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The Oscillation between Tropical Indian Ocean and North Pacific: Evidence and Possible Impact on Winter Climate in China

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Abstract This paper provides evidence that the variation of boreal winter sea level pressure (SLP) over the North Pacific is out-of-phase with SLP fluctuation over the tropical Indian Ocean on both the interdecadal and interannual time scales. Subsequently, a SLP between tropical Indian Ocean and North Pacific (TIO-NP) oscillation index is defined to indicate the variation of such out-of-phase fluctuation. Moreover, the simultaneous surface air temperature and precipitation anomalies in China are closely related to TIO-NP oscillations. Below-normal surface air temperature anomalies in the northern and the eastern part of China, and less rainfall in southern China, correspond to positive TIO-NP oscillation phase with negative SLP anomalies in tropical Indian Ocean and positive anomalies in North Pacific. The TIO-NP oscillation affects China's winter climate anomalies, possibly through modulating the northeast East Asia winter monsoon.

Keywords: North Pacific, tropical Indian Ocean, oscillation, China's climate

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1 Introduction

A century ago, Hildebrandsson (1897) uncovered the first sign of the Southern Oscillation in the form of an out-of-phase relationship between surface pressure anomalies at Sydney and Buenos Aires. Several years later, Lockyer and Lockyer (1902) confirmed the existence of the Sydney Buenos Aires pressure seesaw and estimated its duration to be about 3.8 years. This kind of oscillation, coupled with the tropical Pacific Sea surface temperature (SST) anomalies (Bjerknes, 1969) referred to as the El Niño/Southern Oscillation (ENSO), has a great impact on the global climate. For instance, the ENSO can affect the Indian summer monsoon by modulating Walk circulation (Krishnamurthy and Goswami, 2000), influence North America by propagating Pacific-North America (PNA) teleconnection (Wallace and Gutzler, 1981), and impact East Asian climate through the East Asia-Pacific (EAP) or Pacific-Japan (PJ) teleconnection and tropical Indian Ocean capacitor effect (Huang and Wu, 1989; Nitta, 1987; Yang et al., 2007; Li et al., 2008; Xie et al., 2009; Huang et al., 2010; Xie et al., 2010). Besides Southern Oscillation (SO), which occurs only in the tropical region, some SO-like oscillations between tropical and extra-tropical regions have also been observed.

The boreal winter climate variability of North Pacific sea level pressure (SLP) anomalies is closely related to the tropical Indian Ocean climate variability. Preliminary evidence was presented by Minobe (1997), whose results showed that annually averaged SST anomalies in the tropical Indian Ocean varied coherently with SLP variability in the North Pacific, during boreal winter on interdecadal time scales. A more systematic investigation of the relationship between the North Pacific and the tropical Indian Ocean was presented by Deser et al. (2004). They compared the anomalies of SST, precipitation, cloudiness, and precipitation between epochs of high sea level pressure (1900–24 and 1947–76) and low pressure (1925–46 and 1977–97) over the North Pacific, and discovered that the interdecadal fluctuations in the North Pacific are associated with climate variability over the tropical Indian Ocean. More recently, Deser and Phillips (2006) have confirmed that rainfall anomalies over the tropical Indian Ocean weaken the Aleutian Low in boreal winter with an ensemble simulation of an Atmospheric General Circulation Model (AGCM). Hence, a close relationship exists between the climate fluctuations in the tropical Indian Ocean and the North Pacific on an interdecadal time scale.

In the present study, we investigate the relationship of winter SLP anomalies between the tropical Indian Ocean and North Pacific. The results reveal that an out-of-phase relationship of SLP anomalies between the tropical Indian Ocean and North Pacific exists not only on the interdecadal time scale, but also on the interannual time scale. We also considered the SLP seesaw between the tropical Indian Ocean and the North Pacific as a SLP between tropical Indian Ocean and North Pacific (TIO-NP) oscillation. Moreover, an interesting research question is whether TIO-NP oscillation has any implication on China's winter climate due to China's location in the middle of the Indian Ocean and the North Pacific. However, this question is yet to be understood.

