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ENSO Effects on Annual Variations of Summer Precipitation Stable Isotopes in Lhasa, Southern Tibetan Plateau

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ABSTRACT

Although El Niño–Southern Oscillation (ENSO) influences the Indian summer monsoon, its impact on moisture transport toward the southern Tibetan Plateau (TP) remains poorly understood. Precipitation stable isotopes are useful indices for climate change in the TP. Classical interpretations of variations of precipitation stable isotopes focus on the local surface air temperature or precipitation amount. However, several of the latest studies suggested they may correlate with large-scale modes of variability, such as ENSO. This paper presents a detailed study of ENSO’s effect on annual variations of the oxygen stable isotopic composition of precipitation (δ¹⁸O) at Lhasa in the southern TP for up to 10 years. The stable isotopic composition of water vapor from satellite data [Tropospheric Emission Spectrometer (TES)] and simulations from an isotopically enabled atmospheric general circulation model (zoomed LMDZiso) are used to explore the mechanism that leads to variations of δ¹⁸O at Lhasa. Statistically significant correlations between δ¹⁸O and ENSO indices [Southern Oscillation index (SOI) and Niño-3.4 sea surface temperature index (Niño-3.4)] are observed. This paper shows that ENSO’s effects on the location and intensity of convection over the Arabian Sea, the Bay of Bengal, and the tropical Indian Ocean, along moisture transport paths toward Lhasa, further impact convection from the northern Tibetan Plateau. The changing of this convection results in lower δ¹⁸O at Lhasa in 2007, a La Niña year, and higher δ¹⁸O in 2006, an El Niño year. The study presented here confirms that the regional upstream convection related to ENSO teleconnections plays an important role in variations of δ¹⁸O at the interannual scale and that the more depleted oxygen stable isotopic composition of vapor (δ¹⁸Ov) from the northwestern region of India during a La Niña year intensifies the lower δ¹⁸O at Lhasa in a La Niña year. The study’s results have implications for the interpretation of past variations of archives with precipitation stable isotopes, such as ice cores, tree rings, lake sediments, and speleothems, in this region.

1. Introduction

El Niño–Southern Oscillation (ENSO) is a well-known climatic phenomenon affecting the interannual variability of the Indian summer monsoon (Annamalai et al. 2007; Kumar et al. 1999; Torrence and Webster 1999), with large decadal variability in the ENSO–monsoon relationship (Kumar et al. 1999; Li and Ting 2015).
Previous studies suggested that the western Pacific SSTs dominate the relationship between the ENSO phase and tropical convection in the Bay of Bengal (Felton et al. 2013; Girishkumar and Ravichandran 2012; Girishkumar et al. 2015; Soman and Slingo 1997) and the Asian summer monsoon (Fan et al. 2016; Meehl and Arblaster 2002). El Niño and La Niña are the warm and cold phases of ENSO, respectively, and are associated with different characteristics of SST and tropical convection via the modulation of the Walker circulation or the Hadley circulation (Felton et al. 2013; Fan et al. 2016; Vuille and Werner 2005). In addition, ENSO impacts the onset date of the South Asian summer (e.g., June–September) monsoon (SASM) over the southwestern region of India (Kerala) by modulating the vertical coupling of the different levels of circulation over South Asia (Goswami and Xavier 2005; Liu et al. 2015; Mao and Wu 2007). El Niño shortens the length of the rainy season for the South Asian monsoon (Goswami and Xavier 2005) and appears to have the opposite effect on Indian summer monsoon rainfall (e.g., frequently there is weak Indian summer monsoon rainfall during an El Niño event and strong Indian summer monsoon rainfall during a La Niña event) (Boschat et al. 2011). In addition, previous studies have suggested that the zonal circulation [i.e., Indian Ocean dipole (IOD)] could significantly reduce the impact of ENSO on Indian summer rainfall related to the phase (positive/negative) that co-occurs as a result of the abnormal convection activities over the western Pacific/ western part of the tropical Indian Ocean (Ashok et al. 2004, 2001; Sankar et al. 2011).

