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

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ABSTRACT

The characteristics of explosively developing extratropical cyclones in the northwestern Pacific region are analyzed using the global objectively Analyzed dataset (GANAL) provided by the Japan Meteorological Agency (JMA). In the present paper, these cyclones are classified into three types, depending on positions of formation and of rapid development: OJ cyclones originate over the eastern Asian continent and develop over the Sea of Japan or the Sea of Okhotsk; PO-L cyclones are also formed over the Asian continent and develop over the northwestern Pacific Ocean; and PO-O cyclones are formed and develop over the northwestern Pacific Ocean. Statistical analyses suggest that OJ cyclones frequently appeared in late fall and had the smallest deepening rates of the three types; PO-L cyclones had medium deepening rates and frequently occurred in early and late winter; and PO-O cyclones mainly occurred in midwinter and had the largest deepening rates.

Two kinds of composite analyses were conducted to understand the structures and the mechanisms of development. The first composite analysis used geographically fixed coordinates. The results suggest that the favorable atmospheric conditions for the development of each type of cyclone are closely connected to the presence and extension of the cold air mass over the Asian continent. In addition, these conditions are closely related to seasonal variations across the area. The other analysis of cyclone mesoscale structure, using cyclone-relative coordinates at the maximum deepening rate, suggests that OJ cyclones had a short-wave, upper-level jet streak and a strong baroclinic zone in the lower level. PO-L cyclones, associated with a zonally stretched jet stream, had a remarkable midlevel baroclinic zone. PO-O cyclones with a strong jet streak also had a distinct baroclinic zone in the midlevel, and a large water vapor budget (precipitation minus evaporation) appeared around the cyclone center. These cyclone structures reflected vorticity, temperature, and moisture advection, that is, larger-scale atmospheric conditions that affected cyclone development.

1. Introduction

The rapid deepening of extratropical cyclones is one of the most exciting topics in modern meteorology, in academics as well as weather forecasting, natural disaster protection, and traffic safety. Heavy precipitation and severe winds, which sometimes disturb human activities, are often reported with this event. Rapidly deepening cyclones are also considered to be an important contributor to global climate change and energy transportation. Chen et al. (1991) reported climatological characteristics of extratropical cyclones in eastern Asia, describing two active cyclogenesis areas: one downstream of the mountainous region across the Asian continent, the other over the East China Sea and the Sea of Japan. The former was related to lee cyclogenesis, the latter to coastal cyclogenesis in the east of the continent. Nitta and Yamamoto (1974, 1972) analyzed coastal cyclogenesis for medium-scale cyclones, which were defined as having wavelengths between 1000 and 2000 km. They reported statistical analyses and classified cyclones but did not describe the physical implications. Saito (1977) reported a case study of medium-scale cyclones over the East China Sea during the Air Mass Transformation Experiment (AMTEX) in 1975 and concluded that the crucial factors for cyclogenesis were warm air advection, synoptic-scale updraft, and heat supply from the sea surface. Coastal cyclones occasionally developed more rapidly than other cyclones. Sanders and Gyakum (1980) defined an explosively developing extratropical cyclone as a cyclone that had a central sea level pressure decrease normalized at 60 N over 24 hPa in a day (24 h). Explosively developing extratropical cyclones frequently appear in the cold seasons in the east of a continent, such as the northwestern Pacific Ocean and northwestern Atlantic Ocean (Sanders and Gyakum 1980; Roebber 1984). The rapidly deepening cyclones had complicated developing mechanisms, and several atmospheric phenomena on various scales were interrelated, producing the explosive development. Shapiro et al. (1999) discussed a planetary-scale to mesoscale perspective of extratropical cyclones.
The planetary-scale environment such as tropopause folding, jet stream, upper-level high potential vorticity, and low-level baroclinicity influences the life cycles of extratropical cyclones. The structures and evolutions of explosively developing cyclones were investigated by Neiman and Shapiro (1993), Neiman et al. (1993), and Liu et al. (1997) from an observational point of view; by Kuo and Low-Nam (1990) and Chen and Dell’Osso (1987) from a numerical point of view; and by Manobianco (1989) and Wang and Rogers (2001) using synoptic-scale analyses. These papers suggest that a shortwave trough in the upper and middle troposphere approached over the shallow cyclone, inducing strong upward forcing and creating updrafts that occurred around the cyclone center in rapidly developing cyclones. Kuo and Low-Nam (1990) compared case studies using numerical models and examined the physical processes of cyclone development. Sinclair (1997) and Sinclair and Revell (2000) discussed upper- and lower-level conditions favorable to cyclogenesis. Cyclogenesis frequently occurred above the south entrance of the SST gradient maxima and beneath the equatorward entrance and poleward exit of an upper-level jet streak. In the northwestern Pacific region, Chen et al. (1992) showed that explosive cyclones often appeared over the Sea of Japan and over the Kuroshio Current. They also suggested that two peaks of monthly frequency existed in early winter (January) and late winter (March) over the northwestern Pacific Ocean. However, Sanders and Gyakum (1980) reported that a single peak, in February, occurred over the northwestern Atlantic Ocean. Except for studies by Bullock and Gyakum (1993), Kelly et al. (1994), and Gyakum and Danielson (2000), there have been few analyses of synoptic conditions for rapid development over the northwestern Pacific region.

