Internal Dynamics Related to the Appearance of the Okhotsk High in Midsummer

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The upper-level anomaly pattern corresponding to the appearance of the midsummer surface Okhotsk high is identified. It is confirmed that the pattern is well correlated with surface air temperature anomaly in northern Japan. Positive kinetic energy conversion from the basic field to the anomaly field is estimated, corresponding to the anomaly pattern. The steady response patterns are calculated by a linearized numerical model, giving forcings distributed over the entire Northern Hemisphere. The statistical analysis for the responses detects an anomaly pattern similar to that obtained in the observational analysis. These results suggest that the anomaly pattern associated with the appearance of the Okhotsk high can appear, in relation to the structure of the basic field, even if external forcings are homogeneously distributed.

1. INTRODUCTION

Predominant cool summers are often brought to northern Japan by the frequent appearance of the Okhotsk high. Therefore, many research works have been done about the influence of the Okhotsk high on the summer climate in Japan. However, even in recent years, long-range forecasts can not accurately predict the midsummer climate.

The Okhotsk high is often related to the blocking in the upper troposphere. The feedback from transient eddies are more essential for the formation of blocking in spring season. On the other hand, some recent works from a dynamical point of view have revealed that the upper-level anticyclonic anomaly brought by the propagation of a stationary Rossby wave from Europe or western Siberia plays an essential role in the formation of the midsummer Okhotsk high. However, in many of these works, data are analyzed for some typical cases, and the interannual variation of the dynamical field averaged for midsummer season is not directly considered.

In the present study, we objectively identify the pressure anomaly pattern related to interannual variability of the strength of the Okhotsk high averaged during midsummer. Then, we estimate the barotropic kinetic energy conversion from the basic field to the anomaly field, corresponding to the zonally-varying basic field. Furthermore, the anticyclonic anomaly is simulated as a steady solution of a forced linearized vorticity equation. Based on the numerical results, we discuss the mechanism through which the anomaly patterns are excited by vorticity forcing homogeneously distributed over the whole Northern Hemisphere and maintain themselves for the 30-day period.
2. IDENTIFICATION OF THE ANOMALY

We identify the pressure anomaly patterns related to year-to-year variations in the averaged strength of the Okhotsk high in midsummer. Although the Okhotsk high is a cold high observed near the surface, the pressure anomaly in the upper troposphere is essentially important in the formation of the Okhotsk high\(^3\)\(^6\). Therefore, in the present section, two methods for identification of the Okhotsk high are performed; one uses sea level pressure (SLP) data, and the other focuses on pressure anomaly patterns in the upper layer. Data are analyzed for midsummer (defined as July 20 – August 18) between 1979 and 1995. The subtropical jet is most northerly and weak in the midsummer season defined here (not shown). In the following analyses, reanalysis data of SLP and 300 hPa geopotential height anomaly by the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) are utilized. We also use Surface Daily Product (SDP) by the Japan Meteorological Agency to estimate temperature anomaly in Japan. The 30-day averaged data are analyzed in the present study.

Firstly, the anomaly related to the averaged strength of the Okhotsk high is identified by SLP data. Here, an index is defined as the anomalous SLP difference between 60°N and 40°N averaged from 130°E to 160°E. This index represents the anomalous meridional pressure gradient between the northern part of the Okhotsk Sea and northern Japan. The index is normalized by its standard deviation. The linear regressions of SLP and 300 hPa geopotential height on the normalized index are then calculated. In the regression fields of SLP and geopotential height, positive anomalies centered over the Okhotsk Sea and Siberia are seen, respectively (not shown). The patterns related to the Okhotsk high is well identified here.

Then, 300 hPa height data are analyzed to identify the anomaly. An empirical orthogonal function (EOF) analysis is performed for 300 hPa height anomaly over and around the Okhotsk Sea (30° – 90°N, 90°E – 150°W), expecting that a height anomaly pattern corresponding to the Okhotsk high is identified as the most predominant mode. The regressions of 300 hPa height and SLP on principle component (PC) 1 are then calculated (Figs. 1 and 2). Anticyclonic anomalies can be also seen over Siberia and the Okhotsk Sea, respectively. Besides, the interannual variation of 300 hPa height at each grid point is relatively large over Siberia, corresponding to the positive anomaly center in Fig. 1 (not shown). The index defined here also well represents the Okhotsk high averaged in midsummer, although the difference of the contribution ratios in the EOF analysis is not particularly large (26% for PC 1, and 21% for PC 2). The regression patterns and the temporal index are similar to those obtained by using SLP data in the previous paragraph. In the following analyses, we use the index defined here as that for the strength of the Okhotsk high, since we mainly focus on the dynamics in the upper layer.
Fig. 1 Regression of 300 hPa geopotential height on PC 1. The contour interval is 10 m. Negative contours are dotted. 95% significant positive and negative anomalies are shaded and hatched, respectively.

