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Two Types of Wintertime Teleconnection Patterns over the Western North Pacific associated with Regionally Different Heating Anomalies

Masaya KURAMOCHI¹

Graduate School of Science and Technology
University of Tsukuba, Tsukuba, Japan

and

Hiroaki UEDA

Faculty of Life and Environmental Sciences
University of Tsukuba, Tsukuba, Japan

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1) Corresponding author: Masaya Kuramochi, Graduate School of Science and Technology, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki, 305-8572 JAPAN
Email: kuramochi.masaya.sp@alumni.tsukuba.ac.jp
Tel: +81-29-853-5692
Abstract

The turnabout of air temperature anomalies over East Asia between the first and second halves of winter 2020/21 was examined from a teleconnection perspective with regionally different convective heating anomalies over the Indo-western Pacific sector. In the first half of winter 2020/21, the air temperature over East Asia was lower than normal, accompanied by a pair of anticyclonic and cyclonic anomalies in the upper troposphere southeast of the Tibetan Plateau and north of Japan, respectively. This dipole pattern is newly referred to as Southeast Asia–Japan (SAJ) pattern in this study, indicating the propagation of Rossby waves caused by enhanced tropical convection over the eastern Indian Ocean toward the South China Sea. In the second half of winter 2020/21, the enhanced convection shifted eastward to the Philippine Sea. The subsequent anticyclonic anomaly changed its position to the south of Japan, which was similar to the western Pacific (WP)-like teleconnection pattern, causing warmer conditions over East Asia. The composite analysis indicated that the anomalous anticyclone over the southeastern Tibetan Plateau corresponding to the SAJ pattern emerged simultaneously with intensification of convection over the South China Sea. Half of the cases of the WP-like pattern have been accompanied by enhanced convection over the Philippine Sea. The different circulation patterns were reproduced by prescribing the heat source over the South China Sea and Philippine Sea to the linear baroclinic model. Moreover, the vorticity budget analysis suggested that the presence of upper-tropospheric convergence of winds
to the southeast of the Tibetan Plateau seen in the climatology is conceivable for the in
situ localized anomalous circulation constituting the SAJ pattern due to vortex stretching
effects.

**Keywords** teleconnection; heat-induced atmospheric response; East Asian winter
monsoon; climate variability; vorticity budget
1. Introduction

The western Pacific (WP) pattern is a tropospheric teleconnection pattern in boreal winter, which consists of a north–south dipole of height anomalies over the Kamchatka Peninsula and the western subtropical North Pacific (Wallace and Gutzler 1981). The WP pattern influences climate variability over East Asia (Takaya and Nakamura 2013; Park and Ahn 2016; Shiozaki et al. 2021; Shiozaki and Enomoto 2021) and the frequency of blocking associated with Rossby wave breaking (Pavan et al. 2000; Rivière 2010). The monthly or seasonal geopotential height anomaly corresponding to the WP pattern was investigated in association with the El Niño–Southern Oscillation (ENSO). Observational evidence and numerical studies have shown that a positive (negative) WP pattern tends to appear more frequently when El Niño (La Niña) occurs (Horel and Wallace 1981; Ferranti et al. 1994; Trenberth et al. 1998; Koide and Kodera 1999; Dai and Tan 2019). However, a positive WP pattern has been observed not only in El Niño months but also in La Niña months (Tanaka et al. 2016). In this study, the positive WP pattern is defined as when the southern part of the dipole is high and the northern part is low. It has also been indicated that the emergence of the WP pattern, linked to ENSO, may be affected by anomalous circulation over the Eurasian continent during early winter (Kodera 1998). Tanaka et al. (2016) showed that the WP pattern could be sustained by baroclinic energy conversion associated with heat transport by energetic analysis based on monthly mean data and concluded that the WP pattern could be maintained even without external forcing.
As for the interannual variability of the East Asian winter monsoon, especially in air temperature over the Far East, a more effective north–south dipole pattern could shift slightly westward compared with that of the canonical WP pattern (Takaya and Nakamura 2013). Takaya and Nakamura (2013) referred to the upper-tropospheric pattern as the “WP-like” pattern. These facts indicate that WP-like dipole patterns can appear at slightly different positions from the action center shown by Wallace and Gutzler (1981), and its locality is an important factor influencing climate variability over East Asia.

The variability of the East Asian winter monsoon is closely related to the modulation of tropical convective activity over the Indo-western Pacific sector (Hong and Li 2009; Sakai and Kawamura 2009; Ueda et al. 2015; Abdillah et al. 2017; Kuramochi et al. 2021). They showed a southwest–northeast dipole pattern (or wave train) of circulation anomalies from southern China to Japan in the upper troposphere caused by anomalous diabatic heating around the Maritime Continent, which is a dominant spatial mode over Asia during the winter season (Zheng et al. 2013). For convenience, hereafter, we refer the southwest–northeast dipole pattern as the “southeast Asia–Japan (SAJ) pattern.” The SAJ pattern, especially in the southwestern portion of the dipole, is salient in the upper troposphere (~300–200 hPa); however, becomes obscure in the mid-troposphere (~500 hPa) (Ueda et al. 2015; Abdillah et al. 2017). This vertical structure seems to be consistent with the baroclinic mode of the heat-induced Rossby wave response (Gill 1980; Wu et al. 2015a, 2015b) and differs from the characteristics of the WP pattern.
The winter climate variability over East Asia is affected by both WP(-like) and SAJ patterns. The spatial distributions of the two types of dipole patterns differ, indicating dynamically different excitation mechanisms. Our main objective is to assess the structure and dynamics of the two teleconnection patterns.

In this study, we first focus on a change in air temperature from cold to warm over East Asia during the winter season in 2020/21, linked with the modulation of atmospheric circulation fields (Japan Meteorological Agency [JMA] 2021a, 2021b). Figure 1a shows the time series of the air temperature anomaly at 850 hPa averaged over East Asia [25°–45°N, 100°–140°E] from December 1, 2020, to February 28, 2021. The air temperature anomaly changed from negative to positive around January 14, 2021. In this study, we defined two periods: the colder period (Period 1: from December 13, 2020, to January 11, 2021) and the warmer period (Period 2: from January 23, 2021, to February 21, 2021). The anomalous coldness in Period 1 was associated with the SAJ pattern, while the warmth in Period 2 was the WP-like pattern, as discussed below in Section 3. The present study examines the difference between these two periods and the factor of air temperature transition from the teleconnection perspective; moreover, the inherent physical mechanism involved in the SAJ and WP(-like) patterns anchored with anomalous convection over the tropical western Pacific is investigated by comparing their differences.

2. Data and methods
The data used in this study were monthly mean and 6-hourly data from the Japanese 55-year Reanalysis dataset (JRA-55) with a horizontal resolution of 1.25° and 37 pressure levels (Kobayashi et al. 2015), daily data from the National Oceanic and Atmospheric Administration (NOAA) Interpolated Outgoing Longwave Radiation (OLR) dataset with a horizontal resolution of 2.5° (Liebmann and Smith 1996), and monthly mean sea surface temperature (SST) data from the Centennial in Observation-Based Estimate-SST (COBE-SST; Ishii et al. 2005) for December–February (DJF) during the 47 years from 1974/75 to 2020/21. To examine daily oceanic conditions, the NOAA Daily Optimum Interpolation SST (OISST; Reynolds et al. 2007) from 1981 to 2021 was also utilized. To abstract high-frequency components, an appropriate running mean was applied to the 6-hourly and daily data. In this study, climatological mean states were defined as the 47-year average during the study period (41-year average only for the OISST), and anomalies are defined as deviations from the climatological mean states.

The propagation of stationary Rossby wave packets was analyzed using the quasigeostrophic wave-activity flux defined by Takaya and Nakamura (2001). The horizontal component of the flux \( \mathbf{W} \) is defined as follows:

\[
\mathbf{W} = \frac{p}{2\sqrt{\bar{u}^2 + \bar{v}^2}} \left( \bar{u}(\psi_y'^2 - \psi_y'\psi_x'x) + \bar{v}(\psi_x'\psi_y' - \psi_x'\psi_y'x) + \bar{\psi}'(\psi_y'^2 - \psi_y'\psi_y') \right),
\]

(1)

where the overbar and prime denote the climatological state and anomaly, respectively, \( u \) is the zonal wind, \( v \) is the meridional wind, \( \psi \) is the geostrophic streamfunction, and \( p = (\text{pressure}/1000\text{hPa}) \). The subscripts \( x \) and \( y \) denote partial derivatives concerning
longitude and latitude, respectively.

