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Detecting the relationship between moisture changes in arid central Asia and East Asia during the Holocene by model-proxy comparison

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ABSTRACT

Identifying the relationships between moisture changes in arid central Asia and those in East Asia may help us understand the interplay between the westerlies and the Asian summer monsoon. We combined proxy moisture records with the results from a transient simulation forced by changes in orbital parameters to analyse their relationships during the Holocene (9.5–0 ka BP). The proxy records and simulation results generally agree with a relatively dry early Holocene, the wettest period in the middle Holocene, and a dry late Holocene in East Asia. These periods were not solely controlled by precession-driven East Asian summer monsoon variability, but were significantly influenced by precipitation during the other seasons and by evaporation. However, different proxy records show contrasting results for moisture changes in arid central Asia during the Holocene. To study this, we analysed the climatic signals of the competing proxy records by comparing these proxy records with simulation results. We found that speleothem $\delta^{18}O$ was significantly influenced by water vapour sources and evaporation rather than by the amount of precipitation. Thus, the model data reveals a persistent wetting trend throughout the Holocene that was out-of-phase with the trend in East Asia. The wetting trend in arid central Asia was caused by precipitation that increased faster than evaporation during the Holocene. The enhanced water vapour input from South Asia and the Middle East was the main cause of the increase in precipitation in arid central Asia, which in turn gave rise to the intensification of evaporation.

1. Introduction

Hu (1935) identified the demarcation line in the geography of China's population, which is referred to as the “Aihui-Tengchong Line” or “Huhuanyong Line”. About 96% of China's population lived to the southeast of this line, in an area that only accounted for about 36% of China's total land area at that time. This basic pattern remains unchanged to the present day. Coincidentally, the Huhuanyong Line is in good agreement with the limit of the Asian summer monsoon (ASM) (Gao et al., 1962). The area to the southeast of the monsoon limit (East Asia) is mainly controlled by the ASM and has an annual mean precipitation ranging from 400 to 2000 mm (Wang, 2006). In contrast, the area northwest of the monsoon limit (arid central Asia) is remarkably affected by the prevailing westerlies and has an average annual precipitation less than 400 mm (Chen et al., 2008; Jin et al., 2012; Zhang et al., 2016). Therefore, this monsoon limit reflects the zones of interaction and competition between the ASM and the westerlies.

The ability of a strong ASM to penetrate and bring precipitation to arid central Asia is not only scientifically interesting but socially important. In the present-day climate, the monsoonal front penetrates east Mongolia (eastern part of arid central Asia) during strong East Asian summer monsoon (EASM) years (Li and Zeng, 2005). However, ASM water vapour can only intrude into the Tarim Basin in northwest China (a small part of the core region of arid central Asia) during weak ASM periods (Zhao et al., 2014; Huang et al.,

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2015b), which is also evidenced by the precipitation changes in the ASM region and arid central Asia. Over the past few decades, in the context of global warming induced by greenhouse gases, the intensity of the ASM and its associated precipitation in northern China and South Asia has experienced a persistent weakening trend (Li and Zeng, 2005; Ding et al., 2008), whereas the climate in northwest China has shifted from warm-dry to warm-humid since the 1980s (Jiang et al., 2005; Shi et al., 2007; Su and Wang, 2007; Xu et al., 2015).

This out-of-phase relationship between changes in the amount of moisture in arid central Asia and East Asia also existed on decadal to centennial timescales during the past millennium (Chen et al., 2006, 2010, 2011, 2015b; Huang et al., 2015a). Proxy records suggest that East Asia was generally wetter during the Medieval Climate Anomaly (1000–1300 CE) than during the Little Ice Age (1400–1900 CE), whereas the opposite conditions were present in the core area of arid central Asia (Chen et al., 2010, 2015b). These trends suggest that a strong ASM did not intrude into the core area of arid central Asia in the Medieval Climate Anomaly.

The Indian summer monsoon (ISM) was remarkably strengthened by a high summer insolation during the early Holocene that amplified the land-sea thermal contrast (Kutzbach, 1981). The strength of the ISM and its associated precipitation continues to decline during the Holocene due to a precession-induced reduction in summer insolation (Fleitmann et al., 2003; Wang et al., 2010a,b). Speleothem records from China suggest a similar evolution in the strength of the EASM circulation with the ISM, showing a persistent weakening trend throughout the Holocene (Wang et al., 2005; Cheng et al., 2016a). However, precipitation in East Asia was significantly suppressed during the early Holocene and peaked in the middle Holocene, as documented by loess and pollen records (Lu et al., 2005, 2013; Wang et al., 2010a,b; Chen et al., 2015a; Liu et al., 2015a).