The ENSO signal could be probed at the interannual scale using ice core records in the Tibetan Plateau (TP), but there is only a weak statistical relationship between ice core δ18O and the ENSO index (Thompson et al. 2000a; Yang et al. 2000). Here, we try to clarify the impact of ENSO on the precipitation isotopic composition (δ18O) in the southern TP and the underlying mechanisms. Recent studies have been focused on mechanisms of intra-annual variability of the south Tibetan precipitation δ18O, combining in situ monitoring, back trajectories, remote sensing, and atmospheric modeling (Gao et al. 2013; He et al. 2015; Yao et al. 2013). Day-to-day δ18O variations were shown to reflect the integrated effect of initial vapor conditions, moisture transport (by the Indian summer monsoon and the westerlies), and processes along the moisture transport path (Gao et al. 2013, 2011; Tian et al. 2001; Yao et al. 2013). At interannual and longer time scales, variations in TP precipitation stable isotopes are related to changes in local climate variables (temperature or precipitation amount) (Cai and Tian 2016) and the large-scale atmospheric circulation (Gao et al. 2016; Tian et al. 2003), including ENSO (Thompson et al. 2000b) and the Atlantic Oscillation (AO), which are involved in a seesaw pattern in atmospheric pressure between the North Pole and middle northern latitudes related to changes of the westerlies and a teleconnection with ENSO. However, the exact mechanisms by which ENSO impacts the isotopic composition of precipitation in the southern TP were not previously identified.

The goals of this paper are to detect the possible impact of ENSO on the precipitation stable isotopes in the southern TP and to explore the mechanisms that drive the annual variation of precipitation stable isotopes in this region. Our study uses 10-yr event-based observations at Lhasa (29.70°N, 91.13°E; 3658 m) and the ENSO index. The mechanisms relating ENSO and δ18O are assessed using those datasets with simulations from an atmospheric general circulation model equipped with water stable isotopes (the zoomed LMDZiso model), as well as information from remote sensing for the water vapor isotopic composition (δ18Ov) [from the Tropospheric Emission Spectrometer (TES)] and outgoing longwave radiation (OLR). It is noted that 2006 is classified as a weak El Niño event, which is focused on in this study, and we cannot choose strong events because of the limit of synchronously available TES and observation data. Section 2 describes our datasets and methods. Section 3 presents the relationship between interannual variations in Lhasa δ18O and the ENSO index, and investigates the underlying mechanisms. Finally, our conclusions are summarized in section 4.

2. Data and methods

Lhasa is located in a vast valley near the Brahmaputra River. The Indian summer monsoon is the dominant moisture transport in this region. Event-based precipitation samples were collected at Lhasa from 1997 to 2007. After 2007, observed data are not available so far. Because the amount of summer [June–September (JJAS)] precipitation accounts for about 85% of the annual precipitation amount, only the events that occurred in JJAS are discussed in the paper. All samples were measured by a MAT-253 mass spectrometer (precision of 0.2‰) in the Laboratory of Ice Core and Cold Regions Environment of the Cold and Arid Regions Environmental and Engineering Research Institute, Lanzhou, China. The earlier review study on TP precipitation stable isotopes was based on these data (Yao et al. 2013). Here, we use precipitation δ18O, precipitation amount, and surface air temperature from Lhasa. In this study, monthly and annual
\(\delta^{18}O_p\) are calculated from the event-based data by precipitation amount weighting as 
\[ \delta^{18}O_w = \frac{\sum^n \delta_i P_i}{\sum^n P_i}, \]
where this indicates the amount of weighted \(\delta^{18}O_w\); \(\delta_i\) and \(P_i\) refer to \(\delta^{18}O_p\) and the corresponding amount, respectively, and \(n\) indicates the number of events occurring daily (Table 1). JJAS \(\delta^{18}O_p\) values are the precipitation amount weighted mean \(\delta^{18}O_p\) from June to September in each year.