To assess the role of tropical convection in the excitation and maintenance of circulation patterns, vorticity budget analysis was conducted. The linearized barotropic vorticity equation is written as follows (Sardeshmukh and Hoskins 1988):

\[
\frac{\partial \zeta'}{\partial t} = S' - \bar{v}_\psi \cdot \nabla \zeta' - v'_\psi \cdot \nabla \bar{\zeta} + R',
\]

where \( \zeta \) is the absolute vorticity, \( v_\psi \) is the rotational wind vector, and \( R' \) is the residual term, including the frictional term. \( S' \) is the so-called Rossby wave source (RWS) and is defined as follows:

\[
S' = -\nabla \cdot (v'_x \bar{\zeta}) - \nabla \cdot (\bar{v}_x \zeta') = -\bar{\zeta} D' - \bar{v}'_x \cdot \nabla \bar{\zeta} - \zeta' \bar{D} - \bar{v}_x \cdot \nabla \zeta',
\]

where \( v_x \) is the divergent wind vector and \( D = \nabla \cdot v_x \) is its divergence. The relatively small twisting and vertical advection terms were neglected. Because the second and third terms on the right-hand side of Eq. (2) are related to rotational winds (rotational terms), they represent wave propagation rather than wave source. Perturbation RWS is the convergence of the linearized vorticity flux associated only with the divergent wind component. The first term of Eq. (3) is the vorticity generation by anomalous horizontal divergence (anomalous divergence term; \( S_1 \)), and the second term is the advection of climatological vorticity by anomalous divergent wind (anomalous advection term; \( S_2 \)). The third and fourth terms represent the evolution of vorticity perturbation due to climatological divergence (climatological divergence term; \( S_3 \)) and advection of anomalous vorticity by climatological...
divergent wind (climatological advection term; \(S_4\)), respectively. The \(S_3\) term amplifies perturbations in regions where climatological winds converge (\(\bar{D} < 0\)) and damps perturbations in regions where they diverge (\(\bar{D} > 0\)).

To verify the linear response to tropical diabatic heating, we used the linear baroclinic model (LBM; Watanabe and Kimoto 2000). The LBM is a spectral model based on linearized primitive equations and has 20 sigma levels with a horizontal resolution of T42. The model employed del-forth horizontal diffusion, Rayleigh friction, and Newtonian thermal damping. The e–folding decay time of the diffusion coefficient was set to 4 h. The damping coefficient was set at two days for the lowest three levels, one day for the uppermost two levels, and 30 days elsewhere. The LBM was forced with externally imposed heating and time-integrated to a steady state. The details of the experimental settings, including the prescribed heating and background states, are mentioned in Section 4.2.

3. Turnabout of air temperature and two types of teleconnection patterns in winter 2020/21

3.1 Zonal shift of circulation anomaly linked with anomalous tropical convection

The first half of the winter of 2020/21 was colder than normal over East Asia. In contrast, the latter half became warmer (Fig. 1a). Figures 1b and 1c show circulation and temperature anomalies in the lower troposphere during the two defined periods. In Period 1, East Asia and Siberia were colder than the climatological state, and the anomalous northwesterly flow
was indicative of intensification of the East Asian winter monsoon, together with the deepened northern part of the Aleutian low. However, in Period 2, the cold air remained alive over northern Eurasia; nevertheless, the air temperature over East Asia became warmer than normal, which is associated with an anticyclonic circulation anomaly extending to Japan from the North Pacific. The remote influence of tropical modulations is suggested explaining the variation in air temperature anomalies.

One noteworthy feature of this winter was the continued La Niña condition, which can be seen from the negative values of the Niño-3.4 SST anomaly (Fig. 1a). Niño-3.4, a widely used index of ENSO, is defined as the averaged SST anomaly over the equatorial eastern Pacific [5°S–5°N, 170°E–120°W] (Trenberth 1997). The positive values of the SST anomaly in the Niño-WP [0°–10°N, 130°–150°E] (Hoell and Funk 2013) also exhibit La Niña conditions (Fig. 1a), which set up an easy-to-enhance environment for convection over the tropical western Pacific owing to the in situ anomalous warm SST. In a La Niña winter, the East Asian winter monsoon tends to be stronger than normal (Wang et al. 2000; Zhou and Wu 2010), although the air temperature over East Asia was warmer in the latter half of winter 2020/21. This inconsistency suggests that intraseasonal variability contributed to the dramatic turnabout of temperature anomalies, rather than prolonged SST anomalies.

The anomalies of the upper-tropospheric circulation and OLR, together with the wave-activity flux in the two periods, are shown in Figures 2a and 2b. The negative values of the OLR anomaly in the tropics correspond to the enhancement of tropical convection. In Period
1, anticyclonic and cyclonic circulation anomalies emerged over the region from the southeast of the Tibetan Plateau to southern China and over the northern part of Japan, respectively, exhibiting a southwest–northeast dipole pattern. The northeastward wave-activity flux emanating from the dipole’s southwestern anomaly indicates the propagation of stationary Rossby waves. In addition, southeastward propagation from the Caspian Sea to the northern part of India was confirmed. Concurrently, in the tropics, enhanced convection was discernible over the South China Sea toward the eastern Indian Ocean. These modulated atmospheric fields are responsible for the colder-than-normal conditions and heavy snowfall in Japan during winter 2020/21 (JMA 2021a) and are almost consistent with the features of the SAJ pattern as well as the typical mode of the cold East Asian winter (Hong and Li 2009; Sakai and Kawamura 2009; Ueda et al. 2015; Abdillah et al. 2017; Shiozaki and Enomoto 2021). Corresponding to the enhanced equatorial convection, anomalous divergent flows occurred in the upper troposphere over the Philippines and southern India (Fig. 2c).

In Period 2, the location of the anticyclonic anomaly around 30°N shifted eastward, causing anomalously warm conditions to associate with attenuated cold air outbreaks (Fig. 1). The meridional dipole pattern across the Japanese islands resembles the WP pattern (Fig. 2b), however, this pattern is referred to as the “WP-like” pattern in the present study because the southern anomaly of the dipole is located westward compared to the action center of the canonical WP pattern (160°E). Notably, the northern cyclonic anomaly was not
as clear as the southern anticyclonic anomaly. We could not find any noticeable wave packet propagation from upstream, which seems consistent with the WP-like blocking analyzed by Takaya and Nakamura (2005). The center of the enhanced convection was located from the Philippine Sea to Indonesia, and convective activity over the South China Sea toward the eastern Indian Ocean had already decayed. This zonal shift of the anomalous convection center on the intraseasonal timescale, such as the Madden-Julian oscillation (MJO: Madden and Julian 1972), can also be confirmed from the time–longitude cross-section (Fig. 3). The negative OLR anomaly persisted around 80°–120°E from mid-December 2020 until January 2021 (Period 1), and around 120°–150°E in February 2021 (Period 2). The MJO phase transition induces different upper-tropospheric circulations through modulated divergent fields (Cassou 2008; Seo and Son 2012). Thus, the anomalous divergence and its winds (Figs. 2c and 2d) likely caused the different positions of the subtropical anticyclonic anomaly of the dipole patterns between the two periods, which will be discussed in Subsection 3.2.

3.2 Vorticity budget analysis in the first and second halves of winter 2020/21

Figure 4 shows the climatological mean state of the upper troposphere over the western North Pacific region. The strong westerly jet and northward positive meridional gradient of absolute vorticity are the most important features in East Asia during winter (Fig. 4a). Moreover, the southern Tibetan Plateau in the upper troposphere is a very intense convergence area of winds associated with deep convection over the Indo-western Pacific.
sector (Fig. 4b). These unique background states play essential roles in anomalous vorticity generation in vorticity budget analysis.

