Characteristics of Explosive Cyclones over the Northern Pacific

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ABSTRACT

Explosive cyclones (ECs) over the northern Pacific Ocean during the cold season (October–April) over a 15-yr (2000–15) period are analyzed by using the Final (FNL) Analysis data provided by the National Centers for Environmental Prediction. These ECs are stratified into four categories according to their intensity: weak, moderate, strong, and super ECs. In addition, according to the spatial distribution of their maximum-deepening-rate positions, ECs are further classified into five regions: the Japan–Okhotsk Sea (JOS), the northwestern Pacific (NWP), the west-central Pacific (WCP), the east-central Pacific (ECP), and the northeastern Pacific (NEP). The occurrence frequency of ECs shows evident seasonal variations for the various regions over the northern Pacific. NWP ECs frequently occur in winter and early spring, WCP and ECP ECs frequently occur in winter, and JOS and NEP ECs mainly occur in autumn and early spring. The occurrence frequency, averaged maximum deepening rate, and developing and explosive-developing lifetimes of ECs decrease eastward over the northern Pacific, excluding JOS ECs, consistent with the climatological intensity distributions of the upper-level jet stream, midlevel positive vorticity, and low-level baroclinicity. On the seasonal scale, the occurrence frequency and spatial distribution of ECs are highly correlated with the intensity and position of the upper-level jet stream, respectively, and also with those of midlevel positive vorticity and low-level baroclinicity. Over the northwestern Pacific, the warm ocean surface also contributes to the rapid development of ECs. The composite analysis indicates that the large-scale atmospheric environment for NWP and NEP ECs shows significant differences from that for the 15-yr cold-season average. The southwesterly anomalies of the upper-level jet stream and positive anomalies of midlevel vorticity favor the prevalence of NWP and NEP ECs.

1. Introduction

An explosive cyclone (EC), also known as a meteorological bomb for its rapid intensification (see, e.g., [Rice 1979](#)), can potentially cause serious losses of life and property as a result of extremely bad weather such as severe winds, heavy precipitation, and so on. Some famous EC cases in history were the *Queen Elizabeth II* storm in 1978 ([Gyakum](#)

[1983a,b, 1991](#)) and the Presidents' Day cyclone in 1979 ([Bosart 1981](#); [Bosart and Lin 1984](#)) over the Atlantic Ocean.

[Sanders and Gyakum \(1980\)](#) defined an EC as a cyclone whose central sea level pressure (SLP) decreased at an average rate of at least 1 “bergeron”:

$$1 \text{ bergeron} = (24 \text{ hPa}/24 \text{ h}) \times \sin 60^\circ / \sin \phi, \quad (1)$$

where ϕ is the latitude of the cyclone center and 60° is the adjusted latitude in geostrophically equivalent rate.

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Considering the averaged latitude of most rapid development of ECs and the temporal resolution of data, the definition of EC was slightly modified in later studies (Roebber 1984; Gyakum et al. 1989; Yoshida and Asuma 2004).

The climatological features of ECs over the Pacific and Atlantic Oceans had been investigated by subsequent studies (Sanders and Gyakum 1980; Roebber 1984; Sanders 1986; Gyakum et al. 1989; Chen et al. 1992; Sinclair 1997; Wang and Rogers 2001). The results consistently implied that EC was primarily a cold-season maritime phenomenon that frequently occurred over the midlatitude oceans, especially over the Kuroshio/Kuroshio Extension and Gulf Stream (i.e., western boundary currents). The northwestern Pacific was one of the regions for most frequent occurrence of ECs. Chen et al. (1992) and Yoshida and Asuma (2004) further pointed out that the Japan Sea and the northwestern Pacific along the Kuroshio/Kuroshio Extension were two favorable areas for the rapid development of ECs. In addition, Iwao et al. (2012) found that the frequency of ECs had shown an increasing tendency in the northwestern Pacific in recent years.

The large-scale atmospheric and oceanic environments strongly influence the spatial distribution of ECs. The atmospheric conditions within and at the poleward side of the upper-level jet stream favored the rapid development of ECs (Sanders and Gyakum 1980; Uccellini et al. 1985; Kuwano-Yoshida and Asuma 2008). Sanders and Gyakum (1980) found that ECs usually occurred in the downstream side of a mobile 500-hPa trough, which was supported by Chen et al. (1983, 1985) and Chen et al. (1992). The Kuroshio/Kuroshio Extension in the northwestern Pacific also set a favorable oceanic environment for EC occurrence (Chen et al. 1992; Yoshiike and Kawamura 2009; Iizuka et al. 2013).

EC rapid development was considered to be influenced by several factors, such as the upper-level forcing (Rogers and Bosart 1986; Macdonald and Reiter 1988; Hirschberg and Fritsch 1991; Zehnder and Keyser 1991; Reader and Moore 1995), low-level baroclinicity (Wash et al. 1988; Manobianco 1989; Lim and Simmonds 2002; Seiler and Zwiers 2016), latent heat release (Gall 1976; Anthes et al. 1983; Emanuel et al. 1987; Mullen and Baumhefner 1988; Whitaker and Davis 1994; Ahmadi-Givi et al. 2004), and surface heat fluxes from the ocean (Chen et al. 1992; Kuwano-Yoshida and Asuma 2008; Yoshiike and Kawamura 2009; Kuwano-Yoshida and Enomoto 2013; Hirata et al. 2015). Their relative importance strongly depended on the intensity and region of ECs during their rapidly developing stage (Sanders and Davis 1988; Wash et al. 1988; Wang and Rogers 2001).

Sanders (1986) stratified ECs into three categories of intensity: weak (1.0–1.2 bergerons, moderate (1.3–1.8 bergerons), and strong (>1.8 bergerons) ECs, and his results suggested that the 500-hPa absolute vorticity maxima and cyclonic vorticity advection varied with EC intensity. Yoshida and Asuma (2004) classified ECs over the northwestern Pacific into three types, depending on their positions of formation and rapid development, and many dynamical differences such as upper-level forcing and environmental baroclinicity were found among them. Notable divergences in the structures and development mechanisms of ECs for specific intensities and regions were also shown by many studies (Sanders and Davis 1988; Wash et al. 1988; Nuss and Kamikawa 1990; Bullock and Gyakum 1993; Gyakum and Danielson 2000; Wang and Rogers 2001).

Previous studies usually focused on ECs over the northwestern Pacific; ECs over the northern Pacific, especially over the northeastern Pacific, have received much less attention, although there have been a few papers that investigated ECs over the northeastern Pacific (Murty et al. 1983; Danielson et al. 2006a,b). Allen et al. (2010) indicated that high-resolution reanalysis data could increase the climatological frequency of ECs, but the detailed statistical features of ECs over the northern Pacific have seldom been analyzed by using high-resolution reanalysis data in recent years. Moreover, it is also not clear how the large-scale atmospheric and oceanic environments influence the statistical features of ECs. Because there are many vital shipping lanes over the northern Pacific, it is very important to investigate the statistical features of ECs over the entire northern Pacific to avoid the threat of ECs to maritime safety.

This study investigates the characteristics of ECs over the northern Pacific during the cold season (October–April) over a 15-yr (2000–15) period. The purposes of the study are twofold: 1) to describe the more detailed statistical features of ECs over the northern Pacific by using reanalysis data with relatively high temporal and spatial resolution when compared with previous studies and 2) to investigate the influence of large-scale atmospheric and oceanic environments on the statistical features of ECs from a climate perspective. The paper is organized as follows: Section 2 describes the data and methods. Section 3 gives a modified definition of EC. Classifications of intensity and region are presented in section 4. Section 5 reveals the statistical features of the types of ECs. Section 6 analyzes the relationships between large-scale atmospheric and oceanic environments with the occurrence frequency and spatial distribution of ECs. In section 7, a summary is given.

FIG. 1. Geographic map of the northern Pacific and the northern Pacific warm currents (heavy solid arrows). The outlined region indicates the study domain. Here BS is the Bohai Sea, YS is the Yellow Sea, ES is the East China Sea, JS is the Japan Sea, OS is the Okhotsk Sea, KI is the Kuril Islands, KP is the Kamchatka Peninsula, AI is the Aleutian Islands, and AP is the Alaska Peninsula.

2. Data and method

a. Data

We use the Final (FNL) Operational Global Analysis data (<http://rda.ucar.edu/datasets/ds083.2/>), provided by the National Centers for Environmental Prediction (NCEP), to identify ECs and examine the large-scale atmospheric environment. FNL data are on a $1^\circ \times 1^\circ$ horizontal resolution with 26 vertical levels from 1000 to 10 hPa and are available four times per day at 0000, 0600, 1200, and 1800 UTC.

Advanced Very High Resolution Radiometer (AVHRR) infrared satellite sea surface temperature (SST) data (<http://www.ncdc.noaa.gov/sst>), provided by the National Climatic Data Center (NCDC, now known as the National Centers for Environmental Information) of the National Oceanic and Atmospheric Administration, are used to examine sea surface conditions. The AVHRR SST data are on a $0.25^\circ \times 0.25^\circ$ horizontal grid and 1-day temporal resolution.

b. Method

Although automatic detection and tracking algorithms of extratropical cyclones had been developed by Serreze (1995) for minimum central SLP and by Sinclair (1994) for vorticity centers, some errors usually were found for identifying extratropical cyclones (Wang and Rogers 2001; Allen et al. 2010). Neu et al. (2013)

indicated that the results from 15 cyclone detection and tracking algorithms had important differences and could not judge which methods delivered incorrect results.

