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Relation between a Rossby Wave-Breaking Event and Enhanced Convective Activities in August 2016

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1. Introduction

In August 2016, tropical cyclones formed over an area of enhanced convective activities to the southeast of Japan and moved westward or northward (Fig. 2d) with warm and moist air inflow, causing significant wet conditions in eastern and northern Japan (Fig. 1). Japan Meteorological Agency (JMA) performed climate diagnoses for the event and suggested that the Rossby wave-breaking (RWB) to the east of Japan might induce the enhanced convective activities to the southeast of Japan.

As some associated previous studies, Sato et al. (2005) showed that the southward high potential vorticity (PV) intrusion associated with the upper cold low tends to contribute to enhanced convective activities in the sub-tropical western North Pacific. Molinari and Vollaro (2012) also reported on a similar event with a time scale of several days and suggested the contribution of enhanced troughs near the jet stream exit to the east of Japan to the sub-tropical cyclonic gyre.

In this study, we examine how the RWB to the east of Japan excited the enhanced convective activities and the responses of the cyclonic circulation anomalies which caused the anomalous weather conditions over Japan. This line of the approach is important for JMA to accumulate our knowledge about anomalous circulation and how to monitor it.

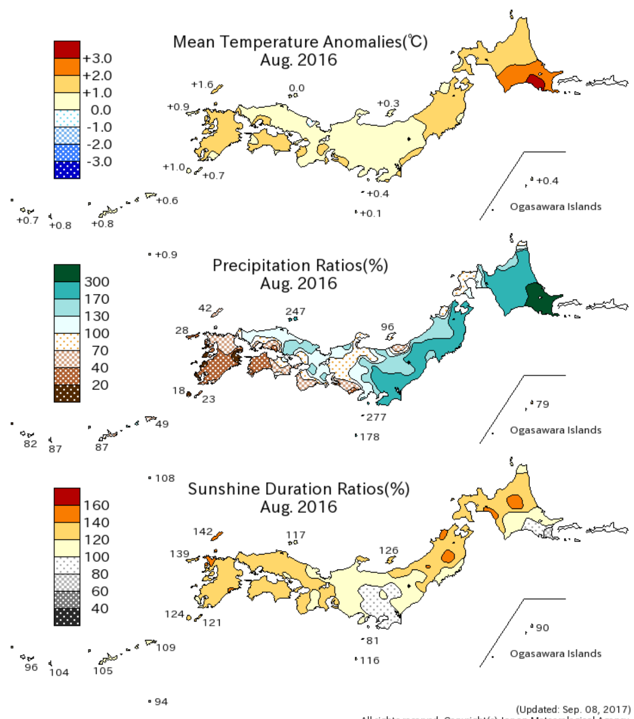

Fig. 1 Monthly mean temperature anomalies, precipitation ratios and sunshine duration ratios in Japan for August 2016.

2. Data and methodology

The Japanese 55-year reanalysis dataset (JRA-55, Kobayashi *et al.* 2015) was used to diagnose atmospheric circulation in August 2016. "Normal" 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 outgoing longwave radiation (OLR) data provided by 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 has the resolution of T42 and is vertically discretized by a finite difference to 40-sigma levels.

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3. Results

Figure 2 shows 300-hPa and 850-hPa stream function 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. 2a). An omega-shaped blocking high, with distinct anti-cyclonic circulation anomalies and an associated meridional PV overturning and southward intrusion of the high PV (Fig. 2b), is observed to the east of Japan. On the other hand, convective activities are enhanced over latitude bands near 20°N to the southwest of the high PV (contour lines in Fig. 2b). Six tropical cyclones formed over the seas south to southeast of Japan in the month (Fig. 2d), corresponding to the enhanced convective activities (Fig. 2b). In the lower troposphere, large-scale cyclonic circulation anomalies are clearly observed over the wide area in the sub-tropical western North Pacific (Fig. 2c), indicating not only circulation accompanied by the tropical cyclones but also a Rossby-wave response to the enhanced convective activities.

