Climatological Features of Strong Winds Caused by Extratropical Cyclones around Japan

HIDETAKA HIRATA^a

^a Faculty of Geo-Environmental Sciences, Rissho University, Kumagaya, Japan

(Manuscript received 20 July 2020, in final form 8 February 2021)

ABSTRACT: We examined the climatological features of strong winds associated with extratropical cyclones around Japan during 40 seasons between November and April from 1979/80 to 2018/19 using reanalysis data. Our assessments revealed that the extratropical cyclones caused most of the strong winds around Japan (80%–90%). Notably, the contribution of explosively developing extratropical cyclones is larger (70%–80%). The strong winds are mainly related to the warm conveyor belt (WCB) and cold conveyor belt (CCB) inside the explosive cyclones. Moreover, the strong winds tend to be distributed widely over the southwestern quadrant of the cyclones. This is due to the intensification of the horizontal pressure gradient between the mature cyclones and the Siberian high extending from the Eurasian continent to Japan. We investigated the regionality of strong winds by highlighting the three areas with high frequencies of strong winds: the area around Hokkaido (i.e., the northernmost island of Japan; area A), and the areas around the Japan Sea side (area B) and the Pacific Ocean side (area C) of the main island of Japan. The features of the seasonal change in the frequency of the strong winds differ in each area, which reflects the seasonal change in the activities of the explosive cyclones. Moreover, the CCB, the head of the CCB and WCB, and the CCB and WCB bring the strong winds to areas A, B, and C, respectively. The timing of the appearance of these windstorms during the life cycles of typical cases highlighted in this study is consistent with that observed in Europe.

KEYWORDS: Synoptic climatology; Extratropical cyclones; Wind

1. Introduction

Developing extratropical cyclones frequently pass around Japan during the period between fall and spring (Yoshida and Asuma 2004; Adachi and Kimura 2007; Hayasaki and Kawamura 2012; Iwao et al. 2012; Iizuka et al. 2013; Tsukijihara et al. 2019), bringing strong winds, which directly damage buildings and infrastructure. Moreover, since the cyclone-induced strong winds are responsible for high waves (Kita et al. 2018; Saruwatari et al. 2019) and drifting snow (Kawano and Kawamura 2018), these are involved in the occurrence of various natural disasters in Japan. Thus, it is important that we understand the features of strong winds associated with extratropical cyclones around Japan.

A number of previous studies have focused on extratropical cyclones associated with strong winds around Japan. Hirata et al. (2016, 2018) demonstrated that the surface latent and sensible heat fluxes from the Kuroshio and Kuroshio Extension can enhance the near-surface wind through diabatic processes using numerical sensitivity experiments with respect to these heat fluxes. Kawano and Kawamura (2018) highlighted an extratropical cyclone causing a severe snowstorm in Hokkaido, Japan, in March 2013 and examined the influence of the distribution of sea ice in the Sea of Okhotsk on

the cyclone from numerical simulations. They indicated that the Okhotsk sea ice distribution affected the strong wind distribution associated with the cyclone by changing the pressure distribution near the surface. Tsukijihara et al. (2019) studied the relationship between the frequency of strong winds in Hokkaido, Japan, and explosively developing extratropical cyclones (i.e., explosive cyclones) in winter from 1979/80 to 2016/17 on the basis of reanalysis data. Their investigations revealed that the increase in strong wind events in Hokkaido resulted from an increase in the explosive cyclones moving northward from the Kuroshio region to Hokkaido. It is therefore clear that strong wind events around Japan are closely related to extratropical cyclones. However, the characteristics of strong winds associated with extratropical cyclones around Japan have not been sufficiently studied.

Recently, the characteristics of strong winds of extratropical cyclones have been examined largely through studies of European windstorms (e.g., Browning 2004; Baker 2009; Baker et al. 2013; Schultz and Sienkiewicz 2013; Smart and Browning 2014; Martínez-Alvarado et al. 2014; Slater et al. 2017) and idealized experiments (Baker et al. 2014, Slater et al. 2015). These studies indicated that the strong winds of extratropical cyclones are characterized by three low-level jets: the warm conveyor belt (WCB), the cold conveyor belt (CCB), and the sting jet. The structure and time evolution of these low-level jets are well summarized in Fig. 17 in Clark et al. (2005), Fig. 1 in Hewson and Neu (2015), and Fig. 1 in Hart et al. (2017). The WCB intensifies along the cold front within the warm sector during the early life stage of the cyclone. The CCB develops on the cold side of the warm and bent-back fronts from just before the time when the cyclone reaches its maximum intensity. The sting jet appears around the tip of the bent-back front during the stage of the most rapid development of the cyclone (Clark

Denotes content that is immediately available upon publication as open access.

Hirata's current affiliation: Faculty of Data Science, Rissho University, Kumagaya, Japan.

Corresponding author: Hidetaka Hirata, hirata@ris.ac.jp

DOI: 10.1175/JCLI-D-20-0577.1

© 2021 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).

and Gray 2018). The WCB and CCB are sub-synoptic-scale phenomena, while the sting jet is a mesoscale phenomenon. Note that not all extratropical cyclones are associated with all the three jets. For instance, previous studies (e.g., Parton et al. 2010; Schultz and Sienkiewicz 2013; Clark and Gray 2018) pointed out that sting jets are associated with Shapiro–Keyser-type cyclones (Shapiro and Keyser 1990). While these strong wind features (WCB, CCB, and sting jets) have been evaluated in European cyclones, no such study exists for Japan and this knowledge gap is addressed here.

Although it is known that strong winds of extratropical cyclones cause disasters in Japan, our understanding remains limited with respect to the features of strong winds of extratropical cyclones around Japan, as noted above. Motivated by this, we examined the climatological features of strong winds associated with extratropical cyclones around Japan. The specific objectives of this study were 1) to quantitatively assess the relationship between extratropical cyclones and strong wind events around Japan, and 2) to clarify the characteristics of the strong winds associated with extratropical cyclones around Japan.

To approach these issues, we utilized the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) dataset (Dee et al. 2011). As will be shown in section 2a, these data capture the characteristics of near-surface winds well, around Japan. On the other hand, sting jets are not represented in the ERA-Interim data due to being a mesoscale phenomenon (e.g., Martínez-Alvarado et al. 2012; Hewson and Neu 2015). Thus, this study mainly highlights the synoptic and sub-synoptic strong winds associated with cyclones. Despite this limitation, this study is meaningful as a first step toward understanding the climatological features of strong winds associated with extratropical cyclones around Japan.

