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Modeling precipitation δ^{18}O variability in East Asia since the Last Glacial Maximum: temperature and amount effects across different timescales

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Abstract. Water isotopes in precipitation have played a key role in the reconstruction of past climate on millennial timescales and longer. However, for midlatitude regions like East Asia with complex terrain, the reliability behind the basic assumptions of the temperature effect and amount effect is based on modern observational data and still remains unclear for past climate. In the present work, we reexamine the two basic effects on seasonal, interannual, and millennial timescales in a set of time slice experiments for the period 22–0 ka using an isotope-enabled atmospheric general circulation model (AGCM). Our study confirms the robustness of the temperature and amount effects on the seasonal cycle over China in the present climatic conditions, with the temperature effect dominating in northern China and the amount effect dominating in the far south of China but no distinct effect in the transition region of central China. However, our analysis shows that neither temperature nor amount effect is significantly dominant over China on millennial and interannual timescales, which is a challenge to those classic assumptions in past climate reconstruction. Our work helps shed light on the interpretation of the proxy record of δ^{18}O from a modeling point of view.

1 Introduction

Stable water isotopes have been recognized as key tracers for tracking temperature footprint and moisture sources in air masses (e.g., Dansgaard, 1964; Grootes et al., 1993; Cuffey et al., 1995; Salamatin et al., 1998; Noone, 2008; Sturm et al., 2010). Based on the present relationship between δ^{18}O records and temperature/precipitation, earlier observational studies suggest that the δ^{18}O–temperature relationship at high latitudes tends to be associated with the "local temperature effect", a positive correlation between δ^{18}O in precipitation and the temperature of ambient air (warmer air provides more energy to rain from ^{18}O-rich water vapor), whereas the δ^{18}O–precipitation relationship in the tropics and low latitudes tends to be associated with the "amount" effect, a negative correlation between δ^{18}O in precipitation and the accumulated total rainfall on local and upstream regions (stronger tropical precipitation leave less δ^{18}O in vapors transported to the subtropics and low latitudes) (Dansgaard, 1964). Thus, the δ^{18}O records in high-latitude ice cores have long been used to infer temperature variability in past climate through the empirical temperature effect assumption (Schneider and Noone, 2007; Schotterer and Oldfield, 1996). Recently, significant studies have emerged of oxygen isotope records from speleothems (Yuan et al., 2004; Wang et al., 2001, 2005,

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2008; Cheng et al., 2009; Chu et al., 2012), ice cores (Davis and Thompson, 2004; Davis et al., 2005; Thompson et al., 2000, 2006), tree rings (Feng et al., 1999; Grießinger et al., 2011), and lake sediments (Morrill et al., 2003, 2006; Zhang et al., 2011) found in the monsoon region, especially in East Asia. These studies tend to suggest that these isotope records reflect the East Asia summer monsoon (EASM) rainfall through the amount effect. This interpretation of monsoon intensity, however, has been challenged recently by isotope modeling studies, which suggest potentially significant deviations from these presumed amount effects (LeGrande et al., 2006; LeGrande and Schmidt, 2009; Pausata et al., 2011; Johnson, 2011; Liu et al., 2014b). One basic and key question is whether the present-day relationship between δ^{18}O and temperature/precipitation in East Asia for, say, a seasonal cycle, is also valid for interpreting past climate on millennial timescales or longer.

East Asia is located at the transition zone between temperature-effect-dominated high latitudes and amount-effect-dominated low latitudes, and thus its climate is influenced by both. As a result, the interpretation of δ^{18}O in precipitation still remains a great controversy, especially on diverse timescales. Modeling δ^{18}O using isotope-enabled general circulation models (GCMs) provides a unique and quantitative approach to reexamine these basic relationships with temporally continuous data and complete spatial coverage (Vuille et al., 2005; Lee et al., 2007, 2008). The simulated temporal slope or correlation between δ^{18}O and surface temperature/precipitation in various regions around East Asia might confirm or challenge those traditional linkages: is it appropriate to interpret the δ^{18}O record as the direct consequences of local temperature/precipitation changes on all the timescales?