Therefore, we visually track cyclones in this paper to set up a more accurate database of ECs over the northern Pacific. Six-hourly surface weather charts with 1-hPa interval are constructed for tracking the cyclones in the deepening stage (from formation to minimum central SLP) lasting longer than 12 h within our study domain (Fig. 1). The center of a cyclone is defined as the grid position with minimum SLP within the innermost closed isobar. If only one cyclone at time step 2 appears within a 10° latitude $\times$ 16° longitude box centered on the cyclone at time step 1, it is taken as the matching cyclone. If there are two or more cyclones found in the box at time step 2, the one with minimum SLP is used as the matching cyclone.

ECs are then identified from the obtained cyclones according to a modified version of the definition of EC from Sanders and Gyakum (1980), which is associated with the deepening rate of central SLP and will be elaborated in section 3. The deepening rate for each cyclone is calculated along its trajectory, and the cyclones with a maximum deepening rate that is larger than 1 bergeron are identified as ECs. The central SLP, maximum deepening rates, and trajectories for the identified ECs are recorded for further analysis.

TABLE 1. The meridional distribution of MDPs according to the definition of EC given by Sanders and Gyakum (1980) and the modified definition given in this paper. The frequency shows the sum of MDPs within 5°-latitude bins.

	Latitude bins (°N)								
	20–25	25–30	30–35	35–40	40–45	45–50	50–55	55–60	60–65
Sanders and Gyakum (1980) definition									
Frequency	0	3	51	209	243	190	51	13	1
Percentage	0.00%	0.39%	6.70%	27.46%	31.93%	24.97%	6.70%	1.71%	0.13%
Modified definition of EC									
Frequency	0	2	53	194	244	193	77	18	2
Percentage	0.00%	0.26%	6.77%	24.78%	31.16%	24.65%	9.83%	2.30%	0.26%

Wang and Rogers (2001) considered the merging and splitting cyclones as “parent cyclones.” ECs that generate outside and inside the parent cyclones are treated as merging and splitting, respectively. The parent cyclones usually decay, whereas ECs generally deepen. Therefore, the parent cyclones are excluded in our study. The parent cyclone and EC rotate with each other cyclonically in the rapid-deepening stage of an EC, and the parent cyclone weakens until disappearance. Two examples are shown in the appendix (Figs. A1 and A2) so that readers may better understand the processes of merging and splitting.

Three key positions in the lifetime of EC are defined. 1) The *initial formation position* (IFP) is defined as the first position of an EC center where the SLP field has at least one closed isobar with 1-hPa intervals. 2) The *maximum-deepening-rate position* (MDP) is defined as the position of the EC centered over the 12-h interval of the most rapid deepening. For example, the position of maximum 12-h deepening is the position of the EC center at 0600 UTC, if the most rapid deepening occurs during the period from 0000 to 1200 UTC. 3) The *minimum central SLP position* (MCP) is defined as the position of an EC center with its minimum central SLP.

According to the deepening rate, the track of an EC from IFP to MCP is classified into three stages. 1) *Pre-explosive-developing track* (PRET) is taken to be the track with a deepening rate that is smaller than 1 bergeron before explosive development. 2) *Explosive-developing track* (EXT) is taken to be the track with a deepening rate of larger than 1 bergeron. 3) *Post-explosive-developing track* (POET) is taken to be the track with a deepening rate that is smaller than 1 bergeron after explosive development.

3. Modification of EC definition

Previous studies had modified the adjusted latitude in geostrophically equivalent rate (Roebber 1984; Gyakum et al. 1989) or “dropped pressure” (Yoshida and Asuma 2004; Kuwano-Yoshida and Asuma 2008; Yoshiike and

Kawamura 2009) singly, depending on the definition of EC given by Sanders and Gyakum (1980). Given the facts that ECs usually occur in the midlatitudes and that the high-resolution reanalysis data are widely used, the adjusted latitude (60°) in geostrophically equivalent rate together with “24-h dropped pressure” should be modified objectively so as to describe the rapidly developing process more accurately.

The definition given by Sanders and Gyakum (1980) is primarily taken to identify ECs using the method as mentioned in section 2b by modifying the calculation of deepening rate, and 761 cases are found. The top half of Table 1 summarizes the meridional distribution of MDPs within 5°-latitude bins. The frequency of MDPs peaks at 40°–45°N. Most MDPs (84.4%) are concentrated in 35°–50°N, and only 17 cases (2.2%) occur south of 30°N or north of 55°N. The averaged latitude of MDPs is 42.7°N. The results indicate that ECs frequently develop rapidly in the midlatitudes (Sanders and Gyakum 1980; Roebber 1984; Gyakum et al. 1989). The features of the meridional distribution of MDPs suggest that 45°N is more suitable for the adjusted latitude in geostrophically equivalent rate in Eq. (1).

Because the temporal resolution of the FNL data that are used in this study is 6 h rather than the 12 h that is used in Sanders and Gyakum (1980), “12-h dropped pressure” can capture the detailed development process of ECs. In this paper, 12-h SLP change is used to find an instance of the most rapid deepening in a cyclone’s life. Therefore, the definition of EC given by Sanders and Gyakum (1980) is revised to be a cyclone whose central SLP decrease normalized at 45°N is greater than 12 hPa within 12 h. The deepening rate of cyclone SLP is calculated with the following formula:

deepening rate of cyclone SLP (hPa h^{-1})

$$= \left(\frac{P_{t-6} - P_{t+6}}{12} \right) \times \left(\frac{\sin 45^\circ}{\sin \frac{\phi_{t-6} + \phi_{t+6}}{2}} \right), \quad (2)$$

where t is time in hours, P is the central SLP, and ϕ is the latitude of the cyclone center. Subscripts “ $t-6$ ” and “ $t+6$ ” represent variables of 6 h before and after present time t , respectively.

In total, 783 ECs (hereinafter when “all ECs” are mentioned it refers to this dataset) are found by using the above modified definition. The meridional distribution of their MDPs, as shown in the bottom half of Table 1, presents features that are similar to those that are based on the definition given by Sanders and Gyakum (1980) (Table 1, top half). The frequency of MDPs peaks at 40°–45°N as well. MDPs are also concentrated in 35°–50°N, with 80.6%. The averaged latitude of MDPs is 43.3°N. These results suggest again that ECs frequently develop rapidly in the midlatitudes.

Although the total frequency of ECs identified by using the definition between the modification and Sanders and Gyakum (1980) does not change significantly, the detected cases show remarkable differences with 12.5% (98 cases), and the modified definition of EC can identify rapidly developing ECs within a short time. In addition, the spatial distribution of MDPs also shows obvious difference (not shown), with a shift in location to farther westward by using the modified definition. Moreover, the modified definition with 12-h dropped pressure and normalizing at 45°N results in an increased frequency of ECs (783 cases) relative to that obtained by using the definition given by Sanders and Gyakum (1980) (761 cases). This result suggests that the modified definition is suitable to describe more detailed processes of the rapid deepening of ECs, because the longer time period for pressure dropping in Sanders and Gyakum (1980) potentially smooths out the rapid development of ECs.

4. Classification of ECs

a. Classification of intensity

Previous studies had demonstrated that the structures and development mechanisms of ECs for a specific intensity showed notable divergences (Sanders and Davis 1988; Nuss and Kamikawa 1990; Bullock and Gyakum 1993; Gyakum and Danielson 2000). In this study, we find some “super” ECs, whose maximum deepening rate is much larger than the criterion of the strong EC (>1.8 bergerons) in Sanders (1986) (Fig. 3a). The most rapidly developing case occurred around 1200 UTC 14 January 2013, and its maximum deepening rate dramatically reached up to 3.07 bergerons. This fact implies that the structures and development mechanisms between strong and super ECs are potentially different and therefore need further investigation. Consequently, on the basis of classification in Sanders (1986), four

TABLE 2. The classification of intensity of ECs.

Intensity	Deepening rate (bergerons)
Weak	1.00–1.29
Moderate	1.30–1.69
Strong	1.70–2.29
Super	≥ 2.30

categories of intensity for ECs are more reasonable, according to the fact that some super cases occurred.

The K -means clustering algorithm is used to determine the threshold values between categories of intensity, which partitions a given dataset into a user-specified cluster K by using the minimum-distance method. The results are shown in Table 2. ECs are classified into four categories of intensity: weak (1.00–1.29 bergerons), moderate (1.30–1.69 bergerons), strong (1.70–2.29 bergerons), and super (≥ 2.30 bergerons) ECs. In addition to the fact that adding super ECs makes the classification of intensity more detailed, use of a K -means clustering algorithm to determine the threshold values between categories is considered to be more objective.

b. Classification of regions

In this study, the weighting factor in Cressman (1959) is used to smooth the spatial distribution of MDPs, which transforms the frequency of ECs at the irregularly spaced positions into data at the positions of a regularly arranged grid. The weighting factor is calculated by using the following formula:

$$W_{ij} = \frac{R^2 - r_{ij}^2}{R^2 + r_{ij}^2} \quad \text{for} \quad r_{ij} < R$$

$$W_{ij} = 0 \quad \text{for} \quad r_{ij} \geq R, \quad (3)$$

where W_{ij} is a weighting factor, i and j indicate the latitudinal and longitudinal grid point, r is the distance between the EC center and the grid point, and the smoothing radius R is set to be 5°. The frequency of ECs at every irregularly spaced position is 1. The resolution of latitudinal and longitudinal grids is $1^\circ \times 1^\circ$.

