Rapid Increase of Explosive Cyclone Activity over the Midwinter North Pacific in the Late 1980s

AKIRA KUWANO-YOSHIDA,^{a,b,c} SATORU OKAJIMA,^d AND HISASHI NAKAMURA^{d,c}

^a *Shirahama Oceanographic Observatory, Disaster Prevention Research Institute, Kyoto University, Shirahama, Japan*

^b *Shionomisaki Wind Effect Laboratory, Disaster Prevention Research Institute, Kyoto University, Kushimoto, Japan*

^c *Application Laboratory, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan*

^d *Climate Science Research Laboratory, Research Center for Advanced Science and Technology, The University of Tokyo, Tokyo, Japan*

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ABSTRACT: Long-term changes in the activity of explosively developing “bomb” cyclones over the wintertime North Pacific are investigated by using a particular version of a global atmospheric reanalysis dataset into which only conventional observations have been assimilated. Bomb cyclones in January are found to increase rapidly around 1987 in the midlatitude central North Pacific. Some of the increased bomb cyclones formed over the East China Sea and then moved along the southern coast of Japan before developing explosively in the central North Pacific. The enhanced cyclone activity is found to be concomitant with rapid warming and moistening over the subtropical western Pacific and the South and East China Seas under the weakened monsoonal northerlies, leading to the enhancement of the lower-tropospheric Eady growth rate and equivalent potential temperature gradient, setting a condition favorable for cyclone formation in the area upstream of the North Pacific storm track. Along the storm track, poleward moisture transport in the warm sector of a cyclone and associated precipitation along the warm and cold fronts tended to increase and thereby enhance its explosive development. After the transition around 1987, a bomb cyclone has become more likely to develop without a strong upper-level cyclonic vortex propagating from Eurasia than in the earlier period. The increased bomb cyclone activity in January is found to contribute to the diminished midwinter minimum of the North Pacific storm track activity after the mid-1980s.

KEYWORDS: North Pacific Ocean; Extratropical cyclones; Storm tracks; Air-sea interaction; Interdecadal variability; Winter/cool season

1. Introduction

Synoptic-scale transient cyclones are a rudimentary component of the extratropical weather and climate system. From an energetic viewpoint, they act as a converter from potential energy associated with meridional thermal gradient to eddy kinetic energy. For example, their activity modifies jet stream meandering in the upper troposphere (Kuwano-Yoshida and Minobe 2017). In particular, explosively developing extratropical cyclones or “bomb cyclones” are of great scientific and socioeconomic importance because they are one of the main causes for wintertime hazards around the North Pacific as well as the North Atlantic and the Southern Ocean (Sanders and Gyakum 1980; Yoshida and Asuma 2004; Sinclair 1995, 1997). However, explosive cyclones in climate models and CMIP future projections exhibit large variations among the models (Seiler and Zwiers 2016a,b).

Interannual variability and decadal modulations of the North Pacific storm track have been investigated largely in the context of the “midwinter suppression” of its activity (Nakamura 1992) measured by local variance or covariance of subweekly fluctuations of atmospheric variables. The mechanisms for the midwinter suppression have been studied from various viewpoints. Harnik and Chang (2004) suggested that the width of an upper-level westerly jet affects downstream growth of baroclinic waves, whereas Penny et al. (2013) suggested that upstream seeding will modify the Pacific storm track activity. Nakamura et al. (2002) pointed out that the midwinter suppression of the North Pacific storm track activity has become substantially less apparent after 1986. The corresponding enhancement of midwinter eddy activity occurred under the weakened Pacific jet and the East Asian winter monsoon. In the strong jet years that often occurred before 1987 in association with the enhanced winter monsoon, upper-tropospheric eddies tend to be trapped into the core region of intensified subtropical jet with its interaction with near-surface baroclinic zone hindered (Nakamura and Sampe 2002), leading to the weakened baroclinic energy conversion from the background temperature gradient (Chang 2001). Recently, Schemm and Rivière (2019) found that the reduction of baroclinic conversion efficiency can contribute to the midwinter suppression. Schemm et al. (2021) reported that fewer and weaker extratropical

