Influence of Positive IOD Events on the Northeastward Extension of the Tibetan High and East Asian Climate Condition in Boreal Summer to Early Autumn

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Abstract

Herein, (i) the remote influence of positive Indian Ocean Dipole (P-IOD) events in enhancing Tibetan High and (ii) its impact on the East Asian climate, from July to September, is analyzed based on composite analysis and linear baroclinic model experiment. In the equatorial Indian Ocean, convective activity enhances over the western part and suppresses over the eastern, which is associated with the zonal contrast of the sea surface temperature anomaly during P-IOD events. A lower-tropospheric clockwise circulation anomaly is evident from the eastern equatorial Indian Ocean where the suppressed convection is seen to the Indochina Peninsula. The streamlines arrive at the seas east of the Philippines, contributing to the enhancement of the monsoon trough. In the upper troposphere, crucial divergence anomaly over a wide area in the western North Pacific and the associated stronger-than-normal northward divergent winds toward East Asia cause strong northward negative-vorticity advection over the northern part of East Asia, contributing to the northeastward extension of the Tibetan High. This circulation anomaly contributes to both the significantly hot conditions in boreal summer and the late-summer heat over East Asia. 

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1. Introduction

The Indian Ocean Dipole (IOD) is one of the main patterns of the sea surface temperature (SST) anomaly over the Indian Ocean with zonal contrast in the equatorial region (e.g., Saji et al. 1999; Saji and Yamagata 2003). IOD events generally begin in late spring, peak in autumn, and end in winter, and they exert a large influence on the climate not only in the countries around the Indian Ocean but also globally (Guan and Yamagata 2003; Saji and Yamagata 2003). Based on correlation analysis, Saji and Yamagata (2003) suggested that the IOD influences the global atmospheric circulation and indicated (i) the statistical relationship between positive IOD (P-IOD) events and equivalent barotropic positive height anomalies in the Northern Hemisphere mid-latitudes and (ii) its impact on the summer climate over East Asia. However, Saji and Yamagata (2003) did not show the related mechanism for the equivalent barotropic height anomaly, and that mechanism remains unclear.

On a regional scale, an extension of the Tibetan High has a large impact on the hot summer conditions in and around Japan. Referred to as the Bonin High, the equivalent barotropic structure (Ogasawara and Kawamura 2008) is due to the propagation of Rossby waves along the Asian jet stream as typified by the Silk Road pattern (Enomoto et al. 2003). Japan has experienced significant hot and dry conditions, such as those in the boreal summers of 1994 and 2018, resulting in a serious impact on its socioeconomic activities. For the case in 1994, Guan and Yamagata (2003) explained one of the impacts of P-IOD events on the anomalous circulation in and around East Asia through the quasi-stationary Rossby-wave propagation. They also suggested an existence of the Rossby-wave source due to the P-IOD-induced diabatic heat forcing around India through the monsoon–desert mechanism (Rodwell and Hoskins 1996). Furthermore, they indicated that the IOD-induced vorticity forcing by the upper-tropospheric divergent wind anomaly caused the Rossby-wave train from India to southern China, also contributing to the anomalous circulation in and around East Asia. Covering the period from 1958 onward, the Japanese 55-year reanalysis dataset (JRA-55; Kobayashi et al. 2015) allows us to assess easily some common characteristics in a number of past P-IOD events by statistical analysis. By means of a composite analysis, Qiu et al. (2014) indicated that (i) P-IOD events have a much larger influence on the climate in China than negative IOD (N-IOD) events and (ii) the P-IOD-induced increase in the moisture flux toward the country contributes to the wet conditions over southern China in the autumn.

The results of the aforementioned studies motivate us to focus on P-IOD events preferentially given their stronger influence on the East Asian climate. There have been many previous studies on the impact of the IOD on the atmospheric circulation and regional climate in the Southern Hemisphere, such as the precipitation anomaly in and around Australia due to the IOD-induced anomalous circulation (e.g., Ashok et al. 2003; Cai et al. 2009). Furthermore, previous studies of the IOD have suggested that there are synchronized and complicated influences of the IOD and the El Niño Southern Oscillation (ENSO) on atmospheric and climate condition (i.e., Ashok et al. 2001, 2004). Hereafter the P-IOD events excluded from the El Niño influences are referred to as the “pure P-IOD” events. In the present study, we examine (i) the statistical characteristics of past pure P-IOD events since 1958 and (ii) how the pure P-IOD events affect the enhancement of the Tibetan High to assess the impacts of P-IOD events alone. This line of attack is important for improving our knowledge about the IOD influence on the Japanese climate and how to monitor and predict that influence.