The upper-tropospheric vorticity budget was determined based on the steady state of Eq. (2), that is,

$$0 \equiv S' + (\text{rotational terms}) + R'$$

$$= S_1 + S_2 + S_3 + S_4 + (\text{rotational terms}) + R'. \quad (4)$$

The distributions of the RWS and rotational terms in the upper troposphere based on the time mean data in Periods 1 and 2 are shown in Figures 5 and 6, respectively. Vorticity fields were applied weak horizontal smoothing. Emphasis is placed on the anomalous subtropical anticyclone that constitutes the southern part of the dipole pattern in each period. In Period 1, negative vorticity (anticyclonic) anomaly was evident over the southeastern Tibetan Plateau toward southern China (contours), which corresponds to the anomalous subtropical anticyclone (Fig. 2a). As shown in Figure 5a, a negative RWS was distributed over the western and northern parts of the anticyclonic vorticity anomaly. The negative RWS to the upstream of the anomalous anticyclone along the subtropical jet (25°–35°N) was almost balanced by the positive vorticity tendency seen in the rotational term (Fig. 5b). In the presence of strong westerlies, wave trains of perturbation cyclonic and anticyclonic circulations are responsible for the positive vorticity advection upstream of the anticyclonic anomaly and downstream of the cyclonic anomaly owing to the mean flow, which was larger than the vorticity advection by anomalous rotational wind corresponding to the $\beta$ term.
between the rotational terms in Eq. (2) (Fig. S1). The RWS (Fig. 5a) primarily arises from the stretching effect of anomalous divergence (S₁; Fig. 5c), and the advection term by anomalous divergent wind (S₂; Fig. 5d) also contributes to negative vorticity generation over the western portion of the anticyclonic vorticity anomaly by crossing the climatological jet northward. Here, note that the RWS, especially S₁, includes not only the effect of extratropical convergence of upper-tropospheric wind induced by enhanced tropical convection (Held and Kang 1987; Rasmusson and Mo 1993) but also the vorticity tendency associated with the stationary Rossby wave trains themselves to maintain their structure in the vertically sheared westerlies, which may be understood by quasi-geostrophic dynamics (Qin and Robinson 1993; Sekizawa et al. 2021). The latter refers to the vortex stretching effect balancing with the vorticity advection by mean flow under strong westerlies, as mentioned above (Lau 1979; Honda et al. 1999; Chen 2005). It is widely accepted that the advection of mean vorticity by upper-tropospheric divergent flow associated with anomalous equatorial heating (i.e., S₂) induces anticyclonic circulation (Sardeshmukh and Hoskins 1988; Jin and Hoskins 1995), which is an important factor in the generation of anomalous circulations also on intraseasonal timescales (Mori and Watanabe 2008; Seo and Lee 2017).

The climatological divergence term (S₃; Fig. 5e) is found over the center of the anticyclonic vorticity anomaly, which is related to vortex stretching due to the intense background convergence over the southern Tibetan Plateau (Fig. 4b) acting on the anomalous vorticity. S₃ seems to counterbalance S₁ over the center of the anomalous
vorticity rather than their nodes, canceling out the mutual stretching effect (Fig. 5c) because $S_3$ cannot balance with the rotational terms. The contribution of $S_3$ may explain the localized anomalous circulation over the southeastern Tibetan Plateau toward southern China when considering a steady state. Indeed, the climatological convergence region can produce a vorticity source on the perturbation vorticity (Sardeshmukh and Hoskins 1988; Trenberth et al. 1998), and its importance has been confirmed by numerical studies (Grimm and Silva 1995a, 1995b). The climatological advection term ($S_4$; Fig. 5f) dominated the southeastern part of the RWS, particularly the positive values around the anomalous anticyclone (Fig. 5a). This term acts to advect the circulation anomaly poleward.

During Period 2 (Fig. 6), the negative vorticity anomaly corresponding to the southern part of the WP-like pattern was located south of Japan. Again, we focused on subtropical anticyclonic anomalies. The RWS (Fig. 6a) counterbalanced the rotational terms (Fig. 6b) over the northwest of the anticyclonic vorticity anomaly. The anomalous divergence ($S_1$; Fig. 6c) and advection terms ($S_2$; Fig. 6d) were the main components of the RWS (Fig. 6a). While, the contributions of climatological divergence and its flow ($S_3$ and $S_4$) were small around the anomalous anticyclonic vorticity (Figs. 6e and 6f). The rotational terms were predominant in the southeastern portion of the vorticity anomaly owing to the strong westerly winds, which may have been compensated by the residuals.

4. Statistical analyses and numerical experiments
4.1 Composite analysis of the SAJ and WP-like patterns

Composite analysis was performed to obtain and compare the statistical characteristics of the SAJ and WP-like patterns. Here, we define two indices that represent the dipole patterns to extract and composite the teleconnection patterns. The index of the SAJ pattern is defined as the deviation of the normalized anomalous geopotential height at 250 hPa (Z250) averaged from the southeast of the Tibetan Plateau to southern China [20°–30°N, 80°–120°E] and the corresponding anomaly over northern Japan [40°–50°N, 130°–160°E], with reference to Ueda et al. (2015). The index of the WP-like pattern is defined as the deviation of the normalized Z250 anomaly averaged over the western North Pacific [20°–40°N, 130°–160°E] and over the Sea of Okhotsk [45°–65°N, 130°–160°E]. Thus, the northern-low southern-high height anomaly patterns correspond to positive phases. These two indices were calculated from the monthly mean data, and normalization was based on the standard deviation of each month. The wintertime months for which each index exceeded +1 (−1) standard deviation for the 141 (DJF × 47 years) calendar months were used as those for the positive (negative) phase of the dipole patterns. For the composite of the WP-like pattern, additional filtering was applied using the OLR anomaly averaged over the domain of 5°S–10°N, 120°–160°E, to determine whether convection was enhanced over the tropical western Pacific. In this analysis, we focused on the positive (negative) WP-like pattern accompanied by enhanced (suppressed) convection over the tropical western Pacific, such as in the case of winter 2020/21. Based on these criteria, 20 months (21
months) were selected as the positive (negative) SAJ pattern months and 11 months (9 months) were selected as the positive (negative) phase of the WP-like pattern accompanied by a negative (positive) OLR anomaly (Table 1). Interestingly, the months of the WP-like pattern were divided by almost half by OLR filtering.

Figure 7 shows the composite anomalies of geopotential height, OLR, and air temperature between the positive and negative phases based on the monthly mean data. The positive phase of the SAJ pattern was significantly correlated with enhanced convection over the Maritime Continent, and its maximum was discernible over the South China Sea (Fig. 7a). The anomalous northwesterly flow in the lower troposphere indicates an intensified East Asian winter monsoon, causing colder-than-normal conditions over the Far East (Fig. 7c). These features bear a considerable resemblance to those described in previous studies; however, the positions of the anomalous convection and northern circulation of the dipole in our results differ slightly from their results based on the DJF mean. When the SAJ index is applied to the DJF mean data (Fig. S2), the anomalous circulation was almost the same as that indicated previously (Zheng et al. 2013; Ueda et al. 2015; Abdillah et al. 2017).

The composited Z250 anomaly based on the WP-like index filtered with the OLR anomaly (Fig. 7b) is more zonally elongated than that of winter 2020/21 (Fig. 2b) and resembles the canonical WP pattern. The defined WP-like index is significantly correlated with the WP index defined at 500 hPa by Wallace and Gutzler (1981) (r = −0.89); note that the sign is the opposite. The weak baroclinic structure of the southern pole of the dipole as a southward tilt
with height (Figs. 7b and 7d) was consistent with that proposed by Tanaka et al. (2016).

Anomalous convective activity was distributed only around the Philippine Sea, and no modulated convection was confirmed over the eastern Indian Ocean and the Malay Peninsula (Fig. 7b), which may be important when considering the effective wave source. Cold anomalies were evident around the Sea of Okhotsk to the far eastern Siberia, and oppositely air temperatures over western Japan tended to be warmer, associated with anomalous southeasterly winds (Fig. 7d).