The purpose of the present paper is to characterize explosive cyclones in the northwestern Pacific region. Geographical and seasonal variation and statistical properties are analyzed first using an objectively analyzed dataset. Favorable synoptic- and planetary-scale environments and mesoscale structures around the cyclone center are investigated using composite analysis. Data sources are described in section 2, and section 3 provides the results of statistical analysis, larger-scale environment, and structure and development factors. The discussion and conclusions are found in sections 4 and 5, respectively.

2. Data sources and a definition of the explosively developing cyclone

The data source for the present paper is the global objectively analyzed dataset (GANAL) provided by the Japan Meteorological Agency (JMA). GANAL includes sea level pressures, geopotential heights, air temperatures, and dewpoint depressions with horizontal resolutions of 1.875° in latitude and longitude and 16 vertical levels from the surface to 10 hPa, collected from March 1988 through February 1996. After this date, resolution improved to 1.25° for horizontal resolution and to 18 vertical levels between the surface and 10 hPa. The temporal interval is 12 h prior to April 1995 and 6 h
afterward. Five cold seasons from 1 October 1994 to 31 March 1999 are used in the present analysis.

The analyzed region was taken between 20° and 65°N in latitude and between 100°E and 180° in longitude (the area surrounded by a bold solid line in Fig. 1b). A cyclone was defined at any grid point with sea level pressure at least 1 hPa lower than the value at an adjacent grid point. The cyclone deepening rate (Bergeron) is calculated from the following definition for each cyclone:

\[
\text{Cyclone deepening rate} = \left\lfloor \frac{p(t_2) - p(t_1)}{12} \right\rfloor \frac{\sin 60°}{\frac{\phi(t_2) - \phi(t_1)}{2}},
\]

where \( t \) is analyzed time in hours, \( p \) is the sea level pressure at the cyclone center, and \( \phi \) is the latitude at the cyclone center. Although the definition of Bergeron by Sanders and Gyakum (1980) used a 24-h pressure change, a 12-h pressure change is used in this paper to find an instance of most rapid deepening in a cyclone’s life. An explosively developing cyclone was defined as having a deepening rate of at least 1 Bergeron. Cyclones that disappeared within 24 h after initial appearance were excluded from the analysis.

3. Results

a. Statistical analysis

In total, 224 explosively developing cyclones were analyzed. Figure 1 shows the locations of formation, maximum deepening, and minimum center pressure. Although they formed over land and ocean (Fig. 1a), the maximum deepening almost always occurred over the ocean at latitudes greater than 35°N (Fig. 1b). The areas of maximum deepening were classified into two regions. One region was over the Sea of Japan and the Sea of Okhotsk, which are near the Asian continent, and the other was over the northwestern Pacific Ocean. Although most cyclones that deepened maximally (developed) over the Sea of Japan and the Sea of Okhotsk were formed on the Asian continent, those that developed over the Pacific Ocean were further classified into two types: those formed over the continent and those formed over the ocean. Therefore, three types of cyclones existed in total: those formed over land and developed over the Sea of Japan or the Sea of Okhotsk (the Okhotsk–Japan Sea type, hereafter referred to as OJ type); those formed over land and developed over the Pacific Ocean (the Pacific Ocean–land type, referred to as PO-L type); and those formed over the ocean and developed over the Pacific Ocean (the Pacific Ocean–ocean type, referred to as PO-O type). Cyclone tracks from place of formation to that of minimum center pressure.

Fig. 2. Cyclone tracks of (a) OJ, (b) PO-L, and (c) PO-O cyclones. Triangles show positions of formation, circles show positions of maximum deepening rate, and crosses show positions of minimum center sea level pressure.
TABLE 1. The number of explosive cyclone events.

<table>
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<tr>
<th></th>
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<th>PO-L</th>
<th>PO-O</th>
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sure are shown in Fig. 2. The OJ cyclones formed over the continent and developed maximally during passage over the sea (Fig. 2a). PO-L cyclones formed over the continent, moved across the Japan archipelago, and developed over the Pacific Ocean (Fig. 2b). PO-O cyclones formed over the ocean near the southern Asian continent, moved to south of Japan, and developed over the ocean (Fig. 2c).

The cyclones identified as explosively developing cyclones were further classified into three categories of intensification: a strong intensification (ST) cyclone is larger than 1.8 Bergeron, a moderate intensification (MO) cyclone ranges between 1.3 and 1.8 Bergeron, and a weak intensification (WE) cyclone is less than 1.3 Bergeron. These three classifications of intensification were followed by Sanders (1986). The frequency of each type is summarized in Table 1. PO-O cyclones occurred most frequently (110 cases), followed by PO-L cyclones (50 cases), and OJ cyclones (42 cases). In the five cold seasons from October 1994 to March 1999, 202 cyclones were classified into the above three types, and the remaining 22 cases were unclassified. Of these, 14 formed and developed over the continent, and 5 formed over the northwestern Pacific Ocean, moved northwestward, and developed over the Sea of Okhotsk. The others formed over the Sea of Okhotsk, moved southeastward, and developed over the northwestern Pacific Ocean. Most of the OJ cyclones were categorized as WE, and only three cases were ST. Most of the PO-L cyclones were MO and most of the PO-O cyclones were also categorized as MO. Approximately two-thirds of ST cyclones belong to PO-O cyclones. Figure 3 shows the frequency distribution of maximum deepening rate of the three types. The average properties of PO-O, PO-L, and OJ cyclones were 1.51 Bergeron (standard deviation: 0.43 Bergeron), 1.49 Bergeron (standard deviation: 0.36 Bergeron) and 1.33 Bergeron (standard deviation: 0.30 Bergeron), respectively. This may in-
dicate that PO-O cyclones are the strongest of the three, PO-L cyclones are next, and OJ cyclones are the weakest. Although the frequency of OJ cyclones peaked at 1.1–1.2 Bergeron, frequency decreased nearly monotonically with intensity. PO-L and PO-O cyclones peaked at 1.3–1.4 and 1.2–1.3 Bergeron, respectively, with several cases stronger than 2.0 Bergeron. The strongest deepening rate for the PO-O cyclones was about 3.0 Bergeron.

