Abstract

This study analyzes a Rossby wave-breaking event east of Japan that enhanced the convective activities over the subtropical western North Pacific Ocean. In August 2016, Rossby-wave packets in the upper troposphere above Eurasia reached over and around the seas east of Japan. The wave-breaking event accompanied the amplification of a blocking ridge and the southward intrusion of upper-level high-potential vorticity (PV) south of the ridge. The high PV (i.e., the enhanced mid-Pacific trough) promoted upward motion and enhancement of convective activities over the subtropical western North Pacific Ocean through a quasi-geostrophic balance. In the lower troposphere, large-scale cyclonic circulation anomalies, including tropical disturbances, were observed south and southeast of Japan, and the anomalies caused significant wet climate conditions in the eastern and northern parts of the country. A linear baroclinic model experiment indicates that the lower-level cyclonic circulation anomalies were the Rossby-wave responses to heating anomalies associated with the enhanced convective activities. These results suggest the existence of dynamic interaction between extratropical and tropical circulation over the western North Pacific Ocean and its influence on boreal summer climate in Japan.

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1. Introduction

In August 2016, typhoons caused landfalls four times, thrice in the Hokkaido region and once on the Pacific side of Tohoku region for the first time, resulting in serious damage in northern Japan. The number of typhoons causing landfalls in the Hokkaido region was the largest on record for August since 1951. These tropical cyclones formed over an area of enhanced convective activities observed to the southeast of Japan and moved westward or northward (Fig. 1b and 1d) with warm and moist air inflow, causing significant wet conditions in eastern and northern Japan. The monthly precipitation amounts on the Pacific side of northern Japan were the highest on record for August since 1946 with precipitation 231 percent of normal, indicating anomalous weather conditions over and around Japan.

In the upper troposphere, the blocking ridge and the resultant southward intrusion of high-potential vorticity (PV) were clearly observed over the seas east of Japan, where background flow is favorable for the occurrence of a Rossby wave-breaking (RWB) event (Abatzoglou and Magnusdottir 2004). The position of enhanced convection was just to the south of the southward-intruding high PV associated with the RWB. The Japan Meteorological Agency (JMA) reported similar atmospheric characteristics in mid-summer of 2012 (JMA 2013), which suggests that the Rossby-wave propagation might induce enhanced convective activities to the south of Japan through an RWB event. These results are consistent with the results of Sato et al. (2005), who showed that the southward intrusion of the high PV associated with the upper cold low (i.e., the enhanced mid-Pacific trough) tends to contribute to enhanced convective activities in the subtropical western North Pacific Ocean; however, the dynamic process from the RWB through the enhanced convective activity and the relation between them were not clearly shown in their study. Molinari and Vollaro (2012; hereinafter, MV12) reported on a similar event with a time scale of several days, which is shorter than the event in August 2016. They suggested the importance of enhanced troughs near the jet stream exit area to the east of Japan for the enhancement of the subtropical cyclonic gyre through the strong confluent flow in the lower troposphere associated with the RWB. They also indicated the influence of quasi-geostrophically induced upward motion on the enhanced convective activities associated with the cyclonic gyre in the subtropical western North Pacific Ocean.

In this study, we examine (1) how the RWB to the east of Japan excited the enhanced convective activity over the subtropical western North Pacific Ocean and (2) the responses of the cyclonic circulation anomalies, which caused the anomalous weather conditions in August 2016. This line of the approach is important to further our knowledge about anomalous atmospheric circulation and how to monitor it.

2. Data, methods, and analysis model

In this study, we used the Japanese 55-year reanalysis dataset (JRA-55; Kobayashi et al. 2015) to diagnose atmospheric circulation in August 2016. “Normal” circulation was defined as the 30-year average during the period from 1981 to 2010, and “anomalies” were defined as deviations from the normal. The propagation of quasi-stationary Rossby-wave packets was analyzed using wave activity flux (WAF) after Takaya and Nakamura (2001). To infer convective activities, we used the data of outgoing longwave radiation (OLR) provided by the National Oceanic and Atmospheric Administration (NOAA).