The correlation coefficients between the Z250 and ENSO indices are listed in Table 2. The SAJ pattern is correlated with ENSO, especially tropical western Pacific SST. These correlations became more potent on the seasonal (DJF) timescale. Indeed, the upper-tropospheric height anomaly over southern China, an action center of the SAJ pattern, is recognizable in the response to the wintertime ENSO (Wang et al. 2000; Shiozaki and Enomoto 2021). A recent study showed that SAJ-type anomalies tend to appear in the first winter of the multi-year La Niña, which is more influential on the East Asian air temperature than the second winter (Nishihira and Sugimoto 2022). In contrast, the WP-like index (not filtered) showed no significant correlation with ENSO.

4.2 Vorticity budget in the composite anomalies

In Section 3.2, it was implied that the SAJ and WP-like patterns were attributed to the different vorticity balances. We also performed the vorticity budget analysis for the
composited anomalies. Figure 8a shows a comparison of the vorticity tendency terms in Eq. 4, averaged over the center and upstream nodes of the subtropical anticyclonic anomaly in the positive phase of the SAJ pattern. At the center of the anomaly (heavy blue bars), the $S_3$ term counterbalances the $S_1$ term, which can be written as

$$S_1 + S_3 = -\bar{\zeta}D' - \zeta'\bar{D} \approx 0. \quad (5)$$

This balance is consistent with the case of winter 2020/21 mentioned in Section 3.2 (Fig. 5) and can be identified as important dynamics of the SAJ pattern. The positive $S_1$ is due to the anomalous convergence of winds ($D' < 0$) induced by the enhanced convection over the Maritime Continent (Fig. 7a). The climatological convergence area ($\bar{D} < 0$) requires anomalous negative vorticity to balance the positive vorticity tendency of the stationary eddy.

In contrast, the RWS term ($S'$) is balanced by the rotational terms (rot.) at the upstream nodes (light blue bars). The positive rotational terms represent the dominant vorticity advection from the upstream cyclonic anomaly by climatological mean flow, as shown in Figures 5b and S1a. Although the negative $S'$ term arises from $S_2$ and $S_3$ in the composite analysis (Fig. 8a), $S_1$ may also theoretically contribute to the balance with the rotational terms (e.g., Honda et al. 1999), as seen in the case of winter 2020/21 (Fig. 5c). The inherent vorticity budget of the anticyclonic perturbation over the southeast of the Tibetan Plateau is schematically summarized in Figure 8b.

Figure 9 shows the vorticity budget of the positive WP-like pattern accompanied by enhanced convection over the tropical western Pacific. Here, emphasis is placed on the
center of the subtropical eddy, however, the compositoed vorticity anomaly is zonally elongated and its center is unclear (upper panel of Fig. 9). The vorticity budget shows the predominant contributions of the rotational, $S_1$, and residual terms. The intense jet stream is responsible for the large magnitude of the rotational terms, and $S_1$ attempts to balance them.

The residual term may be associated with relatively short-period eddies. Indeed, Tanaka et al. (2016) and Sekizawa et al. (2021) indicate the importance of feedback forcing by submonthly and transient eddies in the maintenance of the WP(-like) pattern. Similar to the 2020/21 case (Fig. 6), the relatively small negative $S_2$ term represents advection by anomalous divergent winds induced by the enhanced convection over the Philippine Sea (Fig. 7b). The $S_3$ term is almost zero because of the in situ non-divergence of the background winds (Fig. 4b), which differs from the balance of the SAJ pattern (Fig. 8).

4.3 Sensitivity experiments using the LBM

The previous sections indicated that regionally different heating anomalies in the tropics could be responsible for the two types of teleconnection patterns. To confirm this hypothesis, sensitivity experiments for tropical convective heating were conducted using the LBM described by Watanabe and Kimoto (2000). We performed two experiments that differed only in the positions of the prescribed heating: one was over the South China Sea (the center was at 8°N, 110°E), and the other was over the Philippine Sea (the center was at 10°N, 135°E), which corresponded to the composited OLR peaks (Figs. 7a and 7b). The imposed
heating exhibited an oval shape, with its heating maxima at its center (as shown in Fig. 10). The heating also had a vertical structure that peaked at $\sigma = 0.45$, where the maximum heating rate was approximately $+1.0 \, \text{K day}^{-1}$, which imitated the vertical profile of the composite anomalous diabatic heating calculated as the residual of the thermodynamic equations (Yanai et al. 1973). The background atmospheric state was DJF climatology derived from JRA-55, and the response on day 15 is shown when the model reached a quasi-steady state.

Figure 10 shows the steady response of the upper troposphere to imposed tropical heating. The response to South China Sea heating roughly reproduced the wave train of height anomalies corresponding to the SAJ pattern (Fig. 10a). The anomalous anticyclone north of the Indian subcontinent could be interpreted as the western margins of the Matsuno-Gill type heat-induced atmospheric response (Matsuno 1966; Gill 1980) when the vertical gradient of the heating is considered (Wu et al. 2015a). It should be noted here that the anticyclone seen in the geopotential height field locates slightly westward in comparison with the reanalysis (Fig. 7a). This may be partly due to lack of extratropical forcing as well as a model bias (Tseng et al. 2020). The vorticity balance indicated in the present study (Figs. 5 and 8) is inherently caused by the combined effect of climatological mean flows and external forcing. Hence, the SAJ-like steady perturbation vorticity tends to emerge over the region of convergence area of winds and under the subtropical jet in the climatological mean (Fig. 4).

As for the atmospheric response to heating over the Philippine Sea (Fig. 10b), the positive
height anomaly is recognizable to the south of Japan. Its position is the same as that of the southern part of the WP-like pattern. Note that the northern cyclonic anomaly of the WP(-like) pattern was not clearly reproduced.

The noteworthy difference between the results of the two experiments is the subsequent steady positions of the generated anticyclonic anomalies, although the imposed heat sources were only 25° longitude apart from each other. If we pay attention to its time evolution, after the anticyclone was generated over the northwest of the heat source as a first response in the South China Sea experiment, it shifted northward and consequently stayed north of the Indian subcontinent (Figs. 10a and S3). Similarly, the anticyclonic anomaly seen in the results of the Philippine Sea experiment was also first generated northwest of the heat source, after which, however, it moved northeastward and stayed north of the heat source (Figs. 10b and S3). These meridional shifts of the anomalous circulations may be explained by the effects of the background divergent wind. As mentioned in the RWS analysis, the climatological divergent flow advects the anomalous vorticity poleward in the subtropics (S4, Figs. 5 and 6). Using numerical experiments, Sekizawa et al. (2021) demonstrated that poleward vorticity advection is an essential role of the background divergent wind in the establishment of the subtropical anomalous anticyclone. Based on this idea, the additional eastward shift of the anomalous anticyclone of the WP(-like) pattern can be attributed to advection by the background jet core represented by the rotational terms in Eq. (2). Thus, it is suggested that the unique background winds, as well as the regionally
different anomalous heating, are responsible for the significantly different steady locations of the anomalous anticyclones and the related teleconnection patterns.

5. Discussion

5.1 Significance of the SAJ pattern

The wave train pattern referred to as the SAJ pattern in this study had been indicated in association with East Asian climate variability during winter in previous research. To confirm its significance for the interannual variability of atmospheric circulation in Asia, we performed an empirical orthogonal function (EOF) analysis to the seasonal (DJF) mean Z250 over the domain of 10°S–70°N, 10°–180°E, including the tropical and extratropical upstream regions. The spatial distributions of the anomalies of streamfunction and OLR corresponding to the first (EOF1) and second EOF modes (EOF2) are illustrated in Figure 11. EOF1 explained approximately 23.4% of the total variance for the period 1974/75–2020/21, while EOF2 explained approximately 20.0%. The anomalies of upper-tropospheric circulation and convective activity associated with EOF1 resemble those based on the SAJ index (Figs. 7a, 7c, and S2). The correlation coefficient between the seasonal mean SAJ index and EOF1 is 0.74. Furthermore, EOF1 is similar to the height anomalies associated with the dominant variation of the East Asian winter monsoon (Sakai and Kawamura 2009) and rainfall over the Indo-western Pacific sector (Zheng et al. 2013). In addition, we noticed a similar anomaly around southern China in EOF2 (Fig. 11b) although its amplitude is smaller than that of
EOF1. These results imply that the region from the southeast of the Tibetan Plateau to southern China is an important fluctuation center of the upper-tropospheric circulation from the teleconnection perspective, which may be attributed to the intense background convergence of winds as well as the climatological subtropical jet (Figs. 4, 5, and 8).