The distribution of monthly frequencies for the three types of cyclones during the five cold seasons from October 1994 to March 1999 are shown in Fig. 4. These frequencies for each season are also listed in Table 2. Figure 4a shows the total frequency of the explosively developing cyclones. Although only a single peak, in January, was evident for “total” frequency, monthly frequency patterns were different among cyclone types (Figs. 4b–d): OJ cyclones peaked in November (late autumn), PO-L cyclones peaked in December (early winter) and February (late winter), and PO-O cyclones peaked in January (midwinter). Although there are variations in occurrence in each season (Table 2), the above mentioned seasonal appearance tendencies for the different types are identifiable. Chen et al. (1992) reported that explosive cyclones frequently occurred in January and March over the northwestern Pacific Ocean, while Sanders and Gyakum (1980) reported only a peak in January over the northwestern Atlantic Ocean. While our target area is close to the analysis region of Chen et al. (1992), differences in frequencies between the types are evident.

In summary, explosively developing cyclones over the northwestern Pacific region were classified into three types by locations of formation and of maximum deepening, revealing different characteristic deepening intensities, with occurrence frequencies exhibiting distinct seasonal variations.

b. Larger-scale environment

Schultz et al. (1998) suggested that the surface frontal structure was changed by a larger-scale flow and affected cyclone development. Wang and Rogers (2001) reported that environmental baroclinicity affects the geographical properties of the development of explosive cyclones. They also suggested that cyclone structures may change under the influence of atmospheric and geographical environments. To understand the influence of
the larger-scale environment on each type of cyclone, a composite analysis was conducted. Three cold seasons, from October 1996 to March 1999, were analyzed because of the coarse spatial resolution of the dataset prior to 1996. Composite analysis was performed using geographically fixed positions for each type. All explosive cyclones that occurred during the three winter seasons were used in the analysis. The key time examined in the composite analysis was the time of the most rapid deepening.

Composite charts for OJ cyclones are shown in Fig. 5. An upper-level trough with large curvature can be seen to extend from Siberia to northeastern China at 300 and 500 hPa. A confluence of wind occurred over China, diffuence occurred over the northwestern Pacific Ocean, and a relatively short and weak jet streak associated with the trough was located over the Sea of Japan and the Japanese islands. A baroclinic zone was located over northern China and the east coast of the Asian continent at 850 hPa, behind which a cold air mass presented. The 850-hPa geopotential height was a minimum over the Sea of Okhotsk, and a strong wind was identified southeast of the low. Along the southeastern boundary of the cold air mass, OJ cyclones developed. These conditions suggest that the low-level baroclinicity near the continental coast over the ocean and the upper- and middle-level vorticity advection associated with a short-wave trough are favorable factors for the development of OJ cyclones.

Composite analyses of PO-L cyclones are shown in Fig. 6. A zonally stretched strong jet stream associated with a long-wave upper-level trough can be seen near 35°N at 300 and 500 hPa. The 850-hPa geopotential height was a minimum over the Kamchatka Peninsula. A baroclinic zone, which was weaker than that of OJ cyclones, extended over southern Japan and east of Japan at 500 and 850 hPa. A cold air mass presented over the northeastern Asian continent, and a low-level baroclinic zone was zonally extended over southern Japan and east of the Japan mainland. PO-L cyclones developed in a low-level baroclinic zone east of Japan and northeast of a zonally stretched jet stream.

Figure 7 shows composite analyses of PO-O cyclones. The upper-level trough became shorter than that of PO-L cyclones with its axis extending from Siberia to the northwestern Pacific Ocean, through the Sea of Okhotsk in the upper and middle levels. An upper-level strong jet streak associated with the trough was located over the southeastern coast of Japan. The jet streak was stronger than that of PO-L cyclones at 300 and 500 hPa. An 850-hPa geopotential height was a minimum east of the Kamchatka Peninsula. The features were similar to the synoptic conditions reported by Bullock and Gyakum (1993), Kelly et al. (1994), and Gyakum and Danielson (2000). The baroclinic zone appeared over middle China at 300 hPa and the southeastern coast of Japan at 500 and 850 hPa. It was weaker than that of PO-L cyclones at 850 hPa and stronger at 500 hPa, which may be a result of the differences in the cold air extension from the east coast of the Asian continent to the baroclinic zone. The fetch of a cold air mass from the continent for PO-O cyclones was longer than that for PO-L cyclones. Explosive deepening occurred under the diffluence region of the upper-level jet streak above the low-level baroclinic zone.

