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Role of seasonal transitions and westerly jets in East Asian paleoclimate

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A B S T R A C T

The summer rainfall climate of East Asia underwent large and abrupt changes during past climates, in response to precessional forcing, glacial–interglacial cycles as well as abrupt changes to the North Atlantic during the Last Glacial. However, current interpretations of said changes are typically formulated in terms of modulation of summer monsoon intensity, and do not account for the known complexity in the seasonal evolution of East Asian rainfall, which exhibits sharp transition from the Spring regime to the Meiyu, and then again from the Meiyu to the Summer regime.

We explore the interpretation that East Asian rainfall climate undergoes a modulation of its seasonality during said paleoclimate changes. Following previous suggestions we focus on role of the westerly jet over Asia, namely that its latitude relative to Tibet is critical in determining the stepwise transitions in East Asian rainfall seasons. In support of this linkage, we show from observational data that the interannual co-variation of June (July–August) rainfall and upper tropospheric zonal winds show properties consistent with an altered timing of the transition to the Meiyu (Summer), and with more northward-shifted westerlies for earlier transitions.

We similarly suggest that East Asian paleoclimate changes resulted from an altered timing in the northward evolution of the jet and hence the seasonal transitions, in particular the transition of the jet from south of the Plateau to the north that determines the seasonal transition from Spring rains to the Meiyu. In an extreme scenario – which we speculate the climate system tended towards during stadial (cold) phases of D/O stadials and periods of low Northern Hemisphere summer insolation – the jet does not jump north of the Plateau, essentially keeping East Asia in prolonged Spring conditions.

We argue that this hypothesis provides a viable explanation for a key paleoproxy signature of D/O stadials over East Asia, namely the heavier mean $\delta^{18}O$ of precipitation as recorded in speleothem records. The southward jet position prevents the low-level monsoonal flow – which is isotopically light – from penetrating into the interior of East Asia; as such, precipitation there will be heavier, consistent with speleothem records. This hypothesis can also explain other key evidences of East Asian paleoclimate changes, in particular the occurrence of dusty conditions during North Atlantic stadials, and the southward migration of the Holocene optimal rainfall.

1. Introduction

East Asia experienced large and abrupt climate changes during the Pleistocene. The most remarkable recent evidence of these changes is from stable oxygen isotope ratios ($\delta^{18}O$) of speleothem

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calcium carbonate across various East Asian caves (Wang et al., 2001; Wang et al., 2008) (Fig. 1). They show large fluctuations in the $\delta^{18}O$ on millennial and precessional timescales, with heavier isotopic composition during stadials, and similar fluctuations during periods of low Northern Hemisphere (NH) summer insolation due to precessional changes in the Earth's orbit. Other records corroborate the sense of large and abrupt change in East Asia; for example, paleoproxy dust records show East Asia to be dustier during cold stadials (and in particular Heinrich stadials) (An et al., 2012; Nagashima et al., 2011), and more generally during glacial periods (An et al., 2000).

The dominant interpretation of variability in the speleothem records is as a record of changes in East Asian summer monsoon intensity, with $\delta^{18}O$ relatively light when monsoons are more intense (Clemens et al., 2010; Wang et al., 2001, 2008). This interpretation originated with the 'amount effect' (Dansgaard, 1964) wherein rainfall is observed to be isotopically lighter with stronger rainfall. However, while this relationship works well for convective rainfall where evaporation exceeds precipitation (Lee and Fung, 2008), recent studies from instrumental measurements over East Asia examining the variation of $\delta^{18}O$ find the amount effect influence to be relatively weak on the whole and heterogeneous in space (Dayem et al., 2010; Johnson and Ingram, 2004; Lee et al., 2012); moreover there is significant temperature dependence of $\delta^{18}O$, especially at the northern extremities of the East Asian summer monsoon region. Recent interpretations instead invoke seasonality where lighter $\delta^{18}O$ indicates relatively more summer rainfall following from the fact that summer monsoon rainfall has lighter $\delta^{18}O$ than the rest of the year (Wang et al., 2001). Following this logic, Cheng et al. (2009b) interpret the speleothem record as a measure of the amount of summer monsoon precipitation, or as they refer to as 'summer monsoon intensity'.

Even if this were correct, the 'summer monsoon intensity' interpretation is at best incomplete as it neglects the complexity of the seasonal evolution in East Asian rainfall. The behavior of 'typical' monsoons – such as the West African or South Asian monsoon – are characterized by the onset and retreat of one (summer) rainy season. East Asia spring and summer rainfall, on the other hand, is characterized by several quasi-stationary stages and abrupt transitions in between (see Section 2).

