Structures, Environment and Moisture Transportation of Explosively Developing Extratropical Cyclones in the Northwestern Pacific Region

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1. Introduction

The rapid deepening of extratropical cyclones is one of the most exciting topics in the modern meteorology from academic perspective as well as from the forecasting natural disaster protection and traffic safety perspective. According to past studies, upper vorticity advections and latent heat releases in the lower level are crucial processes for the explosive cyclogenesis. Since extratropical cyclones exchange heat and moisture between the lower and higher latitudes, variations of cyclone tracks are one of the most important topics in the climate research.

The purpose of this study is to characterize explosive cyclones in the northwestern Pacific region. Geographical, seasonal variation and statistical properties are analyzed at first using an objectively analyzed data set and then their favorable synoptic and planetary scale environment, cyclone's interior structures and moisture transportation are focused in this paper.

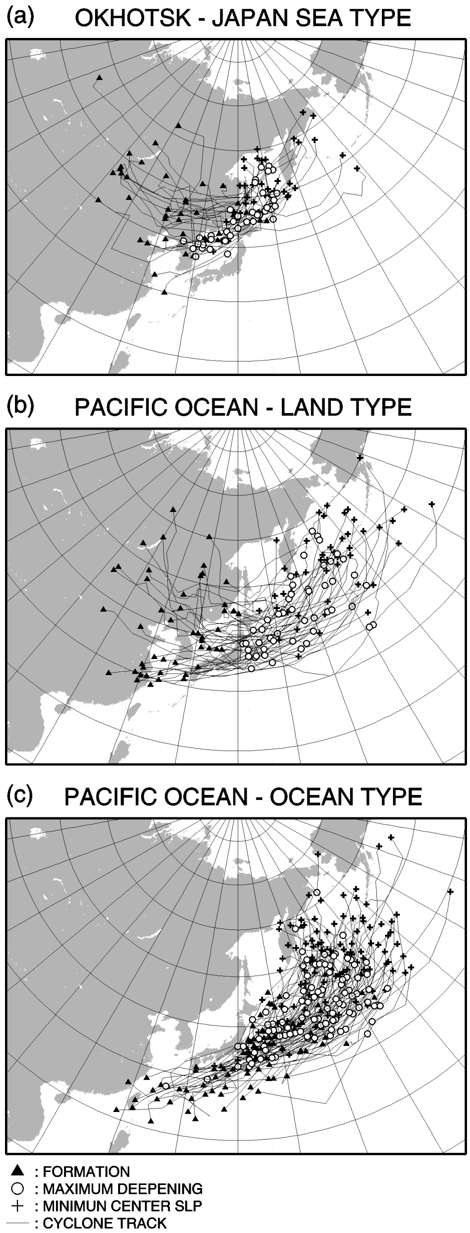

Figure 1. Cyclone tracks of (a) Okhotsk – Japan Sea (OJ), (b) Pacific Ocean – Land (PO-L) and (c) Pacific Ocean – Ocean (PO-O) cyclones.

2. Data and Methodology

The data source for this study is a global objectively analyzed data set (GANAL) provided by Japan Meteorological Agency (JMA). GANAL data set contains sea level pressures, geopotential heights, air temperatures and dew point depressions with 1.25 ° for horizontal resolutions, and 18 vertical levels from surface to 10 hPa. The temporal interval is 12 hour prior to April 1994, and 6 hours afterwards. Five cold seasons between October and March from 1994 to 1999 were used in the analysis. The analyzed region was taken between 100 ° E and 180 ° E in longitude and between 20 ° N and 65 ° N in latitude. A cyclone was defined as a minimum in the sea level pressure field having a pressure difference at least 1 hPa from surrounding grids. A measure of the cyclone deepening (unit: Bergeron) was calculated from the following definition for each cyclone:

$$\left\{\frac{p_{t-6}-p_{t+6}}{12}\right\}\cdot\frac{\sin 60^\circ}{\sin\frac{\phi_{t-6}+\phi_{t+6}}{2}} \ge 1, \qquad (1)$$

where t is analyzed time in hour, p is the sea level cyclone center pressure, and ϕ is the latitude of the cyclone. An explosively developing cyclone was defined as a cyclone that had a deepening rate at least 1 Bergeron. Cyclones that disappeared within 24 hours were excluded from the analysis.

To diagnose explosive developing cyclones, the Zwack – Okossi development equation simplified by Lupo et al. (1992) was used.