Figure 8 shows the difference fields between PO-L and PO-O (PO-L field minus PO-O field). A positive wind difference shows stronger (weaker) wind in PO-L (PO-O) cyclones than in PO-O (PO-L) cyclones and vice versa. A positive region appeared approximately between 40° and 50°N at 300 and 500 hPa, and a negative region appeared approximately between 25° and 40°N. These difference field patterns show that upper- and midlevel winds were stronger in PO-L cyclones in the northern area than at 40°N and were stronger in PO-O cyclones in the southern area. The jet stream in PO-L cyclones was located northward and that in PO-O cyclones was southward. For temperature difference fields, a positive temperature difference indicates colder (warmer) in PO-O (PO-L) cyclones than in PO-L (PO-O) cyclones and vice versa. A positive region extended zonally from the southern Asian continent to the east of the Japanese islands at 850 and 500 hPa. The cold

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(c) Pacific Ocean–land

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(d) Pacific Ocean–ocean

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Fig. 5. Composite charts for OJ cyclones at the maximum deepening rate. (left) The geopotential height (thin solid line, unit of m, contour intervals are 120 m at 300 hPa, 60 m at 500 hPa, and 40 m at 850 hPa), the horizontal wind vector (arrow), and wind velocity (bold solid line and shade) at (a) 300, (c) 500, and (e) 850 hPa. (right) The temperature (thin solid line, unit of K, contour intervals are 4 K) and the horizontal temperature gradient (bold solid line and shade) at (b) 300, (d) 500, and (f) 850 hPa. Circles show surface cyclone centers.

Air mass in the middle and lower atmosphere was more extended southward in PO-O cyclones than that in PO-L cyclones. The extension of the continental cold air mass causes the meridional shift of the jet stream through the thermal wind relationship.

The larger-scale atmospheric conditions exhibited different features for each of the three types. These conditions reflect the presence and extension of a cold air mass over the Asian continent. The extension of the cold air mass was smaller for OJ cyclones and larger for PO-O cyclones. The upper-level trough, the jet streak, and the low-level baroclinicity were associated with the presence of a cold air mass over the continent. While OJ cyclones developed under a shorter upper-level trough located over the eastern Asian continent with a distinct low-level baroclinic zone over the Sea of Japan, PO-L cyclones developed under a zonally stretched upper-level jet stream near 35°N and a relatively weaker low-level baroclinic zone located over southern Japan and the northwestern Pacific Ocean. For PO-O cyclones, a strong jet streak was located over the southeast of Japan and a weaker low-level baroclinic zone extended from the southern coast of Japan to the northwestern Pacific Ocean. The cold air mass spread

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over the northwestern Pacific Ocean and the East China Sea. The seasonal variation of appearance frequency, as shown in Fig. 4, may be related to the extension of the cold air mass. This will be further discussed in section 4.

c. Zwack–Okossi development equation

The previous section discussed the geographically fixed larger-scale atmospheric environments. The analysis revealed that an upper-level jet stream and a low-level baroclinicity, which were related to the cold air mass over the continent, differed among cyclone types. However, their quantitative contributions to cyclone development were vague. A diagnosis using a geostrophic relative vorticity tendency equation will be used to investigate development mechanisms for extratropical cyclones. Figure 9 shows a scatter diagram between the maximum deepening rate and surface vorticity tendency. The vorticity tendency was calculated using the geostrophic wind circulation increment by finite-difference method with a 12-h interval. Values were averaged by an area within 500 km of the cyclone center 6 h after observing the maximum deepening rate. The graph shows a positive correlation, and the surface cyclonic circulation indeed increased after cyclone rapid development. The relationship between the surface pressure tendency and the surface geostrophic vorticity tendency, which shows a relatively good positive correlation, depends on cyclone scale, speed, and magnitude. Figure 9 reveals that a diagnosis for the explosive cyclogenesis analysis through the geostrophic vorticity tendency would be appropriate.

The Zwack–Okossi (1986) development equation (Z–O equation) was used to diagnose explosive cyclogen-
esis. The Z–O equation describes a geostrophic relative vorticity tendency at the lower boundary as a result of dynamic and thermodynamic forcing vertically integrated through the atmosphere. Zwack and Okossi (1986) derived the quasigeostrophic version and Lupo et al. (1992) generalized and simplified the equation, known as the “extended form.” This form may be appropriate for synoptic-scale diagnoses and is used in the present study neglecting the frictional term. The equation can be written as follows:

\[
\frac{\partial \zeta_{gl}}{\partial t} = p_l \int_{p_l}^{p_t} (-\nabla \cdot \nabla \zeta_{gl}) \, dp - p_d \int_{p_t}^{p_l} \left[ R \int_{p_t}^{p} \frac{\nabla \cdot (-\nabla \cdot \nabla T)}{p} \, dp \right] dp
\]

\[
- p_d \int_{p_t}^{p_l} \left[ R \int_{p_t}^{p} \frac{\nabla \cdot (\nabla \phi)}{p} \, dp \right] dp
\]

\[
- p_d \int_{p_t}^{p_l} \left[ R \int_{p_t}^{p} \frac{\nabla \cdot (S v)}{p} \, dp \right] dp
\]

\[
= p_d \int_{p_t}^{p_l} \left( \text{VADV} + \text{TADV} + \text{LATH} + \text{ADIA} \right) \, dp,
\]

where \( p_l \) is the pressure at the lower boundary (1000 hPa), \( p_t \) is the pressure at the upper boundary (50 hPa), \( \zeta_{gl} \) is the geostrophic relative vorticity at the lower boundary, \( \zeta_a \) is the absolute vorticity (\( \zeta_a = \zeta + f \), where \( \zeta \) is the relative vorticity), \( f \) is the Coriolis parameter,
Fig. 8. The difference fields between PO-L and PO-O cyclones (PO-L field minus PO-O field). (left) The wind velocity (thin solid lines and shadings show positive, thin broken lines show negative, and dotted line shows zero) at (a) 300, (c) 500, and (e) 850 hPa. (right) The temperature (thin solid lines and shadings show positive, thin broken lines show negative, and dotted line shows zero) at (b) 300, (d) 500, and (f) 850 hPa.