Here, we will examine the temperature effect and amount effect over China using an isotope-enabled atmospheric general circulation model (AGCM; Noone, 2008). The results show that the robustness of δ^{18}O–climate relations depends highly on timescales. The classic relations derived from a seasonal-cycle timescale might be challenged on interannual and millennial timescales. It is therefore suggested that one should be cautious when applying the relations of two effects in reconstructing paleoclimate using δ^{18}O. The paper is organized as follows: the model, experiments, and the observations for comparison are described in Sect. 2; the model results on seasonal, interannual, and millennial timescales are discussed in Sect. 3. The concluding remarks are summarized in Sect. 4.

2 Model and data

We will study the water isotope response using the isotope-enabled isoCAM3, which incorporates a module simulating stable water isotopes in the NCAR CAM3 (T31) (Noone, 2008). We performed time-slice experiments for the last 22 000 years with each consecutive snapshot 1000 years apart, i.e., 22, 21, 20, 2, 1, and 0 ka. These experiments are forced by realistic green house gas (GHG) concentrations, orbital parameters, land ice sheet and land–ocean mask, as well as the monthly sea surface temperature (SST) and sea ice fraction from a transient simulation of the last 22 000 years from CCSM3 (Liu et al., 2009, 2012, 2014a). In addition, the δ^{18}O values at the sea surface, which is referred to as standard mean ocean water (SMOW) at present, were linearly interpolated from 1.6 ‰ for 22 ka (Schrag et al., 1996) to 0.5 ‰ for 0 ka (Hoffmann et al., 1998) accounting for their change due to the fluctuation of sea level during the deglaciation. More details on isoCAM3 can be found in Noone and Sturm (2010). Each slice was integrated for 50 years and the last 30-year model outputs will be used in the analysis. For more information about the experiments, please refer to Liu et al. (2014b).

A set of four-member AMIP (Atmospheric Model Intercomparison Project)-type experiments are also performed by using isoCAM3 with forcing of observed SST and sea ice from HadISST1.1 (Rayner et al., 2003), covering the period 1975–2004 (30 years). The ensemble mean of these experiments is used to better investigate the variability of isotopes on an interannual timescale.

Global Network of Isotopes in Precipitation (GNIP) data (Schotterer and Oldfield, 1996) will be used for model–observation comparison for the present. We collected monthly mean δ^{18}O in precipitation from 31 stations over China covering the period 1961–2005. This dataset has sufficient spatial coverage, but the majority of the records concentrate on two periods: 1986–1993 and 1996–2003, as shown in Fig. 1b. Moreover, there are only 12 stations with more than 1 year of continuous 12-month observations (as shown as black boxes in Fig. 1b). Thus, the length and discontinuity of the data apparently confine their usefulness in interannual-to-decadal timescale analysis. We average all the available records of each month for each station to derive the mean seasonal cycle of δ^{18}O in precipitation for the following comparison.

3 Results

3.1 Seasonal cycle

The seasonal variability of water isotopes in modern climate in China is significantly affected by East Asia's monsoon climate, i.e., the East Asian summer monsoon (EASM) in June–July–August (JJA) and the East Asian winter monsoon (EAWM) in December–January–February (DJF). In detail, the seasonal cycle of δ^{18}O is dominated by the southwesterly moisture transport from South Asia and the Indian Ocean as well as the western North Pacific Ocean in summer but by the westerly and northerly winds from high-latitude cold air masses in winter.