The equation can be written as follows:

$$\frac{\partial \zeta_{gl}}{\partial t} = \mathrm{P_d} \int_{p_t}^{p_l} (-\mathbf{V}\cdot\nabla\zeta_{\mathbf{a}})dp - \mathrm{P_d} \int_{p_t}^{p_l} \left\{ \frac{R}{f} \int_p^{p_l} \nabla^2(-\mathbf{V}\cdot\nabla T)\frac{dp}{p}\right\} dp - \mathrm{P_d} \int_{p_t}^{p_l}\left\{\frac{R}{f}\int_p^{p_l}\nabla^2\left(\frac{Q}{c_p}\right)\frac{dp}{p}\right\}dp - \mathrm{P_d}\int_{p_t}^{p_l}\left\{\frac{R}{f}\int_p^{p_l}\nabla^2(S\omega)\frac{dp}{p}\right\}dp \qquad (2)$$

$$= \mathrm{P_d} \int_{p_t}^{p_l}(\mathrm{VADV + TADV + LATH + ADIA})\,dp,$$

where p_l is the pressure at the lower boundary (1000 hPa), p_t is that at the upper boundary (50 hPa), ζ_{gl} is the geostrophic relative vorticity as the lower boundary, ζ_a is the absolute vorticity, f is the Coriolis parameter, R is the gas constant of the dry air, **V** is the horizontal wind, Q is the diabatic heating and cooling rate, c_p is the specific heat at constant pressure, S is static stability, ω is the vertical wind in isobaric coordinate, and $\mathrm{P_d} = 1/(p_l - p_t)$. The first term in the right-hand side of the equation (2), which is referred as VADV, is the effect of horizontal absolute vorticity advection on the geostrophic relative vorticity tendency. The second term (TADV) describes the effect of horizontal temperature advection and the third term (LATH) represents diabatic heating and cooling. The fourth term (ADIA) is the isentropic temperature change with vertical motion.

3. Results

A total of 224 explosive developing cyclones were analyzed. They were classified into three types according to positions where they formed and deepened most explosively. Figure 1 shows tracks of three types: first one formed over the continent and developed over the Sea of Okhotsk or the Sea of Japan (Okhotsk – Japan Sea type,