<table>
<thead>
<tr>
<th>Year</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>8</td>
<td>14</td>
<td>21</td>
<td>11</td>
</tr>
<tr>
<td>2006</td>
<td>14</td>
<td>11</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td>2007</td>
<td>9</td>
<td>18</td>
<td>17</td>
<td>10</td>
</tr>
</tbody>
</table>

TES data provide the deuterium content of water vapor (\(\delta D_w\)) from satellite measurements with a precision of 10‰–15‰ for the individual measurement and a footprint of 5.3 km \(\times\) 8.5 km. Worden et al. (2004, 2006, 2007) described the TES measurements and the retrieval methods in detail. The uncertainty and the sensitivity of the retrievals are discussed in detail in earlier studies (Risi et al. 2010), demonstrating that TES data are valuable for precipitation stable isotopes studies on the Tibetan Plateau (He et al. 2015). The valid TES data are available from 2005 only. Here we use the \(\delta D_w\) retrieved by TES at 680 hPa, which is the most sensitive level over the TP during summer, combined with in situ \(\delta^{18}O_p\) at Lhasa from 2005 to 2007. After quality control, 122 days of valid TES measurements are identified from 2005 to 2007 at Lhasa. Here, we
The Southern Oscillation index (SOI), defined as the difference between the 850-hPa zonal wind averaged over the southern Arabian Sea (SAS) from 5° to 15°N and from 40° to 80°E and that averaged over the northern region from 20° to 30°N and from 70° to 90°E, reflecting the large-scale rainfall variability of the Indian summer monsoon (Wang et al. 2009). The AO index is used to describe the surface signature of modulations in the strength of the polar vortex aloft (Thompson and Wallace 1998; http://www.esrl.noaa.gov/psd/data/gridded/). The IOD index is defined as the SST difference between the western Indian Ocean (i.e., the Arabian Sea) and the eastern Indian Ocean (i.e., south of Indonesia) (Saji and Yamagata 2003), and a positive IOD event appears during July 2007 to June 2008. Considering the availability of the different datasets, we employed a case study for the 2005–06 period, where 2005 is a normal year, 2006 is a typical La Niña event, and 2007 is a typical El Niño event. ENSO-neutral conditions appeared during April–June 2005, and the El Niño event occurred from August to October 2006 and dissipated during January–February 2007. La Niña conditions developed from July 2007 to June 2008.

### 3. Results

#### a. Relationships between annual δ18O₀ and ENSO indices

Summer precipitation at Lhasa is mainly associated with the Indian summer monsoon, which brings moisture from the Bay of Bengal, the Arabian Sea, and the Indian Ocean (Fig. 1a). The δ18O₀ exhibits an antevated Z-shape seasonal variability with a seasonal amplitude of