It should be pointed out that the circulation anomalies around Japan of EOF1 and EOF2 differ remarkably from each other (Figs. 11a and 11b), despite the similar anomaly of convective activity around the Maritime Continent and the resultant anomalous circulation over southern China (Figs. 11c and 11d). The wave train northeastward from the Maritime Continent via Japan to the Kamchatka Peninsula seen in EOF2 (Fig. 11b) can be identified as a WP(-like) pattern accompanied by anomalous circulation over southern China rather than the SAJ pattern. The circulation anomaly over southern China can form the WP(-like) pattern by acting as a vorticity source for the emanation of northeastward-propagating stationary waves. Indeed, the modulated circulation field of EOF2 bears a striking resemblance to the geopotential height anomalies associated with variation in the Australian summer monsoon (Sekizawa et al. 2021) and El Niño (Shiozaki et al. 2021), which were reported to induce a circulation anomaly over southern China and the subsequent WP pattern. The OLR anomaly of EOF2 consistently extended to the Southern Hemisphere (Fig. 11d) compared to that of EOF1.

An essential difference between EOF1 and EOF2 appears to be the wave train at higher latitudes. In EOF1 (Fig. 11a), the wave train along the polar jet from northern Europe via
Siberia to Japan can be identified as the Eurasian (EU) pattern (Wallace and Gutzler 1981). The EU pattern shares the anomalous circulation over Japan with the SAJ pattern. It is suggested that this coherent amplification along the polar and subtropical jets is an important factor in generating the different circulation anomalies over Japan compared with EOF2. To assess the relationship between the wave propagation along the two main jet streams is awaited, which are linked with the EU and SAJ patterns respectively.

5.2 Relationship between the WP(-like) pattern and the tropical modulations

As for the controversial issue regarding the WP pattern, its linkage with tropical variations such as ENSO remains unsolved. As shown in Table 1, not all of the positive (negative) WP-like patterns were caused by enhanced (suppressed) convection in the south. Thus, the correlation with tropical modulations is unclear (Table 2). Nevertheless, it is still influential in determining the phase of the WP pattern that is likely to be triggered (Tanaka et al. 2016; Dai and Tan 2019). Our study provides a possible mechanism by which tropical modulation directly induces the WP(-like) pattern by providing a wave source for the southern portion of the dipole.

The anomalous circulation associated with EOF2 indicates another type of WP(-like) pattern concurrent with the opposite convection anomaly, that is, the cyclonic anomaly of the southern part of the dipole against the enhanced convection over the tropical western Pacific (Figs. 11b and 11d). As mentioned in the preceding subsection, this WP(-like) pattern
is accompanied by an anticyclonic circulation anomaly over southern China and intensified heating around the Maritime Continent. The anomalous circulation over southern China could be an important factor in generating the WP(-like) anomaly (Sekizawa et al. 2021).

Thus, in the case of EOF2, the enhanced convection around the Maritime Continent might indirectly induce the negative WP(-like) pattern through wave propagation. The relationship between the phase of the WP(-like) pattern and convective activity over the tropical western Pacific should be surveyed in greater detail in future studies.

6. Summary

In this study, the modulated atmospheric circulation associated with the turnabout of air temperature anomalies over East Asia between the first and latter halves of the winter of 2020/21 was examined. In the colder-than-normal first half, a pair of anticyclonic and cyclonic circulation anomalies appeared in the upper troposphere over the southeastern Tibetan Plateau and northern Japan, respectively. This southwest–northeast dipole pattern (referred to as the SAJ pattern in this study) was accompanied by enhanced convection over the South China Sea toward the eastern Indian Ocean and the stationary Rossby wave propagation along the subtropical jet. However, in the latter half of winter, the anticyclonic anomaly in the subtropics shifted to the south of Japan, and the resultant meridional dipole was identified as the WP-like pattern. It altered the cold airflow around East Asia, causing warmer-than-normal conditions. Simultaneously, the center of the reinforced convection
shifted eastward to the Philippine Sea. The subsequent divergence and flow between the two periods related to the intraseasonal eastward shift of convective activity induced different anomalous vorticity fields in the upper troposphere, satisfying each vorticity balance.

Further analysis revealed the inherent spatial structures and dynamics of the two teleconnection patterns. The composite analysis showed that the SAJ pattern significantly influenced the East Asian winter monsoon, and the magnitude of the anomalous air temperature around the Sea of Japan was larger than that of the WP-like pattern. The center of the modulated convection emerged over the South China Sea when the SAJ pattern appeared on the monthly timescale. The dynamical structures of the SAJ pattern, focusing on the vorticity balance of the anticyclonic anomaly corresponding to the southwestern pole of the dipole, are schematically shown in Figure 8b. Anomalous diabatic heating around the Maritime Continent induces an anticyclonic anomaly in the upper troposphere southeast of the Tibetan Plateau with the aid of climatological divergent winds advecting the anomalous vorticity poleward ($S_4$). At the center of the anticyclonic eddy, the negative vorticity perturbation on the climatological convergence of winds ($S_3$) counterbalances the anomalous convergence associated with the enhanced convection ($S_1$). The negative vorticity advection by anomalous divergent flows crossing the subtropical jet northward ($S_2$) acts to compensate for the positive advection by the mean rotational winds (rot.), together with anomalous divergence to maintain the wave train structure in the upstream nodes of the eddy. The anticyclonic anomaly is responsible for the cyclonic anomaly around Japan.
through the propagation of stationary Rossby waves. The vorticity budget suggests the critical role of the background convergence of the winds over the southeast of the Tibetan Plateau in the emergence and maintenance of the spatially phase-locked anomaly of the SAJ pattern.

In contrast, half of the positive (negative) WP-like patterns were accompanied by enhanced (suppressed) convection over the Philippine Sea, which could directly induce the southern pole of the WP-like pattern. The dominant vorticity advection by the rotational winds and residual terms played essential roles in the vorticity balance of the WP-like pattern. The results of the LBM experiments support the regionally different heat sources and background winds responsible for the two types of teleconnection patterns.

Although we attempted to understand the wintertime climate variability over East Asia in relation to some teleconnection patterns, especially from the perspective of tropical forcing, it is also necessary to investigate it from mid- and higher latitudes. Further studies focusing on tropical–extratropical interactions are required to better understand the dynamics of teleconnections and to improve seasonal forecasting.

Data Availability Statement

The JRA-55 and COBE-SST datasets are provided by JMA (https://jra.kishou.go.jp/JRA-55/index_en.html; https://ds.data.jma.go.jp/tcc/tcc/index.html), the Interpolated OLR and OISST datasets by NOAA PSL (https://psl.noaa.gov/). Documents and codes for the LBM
are available at [https://ccsr.aori.u-tokyo.ac.jp/lbm/sub/lbm.html].

**Supplement**

Supplement 1 shows spatial distributions of decomposed rotational terms in Eq. (2) and the $\beta$ term during Period 1. Supplement 2 shows Z250 anomaly associated with the DJF mean SAJ index. Supplement 3 shows time evolution of upper-tropospheric circulation anomalies in the LBM experiments.

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**References**

Abdillah, M. R., Y. Kanno, and T. Iwasaki, 2017: Tropical–extratropical interactions associated with East Asian cold air outbreaks. Part I: Interannual variability, *J. Climate*, 30,
Cassou, C., 2008: Intraseasonal interaction between the Madden–Julian oscillation and the North Atlantic oscillation. Nature, 455, 523–527.

Chen, T.-C., 2005: The structure and maintenance of stationary waves in the winter Northern Hemisphere. J. Atmos. Sci., 62, 3637–3660.