2. Data and methods

a. Data

To examine the relationship between extratropical cyclones and strong wind events, we used 6-hourly data from the ERA-Interim dataset (Dee et al. 2011) with a horizontal resolution of 0.75° longitude $\times$ 0.75° latitude, provided by ECMWF. This study used 10-m horizontal wind, 2-m temperature, total column water vapor, and sea level pressure (SLP) data. This study focused on the period between fall and spring (November–April) when the extratropical cyclone activity is higher around Japan (e.g., Yoshida and Asuma 2004; Adachi and Kimura 2007; Hayasaka and Kawamura 2012). We analyzed the 40 seasons from 1979/80 to 2018/19.

To confirm the reliability of the ERA-Interim data, we compared the 10-min-averaged wind speed derived from nine observation stations of the JMA (shown in Fig. 1) with the ERA-Interim wind speed at a height of 10 m for the grid points nearest these stations (Fig. 2). Additionally, we calculated the Spearman's rank correlation coefficient between these two variables (Table 1). We selected Spearman's rank correlation coefficient because the frequency distribution of the wind speed was not a normal distribution. The ERA-Interim data capture the characteristics of the wind speed at each station

FIG. 1. The eight regions of Japan, shown by different colors. The dots indicate the locations of nine observation stations of the Japan Meteorological Agency (JMA). The region enclosed by the green line is highlighted in this study.

(Fig. 2), and significant positive correlations were found at all stations (Table 1). The correlations differ among the stations: the strongest correlation was at Aikawa (0.72), while the weakest correlation was at Shionomisaki (0.42). This difference may be due to the differences in the surrounding environment (e.g., topography, altitude, and land use) among these stations. Those comparisons indicated that the 10-m winds of the ERA-Interim data accurately reproduce the features of the near-surface winds around Japan.

b. Algorithm for tracking cyclones

To identify extratropical cyclones, we utilized the tracking algorithm of Tsukijihara et al. (2019). Following their method, we first searched SLP fields over the East Asia region (20° – 65° N, 115° E– 180°) for a minimum point of SLP within a circle with a 300-km radius using the 6-hourly ERA-Interim data ($0.75^\circ \times 0.75^\circ$). If the minimum value was at least 0.5 hPa lower than the areal-averaged value within a 300-km radius from the minimum, it was identified as the candidate of a cyclone center. This search was conducted using an interval of 6 h for the 40 seasons from 1979/80 to 2018/19. Using the method of Wernli and Schwerz (2006), the location of the cyclone center 6 h later was estimated as follows:

$$x(t+6) = x(t) + 0.75[x(t) - x(t-6)], \quad (1)$$

where x is the location of the cyclone center, which is indicated by degree of latitude and longitude, and t is the time in hours. The nearest cyclone-center candidate at $t+6$ within a radius of 600 km from $x(t+6)$ was considered as the cyclone center at $t+6$. Short-lived cyclones (lifetime < 24 h) were eliminated from our analyses.

FIG. 2. Comparisons between 10-min-averaged wind speed derived from the nine observation stations of the JMA (see Fig. 1) and ERA-Interim's wind speed at a height of 10 m of the grid points nearest these stations. In these comparisons, we used 6-hourly data for 10 seasons between November and April from 2009/10 to 2018/19. See text for details.

c. Definition of explosive cyclones

To understand the features of cyclones associated with strong winds in detail, we classified extratropical cyclones into explosive cyclones and nonexplosive cyclones. To define explosive cyclones, we used the cyclone deepening rate ε , expressed as

$$\varepsilon = \frac{p_c(t-6) - p_c(t+6) \sin 60^\circ}{12 \sin \varphi_c}, \quad (2)$$

where p_c and φ_c are the SLP at the center of the cyclone and the latitude at the cyclone center, respectively. According to previous studies (e.g., Yoshida and Asuma 2004; Yoshiike and Kawamura 2009), if the ε of an extratropical cyclone exceeds

TABLE 1. Spearman's rank correlation coefficient between 10-min-averaged wind speed derived from the nine observation stations of the Japan Meteorological Agency (JMA) (see Fig. 1) and the ERA-Interim's wind speed at a height of 10 m for the grid points nearest these stations. To estimate these correlations, we used 6-hourly data during 10 seasons between November–April from 2009/10 to 2018/19. An asterisk (*) indicates that the correlation coefficient satisfies a 1% level of statistical significance.

Nemuro	Suttu	Enoshima	Aikawa	Chosi	Miyakejima	Shionomisaki	Sakai	Makurazaki
0.68*	0.44*	0.55*	0.72*	0.56*	0.65*	0.42*	0.53*	0.52*

1 hPa h^{-1} , it is considered as an explosive cyclone. In the original definition of explosive cyclones (Sanders and Gyakum 1980), the time changes in central pressure of cyclones during a 24-h period are used. On the other hand, the method in this study used those during a 12-h period. The 12-h method can also extract cyclones rapidly developing over a short period. We believed that these cyclones are also dangerous because they cause rapid changes in weathers over a short period. Thus, this study used the 12-h method.

d. Definition of strong winds

To define strong wind events around Japan, we used the 6-hourly 10-m wind speed data from the ERA-Interim dataset within the region enclosed by the green line in Fig. 1. We estimated the 99th percentile of 10-m wind speed from all data of the analyzed region during the 40 seasons. Consequently, the 99th percentile of the wind speed was 15.567 m s^{-1} . On the basis of this statistic, strong wind events (probability $\leq 1\%$) are defined as those with 10-m wind speed exceeding 15.567 m s^{-1} .

3. Overview of strong winds associated with extratropical cyclones

Figure 3 shows the frequency distribution of the strong wind events during the 40 seasons. Note that eight regional names of Japan used in this paper are indicated in Fig. 1. This map indicates that there are three regions where the strong wind events frequently occur around Japan. The first region is around Hokkaido, the second region is on the Japan Sea side of Chubu, Kinki, and Chugoku, and the third region is on the Pacific Ocean side of Tohoku, Kanto, and Chubu. The frequencies of strong wind events were lower around Shikoku and Kyushu than around the other areas.

