environment with relatively large seasonal changes in water availability. Coincidence of obliquity maxima (weak ASM) and 35°N summer insolation maxima (strong ASM) moderates the ASM, results in high PET, and thus drives overprinting of soils by capillary fringe carbonates above a deepened and relatively stable water table. Coincidence of obliquity and insolation minima also moderates the ASM but results in low PET and thus a high water table, which explains the previously documented occurrence of aquatic plants in this section. This context allows us to assign an orbital configuration to atmospheric pCO_2 determined from the paleosols. Our best estimate of pCO_2 during the times of intermediate ice volume is $475 + 650/-230$ ppmV (median value with error reported as 84th–16th percentile values). Southern hemisphere control of ASM variability during the Middle Miocene may have resulted in larger orbital scale water availability variations compared with the Pleistocene.

Abbreviations: Asian Summer Monsoon, ASM; East Asian Summer Monsoon, EASM; Northern hemisphere, NH; Southern hemisphere, SH; cross-equatorial pressure gradient, XEPG; meridional temperature gradient, MTG; Miocene Climate Transition, MCT; Middle Miocene Climatic Optimum, MMCO; potential evapotranspiration, PET; Chinese Loess Plateau, CLP; $\delta^{18}O$ and $\delta^{13}C$ values of carbonate nodules, $\delta^{18}O_{cn}$ and $\delta^{13}C_{cn}$; $\delta^{18}O$ and $\delta^{13}C$ values of the $CaCO_3$-cemented horizon matrix, $\delta^{18}O_{mx}$ and $\delta^{13}C_{mx}$; $\delta^{13}C$ values of occluded organic matter, $\delta^{13}C_{om}$.

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1. Introduction

The most recent report from the Intergovernmental Panel on Climate Change (IPCC) has predicted that mean annual precipitation and frequency of extreme events will increase in the South and East Asian monsoon regions (Hijioka et al., 2014). Thus, understanding the monsoon and its variability is necessary for water resources management. However, it is currently unclear how the Asian monsoon will respond under altered global boundary conditions, specifically an Earth without a Greenland ice sheet. To address this deficit there is a need to study geologic records to better understand modern and future water variability.

Despite the extensive work on Pleistocene–Pliocene monsoon variability, there are few records from the Middle Miocene, which is likely the best analog for a future Earth without a Greenland ice sheet. The sedimentary record studied here post-dates the cooling and Antarctic ice volume increase during the Miocene Climate Transition (MCT; 13.9–13.7 Ma; Knorr and Lohmann, 2014) but predates the expansion of northern hemisphere (NH) ice sheets in the Pliocene.

Whereas most studies focus primarily on precipitation, we consider water availability, which is controlled by both inputs and outputs. The volume of water leaving a system by evapotranspiration and runoff is equally significant to the volume of water entering a system by precipitation. Understanding the post-MCT orbital variation of water availability in the Asian monsoon region 1) requires consideration of the controls on evapotranspiration and precipitation, and 2) is relevant because the Middle Miocene global boundary conditions are comparable to near future Earth projections.

2. The Asian monsoon and its Plio–Pleistocene variability

The Asian Summer Monsoon (ASM) is driven by atmospheric pressure gradients. During boreal summer, a zone of low atmospheric pressure develops in central Asia at ∼35°N from sensible heating of the Tibetan Plateau and surrounding regions. Concurrently, during austral winter, high pressure zones strengthen over Australia and the southern Indian Ocean. The resulting cross-equatorial pressure gradient (XEPG) drives surface winds from the cold southern hemisphere across the warm equatorial ocean and transports moisture to Southeast and central Asia. Meanwhile, high pressures over the W Pacific Ocean create a land–sea pressure gradient that drives moisture flow to Northeast Asia (Fig. 1; Webster et al., 1998; Wang, 2006).

Asian monsoon variability for the Pliocene–Pleistocene is well-documented from marine records (e.g., Clemens et al., 2008), speleothem records (e.g. Yuan et al., 2004; Cai et al., 2015; Cheng et al., 2016) and paleosol–loess sequences on the Chinese loess plateau (e.g. An et al., 2001; Guo et al., 2002; Clemens et al., 2008; Passey et al., 2009; Nie et al., 2014; Li et al., 2017). In general, these Pliocene–Pleistocene records show that the major controls on ASM intensity are 1) the fast physics response of heating/cooling of the Asian continent and the Pacific and Indian Oceans, and 2) the slow physics response of atmospheric pressure gradients that are influenced by polar ice volume (An et al., 2011; Liu and Ding, 1998; Sun et al., 2015; Ao et al., 2016).