Dai, Y., and B. Tan, 2019: Two types of the western Pacific pattern, their climate impacts, and the ENSO modulations. J. Climate, 32, 823–841.

Ferranti, L., F. Molteni, and T. N. Palmer, 1994: Impact of localized tropical and extratropical SST anomalies in ensembles of seasonal GCM integrations. Quart. J. Roy. Meteor. Soc., 120, 1613–1645.

Gill, A. E., 1980: Some simple solutions for heat-induced tropical circulation. Quart. J. Roy. Meteor. Soc., 106, 447–462.

Grimm, A. M., and P. L. Silva Dias, 1995a: Use of barotropic models in the study of the extratropical response to tropical heat sources. J. Meteor. Soc. Japan, 73, 765–780.

Grimm, A. M., and P. L. Silva Dias, 1995b: Analysis of tropical extratropical interactions with influence functions of a barotropic model. J. Atmos. Sci., 52, 3538–3555.

Held, I. M., and I.-S. Kang, 1987: Barotropic models of the extratropical response to El Niño. J. Atmos. Sci., 44, 3576–3586.

Hoell, A., and C. Funk, 2013: The ENSO-related west Pacific sea surface temperature gradient. J. Climate, 26, 9545–9562.
Honda, M., K. Yamazaki, H. Nakamura, and K. Takeuchi, 1999: Dynamic and thermodynamic characteristics of atmospheric response to anomalous sea-ice extent in the Sea of Okhotsk. *J. Climate*, **12**, 3347–3358.

Hong, C-C., and T. Li, 2009: The extreme cold anomaly over Southeast Asia in February 2008: roles of ISO and ENSO. *J. Climate*, **22**, 3786–3801.

Horel, J. D., and J. M. Wallace, 1981: Planetary-scale atmospheric phenomena associated with the Southern Oscillation. *Mon. Wea. Rev.*, **109**, 813–829.

Ishii, M., A. Shouji, S. Sugimoto, and T. Matsumoto, 2005: Objective analyses of sea-surface temperature and marine meteorological variables for the 20th century using ICOADS and the Kobe Collection. *Int. J. Climatol.*, **25**, 865–879.

Jin, F-F., and B. J. Hoskins, 1995: The direct response to tropical heating in a baroclinic atmosphere. *J. Atmos. Sci.*, **52**, 307–319.

JMA, 2021a: Factors behind the heavy snowfall and low temperatures in Japan from mid-December 2020 onward and weather outlook (Available online at: http://ds.data.jma.go.jp/tcc/tcc/news/press_20210115.pdf, accessed 23 February 2022).

JMA, 2021b: TCC News No. 64: Summary of the 2020/2021 Asian winter monsoon (Available online at http://ds.data.jma.go.jp/tcc/tcc/news/tccnews64.pdf, accessed 23 February 2022).

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka, and K. Takahashi, 2015: The JRA-55 Reanalysis:
General specifications and basic characteristics. *J. Meteor. Soc. Japan*, 93, 5–48.

Kodera, K., 1998: Consideration of the origin of the different midlatitude atmospheric responses among El Niño events. *J. Meteor. Soc. Japan*, 76, 347–361.

Koide, H., and K. Kodera, 1999: A SVD analysis between the winter NH 500-hPa height and surface temperature fields. *J. Meteor. Soc. Japan*, 77, 47–61.

Kuramochi, M., H. Ueda, C. Kobayashi, Y. Kamae, and K. Takaya, 2021: Anomalous warm winter 2019/2020 over East Asia associated with trans-basin Indo-Pacific connections. *SOLA*, 17B, 9–13.

Lau, N-C., 1979: The observed structure of tropospheric stationary waves and the local balances of vorticity and heat. *J. Atmos. Sci.*, 36, 996–1016.

Liebmann B., and C. A. Smith, 1996: Description of a complete (interpolated) outgoing longwave radiation dataset. *Bull. Amer. Meteor. Soc.*, 77, 1275–1277.

Madden, R. A., and P. R. Julian, 1972: Description of global-scale circulation cells in the tropics with a 40–50 day period. *J. Atmos. Sci.*, 29, 1109–1123.

Matsuno, T., 1966: Quasi-geostrophic motions in the equatorial area. *J. Meteor. Soc. Japan*, 44, 25–43.

Mori, M., and M. Watanabe, 2008: The growth and triggering mechanisms of the PNA: A MJO-PNA coherence. *J. Meteor. Soc. Japan*, 86, 213–236.

Nishihira, G., and S. Sugimoto, 2022: Severe cold winters in East Asia linked to first winter of La Niña events and in North America linked to second winter. *Geophys. Res. Lett.*, 49,
Park, H.-J., and J.-B. Ahn, 2016: Combined effect of the Arctic oscillation and the western
Pacific pattern on East Asia winter temperature. *Climate Dyn.*, **46**, 3205–3221.

Pavan, V., S. Tibaldi, and Č Branković, 2000: Seasonal prediction of blocking frequency:
Results from winter ensemble experiments. *Quart. J. Roy. Meteor. Soc.*, **126**, 2125–2142.

Qin, J., and W. A. Robinson, 1993: On the Rossby wave source and the steady linear
response to tropical forcing. *J. Atmos. Sci.*, **50**, 1819–1823.

Rasmusson, E. M., and K. Mo, 1993: Linkages between 200-mb tropical and extratropical
circulation anomalies during the 1986–1989 ENSO cycle. *J. Climate*, **6**, 595–616.

Reynolds, R. W., T. M. Smith, C. Liu, D. B. Chelton, K. S. Casey, and M. G. Schlax, 2007:
Daily high-resolution-blended analyses for sea surface temperature. *J. Climate*, **20**, 5473–
5496.

Rivière, G., 2010: Role of Rossby wave breaking in the west Pacific teleconnection.
*Geophys. Res. Lett.*, **37**, L11802, doi:10.1029/2010GL043309.

Sakai, K., and R. Kawamura, 2009: Remote response of the East Asian winter monsoon to
tropical forcing related to El Niño–Southern oscillation. *J. Geophys. Res.*, **114**, D06105,
doi:10.1029/2008JD010824.

Sardeshmukh, P. D., and B. J. Hoskins, 1988: The generation of global rotational flow by
steady idealized tropical divergence. *J. Atmos. Sci.*, **45**, 1228–1251.

Sekizawa, S., H. Nakamura, and Y. Kosaka, 2021: Remote influence of the interannual
variability of the Australian summer monsoon on wintertime climate in East Asia and the western North Pacific, *J. Climate*, **34**, 9551–9570.

Seo, K.-H., and S.-W. Son, 2012: The global atmospheric circulation response to tropical diabatic heating associated with the Madden–Julian oscillation during northern winter. *J. Atmos. Sci.*, **69**, 79–96.

Seo, K.-H., and H.-J. Lee, 2017: Mechanisms for a PNA-like teleconnection pattern in response to the MJO. *J. Atmos. Sci.*, **74**, 1767–1781.

Shiozaki, M., T. Enomoto, and K. Takaya, 2021: Disparate midlatitude responses to the eastern Pacific El Niño. *J. Climate*, **34**, 773–786.

Shiozaki, M., and T. Enomoto, 2021: Two types of mid-latitudes responses during La Niña. *SOLA*, **17**, 103–108.

Takaya, K., and H. Nakamura, 2001: A formulation of a phase-independent wave-activity flux for stationary and migratory quasigeostrophic eddies on a zonally varying basic flow. *J. Atmos. Sci.*, **58**, 608–627.

Takaya, K., and H. Nakamura, 2005: Geographical dependence of upper-level blocking formation associated with intraseasonal amplification of the Siberian high. *J. Atmos. Sci.*, **62**, 4441–4449.

Takaya, K., and H. Nakamura, 2013: Interannual variability of the East Asian winter monsoon and related modulations of the Planetary waves. *J. Climate*, **26**, 9445–9461.

Tanaka, S., K. Nishii, and H. Nakamura, 2016: Vertical structure and energetics of the
western Pacific teleconnection pattern. *J. Climate*, **29**, 6597–6616.

Trenberth, K. E., 1997: The definition of El Niño. *Bull. Amer. Meteor. Soc.*, **78**, 2771–2777.