To investigate the degree to which strong wind events around Japan are related to extratropical cyclones, we estimated the probability that the strong wind events occur in association with the cyclones (Fig. 4a). We considered strong wind events occurring within a 1500-km radius from the centers of cyclones as the cyclone-related events. If a grid point value satisfies the strong wind criterion (section 2c) within a 1500-km radius from two or more cyclone centers, we regarded this situation as one event. As seen in Fig. 4a, the extratropical cyclones are related to $>80\%$ of the strong wind events over the whole analytical domain. Around Hokkaido, Tohoku, and Kanto, where the frequencies of strong winds are higher (Fig. 3), the probability exceeds 90%. These results indicate that extratropical cyclones are associated with strong winds around Japan between fall and spring.

To assess the relative contributions of the explosive and nonexplosive cyclones to the strong wind events, Figs. 4b and 4c show the probability of strong wind events occurring in association with the explosive and nonexplosive cyclones, respectively. The probability that the events occur around Japan in relation to the explosive cyclones is $>70\%$ (Fig. 4b). In particular, this probability exceeds 80% around Hokkaido and Tohoku. Nonexplosive cyclones account for approximately 20%–40% of the strong wind events around Japan (Fig. 4c). As described in Table 2, the number of explosive cyclones passing around Japan (29° – 47°N , 127° – 147°E) is smaller than that of nonexplosive cyclones. However, the strong wind events are mainly caused by the explosive cyclones rather than the nonexplosive cyclones. This is one of the important features of extratropical cyclones causing strong winds around Japan.

To determine where the strong winds occur inside cyclones, their frequency relative to the center of explosive and nonexplosive cyclones is shown in Figs. 5a and 5b, respectively. Within the explosive cyclone system, the strong winds frequently occur over the northwest and southwest quadrants of the cyclone (Fig. 5a). Specifically, the strong wind frequencies were the highest around the south and southwest of the cyclone center (Fig. 5a). To the east of the cyclone center, the middle frequencies of the strong winds (≥ 100) were observed (Fig. 5a). Compared to the other quadrants, the middle frequencies of

FIG. 3. Frequency distribution of the strong wind events around Japan during the 40 seasons.

FIG. 4. Probability of strong wind events occurring in association with (a) all extratropical cyclones, (b) the explosive cyclones, and (c) the nonexplosive cyclones. If the frequencies of the strong winds are <200 (see Fig. 3), probabilities are suppressed.

the strong winds (≥ 100) spread widely over the southwest quadrant of the explosive cyclone (Fig. 5a). As for the non-explosive cyclone, the strong wind events mainly encircle the cyclone center (Fig. 5b). The frequencies of the strong winds are significantly lower in the nonexplosive cyclone category than in the explosive cyclone category. These results also indicated that the explosive cyclones are the main contributors to the strong winds around Japan. Based on the results illustrated in Figs. 4 and 5, we specifically focus on the explosive cyclones in the following paragraphs.

To see the mean structure of near-surface winds associated with explosive cyclones, we produced composite maps of 10-m horizontal winds relative to the center of explosive cyclones related to the strong winds (Fig. 6). The strong wind frequency and composited meridional winds at a height of 10 m are also shown in Figs. 6a and 6b, respectively. To the east of the cyclone center, where the middle frequencies of the strong winds were observed (Fig. 6a), southerly winds were strong inside the cyclone (Fig. 6b). Around the northwest quadrant of the cyclone, where the strong wind frequencies were relatively high (Fig. 6a), easterly or northerly winds prevailed (Fig. 6). To the south and southwest of the cyclone center, where the strong wind frequencies were the highest (Fig. 6a), westerly winds dominated. To the south of the cyclone center, meridional winds transitioned from northerly to southerly winds (Fig. 6b). Over the southwest quadrant of the cyclone, where the strong winds frequencies were widely distributed, northwesterly winds were evident (Fig. 6a).

Next, to examine the characteristics of the strong winds associated with explosive cyclones, we produced composite maps of temperature at 2 m in height and total column water vapor relative to the center of explosive cyclones related to the strong winds (Fig. 7). The composited horizontal winds at a height of 10 m are also shown in Fig. 7. To the east of the cyclone center, the southerly winds associated with relatively high temperature (Fig. 7a) and moisture content (Fig. 7b) dominated. These

features of the southerly winds correspond well to those of the WCB (e.g., Carlson 1980; Browning and Roberts 1994; Madonna et al. 2014). Around the north and west of the cyclone center, the easterly and northerly winds associated with relatively low temperature (Fig. 7a) and moisture content (Fig. 7a) were observed. These features of the easterly and northerly winds are consistent with those of the CCB (e.g., Carlson 1980; Schultz 2001; Hirata et al. 2019). To the southwest of the cyclone center, the moisture content is relatively low, and the temperature transitioned from low to high values. Moreover, the northwesterly winds prevailed over the southwest. These features suggest that the head of the CCB is related to the strong wind around the southwest of the cyclone center. To the south of the cyclone center, the composited temperature was relatively high, and the moisture content increased from west to east. The relatively high temperature suggests that the WCB is related to the strong winds, while the transition of the moisture content implies that the head of the CCB is also related to the strong winds. The transition from the northerly to southerly winds (shown in Fig. 6b) also suggests that both the WCB and CCB contribute to the strong winds around the south of the cyclone center; this is discussed in greater detail in section 4b.

As seen in Figs. 5a and 6a, the strong winds are distributed widely over the southwest quadrant of the cyclones, and it is important to consider the reason why this asymmetry occurs. Yamashita et al. (2012) reported that when an explosive

TABLE 2. Number of explosive cyclones and nonexplosive cyclones passing around Japan (29° – 47° N, 127° – 147° E) and their percentage of total extratropical cyclones.

Category	Number	Percentage (%)
Explosive cyclones	1705	35
Nonexplosive cyclones	3134	65

FIG. 5. Frequency distribution of the strong wind events relative to the center of (a) explosive and (b) nonexplosive cyclones.

cyclone grew around Japan, a cold continental high in East Asia, the Siberian high (e.g., Takaya and Nakamura 2005), often extends from the Eurasian continent to Japan, and thus the horizontal pressure gradient increases between these two systems around the southwest quadrant of the cyclone, which enhances northwesterly geostrophic winds around Japan (see Fig. 12 in Yamashita et al. 2012).