Fig. 2 The same as in Fig. 1, except for sea level pressure. The contour interval is 1 hPa.

Figures 3 and 4 indicate the interannual variations of the index and the temperature anomaly in northern Japan averaged over the 30-day period. The mean temperature is defined as the average for the two representative sites selected by Nishimori (1999). A clear negative correlation (the correlation coefficient is −0.871) can be seen between them. The index is also significantly correlated with temperature anomalies in eastern and western Japan calculated in similar ways following the definitions by Nishimori (1999) (the correlation coefficients are −0.717 and −0.563, respectively). These correlations are in part related to cool summer brought by "Yamasu", the cool northeasterly wind, associated with the Okhotsk high.

Fig. 3 PC 1 for 300 hPa geopotential height for July 20 to August 18.

Fig. 4 Temperature anomaly in northern Japan for July 20 to August 18.

Moreover, a separate EOF analysis for an annular region at 30°-60°N detects a similar wave train as the first mode (not shown). The anomaly pattern in Fig. 1 can therefore be considered as the dominant variability at NH midlatitudes.

3. VERTICAL STRUCTURE AND HEAT BUDGET

In the present section, the vertical structure of the anomaly field is examined. In Figs. 1 and 2, the sign of anomaly is almost the same in the upper and lower layers over most regions. The amplitude is largest near the tropopause. It is also confirmed, by analyzing vorticity budget, that the contribution of stretching term is much smaller than those of linear advection and $\beta$-effect (not shown). Similar results are obtained for the anomaly field corresponding to the index defined by SLP data. The surface high is shifted southeastward compared with the upper-level anticyclonic anomaly over Siberia, as shown in Fig. 2. The center of the positive anomaly at each level is almost the same in the upper and middle troposphere, and a baroclinic structure is seen only near the surface (not shown). This baroclinic structure corresponds to the low-level
negative temperature anomaly over the Okhotsk Sea, and is consistent with the fact that the Okhotsk high is often recognized as a cold high.

Heat budget analysis in the lower level reveals that the negative temperature anomaly over the Okhotsk Sea is brought by the advection of the climatological cold air mass around the Bering Sea by the low-level anomalous northeasterly wind related to the upper-level anticyclonic anomaly over Siberia, as was suggested by Nakamura and Fukamachi (2004)\textsuperscript{2}). In this anomaly field, apparent diabatic heating is positive (not shown). In other words, the diabatic heating damps the anomaly. It is inferred that the cold anomaly is not directly excited by changes in the lower boundary condition like sea surface temperature (SST). These results are consistent with those obtained in some previous studies\textsuperscript{3}). The center of the positive pressure anomaly is located near the tropopause, although the Okhotsk high itself is usually recognized as a cold low-level high.

4. BAROTROPIC KINETIC ENERGY CONVERSION

Corresponding to the results of the previous section, we analyzed the data at the 300 hPa level assuming non-divergent condition in the following. The stretching term is actually much smaller compared with the linear advection and the effective $\beta$ term in the vorticity field at 300 hPa. The nonlinear term of vorticity advection is also small (not shown). Barotropic kinetic energy conversion is calculated at 300 hPa assuming linear condition, in order to assess the possibility that the anomaly pattern shown in Fig. 1 appears through the interaction with the basic field (climatological mean field for the midsummers from 1979 to 1995; see Fig. 5). In general, the deformation of the basic field can contribute to the appearance of some specific anomaly patterns\textsuperscript{4}). Using the local Cartesian coordinate, barotropic kinetic energy conversion $CK$ between the basic and anomaly fields can be written as

$$
CK = -u'^2 \frac{\partial}{\partial x} \bar{u} - u'v' \frac{\partial}{\partial y} \bar{u} - u'v' \frac{\partial}{\partial x} \bar{v} - v'^2 \frac{\partial}{\partial y} \bar{v}.
$$