The primary objectives of the present study are to illustrate the observed and simulated evidence for TIO-NP oscillation, define a TIO-NP index that indicates this oscillation, and discuss the possible impact of such an os-

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cillation on China's climate during boreal winter.

The observational datasets and the AGCM tool employed in this study are described in section 2. The observed and simulated evidence of TIO-NP oscillation and index definition is presented in section 3. The possible impact of TIO-NP oscillation on China's climate in winter is presented in section 4. The main conclusions of this study are summarized and discussed in section 5.

2 The data and model

China's monthly mean surface air temperature and precipitation datasets used in this study include 160 stations in China from 1951–2008 and were provided by the National Climate Center, China Meteorological Administration.

The global SLP dataset used in this study is Hadley Centre Sea Level Pressure dataset (HadSLP2; Allan and Ansell, 2006), which is available on a 2.5°×2.5° grid starting from January 1850 to December 2004 and was provided by the Hadley Center.

The present study uses wind and height fields from the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) (Kalnay et al., 1996). These variables are available on 2.5°×2.5° grids from 1948 to the present.

The AGCM used is ECHMA5, the latest Hamburg version of the European Centre for Medium-Range Weather Forecasts (ECMWF) model. A detailed description of ECHAM5 is given by Roeckner et al. (2003). We use a version with a triangular truncation at zonal wave number 63 (T63; equivalent to 1.9° horizontal resolution) and 19 sigma levels in the vertical. The model is forced with the observed monthly mean SST and climatological sea ice data from 1870 to 2007. Finally, the SST forcing of AGCM is derived from the HadISST1 (Rayner et al., 2003), which was provided by the Hadley Center.

3 Observed evidence of the out-of-phase relation between SLP anomalies over TIO and NP, and index definition

Based on the definition provided by previous research (Deser et al., 2004), an index of SLP fluctuation in the North Pacific, referred to as the NP index, is constructed by averaging the December-January-February (DJF) SLP over the domain within 30–65°N and 160°E–140°W. Analogously, we constructed a TIO index by averaging the DJF SLP over the tropical Indian Ocean (15°S–15°N, 40–100°E). Figure 1a shows the normalized NP and TIO index from 1870 to 2004. Apparently, the NP index is significantly out-of-phase with the TIO index by –0.53 in