We seek a more concrete interpretation of the East Asian paleo rainfall changes that incorporates the complexity of the seasonal cycle. The role of seasonality and seasonal transitions has been previously invoked in several previous East Asian paleoclimate studies, though none of them comprehensively. An et al. (2000)

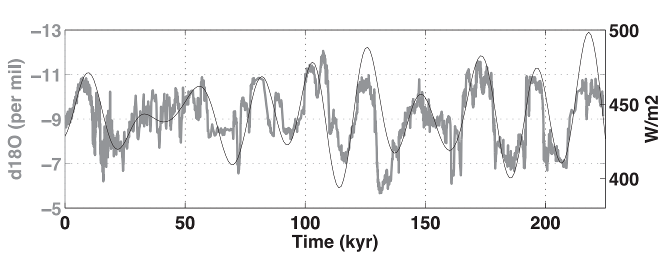

Fig. 1. Thick gray line (left scale) is speleothem δ18O record from Wang et al. (2008), and thin black line is July 21 insolation (right scale). The speleothem δ18O record is interpreted as variation in the East Asian rainfall climate over the last 220,000 years. The record is stitched from several speleothems from the Hulu, Dongge and Sanbao cave sites in China. They clearly show changes on precessional timescales (as compared to the insolation line). They also fluctuate in sync with D/O events during the Last Glacial period. The Wang et al. (2008) speleothem data was obtained from the NOAA National Climatic Data Center (http://www.ncdc.noaa.gov). The insolation curve was computed from a MATLAB code by Huybers and Eisenman (2006), following the algorithm by Berger (1978).

argued for stepwise changes to the East Asian monsoon during the Holocene whereby the region experiencing its 'Holocene optimal' (maximum rainfall during the course of the Holocene) shift with the phase of precession: peak rainfall was attained during 10,000–7000 yr ago in north-central and northern east-central China; ca 7000–5000 yr ago in the middle and lower reaches of the Yangtze River; and ca 3000 yr ago in southern China. Clemens et al. (2010) argued for significant contributions of wintertime East Asian rainfall in order to explain the phasing of East Asian precipitation relative to its South Asian counterparts. Following the summer/non-summer rainfall ratio interpretation by Wang et al. (2001) and Cheng et al. (2009b), Dayem et al. (2010) also explored the ramifications of changes in the seasonality of precipitation on precipitation $\delta^{18}O$.

The quasi-stationary stages of East Asian rainfall and abrupt transitions indicates a *dynamic* seasonality driven by circulation changes, and not simply a continuous response to increasing insolation; moreover, it suggests that the dynamics underlying such changes could be usefully applied to the paleoclimate scenarios. The view we promote is centered on the role of the westerly jet impinging on Tibet; modern-day dynamical studies point to the seasonal north–south evolution of the jet as playing a key role in the abrupt transitions in the East Asian rainfall climate. It also turns out (as we will argue) that the meridional position of jet is sensitive to many paleoclimate influences, including orbital changes, the topographic effect of the Laurentide ice sheet, and slowdowns on the Atlantic Meridional Overturning circulation (AMOC). Thus, the westerly jet gives us a way to connect paleoclimate influences to specific changes in the East Asian rainfall climate.

The role of the westerly jet and jet transitions in East Asian paleoclimate is an emerging hypothesis. The westerlies features prominently in how the rise of Tibetan Plateau over the last several million years altered Asian climate; Molnar et al. (2010) provide a summary and perspective on these ideas, and also speculate on the role of the westerly jet in the more recent paleoclimate changes. However, the first and most comprehensive exposition (to the authors' knowledge) of the role of jet transitions during the Last Glacial period and Holocene was advanced by Kana Nagashima and colleagues (Nagashima et al., 2007; Nagashima et al., 2011; Nagashima and Tada, 2012), who hypothesized a delayed seasonal jet transition from south of Tibet to the North during D/O stadials. They proposed this hypothesis specifically to explain their dust flux record from an ocean sediment core in the Sea of Japan, and drew on contemporary understanding of westerly jet dynamics in formulating their hypothesis. While we follow similar motivations as with Nagashima and colleagues in formulating our hypothesis, we expand the hypothesis by exploring the ramifications of the hypothesis in particular to the atmospheric circulation dynamics and oxygen isotopic changes in rainfall. We also present initial modeling evidence supporting this hypothesis, as well as presenting a modern-day analog that illustrates in detail the nature of a delayed jet transition on the climate of East Asia and surroundings.

We first summarize what is known regarding the East Asian seasonal transitions, and their relationship to the seasonal jet transition (Section 2). We then advance a specific hypothesis (the 'Jet Transition' hypothesis) for East Asian paleoclimate changes, and discuss the predictions of the hypothesis (Section 3). In Section 4, we show observational evidence that the meridional position of the westerly jet is tied to modulation of the timing of seasonal transitions in today's East Asian monsoon variability. Following this, we explore our hypothesis with model simulations of two paleoclimate scenarios, North Atlantic cooling and orbital variations (precession), showing the viability of the hypothesis (Section 5). We then explore how the hypothesis can be made consistent with