Trenberth, K. E., G. W. Branstator, D. Karoly, A. Kumar, N. C. Lau, and C. Ropelewski, 1998: Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures. *J. Geophys. Res.*, **103**, 14291–14324.

Tseng, K., E. Maloney, and E. A. Barnes, 2020: The consistency of MJO teleconnection patterns on interannual time scales. *J. Climate*, **33**, 3471–3486.

Ueda, H., A. Kibe, M. Saitoh, and T. Inoue, 2015: Snowfall variations in Japan and its linkage with tropical forcing. *Int. J. Climatol.*, **35**, 991–998.

Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.*, **109**, 784–812.

Wang, B., R. Wu, and X. Fu, 2000: Pacific–East Asian teleconnection: How does ENSO affect East Asian climate? *J. Climate*, **13**, 1517–1536.

Watanabe, M., and M. Kimoto, 2000: Atmosphere-ocean thermal coupling in the North Atlantic: a positive feedback. *Quart. J. Roy. Meteor. Soc.*, **126**, 3343–3369.

Wu, G., B. He, Y. Liu, Q. Bao, and R. Ren, 2015a: Location and variation of the summertime upper-troposphere temperature maximum over South Asia. *Climate Dyn.*, **45**, 2757–2774.

Wu, G., A. Duan, Y. Liu, J. Mao, R. Ren, Q. Bao, B. He, B. Liu, and W. Hu, 2015b: Tibetan Plateau climate dynamics: recent research progress and outlook. *National Science Review*, **2**, 100–116.
Yanai, M., S. Esbensen, and J. H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *J. Atmos. Sci.*, **30**, 611–627.

Zheng, J., Q. Liu, C. Wang, and X.-T. Zheng, 2013: Impact of heating anomalies associated with rainfall variations over the Indo-western Pacific on Asian atmospheric circulation in winter. *Climate Dyn.*, **40**, 2023–2033.

Zhou, L. T., and R. Wu, 2010: Respective impacts of the East Asian winter monsoon and ENSO on winter rainfall in China. *J. Geophys. Res.*, **115**, D02107, doi:10.1029/2009JD012502.
Fig. 1 (a) Time series of 5-day running mean air temperature anomaly at 850 hPa over East Asia [25°–45°N, 100°–140°E] (red and blue shading) and SST indices (blue and orange lines) (unit: °C). The indices are defined as SST anomalies averaged as follows: in Niño-3.4 as [5°S–5°N, 170°E–120°W]; and in Niño-WP as [0°–10°N, 130°E–150°E]. (b) Anomalies of streamfunction (contours; unit: $10^6$ m$^2$ s$^{-1}$), air temperature (shading; unit: °C), and horizontal wind (vectors; unit: m s$^{-1}$) at 850 hPa averaged in Period 1 (December 13, 2020–January 11, 2021). (c) Same as (b) but for Period 2 (January 23, 2021–February 21, 2021). Purple rectangle indicates the East Asia region in this study.

Fig. 2 (a) Averaged anomalies of streamfunction (contours with an interval of $3.0 \times 10^6$ m$^2$ s$^{-1}$) at 250 hPa and OLR (shading; unit: W m$^{-2}$) in Period 1. Gray vectors indicate the wave-activity flux (unit: m$^2$ s$^{-2}$) at 250 hPa. (b) Same as (a), but for Period 2. (c) Averaged anomalies of velocity potential (contours; unit: $10^6$ m$^2$ s$^{-1}$) and divergent wind (vectors; unit: m s$^{-1}$) at 200 hPa in Period 1. (d) Same as (c) but for Period 2. Scale for arrows is given on the lower-right side.

Fig. 3 Time–longitude cross sections of 7-day running mean OLR anomaly averaged over the tropics 10°S–10°N in the Indo–Pacific region during the winter of 2020/21. The unit is...
Fig. 4 DJF climatological mean (a) absolute vorticity (shading; unit: $10^{-5}$ s$^{-1}$), zonal wind (white contours; unit: m s$^{-1}$), (b) divergence of wind (shading; unit: $10^{-6}$ s$^{-1}$), and divergent wind (vectors; unit: m s$^{-1}$) at 250 hPa. Scale for arrows is given on the lower-right side.

Fig. 5 (a) RWS and (b) rotational terms in Eq. (2) based on time-averaged flow at 250 hPa in Period 1 (shading). (c)–(f) Decomposition of RWS into (c) anomalous divergence term ($S_1; -\bar{\zeta} \tilde{D}'$), (d) anomalous advection term ($S_2; -\mathbf{v}' \cdot \nabla \bar{\zeta}$), (e) climatological divergence term ($S_3; -\tilde{\zeta}' \bar{D}$), and (f) climatological advection term ($S_4; -\bar{\mathbf{v}} \cdot \nabla \tilde{\zeta}'$) in Eq. (3). Intervals of shading are $0.4 \times 10^{-10}$ s$^{-2}$. Black contours indicate vorticity anomaly averaged in the period (unit: $10^{-5}$ s$^{-1}$).

Fig. 6 Same as Fig. 5, but for Period 2.

Fig. 7 (a) Composited deviations of geopotential height (contours; unit: m) at 250 hPa and OLR (shading; unit: W m$^{-2}$) between the 20 strongest positive months and the 21 negative months of the SAJ index. (b) Same as (a), but for the deviations between the 11 strongest positive months and the 9 negative months of the WP-like index which satisfied the criteria of tropical convection (see text for definitions of the indices and details of the criteria).
Rectangles indicate regions used for the indices. (c, d) Same as (a, b), respectively, but for geopotential height (contours; unit: m), air temperature (shading; unit: °C), and horizontal wind (vectors; unit: m s\(^{-1}\)) at 850 hPa. Black dots indicate statistical significance at the 95% level of the shading quantities. Vectors are plotted only where the zonal or meridional component is statistically significant at the 95% confidence level.

Fig. 8 (a) (Upper) Composited anomaly of vorticity at 250 hPa in the positive months of the SAJ index. Solid and dashed contours with an interval of \(1.0 \times 10^{-5}\) s\(^{-1}\) indicate positive and negative values, respectively, and zero contours are omitted. Heavy solid and light dashed color rectangles denote the region of the center [20°–30°N, 90°–110°E] and upstream node [20°–30°N, 75°–95°E] of the anticyclonic eddy, respectively. (Lower) Area-averaged vorticity tendency terms at 250 hPa based on Eq. (4) (unit: \(10^{-10}\) s\(^{-2}\)). Heavy and light color bars indicate the center and upstream node of the eddy. (b) Schematic of the vorticity budget of the anticyclonic eddy (AC’) over the southeast of the Tibetan Plateau in the upper troposphere associated with the positive phase of the SAJ pattern. Underlines denote the negative value of the term in the vorticity balance. See the text in Sections 4.3 and 6 for the detail.

Fig. 9 (Upper) Composited anomaly of vorticity at 250 hPa in the positive months of the WP-like index satisfied with the OLR– criteria. Solid and dashed contours with an interval of
1.0 × 10⁻⁵ s⁻¹ indicate positive and negative values, respectively, and zero contours are omitted. Rectangle denotes the area-averaged region [20°–30°N, 130°–160°E]. (Lower) Area-averaged vorticity tendency terms at 250 hPa based on Eq. (4) (unit: 10⁻¹⁰ s⁻²).

Fig. 10 Atmospheric response on day 15 in the LBM to the prescribed heating centered at (a) the South China Sea (8°N, 110°E) and (b) the Philippine Sea (10°N, 135°E). The geopotential height at 250 hPa are plotted (contour intervals: 2.0 m). Purple solid contours indicate prescribed heating (+0.6 K day⁻¹ and +0.3 K day⁻¹) at σ = 0.45. Black dots are the anticyclone center specified as the maximum of the streamfunction at 250 hPa on days 1, 2, 3, 5, 10, and 15 in the LBM. The numbers near the dots denote the days.