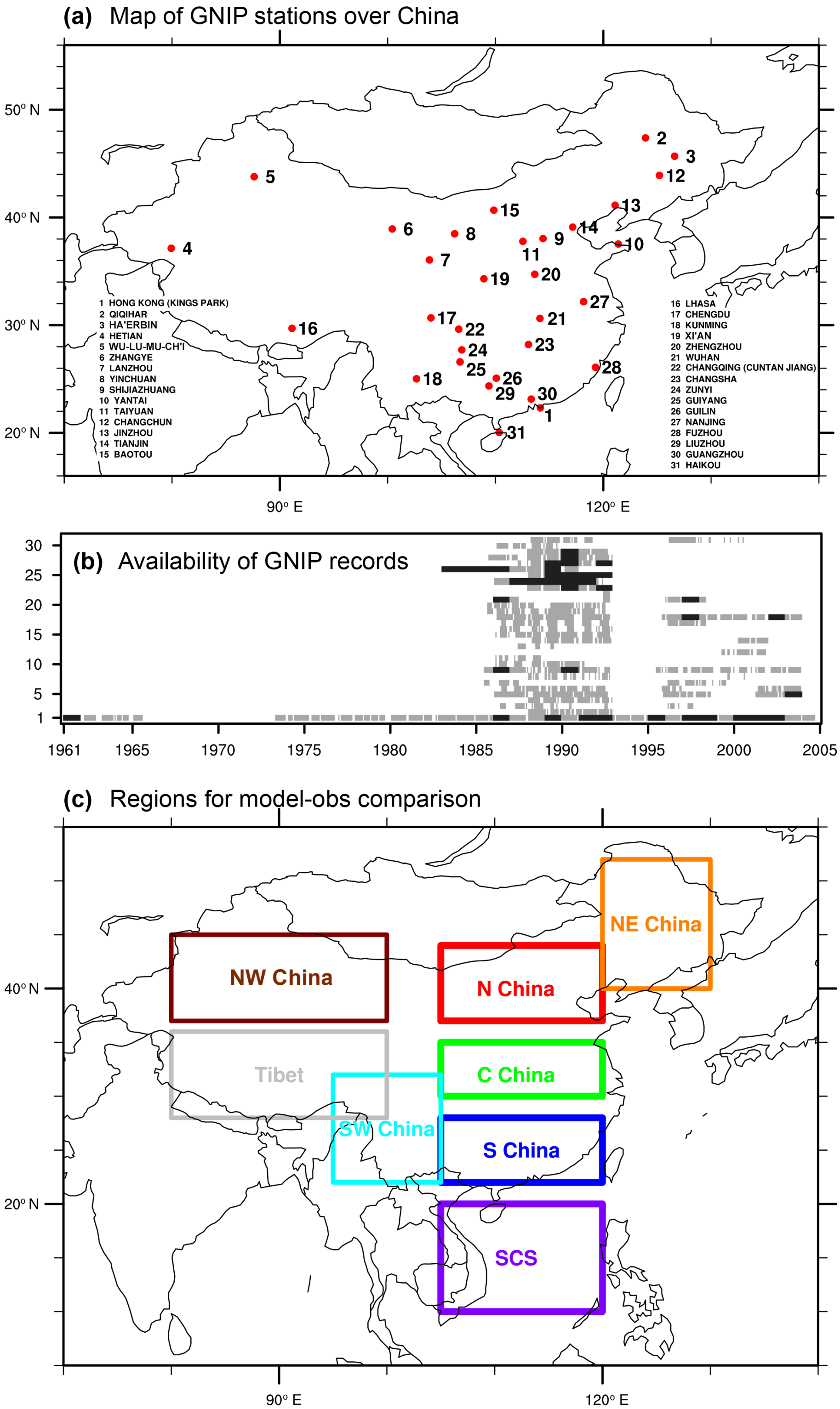

Figure 1. Map of the stations in GNIP network over China **(a)** and the availability of δ^{18}O data during the period 1961–2005 **(b)**. The valid monthly mean δ^{18}O records are marked in gray. In particular, a complete year of data is shown in black. The eight regions defined in model outputs are displayed in **(c)**.

We first compare the seasonal cycles of the precipitation δ^{18}O in 0 ka snapshot with the GNIP observations in China, to examine the model's ability to reproduce the key variable that might be linked with both temperature and amount effects. The seasonal cycle of monthly mean δ^{18}O in precipitation, surface temperature, and total precipitation are compared for eight regions in China (Fig. 2; see Fig. 1c for the definition of the regions). For each region, the modeled seasonal cycle is derived from the last 30 years of the 0 ka time slice (Fig. 2, right column), whereas the observed seasonal cycles are selected from the GNIP station that has the longest records in that region (Fig. 2, left column). The correlation coefficients for δ^{18}O with temperature and precipitation are marked in the top-right corner of each subplot.

At all sites in China, the temperature and precipitation exhibits a simple seasonal cycle, with a summer maximum and winter minimum in the observations, which is a typical monsoon feature (Fig. 2, left column). These seasonal cycles are largely reproduced by the model in different regions across China (Fig. 2, right column). The seasonal cycle of δ^{18}O and its covariance with temperature and precipitation, however, are more complex. They can be grouped into three typical and distinct "modes".

