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Influence of Positive IOD Events on the Northeastward Extension of the Tibetan High in Boreal Summer to Early Autumn

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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 among those patterns whose zonal contrast is 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). Previous studies indicated the statistical relationship between positive IOD (P-IOD) events and equivalent barotropic positive height anomalies in the Northern Hemisphere mid-latitudes associated partly with an enhancement of the Tibetan High. However, the related mechanism for the equivalent barotropic height anomaly remains unclear. The results of the aforementioned studies motivate us to focus on P-IOD events preferentially given their stronger influence on the East Asian climate.

In the present study, we examine (i) the statistical characteristics of past P-IOD events since 1958 and (ii) how P-IOD events affect the enhancement of the Tibetan High. 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 methodology

We used three-month means from July to September (JAS) of JRA-55 (Kobayashi *et al.* 2015) and COBE-SST (Ishii *et al.* 2005) to diagnose the atmosphere circulation and the oceanographic conditions. Those three months correspond to the period from boreal summer to early autumn in the Northern Hemisphere. Normal circulation is 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 statistical characteristics of the pure P-IOD events that occurred in eight of the years between 1958 and 2012, namely 1961, 1967, 1994, 2006, 2007, 2008, 2011,

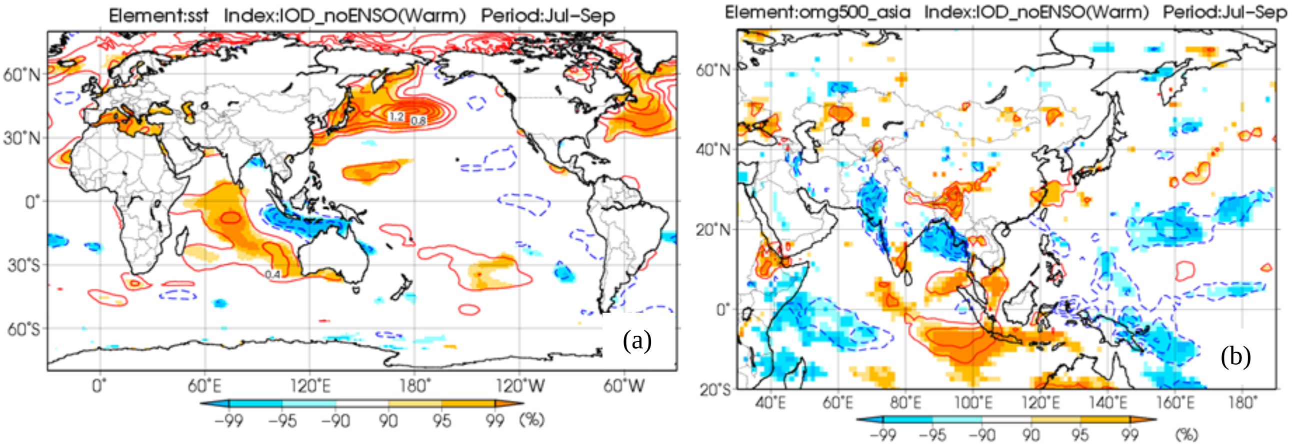

Fig. 1 Composite anomaly maps of JAS mean of (a) sea surface temperature (SST) and (b) 500-hPa vertical p-velocity in pure positive Indian Ocean Dipole (P-IOD) events from July to September. The contour lines denote the composite anomalies at intervals of (a) 0.2°C and (b) 1×10^{-2} Pa/s. The shading indicates the statistical confidence levels.

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and 2012. To extract those IOD events, we define the dipole mode index (DMI) after Saji *et al.* (1999) as the difference between the SST deviation averaged over the western part (10°S–10°N, 50–70°E) of the equatorial Indian Ocean and that averaged over the eastern part (10°S–Eq., 90–110°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 running mean DMI exceeds +0.4°C for at least three consecutive months. To assess the impacts of IOD events alone, we extracted the pure P-IOD events from the P-IOD+ENSO events by removing those years in which ENSO events occurred simultaneously.