Figure 2 shows the smoothed spatial distribution of MDPs. Five distinctive high-frequency centers are found: the central Japan Sea (41.0°N, 135.0°E), the northwestern Pacific (37.0°N, 144.5°E), the west-central Pacific (45.5°N, 175.0°E), the east-central Pacific (46.5°N, 167.5°W), and the northeastern Pacific (48.5°N, 142.5°W). Previous studies indicated that the structures and mechanisms of ECs over various regions showed significant differences stemming from local atmospheric and oceanic environments, especially at the maximum-deepening-rate moment (Wang and Rogers 2001;

FIG. 2. The smoothed frequency (thin solid contours; contour interval = 3) of MDPs (dots) for all ECs. The boundaries of ECs for distinguishing the various regions are drawn with a thick dashed line.

Yoshida and Asuma 2004). Hence, the spatial distribution of MDPs is reasonable for taking as a basis for classification of regions.

The ECs over the northern Pacific are classified into five regions according to the spatial distribution of their MDPs for the five distinct high-frequency centers that are identified above; hereinafter we refer to them as the Japan–Okhotsk Sea (JOS), the northwestern Pacific (NWP), the west-central Pacific (WCP), the east-central Pacific (ECP), and the northeastern Pacific (NEP). The boundary between JOS and NWP ECs is the Japan Islands, Kuril Islands, and Kamchatka Peninsula. The boundaries for distinguishing other regions are determined by using two principles: 1) The dividing lines must be simple enough to distinguish ECs and 2) the lines should be located in areas with local minimum frequency. The five regions, as distinguished with dashed lines, are shown in Fig. 2.

5. Statistical characteristics of ECs

a. The occurrence frequency and maximum deepening rate

We identified 783 cases. Detailed information on strong and super ECs is in the appendix (Table A1). The

occurrence frequency and percentage of ECs for the various regions and intensities are summarized in Table 3. It is seen that NWP ECs occur most frequently (274 cases), followed by WCP ECs (166 cases), ECP ECs (120 cases), NEP ECs (120 cases), and JOS ECs (103 cases). With the exception of JOS ECs, the occurrence frequency of ECs decreases as one moves eastward over the northern Pacific (*t* test of linear trend; 95% confidence intervals).

Figure 3 shows the frequency distribution of maximum deepening rate for the various regions. The occurrence frequency of ECs decreases monotonically with intensity for all regions—more clearly for JOS and NEP ECs (Figs. 3b,f). The averaged maximum deepening rate of NWP ECs is the largest (1.44 bergerons), followed by WCP (1.41 bergerons), ECP (1.38 bergerons), NEP (1.34 bergerons), and JOS (1.27 bergerons) ECs. In addition, most strong and super ECs are in the NWP region (47.2% and 43.8%, respectively), which suggests that strong and super ECs predominantly occur over the northwestern Pacific (Table 3). Those results indicate that in general NWP ECs develop most rapidly, followed by WCP, ECP, and NEP ECs, and that JOS ECs develop most slowly. It is interesting that the averaged deepening rate of ECs also decreases eastward

TABLE 3. The occurrence frequency (labeled FRE) and percentage (labeled PER) of ECs by region and intensity.

Categories	All		JOS		NWP		WCP		ECP		NEP	
	FRE	PER	FRE	PER	FRE	PER	FRE	PER	FRE	PER	FRE	PER
All	783	100.00%	103	13.15%	274	35.00%	166	21.20%	120	15.33%	120	15.33%
Weak	397	50.70%	67	65.05%	125	45.62%	73	43.98%	64	53.33%	68	56.67%
Moderate	262	33.46%	30	29.13%	91	33.21%	64	38.55%	38	31.67%	39	32.50%
Strong	108	13.79%	4	3.88%	51	18.61%	26	15.66%	16	13.33%	11	9.17%
Super	16	2.04%	2	1.94%	7	2.55%	3	1.81%	2	1.67%	2	1.67%

FIG. 3. Frequency of maximum deepening rate for (a) all, (b) JOS, (c) NWP, (d) WCP, (e) ECP, and (f) NEP regions' ECs. The horizontal axis shows the maximum deepening rate with 0.1-bergeron intervals, and the vertical axis indicates the frequency of ECs.

over the northern Pacific, excluding JOS ECs (*t* test of linear trend; 99% confidence intervals), which is similar to the feature of occurrence frequency of ECs.

b. Seasonal variation

Figure 4 illustrates the monthly frequency distribution of ECs for the various regions. Two peaks of monthly frequency for all ECs are identified: December and March (Fig. 4a). All ECs frequently occur in winter (from December to February) and early spring (March), with 69.2% of the cases. The monthly frequency patterns are different among the various regions. There are two peaks for the monthly frequency of JOS, NWP, and NEP ECs. These three regions share a similar peak in March and show a second peak in November, December, and October, respectively (Figs. 4b,c,f). There is a single peak for the monthly frequency of WCP and ECP ECs that occurs in January and December, respectively (Figs. 4d,e). Those results suggest that ECs frequently occur in winter and early spring for the

combined data and the NWP region, JOS and NEP ECs mainly occur in autumn and early spring, and WCP and ECP ECs frequently occur in winter.

c. The developing lifetime

Table 4 shows the frequency of developing lifetime (measured in days) for the various regions. The developing lifetime is taken to be the time duration from IFP to MCP. More than 70% of ECs fall within a developing-lifetime span of 2.25 days for the various regions. The 70% concentration of developing lifetimes for NWP covers 1.25–3.50-day lifetimes, beginning at a duration that is 0.25 days longer than that for JOS, WCP, and ECP ECs (1.00–3.25 days) and 0.50 days longer than that for NEP ECs (0.75–3.00 days). The averaged developing lifetime for NWP ECs is the longest (2.63 days), followed by JOS (2.32 days), ECP (2.31 days), WCP (2.26 days), and NEP (1.85 days) ECs. These results indicate that ECs tend gradually to have shorter and shorter lifetimes from west to east over the

FIG. 4. The monthly frequency for (a) all, (b) JOS, (c) NWP, (d) WCP, (e) ECP, and (f) NEP regions' ECs. The horizontal axis shows the month, and the vertical axis indicates the frequency of ECs.

northern Pacific, with the exception of JOS ECs (t test of linear trend; 98% confidence intervals).

d. The explosive-developing lifetime

Table 5 depicts the frequency of explosive-developing lifetime (also measured in days) for the various regions. The explosive-developing lifetime is taken as the

time duration of the EXT stage. The frequency of ECs decreases monotonically with increasing explosive-developing lifetime for all regions. The explosive-developing lifetime with more than 70.0% of cases for all, WCP, and ECP regions' ECs is shorter than 1 day, whereas that for JOS and NEP ECs is shorter than 0.75 days (the shortest) and that for NWP ECs is shorter

TABLE 4. Frequency of ECs within different developing-lifetime ranges (in days) by region.

	0.50–0.75	1.00–1.25	1.50–1.75	2.00–2.25	2.50–2.75	3.00–3.25	3.50–3.75	4.00–4.25	4.50–4.75	5.00–5.25	5.50–5.75	6.00–6.25	6.50–6.75
All	40	116	137	145	112	109	62	29	14	12	2	3	2
JOS	1	14	19	26	14	20	5	2	2	0	0	0	0
NWP	5	14	44	59	46	47	34	13	4	5	1	1	1
WCP	6	28	36	28	26	18	13	6	4	1	0	0	0
ECP	4	28	23	16	13	16	6	5	4	4	0	0	1
NEP	24	32	15	16	13	8	4	3	0	2	1	2	0

TABLE 5. Frequency of ECs for different explosive-developing lifetimes (in days) by region.