The first mode is the "northern mode", which is dominant in the observations in northeastern China (Fig. 2a), northern China (Fig. 2c), and northwestern China (Fig. 2e). This mode is characterized by a single summer maximum/winter minimum in δ^{18}O that correlates positively with the temperature and precipitation. This seasonal cycle of δ^{18}O is largely reproduced in the model (Fig. 2b, d, f). We note that Tibet (Fig. 2o, p) should also be included in this mode, although the observation shows irregular variations of δ^{18}O, most likely due to the short period of the record, especially in autumn and winter. The δ^{18}O in the northern mode is dominated by the temperature effect, as in cold high-latitude regions, such as Greenland and Antarctica (Lee et al., 2007). Indeed, the annual mean temperature of these regions is the coldest in China, ranging from $-5\,^{\circ}$C in NE China to $+4\,^{\circ}$C in NW China.

The second mode is the "southern mode", which is dominant in the South China Sea (SCS) and the surrounding southern cities, such as Hong Kong and Haikou (Fig. 2k, m). By contrast with the northern mode, the δ^{18}O of the southern mode exhibits a single summer minimum/winter maximum in δ^{18}O, which correlates negatively with temperature and precipitation. The δ^{18}O evolution is clearly dominated by the amount effect, with a greater rainfall amount leading to more depleted δ^{18}O. The model is able to reproduce this δ^{18}O evolution in the SCS (Fig. 2n). In southern China, the model is able to simulate the summer δ^{18}O minimum but not the winter maximum (Fig. 2l). Instead, the modeled δ^{18}O in southern China exhibits a double maximum in spring and fall partly caused by incorrect seasonality of precipitation with its maximum occurring near May–June. The model cannot reproduce the climatology here well as this region slightly resembles the third mode to be discussed next.

The third mode is the "central mode", which is dominant in the observation in central China (Fig. 2g), southwest China (Fig. 2i), and southern China (Fig. 2k). The central mode δ^{18}O is characterized by double maxima in spring and autumn sandwiched by a strong summer minimum. In this mode, the correlation between δ^{18}O and temperature/precipitation tends to be insignificant. For example, central China is a typical central mode region (Fig. 2g), showing correlation coefficients as low as -0.1 between δ^{18}O and temperature/precipitation. The model is able to simulate this double-peak structure of δ^{18}O in central China (Fig. 2h), southwestern China (Fig. 2j), and southern China (Fig. 2l). This more complex behavior of the δ^{18}O seems to reflect the nature of the complex climate in these regions, which is located in a transition area between the northern mode, where the temperature effect is dominant, and the southern mode, where the amount effect tends to dominate. Therefore, the interpretation of the δ^{18}O is more complex, and one should be cautious. This has important implications for the interpretation of the stalagmite proxies, which are found mostly in this area, such as the Hulu cave δ^{18}O records near Nanjing city (Wang et al., 2001). Thus, we would suggest that one should *not* interpret the δ^{18}O records around this region simply as the monsoon rainfall amount, although the migration of this region with Asian monsoon's advancing/retreating during the glacial–interglacial cycle could brings slight uncertainties.

In spite of the success of isoCAM3 in capturing the phase of the seasonal cycle of δ^{18}O over most regions in China, the model has some deficiencies in quantitatively reproducing the annual range of δ^{18}O. Compared with the GNIP observation, the seasonal cycle of the model δ^{18}O is 3 ‰ (about 25 %) lower for the northern mode region, 0.5 ‰ (less than 10 %) higher for the souther mode region, and about comparable for the central mode region with the observation. Overall, the model–observation comparison suggests that the model is capable of reproducing the major features of the seasonal climatology of δ^{18}O in different regions of China, which seems to be controlled by complex processes of both temperature and amount effect in different regions.

The temperature effect dominates the δ^{18}O–temperature relation over most of northern China, while the amount effect dominates the δ^{18}O–precipitation relation over southern China and the SCS; the central transition region, however, seems to be controlled by a mixture of mechanisms. These three distinctively different regions can be seen in the correlation map between the seasonal cycles of δ^{18}O and temperature (Fig. 3a) and precipitation (Fig. 3b) in the model, which shows a positive correlation in the north and a negative correlation in the south and leaves a blank area in the central transition latitudes of China. Thus, in the following discussions, we use "temperature effect" when referring to positive δ^{18}O–temperature correlations and "amount effect" when referring to negative δ^{18}O–precipitation correlations.