$R$ is the gas constant of 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 the static stability [$S = \frac{-T(\theta)}{u}(\theta/d\theta/dp)$, where $\theta$ is potential temperature], $\omega$ is the vertical motion in isobaric coordinates ($\omega = dp/dt$), and $P_d = 1/(\rho_i - \rho_v)$. The first term on the right-hand side of Eq. (2), which is referred to as VADV, is dynamic forcing and the effect of horizontal absolute vorticity advection on the geostrophic relative vorticity tendency at the lower boundary. 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 effect of adiabatic temperature change due to vertical motion. Fourth-order and second-order finite-difference methods were used for horizontal and vertical differentiations, respectively, and a trapezoidal method was used for vertical integration to calculate physical quantities. To reduce subsynoptic-scale noise, each term was smoothed by the two-dimensional second-order filtering scheme explained by Shapiro (1970). Results contain less than 25% of the original information with wave-
FIG. 9. A scatter diagram between the cyclone maximum deepening rate (Bergeron, horizontal axis) and the geostrophic vorticity tendency at 1000 hPa [lhs in Eq. (2) by finite-difference method] averaged over an area within 500 km of the surface cyclone center 6 h after observing the maximum deepening rate (unit in $10^{-9} \text{s}^{-2}$; vertical axis). A solid line shows the regression line.

FIG. 10. A scatter diagram between the geostrophic vorticity tendency at 1000 hPa [lhs in Eq. (2) by finite-difference method, horizontal axis] and the total of rhs in Eq. (2) (vertical axis) averaged over an area within 500 km around surface cyclone center 6 h after observing the maximum deepening rate. Units are in $10^{-9} \text{s}^{-2}$. A bold line shows the regression line.

Vertical velocities $\omega$ were calculated by the kinematic method (O’Brien 1970), derived from the vertical integration of horizontal divergence and the boundary conditions where vertical velocities are zero at 1000 and 50 hPa. The diabatic heating and cooling rate ($Q$) expresses both explicit and implicit processes. Evaporative and radiative cooling processes were not considered. The explicit process was considered as the latent heat release on the grid scale and the implicit process as the convective latent heat release in the subgrid scale. The explicit latent heat release was calculated using the methods of Krishnamurti and Moxim (1971) and Vincent et al. (1977) for the grid scale and was proportional to the vertical advection of the saturated specific humidity. This was calculated under the following conditions: 1) upward motion, 2) positive vertical gradient of saturated water vapor mixing ratio, and 3) relative humidity ≥80%. The convective latent heat release in the subgrid scale was calculated by Kuo’s parameterization scheme (Kuo 1965, 1974), improved by Edmon and Vincent (1976), Lin and Smith (1979), and Smith et al. (1984). Kuo’s scheme parameterizes the convective latent heat release (CLHR) as follows:

$$CLHR = \frac{g(1 - b)L}{\left(\frac{\rho_c}{\rho^*} - T(p)\right)} \left(\frac{T_c - T}{T}\right) \int_{\rho^*}^{\rho_c} (T_c - T)\, dp,$$

where $M_t$ is the rate of moisture convergence from the surface to the cloud top; $T$ is the environmental temperature; $T_c$ is the temperature within the cloud; $\theta$ is the potential temperature; $L$ is the latent heat of condensation ($2.501 \times 10^6 \text{ J kg}^{-1}$ for $T \geq -20^\circ\text{C}$; $2.835 \times 10^6 \text{ J kg}^{-1}$ for $T < -20^\circ\text{C}$); $p_b$ is the pressure at the cloud base, the base of the first conditionally unstable layer; $p_t$ is the pressure at the cloud top, the level where the moist adiabat from the cloud base crosses the environmental sounding; $g$ is gravitational acceleration; and $b$ is the fraction of converged water vapor that moistens the atmosphere. When the mean relative humidity from the surface to 500 hPa (RHAV) was greater than 0.8, $b$ was 0. When RHAV was smaller than 0.4, $b$ was 1.0. When RHAV was between these two limiting values, $b = 1.0 - \text{RHAV}$. Following Rausch and Smith (1996), the geostrophic relative vorticity tendency at the lower boundary ($\partial \zeta / \partial t$) forced by each level above was calculated and then vertically integrated.