	0.50	0.75	1.00	1.25	1.50	1.75	2.00
All	241	230	136	101	45	20	10
JOS	40	41	12	7	2	1	0
NWP	67	65	51	43	26	13	9
WCP	47	46	34	25	7	6	1
ECP	36	38	24	14	8	0	0
NEP	51	40	15	12	2	0	0

than 1.25 days (the longest). The averaged explosive-developing lifetime for all ECs is 0.84 days. That for NWP is the longest (0.97 days), followed by WCP (0.88 days), and ECP ECs (0.83 days); that for JOS and NEP ECs is the shortest (0.74 days). Therefore, the explosive-developing lifetime of NWP ECs is distinctly longer than that for other regions, followed by WCP, ECP, JOS, and NEP ECs. When excluding JOS ECs, the explosive-developing lifetime of ECs tends to be shorter and shorter from west to east over the northern Pacific (t test of linear trend; 99% confidence intervals), which is similar to the pattern of developing lifetime indicated previously in section 5c.

e. The moving tracks

Because the behavior of tracks is similar within a given region and is different across regions (not shown), the moving tracks of strong ECs for the various regions are taken to show their characteristics (Fig. 5). Strong JOS ECs generally form over continental East Asia and the northeastern coast of China, then develop explosively when they move from land or offshore to the Japan and Okhotsk Sea in a northeastward direction (Fig. 5a). The moving tracks of strong NWP ECs are also typically in a northeastward direction, and they mainly originate from the East China Sea, the body of water to the south and southeast of the Japan Islands (Fig. 5b). Strong NWP ECs travel along the axis of the Kuroshio/Kuroshio Extension, consistent with previous studies (Sanders and Gyakum 1980; Gyakum et al. 1989; Chen et al. 1992). Strong WCP ECs usually form over the water to the east and southeast of the Japan Islands (Fig. 5c). They usually move eastward in their early stages and then turn northeastward in later stages with longer paths. Strong ECP ECs are mainly generated over the northwestern Pacific, and their moving tracks are similar to those of strong WCP ECs (Fig. 5d). Strong NEP ECs frequently form over the central and east-central Pacific (Fig. 5e). The moving tracks of strong NEP ECs originating from the central Pacific are similar to those of strong WCP ECs, whereas those strong NEP ECs forming over the east-central Pacific generally show short moving tracks in northeastward directions.

6. Large-scale atmospheric and oceanic environments

In section 5, it was shown that the averaged maximum deepening rate and occurrence frequency of ECs decrease eastward over the northern Pacific, excluding JOS ECs. In addition, the occurrence frequency of ECs shows significant variations on the seasonal scale over the northern Pacific. To better understand the characteristics of large-scale atmospheric and oceanic environments for the eastward-decreasing trend of the occurrence frequency and averaged maximum deepening rate and the seasonal variations of occurrence frequency, the climatological distributions of the upper-level jet stream, midlevel positive vorticity, low-level baroclinicity, SST, and SST gradient associated with cyclone activities over the northern Pacific are investigated.

a. Upper-level jet stream

Because the upper-level forcing favors the rapid development of ECs (Uccellini and Kocin 1987; Wash et al. 1988; Wang and Rogers 2001; Yoshida and Asuma 2004), the upper-level jet stream is investigated to understand the upper-level larger-scale atmospheric environment for the occurrence frequency and spatial distribution of ECs (Fig. 6). The upper-level jet stream with wind speed greater than 60 m s^{-1} at 300 hPa appears over the mid- and low-latitude northern Pacific, extending from the western Pacific to the east-central Pacific with an east–west orientation (Fig. 6a). The jet core is located to the south of the Japan Islands, and the wind speed decreases eastward. The high-frequency centers of all ECs predominantly appear at the poleward side of the jet axis. We have found that the occurrence frequency and averaged maximum deepening rate of ECs gradually decrease eastward over the northern Pacific (see section 5a). This eastward-decreasing trend is correlated well with the decrease of jet stream intensity across the northern Pacific.

From October to April (Figs. 6b–h), ECs also mainly occur at the poleward side of the jet axis. Moreover, the occurrence frequency and spatial distribution of ECs present high correlations with the intensity and position of the jet stream on the seasonal scale, respectively. From October to January (Figs. 6b–e), the intensity of the jet stream gradually enhances from 45 to 75 m s^{-1} and the jet axis marches southward from 40° to 30°N . Correspondingly, the occurrence frequency of ECs increases and the spatial distribution of ECs shifts southward. Moreover, the spatial distribution of ECs tends to concentrate on the poleward side of the jet axis closely with the enhancement of the jet stream. From January to April (Figs. 6e–h), the jet stream shows the opposite

FIG. 5. The moving tracks of strong (a) JOS, (b) NWP, (c) WCP, (d) ECP, and (e) NEP ECs. Dashed lines with open squares indicate PRET, solid lines with filled circles indicate EXT, and dashed lines with open triangles indicate POET.

behavior: its intensity weakens gradually and its position shifts northward. The occurrence frequency and spatial distribution of ECs change in corresponding ways.

In particular, we have shown that JOS and NEP ECs frequently occur in autumn (see section 5b), which perhaps results from the jet stream being located farther north and extending to the northeastern Pacific, respectively, during that period. The jet stream cannot explain why the high-frequency center of MDPs over the northeastern Pacific appears in March, however. The morphological feature of the jet stream shows notable differences in October from that in other months, which is associated with an anticyclonic curve to the eastern coast of the Japan Islands. The left-front region of the jet stream with an anticyclonic curve is unfavorable for the rapid development of ECs, with the result that few ECs occur over there in October (see the discussion in the next paragraph).

Although the fact that ECs frequently occur at the poleward side of a jet axis had been demonstrated by previous studies (Sanders and Gyakum 1980; Wash et al. 1988; Yoshida and Asuma 2004), it had not been revealed that the occurrence frequency and spatial distribution of ECs are highly correlated with the intensity and position of the upper-level jet stream, respectively, on the seasonal scale. This study demonstrates clearly that the upper-level jet stream plays an important role in

controlling the occurrence frequency and spatial distribution of ECs over the northern Pacific. The divergence center and the positive vorticity advection usually appeared in the left-front region of straight or cyclonic-curved jet streams (Uccellini and Kocin 1987; Wash et al. 1988; Cammas and Ramond 1989; Nakamura 1993), which were strongly related to surface cyclogenesis (Keyser and Shapiro 1986; Wash et al. 1988). This upper-level atmospheric environment results in ECs frequently occurring in the left-front region of straight or cyclonic-curved jet streams. In addition, Ziv and Paldor (1999) indicated that the convergence center usually appeared in the exit region of the anticyclonic-curved jet stream, which may explain why ECs occur rarely off the eastern coast of the Japan Islands in October.

b. Midlevel positive vorticity

Subsequent studies emphasized that midtropospheric conditions, such as troughs, positive vorticity, and positive vorticity advection, were the important factors for the rapid development of ECs (Sanders and Gyakum 1980; Sanders 1986; Wash et al. 1988; Lupo et al. 1992; Azad and Sorteberg 2014); the midlevel positive vorticity is analyzed to examine the midtropospheric condition for the occurrence frequency and spatial distribution of ECs (Fig. 7). A zonal belt with large

FIG. 6. Time-mean charts of the 300-hPa jet stream (shaded, with ≥ 30 and 5 m s^{-1} intervals), jet axis (thick dashed arrow), and horizontal wind vector (thin solid arrows, showing $\geq 30 \text{ m s}^{-1}$) for (a) the cold season, (b) October, (c) November, (d) December, (e) January, (f) February, (g) March, and (h) April. The dashed contours indicate the smoothed frequency of ECs [≥ 9 with a contour interval of 3 in (a), and ≥ 2 with a contour interval of 2 in (b)–(h)].

positive vorticity at 500 hPa is found over the mid- and high-latitude northern Pacific (Fig. 7a), with a major center over the northwestern Pacific and a minor center over the northeastern Pacific. The high-frequency centers of all ECs are located within and at the equatorward side of the belt with large positive vorticity.

On the seasonal scale, the occurrence frequency and spatial distribution of ECs are also highly correlated with the intensity and position of positive vorticity, respectively. From October to January (Figs. 7b–e), the center of positive vorticity over the northeastern Pacific weakens. Consistent with that, the occurrence frequency of ECs over there decreases gradually, while the positive vorticity with a center over the northwestern Pacific is enhanced and its location shifts southward gradually. Meanwhile, the occurrence frequency of ECs increases

and the spatial distribution of ECs shifts southward over the northwestern Pacific as well. From January to April (Figs. 7e–h), the seasonal variations of occurrence frequency and spatial distribution of ECs also follow the intensity and position of positive vorticity, respectively, but the occurrence frequency decreases and the spatial distribution shifts northward gradually, in contrast to those features from October to January.

The results show that the occurrence frequency and spatial distribution of ECs present high concordance with the intensity and position of positive vorticity, respectively, on the seasonal scale. Sanders (1986) pointed out that the positive vorticity had an important influence on the occurrence of ECs. Subsequent studies had revealed that positive vorticity advection was the major forcing process in the rapid development of ECs

FIG. 7. As in Fig. 6, but for 500-hPa positive vorticity (shaded, with $0.5 \times 10^{-5} \text{ s}^{-1}$ intervals).

(Wash et al. 1988; Lupo et al. 1992; Azad and Sorteberg 2014). The positive-vorticity-associated westerly flow at 500 hPa usually makes positive vorticity advection appear over the high-frequency regions of ECs, which favors the frequent occurrence of ECs. Thus, positive vorticity has significant influence on the occurrence frequency and spatial distribution of ECs over the northern Pacific.

c. Low-level baroclinicity

ECs generally had a remarkable baroclinic zone at low level during their rapid-development stages (Bosart and Lin 1984; Rogers and Bosart 1986; Sanders and Davis 1988; Kuwano-Yoshida and Asuma 2008). Figure 8 shows the time-mean low-level baroclinicity. Strong low-level baroclinicity, which is represented by the horizontal gradient of potential temperature, exists over the midlatitude northern Pacific and is centered over the northwestern Pacific (Fig. 8a). The high-frequency centers of all ECs predominantly appear over the belt of strong low-level

baroclinicity. The low-level baroclinicity decreases eastward across the northern Pacific; this is correlated with the eastward decreasing trend of the occurrence frequency and averaged maximum deepening rate of ECs. In each month (Figs. 8b–h), ECs also mainly occur over the belt of strong low-level baroclinicity. From October to January (Figs. 8b–e), low-level baroclinicity is enhanced slowly from 1.0×10^{-5} to $1.2 \times 10^{-5} \text{ K m}^{-1}$ and its location shifts southward slightly, whereas from January to April (Figs. 8e–h), the features of low-level baroclinicity show the opposite behavior. It is seen that the occurrence frequency and spatial distribution of ECs coincide with the intensity and position of low-level baroclinicity, respectively, on the seasonal scale. These results indicate that low-level baroclinicity has significant effects on the occurrence frequency and spatial distribution of ECs over the northern Pacific.