Whether the strong ASM intruded into the core area of arid central Asia during the early Holocene remains controversial on millennial and orbital timescales. The speleothem oxygen isotope ($\delta^{18}O$) record from Kesang Cave in Xinjiang, northwestern China (42° 52′ N, 81° 45′ E, elevation *c.* 2000 m a.s.l.), shifted from light during the early Holocene to heavy during the late Holocene, a pattern similar to that in speleothem records from ASM regions (Cheng et al., 2012, 2016b; Cai et al., 2017). The speleothem $\delta^{18}O$ variability was interpreted as a drying trend in arid central Asia throughout the Holocene (Cheng et al., 2012; Cai et al., 2017). A similar evolutionary pattern was also found in a pollen record by Li et al. (2011) in the Yili River valley of Xinjiang, China. Cheng et al. (2012) attributed the speleothem $\delta^{18}O$ variability to the incursion of a strong ASM into arid central Asia. However, many other records, including lake records, aeolian sedimentary sequence, loess-palaeosol sequences, and the peatland record, have indicated a generally wetting trend in the core area of arid central Asia during the Holocene (An et al., 2012; Wang and Feng, 2013; Hong et al., 2014; Long et al., 2014, 2017; Chen et al., 2016a). These records indicate that a strong ASM did not intrude into the core area of arid central Asia during the early Holocene.

Considering the controversy about the history of moisture in arid central Asia and its relationship with that in East Asia during the Holocene, it is essential to examine new independent evidence for moisture changes in arid central Asia and to compare this evidence with competing proxy records. In this study, we compared multiple proxy records of moisture with the results from a transient simulation forced by changes in orbital parameters performed in a coupled atmosphere-ocean general circulation model, and we investigated the evolution of the amount of moisture in arid central Asia and East Asia during the Holocene. This work provided new insights into the interplay between the westerlies and the Asian summer monsoon during the Holocene.

2. Methods

2.1. Climate simulation

To examine the relationship between the evolution of moisture in arid central Asia and that in East Asia during the Holocene, we compared proxy data with a transient simulation of climatic evolution for the last 9.5 ka (Jin et al., 2014). The transient simulation was conducted using the Kiel Climate Model (KCM; Park et al., 2009), a coupled atmosphere-ocean-sea ice general circulation model. The KCM includes the spectral atmospheric model ECHAM5 (Roeckner et al., 2003) and the ocean-sea ice general circulation model Nucleus for European Modeling of the Ocean (NEMO) (Madec, 2008) coupled through OASIS3 (Valcke, 2006). These models do not couple anomalies or use a flux correlation. The horizontal resolution of ECHAM5 is 3.75° × 3.75° (T31) with 19 levels in the vertical resolution up to 10 hPa. The horizontal resolution of NEMO is 1.3° on average, based on 2° Mercator meshes. It has a finer resolution in the tropical regions, where the meridional grid-point separation reaches 0.5°. NEMO assumes 31 vertical levels. A detailed description of the KCM is given in Park et al. (2009), including further information on the performance of the model.

Before the Holocene transient (HT) simulation, two 1000-year equilibrium experiments—pre-industrial (0 ka BP, H0K) and early Holocene (9.5 ka BP, H9K)—were performed using the KCM with Earth's orbital parameters (eccentricity, obliquity, and precession; Berger and Loutre, 1991). The HT simulation was initialized using output from the H9K simulation, and it was then forced by varying the orbital parameters according to the respective period from 9.5 to 0 ka BP with a tenfold acceleration scheme (Lorenz and Lohmann, 2004). Hence, the climate trends and feedbacks during the last 9500 years (9.5–0 ka BP) imposed by the external, orbitally driven insolation changes were represented in the experiment by 950 model years at 10-year intervals. Other forcing factors apart from insolation forcing—for example, greenhouse gas concentrations, continental ice sheets, and meltwater fluxes—were taken at pre-industrial (1850 CE) levels. In this regard, this approach is effectively a sensitivity test of climate models to variations in insolation.

Fig. 1 compares the annual mean surface temperature and precipitation from the Climate Research Unit (CRU) TS3.24 dataset (Harris et al., 2014) for 1961–1990 and from the H0K (pre-industrial) simulation. The spatial distributions of the annual mean temperature and precipitation reproduced by the KCM are in good agreement with the CRU observations. However, the KCM underestimates the absolute values of the annual mean temperature. The underestimation of the surface temperature is probably due to the emission of anthropogenic greenhouse gases since the industrial revolution. In addition, the KCM accurately reproduces the general features of atmospheric circulations controlling climate changes in arid central Asia and East Asia (Fig. 2). On the whole, our simulation results are trustworthy.

2.2. Proxy records

Four moisture-sensitive proxy records that cover most of the Holocene in arid central Asia were selected for study. Chen et al. (2008) synthesized a moisture index for arid central Asia using eleven lake records that spread from 40° E to 120° E at mid-latitudes. These records cover several climate zones, including the arid central Asian region as well as the East Asian monsoon margin region. Since the present study focused on the core area of arid