To confirm this influence of the Siberian high, we produced the composite map of SLP and geostrophic component of horizontal wind estimated from SLP relative to the cyclone center (Fig. 8). We selected explosive cyclones causing strong

winds in their southwest quadrants as the samples for this analysis. The high pressure is located to the west of the cyclone, corresponding to the Siberian high. The high extends to the southwest of the cyclone center, and thus the horizontal pressure gradient intensifies in situ. The region accompanied by the relatively strong geostrophic winds ($\geq 18 \text{ m s}^{-1}$) is distributed widely over the southwest quadrant of the cyclone compared with the other quadrants, which is consistent with the frequency distribution of the strong winds shown in Fig. 5a. These results indicate that the combination of the explosive cyclone development and the Siberian high may cause the higher

FIG. 6. Composite map of 10-m horizontal winds (vectors) and sea level pressure (SLP; contours) relative to the center of explosive cyclones associated with the strong winds. The contour interval is 5 hPa. The reference arrow is 10 m s^{-1} (shown between the color bars). Frequency distribution of the strong wind events (shading) and composited 10 m meridional wind (shading; m s^{-1}) are also shown in (a) and (b), respectively.

FIG. 7. (a) Composite map of temperature at 2 m in height (shading), 10-m horizontal winds (vectors), and SLP (contours) relative to the center of explosive cyclones associated with the strong winds. The shading interval 3 K, and the contour interval is 5 hPa. The reference arrow is 10 m s^{-1} (shown between the color bars). (b) As in (a), but for total column water vapor. The shading interval is 3 kg m^{-2} .

frequency of strong wind events over the southwest quadrant of the cyclones.

4. Regionality of strong winds associated with extratropical cyclones

As shown in Fig. 3, there are the three areas where the strong winds frequently occur around Japan; the area around Hokkaido,

the area west of Chubu, Kinki, and Chugoku, and the area east of Tohoku, Kanto, and Chubu. In this section, to deepen our understanding of the cyclone-induced strong winds, we conducted a detailed examination of the three areas described above. On the basis of the frequencies of the strong winds (Fig. 3), we defined the three areas as shown in Fig. 9. For convenience, these regions are referred to as A, B, and C. In this section, we highlight explosive cyclones, since these are related to many strong wind

FIG. 8. (a) Composite map of sea level pressure (SLP) (contour) relative to the center of explosive cyclones associated with strong winds in their southwest quadrants. The shading interval 5 hPa. (b) As in (a), but for the geostrophic component of horizontal wind estimated from SLP. The shading interval is 4 m s^{-1} .

FIG. 9. Study areas A, B, and C, shown by orange, blue, and light green shading, respectively.

events around Japan, as described in section 3. We provide results derived from climatological and prototype analyses in sections 4a and 4b, respectively.

a. Climatological analysis

We first surveyed the seasonality of the frequency of strong winds in areas A, B, and C. Figures 10a–c show the frequency of the strong wind events from November to April in areas A, B, and C, respectively. The frequency corresponds to the number of grid points satisfying the criterion of the strong wind divided by the total number of grid points in each area. As can be seen, the seasonality in the three areas differs. The frequency in November is higher in area A (Fig. 10a) compared to

the other areas (Figs. 10b,c). The frequency in area A reaches its peak in December and then subsequently decreases, and is slightly higher in March than in February, which is also a unique characteristic of area A (Fig. 10a). In April, the frequency drastically decreases in area A (Fig. 10a). Although the frequency in area B is low in November, it rapidly increases and reaches the maximum in December (Fig. 10b). Subsequently, the frequency gradually decreases until April (Fig. 10b). As with area B, the frequency suddenly increases from November to December in area C; its peak is observed in January (Fig. 10c). Although the frequency decreases from January to March, the values are almost the same (Fig. 10c), whereas from March to April the frequency rapidly decreases (Fig. 10c).

The seasonal change in the frequency of the strong winds, as shown in Fig. 10, corresponds well to the seasonal change in the frequency of the explosive cyclones shown in Fig. 11. In November, high cyclone densities are observed around the northernmost part of the Japan Sea and the Okhotsk Sea, or the western and northern parts of area A (Fig. 11a). This observation is consistent with the higher frequency of the strong wind events in November in area A (Fig. 10a). In December, the cyclone densities around the southern part of the Japan Sea suddenly increase (Fig. 11b), which corresponds to the rapid increase in the frequency of the strong wind events in area B (Fig. 10b). Moreover, the cyclone densities also increase around Kanto in December (Fig. 11b). This corresponds to the increase in the frequency of the strong wind events in area C in December (Fig. 10c). The cyclone densities over the Sea of Japan gradually decrease from December to April (Figs. 11b–f), which corresponds well with the change in the strong wind frequency of area B (Fig. 10b). On the other hand, the higher densities of the cyclones were maintained from December to March around the Pacific Ocean side of Japan (Figs. 11b–e). This is similar to the seasonal transition of the strong wind frequencies in area C (Fig. 10c). Focusing on the cyclone densities around the Sea of Okhotsk, we can see that those are higher in March than in February (Figs. 11d,e). This difference in the cyclone densities corresponds well to the difference in the strong wind frequency in area A between February and

FIG. 10. Monthly frequencies of the strong wind events in areas (a) A, (b) B, and (c) C.

FIG. 11. Frequency distributions of explosive cyclones in (a) November, (b) December, (c) January, (d) February, (e) March, and (f) April.

March (Fig. 10a). The cyclone densities around Japan drastically decrease from March to April (Figs. 11e,f), which resembles the seasonal reduction of the strong wind events in all areas (Fig. 10).

To investigate the features of the strong winds caused by explosive cyclones in areas A, B, and C, we produced the frequency map of the strong winds relative to the cyclone center with respect to each area (Fig. 12). In area A, higher

FIG. 12. Frequency distributions of the strong wind events relative to the center of the explosive cyclones in areas (a) A, (b) B, and (c) C.