In addition, low-level baroclinicity over the northwestern Pacific is stronger than that over the northeastern

FIG. 8. As in Fig. 6, but for potential temperature gradient (shaded, with $0.2 \times 10^{-5} \text{ K m}^{-1}$ intervals).

Pacific, and low-level baroclinicity changes evidently over the northwestern Pacific and insignificantly over the northeastern Pacific on the seasonal scale. Yoshida and Asuma (2004) showed that ECs over the northwestern Pacific had a strong baroclinic zone at low or midlevels resulting from the presence and extension of the cold air mass from the Eurasian continental area while the oceanic air mass is relatively uniform over the northeastern Pacific, leading to weak baroclinicity. These results indicate that low-level baroclinicity has stronger effects on ECs over the northwestern Pacific than on those over the northeastern Pacific.

d. SST and SST gradient

The Kuroshio, North Pacific Current, and Gulf of Alaska are three significant warm currents in the northern Pacific (Fig. 1). Because the oceanic environment is considered to be crucial for the rapid development of ECs (Chen et al. 1983, 1985; Kuo et al. 1991a;

Yoshiike and Kawamura 2009; Iizuka et al. 2013), the time-mean SST gradient (Fig. 9) and surface heat fluxes (Fig. 10) over the northern Pacific are analyzed. As a whole, the high-frequency centers of all ECs are located over the belt of strong SST gradient. Although the seasonal variations of SST and SST gradient are insignificant over the northern Pacific (Figs. 9b–h), the surface sensible and latent heat fluxes present evident differences on the seasonal scale over the northwestern Pacific (Figs. 10b–h). The surface sensible and latent heat fluxes increase from October to January and decrease from January to April. They reach a maximum in winter, resulting from the southward intrusion of cold air. In the northeastern Pacific, the surface sensible and latent heat fluxes are small, however, and their variations are insignificant on the seasonal scale.

In the vicinity of the northwestern Pacific, ECs tend to concentrate over the Kuroshio/Kuroshio Extension, which implies that the warm ocean current plays a key

FIG. 9. As in Fig. 6, but for SST (white contours, with 4°C intervals) and SST gradient (shaded, with $0.2 \times 10^{-4}^{\circ}\text{C m}^{-1}$ intervals).

role in the rapid development of ECs (Chen et al. 1992; Yoshiike and Kawamura 2009; Hirata et al. 2015). The warm ocean current supplied a large amount of sensible and latent heat fluxes to the midlatitude atmosphere (Kelly et al. 2010; Kwon et al. 2010). Abundant sensible and latent heat fluxes contributed to facilitating rapid intensification of ECs (Davis and Emanuel 1988; Kuwano-Yoshida and Asuma 2008; Kuwano-Yoshida and Enomoto 2013), through destabilizing the lower atmosphere and increasing latent heat release (Kuo et al. 1991a,b; Neiman and Shapiro 1993; Reed et al. 1993; Takayabu et al. 1996; Booth et al. 2012). Consequently, a large amount of surface heat fluxes from the Kuroshio/Kuroshio Extension provide a favorable oceanic environment for the rapid development of ECs, resulting in the frequent occurrence of ECs over the northwestern Pacific.

Although the North Pacific Current and Gulf of Alaska exist over the midlatitude eastern Pacific, they

are weaker than the Kuroshio/Kuroshio Extension. Meanwhile, ECs developing rapidly over the northeastern Pacific generally originate from the adjacent low-latitude ocean with shorter trajectories or from the northwestern Pacific with longer trajectories. The former ECs at low level already have similar properties to the ocean when they form. The latter ECs experience airmass modification when they move from the northwestern Pacific to the northeastern Pacific with longer tracks. The weaker warm ocean currents and similar properties between air and sea surface result in surface heat fluxes that are weaker, and their variations are indistinct on the seasonal scale over the northeastern Pacific, which suggests that warm ocean currents associated with surface heat fluxes have a weak influence on the rapid development of ECs over the northeastern Pacific.

The above results indicate that the large-scale atmospheric and oceanic environments have a significant

FIG. 10. As in Fig. 6, but for surface heat fluxes (the sum of surface sensible heat fluxes and surface latent heat fluxes) (shaded, with 50 W m^{-2} intervals).

influence on EC activity on the seasonal scale. In addition, in spatial distribution, the upper-level jet stream, midlevel positive vorticity, low-level baroclinicity, and surface heat fluxes consistently decrease eastward in the cold season. In seasonal variation, they consistently are located southward and are much stronger in winter. These results suggest that the large-scale atmospheric and oceanic environments between upper level and low level exhibit a close connection, especially over the northwestern Pacific. The surface heat fluxes from the Kuroshio/Kuroshio Extension can maintain low-level baroclinicity over the northwestern Pacific (Hoskins and Valdes 1990; Hotta and Nakamura 2011). Low-level baroclinicity drives the East Asian subtropical westerly jet at the upper level through the thermal wind. The upper-level jet stream associated with positive vorticity affects midtropospheric conditions. The combination of these large-scale atmospheric and oceanic environments

results in the characteristics of the eastward-decreasing trend of the occurrence frequency and averaged maximum deepening rate as well as the seasonal variations of occurrence frequency and spatial distribution of ECs. In addition, Nakamura (1992) pointed out that the storm track over the northern Pacific was dominant in late autumn and early spring on the seasonal scale, which is distinct from the most frequent ECs in winter. This different seasonality between storm track and EC is probably due to the difference in their definitions. Moreover, Chen et al. (1991) also indicated that cyclogenesis over the northwestern Pacific occurred only in the cold season, which was related to the development of ECs.

e. Composite analyses for NWP and NEP ECs

NWP ECs occur most frequently, and NEP ECs have received much less attention in previous studies. Therefore, to better understand the characteristics of

FIG. 11. Composite charts of the 300-hPa jet stream (shaded, with ≥ 30 and 5 m s^{-1} intervals) and horizontal wind vector (arrows, showing $\geq 30 \text{ m s}^{-1}$) for (a) NWP and (c) NEP ECs. Also shown are the anomalies of jet stream (shaded, with ≥ 4 and 2 m s^{-1} intervals) and horizontal wind vector (arrows, showing $\geq 4 \text{ m s}^{-1}$) for (b) NWP and (d) NEP ECs. The dot indicates the high-frequency center.

favorable large-scale atmospheric environment for the frequent occurrence of NWP and NEP ECs, a composite analysis by using geographically fixed coordinates is conducted. NWP and NEP ECs that occur during the 15-yr cold seasons are employed in the composite analysis. The key time examined in the composite analysis for the jet stream is the time of maximum deepening rate, and that for positive vorticity is 6 h before the time of the maximum deepening rate. Furthermore, the anomaly fields between the composite fields and the 15-yr cold-season averaged fields are prepared for NWP and NEP ECs, respectively, which are computed by the composite fields minus the 15-yr cold-season averaged fields.

1) COMPOSITE UPPER-LEVEL JET STREAM

Relative to the 15-yr cold-season averaged jet stream (Fig. 6a), the composite jet stream for NWP ECs with wind speed greater than 65 m s^{-1} at 300 hPa extends more meridionally but less zonally (Fig. 11a). The high-frequency center of NWP ECs appears at the polarward side of the jet core. Figure 11b shows the jet-stream anomalies for NWP ECs at 300 hPa. The westerly anomalies occur near the jet core, which enhances the jet stream. The southwesterly anomalies with wind speed greater than 8 m s^{-1} appear to the east of the Japan Islands, which strengthens the southwesterly flow over the exit region of the jet stream. The high-frequency center of NWP ECs is located to the west of the southwesterly anomaly core.

The pattern of composite jet stream for NEP ECs shows distinct differences from that for NWP ECs. The jet stream for NEP ECs with wind speed greater than 60 m s^{-1} at 300 hPa is more zonal (Fig. 11c). It extends to the northeastern Pacific and shows cyclonic curve over there. The high-frequency center of NEP ECs appears over the northwest of the cyclonic curve. Figure 11d shows the jet-stream anomalies for NEP ECs at 300 hPa. Strong southwesterly anomalies with wind speed greater than 10 m s^{-1} appear over the area of the cyclonic curve of the jet stream, which enhances the jet stream over the northeastern Pacific. The high-frequency center of NEP ECs is also located to the west of the southwesterly anomaly core.