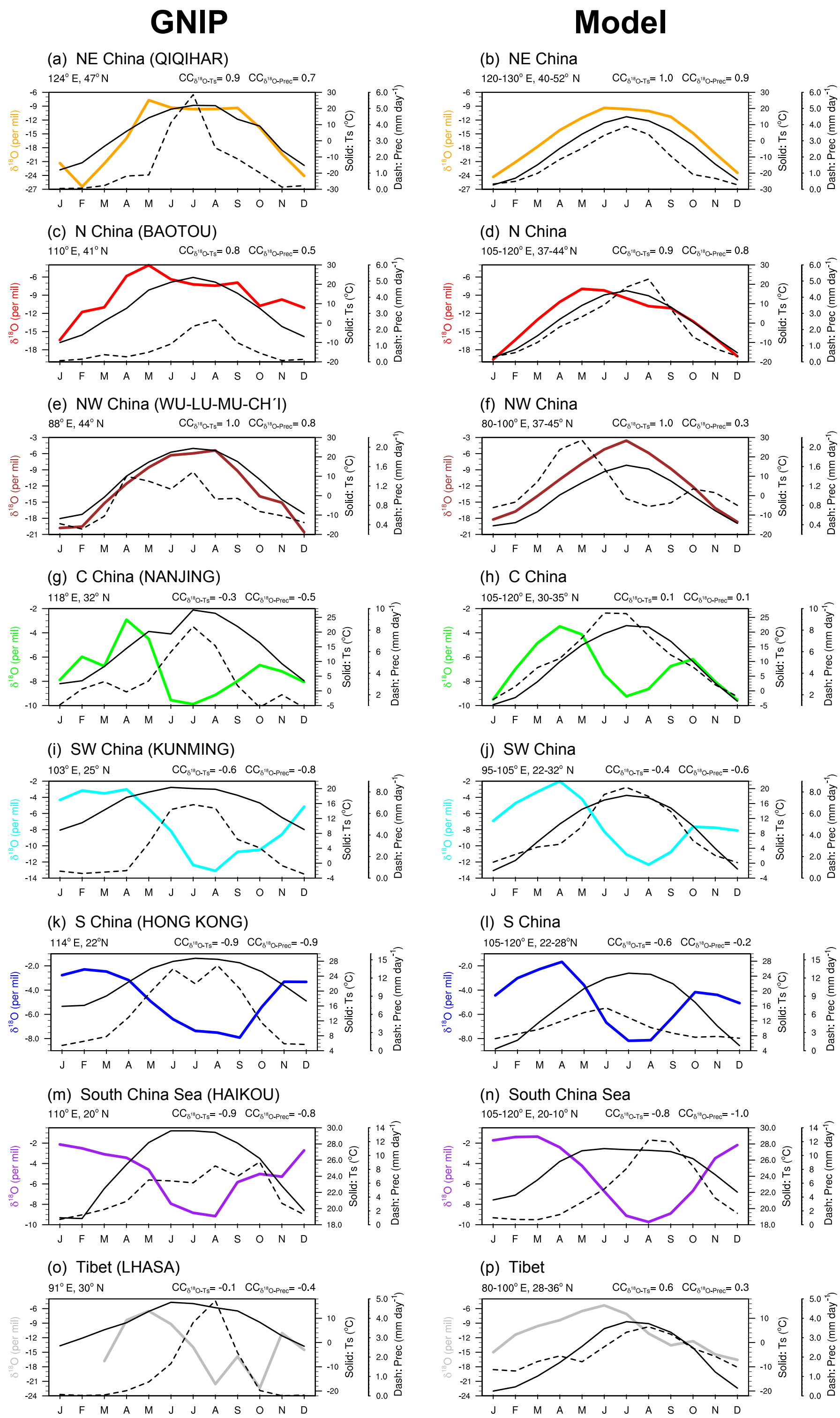

Figure 2. Seasonal cycles of $\delta^{18}O$ in precipitation (color lines), surface temperature (solid lines), and precipitation (dashed lines) over eight regions in China. The left column shows typical profiles from eight stations within the GNIP network, whereas the right column shows model results averaged over the corresponding region defined in Fig. 1c.