FIG. 13. Horizontal winds at a height of 10 m (vectors), their magnitude (shading), and SLP (contours) at (a) 1200 UTC 2 Mar 2013, (b) 1200 UTC 3 Apr 2012, (c) 1200 UTC 30 Dec 1985, (d) 1800 UTC 14 Feb 2007, (e) 1200 UTC 16 Jan 2005, and (f) 1200 UTC 13 Mar 2014. The reference arrow is 40 m s^{-1} (shown beside the color bar). Winds $< 10 \text{ m s}^{-1}$ are suppressed. The shading interval is 3 m s^{-1} . The contour interval is 5 hPa. The cyclones seen in (a)–(f) are referred to as cases 1–6, respectively.

frequencies are found over the northwest and southwest quadrants of the cyclone (Fig. 12a). This distribution of the strong winds corresponds well to the feature of the CCB. In area B, higher frequencies are seen to the south of the cyclone center (Fig. 12b), and this distribution of the strong winds resembles the feature of the WCB. Additionally, part of the frequencies to the south of the cyclone center may include the influence of the tip of the CCB, which is further discussed in section 4b. The relatively low frequencies are also observed to the northwest of the cyclone center in area B (Fig. 12b), which may derive from the CCB of cyclones located over the Pacific Ocean. In area C, the high frequencies of the strong winds appear from the southwest of the cyclone center to the east (Fig. 12c), which may reflect the influence of both the WCB and CCB. Moreover, relative high frequencies, between 60 and 100, are observed to the north, northwest, and west of the cyclone center, which is consistent with the feature of the CCB. Additionally, the middle frequencies, between 40 and 80, extend meridionally over the southeastern quadrant of the cyclone in area C. This strong wind zone may also be related to the WCB of the cyclones located over the Japan Sea, which is discussed in detail in section 4b. Compared to the other quadrants, the middle frequencies are distributed widely over the southwest

quadrant of the cyclone in all areas, which is consistent with Fig. 5a.

b. Prototype analysis

To gain further insights into the features of the strong winds associated with the cyclones around Japan, we conducted analyses of typical cases causing strong wind in areas A, B, and C (Figs. 13 and 14). Figure 13 illustrates snapshots of 10-m horizontal winds, their magnitude, and SLP when strong wind events occurred around Japan in relation to six explosive cyclones, identified as cases 1, 2, 3, 4, 5, and 6. Case 1 is relevant to strong winds in area A; cases 2, 3, and 4 are relevant to area B; and cases 2, 5, and 6 are relevant to area C. The times in Fig. 13 correspond to the times when strong wind events occurred in each area. Figure 14 displays the time evolution of the central pressure of each cyclone, wherein the red circles indicate the times of Fig. 13.

We first examined case 1, which caused damage in area A. At 1200 UTC 2 March 2013, the cyclone existed to the east of Hokkaido (Fig. 13a). The strong surface winds in excess of 18 m s^{-1} are observed over the northwestern and southwestern quadrants of the cyclone. These strong winds are consistent with the CCB and corresponds well to the cyclone composite strong winds in area A (Fig. 12a).

FIG. 14. (a)–(f) Time evolution of the central pressure of cases 1–6, respectively. Red circles indicate the times of Fig. 13.

At 1200 UTC 2 March 2013, case 1 was at the mature stage (Fig. 14a). Previous studies showed that the CCB associated with European cyclones tends to develop during their mature stage (Clark et al. 2005; Hewson and Neu 2015; Hart et al. 2017). Thus, the time of the development of the CCB seen in case 1 is consistent with that of European cyclones.

We next focused on the cases bringing strong winds in area B. At 1200 UTC 3 April 2012 and 1200 UTC 30 December 1985, the centers of both cases 2 and 3 are in almost same position to the north of area B (Figs. 13b,c). However, the features of the strong winds of the two cyclones differ. The northwesterly and westerly winds of case 2 (Fig. 13b) caused the strong winds in area B at 1200 UTC 3 April 2012. On the other hand, the southwesterly winds of case 3 (Fig. 13c) brought strong winds in area B at 1200 UTC 30 December 1985. The features of the strong winds associated with cases 2 and 3 correspond well to the features of the CCB and WCB, respectively.

The times 1200 UTC 3 April 2012 and 1200 UTC 30 December 1985 were the times of the late development stage of case 2 (Fig. 14b) and of the middle development stage of case 3 (Fig. 14c), respectively. Studies of European cyclones showed that the CCB and WCB appear at the late development stage of the cyclone, and that the WCB intensifies at the middle development stage of the cyclone, while the CCB does not occur at this

stage (Clark et al. 2005; Hewson and Neu 2015; Hart et al. 2017). Thus, the timing of the occurrence of the windstorms associated with cases 2 and 3 corresponds well to that of European windstorms (Clark et al. 2005; Hewson and Neu 2015; Hart et al. 2017).

As shown in Fig. 13d, the center of case 4 is located to the west of Hokkaido at 1800 UTC 14 February 2007, at which time the Siberian high extended from the continent to the western part of Japan. Consequently, the horizontal pressure gradient was enhanced between the low and high pressure systems over the southwestern quadrant of the cyclone, which induced the strong southwesterly winds over area B. As discussed in the last paragraph in section 3, this combination of the explosive cyclone and the continental high appears to be a cause of the higher frequencies of the strong winds over the southwestern quadrant of the cyclones seen in Figs. 5a and 12. The life stage of case 4 at 1800 UTC 14 February 2007 is the mature stage (Fig. 14d). This lower pressure associated with the mature cyclone is favorable for the intensification of the horizontal pressure gradient.

Next, we examined the cases causing strong winds in area C. At 1200 UTC 16 January 2005 and 1200 UTC 13 March 2014, cases 5 and 6 existed over the ocean to the east of Kanto (Fig. 13e) and over Kanto (Fig. 13f), respectively. The northeasterly, northerly, and southwesterly winds of case 5 and the southwesterly winds of case 6 were responsible for the strong

wind events in area C. The features of the strong winds of cases 5 and 6 correspond well to those of the CCB and WCB. Thus, the CCB and WCB appear to influence the climatological distribution of the strong winds in area C (Fig. 12c). In both cases 5 and 6, weak wind areas were found to the west of the cyclone center over the main island of Japan. This may be due to an increase in the surface friction over land, which is discussed in section 5. Focusing again on the strong winds associated with case 2 (Fig. 13b), the southerly strong winds, corresponding to the WCB, flow over area C, although its center is situated over the Japan Sea. The relatively high frequencies of the strong winds over the southeastern quadrant of the cyclone (seen in Fig. 12c) likely reflect the influences of the WCB of the cyclones situated over the Sea of Japan.

The times 1200 UTC 16 January 2005 and 1200 UTC 13 March 2014 are the mature stage of case 5 (Fig. 14e) and the middle development stages of case 6 (Fig. 14f), respectively. As with case 1, the timing of the appearance of the CCB of case 5 corresponds to that of European windstorms. Moreover, as with case 3, the appearance time of the WCB of case 6 is also consistent with that observed in European windstorms.