<table>
<thead>
<tr>
<th>Climate indices</th>
<th>Observed δ18O₀</th>
<th>Simulated δ18O₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>y = -0.01x – 13.94</td>
<td>R = -0.44</td>
</tr>
<tr>
<td>T</td>
<td>y = 0.15x – 24.82</td>
<td>R = 0.2</td>
</tr>
<tr>
<td>SOI</td>
<td>y = -0.22x – 16.78</td>
<td>R = -0.82</td>
</tr>
<tr>
<td>Niño-3.4</td>
<td>y = 2.16x – 76.51</td>
<td>R = 0.73</td>
</tr>
<tr>
<td>IOD</td>
<td>y = 4.11x – 17.20</td>
<td>R = 0.51</td>
</tr>
<tr>
<td>AO</td>
<td>y = 0.01x – 17.27</td>
<td>R = 0</td>
</tr>
<tr>
<td>ISM</td>
<td>y = -0.57x – 13.09</td>
<td>R = -0.21</td>
</tr>
</tbody>
</table>
The $\delta^{18}$O$_p$ increases beginning in January, and the highest $\delta^{18}$O$_p$ is observed in May, whereas the $\delta^{18}$O$_p$ depletion occurs in June and reaches a minimum in August. A second increase is exhibited from September to November. The seasonal pattern of $\delta^{18}$O$_p$ is captured by the zoomed LMDZiso, although with a slight overestimation of the summer $\delta^{18}$O$_p$ (Fig. 1b). During the period from 1997 to 2007, maximum JJAS $\delta^{18}$O$_p$ is observed in 2006, and minimum JJAS $\delta^{18}$O$_p$ is observed in 1998; the difference of JJAS $\delta^{18}$O$_p$ between these two years is $\sim 7_{\%}$. At the interannual scale, the zoomed LMDZiso is able to simulate features of the observed interannual variation of summer $\delta^{18}$O$_p$ at Lhasa with a correlation coefficient of 0.7 (Fig. 1c), with better performance after 2002. The large deviation in Fig. 1b may result from the missed observation in 1999 and the imperfect matching between observations and simulations in 1998 and 2000. The TES data that are available since 2005 are also comparable with simulations from the zoomed LMDZiso with a correlation coefficient of 0.6 ($p < 0.1$; not shown). Thus, simulations from the zoomed LMDZiso and TES data can be used in this study.
FIG. 3. (a) Difference in averaged JJAS δD, at 680 hPa from TES data between 2005 and 2006. The circle shows the location of Lhasa, and the color shows the difference of averaged JJAS δ18O, at Lhasa from in situ observations. (b) As in (a), but for 2007 and 2006. We compare 2005–06 and 2007–06 to check the robustness of our results, and compare outputs from zoomed LMDZiso simulations with results from TES. (c) Difference in averaged JJAS δD, at 680 hPa from zoomed LMDZiso simulations between 2005 and 2006. (d) As in (c), but for
The local surface air temperature and precipitation amount are thought to be generally remarkable factors that impact $\delta^{18}O_p$ in the southern TP (Yao et al. 2013; Gao et al. 2013). However, no statistical relationship can be identified between JJAS $\delta^{18}O_p$ and the corresponding local precipitation amount or the local surface air temperature at Lhasa for observations from 1997 to 2007 (Table 2). A significant negative correlation is shown between JJAS $\delta^{18}O_p$ and SOI ($R = -0.82; P < 0.05$) during 1997–2007 (Fig. 2a); meanwhile, a prominent correlation is shown between JJAS $\delta^{18}O_p$ and Niño-3.4 SST ($R = 0.73; P < 0.05$). No significant correlations can be identified with any other indices [e.g., westerly shear index (WSI), AO, IOD, and ISM]. This suggests that ENSO is the main driver of interannual variations in JJAS $\delta^{18}O_p$ at Lhasa. Simulations from the zoomed LMDZiso model produced similar results, although the model underestimated these correlations between JJAS $\delta^{18}O_p$ and each index (Table 2).

b. Mechanisms of teleconnections between ENSO and southern TP JJAS $\delta^{18}O_p$

Here we combine the in situ observations, TES data, zoomed simulations, and reanalysis data to explore the mechanism of the teleconnection between ENSO and annual JJAS $\delta^{18}O_p$ at Lhasa. The $\delta^{18}O_p$ during the 2007 La Niña year is on average $-2.3\%o$ more depleted than during the 2006 El Niño year, which is identified with a discrepancy of $\delta^{18}O_p$ during the 1998 strong La Niña year and the 1997 strong El Niño year (on average $-5.5\%o$; Fig. 2a).

We use HYSPLIT to calculate back trajectories to Lhasa at 1000 m AGL for all days when rain events occurred from 2005 to 2007. HYSPLIT uses NCEP reanalysis data and computes trajectories with a 6-h time step back to 5 days. Results are then clustered into three paths (Figs. 2b–d), that is, moisture originating from the Bay of Bengal (BOBA), from the northwestern region of India (NWI), and from the northern region of the TP (NTP).