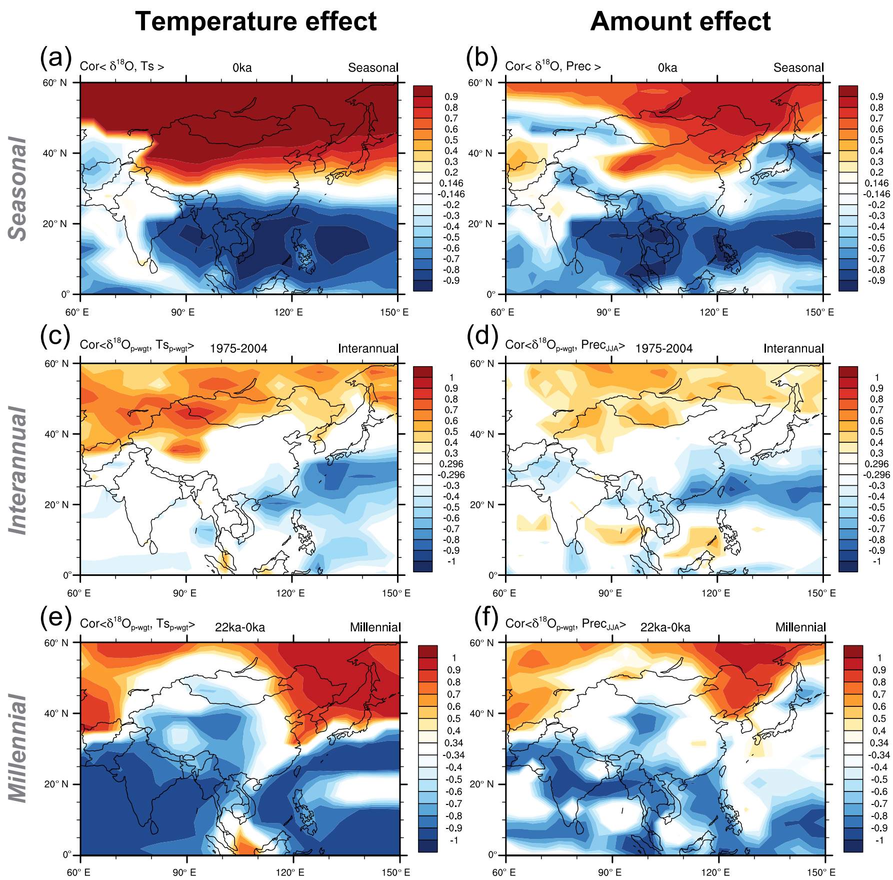

Figure 3. The point-by-point correlation coefficients between $\delta^{18}O$ and temperature (left column) or precipitation (right column) on three timescales. The seasonal timescale **(a, b)** uses the last 30-year monthly data from the 0 ka snapshot, excluding March–April–May (MAM; spring) and September–October–November (SON; fall) months to avoid the noise. The interannual timescale **(c, d)** uses 1975–2004 AMIP-type ensemble mean $\delta^{18}O$ (p-weighted) and temperature (p-weighted) and JJA precipitation. The millennial timescale **(e, f)** uses the climatology data from 23 snapshots (22, 21, 01, 0 ka). All the statistically insignificant areas under the 95 % confidence level are left blank.

3.2 Interannual variability

In sharp contrast to the seasonal cycle, there is little correlation between the interannual variability of $\delta^{18}O$ and temperature/precipitation. This can be seen in the point-by-point correlation coefficients between precipitation-weighted annual mean $\delta^{18}O$ and surface temperature (Fig. 3c) as well as JJA precipitation (Fig. 3d) using the last 30 years of model output of the 0 ka time slice. The area with a significance level greater than 90 % is shaded in colors; we can see in Fig. 3c and d that neither temperature effect nor amount effect is significant over most of China. In the mean time, there is a slight correlation of temperature effect over Xinjiang and amount effect over South China and the SCS. Therefore, in this model, in spite of a seemingly significant implication of temperature and precipitation effect in the seasonal cycle over different regions in China, the interannual variability of water isotope is not a good indicator as temperature or rainfall variability. This is consistent with previous findings (Maher, 2008; Dayem et al., 2010). The relatively significantly correlated belt (Fig. 3d) over South China to Taiwan implies the independent and complex nature of a monsoon moisture source remotely transported to East Asia, which is different from South Asia, which derives its moisture locally from the Indian Ocean (Pausata et al., 2011; Liu et al., 2014b).