On the basis of the results obtained in section 4, the WCB and CCB (and their associated features) account for the strong winds around the cyclone center in areas A, B, and C. The timing of the occurrence of the WCB and CCB associated with the Japanese cyclones is very similar to that of European windstorms. Moreover, the enhancement of the strong winds over the southwestern quadrant appears to be due to the combination of a mature cyclone and the Siberian high extending from the continent to Japan. This is a unique characteristic of the strong winds associated with the cyclones around Japan, which is related to the geographical feature that Japan is located to the east of the Eurasian continent.

5. Summary and discussion

In this study, we examined the climatological features of strong winds caused by extratropical cyclones around Japan during 40 seasons between November and April from 1979/80 to 2018/19 using the ERA-Interim dataset. First, we quantitatively assessed the contribution of extratropical cyclones to strong wind events, which showed that a substantial portion of the strong wind events (80%–90%) is related to extratropical cyclones (Fig. 4a). The contributions of the explosive cyclones (70%–80%) are larger than that of the nonexplosive cyclones (20%–40%) (Figs. 4b,c). This study is the first to quantitatively illustrate the close relationship between the strong winds and the extratropical cyclones, especially the explosive cyclones, around Japan.

Investigations of the characteristics of the strong winds associated with extratropical cyclones around Japan revealed that the WCB and the CCB associated with the cyclones mainly bring the strong winds around Japan (Figs. 5–7). Although previous studies reported the relationship between the strong wind events and the WCB and the CCB around Europe (e.g., Clark et al. 2005; Hewson and Neu 2015; Hart et al. 2017), this relationship around Japan was uncertain. To the best of our knowledge, this study is the first to clearly show that the WCB

and CCB are responsible for the strong wind events around Japan. Moreover, we found that the frequencies of the strong winds are distributed widely over the southwest quadrant of the cyclones, compared to the other quadrants (Figs. 5a and 6a). We pointed out that the higher frequencies over the southwest quadrant are due to the strong horizontal pressure gradient between the Siberian high extending from the Eurasian continent to Japan and the mature cyclones (Figs. 8 and 13d).

We next focused on three areas with the high frequencies of the strong winds (Figs. 3 and 9), which are the area around Hokkaido (area A), the area around Japan Sea side of Chubu, Kinki, and Chugoku (area B), and the area around Pacific Ocean side of Tohoku, Kanto, and Chubu (area C), and examined the regionality of strong winds associated with extratropical cyclones. The results showed that the features of the seasonal change in the strong wind frequencies differ among each area (Fig. 10). Moreover, the seasonal change in the frequencies of the explosive cyclones explain the seasonal change in the strong wind frequencies well in each area (Fig. 11). This again demonstrated the close relationship between the strong winds and the explosive cyclones around Japan.

The characteristics of the strong winds caused by explosive cyclones in areas A, B, and C were also examined (Figs. 12 and 13). In area A, the strong winds are associated with the CCB (Figs. 12a and 13a). In area B, the WCB and the head of the CCB bring the strong winds (Figs. 12b and 13b,c). In area C, both the WCB and CCB induce the strong winds around the cyclone center (Figs. 12c, and 13e,f). Moreover, when cyclones are situated over the Japan Sea, the associated WCB often develops over area C, contributing to the occurrence of the strong winds in area C (Figs. 12c and 13b). In all areas, the relative high frequencies of strong winds are observed over the southwest quadrant of the cyclone (Fig. 12).

The results of this study indicated that the strong winds within cyclones are closely linked to the WCB and CCB around Japan, similar to those around Europe. Moreover, the horizontal structure and time evolution of the WCB and CCB around Japan are similar to those around Europe. These similarities imply that these features of strong winds associated with extratropical cyclones are universal. Thus, we presume that the WCB and CCB contribute to the occurrence of strong wind events associated extratropical cyclones in other regions. As the analysis methods used in this study can be applied to other regions, further studies using our methods can verify this hypothesis.

The timing of the appearance of the WCB and CCB during the life cycles of the typical cyclones around Japan (Figs. 13 and 14) also resemble that observed in European cyclones (Clark et al. 2005; Hewson and Neu 2015; Hart et al. 2017). The timing of the appearance of the WCB and CCB may reflect the physical mechanisms of the formation of the windstorms. The CCB intensifies during the mature stage of cyclones. Slater et al. (2015) showed that the horizontal pressure-gradient force is the primary cause of the acceleration of near-surface winds associated with the CCB. During the mature stage of cyclones, the pressure-gradient force around the cyclone center strengthens due to the lowest pressure in the cyclone center. Thus, the time

evolution of the pressure-gradient force around the cyclone center appropriately explains the timing of the development of the CCB. The WCB develops during the early stage of cyclones, which suggests that the physical mechanisms of WCB development differ from that of the CCB. Lackmann (2002) demonstrated that latent heat release was enhanced along a cold-frontal precipitation band associated with an extratropical cyclone, creating maxima of positive potential vorticity (PV) anomalies along the front in the lower troposphere. They indicated that the circulation induced by the cold-frontal PV anomalies strengthened the low-level jet corresponding to the WCB. The results of Lackmann (2002) suggest that the evolution of latent heat release along cold fronts is a key factor determining the evolution of the WCB. Further studies are required to clarify the effect that latent heat release along cold fronts has on the evolution of the WCB and why the WCB develops during the early life stage of cyclones.

Moreover, we found that the higher frequencies of strong winds were observed over the southwest quadrant of the cyclone around Japan (Figs. 8 and 13d). We pointed out that these higher frequencies are related to the Siberian high. The Siberian high is an important element of the winter East Asia monsoon system (e.g., Takaya and Nakamura 2005). Thus, we speculate that this is a unique feature of the strong winds associated with extratropical cyclone over the East Asia monsoon area. The strong winds over the southwest quadrant of a cyclone tend to occur during the mature stage of the cyclones (Figs. 13d and 14d). This is because the lowest pressure in the mature cyclone is responsible for the strong horizontal pressure gradient between the extending Siberian high and the cyclone.

This study showed that extratropical cyclones, especially explosive cyclones, are the key contributors in bringing strong winds around Japan during the period from fall to spring. These results suggest that forecasting and monitoring of explosive cyclones is particularly important for preventing disasters related to the strong winds during the cold season around Japan. We believe that the distinct characteristics of the strong winds of the explosive cyclones around areas A, B, and C, which are revealed in this paper, are useful for regional disaster prevention in Japan. Moreover, our results suggest that highlighting long-term variations of explosive cyclones is a valuable strategy for comprehending long-term variations of strong wind events around Japan, which is in agreement with the viewpoint of Tsukijihara et al. (2019).