Most trajectories originate from BOBA, with a proportion that remains almost constant in 2005–07 (62% during the 2006 El Niño year, 59% during the 2005 normal year, and 60% during the 2007 La Niña year). The ENSO phase appears to affect only the relative proportion of trajectories from NWI and NTP, with the proportion of NTP trajectories decreasing from 17% during the El Niño year to 9% during the normal year and almost 10% during the La Niña year (Figs. 2b–d). However, considering the $\delta^{18}O_p$ associated with these trajectories, this proportion change does not explain the more depleted $\delta^{18}O_p$ values (about 4\%o; Fig. 2e) observed during the 2007 La Niña year.

We now focus on the $\delta^{18}O_p$ at Lhasa and the precipitation amount along BOBA trajectories (Figs. 2e and 2f). BOBA trajectories during the 2007 La Niña year lead to 4\%o more depleted $\delta^{18}O_p$ than during the 2006 El Niño year at Lhasa. A higher precipitation amount appeared during the 2005 normal year than during the 2007 La Niña year from the BOBA trajectory, but $\delta^{18}O_p$ during the 2005 normal year is on average enriched 0.5\%o, compared with that during the 2007 La Niña year at Lhasa. This may result from the change in the moisture origin along BOBA, which is discussed in the next section. Moisture trajectories from BOBA fall mostly over land in 2006, while more BOBA trajectories fall over water in 2007. This may result in enriched $\delta^{18}O_p$ along BOBA in 2006. Because of the average $-2.3\%o$ difference in annual $\delta^{18}O_p$ between 2007 and 2006 (Fig. 2a), we deduced that changes in the NTP trajectory resulted in the 1.7\%o enrichment of $\delta^{18}O_p$. The change in precipitation amount of about 100 mm from the NWI and NTP trajectories may result in more than a 3\%o change in $\delta^{18}O_p$ at Lhasa between the 2007 La Niña year and the 2005 normal year (Figs. 2e and 2f). This implies that ENSO-influenced processes along the moisture path to Lhasa impact the interannual variations in the final $\delta^{18}O_p$ values. The BOBA trajectory determines the overall features of $\delta^{18}O_p$ at Lhasa, while the NWI and NTP trajectories show remarkably opposite impacts on $\delta^{18}O_p$ in ENSO events. Given the current knowledge on intraannual variations, we now explore how ENSO affects convective activity along the moisture paths to Lhasa.

For this purpose, we use remote sensing information on vapor $\delta D$, which is expected to show variations similar to vapor $\delta^{18}O$ in the TP (He et al. 2015). The retrieved vapor $\delta D$ from TES at 680 hPa and the simulated vapor $\delta D$ from the zoomed LMDZiso model at 680 hPa...
are compared in the 2006 El Niño year, the 2007 La Niña year, and the 2005 normal year. Figures 3a and 3b show that the vapor δDv is about 20‰ lower at Lhasa in the La Niña year than in the El Niño year. During the La Niña year, δDv is much higher in the NWI and in the west Indian Ocean, and at the same time a little higher in southeast China than in the El Niño year (Fig. 3b). However, more depleted δDv appears in the west Indian Ocean and BOBA in the normal year than in the El Niño year (Fig. 3a). Those patterns are also captured in the LMDZiso simulations during the normal year (Fig. 3c), but the simulations failed in the tropical Indian Ocean during the La Niña year (Fig. 3d). This indicates that enriched δDv appears in the west Indian Ocean and the Bay of Bengal during the La Niña year but not in the normal year. During the La Niña year, much more precipitation occurs in the southern TP and in northern India, especially along the Himalayas, and in the Arabian Sea, and more precipitation occurs in the Bay of Bengal than during the El Niño year (Fig. 3f). However, less precipitation occurs in Bangladesh and the Arabian Sea during the normal year than during the El Niño year (Fig. 3e). This indicates that more precipitation occurs from NWI and a portion of BOBA during the La Niña year than in other years.