To examine the atmospheric responses to the diabatic heating anomalies associated with enhanced convective activities, we used a linear baroclinic model (LBM; 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.

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. 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 area from the seas south of India to the Maritime Continent, implying that the Rossby-wave response to the suppressed convective activity is seen (Fig. 1b). The anticyclonic circulation anomaly brings a stronger-than-normal lower-tropospheric westerly wind over the area from the Arabian Sea to the seas east of the Philippines (Fig. 2b), corresponding to an enhanced Asian

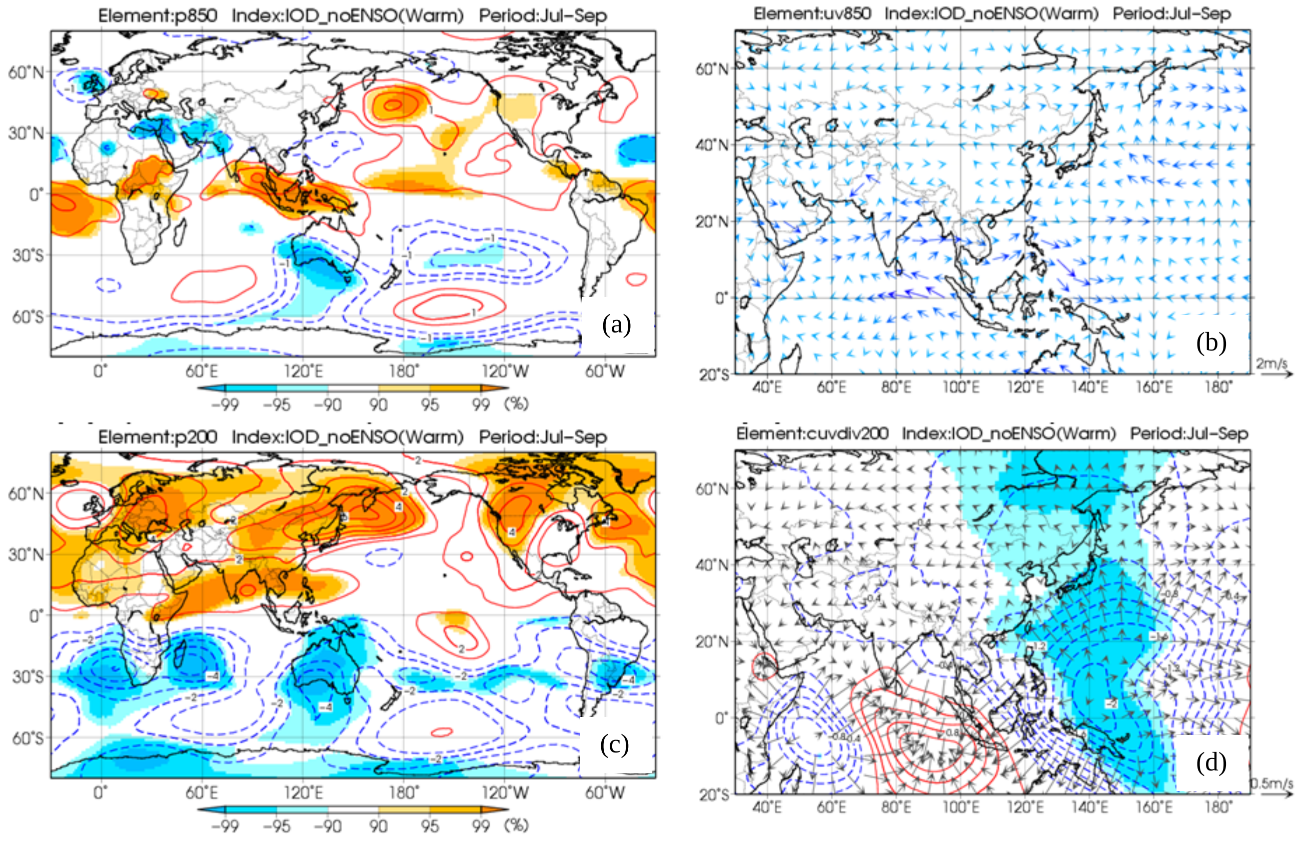

Fig. 2 As Fig. 1 but for composite anomaly maps of (a) 850-hPa streamfunction, (b) 850-hPa horizontal wind (vectors), (c) 200-hPa streamfunction, and (d) 200-hPa velocity potential and divergent wind (vectors). The contour intervals are (a) 0.5×10^6 m^2/s, (c) 1×10^6 m^2/s, and (d) 0.2×10^6 m^2/s.

summer-monsoon circulation. The westerly-wind 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. These stronger-than-normal monsoon circulation and monsoon trough are associated with enhanced convective activities in the latitudinal band from 10°N to 20°N such as western India, the Bay of Bengal, and the wind area of the western North Pacific (Fig. 1b). The relationship between the P-IOD events and the stronger-than-normal Asian summer-monsoon circulation is also suggested by some previous studies such as Ashok *et al.* (2004) and Yang *et al.* (2010), and the enhanced convective activity over the western North Pacific can be explained by the stronger-than-normal monsoon circulation and corresponds partly to the positive SST anomaly to the east of the Philippines (Fig. 1a).

In the upper troposphere, a significant divergence anomaly is seen over a wide area of the western North Pacific (Fig. 2d) associated with 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 strong meridional gradient of potential vorticity 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 northeastward extension of the Tibetan High. To identify the origin of the 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 shown in Fig. 3c indicates negative-vorticity forcing over the northern part of East Asia, contributing to the northward shift of the Asian jet stream (Fig. 3a) and the northeastward extension of the Tibetan High (Fig.