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Corresponding author: Akira Kuwano-Yoshida, yoshida.akira.4z@kyoto-u.ac.jp

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cyclones from Kamchatka led to the midwinter suppression, whereas cyclones from the East China Sea partially opposed the suppression during 1979–2018. Meanwhile, [Park and Lee \(2020\)](#) suggested that planetary waves enhanced in midwinter by warm pool convection lead to reduced storm track activity in the North Pacific.

In contrast, there have been fewer studies on interannual or interdecadal variability of bomb cyclones over the North Pacific. Using ERA-Interim data ([Dee et al. 2011](#)), the Inter-comparison of Mid Latitude Storm Diagnostics (IMILAST) project ([Neu et al. 2013](#)) compared linear trends of cyclone numbers among the various tracking algorithms available, and they found no clear or robust trend over the western North Pacific from 1 January 1989 to 31 March 2009. [Tilina et al. \(2013\)](#) pointed out that a statistically significant linear trend in the number of deep cyclones can be detected only in one of the five atmospheric reanalysis datasets from 1979 to 2010. Meanwhile, [Iwao et al. \(2012\)](#) argued that the number of bomb cyclones has recently increased over the northwestern Pacific from 1979/80 to 2010/11. [Tsukijihara et al. \(2019\)](#) reported that bomb cyclones migrating along the Kuroshio tend to approach the Hokkaido region in recent years from 1979/80 to 2016/17.

It must be kept in mind that these studies used reanalysis data including satellite observations whose availability has increased in recent decades, which might yield some artificial long-term variations in data quality. [Masunaga et al. \(2015\)](#) found that near-surface winds, clouds, and precipitation represented in the ERA-Interim tend to become more consistent with satellite observations after 2001 due to increased horizontal resolution of prescribed SST. As a subset of the Japanese 55-year Reanalysis (JRA-55; [Kobayashi et al. 2015](#); [Harada et al. 2016](#)), the Japan Meteorological Agency produced JRA-55C ([Kobayashi et al. 2014](#)) by assimilating only conventional atmospheric observations under SST fields with a fixed horizontal resolution but without any satellite data. Compared to the main product of JRA-55, the data quality is more homogenous in time and therefore suited for analyzing long-time variations in the 55-yr period from 1958, which is much longer than analysis periods in most of the previous studies about interdecadal variations of the bomb cyclones. The present study uses JRA-55C to investigate long-term variations of bomb cyclone activity over the wintertime North Pacific to verify their relationship to the recent weakening of midwinter suppression in comparison with the period before the satellite era.

The remainder of the present paper is organized as follows. Data and methods are described in [section 2](#). In [section 3](#), long-term change of monthly mean bomb cyclone activity and environments and composite analysis for individual events are described. In [section 4](#), intraseasonal differences in bomb cyclone activity and their relation to eddy heat flux are discussed. Finally, conclusions are presented in [section 5](#).

2. Data and methods

We use 6-hourly data of the JRA-55C for the boreal cold season (October–May), available for the period from 1958/59 to 2011/12, to define bomb cyclone activity through the two methods below. One is tracking a local sea level pressure

(SLP) minimum as a moving cyclone using 6-hourly SLP output of the JRA-55C. The detailed procedure and justification of the tracking method are described in the appendix. The tracking algorithm based on SLP and its Laplacian is designed to identify cyclone centers as those represented on a weather chart and therefore suited for investigating bomb cyclones.

A particular tracked cyclone is regarded as a bomb cyclone if a time tendency of its central pressure (P_c) meets the following criterion:

$$\text{NDR24} = - \frac{p_c(t) - p_c(t - 24 \text{ h})}{24} \left| \frac{\sin 60^\circ}{\sin \left[\frac{\theta_c(t) + \theta_c(t - 24 \text{ h})}{2} \right]} \right| \geq 1 \left(\text{hPa h}^{-1} = \text{Bergeron} \right), \quad (1)$$

where θ_c denotes the latitude of the cyclone center and t the time. The definition is almost the same as in [Sanders and Gyakum \(1980\)](#).