To evaluate the significance of Eq. (2), we compare the sum of the four terms on the right-hand side (rhs) and the surface vorticity tendency on the left hand side (lhs). The surface vorticity tendency was evaluated using the finite-difference method with a 12-h interval. Values were averaged within 500 km from the cyclone center, 6 h after observing the maximum deepening rate. The results are shown in Fig. 10. The sum of each term on the rhs would be equal to the surface vorticity tendency ($\partial \zeta / \partial t$) on the lhs, if excluded terms and errors in data and estimation are not considered. The sum of each term on the rhs in Eq. (2) is somewhat overesti-
mated. However, this result may be reasonable, as the tendencies estimated by the rhs in Eq. (2) show instant values at the maximum deepening rate and those on the lhs show averaged values over 12 h using the finite-difference method. The positive correlation between the two sides supports the justification of diagnosing the explosive deepening cyclones using Eq. (2).

d. Structures and development factors

To investigate mesoscale 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 the surface cyclone center at its maximum deepening rate. The analysis domain was the area within 1500 km from the cyclone center in the zonal and meridional directions. To reduce the influence of the cyclone strength dispersion, analyses were conducted on MO deepening cyclones, as discussed in section 3a. Each term of Eq. (2) was also evaluated to provide an understanding of the development mechanisms.

Composite analyses of the geopotential heights, horizontal winds, and vertical motions for each type of cyclone are shown in Fig. 11. The legends show the same scale of contour lines and arrows at each height (300, 500, and 850 hPa). On the whole, horizontal winds became stronger with height, stronger updrafts appeared in the middle level (500 hPa), and cyclonic circulation was evident in the lower level (850 hPa). Horizontal winds were weaker in OJ cyclones and stronger in PO-O cyclones. The wavelength of the upper-level trough was shorter in OJ cyclones and became longer in PO-L and PO-O cyclones. The upper-level jet streak was shorter and weaker in OJ cyclones and was longer in PO-O cyclones. In PO-O cyclones, the upper-level jet streak clearly terminated near the center of the cyclones with horizontal winds divergent east of the cyclone. Updrafts were stronger in PO-L and PO-O cyclones and weaker in OJ cyclones. Low-level strong winds were identified in the southeast quadrant, especially in PO-L and PO-O cyclones. Low-level winds tended to be drawn into the cyclone center and northward in PO-O cyclones, while the cyclones were zonally stretched and the air mass was found to move quickly ahead of the cyclone (eastward) in the PO-L case.

Figure 12 shows the relative vorticities and contributions of the VADV term to the surface vorticity tendency. Large cyclonic vorticities, associated with the upper-level trough, extended from the northwest to the cyclone center and were strongest in OJ cyclones. The contributions of VADV were stronger at 300 hPa and extended around the cyclone center but were weaker in the middle and lower levels.

Composite maps for potential temperatures, their horizontal gradients, and contributions of the TADV term are shown in Fig. 13. A meridionally extended baroclinic zone was identified in the lower level of OJ cyclones. While a strong and zonally extended baroclinic zone was present in PO-L and PO-O cyclones in the middle level, it was weaker in the lower level. As discussed in the previous section, each type of cyclone had a characteristic atmospheric environment structure reflecting the extension of a cold air outbreak over the ocean. These baroclinic structures revealed that OJ cyclones developed near the continent during the smaller cold air mass extension, and PO-L and PO-O cyclones developed with a long distance fetch apart from the continent during the larger cold air mass extension. Since the strong jet stream was longer in PO-L cyclones, the baroclinic zone was more zonally elongated in PO-L cyclones than that in PO-O cyclones. The TADV contributions were positive (deepening) in the eastern part of the cyclone because of warm air advection and negative (filling) in the western part because of the cold air advection at the lower level, while the TADV term was positive north or northwest of cyclones in the upper level. Contributions in the upper and lower levels were larger than those in the middle level.

Figure 14 shows moisture conditions of specific humidities and LATH contributions. Specific humidities were smaller in OJ and PO-L cyclones, but were significantly larger in PO-O cyclones. Moist air moved into the cyclone center from the south in PO-O cyclones, but moved eastward in OJ and PO-L cyclones except at the lower level. Although the contributions of LATH were larger near the cyclone center in the lower level of OJ and PO-L cyclones, the largest contributions were in PO-O cyclones. A significant amount of latent heat was released because of the low-level moist air advection under the strong midlevel updraft region (Fig. 11) in PO-O cyclones. A large amount of latent heat release may lead to the higher deepening rate of PO-O cyclones, as discussed in section 3a.

To estimate the contributions of each term to explosive cyclogenesis, correlations between each term on the rhs and the surface vorticity tendency of the lhs in Eq. (2) were plotted in Fig. 15. The surface vorticity tendency was averaged within 500 km around the cyclone center, 6 h after observing the maximum deepening rate. The gradient of the regression line is a measure of the degree of the contribution to the cyclone development. Figure 15 shows that VADV, TADV, and LATH positively contributed to cyclone development, while ADIA contributed negatively. The contribution of TADV was largest, with a high correlation coefficient among the positive contributors. This tendency can be seen in each type of cyclone. Except for this feature, LATH in PO-O cyclones had a larger contribution than that of the other two cyclone types, and VADV in OJ cyclones was also larger. The negative contribution of ADIA was large in the order of PO-O, PO-L, and OJ cyclones. As discussed in the first half of this section, these tendencies would be supported by composite analyses for mesoscale cyclone structures. The rapid deepening of cyclones occurred in the baroclinic zone, PO-
O cyclones had a strong low-level moisture advection, and OJ cyclones had a strong upper-level vorticity advection. These factors characterize cyclone types and their mesoscale structures.