2. Data and methods

In the present study, we used three-month means from July to September (JAS) of JRA-55 and COBE-SST (Ishii et al. 2005) to diagnose the atmospheric circulation and the oceanographic conditions. Those three months correspond to the period from boreal summer to early autumn in the Northern Hemisphere, and taking averages over that period reduces the influence of intra-seasonal variability including the Madden–Julian oscillation. We confirmed that an analysis based on the period from August to October (ASO) gives similar results. Unless stated otherwise, normal circulation conditions are defined as the 55-year average from 1958 to 2012 and anomaly is defined as any deviation from that.

We conducted a composite analysis to determine the statis-
tical characteristics of the pure P-IOD events in JAS period that occurred in eight of the years between 1958 and 2012, namely 1961, 1967, 1994, 2006, 2007, 2008, 2011, and 2012. To extract those IOD events, we define the dipole mode index (DMI) on monthly basis after Saji et al. (1999) as the difference between the SST deviation averaged over the western part (10°S–10°N, 90°E–70°E) of the equatorial Indian Ocean and that averaged over the eastern part (10°S–Eq., 90°E–110°E). The SST deviation is defined as the deviation from the latest sliding 30-year mean. A P-IOD event is recognized if the three-month (JAS) running mean DMI exceeds +0.4°C for at least three consecutive months (i.e. from July (JJA mean) to September (ASO mean)). To assess the impacts of IOD events alone, we extracted the P-IOD events from the P-IOD+El Niño events by removing those years in which El Niño years occurred simultaneously. Here, the El Niño years are based on the Japan Meteorological Agency’s definition that the five-month running mean SST deviation for NINO.3 satisfies above +0.5°C for at least six consecutive months. Doing so, has suggested that the atmospheric-circulation responses to P-IOD events do not always correspond to those to N-IOD events (Qiu et al. 2014). Therefore, composite analysis has an advantage when deriving these asymmetric responses to theIOD phases and is suitable for examining the characteristic patterns in P-IOD events.

To examine the atmospheric responses to the diabatic heating anomalies associated with enhanced convective activities, we used a linear baroclinic model (LBMM; Watanabe and Kimoto 2000, 2001) comprising primitive equations linearized exactly about a basic state defined as the 30-year average from 1981 to 2010. The model was expanded horizontally by spherical harmonics having an equation with the resolution of T42 and discretized vertically by a finite difference to 40-sigma levels. The model also included (i) bi-harmonic horizontal diffusion with an e-folding time of 1 h, (ii) very weak vertical diffusion to remove vertical noise arising from the finite differences, and (iii) Newtonian damping and Rayleigh friction represented by a linear drag with an e-folding time of 30 d in most of the free atmosphere, 0.5 d for the four lowest and nine highest levels, and 1 d for the fifth and sixth lowest ones.

3. Results

Figure 1 shows the composite SST and 500-hPa vertical p-velocity anomaly during the pure P-IOD events. The SST anomaly over the Indian Ocean is positive over the western to central parts and negative over the eastern part (Fig. 1a), exhibiting the typical P-IOD pattern. We see that the ENSO influence is properly removed from the pure IOD composite field because there is no significant SST signal over the Pacific Ocean except for a small area to the east of the Philippines. Corresponding to the SST anomaly over the Indian Ocean, the 500-hPa vertical velocity anomalies indicate that convective activity is enhanced over the western part of the ocean and suppressed over the eastern part (Fig. 1b). The 850-hPa streamfunction anomaly shown in Fig. 2a exhibits a clear anticyclonic circulation anomaly over the Bay of Bengal, corresponding to the Rossby-wave response to the suppressed convective activity over the eastern Indian Ocean (Fig. 1b). In association with the circulation response, there is an anomalous lower-tropospheric clockwise stream from the western Indian Ocean to the Indochina Peninsula (Fig. 2b). The circulation anomaly arrives at the seas east of the Philippines and exhibits stronger-than-normal convergence with the trade winds (Fig. 2b), contributing to the enhanced monsoon trough over the area shown as a negative sea level pressure anomaly in Fig. 2c. These stronger-than-normal monsoon trough are associated with enhanced convective activities over a wide area of the western North Pacific (Fig. 1b). The relationship between the P-IOD events and the stronger-than-normal monsoon trough to the east of the Philippines is consistent with the results of some previous studies such as Ashok et al. (2004) and Yang et al. (2010). The enhanced convective activity over the western North Pacific can be explained by the stronger-than-normal monsoon circulation. The enhanced convection also corresponds partly to the positive SST anomaly to the east of the Philippines (Fig. 1a), and it is consistent with the numerical experiment result by Wu et al. (2014).