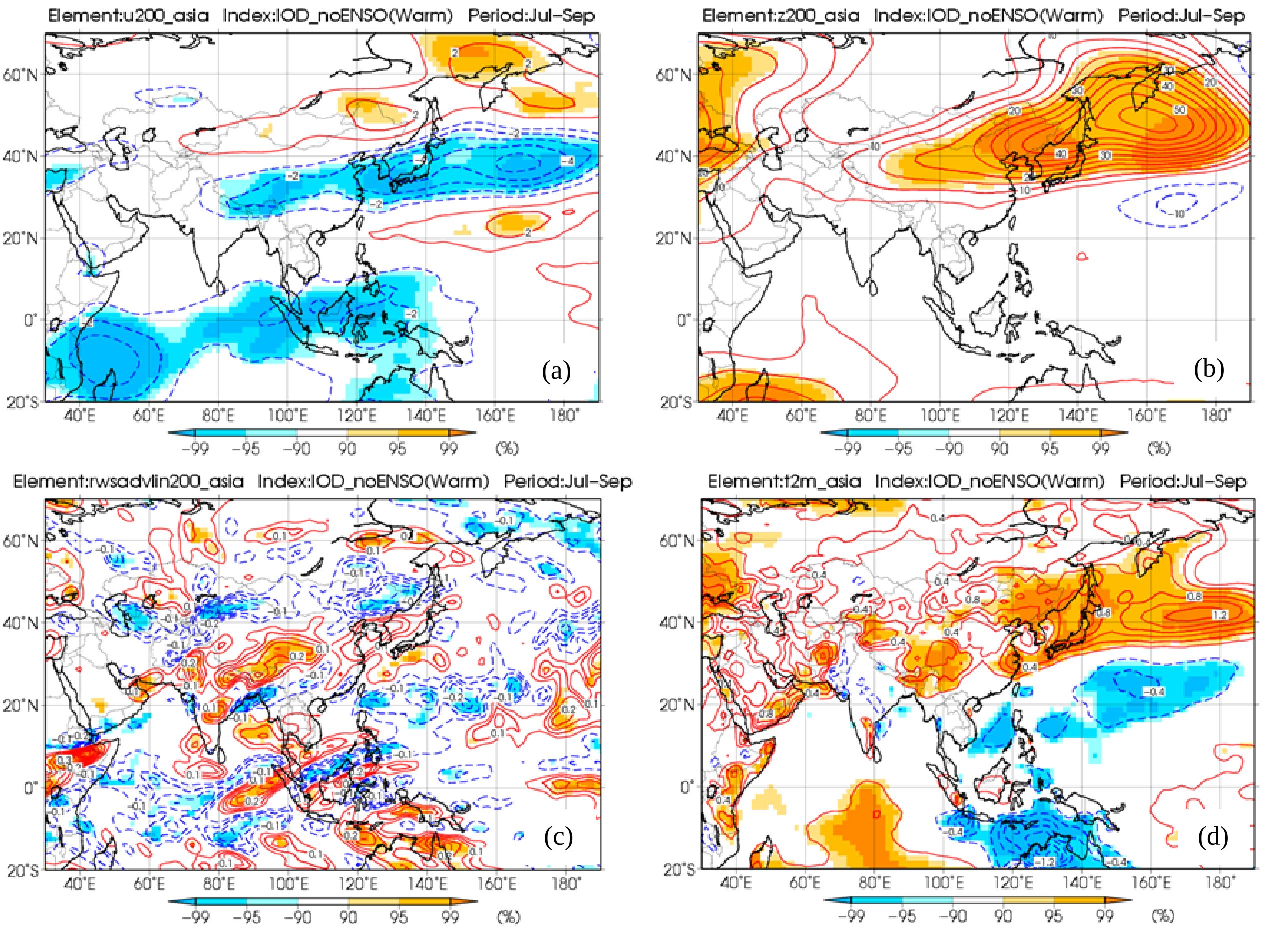

Fig. 3 As Fig. 1 but for composite anomaly maps of (a) 200-hPa zonal wind, (b) 200-hPa geopotential height, (c) 200-hPa absolute-vorticity advection by divergent wind, and (d) 2-m temperature. The contour intervals are (a) 1 m/s, (b) 5 m, (c) 0.05×10^{-5} $s^{-1}d^{-1}$, and (d) 0.2°C.

3b). The 2-m 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.

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. 4a) and 5°N, 150°E (Experiment 2, Fig. 4c) 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. 4a and 4b 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. 4b) to the P-IOD-associated cool source (Fig. 4a) show anticyclonic circulation anomalies over the North Indian Ocean and the associated lower-tropospheric westerly-wind anomalies over the area from the Arabian Sea to the seas east of the Philippines, corresponding to the composite lower-tropospheric circulation anomaly shown in Figs. 2a and 2b. These responses indicate that the P-IOD-associated suppressed convective activity over the eastern equatorial Indian Ocean helps to enhance the Asian summer-monsoon westerly wind. Furthermore, the LBM responses of the 200-hPa velocity potential and divergent wind (Fig. 4d) to the warm source to the east of the Philippines (Fig. 4c) show a divergence anomaly and the associated northwestward divergent flow toward the northeastern part of East Asia (Fig. 4b), 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.

