A Precursor of the Monthly-Mean Large-Scale Atmospheric Circulation Anomalies over the North Pacific

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Abstract

The North Pacific shows dominant monthly-mean large-scale atmospheric circulation anomalies, even after removing the variabilities of the Northern Hemisphere annular mode and the El Niño/Southern Oscillation. This work examines the precursors and their development for these residual anomalous circulations by applying objective reanalysis data to empirical orthogonal function (EOF) analysis. The first EOF mode (EOF1) features a monopole, while a dipole characterizes the second EOF mode (EOF2) over the North Pacific. Transient eddies (TEs) interactively induce the two EOF modes.

The precursors of EOF1 and EOF2 are detected in the anomalies of one month earlier; these are the systematic zonal bands detected in surface temperature and baroclinic instability (BI) in the lower troposphere over Eurasia and North America. The BI anomalies further extend into the central North Pacific at different latitudes between EOF1 and EOF2. Coherent zonal bands also appear in the geopotential height anomalies of upper troposphere. Such zonal bands reflect the ovalization of Arctic circumpolar vortices of one month earlier; these are the systematic zonal bands that encircle along the coastline of the Arctic Ocean.

About the physical mechanisms of the teleconnection patterns, Lau and Holopainen (1984) pointed out that the convergence of transient eddy (TE) transports of heat and vorticity forces the geopotential tendency of the anomalous time-mean flow. Lau (1988) found that the storm tracks were located at and slightly downstream of quasi-stationary troughs. Using the outputs of general circulation model experiments, Branstator (1992) revealed that the vorticity flux anomalies of TEs were a primary source of the anomalous monthly-mean large-scale atmospheric circulation anomalies, even after removing the climatological annual cycle after removing the linear trend. Before applying the above four monthly indices to multiple regression analysis, these indices were normalized. All anomaly fields of atmospheric parameters including surface variables that encircle along the coastline of the Arctic Ocean.

1. Introduction

Many works have reported the dominant wintertime atmospheric teleconnection patterns over the Northern Hemisphere (NH) (Wallace and Gutzler 1981; Barnston and Livezey 1987): (1) the North Pacific Oscillation (NPO), (2) the North Atlantic Oscillation, (3) the Pacific/North American (PNA) pattern, and (4) the Northern Hemisphere annular mode (NAM) (Thompson and Wallace 1998). Smoliak and Wallace (2015) also classified such teleconnection patterns in sea level pressure (SLP) into three categories: (1) NAM, (2) PNA, and (3) local monopole patterns that encircle along the coastline of the Arctic Ocean.

About the physical mechanisms of the teleconnection patterns, Lau and Holopainen (1984) pointed out that the convergence of transient eddy (TE) transports of heat and vorticity forces the geopotential tendency of the anomalous time-mean flow. Lau (1988) found that the storm tracks were located at and slightly downstream of quasi-stationary troughs. Using the outputs of general circulation model experiments, Branstator (1992) revealed that the vorticity flux anomalies of TEs were a primary source of the anomalous monthly-mean large-scale atmospheric circulation anomalies, even after removing the climatological annual cycle after removing the linear trend. Before applying the above four monthly indices to multiple regression analysis, these indices were normalized. All anomaly fields of the objective variable, which are linearly explained by the four explanatory variables in the multiple regression analysis, were estimated using the least-squares method. The residuals between the original and the regressed anomalies, which still retain more than 70% in variance (Supplement), were diagnosed to determine the intrinsic atmospheric circulations over the North Pacific. To extract the dominant spatiotemporal anomalies over the North Pacific, this work used the empirical orthogonal function (EOF) analysis with the residual monthly Z300 anomalies. Before performing the EOF analysis, each gridded data was weighted by the area, i.e., $\cos^f \phi$, where $\phi$ is the latitude.

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3. Prominent atmospheric circulation anomalies over the North Pacific

Figure 1 shows the first EOF mode (EOF1) having 23.3% of the total variance. The spatial distribution of the eigenvector (Fig. 1a) indicates a monopole in the North Pacific; the northern center is three times larger than the southern one in magnitude. The score time series (Fig. 1b) demonstrates large year-round month-to-month variability on interannual modulations (Fig. 1c) that are not due to NAM and ENSO. The spatial pattern of EOF1 is similar to the wintertime PNA pattern (Nigam 2003), although both cold and warm seasons are considered and the variabilities of NAM and ENSO are precluded in this work.

The second EOF mode (EOF2), which has variance ratio of 18.6%, features a meridional dipole similar to the wintertime WP/NPO in the North Pacific (Fig. 2a), where the two centers are comparable. The score time series (Fig. 2b) again exhibits large year-round month-to-month variability with the interannual modulations (Fig. 2c). This score time series (Fig. 2b) has no correlation with that of EOF1 (Fig. 1b), even if the lags are taken for 24 months from −12 to +12 months (not shown). The absence of lag correlations between the two score time series suggests that they are not in a quadrature phase relationship in time; i.e., the two EOF modes develop independently. This work examined these two leading EOF modes, while the third (12.2%, not shown) represents the Pacific-Japan pattern arched in the North Pacific (Nitta 1987).