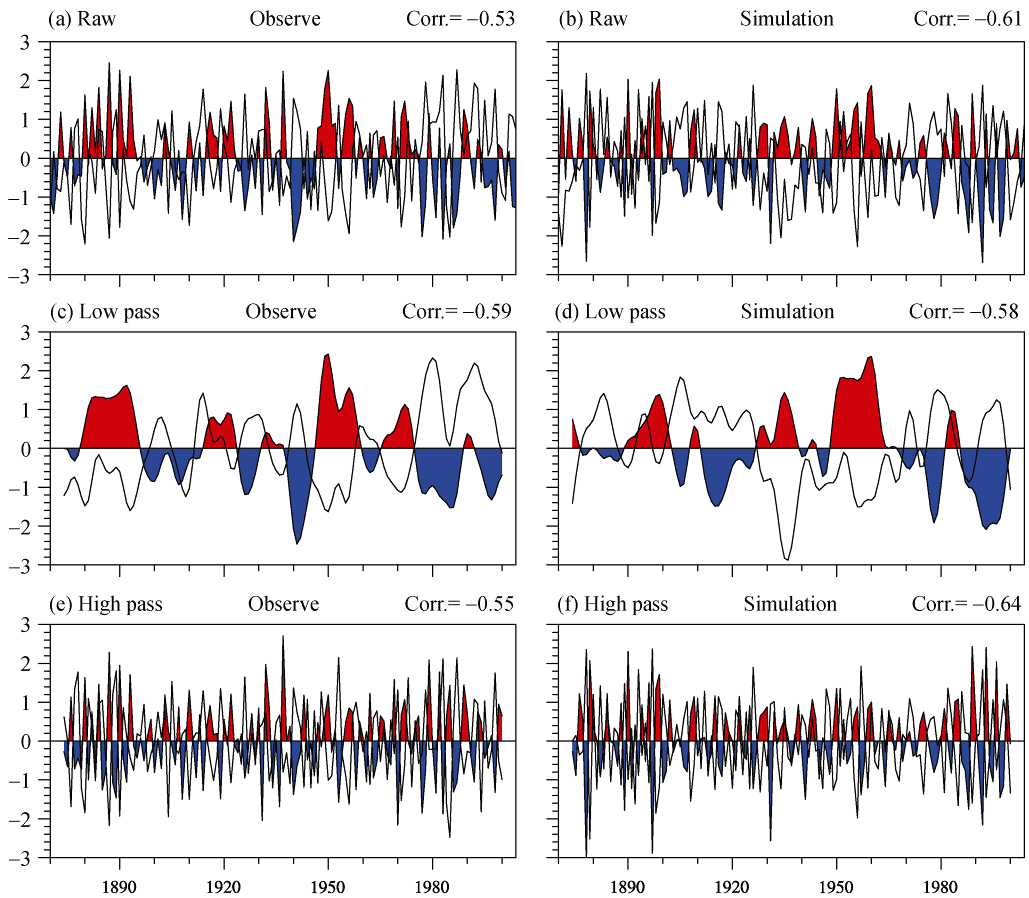

Figure 1 The normalized time series of the area average of DJF SLP over the North Pacific (color; 30–65°N, 160°E–140°W) and over the tropical Indian Ocean (line; 15°S–15°N, 40–100°E) based on observation (left panel) and model simulation (right panel) from 1870 to 2004. Raw index in the upper panel, low pass index (⩾nine years) in the middle panel, and high pass index (<nine years=in the lower panel. The correlation coefficient between the two indices is shown in the tile of each figure.

correlation for 135 years. This result indicates that SLP variation in the North Pacific is closely related to that in the tropical Indian Ocean.

Previous studies mainly focus on the interdecadal fluctuation of the North Pacific and the tropical Indian Ocean SLP. In this study, we demonstrate that SLP variations over the North Pacific and the tropical Indian Ocean also have considerable interannual fluctuation (Fig. 1a). To study the relationship between TIO and NP on interdecadal and interannual time scales, we split the raw index into longer than nine years and shorter than nine years variation through harmonic analysis. On interdecadal timescale (Fig. 1c), the NP index has several phase changes during 1870–2004 with three high SLP epochs (1880–95, 1915–25, and 1947–76) and three low SLP epochs (1895–1915, 1926–46, and 1977–2004). The TIO index also has several phase changes, but its phases are in contrast to the NP index with a correlation coefficient of −0.55 between them. The significant out-of-phase relationship between the TIO and the NP index is consistent with the findings of Deser and Phillips (2006) suggesting that Indian Ocean variability may be attributed to the decadal transition of the Aleutian Low. Moreover, the NP index is closely related to the TIO index on the interannual time scale. As shown in Fig. 1e, the correlation coefficient between the interannual variability of TIO and NP indices is −0.55 for 135 years.

Analogous computations based on the model data have also been conducted. Figure 1b shows the raw NP and TIO indices obtained by model simulation from 1870 to 2004. Consistent with observed analyses, the simulated NP and TIO indices have a significant out-of-phase relationship with a correlation coefficient of −0.61. Additionally, both simulated NP and TIO indices have considerable interannual and interdecadal variability. Moreover, the AGCM can capture the out-of-phase relation of TIO and NP indices on both interdecadal and interannual time scales with a correlation of −0.58 and −0.64, respectively. Because the AGCM is forced by SST, the consistency between observation and AGCM simulation suggests that the oscillation between the tropical Indian Ocean and the North Pacific is robust and partly forced by SST variability.

Overall, the winter SLP variability over tropical Indian Ocean is out-of-phase with simultaneous SLP variability over North Pacific on interannual and interdecadal time scales, and this relationship is confirmed by AGCM simulation. Thus, it is reasonable to consider the SLP seesaw between the tropical Indian Ocean and North Pacific as a TIO-NP oscillation. However, defining an index that indicates the variation of this oscillation is still not resolved. Because the variability of SLP over the North Pacific is much larger than that over the tropical Indian Ocean, with a standard deviation of 237 Pa and 38 Pa, respectively, it is unreasonable to define the TIO-NP oscillation index using the SO index definition by computing the difference of winter SLP anomalies between the two regions.