The jet stream favoring rapid development for NWP and NEP ECs shows significant differences from that for the 15-yr cold-season average. The southwesterly anomalies appear to the east of the high-frequency centers of NWP and NEP ECs, which enhances the southwesterly flow of the jet stream there. The increasing southwesterly flow leads to stronger positive shear vorticity over their high-frequency center. In addition, Hoskins et al. (1985) indicated that upper-level cyclonic anomalies induced low-level cyclonic circulation, leading to an intense low-level cyclone through the interaction between the upper-level and low-level anomalies. The upper-level cyclonic anomalies that appear upstream of the high-frequency centers of NWP and NEP ECs favor the frequent occurrence of NWP and NEP ECs. The jet stream for NWP ECs differs from

FIG. 12. As in Fig. 11, but for 500-hPa positive vorticity at 6 h before the maximum-rapid-deepening moment (shaded, with $0.5 \times 10^{-5} \text{ s}^{-1}$ intervals) and the anomalies of positive vorticity (shaded, with $0.5 \times 10^{-5} \text{ s}^{-1}$ intervals).

that for NEP ECs. The jet stream for NEP ECs is more zonal but weaker than that for NWP ECs, whereas the jet-stream anomalies for NEP ECs are stronger than those for NWP ECs to the east of their high-frequency centers.

2) COMPOSITE MIDDLELEVEL POSITIVE VORTICITY

Both the composite 500-hPa vorticity at 6 h before the maximum-deepening-rate moment for NWP ECs and that for NEP ECs have major and minor regions with large positive vorticity (Figs. 12a,c). The pattern shows bimodal distribution. The major regions with large positive vorticity for NWP and NEP ECs appear upstream of their high-frequency centers, which are located off the eastern coast of the Japan Islands and over the northeastern Pacific, respectively. Figures 12b and 12d show the positive-vorticity anomalies for NWP and NEP ECs, respectively. The positive-vorticity anomalies for both NWP ECs and NEP ECs have single prominent areas, which are located near their major regions with large positive vorticity. The high-frequency centers of NWP and NEP ECs appear downstream of their respective prominent positive-vorticity-anomaly areas.

Although the patterns of composite 500-hPa vorticity for NWP and NEP ECs show bimodal distribution, their positive-vorticity-anomaly areas just appear over their major regions with large positive vorticity, which are also the positions of their high-frequency centers. Those results indicate that the positive-vorticity anomalies strengthen the positive vorticity over the high-frequency centers of NWP and NEP ECs and that the enhanced positive vorticity favors the frequent occurrence of

NWP and NEP ECs. The location and intensity of positive vorticity for NWP ECs differ from those for NEP ECs. In addition, the positive-vorticity anomalies for NEP ECs with more than $2.5 \times 10^{-5} \text{ s}^{-1}$ over the northeastern Pacific are stronger than those for NWP ECs with more than $2.0 \times 10^{-5} \text{ s}^{-1}$ off the eastern coast of the Japan Islands.

7. Summary

In this study, the characteristics of ECs over the northern Pacific during the cold season (October–April) over a 15-yr (2000–15) period are investigated by using FNL reanalysis data. According to the spatial distribution of MDPs and the temporal improvement of data, the definition of EC given by Sanders and Gyakum (1980) is modified to be a cyclone whose central SLP decrease normalized at 45°N is greater than 12 hPa within 12 h. These ECs are stratified into four categories of intensity according to their maximum deepening rates: weak (1.00–1.29 bergerons), moderate (1.30–1.69 bergerons), strong (1.70–2.29 bergerons), and super (≥ 2.30 bergerons) ECs. In addition, ECs are further classified into five regions: JOS, NWP, WCP, ECP, and NEP ECs, on the basis of the five high-frequency centers of MDPs.

In total, 783 ECs are found over the northern Pacific. The occurrence frequency of ECs shows evident variations on the seasonal scale for the various regions over the northern Pacific. NWP ECs frequently occur in winter and early spring, WCP and ECP ECs frequently occur in winter, and JOS and NEP ECs mainly occur in

TABLE A1. The information for strong (ST) and super (SU) ECs over the northern Pacific during the cold season (October–April) over a 15-yr (2000–15) period. Here, ID, PRE, lon, lat, MDR, NS, and IN indicate the identifier, the minimum central SLP, the longitude, the latitude, the maximum deepening rate, the classification number of the explosive-developing stage (see text), and the intensity (ST or SU) at the given time, respectively. The coding for the times is as follows: the first four digits are the year, the next two are the month, the next two are the day, and the final two are the hour (UTC) divided by 100. Thus, for example, the first entry 2004111418 corresponds to 1800 UTC 14 Nov 2004.

ID	IFP				MDP					MCP				NS	IN
	Time	PRE	Lon	Lat	Time	PRE	Lon	Lat	MDR	Time	PRE	Lon	Lat		
JOS ECs															
1	2004111418	1002.8	133.0	49.0	2004111506	987.6	141.0	46.9	1.7	2004111606	956.8	150.0	51.9	1	ST
2	2004112600	1009.8	129.7	41.0	2004112606	992.6	133.0	42.0	2.24	2004112718	950.2	154.1	50.9	2	ST
3	2012040200	1006.2	112.6	31.2	2012040300	988.2	132.0	38.0	2.58	2012040406	956.8	145.0	47.0	2	SU
4	2013110918	1001.8	138.0	44.0	2013111006	973.6	146.0	48.9	2.34	2013111018	960.8	149.0	53.0	1	SU
5	2014121500	1023.6	120.0	39.3	2014121600	1000.8	134.9	41.0	1.71	2014121618	977.0	139.0	44.9	1	ST
6	2014121906	1019.8	121.8	38.6	2014122100	976.0	145.0	49.9	2.03	2014122112	957.0	145.4	53.3	1	ST
NWP ECs															
1	2000123018	1002.4	130.6	23.9	2001010100	976.2	148.1	36.9	2.24	2001010112	954.4	151.0	43.0	2	ST
2	2001122100	1018.0	136.1	32.0	2001122300	968.2	167.0	47.9	1.71	2001122400	942.8	182.5	52.0	2	ST
3	2002112100	1010.8	147.5	43.6	2002112112	990.0	155.0	48.0	1.94	2002112218	965.6	168.0	48.0	1	ST
4	2002122500	1009.6	133.4	37.0	2002122606	970.8	159.0	41.0	1.89	2002122718	938.6	166.0	54.0	1	ST
5	2003012200	1012.0	121.9	33.0	2003012312	982.8	143.0	36.0	1.96	2003012418	958.2	153.0	43.0	1	ST
6	2003021500	1017.0	125.0	28.9	2003021700	986.4	158.0	36.0	1.75	2003021806	950.6	179.0	45.0	1	ST
7	2003022818	1008.4	127.5	32.1	2003030112	993.4	137.4	34.6	1.71	2003030206	969.4	148.2	39.0	1	ST
8	2003031600	1013.4	125.1	32.0	2003031718	985.0	162.0	37.0	1.92	2003031806	969.2	169.0	40.0	1	ST
9	2003121600	996.4	147.0	38.2	2003121700	967.0	167.1	47.0	1.76	2003121718	945.0	173.0	54.0	1	ST
10	2004011218	1007.2	137.1	33.0	2004011306	990.6	145.0	38.0	1.94	2004011406	963.0	149.0	43.1	1	ST
11	2004040800	999.6	152.9	41.0	2004040818	970.6	165.0	50.5	1.89	2004040906	952.8	167.0	52.0	1	ST
12	2004120400	999.2	122.0	23.9	2004120412	991.0	132.1	33.0	1.82	2004120506	969.4	147.9	41.0	1	ST
13	2004122812	1009.4	127.6	25.8	2004123000	968.2	158.3	40.8	2.25	2004123018	949.2	170.0	47.0	1	ST
14	2005020900	1022.4	130.0	39.1	2005021018	978.0	159.0	46.0	2.02	2005021112	954.4	160.0	51.0	1	ST
15	2005031018	1009.0	124.9	27.2	2005031112	993.6	142.5	37.2	1.88	2005031218	955.6	153.0	49.0	1	ST
16	2005111100	1009.6	125.6	30.0	2005111212	981.4	155.0	40.0	2.25	2005111218	968.8	157.1	42.0	1	ST
17	2005122018	1017.0	132.8	38.0	2005122118	986.2	144.9	38.4	1.80	2005122312	946.8	170.0	48.0	1	ST
18	2006010106	1012.8	131.2	23.8	2006010300	977.4	150.6	41.6	1.95	2006010318	955.6	153.0	46.0	1	ST
19	2006013118	1013.8	129.4	27.9	2006020118	983.8	148.0	40.0	2.35	2006020306	962.4	176.3	47.7	1	SU
20	2006122506	1009.6	127.5	25.5	2006122700	986.2	142.0	37.6	1.75	2006123018	954.0	175.7	47.0	1	ST
21	2007010518	1012.4	133.7	28.5	2007010612	988.4	142.1	38.0	2.29	2007010806	945.6	153.7	47.0	2	ST
22	2007120118	1020.6	119.7	31.9	2007120412	968.4	166.0	50.1	1.78	2007120500	951.2	170.0	52.0	1	ST
23	2008020206	1008.6	128.0	27.0	2008020312	987.2	147.0	35.0	2.19	2008020506	958.2	176.0	46.0	1	ST
24	2008020606	1009.8	139.3	32.8	2008020718	973.0	159.0	42.1	1.82	2008020806	952.2	165.0	46.0	1	ST
25	2008022606	1003.0	142.0	43.1	2008022700	977.0	150.0	44.0	2.30	2008022718	950.8	153.9	48.0	1	SU
26	2008032918	1006.8	126.0	30.0	2008033112	977.8	146.9	38.1	2.54	2008040100	958.0	147.9	41.0	1	SU
27	2008121400	1005.8	140.0	31.0	2008121506	968.8	163.0	48.9	1.78	2008121518	958.4	164.0	56.0	1	ST
28	2009020400	1016.4	141.1	32.0	2009020612	986.8	157.0	37.0	1.91	2009020800	963.2	169.1	48.0	1	ST
29	2009021906	1010.6	124.3	30.0	2009022006	988.4	143.0	38.9	2.26	2009022100	963.0	149.0	44.9	1	ST
30	2009030900	1011.2	126.0	25.0	2009031012	975.8	152.9	41.0	1.96	2009031100	956.8	155.0	46.6	2	ST
31	2009102600	994.8	134.0	28.0	2009102706	969.0	149.0	42.0	1.98	2009102712	955.2	152.1	44.0	1	ST
32	2009111618	1009.2	130.0	28.7	2009111812	974.6	159.0	46.9	2.05	2009111906	952.0	168.0	53.0	2	ST
33	2010011118	1009.2	131.9	23.3	2010011300	977.2	152.0	41.9	2.01	2010011418	946.6	176.0	50.0	1	ST
34	2010013118	1011.8	129.4	30.1	2010020118	987.2	148.9	36.0	1.94	2010020218	963.8	164.0	44.0	1	ST
35	2010022712	1009.8	134.5	31.9	2010030106	979.8	166.1	46.1	1.79	2010030212	957.4	185.0	54.0	1	ST
36	2010040400	1014.8	123.0	25.0	2010040606	988.8	155.0	38.0	1.71	2010040700	974.0	167.0	43.9	1	ST
37	2010102418	1003.6	140.9	44.2	2010102612	964.2	164.0	54.0	1.74	2010102706	948.4	172.0	59.0	1	ST
38	2011011506	1003.4	141.0	35.9	2011011612	960.0	160.7	40.5	2.48	2011011706	934.2	167.0	44.0	1	SU
39	2011021618	1015.2	125.8	28.3	2011021812	982.4	150.0	44.0	1.75	2011021906	964.2	157.9	51.0	1	ST
40	2011031400	1013.4	132.4	29.0	2011031612	965.8	156.0	41.1	2.15	2011031712	936.6	165.0	48.0	1	ST
41	2012010106	1014.4	134.3	27.9	2012010212	984.8	150.0	38.0	2.21	2012010306	960.2	153.0	43.0	1	ST
42	2012011012	1016.8	144.0	33.7	2012011200	973.2	163.0	45.0	2.22	2012011218	945.0	162.0	51.0	1	ST
43	2012012418	1009.8	142.1	35.2	2012012612	984.4	163.2	40.0	1.73	2012012718	953.6	165.3	43.0	1	ST
44	2012113006	1009.0	139.9	31.0	2012120112	976.8	155.1	45.0	2.02	2012120200	961.4	154.0	50.0	1	ST