This study defined strong wind events on the basis of the 99th percentile of 10-m wind speed from all data within the study area (see section 2d). Near-surface winds are weaker over land than over the ocean due to the differences in surface friction between the land and ocean, as shown in Figs. 13e and 13f. Consequently, most of the strong wind events were extracted over the ocean in our analyses (Fig. 3). Thus, the results of this study mainly showed the features of the strong winds associated with extratropical cyclones over the coastal areas and ocean around Japan. Features of strong winds over land are expected to be more complicated than those over the ocean because several factors (e.g., topography and land use) over land may modify the structure of strong winds associated with

extratropical cyclones. This issue will be addressed in detail in future studies.

As noted in section 1, our analyses were unable to assess the influences of the mesoscale sting jet. On the other hand, Shapiro–Keyser-type cyclones, which are associated with sting jets (e.g., Schultz and Sienkiewicz 2013; Clark and Gray 2018), often appeared around Japan (Takano 2002; Hirata et al. 2015, 2016), and Hirata et al. (2018) reported that a strong wind area similar to a sting jet occurred around Japan (Fig. 4 in Hirata et al. 2018). To further understand the relationship between strong winds and extratropical cyclones around Japan, we plan to conduct examinations focusing on the sting jet using high-resolution cloud-resolving simulations and a diagnostic method for sting-jet precursor conditions (e.g., Martínez-Alvarado et al. 2012; Hart et al. 2017).

Acknowledgments. The authors thank the three anonymous reviewers for their very helpful comments. The author wishes to thank Eigo Tochimoto and Yousuke Yamashita for offering helpful suggestions. This work was supported by JSPS KAKENHI 19K14794.

Data availability statement. The ERA-interim dataset was provided by ECMWF (<https://apps.ecmwf.int/datasets/>). JMA observational data can be downloaded from the JMA website (<http://www.jma.go.jp/jma/index.html>).

REFERENCES

- Adachi, S., and F. Kimura, 2007: A 36-year climatology of surface cyclogenesis in East Asia using high-resolution reanalysis data. *SOLA*, **3**, 113–116, <https://doi.org/10.2151/sola.2007-029>.
- Baker, L. H., 2009: Sting jets in severe northern European wind storms. *Weather*, **64**, 143–148, <https://doi.org/10.1002/wea.397>.
- , O. Martínez-Alvarado, J. Methven, and P. Knippertz, 2013: Flying through extratropical cyclone Friedhelm. *Weather*, **68**, 9–13, <https://doi.org/10.1002/wea.2047>.
- , S. L. Gray, and P. A. Clark, 2014: Idealised simulations of sting-jet cyclones. *Quart. J. Roy. Meteor. Soc.*, **140**, 96–110, <https://doi.org/10.1002/qj.2131>.
- Browning, K. A., 2004: The sting at the end of the tail: Damaging winds associated with extratropical cyclones. *Quart. J. Roy. Meteor. Soc.*, **130**, 375–399, <https://doi.org/10.1256/qj.02.143>.
- , and N. M. Roberts, 1994: Structure of a frontal cyclone. *Quart. J. Roy. Meteor. Soc.*, **120**, 1535–1557, <https://doi.org/10.1002/qj.49712052006>.
- Carlson, T. N., 1980: Airflow through midlatitude cyclones and the comma cloud pattern. *Mon. Wea. Rev.*, **108**, 1498–1509, [https://doi.org/10.1175/1520-0493\(1980\)108<1498:ATMCAT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1980)108<1498:ATMCAT>2.0.CO;2).
- Clark, P. A., and S. L. Gray, 2018: Sting jets in extratropical cyclones: A review. *Quart. J. Roy. Meteor. Soc.*, **144**, 943–969, <https://doi.org/10.1002/qj.3267>.
- , K. A. Browning, and C. Wang, 2005: The sting at the end of the tail: Model diagnostics of fine-scale three-dimensional structure of the cloud head. *Quart. J. Roy. Meteor. Soc.*, **131**, 2263–2292, <https://doi.org/10.1256/qj.04.36>.
- Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, <https://doi.org/10.1002/qj.828>.