3.3 Millennial variability

We further show that the change in modeled $\delta^{18}O$ climatology on a millennial timescale does not reflect the change in temperature and precipitation in China either. This can be seen in the cross-snapshot correlation coefficients between the millennial climatological variability of the annual mean $\delta^{18}O$ (weighted with precipitation) and surface temperature (Fig. 3e) as well as precipitation (Fig. 3f), indicating the amplitudes of temperature and amount effects on a millennial timescale. The millennial climatology is derived from each time slice by averaging the last 30 years out of 50-year raw results. We can see that the correlations on this timescale are,

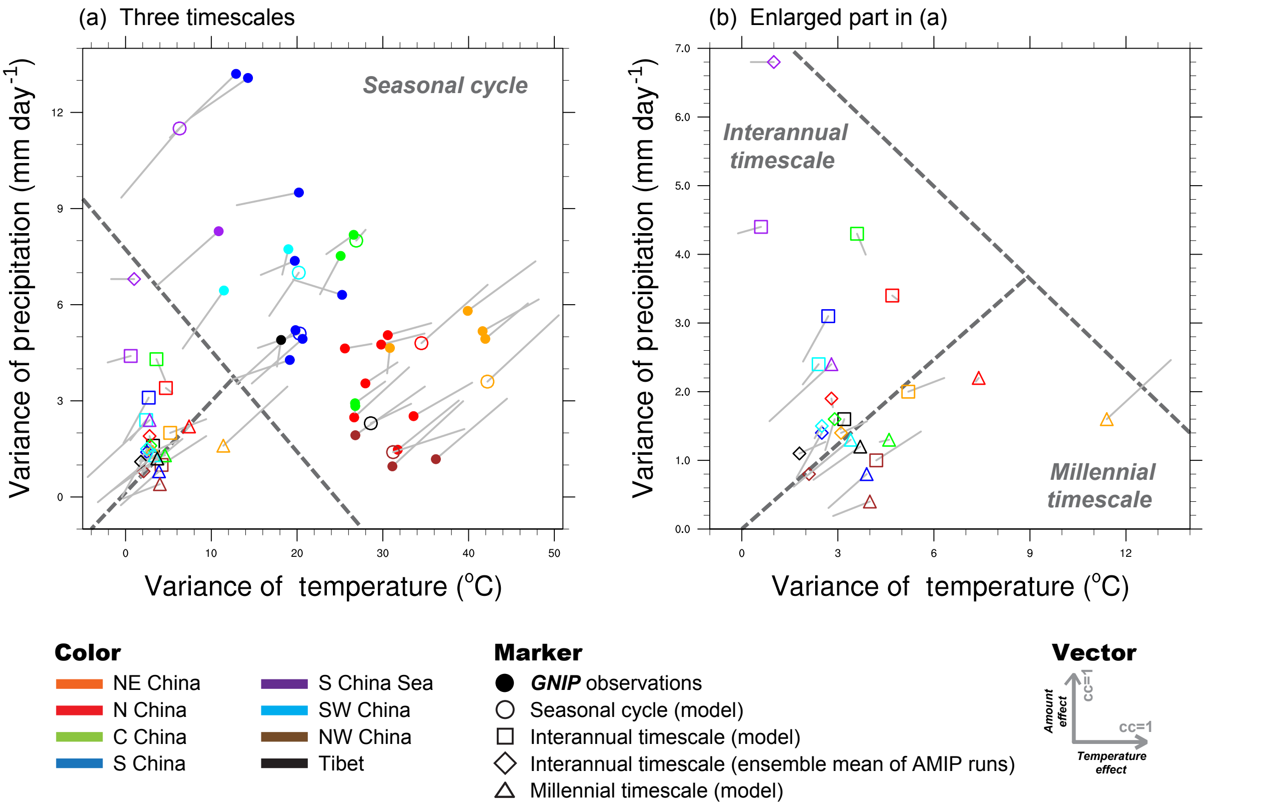

Figure 4. Temperature effect and amount effect (vectors) of δ^{18}O records in model outputs (open markers) and GNIP observations (solid circle) over eight regions (colors) in China with respect to the variances of temperature and precipitation on three timescales. The bottom-left corner in **(a)** is enlarged as **(b)**. Each of the timescales shows a distinct regime in this diagram.

overall, more significant than on an interannual timescale but much less than on a seasonal timescale. It is also shown that neither effect is significant over eastern China (105–120° E, 22–42° N) including North China, central China, and South China. Hence, the model does not support a strong link between stalagmite δ^{18}O records found in the surrounding area with either local temperature or precipitation. Some exceptions are found in the SCS, showing negative correlations with temperature and precipitation, as well as in northeast China, showing positive correlation with precipitation.