The composite anomaly of the 850-hPa streamfunction shown in Figs. 2a exhibits a meridional pattern with cyclonic circulation anomaly to the south of Japan and anticyclonic circulation anomaly from northern Japan to its east, indicating the North Pacific Subtropical High extension toward Japan, and is to some extent similar to the Pacific–Japan (PJ) teleconnection pattern (Nitta 1987). However, the composite anomalies are lack of significance. We reason that the East Asian climate is affected also by the lower-tropospheric circulation characteristics, indicating a need to investigate further the P-IOD impact on the lower-tropospheric circulation.

In the upper troposphere, a significant wind divergence anomaly is seen over a wide area of the western North Pacific (Fig. 2d) as a result of the enhanced convective activity over and around the area (Fig. 1b). This causes northward divergent wind anomalies over the area from the seas east of the Philippines to East Asia across the westerly flow associated with the Asian jet stream. Over East Asia, the Asian jet stream shifts northward from its normal position (Fig. 3a) and the 200-hPa height shows a zonally elongated positive anomaly over the latitudinal band of 40°N (Fig. 3b), indicating a northeasterward extension of the Tibetan High from its normal position. To identify the origin of the positive height anomaly, the composite absolute-vorticity advection term in the Rossby-wave source is calculated with reference to Sardeshmukh and Hoskins (1988). The advection term $S_{adv}$ can be written as

$$S_{adv} = -\nabla_r \cdot \nabla X_r - \nabla_r \cdot \nabla (\zeta + f),$$

where $\nabla_r$ is the divergent horizontal wind vector, $\zeta$ is the relative vorticity, and $f$ is the Coriolis parameter. For a variable $X$, $\nabla X$ denotes the normal and $\nabla'$ the anomaly. The advection term shown in Fig. 3c indicates negative-vorticity forcing over the northern part of East Asia due to the northward divergent wind anomaly across the normal Asian jet stream. The vorticity advection anomalies are presumed to contribute to the northward shift of the Asian jet.
stream (Fig. 3a) and the northeastward extension of the Tibetan High (Fig. 3b). In association with the Tibetan High extension, the lower-tropospheric anticyclonic circulation anomaly is also seen particularly in northern Japan (Fig. 2a) although the anomaly is not significant, indicating an extension of the North Pacific Subtropical High toward Japan. 850-hPa temperature shown in Fig. 3d exhibits significant positive anomalies over a wide area of East Asia, contributing to the significantly hot conditions in boreal summer and the late-summer heat over the area, particularly in Japan. Figures 4a and 4b shows latitude–height cross sections of the relative vorticity and temperature anomalies averaged over the longitudinal range from 90°E to 150°E. A negative relative vorticity anomaly is seen over and around 40°N in the troposphere with the equivalent barotropic structure (Fig. 4a), indicating a strong northeastward extension of the Tibetan High. Figure 4b indicates a significant above-normal temperature over the mid-latitudes, indicating general warmer-than-normal conditions of the tropospheric air column over East Asia.

Figures 3b show the upper-tropospheric meridional circulation pattern with positive height anomalies to the east of Japan and...
negative height anomalies to its south, indicating suitable conditions for Rossby-wave breaking and the associated stronger-than-normal mid-Pacific trough (MPT). We reason from this pattern that the intrusion of high potential vorticity associated with the MPT contributes partly to the enhanced convective activity over the western North Pacific suggested by Takemura et al. (2017). These characteristics deserve further investigation in terms of extra-tropical and tropical atmospheric interaction.