TABLE A1. (Continued)

ID	IFP				MDP					MCP				NS	IN
	Time	PRE	Lon	Lat	Time	PRE	Lon	Lat	MDR	Time	PRE	Lon	Lat		
45	2013011312	1002.4	128.1	24.9	2013011412	966.8	145.1	35.0	3.07	2013011506	935.2	159.1	40.3	1	SU
46	2013020318	1018.2	141.1	35.1	2013020500	979.8	161.0	42.0	2.28	2013020600	951.0	171.0	47.0	1	ST
47	2013021200	1017.8	126.0	27.0	2013021306	991.4	147.3	38.3	1.77	2013021506	965.4	172.0	44.0	1	ST
48	2013021418	1012.8	130.8	30.1	2013021518	988.2	152.2	37.9	1.94	2013021618	957.0	165.0	45.0	1	ST
49	2013031918	1007.0	123.0	31.0	2013032100	968.6	152.0	45.9	2.07	2013032112	948.6	154.0	49.0	1	ST
50	2013033112	1011.4	148.1	37.0	2013040106	991.0	161.0	43.0	1.99	2013040200	965.2	171.0	46.1	1	ST
51	2013110318	1010.8	151.0	40.1	2013110506	969.2	167.0	47.1	1.71	2013110618	952.2	179.0	58.1	1	ST
52	2013122606	1010.4	133.0	31.0	2013122718	964.4	151.0	46.0	1.90	2013122806	949.4	152.0	49.0	1	ST
53	2014110612	993.6	143.0	32.0	2014110712	962.2	165.0	49.0	2.72	2014110812	933.6	171.5	55.5	1	SU
54	2014120406	1008.0	141.7	36.3	2014120506	974.6	158.1	44.0	2.06	2014120518	955.8	166.0	48.0	1	ST
55	2014120912	1011.6	149.0	35.0	2014121006	988.8	162.0	37.0	1.94	2014121106	970.8	178.0	42.0	1	ST
56	2014121512	1018.6	126.4	28.1	2014121612	987.4	142.9	37.3	2.84	2014121706	958.8	146.1	44.6	1	SU
57	2014122812	1014.2	134.8	31.6	2014122918	982.4	152.0	42.0	2.17	2014123018	950.0	161.0	49.0	1	ST
58	2015010212	1007.4	142.2	34.5	2015010318	965.2	164.0	43.2	2.15	2015010406	954.4	166.1	47.0	1	ST
WCP ECs															
1	2001020600	1009.6	144.0	31.9	2001020706	984.0	171.0	47.8	1.95	2001020718	959.6	174.0	53.0	1	ST
2	2001100712	1003.8	137.0	25.9	2001101006	981.0	175.0	40.0	1.82	2001101018	966.8	183.0	44.0	1	ST
3	2001120218	1009.2	162.6	30.7	2001120312	985.0	172.0	38.3	2.14	2001120500	961.4	175.0	51.0	1	ST
4	2002101000	1016.8	151.1	34.7	2002101200	988.4	183.9	46.0	1.81	2002101218	963.6	192.1	50.9	1	ST
5	2003121100	1017.0	128.8	29.3	2003121312	964.4	180.1	48.0	1.71	2003121406	945.0	189.0	52.0	2	ST
6	2004101800	991.0	176.0	52.1	2004101818	961.2	182.9	60.9	1.75	2004101906	945.0	183.0	65.0	1	ST
7	2004121000	1018.8	138.5	29.6	2004121218	973.6	181.0	44.0	1.89	2004121312	960.8	187.0	44.0	2	ST
8	2005021300	1020.6	142.9	33.0	2005021406	989.0	164.0	36.0	2.05	2005021512	963.0	185.9	44.0	1	ST
9	2006021112	1008.4	141.5	35.6	2006021218	974.2	169.0	42.0	1.76	2006021318	957.0	180.0	49.0	1	ST
10	2006113000	1013.4	144.9	34.0	2006120106	983.6	172.0	43.0	1.84	2006120200	958.2	179.9	50.5	1	ST
11	2007031018	1007.2	174.9	25.0	2007031106	996.2	177.0	31.0	2.00	2007031206	977.0	184.0	35.0	2	ST
12	2007112206	1000.0	165.0	39.1	2007112300	978.4	173.9	49.0	1.90	2007112318	951.4	169.9	54.0	1	ST
13	2007121806	1003.8	158.0	38.5	2007121900	986.0	174.0	45.0	1.70	2007122000	964.2	183.1	53.0	1	ST
14	2008010418	1009.8	161.1	26.0	2008010518	992.2	179.0	36.1	1.99	2008010618	964.8	189.9	44.5	1	ST
15	2008020906	1013.6	137.0	32.9	2008021118	966.8	176.0	37.9	2.35	2008021212	944.4	185.0	42.4	2	SU
16	2009021912	1004.4	168.0	32.0	2009021918	992.2	172.0	35.0	2.39	2009022006	972.0	175.0	41.9	1	SU
17	2009113018	1012.2	148.3	34.5	2009120212	983.2	179.0	39.0	1.90	2009120312	958.6	190.0	44.0	1	ST
18	2009121512	1014.4	127.0	26.1	2009121712	973.0	168.0	43.0	1.99	2009121806	951.8	173.1	50.0	1	ST
19	2010030212	1009.6	144.2	33.6	2010030406	978.6	178.0	45.9	2.10	2010030500	957.0	191.0	51.1	1	ST
20	2011012406	1010.8	141.0	35.0	2011012606	971.4	177.1	42.0	1.73	2011012706	953.6	189.0	48.0	1	ST
21	2011031106	1011.4	147.7	34.5	2011031212	984.8	170.7	41.0	1.99	2011031300	968.2	178.1	43.1	1	ST
22	2011031806	1003.2	163.8	32.4	2011031912	975.0	185.0	47.0	1.79	2011032000	958.2	189.7	53.3	1	ST
23	2011040318	1011.0	143.1	31.6	2011040612	964.6	179.0	51.7	2.14	2011040706	936.0	182.9	57.0	1	ST
24	2012021206	1010.8	157.0	32.0	2012021306	979.4	181.3	39.0	2.53	2012021400	948.4	187.1	46.2	1	SU
25	2013112406	1016.8	156.3	31.8	2013112606	983.4	182.0	40.0	1.70	2013112700	968.4	181.5	40.4	1	ST
26	2013121612	982.0	172.6	35.9	2013121618	971.6	175.0	38.0	1.90	2013121718	951.4	170.0	41.0	1	ST
27	2014022406	1020.4	144.7	32.4	2014022618	974.6	171.0	42.0	1.78	2014022712	958.6	175.1	43.0	1	ST
28	2014103012	995.0	174.9	48.1	2014103018	983.8	178.1	50.6	1.75	2014103112	969.0	188.5	56.0	1	ST
29	2014121600	998.8	170.0	39.0	2014121612	984.2	181.0	42.0	1.80	2014121712	958.8	198.0	47.9	1	ST
ECP ECs															
1	2001111606	986.0	199.0	44.0	2001111612	974.0	202.0	45.0	1.74	2001111712	956.4	205.1	51.0	1	ST
2	2001122106	1007.8	173.4	36.6	2001122206	982.6	198.1	39.0	1.76	2001122300	961.4	209.0	43.0	1	ST
3	2002102606	1000.6	183.0	40.0	2002102700	974.6	192.1	42.0	1.87	2002102800	961.6	201.1	44.9	1	ST
4	2002112612	993.4	165.9	34.0	2002112718	973.0	200.0	38.9	2.17	2002112812	954.2	204.0	44.0	1	ST
5	2003010206	1004.0	154.3	32.1	2003010318	975.2	185.0	35.0	2.23	2003010412	950.0	198.1	38.0	1	ST
6	2005030118	1004.8	164.0	37.0	2005030306	967.2	194.0	44.9	1.70	2005030400	955.0	200.9	49.0	1	ST
7	2005121212	1001.4	162.0	32.0	2005121312	982.0	191.1	43.0	1.83	2005121400	963.6	198.1	48.2	1	ST
8	2007112412	996.8	188.2	40.9	2007112500	982.0	201.6	44.0	1.93	2007112518	961.8	208.1	54.0	1	ST
9	2007112900	1001.6	137.0	29.0	2007120200	980.4	201.0	36.0	2.50	2007120300	951.6	211.0	39.0	1	SU
10	2009100812	1000.6	189.1	35.0	2009100900	983.4	200.0	40.0	2.08	2009100918	967.0	204.0	48.9	1	ST
11	2009112100	1014.0	145.1	35.1	2009112300	991.0	185.3	40.1	1.75	2009112400	961.2	201.0	44.0	1	ST
12	2010022300	1010.8	131.9	22.4	2010022606	975.6	186.0	39.0	2.20	2010022700	951.0	190.0	45.0	2	ST