4. TE activities associated with EOF1 and EOF2

The TEs with synoptic or smaller scales, which are defined by the periods less than seven days in this work, is a major forcing of monthly-mean large-scale atmospheric circulations (Lau and Holopainen 1984; Lau 1988; Branstator 1992). This section diagnoses the effects of TEs on EOF1 and EOF2.

As the TE activities, this work examined the vertically (850−200 hPa) integrated kinetic energy (KE) of TEs and the divergence of tensor \( \nabla \cdot E \) at the 300 hPa level. The KE is expressed by

\[
\text{KE} = \frac{1}{g} \int \frac{1}{2} (u'^2 + v'^2) dp,
\]

where \( p \) is pressure, \( g \) is gravitational acceleration, \( \mathbf{v} = (u, v) \) is horizontal wind, and a prime indicates an anomaly from the seven-day box-car mean. Hoskins et al. (1983) defined \( E \) as

\[
E = \left( \frac{1}{2} u'^2 + \frac{1}{2} v'^2, -uv' \right),
\]

where the overbar indicates the time mean. Positive \( \nabla \cdot E \) denotes eastward acceleration of the time-mean barotropic zonal flow.

Figures 3a and 3b show the differential anomalies of KE for EOF1 and EOF2 with the Z300 anomalies that expand Figs. 1a and 2a to the NH. In EOF1 (Fig. 3a), the Z300 anomalies appear along two wave trains: one from the North Pacific to southeastern North America; the other from the North Atlantic to East Asia. The center of action in the North Pacific is the largest and strongest of the seven centers. On the other hand, the Z300 anomalies in EOF2 (Fig. 3b) spread only from the North Pacific to northern North America. In the North Pacific, large positive KE anomalies are found in the northwestern part of positive Z300 anomalies in EOF1 (Fig. 3a) and in the southeastern part of negative Z300 anomalies in EOF2 (Fig. 3b). The negative KE anomalies are distributed in the southeastern part of positive Z300 anomalies in both EOF modes (Figs. 3a and 3b).

Figures 3c and 3d show the anomalies of \( \nabla \cdot E \) associated with EOF1 and EOF2. In the North Pacific, the two EOF modes have large divergence (convergence) anomalies where the KE ones are positively (negatively) large. The relationship between the KE and \( \nabla \cdot E \) anomalies is weak over Eurasia and North America. The acceleration and deceleration of time-mean westerlies by TEs interactively form the anomalous low-frequency circulations of EOF1 and EOF2 in the North Pacific. The large month-to-month variability in the score time series of the two EOF modes (Figs. 1b and 2b) and the insignificant auto-correlations at the lags of ±1 months (not shown) indicate that the development and decay of these two EOF modes are completed within a month.

The anomalies of wave activity flux at the 300 hPa level (WAF300) (Takaya and Nakamura 2001) were diagnosed for later
Fig. 3. Differential anomalies associated with EOF1 (left) and EOF2 (right), which are estimated by the difference (positive – negative) between monthly means of composites. The composited months were based on ±1σ of the score time series of EOF1 (Fig. 1b) and EOF2 (Fig. 2b). (a, b), KE (10^5 J m^-2; color); (c, d), \nabla \cdot \mathbf{E} at 300 hPa (10^{-5} m s^{-2}; color); and (e, f), WAF300 (m^2 s^{-2}; vector). The differential Z300 anomalies (gpm) are overlaid by contours in all panels, where the interval is 1 hPa, and the dashed contours indicate negative anomalies. The color scale is placed at the right. Dots indicate statistical significance at the 95% level for KE anomalies. The vector scale is shown at the bottom.

5. Precursors and the development of EOF1 and EOF2

The TE activity and the induced slow change of time-mean flow interactively control low-frequency large-scale atmospheric circulations over the North Pacific (Branstator 1992; Feldstein 1998). A question here is how the storm tracks are converged into different regions of the North Pacific before the development of EOF1 and EOF2. This work detects the precursors in the one-month-earlier anomalies. The insignificant auto-correlations at lags of ±1 month in the score time series of the two EOF modes (not shown) imply that the persistence of the anomalous spatial patterns is one month or shorter (Figs. 1 and 2). However, this does not mean that there is no precursor for the patterns; there may be precursors with different spatial patterns one month earlier.

Figure 4 shows the anomalies of SLP and temperature at 2 m height (T2) in one-month-earlier data. The T2 anomalies of EOF1 (Fig. 4a) demonstrate a systematic four striped pattern over Eurasia and North America. In the two ocean basins, there are no large and significant T2 anomalies except for off Japan. The SLP anomalies of EOF1 (Fig. 4a) exhibit a systematic contrast between northern Eurasia and northern North America (positive), and the anomalies are positively large in the eastern North Pacific. In EOF2 (Fig. 4b), a systematic striped pattern is again observed over the two continents in the T2 anomalies; however, the spatial phase is shifted by a quarter (10°–20°) toward southern Eurasia. Over the two ocean basins, there are no large and significant T2 anomalies except for off Japan. In the SLP anomalies of EOF2 (Fig. 4b), an obvious contrast again appears in the Arctic Circle: positive over northern Eurasia and negative in high latitudes of the Western Hemisphere. In the eastern North Pacific, the SLP anomalies show a meridional dipole with northern negative and southern positive polarities.