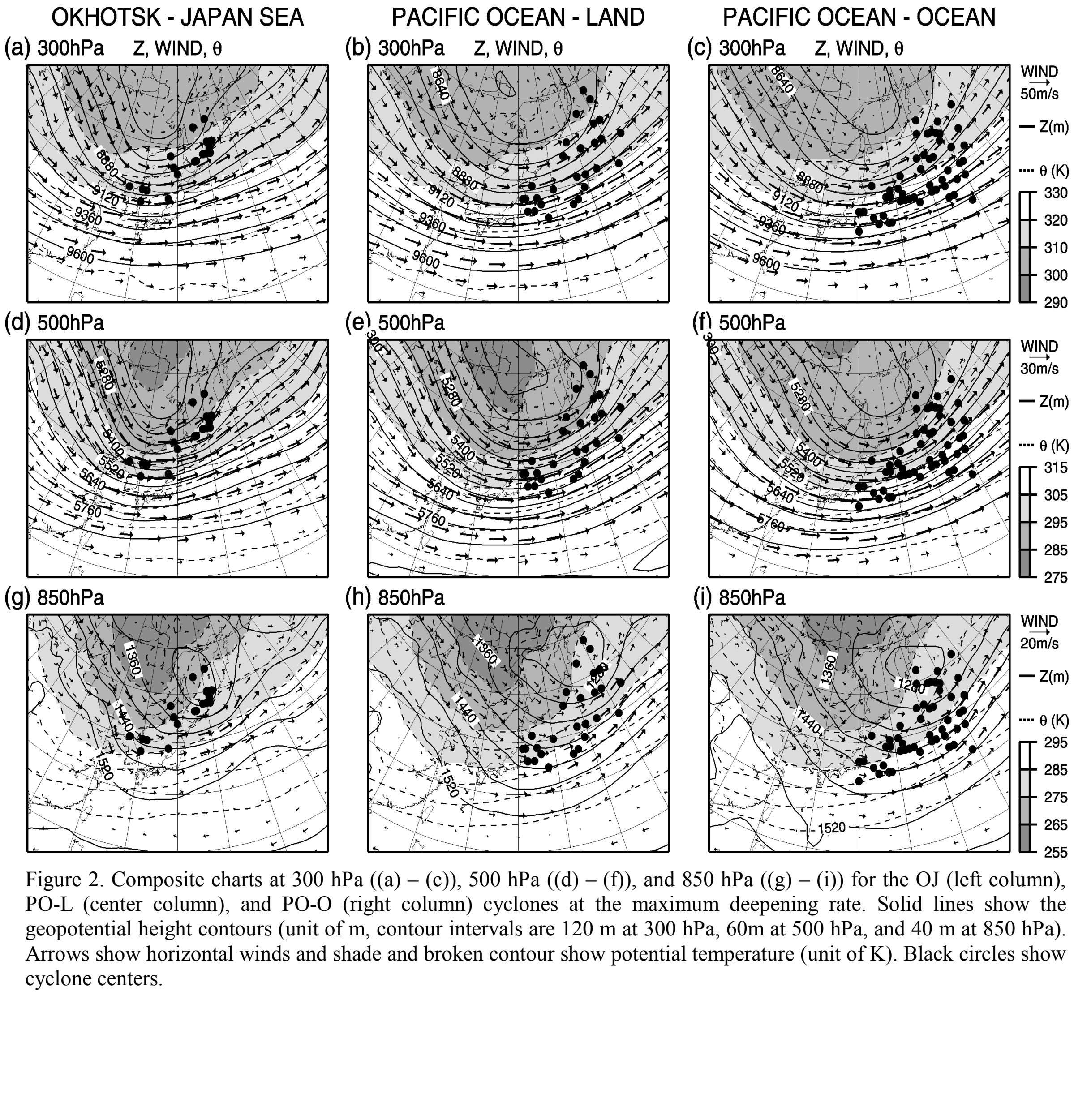

Figure 2. Composite charts at 300 hPa ((a) – (c)), 500 hPa ((d) – (f)), and 850 hPa ((g) – (i)) for the OJ (left column), PO-L (center column), and PO-O (right column) cyclones at the maximum deepening rate. Solid lines show the geopotential height contours (unit of m, contour intervals are 120 m at 300 hPa, 60m at 500 hPa, and 40 m at 850 hPa). Arrows show horizontal winds and shade and broken contour show potential temperature (unit of K). Black circles show cyclone centers.

hereafter referred as OJ type); second one formed over the land and developed over the Pacific Ocean (Pacific Ocean – Land type, referred as PO-L type); last one formed over the ocean and developed over the Pacific Ocean (Pacific Ocean – Ocean type, referred as PO-O type). Statistical analyses suggests that OJ cyclones frequently appear in late fall and have the lowest deepening rates of the three type; PO-L cyclones had minimum deepening rates and frequently occurred in early and late winter; and PO-O cyclones mainly occurred in mid-winter and had the largest deepening rates.

Two kinds of composite analyses were conducted to understand the structures and mechanisms of development. The first composite analysis used geographically fixed coordinates. Composite charts when each cyclone had maximum deepening rate are shown in Fig. 2. OJ cyclones develop explosively accompanied with a relatively small upper level trough over the northern China with short jet streak and the cold air mass still weak over the Asian Continent. As the cold air outbreak is weak, a low level broclinic zone forms over the Sea of Japan and the Sea of Okhotsk where OJ cyclones develop explosively. PO-L cyclones are accompanied with a zonally stretched jet stream over Japan and the northwestern Pacific Ocean in upper level. A cold air mass forms over the northern Asian Continent and a baroclinic zone forms over the southeastern coast of Japan toward eastern offshore at lower level. When PO-O cyclones develop, a strong jet streak is associated with an upper trough located over the south coast of Japan and a cold air mass extends over the northwestern Pacific Ocean. These conditions reflect the formation of the cold air mass over the Asian Continent, and lead to seasonal variation of occurrence frequency.