Deterministic numerical experiments are performed using the LBM. The LBM is solved with two types of hypothetical elliptical heat source centered at the points 5°S, 100°E (experiment 1, Fig. 5a) and 10°N, 140°E (experiment 2, Fig. 5c) with reference to the composite 500-hPa vertical p-velocity (Fig. 1b) and 200-hPa velocity potential (Fig. 2d). These two experiments are implemented to assess the impact of suppressed convective activity over the eastern equatorial Indian Ocean associated with the P-IOD events for experiment 1 and the stronger-than-normal lower (resp. upper) tropospheric convergence (resp. divergence) over the western North Pacific for experiment 2. The vertical integrated heating anomaly shown as the colored shading in Figs. 5a and 5c indicates cool and warm sources over the eastern Indian Ocean and the western North Pacific, respectively. The LBM responses of the 850-hPa streamfunction and horizontal wind (Fig. 5b) to the P-IOD-associated cool source (Fig. 5a) show anticyclonic circulation anomalies and the associated clockwise wind anomalies over the Bay of Bengal, and the lower-tropospheric westerly-wind anomalies arrive to the seas east of the Philippines, corresponding to the composite lower-tropospheric circulation anomaly shown in Figs. 2a and 2b. Although there are some differences between the LBM responses and the composite analysis results, these responses also indicate that the P-IOD-associated suppressed convective activity over the eastern equatorial Indian Ocean helps to enhance the lower-tropospheric clockwise flow and westerly wind from the Bay of Bengal to the east of the Philippines. However, the enhanced monsoon trough to the east of the Philippines and the PJ-like teleconnection pattern are not reproduced by this experiment. Furthermore, the LBM responses of the 200-hPa velocity potential and divergent wind (Fig. 5d) to the warm source to the east of the Philippines (Fig. 5c) show a divergence anomaly and the associated northwestward divergent flow toward the northeastern part of East Asia (Fig. 5d), also corresponding well to the composite anomaly characteristics (Fig. 2d). These two LBM experiments suggest that the P-IOD events have an indirect impact on the northeastward extension of the Tibetan High through the enhanced Asian summer-monsoon circulation.
4. Conclusion and discussion

This study investigated the dynamic relationship and processes between P-IOD events and the northeastward extension of the Tibetan High, and its impact on the East Asian climate from boreal summer to early autumn based on a statistical analysis and LBM experiments. The composite analysis of P-IOD events with ENSO events removed shows a zonal contrast of the anomalous convective activities in the equatorial Indian Ocean associated with the P-IOD-related SST anomaly. The lower-tropospheric anticyclonic circulation anomaly in response to the suppressed convective activity over the eastern Indian Ocean contributes to enhance (i) the lower-tropospheric clockwise circulation associated with the Rossby wave response and westerly wind from the Bay of Bengal to the sea east of the Philippines and the associated monsoon trough to the east of the Philippines and (ii) the convective activity over the western North Pacific. The positive SST anomalies to the east of the Philippines may also contribute partly to the enhanced convective activity over that region. The resultant significant divergent wind over the western North Pacific in the upper troposphere crosses the Asian jet stream and provides strong negative-vorticity forcing over the northern part of East Asia, contributing to the northeastward extension of the Tibetan High. This circulation anomaly is presumed to contribute to the significantly hot conditions in boreal summer and the late-summer heat over East Asia, particularly in Japan. The responses of (i) the anticyclonic circulation anomaly over and around the Bay of Bengal and the enhanced westerly flow in the lower troposphere to the P-IOD-associated suppressed convective activity and (ii) the upper-tropospheric northward divergent wind in the direction of East Asia to the enhanced convective activity over the western North Pacific are expressed well by the LBM numerical experiments. These impacts on the East Asian summer climate can be understood as remote and indirect influences of pure P-IOD events via the summer monsoon activity.

In this study, we performed the composite analysis of pure P-IOD events with a sample of eight years. There were a few cases that indicate weaker-than-normal monsoon trough over the western North Pacific in contrast to the composite analysis results, indicating the influence by other factors such as strong inter-seasonal variability and extratropical internal variability. There is a need for the sample accumulation for statistical assessment, and for considering how to extract the pure IOD impacts on atmospheric circulation in our future works.

Although we examined P-IOD events in this study, the opposite atmospheric circulation characteristics were not seen in a composite analysis of N-IOD events (not shown). These asymmetric atmospheric responses of the IOD phases should be examined in future work.

Clarification of the relationship between IOD events and the East Asian summer climate is also important for assessing the predictability and progress of operational seasonal forecasting. For future perspectives on operational seasonal forecasting, using the predicted indices representing the IOD condition gives us a potential way to predict the climate from boreal summer to early autumn in and around East Asia as suggested in previous studies.

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