To examine the dynamic relation between the southward intrusion of the high PV and the enhanced convective activities based on the quasi-geostrophic (QG) theory, vertical motion induced by the QG balance was diagnosed using Q-vectors field. In the Q-vectors and its divergence 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. A daily time series for the Q-vectors divergence over the same area (bars in Fig. 3d) indicates convergence, particularly two

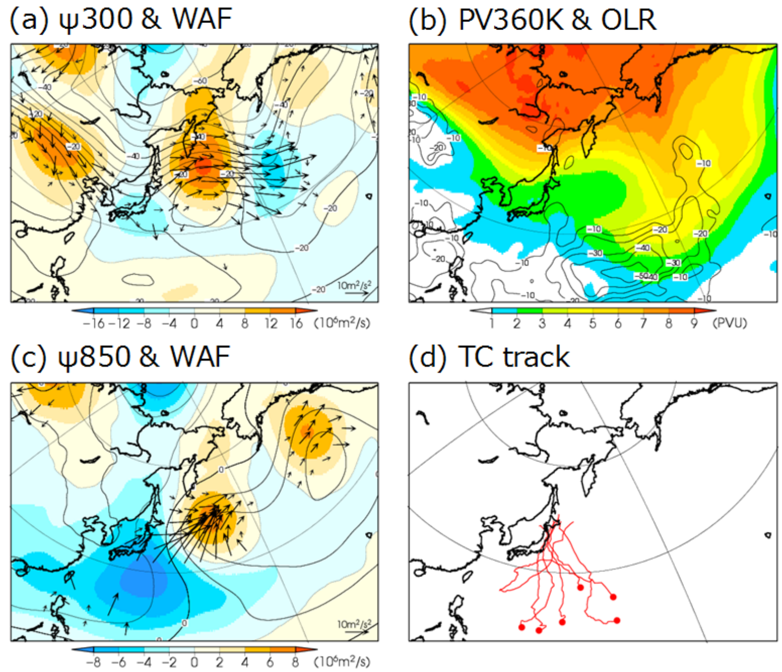

Fig. 2 Monthly mean (a) 300-hPa and (c) 850-hPa stream function (contour lines) and its anomalies (shading); contour lines at intervals of 5×10^6 m^2/s; WAF (vector) and (b) OLR anomalies (contour lines at intervals of 10 W/m^2, positive anomaly values omitted); and 360-K PV (shading at intervals of 1 PVU) in August 2016. The red closed circle and lines in (d) shows the points of origin for the typhoon formed over the seas south to southeast of Japan in the month and its best tracks, respectively, based on data from JMA.

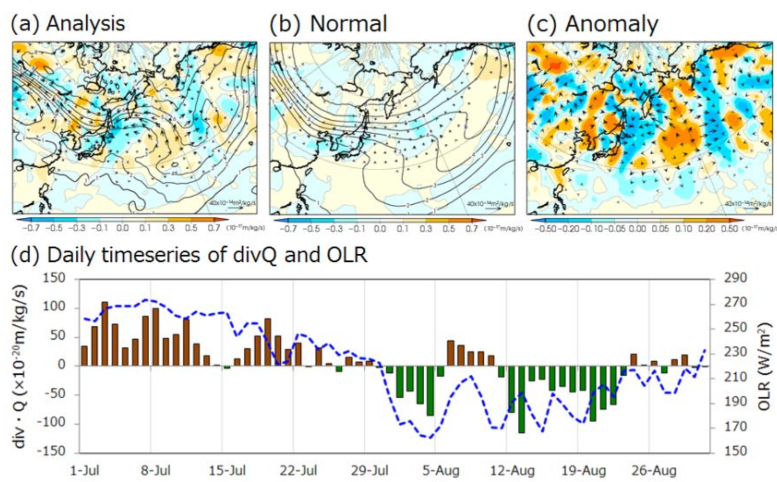

Fig. 3 (a) Actual, (b) normal, and (c) anomalous Q-vectors at 500 hPa (vector; unit: $m^2/kg/s$) and its divergence (shading; unit: m/kg/s) derived from monthly mean in August 2016. The contour lines in (a) and (b) show 360-K PV at intervals of 1 PVU. (d) Daily time series of the Q-vectors divergence (brown bars denote divergence and green ones denote convergence) and OLR (blue dashed lines) averaged over 15^oN–25^oN and 150^oE–180^oE.