Singular Value Decomposition (SVD) analysis is introduced to resolve the abovementioned problem. First, to examine the relationship between spatial and temporal variability of winter SLP over the tropical Indian Ocean and the North Pacific, we performed a SVD analysis on the DJF average SLP over the tropical Indian Ocean (15°S–15°N, 40–100°E) and the North Pacific (30–70°N, 160°E–140°W) from 1870 to 2004. The details of the SVD method are described on the National Center for Atmospheric Research (NCAR) Command Language (NCL) website at http://www.ncl.edu.cn/.

As Fig. 2 indicates, the first leading heterogeneous SVD mode (the left panel of Fig. 2) is characterized by above-normal sea level pressure in the North Pacific, especially from the Bering Strait to west coast of North America, and below-normal sea level pressure in the tropical Indian Ocean, especially over the Southwest Indian Ocean. This mode accounts for 95.5% of the total squared covariance. The first leading SVD patterns (the right panel of Fig. 2), based on AGCM data from 1870 to 2004 and accounting for 92.2% of the total squared covariance, are consistent with this observation. The results suggest that the seesaw pattern of the winter seasonal mean, SLP, over the tropical Indian Ocean and the North Pacific is the most prominent. Moreover, this seesaw pattern of SVD analysis can represent TIO-NP oscillation.

We examined the temporal variability of first leading left SVD model (TIO model) for observation and AGCM simulation in the lower panel of Fig. 2. Because SLP variation over the Indian Ocean plays an active role in TIO-NP oscillation (Deser and Phillips, 2006), and because the SVD1 mode is able to represent TIO-NP oscillation, we chose the time series of the first leading left SVD model (TIO mode) to indicate the variation of TIO-NP oscillation. We also checked the relationship among the PC1 of TIO mode (TIO_PC1), PC1 of NP mode (NP_PC1), TIO index, and NP index. The correlation coefficients between TIO_PC1 vs. NP_PC1, NP_PC1 vs. NP index, and NP_PC1 vs. TIO index were 0.66, 0.85, and −0.65, respectively, for the period of 1870–2004. Thus, it is reasonable to select the time series of the TIO mode to indicate the variation of TIO-NP oscillation. Notably, AGCM can capture the interannual and interdecadal variability of TIO-NP oscillation by 0.34 in correlation with observations for 135 years, indicating that the variation of TIO-NP oscillation is partly a result of external forcing.

4 The impact of TIO-NP oscillation on China's climate during winter

To delineate the possible impact of TIO-NP oscillation on China's climate during winter, we correlated the TIO-NP oscillation index with winter precipitation and surface air temperature during 1951–2004 (Fig. 3). Corresponding to the phase of below-normal SLP over the tropical Indian Ocean and above-normal SLP over the North Pacific, the rainfall decreased significantly in south China (past 95% significant level) with a correlation coefficient of about −0.3 for 55 years, and increased insub-