The millennial variability study here is consistent with previous modeling studies. In a series of snapshot simulations for the Holocene (LeGrande and Schmidt, 2009) and in an idealized millennial variability (hosing) experiment (Pausata et al., 2011), it is suggested that the millennial variability of cave δ^{18}O in southeastern China does not represent local monsoon rainfall; rather, it reflects the change in the upstream moisture transport and the variability in the upstream Indian Ocean and South Asian monsoon region. However, a new study (Liu et al., 2014b) suggests that the Chinese cave records are still a good indicator, on a millennial timescale, in representing southerly monsoon wind and rainfall in North China but local monsoon rainfall around the cave sites in South China. These dynamics explain the monsoon's continental-scale coherent response to orbital forcing over the vast upstream region and rainfall in northern China (Liu et al., 2014b). Hence, we conclude that one needs to very cautious when interpreting the water isotope records in the proxy records in central to southern China. Instead of using the modern-day seasonal cycle as a simple analogy, the interpretation of the δ^{18}O variability of millennial timescales differs in different regions. A credible interpretation requires a better understanding of the monsoon rainfall processes and their linkage with water isotope variations.

4 Conclusions

We have examined the temperature and amount effects on seasonal, interannual, and millennial timescales in East Asia in an isotope-enabled atmospheric GCM. It is found that, the two effects hold well on the seasonal timescale, with the temperature effect dominating in northern China and the amount effect dominating in very southern China. However, neither the temperature effect nor the amount effect is robust for interannual variability. Neither effect is strong on a millennial timescale either, albeit they are somewhat stronger than that on an interannual timescale.

The cause of the different isotope–climate relations on different timescales remain to be studied in the future. Tentatively, we speculate that part of the reason that temperature effects and the amount effect are robust for the seasonal cycle is that the seasonal cycle has a large variance and therefore perhaps large signals. Figure 4 summarizes the correlations of δ^{18}O–temperature and δ^{18}O–precipitation (in vectors) in various regions on three distinct timescales in China, with respect to the local variances of temperature and precipitation. It is shown that the temperature and amount effects are robust on seasonal timescales (with correlation coefficients mostly over 0.6). Furthermore, the temperature effect tends to be dominant for regions of large temperature variability in seasonal cycle (northern China), while the amount effects (negative correlation) tend to be robust in regions of large rainfall seasonal cycle (southern China). This is consistent with the observations from GNIP networks in China (Fig. 4a). In comparison, the temperature and amount effects are weak on interannual and millennial timescales, partly because of their small variances of temperature and precipitation and induced small signal-to-noise ratio.

Our model suggests that the classic empirical relations between oxygen isotopes and local temperature and precipitations as derived from the seasonal cycle cannot be applied to other timescales in general. Hence, one should be cautious in using present isotope–climate relations for long-term paleoclimate reconstructions. An interesting example is that, although the oxygen isotope variability in southeastern China is not caused directly by local precipitation variability, it could still be correlated with the intensity of the East Asian summer monsoon, which is correlated with the intensity of southerly monsoon wind, moisture transport, and the associated large-scale rainfall response over North China (Liu et al., 2014b). Therefore, we suggest that for paleoclimate studies one should focus more on the large-scale circulations associated with the stable water isotopes rather than relying heavily on local isotope–climate relations.

5 Data availability

The climate model data and other figure-related data used in this study are available at Harvard Dataverse (doi:10.7910/DVN/7BG06U, Wen, 2016).

Author contributions. X. Wen and Z. Liu conceived the study and wrote the paper, D. Noone developed the module of water stable isotopes in CAM3, X. Wen and E. Brady performed the slice simulations, Z. Chen contributed to interpreting GNIP observations, and Q. Zhu and J. Guan performed the analysis. All authors discussed the results and provided inputs to the paper.

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