4. Discussion

Statistical analysis suggests that there were two prominent characteristics of the three types of rapid deepening cyclones in the northwestern Pacific region. One is seasonal variation of occurrence frequency and another is the relationship between maximum deepening rate and cyclone type. The former is consistent with the results of Chen et al. (1991), which showed that cyclogenesis over east Asia was active near 40°N in late fall and early winter, and near 30°N from midwinter to late winter. The seasonal variation may reflect larger-scale atmospheric conditions, such as the cold air mass over the Asian continent and the upper jet streak. Figure 16 shows monthly averaged geopotential height and rela-
Fig. 12. Composite maps at the maximum deepening rate at (a)–(c) 300, (d)–(f) 500, and (g)–(i) 850 hPa for the (left) OJ, (middle) PO-L, and (right) PO-O cyclones of relative vorticity (thin solid lines are positive, thin broken lines are negative, the contour line interval is $2 \times 10^{-5}$ s$^{-1}$, area greater than $2 \times 10^{-5}$ s$^{-1}$ is shaded) and VADV term (bold solid lines are positive, bold broken lines are negative in $10^{-3}$ s$^{-1}$, the contour interval is $1 \times 10^{-3}$ s$^{-1}$). Closed circles show the position of the surface cyclone center 6 h after observing the maximum deepening rate, and the center of each panel shows the surface cyclone center.

Positive vorticity for the three cold seasons between October 1996 and March 1999 at 300 hPa, superimposed on the tracks of the explosively developing cyclones from formation to maximum deepening. Figure 17 shows monthly averaged potential temperature and its horizontal gradient at 850 hPa. These figures clearly show the tendency for explosive cyclones to form in the planetary-scale low-level baroclinicity between subtropical and subpolar regions and develop under the upper-level positive vorticity maximum. The upper-level positive vorticity maximum (Fig. 16) exhibits a zonal extension over northern Japan toward the east in the midwinter of January and February, especially noticeable in January. This extends over the northern Sea of Japan and the Sea of Okhotsk in late autumn (November) and in early and late winter (December and March), but is weaker in October. As the strong cold air mass forms over the Asian continent in midwinter, the low-level baroclinic zones (Fig. 17) extend over southern China, the East China Sea, and the southern coast of Japan toward the
Fig. 13. Composite maps at the maximum deepening rate at (a)–(c) 300, (d)–(f) 500, and (g)–(i) 850 hPa for the (left) OJ, (middle) PO-L, and (right) PO-O cyclones of potential temperature (thin lines in K, the contour interval is 4 K), TADV term (bold solid lines are positive, bold broken lines are negative in $10^{10}$ s$^{-2}$, the contour interval is $2 \times 10^{10}$ s$^{-2}$), and horizontal gradients of potential temperature [shade in K (100 km)$^{-1}$]. Closed circles show the position of the surface cyclone center 6 h after observing the maximum deepening rate, and the center of each panel shows the surface cyclone center.

east in January and February, especially prominent in January. This extends from northern China and southern Russia across the central Sea of Japan toward the east of Japan in early and late winter (December and March), and extends from the central continent along the western coastal line of the Sea of Japan in late autumn (November), then becomes weaker and slightly less easily identified above the central continent in autumn (October). As the cold air mass over the Asian continent affects the upper jet stream as well as the location of the low-level baroclinic zone, it also affects cyclone development and tracks.

The moisture budget is computed by considering the local tendency of the amount of moisture in the air column above the ground as a water vapor budget of the precipitation and evaporation on the ground ($P - E$), where $P$ is the amount of precipitation and $E$ is the amount of evaporation. The moisture budget may be written as...
Fig. 14. Composite maps at the maximum deepening rate at (a)-(c) 300, (d)-(f) 500, and (g)-(i) 850 hPa for the (left) OJ, (middle) PO-L, and (right) PO-O cyclones of specific humidity (shade in g kg$^{-1}$) and LATH term (solid lines are positive, broken lines are negative in $10^{-10}$ s$^{-2}$, the contour interval is $2 \times 10^{-10}$ s$^{-2}$). Closed circles show the position of the surface cyclone center 6 h after observing the maximum deepening rate, and the center of each panel shows the surface cyclone center.

\[ P - E = -\frac{\partial}{\partial t} \left( \frac{1}{g} \int_{p_b}^{p_t} q \, dp \right) - \frac{1}{g} \int_{p_b}^{p_t} \nabla \cdot (qv) \, dp, \quad (4) \]

where $g$ is gravitational acceleration, $q$ is specific humidity, $p$ is pressure, $p_t$ is the upper boundary of the air column (=300 hPa), $p_b$ is sea level pressure, and $v$ is the horizontal wind vector. Figure 18 shows composite charts for moderate explosive cyclones where moisture analysis was completed at the maximum deepening rate. When OJ cyclones developed explosively, the vertically integrated horizontal vapor flux was larger over the southeastern quadrant, which corresponds to the northwestern Pacific Ocean. The amount of moisture advection into the cyclone center was relatively small. As a result, the amount of $P - E$ was smaller and latent heat release may not have contributed strongly to cyclone development. In the case of PO-L cyclones, water vapor was transported from the south and southwest toward the northeast and converged along the eastern flank of the cyclone center, which corresponded to a warm front. As PO-L cyclones had a zonally stretched strong upper- and midlevel jet, moisture tended to be...
transported toward the east of the cyclone. Thus the moisture convergence zone was spread over eastward and the net budget was larger than that of OJ cyclones but smaller than that of PO-O cyclones. For PO-O cyclones, most of the southern part of the cyclone contained precipitable water over 20 mm. Stronger vapor flux toward the cyclone center existed, and the amount of $P - E$ was greatest. Case studies of cyclones over the northwestern Pacific Ocean and the East China Sea (Chen et al. 1985; Chang et al. 1987; Liou and Elsberry...
Fig. 16. Monthly average from Oct 1996 to Mar 1999 at 300 hPa of geopotential heights (thin solid lines in m, contour interval is 60 m), relative vorticity (shade in $10^{-2} s^{-1}$), and cyclone tracks from formation (open symbols) to maximum deepening rate (closed symbols) for OJ (dotted line, circle), PO-L (broken line, triangle), and PO-O (bold solid line, square) cyclones in (a) Oct, (b) Nov, (c) Dec, (d) Jan, (e) Feb, and (f) Mar.