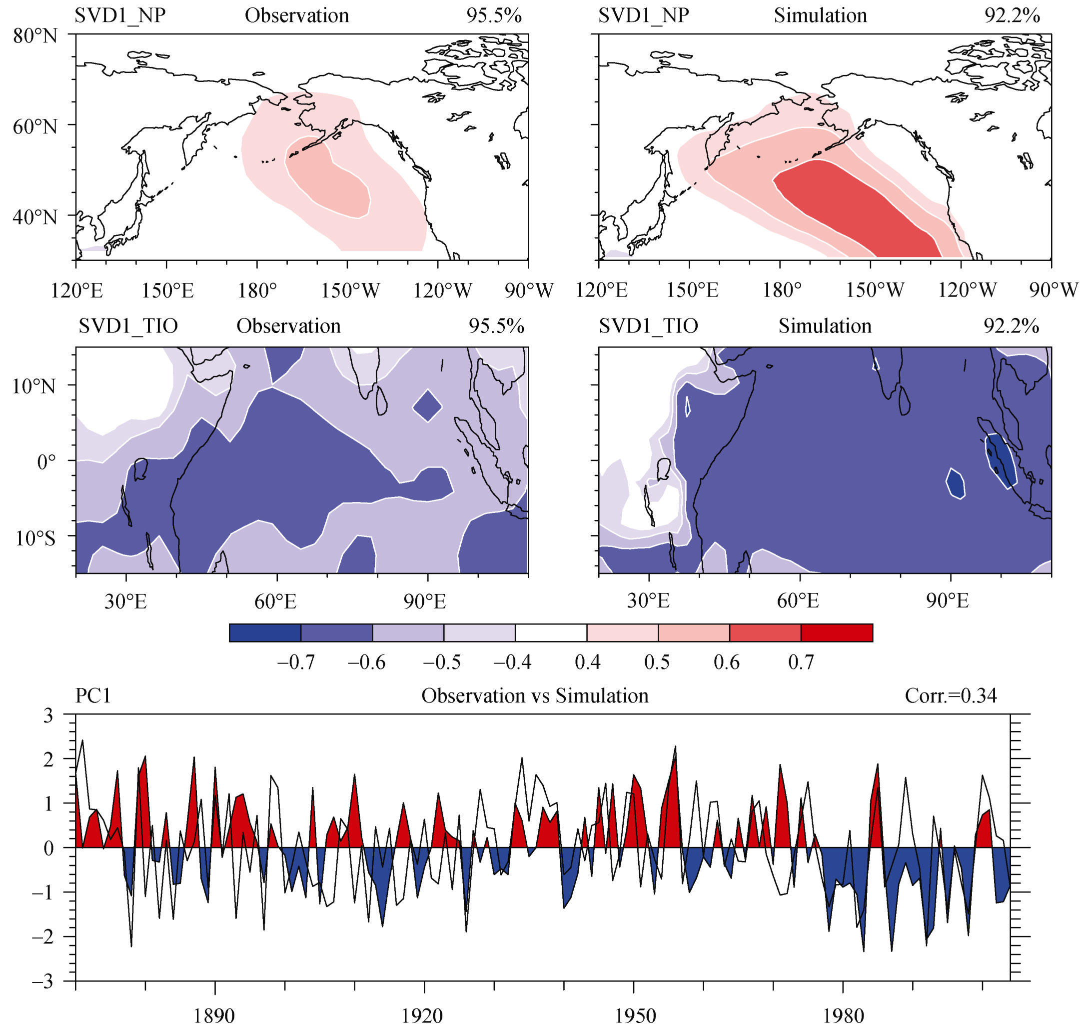

Figure 2 The first leading SVD heterogeneous mode of winter SLP over the North Pacific (30–80°N, 120°E–90°W; upper panels) and the tropical Indian Ocean (15°S–15°N, 20–110°E; middle panels) for observation (left panels) and model simulation (right panels) from 1870 to 2004. The normalized time series (lower panels) of the first leading SLP SVD mode over tropical Indian Ocean for observation (color) and model simulation (line) are indicated. The SVD analysis is based on the data from the year of 1951 to 2008.

stantially in the eastern part of North China (Fig. 3a). Furthermore, the TIO-NP oscillation index is more closely related to China's surface air temperature in winter. The significant negative correlations (past 95% significant level) are distributed in the majority of regions in China, except Southwest China, with a correlation of about –0.4 in the eastern part of China (Fig. 3b). The results forecast a cold winter in northern and eastern China and a dry winter in South China when TIO-NP is in a positive phase. These forecasts are of vital importance to the population density in these regions.