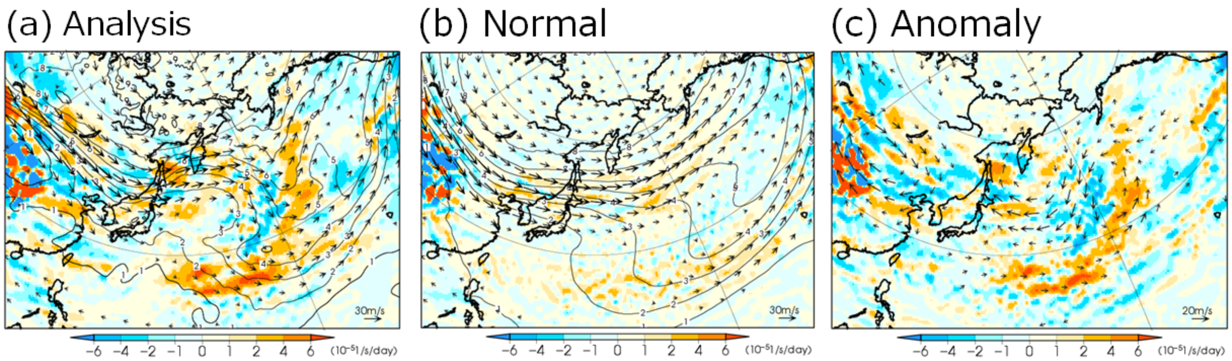

Fig. 4 Monthly mean (a) actual, (b) normal, and (c) anomalous vertical differences (200 to 850 hPa) of vorticity advection (shading; unit: 10^{-5} s^{-1} day^{-1}) by QG horizontal wind (vector) in August 2016. The contour lines in (a) and (b) show 360-K PV at intervals of 1 PVU.

or three peaks of strong convergence during the period from end of July to late 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 sub-tropical western North Pacific (Figs. 2b and 2c).

Figure 4 shows vertical differences of vorticity advection by QG horizontal wind between 200 hPa 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. 2b). 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 influence of extra-tropical circulation on the sub-tropical circulation in August 2016, the Q-vector and vorticity budget diagnoses indicate that the RWB to the east of Japan and the associated strong mid-Pacific trough contribute to the enhanced convective activities over the sub-tropical western North Pacific through the QG upward motion.

An inter-annual time series of 350-K PV averaged over the area east of Japan and OLR anomalies and Q-vector divergence averaged over latitude bands near 20°N in the western Pacific (Figs. 5a, 5b and 5c) indicates the lowest on record in August 2016 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 the enhanced convective activities through the QG upward motion and the associated formation of tropical cyclones.

To assess the impact of the tropical convective activities on the atmospheric circulation, a deterministic numerical

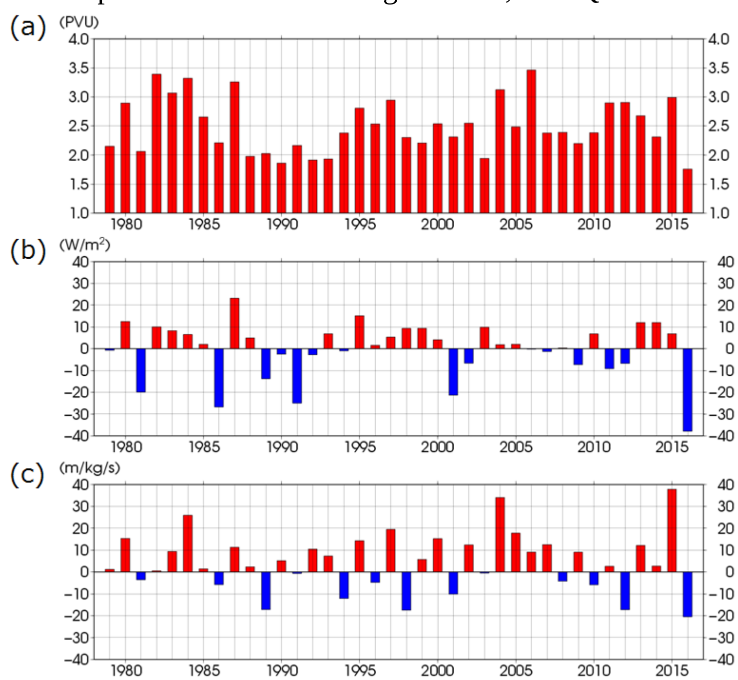

Fig. 5 For August, from 1979 to 2016, inter-annual time series of monthly mean (a) 350-K PV (PVU) averaged over 35°N–45°N and 150°E–180°E; (b) OLR anomalies (W/m^2) averaged over 15°N–25°N and 150°E–180°E; and (c) Q-vectors divergence anomalies (10^{-17} m/kg/s) averaged over 15°N–25°N and 150°E–180°E.