To investigate interior structures and development mechanisms for each type of cyclone, Another kind of composite analysis was conducted in which each element to be analyzed was superimposed over the position of

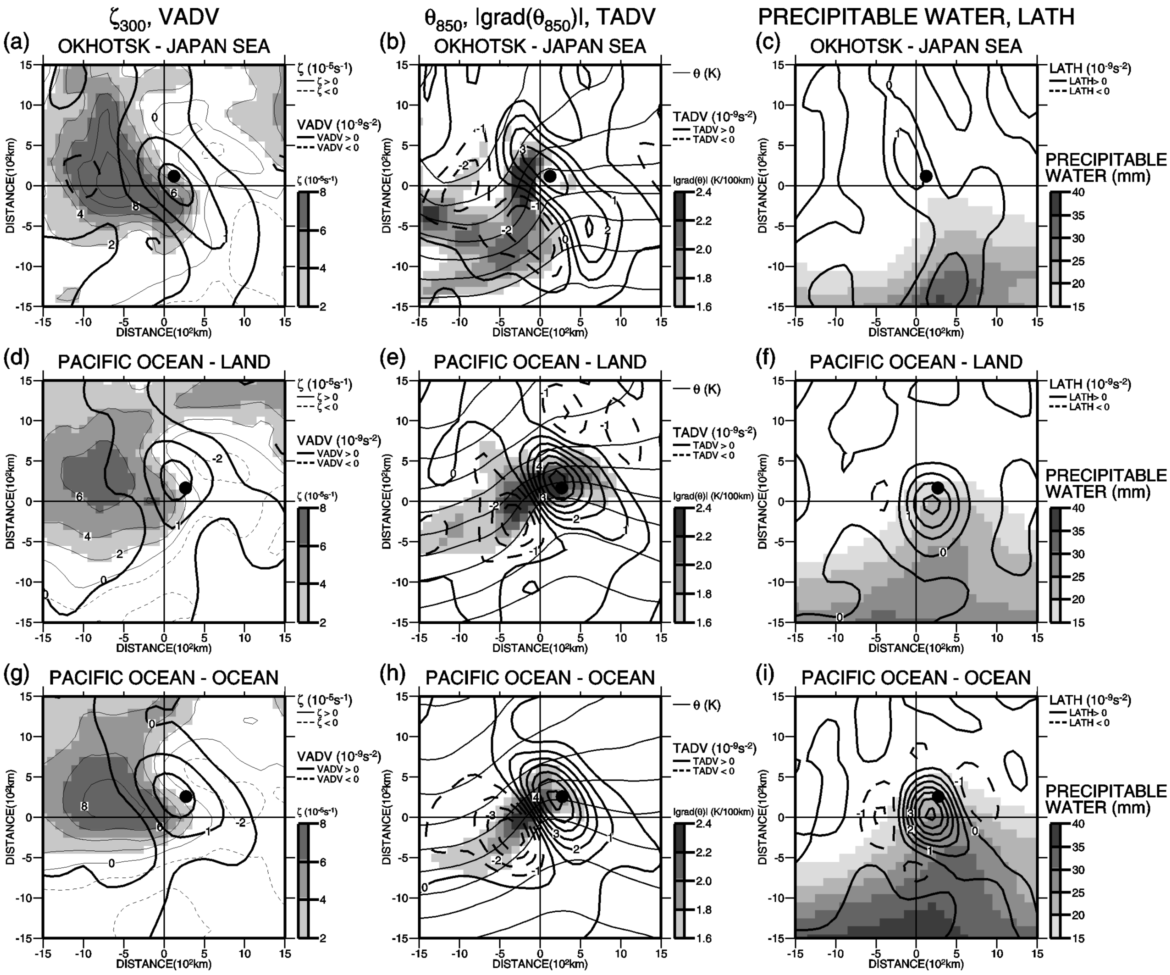

Figure 3. Composite maps at maximum deepening rate of VADV, relative vorticity at 300 hPa (left column), TADV, potential temperature and gradient at 850 hPa (center column) LATH and precipitable water (right column) for OJ ((a) – (c)), PO-L ((d) – (f)), and PO-O ((g) – (i)) cyclones. Black circles show the cyclone center 6 hours after maximum deepening rate and center of figure shows cyclone center.

the surface cyclone center at its maximum deepening rate. Figure 3 shows the composite charts of each term integrated vertically in equation (2) and related physical quantities. The VADV term associated with an upper trough and TADV associated with lower level temperature advection contribute to development of OJ cyclones mainly. In the PO-L cyclones the TADV contribution is largest with LATH and VADV contributions secondary, since PO-L cyclones are associated with strong westerly jet stream. In PO-O cyclones, the LATH term associated with the inflow of moist air near cyclone center mainly contributes to the development. The distribution of latent release maximum may relate to the difference of maximum deepening rate of each type.