To understand how TIO-NP oscillation impacts China's climate in winter, in Fig. 3c, we demonstrate the low-level wind anomalies associated with TIO-NP oscillation over China. An anomalous anticyclone circulation is situated over North China. In the eastern part of this anticyclone, significant northwest winds (past 95% significant level) control the southern and the eastern part of China from South Korea to the South China Sea, contributing to the cold winter in the eastern parts of China by bringing cold air from the north. In contrast, southwest wind anomalies control Southwest China, which may lead to above-normal temperatures in Southwest China by bringing warm air from lower-latitude regions. In addition to temperature anomalies, rainfall anomalies may also result from low-level wind anomalies. Northeasterly anomalies push the rain band further south (the figure has not been shown) and cause less rainfall in South China. Subsequently, it is possible that the TIO-NP oscillation affects China's surface air temperature and precipitation anomalies by modulating the northeast winter monsoon.

To understand how the TIO-NP oscillation influences the lower level winds in China, we calculated the correlation between the TIO-NP oscillation index and the upper (200 hPa), middle (500 hPa), and lower (850 hPa) level height field anomalies over the tropical and the Northern Hemispheres. In the upper level, corresponding to the oscillation of below-normal SLP in the tropical Indian Ocean and above-normal SLP in the North Pacific, belt-like negative height field anomalies formed around all tropical regions and wave-like height field anomalies formed at higher latitudes; especially with the negative

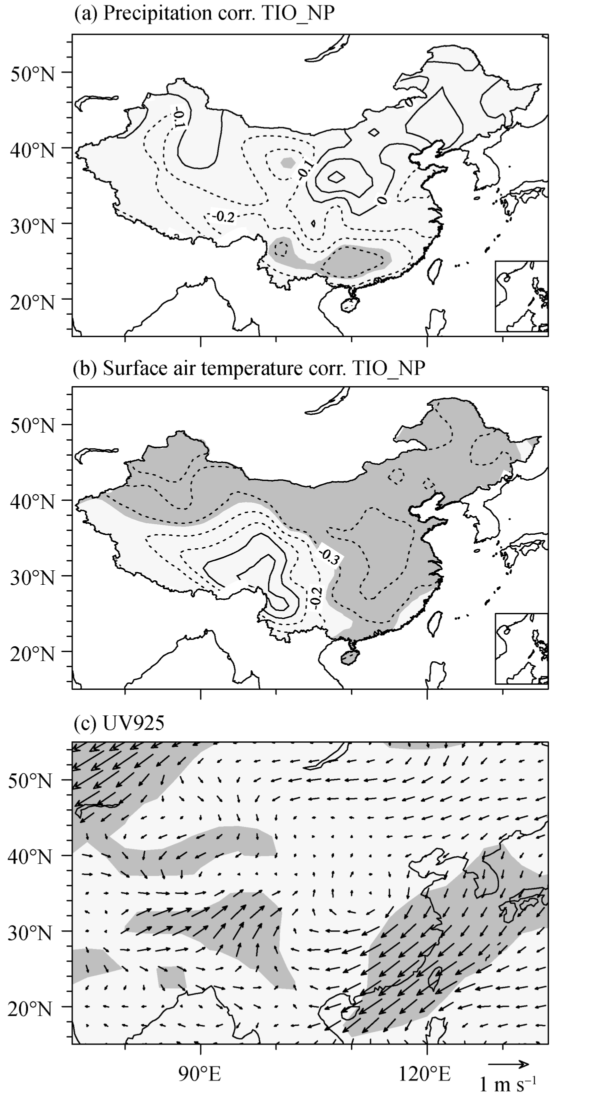

Figure 3 Correlation of the TIO-NP oscillation index with winter climate in China's (a) precipitation and (b) surface air temperature from 1951 to 2004. Regression of TIO-NP index on winter wind field (c) at 925 hPa from 1951 to 2004. The shading denotes the 95% confidence level.