Here, the $x$- and $y$-coordinates are used as the zonal and meridional coordinates. In the above equation, $\bar{u}$ and $\bar{v}$ respectively represent the zonal and meridional winds of the basic field, while $u'$ and $v'$ respectively denote the anomalous zonal and meridional winds. By integrating the energy conversion calculated from eq. (1) over a region of $(30^\circ - 90^\circ N, 45^\circ E - 180^\circ E - 135^\circ W)$, where the anomaly pattern has significant amplitude in Fig. 1, we obtained a value of $<CK> = +2.22 \times 10^{-6} \text{ m}^2/\text{s}^3$. On the other hand, the integration of kinetic energy $KE$ of the anomaly is $<KE> = 2.96 \text{ m}^2/\text{s}^2$. The time scale at which the anomaly field obtains energy from the basic field is about 15 days. When the integrations were performed over all longitudes for $30^\circ - 90^\circ N$, we obtained $<CK> = +0.92 \times 10^{-6} \text{ m}^2/\text{s}^3$, while $<KE> = 2.19 \text{ m}^2/\text{s}^2$. In this case, the time scale is 28 days. This energy conversion significantly contributes to the formation of the anomaly pattern shown in Fig. 1, since the 30-day averaged fields are analyzed here. The value of $CK$ at each grid point is shown in Fig. 6. Positive energy conversion is estimated around the entrance (near the Black Sea) and the exit (over northeastern China and the Okhotsk Sea) of the Asian jet (the strong subtropical jet over the Eurasian continent), and over the region where another jet is seen along the coast of the Arctic Ocean. In these regions, the basic field of absolute vorticity is largely distorted (Fig. 5). It is confirmed that the distortion of the basic field is related to kinetic energy conversion.
Fig. 5 300 hPa absolute vorticity on the basic field. The contour interval is $10 \times 10^{-6}$ /s.

Fig. 6 Barotropic kinetic energy conversion between the basic and anomaly fields. The contour interval is $20 \times 10^{-6}$ m$^2$/s$^3$. The zero contour is suppressed and negative contours are dotted.

5. STEADY RESPONSES IN A LINEARIZED BAROTROPIC MODEL

Concerning the results of the previous section, it is examined here how the anomaly pattern shown in Fig. 1 is statistically excited by homogeneously-distributed forcings through the interaction with the basic field. A linear barotropic model described below is utilized at the 300 hPa level.

$$\frac{\partial}{\partial t} \xi' + \mathbf{u} \cdot \nabla \xi' + \mathbf{u}' \cdot \nabla (f + \hat{\xi}) + \nu \nabla^4 \xi' + \frac{1}{\tau} \xi' = F$$

where $\xi$ is the absolute vorticity of the basic field, $\xi'$ is the anomalous vorticity, and $f$ is the Coriolis parameter. Vectors $\mathbf{u}$ and $\mathbf{u}'$ are respectively defined as $(\hat{u}, \hat{v})$ and $(u', v')$. The values of super diffusion coefficient $\nu$ and time-scale of damping $\tau$ are respectively set as $\nu = 2 \times 10^{10}$ m$^4$/s and $\tau = 5$ days, following a previous study7. There are no unstable modes in this linear model. External vorticity forcings $F$ are given as localized negative vorticity forcings centered at 108 points distributed almost homogeneously over the all longitudes to the south of 30°N in the Northern Hemisphere. Here, vorticity forcings associated with cumulus convection in the low latitudes are considered. The value of $F$ at the center is $-fD$ where $D = 2 \times 10^{-6}$ /s following the previous study7. The spatial size of each forcing is $10 \pi R_e/180$ where $R_e$ is Earth's radius, which is about one-seventh of that in the previous work7. In the present experiment, the 108 solutions of steady response patterns are indicated as geopotential height anomalies, for convenience of comparison with observational results. In order to obtain geopotential height anomaly, stream function is calculated from vorticity anomaly by solving the Poisson equation. The stream function is then converted into geopotential height anomaly under an assumption of geostrophic balance. After that, the same statistical analysis as was used in Fig. 1 is applied to the 108 samples here, so that PC 1 is obtained from steady response patterns. The basic concept of this analytical technique in this section is the same as that of a singular value decomposition (SVD) analysis applied to a linear operator describing the temporal evolution of the anomalies. Here, the analytical method used in Fig. 1 is applied again instead of SVD analysis, in order to compare the numerical result with the observational result shown in Fig. 1, and to separately estimate the effect of the forcings placed in the low latitudes and that in the mid and high latitudes. The regressed geopotential height on the PC 1 is shown in Fig. 7. The contribution ratios of PCs 1 and 2 are 41% and 20%, respectively. The spatial structure is similar to that in Fig. 1 around the Okhotsk Sea. As we can see in eq. (1), the aspect ratio on the horizontal plane and the tilt of the axis seen in the horizontal structure of the anomaly pattern is essential to the energy conversion. The statistical pattern shown in Fig. 7 has some common features
with that in Fig. 1, with respect to the location of the anomaly center over Siberia, the aspect ratio and the northeast-southwest tilt around Japan and the Okhotsk Sea. The time scale of the integrated energy conversion over the region of (30°–90°N, 45°E–180°–135°W) is 8 days. A value of 4 days is obtained if the integration is performed over all the longitudes for 30°–90°N. It is confirmed that the energy conversion significantly contributes to the appearance of the anomaly pattern. The locations of the anomaly centers, and their northeast-southwest tilts are similar to Fig. 1, when the forcings are distributed at 102 points to the north of 30°N (Fig. 8). The difference in the contribution ratios for PCs 1 and 2 is large also in this case (44% and 24%). The time scale of the energy conversion is 13 days for the region of (30°–90°N, 45°E–180°–135°W), and 11 days for all the longitudes to the north of 30°N. The spatial patterns corresponding to PC 1 shown in Figs. 7 and 8 do not largely change, when we add the +1- or −1-σ (standard deviation) anomaly field shown in Fig. 1 to the basic field. When the forcings are given over the whole Northern Hemisphere, the result is almost the same as that shown in Fig. 8.