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

3. Results

Figure 1 shows 300 and 850 hPa stream anomalies and 360 K isentropic PV and OLR anomalies averaged in August 2016. The wave patterns of the circulation anomalies in the upper troposphere are observed along the Asian jet stream over an area extending from Eurasia to the seas east of Japan (Fig. 1a). The ob-
served wave patterns are out of phase with MV12’s case by about 1/4 wavelength (see Fig. 5b of MV12). An omega-shaped blocking high, with distinct anticyclonic circulation anomalies (Fig. 1a) and an associated meridional PV overturning and southward intrusion of the high PV (hereinafter referred to as RWB; shading in Fig. 1b), is observed to the east of Japan. On the other hand, convective activities are enhanced over latitude bands near 20°N to the southwest to southeast of the high PV (contour lines in Fig. 1b). As mentioned later, stronger-than-normal southward cyclonic vorticity advection in the upper troposphere may contribute to the enhanced convection on the south side of the intruding high PV. Six tropical cyclones formed over the seas south to southeast of Japan in the month (red lines in Fig. 1d); their formation corresponds to the enhanced convective activity (Fig. 1b). In the lower troposphere, large-scale cyclonic circulation anomalies are clearly observed over the wide area in the subtropical western North Pacific Ocean (Fig. 1c), indicating not only circulation accompanied by the tropical cyclones but also a Rossby-wave response to the enhanced convective activities. The influence assessment for the Rossby-wave response to the active convection will be discussed later based on the results of the LBM experiment. An interannual (1979 to 2016) time series of 350-K PV averaged over the area east of Japan and OLR anomalies averaged over latitude bands near 20°N in the western North Pacific Ocean (Figs. 2a and 2b) indicates that the August 2016 measurements are the lowest on record since 1979 and that they exhibit the significant characteristics of the circulation mentioned above. These characteristics suggest that compared with the normal, a Rossby-wave packet that propagated along the Asian jet stream converged to the east of Japan and contributed to the enhanced convective activity and the

Fig. 1. Monthly mean (a) 300 and (c) 850 hPa stream function (contour lines) and its anomalies (shading); contour lines at intervals of $5 \times 10^6$ m$^2$ s$^{-1}$; wave activity flux (WAF) after Takaya and Nakamura (2001) (vector) and (b) outgoing longwave radiation (OLR) anomalies (contour lines at intervals of 10 W m$^{-2}$, positive anomaly values omitted); and 360-K potential vorticity (PV) (shading at intervals of 1 PVU) in August 2016. The red closed circle and lines in (d) shows the point of origin for the typhoon formed over the seas south to southeast of Japan in the month and its preliminary best track, respectively, based on data from the Japan Meteorological Agency (JMA).

Fig. 2. For August, from 1979 to 2016, interannual time series of monthly mean (a) 350-K PV (PVU) averaged over 35°N−45°N and 150°E−180°E; (b) OLR anomalies (W m$^{-2}$) averaged over 15°N−25°N and 150°E−180°E; and (c) Q-vectors divergence anomalies (10$^{-17}$ m/kg/s) averaged over 15°N−25°N and 150°E−180°E.
associated formation of tropical cyclones.

To examine the dynamic relation between the southward intrusion of the high PV and the enhanced convective activity based on the quasi-geostrophic (QG) theory, vertical motion induced by the QG balance was diagnosed using Q-vectors (Holton 1992) field. The traditional diagnostic equation for the vertical motion (called the omega equation) can be approximately written as Eq. (1) without the diabatic heating effect and the Q-vectors is defined as Eq. (2).