- Hart, N. C. G., S. L. Gray, and P. A. Clark, 2017: Sting-jet windstorms over the North Atlantic: Climatology and contribution to extreme wind risk. *J. Climate*, **30**, 5455–5471, <https://doi.org/10.1175/JCLI-D-16-0791.1>.
- Hayasaka, M., and R. Kawamura, 2012: Cyclone activities in heavy rainfall episodes in Japan during spring season. *SOLA*, **8**, 45–48, <https://doi.org/10.2151/sola.2012-012>.
- Hewson, T. D., and U. Neu, 2015: Cyclones, windstorms and the IMILAST project. *Tellus*, **67A**, 27128, <https://doi.org/10.3402/tellusa.v67.27128>.
- Hirata, H., R. Kawamura, M. Kato, and T. Shinoda, 2015: Influential role of moisture supply from the Kuroshio/Kuroshio Extension in the rapid development of an extratropical cyclone. *Mon. Wea. Rev.*, **143**, 4126–4144, <https://doi.org/10.1175/MWR-D-15-0016.1>.
- , —, —, and —, 2016: Response of rapidly developing extratropical cyclones to sea surface temperature variations over the western Kuroshio–Oyashio confluence region. *J. Geophys. Res. Atmos.*, **121**, 3843–3858, <https://doi.org/10.1002/2015JD024391>.
- , —, —, and —, 2018: A positive feedback process related to the rapid development of an extratropical cyclone over the Kuroshio/Kuroshio Extension. *Mon. Wea. Rev.*, **146**, 417–433, <https://doi.org/10.1175/MWR-D-17-0063.1>.
- , —, M. Nonaka, and K. Tsuboki, 2019: Significant impact of heat supply from the Gulf Stream on a “superbomb” cyclone in January 2018. *Geophys. Res. Lett.*, **46**, 7718–7725, <https://doi.org/10.1029/2019GL082995>.
- Iizuka, S., M. Shiota, R. Kawamura, and H. Hatsushika, 2013: Influence of the monsoon variability and sea surface temperature front on the explosive cyclone activity in the vicinity of Japan during northern winter. *SOLA*, **9**, 1–4, <https://doi.org/10.2151/sola.2013-001>.
- Iwao, K., M. Inatsu, and M. Kimoto, 2012: Recent changes in explosively developing extratropical cyclones over the winter northwestern Pacific. *J. Climate*, **25**, 7282–7296, <https://doi.org/10.1175/JCLI-D-11-00373.1>.
- Kawano, T., and R. Kawamura, 2018: Influence of Okhotsk Sea ice distribution on a snowstorm associated with an explosive cyclone in Hokkaido, Japan. *SOLA*, **14**, 1–5, <https://doi.org/10.2151/sola.2018-001>.
- Kita, Y., T. Waseda, and A. Webb, 2018: Development of waves under explosive cyclones in the northwestern Pacific. *Ocean Dyn.*, **68**, 1403–1418, <https://doi.org/10.1007/s10236-018-1195-z>.
- Lackmann, G. M., 2002: Cold-frontal potential vorticity maxima, the low-level jet, and moisture transport in extratropical cyclones. *Mon. Wea. Rev.*, **130**, 59–74, [https://doi.org/10.1175/1520-0493\(2002\)130<0059:CFPVMT>2.0.CO;2](https://doi.org/10.1175/1520-0493(2002)130<0059:CFPVMT>2.0.CO;2).
- Madonna, E., H. Wernli, H. Joos, and O. Martius, 2014: Warm conveyor belts in the ERA-Interim dataset (1979–2010). Part I: Climatology and potential vorticity evolution. *J. Climate*, **27**, 3–26, <https://doi.org/10.1175/JCLI-D-12-00720.1>.
- Martínez-Alvarado, O., S. L. Gray, J. L. Catto, and P. A. Clark, 2012: Sting jets in intense winter North-Atlantic windstorms. *Environ. Res. Lett.*, **7**, 024014, <https://doi.org/10.1088/1748-9326/7/2/024014>.
- , L. H. Baker, S. L. Gray, J. Methven, and R. S. Plant, 2014: Distinguishing the cold conveyor belt and sting jet airstreams in an intense extratropical cyclone. *Mon. Wea. Rev.*, **142**, 2571–2595, <https://doi.org/10.1175/MWR-D-13-00348.1>.
- Parton, G. A., A. Dore, and G. Vaughan, 2010: A climatology of mid-tropospheric mesoscale strong wind events as observed by the MST radar, Aberystwyth. *Meteor. Appl.*, **17**, 340–354, <https://doi.org/10.1002/met.203>.
- Sanders, F., and J. R. Gyakum, 1980: Synoptic–dynamic climatology of the “bomb”. *Mon. Wea. Rev.*, **108**, 1589–1606, [https://doi.org/10.1175/1520-0493\(1980\)108<1589:SDCOT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1980)108<1589:SDCOT>2.0.CO;2).
- Saruwatari, A., K. Fukuhara, and Y. Watanabe, 2019: Probabilistic assessment of storm surge potential due to explosive cyclogenesis in the northwest Pacific region. *Coast. Eng. J.*, **61**, 520–534, <https://doi.org/10.1080/21664250.2019.1651519>.
- Schultz, D. M., 2001: Reexamining the cold conveyor belt. *Mon. Wea. Rev.*, **129**, 2205–2225, [https://doi.org/10.1175/1520-0493\(2001\)129<2205:RTCCB>2.0.CO;2](https://doi.org/10.1175/1520-0493(2001)129<2205:RTCCB>2.0.CO;2).
- , and J. M. Sienkiewicz, 2013: Using frontogenesis to identify sting jets in extratropical cyclones. *Wea. Forecasting*, **28**, 603–613, <https://doi.org/10.1175/WAF-D-12-00126.1>.
- Shapiro, M. A., and D. Keyser, 1990: Fronts, jet streams and the tropopause. *Extratropical Cyclones: The Erik Palmén Memorial Volume*, C. W. Newton and E. O. Holopainen, Eds., Amer. Meteor. Soc., 167–191.
- Slater, T., D. M. Schultz, and G. Vaughan, 2015: Acceleration of near-surface strong winds in a dry, idealised extratropical cyclone. *Quart. J. Roy. Meteor. Soc.*, **141**, 1004–1016, <https://doi.org/10.1002/qj.2417>.
- , —, and —, 2017: Near-surface strong winds in a marine extratropical cyclone: Acceleration of the winds and the importance of surface fluxes. *Quart. J. Roy. Meteor. Soc.*, **143**, 321–332, <https://doi.org/10.1002/qj.2924>.
- Smart, D. J., and K. A. Browning, 2014: Attribution of strong winds to a cold conveyor belt and sting jet. *Quart. J. Roy. Meteor. Soc.*, **140**, 595–610, <https://doi.org/10.1002/qj.2162>.
- Takano, I., 2002: Analysis of an intense winter extratropical cyclone that advanced along the south coast of Japan. *J. Meteor. Soc. Japan*, **80**, 669–695, <https://doi.org/10.2151/jmsj.80.669>.
- Takaya, K., and H. Nakamura, 2005: Mechanisms of intraseasonal amplification of the cold Siberian high. *J. Atmos. Sci.*, **62**, 4423–4440, <https://doi.org/10.1175/JAS3629.1>.
- Tsukijihara, T., R. Kawamura, and T. Kawano, 2019: Influential role of inter-decadal explosive cyclone activity on the increased frequency of winter storm events in Hokkaido, the northernmost island of Japan. *Int. J. Climatol.*, **39**, 1700–1715, <https://doi.org/10.1002/joc.5910>.
- Wernli, H., and C. Schwierz, 2006: Surface cyclones in the ERA-40 data set (1958–2001). Part I: Novel identification method and global climatology. *J. Atmos. Sci.*, **63**, 2486–2507, <https://doi.org/10.1175/JAS3766.1>.
- Yamashita, Y., R. Kawamura, S. Iizuka, and H. Hatsushika, 2012: Explosively developing cyclone activity in relation to heavy snowfall on the Japan Sea side of central Japan. *J. Meteor. Soc. Japan*, **90**, 275–295, <https://doi.org/10.2151/jmsj.2012-208>.
- Yoshida, A., and Y. Asuma, 2004: Structures and environment of explosively developing extratropical cyclones in the northwestern Pacific region. *Mon. Wea. Rev.*, **132**, 1121–1142, [https://doi.org/10.1175/1520-0493\(2004\)132<1121:SAEOED>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<1121:SAEOED>2.0.CO;2).
- Yoshiike, S., and R. Kawamura, 2009: Influence of wintertime large-scale circulation on the explosively developing cyclones over the western North Pacific and their downstream effects. *J. Geophys. Res.*, **114**, D13110, <https://doi.org/10.1029/2009JD011820>.