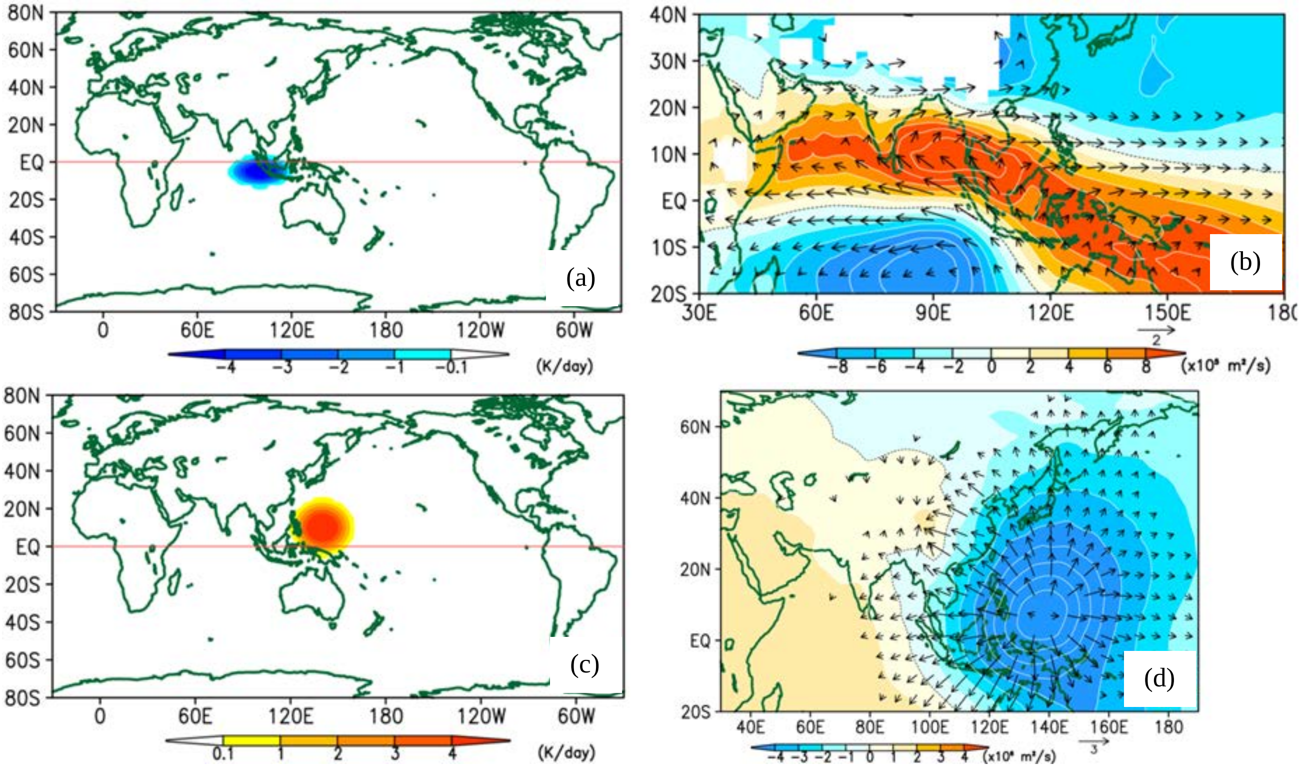

Fig. 4 Steady linear responses of (b) 850-hPa streamfunction anomaly (contours and shading) and horizontal wind anomaly (vectors) to (a) a cool source at 5°S, 100°E, and (d) 200-hPa velocity potential anomaly (contours and shading) and divergent wind anomaly (vectors) to (c) a warm source at 10°N, 140°E in the linear baroclinic model (LBM). The anomalies represent deviation from the basic states defined as normal during the period from July to September. (a) and (c) show vertically integrated heat forcing with a maximum amplitude of 8 K/d, a longitudinal width of 20°, a latitudinal width of (a) 8° and (c) 15°, and a gamma vertical distribution around the 400-hPa level. The contour intervals are (b) 2×10^5 m^2/s and (d) 1×10^6 m^2/s.

4. Conclusions

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 westerly wind of the Asian summer-monsoon circulation and the associated monsoon trough 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. The responses of (i) the anticyclonic circulation anomaly over the North Indian Ocean and the Asian summer-monsoon westerly in the lower troposphere to the P-IOD-associated suppressed convective activity and (ii) the upper-tropospheric divergence 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 enhanced Asian summer-monsoon circulation.

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 late summer to autumn in and around East Asia as suggested in previous studies.

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