\[
\nabla^2 \omega + \frac{f_0^2}{\sigma} \frac{\partial^2 \omega}{\partial p^2} = \frac{f_0}{\sigma} \frac{\partial}{\partial p} \left( v \frac{f_0}{\sigma} \nabla^2 \Phi + f \right) + \nabla \cdot \left( \frac{\beta}{\sigma} \frac{\partial}{\partial y} \frac{\partial \Phi}{\partial y} \right) \\
\simeq -\frac{2}{\sigma} \nabla \cdot \mathbf{Q} + \frac{f_0}{\sigma} \beta \frac{\partial v}{\partial y} \frac{\partial \Phi}{\partial y} \frac{\partial T}{\partial y} 
\]

\[Q = \frac{R}{\sigma} \frac{\partial v}{\partial y} \nabla T - \frac{R}{\sigma} \frac{\partial v}{\partial y} \frac{\partial \Phi}{\partial y} \frac{\partial T}{\partial y} \]

Here \( \omega \) is the pressure vertical velocity, \( f_0 \) and \( f \) the Coriolis parameter, \( \sigma \) the static stability, \( v = (u, v) \) the geostrophic horizontal velocity, \( \Phi \) the geopotential, \( Q \) the Q-vector, \( T \) the temperature. The Eq. (1) indicates that the vertical motion is balanced with vertical derivatives of vorticity advection (first term of its right-hand side) and temperature advection (second term of that). The vertical motion also can be represented by the Q-vectors field with its convergence corresponds to ascent and vice versa. For adiabatic flow, the vertical motion may be represented solely by the patterns of the Q-vectors. For practical purposes, the value of Q may be estimated from geopotential and temperature observations on a single isobaric surface. In the Q-vectors and its divergence field derived from the monthly mean in August 2016 shown in Fig. 3, convergence anomalies are seen along just south of the area (near 20°N; Fig. 3c) where the stronger-than-normal southward intrusion of high PV is observed (Figs. 3a and 3b), indicating that QG upward motion is induced due to temperature advection or vertical derivatives of vorticity advection. An interannual time series of the Q-vectors divergence anomalies averaged over latitude bands near 20°N in the western North Pacific Ocean shown in Fig. 2c indicates that the strongest Q-vectors convergence on record since 1979 occurred in August 2016. A daily time series for the Q-vectors divergence over the same area (bars in Fig. 3d) indicates convergence, particularly two or three peaks of strong convergence during the first half of early August and during the early to middle part of the second half of August. The time variation of the Q-vectors divergence is consistent with that of OLR, indicating that the QG upward motion induced by the high PV primarily contributed to the enhanced convective activities over the subtropical western North Pacific Ocean (Figs. 2b and 2c). These Q-vectors diagnoses indicate that the QG dynamics are presumed to be essential processes for the broad area of the persistent enhanced convection, which is in contrast to MV12’s remarks that the exclusive area of the enhanced convection does not necessarily correspond to the area of the QG upward motion. Figure 4 shows vertical differences of vorticity advection by quasi-geostrophic horizontal wind between 200 and 850 hPa. In association with cyclonic vorticity advection due to stronger-than-normal southward wind in the upper troposphere, positive anomalous vertical differences of the vorticity advection are seen (Fig. 4) over and around the area where the Q-vectors convergence anomalies are observed (Fig. 3) and south of the intruding high PV (Fig. 1b). Warm-air advection in the mid-troposphere, which is one of the factors that induces the QG upward motion, is not clearly seen over and around the same area (not shown). For the extratropical circulation to influence the subtropical circulation in August 2016, the Q-vectors and vorticity budget diagnoses indicate that the RWB to the east of Japan and the associated strong mid-Pacific trough contribute

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**Fig. 3.** (a) Actual, (b) normal, and (c) anomalous Q-vectors at 500 hPa (vector; unit: m^2/kg/s) and its divergence (shading; unit: m/kg/s) derived from monthly mean in August 2016. The contour lines in (a) and (b) show 360-K PV at intervals of 1 PVU. (d) Daily time series of the Q-vectors divergence (brown bars denote divergence and green ones denote convergence) and OLR (blue dashed lines) averaged over 15°N−25°N and 150°E−180°E.
to the enhanced convective activities over the subtropical western North Pacific Ocean through the QG upward motion.