Finally, the moisture transportation associated with each type of cyclone was investigated. Figure 4 shows composite charts of vertical integrated horizontal vapor flux, its divergence, and sea level pressure averaged between cyclone formation and maximum deepening rate for each type of cyclone. For OJ type, southwesterly vapor flux is stronger over the east of Japan and converges around southern part of the Kamchatka Peninsula. PO-L type shows strong zonal water vapor flux from the south coast of Japan to the northeastern Pacific Ocean and the convergence area appears over the northeastern Pacific Ocean. As the PO-O cyclones develop deeply, a strong convergence zone and remarkable northeastward vapor fluxes are identified over the central northern Pacific Ocean.

4. Summary

To better understand explosively developing extratropical cyclones in the northwestern Pacific region, formation and maximum deepening positions, tracks, atmospheric conditions, and moisture transportation were analyzed using a global objectively analyzed data set (GANAL) provided by Japan Meteorological Agency (JMA). Explosively deepening cyclones were classified into three types by places of formation and rapidly development. OJ cyclones appeared over the east Asian Continent and developed over the Sea of Okhotsk and the Sea of Japan, and developed due to vorticity advections associated with an upper short wave trough and temperature advections at lower level. PO-L cyclones formed over the eastern Asian Continent, traveled eastward and developed over the northwestern Pacific Ocean with zonally stretched jet stream. Temperature advection and latent heat release mainly contributed to the development. PO-O cyclones formed and developed over the northwestern Pacific Ocean, occurred most frequently and tended to have most rapidly deepening in three types. They were developed by latent heat release coupled close to cyclone center.

The analyses of moisture transportation suggested that OJ cyclones transported water vapor to the Kamchatska Peninsula and the eastern Bering Sea, PO-L cyclones to the northeastern Pacific Ocean, and PO-O cyclones to the Bering Sea and the Gulf of Alaska.

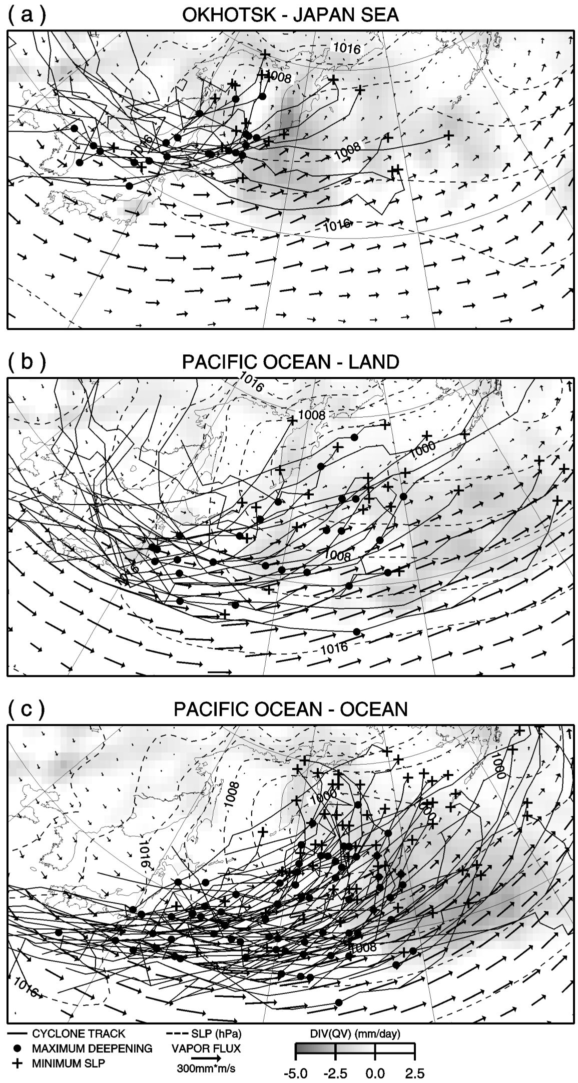

Figure 4. Composite charts of vertically integrated water vapor flux, divergence and sea level pressure averaged from formation to maximum deepening rate, and cyclone tracks for (a) OJ, (b) PO-L and (c) PO-O cyclones.

References

Lupo, A. R., P. J. Smith, and P. Zwack, 1992: A diagnosis of the explosive development of two extracyclones. *Mon. Wea. Rev.*, 120, 1490-152.