The fast physics responses have traditionally been considered to be dominated by variations in NH summer insolation, which on orbital timescales are controlled by Earth's axial precession. Increased summer insolation over central Asia deepens the pressure low and thus strengthens summer monsoonal circulation. Chinese speleothem oxygen isotope records are consistent with this summer insolation control (e.g., Yuan et al., 2004; Wang et al., 2008; Cheng et al., 2016). However, recent studies suggest that obliquity also paces Pleistocene East Asian (Li et al., 2017) and tropical SH (Liu et al., 2015) precipitation variability. Obliquity controls the magnitude of meridional temperature and pressure gradients (MTG). A change from high to low obliquity results in a larger decrease in insolation at high compared to low latitudes, increasing the MTG. Low obliquity, resulting in a large MTG, has been interpreted to weaken the W Pacific Ocean – E Asian continent land–sea pressure gradient and thus weaken the East Asian Summer Monsoon (EASM) (Li et al., 2017). Perhaps incompatibly, low obliquity and high MTG may shift the Intertropical Convergence Zone (ITCZ) northward in toward Indonesia, drying the SH tropics, due to weaker northerly resistance resulting from a weaker Asia–Australia pressure gradient during austral summer (Liu et al., 2015).

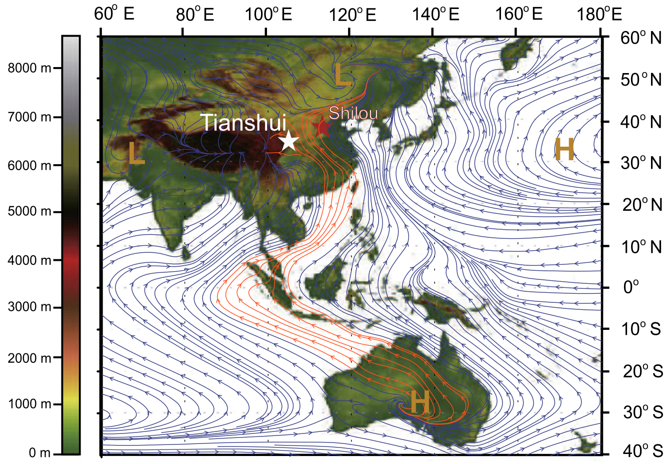

Fig. 1. Elevation map of Asia and Australia continents, Indian Ocean and W Pacific Ocean, and a surficial streamline field of atmospheric circulation driving the Asian summer monsoon. The white star represents the location of the Tianshui Basin (34°58′N, 105°34′E) where the Yanwan section resides, and the red star represents the location of the Shilou section from Ao et al. (2016), both of which are on the Chinese Loess Plateau (CLP). The "L" represents low pressure zones over central Asia and the "H" represents high pressure zones over the Western Pacific and Australia. The resulting pressure gradients drive cross equatorial flow of heat and moisture from the southern hemisphere to India and SE Asia. The orange streamlines highlight cross-equatorial atmospheric flow from the high pressures over Australia to the low pressures over the CLP. Increases in northern hemisphere summer insolation increase the strength of the low-pressure zone over central Asia, strengthening the monsoon. Increases in Antarctic ice volume increase the strength of the high-pressure zone over Australia, thus also strengthening the ASM (An et al., 2011). As NH ice sheets expand, the low-pressure zone weakens and shifts to the south, weakening the ASM. This figure was adapted from Ao et al. (2016), who used atmospheric circulation data averaged from June to August from 1981–2010 sourced from the European Centre for medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA) data (Dee et al., 2011).

The slow physics responses complicate the orbital scale forcing of monsoonal circulation. Previous work has recognized multiple potential effects of ice volume (Nie et al., 2017 and references therein). First, sea level variations could have caused periodic advance and retreat of the ASM. Second, tropical ocean evaporation could vary with changes in sea surface temperatures (SST). Third, ice volume could affect the pressure gradients that drive ASM circulation. For instance, cooling of central Asia resulting from the presence of large NH ice sheets is thought to weaken the boreal summer land–sea pressure gradient and thus weaken the ASM (e.g., Sun et al., 2006). Changes in southern hemisphere ice volume have the opposite effect; increase SH ice volume tends to enhance ASM circulation as shown by Cenozoic proxy records (e.g. An et al., 2011; Nie et al., 2017) and climate models (e.g. Ao et al., 2016). The relevant teleconnection is as follows: larger SH ice volume increases high pressure over Australia and the southern Indian ocean, which increases the cross equatorial pressure gradient (XEPG) and thus results in strengthened boreal summer southerly