To assess the impact of the tropical convective activities on the atmospheric circulation, a deterministic numerical experiment was performed using the LBM. The LBM was solved with monthly mean diabatic heating anomalies over the area from 30°S to 30°N in August 2016. The vertical integrated heating anomalies (see shading in Fig. 5) indicate the existence of strong heat sources associated with enhanced convective activities over and around 20°N in the western North Pacific Ocean. The LBM responses of 300 and 850 hPa height fields show positive (anticyclonic) and negative (cyclonic) anomalies over the seas southeast of Japan, respectively, indicating the strong heat sources (Figs. 5a and 5b) to be the Rossby-wave response. The responses of cyclonic circulation anomalies at 850 hPa are consistent with the circulation anomalies observed in August 2016 (Fig. 1c), indicating the influences of the enhanced convective activities over the subtropical western North Pacific Ocean on the large-scale cyclonic circulation anomalies and presumably on the origin and track of the tropical cyclones. The lower tropospheric responses also support MV12’s discussion for the relation between the enhanced convection and cyclonic gyre. By contrast, the responses of anticyclonic circulation anomalies at 300 hPa differ from the anomaly patterns observed in August 2016 (Fig. 1a), indicating that the upper tropospheric circulation anomalies primarily formed not by the responses to the enhanced convective activities in the subtropical western North Pacific Ocean but by the quasi-stationary Rossby-wave propagation from Eurasia along the Asian jet stream (see WAF shown in Fig. 1a).

The results of Q-vectors diagnoses and LBM experiments mentioned above suggest that the RWB to the east of Japan and the quasi-geostrophically induced convection over the subtropical western North Pacific Ocean contributed to a series of typhoon formations or landfalls, which caused significant wet conditions in eastern and northern Japan in August 2016.

4. Discussion and conclusions

We investigated the dynamic relation between the RWB to the east of Japan and the associated enhanced convective activities over the subtropical western North Pacific Ocean and their influence on Japan’s climate in August 2016. In the monthly mean atmospheric circulation, the quasi-stationary Rossby-wave propagation is observed along the Asian jet stream and resultant wave packet convergence to the east of Japan (i.e., the occurrence of RWB). The RWB accompanies meridional PV overturning and southward intrusion of the high PV in the upper troposphere (i.e., the enhanced mid-Pacific trough). The enhanced convective activities in the subtropical western North Pacific Ocean are presumed to be mainly associated with the upper tropospheric southward positive vorticity advection through the QG upward motion. The LBM experiment indicates that the 850-hPa cyclonic circulation anomalies over the wide area in the subtropical western North Pacific Ocean are associated with the Rossby-wave response to the enhanced convective activities. The convective activities and cyclonic circulation anomalies are presumed to be related to the formation of four tropical cyclones and significant wet conditions mainly owing to a series of typhoons passing over eastern to northern Japan.

The Q-vectors and vorticity budget diagnoses infer that the QG upward motion associated with the strong mid-Pacific trough
induced the enhanced convective activities in the subtropical western North Pacific Ocean. To demonstrate the causal relation between them, some impact experiments with the relaxation area over and around the mid-Pacific trough were performed using JMA’s operational one-month ensemble prediction system. The results of the experiments indicate the existence of the causal processes from the mid-Pacific trough to the subtropical convective activities associated with the QG balance; these results support the inferences mentioned above. The detailed results and discussion will be presented in another paper.

Further investigations are needed to identify the primary factors that caused the significant atmospheric circulation in August 2016, as shown in the interannual time series of some area-averaged elements in Fig. 2. The significant amplification of the blocking high to the east of Japan (Fig. 1a) and the lower tropospheric large-scale cyclonic circulation over the subtropical western North Pacific Ocean (Fig. 1c) are presumed to be associated with some atmospheric instability with its seasonal basic states. To assess the contribution of the atmospheric instability to the significant amplification, baroclinic and barotropic energy conversion from the basic states defined as the normal to the anomaly patterns will be calculated in future studies and detailed results will be presented.

Although this is a case study for the anomalous summer conditions over and around Japan in August 2016, we expect that studying the dynamic interaction between extratropical and tropical circulation is important to make further progress in both climate system monitoring and seasonal forecasting.

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