TABLE A1. (Continued)

ID	IFP				MDP					MCP				NS	IN
	Time	PRE	Lon	Lat	Time	PRE	Lon	Lat	MDR	Time	PRE	Lon	Lat		
13	2010102806	1006.0	138.7	31.9	2010103012	964.0	191.0	49.0	2.77	2010103100	939.4	198.0	50.0	1	SU
14	2012011906	1010.6	130.0	30.0	2012012218	979.8	184.0	36.0	2.09	2012012306	962.8	189.0	40.0	1	ST
15	2012020906	997.0	164.1	37.9	2012021006	964.0	189.0	44.0	2.14	2012021100	950.2	198.9	50.9	1	ST
16	2012122900	982.8	193.0	38.0	2012122906	968.0	198.0	40.1	2.07	2012123006	951.0	206.4	52.5	1	ST
17	2014011600	977.8	199.0	39.0	2014011606	969.0	201.0	41.1	1.73	2014011700	953.8	201.0	48.1	1	ST
18	2014111800	1008.8	151.9	36.9	2014111912	977.8	188.0	43.3	1.71	2014112012	953.6	202.4	52.0	1	ST
NEP ECs															
1	2000102512	1012.4	184.0	36.0	2000102700	988.4	212.9	50.0	1.89	2000102800	961.2	223.9	50.0	1	ST
2	2001102506	1011.4	212.0	42.0	2001102600	987.6	224.0	49.0	1.72	2001102612	972.4	228.0	54.0	1	ST
3	2004100518	1015.2	177.7	43.9	2004100706	980.2	214.0	46.0	2.21	2004100718	964.8	219.0	49.0	1	ST
4	2006010318	999.0	208.0	32.0	2006010400	983.2	213.1	34.0	2.97	2006010412	964.4	218.0	39.1	1	SU
5	2006122306	995.2	201.3	40.5	2006122400	961.6	212.0	46.9	2.13	2006122412	945.0	214.0	49.0	1	ST
6	2006122806	993.8	208.8	40.9	2006122818	972.8	214.0	47.0	2.27	2006122918	950.4	215.0	57.0	1	ST
7	2007100712	1014.6	189.2	44.0	2007100818	984.0	222.1	41.0	2.49	2007100912	965.4	227.0	46.0	1	SU
8	2008022300	990.0	219.0	35.0	2008022306	977.8	221.0	37.0	1.72	2008022312	972.8	223.2	37.4	1	ST
9	2010021012	998.4	159.0	45.0	2010021212	971.2	205.6	41.0	2.14	2010021300	951.2	213.5	45.0	1	ST
10	2010111618	1018.6	217.0	48.0	2010111700	1006.6	222.8	49.1	2.09	2010111712	982.8	228.0	52.0	1	ST
11	2012033012	1006.0	171.8	31.1	2012040112	984.4	210.0	44.0	1.97	2012040212	958.6	221.0	52.0	1	ST
12	2014022718	990.8	226.0	34.0	2014022800	981.0	226.2	36.0	1.92	2014022812	971.6	227.1	36.9	1	ST
13	2015013006	996.6	207.0	34.2	2015013018	977.6	208.5	42.0	2.11	2015013112	954.0	205.0	45.1	1	ST

autumn and early spring. The occurrence frequency, averaged maximum deepening rate, and developing and explosive-developing lifetimes of ECs decrease eastward over the northern Pacific, excluding JOS ECs. The moving tracks of JOS and NWP ECs are usually in the northeastward direction. Those of WCP and ECP ECs are generally in the eastward direction in early stages, and they turn to the northeastward direction in later stages. NEP ECs travel along the two directions as mentioned above depending on their initial formation positions.

ECs predominantly appear at the poleward side of the upper-level jet stream, within and at the equatorward side of midlevel positive vorticity, and over strong low-level baroclinicity. Moreover, these large-scale environments decrease eastward over the northern Pacific, which results in the characteristics of the eastward-decreasing trend of the occurrence frequency, averaged maximum deepening rate, and developing and explosive-developing lifetimes of ECs in the cold season. The occurrence frequency and spatial distribution of ECs are highly correlated with the intensity and position of the upper-level jet stream, respectively, on the seasonal scale and also with those of midlevel positive vorticity and low-level baroclinicity. A warm ocean surface associated with abundant sensible and latent heat fluxes also favors rapid intensification of ECs, this process is more important over the northwestern Pacific and leads to more frequent activities of ECs over the Kuroshio/Kuroshio Extension. The composite analysis

indicates that the large-scale atmospheric environment for NWP and NEP ECs shows significant differences from that for the 15-yr cold-season average. The southwesterly anomalies of upper-level stream and positive anomalies of midlevel vorticity favor the frequent occurrence of NWP and NEP ECs.

We have discussed the large-scale atmospheric and oceanic environments, such as the upper-level jet stream, midlevel positive vorticity, low-level baroclinicity, SST, and SST gradient, in relation to the occurrence frequency and spatial distribution of ECs. In addition, the diabatic process was also taken as an important factor favoring the rapid development of ECs (Ahmadi-Givi et al. 2004; Kuwano-Yoshida and Asuma 2008; Kuwano-Yoshida and Enomoto 2013; Hirata et al. 2015), and we have tried to use precipitable water, specific humidity, moisture flux, and moisture flux convergence to investigate the influence of the diabatic process on the occurrence frequency and spatial distribution of ECs on the seasonal scale (not shown). These meteorological variables showed insignificant correlation with the occurrence frequency and spatial distribution of ECs on the seasonal scale. Other meteorological variables or methods are still needed to examine the diabatic process. Moreover, composite analyses and case studies are required for further understanding the development mechanisms and detailed structures of various types of ECs. The diabatic process can probably be investigated successfully in such future work.

FIG. A1. The progression of the SLP pattern (3-hPa contours) for a merged EC: (a) 1800 UTC 4, (b) 0000 UTC 5, (c) 0600 UTC 5, (d) 1200 UTC 5, (e) 1800 UTC 5, and (f) 0000 UTC 6 Apr 2011. The label PC indicates the parent cyclone.

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FIG. A2. As in Fig. A1, but for a splitting EC: (a) 1200 UTC 16, (b) 1800 UTC 16, (c) 0000 UTC 17, (d) 0600 UTC 17, (e) 1200 UTC 17, and (f) 1800 UTC 17 Dec 2013.

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APPENDIX

Detailed Information and Examples

Detailed information about strong and “super” ECs over the northern Pacific during the cold season (October–April) over a 15-yr (2000–15) period is given in Table A1. The SLP patterns with time for examples of merged and splitting ECs are shown in Figs. A1 and A2, respectively.

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