The spatial patterns of OLR are remarkably different between the El Niño year and the La Niña year, supporting our finding. During the normal year, a bit stronger convection appears in the southern TP and in northern India, especially along the Himalayas, and in the Arabian Sea, and more precipitation occurs in the Bay of Bengal than during the El Niño year (Fig. 3g). In the La Niña year, stronger deep convection appears in the Bay of Bengal, the South China Sea, and the Indian Ocean around Indonesia than in the El Niño year, while weaker convection appears in the Arabian Sea and the western region of the Indian Ocean, which is associated with enriched δDv (Figs. 3b and 3h). This indicates that 1) weaker convection in the Bay of Bengal and the eastern region of the Indian Ocean results in reduced precipitation and less depleted vapor during the 2006 El Niño year and 2) reduced precipitation in northern India and along the Himalayas in the southern region of the TP further contributes to less depleted vapor isotopes at Lhasa during the El Niño year compared with the La Niña year.

The discrepancy of precipitation amount and δ18Ov along the three moisture transport paths confirm the ENSO impacts. The distance is calculated from Lhasa along trajectory paths. Less precipitation occurs along BOBA from 1800 to 800 km during the La Niña year, but the opposite condition exists during the normal year (Figs. 3i and 3j). More than 50 mm of precipitation occurs along NTP in 2007 compared with 2005 between 200 and 1200 km, and NWI shows opposite variations between the La Niña year and the normal year. NTP and NWI δ18Ov show remarkable differences from 1400 to 700 km between the La Niña year and the normal year, and the fast depletion of NTP and NWI δ18Ov intensified the lower amount of δ18Ov during the La Niña year (Figs. 3k and 3l). Considering the corresponding BOBA δ18Ov, we deduced that the convection along BOBA dominates the differences in δ18Ov between the La Niña year and other years from the tropical Indian Ocean to Lhasa, and the more depleted δ18Ov from NWI intensifies the depleted δ18Ov at Lhasa.

4. Conclusions

Based on 10 years of event-based precipitation sampling at Lhasa, we investigated the relationship between ENSO indices and summer δ18Ov interannual variations. We confirmed earlier studies based on ice core records and concluded a discernable ENSO influence that explains more than 60% of the interannual Lhasa summer δ18Ov variations. No relationships are shown between summer δ18Ov, the local precipitation amount effect, and the surface air temperature, at the interannual scale. The satellite data and LMDZiso simulations confirmed the difference in vapor and precipitation stable isotopes between the El Niño year and the La Niña year. We strengthened the earlier conclusions on the role of regional upstream convection activity on south Tibet summer δ18Ov previously identified at the intra-annual scale (Gao et al. 2013) and concluded a similar mechanism affects the relationship between the interannual scale and ENSO teleconnections. Because of the large deviation of annual δ18Ov between in situ observations and simulations before 2002, we did not use simulations and TES data to extend the ENSO teleconnections directly. It is noted that 2006 was a weak El Niño event and assessing the robustness of this mechanism will require analyses on multiple El Niño and La Niña events, in order to account for the decadal variability of teleconnections. For this purpose, a network of long-term monitoring of precipitation and vapor isotopic composition as well as sustained remote sensing of tropospheric vapor isotopic composition will be greatly needed. One should be cautious when using our results to explain the long-term mechanisms, and the possible extension of our results is limited by the obvious deviation appearing among the in situ observations and simulations from 1997 to 2001. Because of a lack of a comparison between in situ observations that are not available after 2007 and satellite data, more TES data covering more ENSO events are not probed in this study.

Our results also have implications for the climatic interpretation of oxygen isotope records extracted from the southern TP natural archives, such as ice cores, tree rings, lake sediments, and speleothems. The spatial heterogeneity of variations from nearby ice core records (Gao
et al. 2016) may arise from the complex patterns of moisture transport pathways and underlying variations in the integrated precipitation amount, convective activity, and the influence of ENSO along these pathways. Moreover, they also have implications for past ENSO reconstructions (e.g., McGregor et al. 2010). Provided that methodologies are developed to extract the ENSO fingerprint from networks of seasonally resolved proxy records in the southern Tibetan Plateau, new information may be available to strengthen past reconstructions of ENSO variance and associated teleconnections.

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