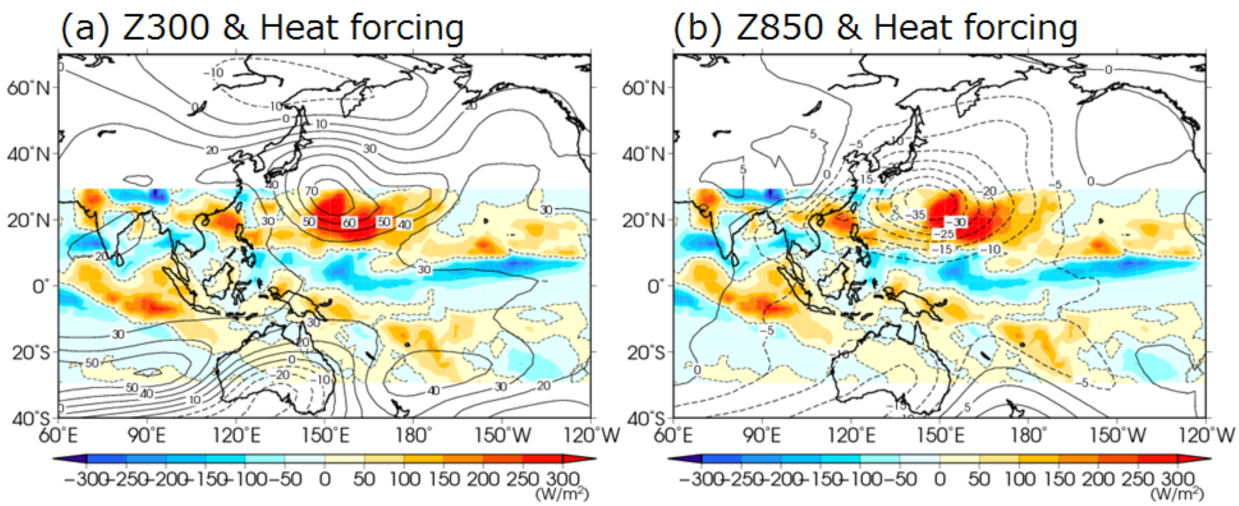

Fig. 6 Steady linear responses of (a) 300-hPa and (b) 850-hPa height (contour lines) in the LBM to diabatic heating anomalies in the tropics (30°S–30°N) for August 2016 (shading). The anomalies represent deviations from the basic states of the normal in August. The contour intervals is (a) 10 and (b) 5 m. Dashed contours show negative values.

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 (shading in Fig. 6) indicate the existence of strong heat sources associated with enhanced convective activities over and around 20°N in the western North Pacific. The LBM responses of 300-hPa and 850-hPa height fields show positive (anti-cyclonic) and negative (cyclonic) anomalies over the seas southeast of Japan, respectively, indicating the Rossby-wave response to the strong heat sources (Figs. 6a and 6b). The responses of cyclonic circulation anomalies at 850 hPa are consistent with the circulation anomalies observed in August 2016 (Fig. 2c), indicating the influences of the enhanced convective activities over the sub-tropical western North Pacific on the large-scale cyclonic circulation anomalies and presumably on the origin and track of the tropical cyclones. By contrast, the responses of anti-cyclonic circulation anomalies at 300 hPa differ from the anomaly patterns observed in August 2016 (Fig. 2a), indicating that the upper tropospheric circulation anomalies primarily formed not by the responses to the enhanced convective activities in the sub-tropical western North Pacific but by the quasi-stationary Rossby-wave propagation from Eurasia along the Asian jet stream (see WAF shown in Fig. 2a).

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 sub-tropical western North Pacific 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 sub-tropical western North Pacific 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 sub-tropical western North Pacific 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 sub-tropical western North Pacific 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 six 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 sub-tropical western North Pacific. 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 sub-tropical 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. 5. The significant amplification of the blocking high to the east of Japan (Fig. 2a) and the lower tropospheric large-scale cyclonic circulation over the sub-tropical western North Pacific 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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