This work hypothesized that the SLP precursors in the eastern North Pacific (Fig. 4) were amplified westward with the guided activation of TEs in the west like the development of blocking with TEs (Hoskins et al. 1983; Mullen 1987). To verify this hypothesis, we evaluated the baroclinic instability in the lower troposphere (850–700 hPa) (BI) through the Eady growth rate maximum (Lindzen and Farrell 1980; Hoskins and Vales 1990), which is expressed as follows:

\[
BI = \frac{f}{s} \left| \frac{\partial T}{\partial p} \right|
\]

where

\[
s = \frac{RT}{c_p} - \frac{\partial T}{\partial p}
\]

is a stability parameter, and the other parameters are conventional: \(f\) is the Coriolis parameter, \(T\) temperature, \(R\) the gas constant, and \(c_p\), the specific heat of dry air at constant pressure. An overbar denotes a monthly mean.

The BI anomalies exhibit significant systematic signals in the one-month-earlier analysis for both EOF1 and EOF2 (Fig. 5). The positive BI anomalies, the polarity of which indicates baroclinic instability, zonally extend along 55°N from Europe to the central North Pacific for EOF1 (Fig. 5a). The latitude of the corresponding positive zonal band for EOF2 (Fig. 5b), 40°N, is lower than

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*Fig. 4. Differential anomalies of SLP (hPa; contour) and of T2 (K; color) in one-month-earlier data, which were estimated based on ±1σ of the score time series of EOF1 (Fig. 1b) (a) and EOF2 (Fig. 2b) (b). The contour interval is 1 hPa, and the dashed contours indicate negative anomalies. The color scale is placed at the right. Dots indicate statistical significance at the 95% level for the T2 anomalies.*
that for EOF1 by about 15°. The eastern edge of the anomalous positive BI band reaches northwest of positive SLP anomalies in the eastern North Pacific for the two EOF modes (Fig. 4). This spatial phase relationship is suitable to the development of EOF1 and EOF2 by the following month (Nakamura and Wallace 1990).

The BI is positively larger than the climatology in a zonal band where the meridional T2 gradient is negatively large (Figs. 4 and 5). Note that the positive BI anomalies zonally protrude into the central North Pacific where there are neither large T2 anomalies (Fig. 4) nor a large negative meridional gradient (not shown). Instead, anomalous convergence of temperature fluxes is large in the lower troposphere (850−700 hPa) in and around the zonal bands of positive BI anomalies in the North Pacific (Fig. 5). To find precursors in the upper troposphere, the anomaly fields of Fig. 3 but one month earlier were examined (Fig. 6). In Figs. 6a and 6b, the KE anomalies are smaller than those in Figs. 3a and 3b in the North Pacific. The Z300 anomalies reflect systematic deformation of polar vortex with its meridional shift toward Eurasia (Fig. 6a) or North America (Fig. 6b), although the negative anomalies are large in the Bering Sea in the latter. The Z300 anomalies in the eastern North Pacific seem to be rooted to the deformation of polar vortex with a specific continent-ward shift (Fig. 5), which runs parallel to (1), (4) elongation of (3) into the central North Pacific with anomalous convergence of temperature fluxes (Fig. 5).

The one-month-earlier precursors for EOF1 and EOF2 are summarized as follows: (1) the systematic zonal bands of T2 anomalies over Eurasia and North America (Fig. 4), (2) a zonal band of positive BI anomalies in the eastern North Pacific (Fig. 5), (3) a zonal band of positive BI anomalies over Eurasia and North America (Fig. 4); and (4) the ovalization of Arctic circumpolar circulation with its continent-ward shift (Figs. 4 and 6). Before the development of EOF1, the long axis is shifted to the largest continent in the NH, Eurasia, while before EOF2, it is shifted to the second one, North America. By the following month, these precursors excite the guided development of TEs along a designated latitude and interactively induce the amplification of Z300 anomalies in the eastern North Pacific with westward extension, i.e., EOF1 and EOF2.

The Arctic circumpolar circulation has favorable deformation, which is likely caused by the distribution of oceans and continents in the NH, and the deformation disappears by the following month, which means that EOF1 and EOF2 are predictable, even...
though they are not periodic. Finally, we should note the limitation of this work; that is, the present results are effective for only monthly-mean anomalies, since the balance of forcing is probably different with the time scales, i.e., one month, a three-month winter, and a longer cold period (cf. Branstator 1992; Feldstein 1998).

Acknowledgements

The authors are grateful to two anonymous reviewers for their valuable comments and suggestions. This work was supported by Grants-in-Aid for Scientific Research (22106005, 25287125) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

Edited by: H. Mukougawa

Supplement

Supplement exhibits the monthly-mean large-scale atmospheric circulation anomalies appearing with NAM and ENSO.

References


Manuscript received 11 January 2017, accepted 4 April 2017
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