anomalies centered in Asia and Canada, and positive anomalies centered in the North Pacific. The height field anomalies at 500 hPa and 200 hPa are similar to that at 850 hPa, suggesting that the TIO-NP oscillation is linked to barotropic anomalies in the tropical and the Northern Hemisphere. Figure 4b shows that the geopotential fluctuation at 500 hPa is similar to the PNA pattern. A previous study (Wallace and Gutzler, 1981) suggests that PNA is a kind of an atmospheric intrinsic mode that is partly affected by the SST anomalies in tropical eastern Pacific. The PNA-like geopotential fluctuation in Fig. 4 could result on two grounds. First, the SLP anomalies in the tropical Indian Ocean are linked to tropical eastern Pacific SLP anomalies through Walk circulation, and the associated convection anomalies over the tropical eastern Pacific can lead to PNA pattern climate anomalies. Second, the corresponding TIO precipitation anomalies contribute to the circulation anomalies in the North Pacific (Deser and Phillips, 2006); furthermore, the circulation anomalies in the North Pacific can lead to climate anomalies in North America by propagating planetary waves. However, there is little difference between height anomalies at lower and upper levels, such as the negative height anomalies are more concentrated over the Indian, Atlantic, and West Pacific Oceans. Additionally, we calculated the tropical and Northern Hemisphere low-level wind (at 925 hPa) anomalies, which are associated with TIO-NP oscillation. Corresponding to the positive height field anomalies in the North Pacific, there are anomalous low-level anticyclone circulations over the North Pacific and significant anomalous easterlies in the southern flank of anticyclone anomalies. In East Asia, there are anomalous northeasterlies. The results are consistent with the study of Wang et al. (2009), who suggest that the zonal winds over mid-Pacific (around 30°N) are out-of-phase with the East Asia winter monsoon.

In summary, the TIO-NP oscillations are closely related to China's surface air temperature and precipitation anomalies in winter. During the phase of below-normal SLP over the tropical Indian Ocean and above-normal SLP over the North Pacific, there is a colder winter in the eastern and northern parts of China and less rainfall in south China. The surface air temperature and precipitation anomalies may be a result of the low-level anomalous wind.

5 Discussion and summary

First, we illustrated the observed and simulated evidence of the out-of-phase relationship between SLP anomalies over the tropical Indian Ocean and the North Pacific, and subsequently defined a TIO-NP oscillation index to represent the variation of this oscillation. The SLP anomalies over the North Pacific are closely related to tropical Indian Ocean on interdecadal and interannual time scales during the period of 1870–2004, with a significant negative correlation between them, as confirmed by AGCM simulation. We consider such an out-of-phase relation between the tropical Indian Ocean and the North Pacific as a kind of oscillation. This oscillation is also demonstrated by the first leading SVD mode of winter SLP over the tropical Indian Ocean and the North Pacific, accounting for a majority of the total squared covariance. A previous study shows that the Indian Ocean plays an active role in climate anomalies in the North Pacific. Thus, we chose the time series of the left SVD mode (TIO mode) to indicate the variation of TIO-NP oscillation, and referred to it as the TIO-NP oscillation index. The AGCM simulation could capture the spatial and temporal features of TIO-NP oscillation. The high correlation of the TIO-NP oscillation index between the observation and simulation suggests that SST variation contributes to the oscillation between the tropical Indian Ocean and the North Pacific. Because the SST, especially the tropical SST, have larger predictability than the atmosphere, the TIO-NP oscillation may also have some predictability.

Secondly, we investigated the possible impacts of TIO-NP oscillation on surface air temperature and pre-