1987) suggest that latent heat release at lower levels is an important factor for the rapid cyclogenesis. As discussed in this section, latent heat release helps the rapid deepening of cyclones, and a tendency existed for cyclones with larger maximum deepening rates to have larger contributions from latent heat release. The distribution of moisture budgets was influenced by environmental wind and moisture and contributed to cyclone deepening. As the OJ cyclones traveled over land at high latitudes, moved over the sea, and quickly developed, they exhibited a smaller amount of $P - E$, the smaller contribution of the latent heat release for the rapid deepening. The PO-O cyclones were born at relatively lower latitudes over the ocean, traveled toward the north, and developed in the higher latitudes, therefore exhibiting a larger amount of $P - E$ and
larger contributions from latent heat release to development.

5. Conclusions

To better understand explosively developing extratropical cyclones in the northwestern Pacific region, formation and maximum deepening positions, tracks, and atmospheric conditions were analyzed using GANAL, provided by JMA. Explosively deepening cyclones were classified into three types by birth locations and rapid development locations: OJ cyclones appeared over the east Asian continent and developed over the Sea of Okhotsk and the Sea of Japan; PO-L cyclones also formed over the eastern Asian continent, traveled eastward, and developed over the northwestern Pacific
Ocean; and PO-O cyclones formed over the ocean near the East China Sea, traveled northeastward, and developed over the northwestern Pacific Ocean at higher latitudes. During five cold seasons, from 1994 to 1999, there were 224 cases of explosive cyclones in total, with approximately 49% (110 cases) of them PO-O cyclones, while PO-L cyclones accounted for 22% (50 cases) and OJ cyclones accounted for 19% (42 cases). A relationship between the maximum deepening rate and cyclone types was found. PO-O cyclones had the strongest deepening rate, followed by PO-L cyclones, with OJ cyclones the weakest. While OJ cyclones frequently occurred in late autumn (November), PO-L cyclones occurred in early and late winter (December and February), and PO-O cyclones occurred in midwinter (January).

Larger-scale atmospheric conditions and cyclone structures were examined using composite analyses. As a summary of these analyses, schematic illustrations of explosive developing cyclones are shown in Fig. 19. The OJ cyclones develop in the presence of a relatively small upper-level trough over northeastern China with a short jet streak. As the cold air mass outbreak is still weak, a baroclinic zone forms over the Sea of Japan and the Sea of Okhotsk where OJ cyclones develop explosively. Analyses of the mechanism of development reveal large contributions from low-level temperature advection and upper-level vorticity advection and smaller contributions from latent heat release. The magnitude of the deepening rate is the smallest of the three. PO-L cyclones develop in early and late winter and have a zonally stretched jet stream over southern Japan and the northwestern Pacific Ocean in the upper level. A cold air mass forms over the northern Asian continent and extends over the Pacific Ocean, and a baroclinic zone forms over the southern part of Japan toward the east of Japan, where PO-L cyclones develop. PO-L cyclones are mainly developed by temperature advection. PO-O cyclones develop in midwinter. A cold air mass over the Asian continent extends largely over the northwestern Pacific Ocean with a long fetch. A strong jet streak associated with the upper-level short-wave trough is present west of the cyclone. A jet stream exit can be seen near the cyclone center. Upper-level forcing induces a strong updraft near the cyclone center and a large amount of latent heat is released. The latent heat release is an important contributor to the explosive development and results in a stronger deepening rate.

We have reported statistical and composite analyses on the explosively developing cyclones in the northwestern Pacific region in the present paper, and have suggested that tracks, structures, and developing mech-

Fig. 18. Moisture composite analyses at the maximum deepening rate for (a) OJ type, (b) PO-L, and (c) PO-O cyclones. Bold solid lines show $P - E$ ($P$: precipitation, $E$: evaporation) in mm h$^{-1}$, contour interval is 0.5 mm h$^{-1}$, thin solid lines show the sea level pressure in hPa (contour interval is 4 hPa), grayscale shows precipitable water in mm, and arrows show vertically integrated horizontal water vapor flux. The center of each panel shows the surface cyclone center.
anisms changed to reflect the presence and extension of a cold air mass over the continent and moisture distribution over the ocean. Special case studies may need to be analyzed to further understand the development, evolution, and detailed structure of cyclones using numerical simulations and field experiments. Extratropical cyclones also play an important role in energy and water vapor exchange between lower and higher latitudes on a global scale. Cyclone activities impact regional climate, whereas global climate affects cyclone activities. Clarifying the interaction between cyclone activity and the climate may be an important topic in future research.

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Fig. 19. Schematic illustrations of the three types of cyclones: (a) OJ, (b) PO-L, and (c) PO-O.
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