![Image](image.png)

Fig. 7 Regression of geopotential height on PC 1 in the steady response problem. The result for forcings given to the low latitudes is shown. The contour interval is 1 m. Zero contour is suppressed. Negative contours are dotted.

![Image](image.png)

Fig. 8 The same as in Fig. 7, except for forcings given to the middle and high latitudes. The contour interval is 5 m.

These results suggest that the anomaly pattern like that in Fig. 1 can statistically appear through dynamical interactions with the basic field, even when external forcings were homogeneously given. Note here that the amplitude of responses to forcings in the low latitudes is about one-fifth of that in the mid- and high-latitudes, when the strength of external forcings is constant. It is difficult to quantitatively evaluate the relative importance of the vorticity forcing between the low latitudes and in the mid- and high-latitudes in the real atmosphere. In general, vorticity forcing by the feedback from transient eddies in the mid- and high-latitudes plays an essential role in the formation of blocking3). It means that the convergence of eddy vorticity flux significantly contributes to the excitation of vorticity anomaly. However, the feedback may be much weaker in summer than in the other seasons3). On the other hand, convective activity is stronger in the subtropical region in summer than in winter. Thus, the authors think that the effect of cumulus convection in the low latitudes may not be neglected. Further analyses are required to quantitatively compare the external forcings in the low latitudes and those in the mid- and high-latitudes.

In the above numerical experiments, the forcings placed at (65°N, 50°E), (65°N, 150°E) and (25°N, 45°E) are found to excite most effectively the anomaly pattern corresponding to PC 1 shown in Figs. 7 and 8, for example. However, the spatial pattern of each response differs considerably from one another, although it commonly has a maximum amplitude over Siberia.
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and a northeast-southwest tilt around Japan and the Okhotsk Sea (Figs. 9–11). In other words, there may be several different hemispheric-scale dynamical processes related to the appearance of the Okhotsk high. The three anomaly patterns are accompanied by positive energy conversion over the region (30°–90°N, 45°E–180°–135°W). The time scales of the energy conversion are 6–9 days. The observed anomaly patterns in the Northern Hemisphere from July 20 to August 18 for 1980, 1991 and 1993 when the Okhotsk high was strong, are then compared (Figs. 12–14). The observed anomaly patterns actually differs from year to year, although they all have a positive anomaly center over Siberia and a northeast-southwest tilt around Japan and the Okhotsk Sea. The results presented here suggest many different external forcings are related to the formation of the Okhotsk high.

Fig. 9 Response pattern for forcing at (65°N, 50°E). The contour interval is 30 m. Negative contours are dotted. Mark "x" denotes the center of the forcing.

Fig. 10 The same as in Fig. 9, except for forcing at (65°N, 150°E).

Fig. 11 The same as in Fig. 9, except for forcing at (25°N, 45°E). The contour interval is 5 m.

Fig. 12 Geopotential height anomaly for July 20 to August 18 in 1980. The contour interval is 30 m.

Fig. 13 The same as in Fig. 12, except for 1991.

Fig. 14 The same as in Fig. 12, except for 1993.
6. CONCLUSIONS

The upper-level pressure anomaly pattern corresponding to the appearance of the midsummer Okhotsk high and negative surface temperature anomaly in northern Japan was identified. Positive kinetic energy conversion from the basic field to the anomaly field contributes to the maintenance of the anomaly pattern. Various vorticity sources and sinks in the Northern Hemisphere can form the anomaly pattern related to the appearance of the Okhotsk high. There are several different anomaly patterns and corresponding external forcing patterns related to the strength of the Okhotsk high. It is implied that numerical prediction for the strength of the Okhotsk high is especially difficult, since it is required to appropriately give all the external vorticity forcings over the entire Northern Hemisphere.

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