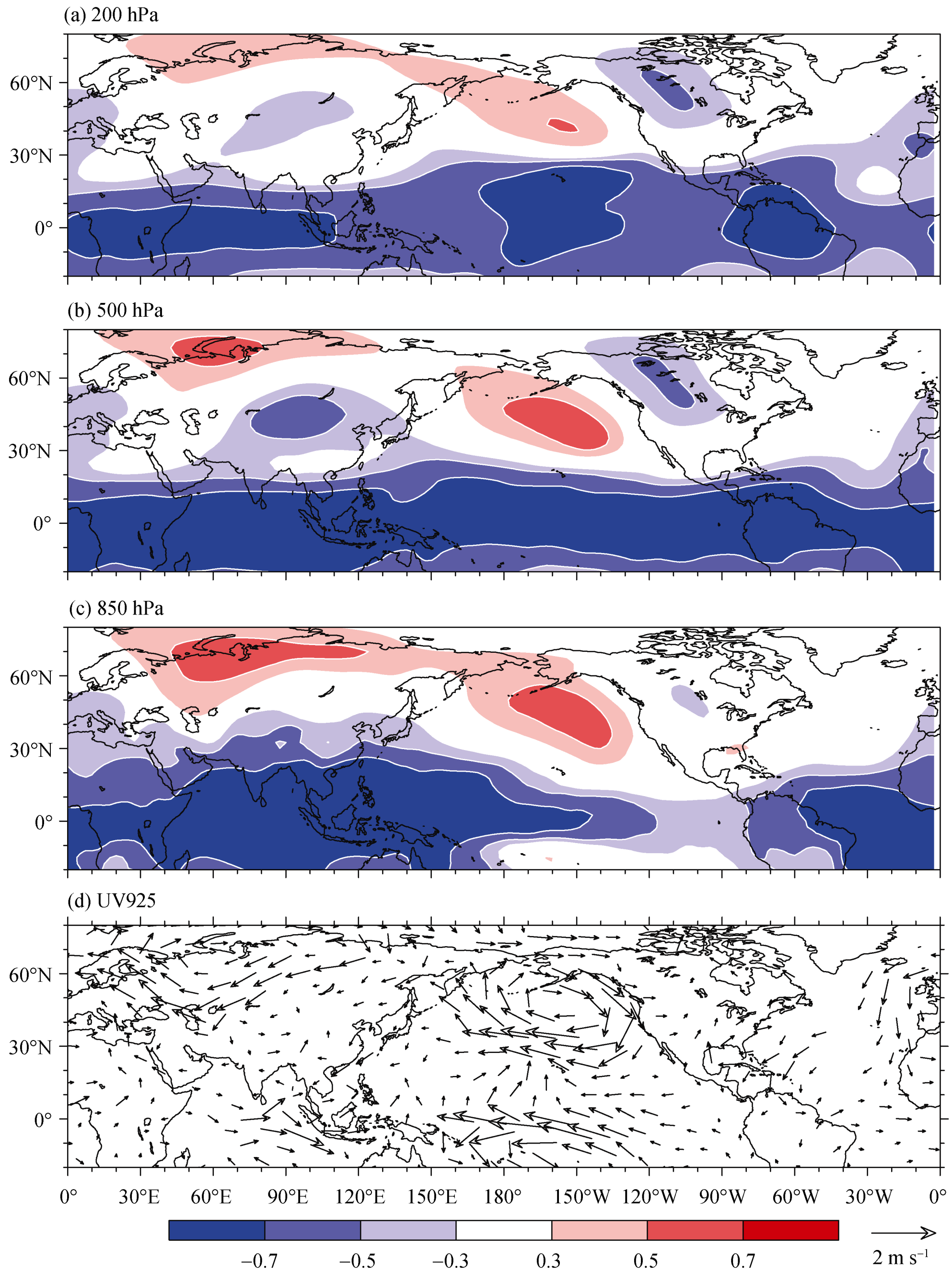

Figure 4 Correlation of the TIO-NP oscillation index with height field at (a) 200 hPa, (b) 500 hPa, and (c) 850 hPa, and (d) regression of TIO-NP oscillation index on wind field at 925 hPa for the period of 1951–2004. Wind vectors pass 95% confidence level. Correlation at 0.27, 0.35, and 0.44 denote 95%, 99%, and 99.9% confidence levels.

cipitation anomalies in China during boreal winter. In the phase of low SLP in the tropical Indian Ocean and high SLP in the North Pacific, there is a colder winter in the northern and the eastern part of China, and lesser rainfall in South China. The surface air temperature and precipitation anomalies are potentially a result of enhancing the northeast winter monsoon.

We also demonstrated the observed and simulated evidence of TIO-NP oscillation and its impact on China's winter climate, although its underlying physical mechanism has not been investigated in the present study. Because the TIO-NP oscillation is partly a result of SST fluctuation, it may be a good predictor of China's winter surface temperature and precipitation. However, its predictability has not been investigated in this present study and needs further investigation.

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