Fig. 11 Upper-tropospheric perturbation associated with the EOF modes of the interannual variation of geopotential height at 250 hPa over Asia [10°S–70°N, 10°–180°E] from 1974/75 to 2020/21. Black contours denote regression coefficients between the streamfunction at 250 hPa and the (a) first and (b) second principal component indices (unit: 10⁶ m² s⁻¹). Red and blue shading denote positive and negative correlation exceeding the 90% confidence level, respectively. (c, d) Same as (a, b), respectively, but for OLR (shading; unit: W m⁻²). Black dots indicate statistical significance at the 90% level. The signs of second mode were adjusted to the opposite.
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Fig. 3 Time–longitude cross sections of 7-day running mean OLR anomaly averaged over the tropics 10°S–10°N in the Indo–Pacific region during the winter of 2020/21. The unit is W m\(^{-2}\).
Fig. 4 DJF climatological mean (a) absolute vorticity (shading; unit: $10^{-5}$ s$^{-1}$), zonal wind (white contours; unit: m s$^{-1}$), (b) divergence of wind (shading; unit: $10^{-6}$ s$^{-1}$), and divergent wind (vectors; unit: m s$^{-1}$) at 250 hPa. Scale for arrows is given on the lower-right side.
Fig. 5 (a) RWS and (b) rotational terms in Eq. (2) based on time-averaged flow at 250 hPa in Period 1 (shading). (c)–(f) Decomposition of RWS into (c) anomalous divergence term \((S_1; -\bar{\zeta} \bar{D}')\), (d) anomalous advection term \((S_2; -\mathbf{v}' \cdot \nabla \bar{\zeta})\), (e) climatological divergence term \((S_3; -\zeta' \bar{D})\), and (f) climatological advection term \((S_4; -\bar{\mathbf{v}}' \cdot \nabla \zeta')\) in Eq. (3). Intervals of shading are \(0.4 \times 10^{-10} \text{ s}^{-2}\). Black contours indicate vorticity anomaly averaged in the period (unit: \(10^{-5} \text{ s}^{-1}\)).
Fig. 6  Same as Fig. 5, but for Period 2.
Fig. 7 (a) Composited deviations of geopotential height (contours; unit: m) at 250 hPa and OLR (shading; unit: W m$^{-2}$) between the 20 strongest positive months and the 21 negative months of the SAJ index. (b) Same as (a), but for the deviations between the 11 strongest positive months and the 9 negative months of the WP-like index which satisfied the criteria of tropical convection (see text for definitions of the indices and details of the criteria). Rectangles indicate regions used for the indices. (c, d) Same as (a, b), respectively, but for geopotential height (contours; unit: m), air temperature (shading; unit: °C), and horizontal wind (vectors; unit: m s$^{-1}$) at 850 hPa. Black dots indicate statistical significance at the 95% level of the shading quantities. Vectors are plotted only where the zonal or meridional component is statistically significant at the 95% confidence level.
Fig. 8 (a) (Upper) Composited anomaly of vorticity at 250 hPa in the positive months of the SAJ index. Solid and dashed contours with an interval of $1.0 \times 10^{-5}$ s$^{-1}$ indicate positive and negative values, respectively, and zero contours are omitted. Heavy solid and light dashed color rectangles denote the region of the center [$20^\circ$–$30^\circ$N, $90^\circ$–$110^\circ$E] and upstream node [$20^\circ$–$30^\circ$N, $75^\circ$–$95^\circ$E] of the anticyclonic eddy, respectively. (Lower) Area-averaged vorticity tendency terms at 250 hPa based on Eq. (4) (unit: $10^{-10}$ s$^{-2}$). Heavy and light color bars indicate the center and upstream node of the eddy. (b) Schematic of the vorticity budget of the anticyclonic eddy (AC') over the southeast of the Tibetan Plateau in the upper troposphere associated with the positive phase of the SAJ pattern.
Underlines denote the negative value of the term in the vorticity balance. See the text in Sections 4.3 and 6 for the detail.
Fig. 9 (Upper) Composited anomaly of vorticity at 250 hPa in the positive months of the WP-like index satisfied with the OLR− criteria. Solid and dashed contours with an interval of $1.0 \times 10^{-5}$ s$^{-1}$ indicate positive and negative values, respectively, and zero contours are omitted. Rectangle denotes the area-averaged region [20°–30°N, 130°–160°E]. (Lower) Area-averaged vorticity tendency terms at 250 hPa based on Eq. (4) (unit: $10^{-10}$ s$^{-2}$).
Fig. 10 Atmospheric response on day 15 in the LBM to the prescribed heating centered at
(a) the South China Sea (8°N, 110°E) and (b) the Philippine Sea (10°N, 135°E). The
geopotential height at 250 hPa are plotted (contour intervals: 2.0 m). Purple solid contours
indicate prescribed heating (+0.6 K day$^{-1}$ and +0.3 K day$^{-1}$) at $\sigma = 0.45$. Black dots are
the anticyclone center specified as the maximum of the streamfunction at 250 hPa on
days 1, 2, 3, 5, 10, and 15 in the LBM. The numbers near the dots denote the days.
Fig. 11 Upper-tropospheric perturbation associated with the EOF modes of the interannual variation of geopotential height at 250 hPa over Asia [10°S–70°N, 10°–180°E] from 1974/75 to 2020/21. Black contours denote regression coefficients between the streamfunction at 250 hPa and the (a) first and (b) second principal component indices (unit: 10^6 m^2 s^{-1}). Red and blue shading denote positive and negative correlation exceeding the 90% confidence level, respectively. (c, d) Same as (a, b), respectively, but for OLR (shading; unit: W m^{-2}). Black dots indicate statistical significance at the 90% level. The signs of second mode were adjusted to the opposite.
Table 1 The months that the SAJ and WP-like indices exceeded +1 (-1) standard deviation.

The 20 positive SAJ months and 21 negative SAJ months were used for the composite analysis of the SAJ pattern. The 11 positive WP-like with OLR− months and 9 negative WP-like with OLR+ months were used for the composite analysis of WP-like pattern accompanied by corresponded anomalous convection. See text for definitions of the indices and details of the criteria.

Table 2 Correlation coefficients between the teleconnection indices (the SAJ pattern and the WP-like pattern) and the ENSO indices (Niño-3.4 and Niño-WP) based on monthly mean data (n = 141 months). The values in parentheses are based on DJF mean (n = 47 winters). Single and double asterisks denote the 95% and 99.9% confidence levels, respectively.
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|                | Positive                                                                 | Negative                                                                |
|----------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------|
| **SAJ**        | Feb 1977, Feb 1978, Jan 1981, Feb 1984, Jan 1986, Feb 1988, Feb 1999, Dec 2000, Jan 2001, Dec 2005, Feb 2006, Dec 2011, Feb 2012, Dec 2013, Dec 2014, Dec 2017, Dec 2020, and Jan 2021 (n = 20) | Feb 1976, Feb 1979, Dec 1979, Dec 1986, Jan 1990, Feb 1990, Dec 1991, Jan 1992, Dec 1992, Jan 1993, Dec 1997, Dec 2000, Feb 2007, Feb 2011, Feb 2014, Feb 2015, and Jan 2020 (n = 21) |
| **WP-like**    | **OLR−** Dec 1974, Jan 1989, Dec 1998, Dec 1999, Feb 2001, Dec 2006, Dec 2008, Dec 2009, Feb 2012, Dec 2013, and Jan 2021 (n = 11) | **OLR+** Dec 1980, Feb 1982, Dec 1987, Jan 1988, Dec 2006, Jan 2016, Feb 2016, Dec 2018, Feb 2019, Dec 2019, and Dec 2020 (n = 10) | **OLR−** Dec 1982, Dec 1983, Dec 2006, Jan 2016, Feb 2016, Dec 2018, Feb 2019, Dec 2019, and Dec 2020 (n = 10) | **OLR+** Dec 1980, Feb 1982, Dec 1983, Dec 2006, Jan 2016, Feb 2016, Dec 2018, Feb 2019, Dec 2019, and Dec 2020 (n = 10) |
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|          | Niño-3.4       | Niño-WP       |
|----------|----------------|---------------|
| SAJ      | -0.25* (-0.38*) | 0.27** (0.51**) |
| WP-like  | 0.10 (0.13)     | 0.11 (0.16)   |