Another method is the local deepening rate (LDR; [Kuwano-Yoshida 2014](#)). It is an Eulerian measure of cyclone development defined locally as follows:

$$\text{LDR} = - \frac{\partial p_{\text{sfc}}}{\partial t} \left| \frac{\sin 60^\circ}{\sin \theta} \right|, \quad (2)$$

where p_{sfc} is surface pressure and θ latitude. In the present study, we use a 24-h pressure tendency based on the 6-hourly surface pressure data, which is referred to as LDR24, as follows:

$$\text{LDR24} = - \frac{p_{\text{sfc}}(t + 12 \text{ h}) - p_{\text{sfc}}(t - 12 \text{ h})}{24} \left| \frac{\sin 60^\circ}{\sin \theta} \right|. \quad (3)$$

Monthly bomb cyclone activities (LDR24P1 and NDR24P1) at a given location are then defined as follows:

$$\text{LDR24Pm} = \frac{1}{n} \sum_{i=1}^n \sigma_m(t = i),$$

$$\sigma_m = \begin{cases} \text{LDR24, if } \text{LDR24} \geq m \text{ hPa h}^{-1} \\ 0, \text{ otherwise} \end{cases}, \quad (4)$$

$$\text{NDR24Pk} = \frac{1}{n} \sum_{i=1}^n \sigma_k(t = i),$$

$$\sigma_k = \begin{cases} \text{NDR24, if } \text{NDR24} \geq k \text{ Bergeron} \\ 0, \text{ otherwise} \end{cases}, \quad (5)$$

where n is the number of time steps in the month.

To diagnose the factors contributing to LDR, we calculate each component of the pressure tendency equation introduced by [Fink et al. \(2012\)](#):

$$\text{LDR} = - \left[\frac{\sin 60^\circ}{\sin \theta} \left(\rho_{\text{sfc}} \frac{\partial \phi_{p_2}}{\partial t} + \rho_{\text{sfc}} R_d \int_{\text{sfc}}^{p_2} \frac{\partial T_v}{\partial t} d \ln p + g(E - P) + \text{RES}_{\text{PTE}} \right) \right], \quad (6)$$

where p is pressure, ρ_{sfc} surface air density, ϕ_{p_2} geopotential height at p_2 ($=100$ hPa), R_d the gas constant for dry air, T_v virtual temperature, g gravity acceleration, E surface evaporation, P precipitation, and RES_{PTE} the residuum due to discretization. The second term in (6) represents the vertically integrated virtual temperature tendency (ITT), which may be decomposed as follows:

$$\begin{aligned} \text{ITT} = & \rho_{\text{sfc}} R_d \int_{\text{sfc}}^{p_2} -\mathbf{v} \cdot \nabla_p T_v d\ln p & (\text{horizontal advection}) \\ & + \rho_{\text{sfc}} R_d \int_{\text{sfc}}^{p_2} \left(\frac{R_d T_v}{c_p p} - \frac{\partial T_v}{\partial p} \right) \omega d\ln p & (\text{vertical advection}) \\ & + \rho_{\text{sfc}} R_d \int_{\text{sfc}}^{p_2} \frac{T_v Q}{c_p T} d\ln p & (\text{diabatic heating}) \\ & + \text{RES}_{\text{ITT}}, \end{aligned} \quad (7)$$

where $\mathbf{v}$ denotes the horizontal wind vector, ω pressure velocity, T temperature, c_p the specific heat at constant pressure, Q diabatic heating rate, and RES_{ITT} the residuum due to discretization. The first term on the right-hand side represents a contribution from horizontal temperature advection, the second term vertical advection, and the third term diabatic heating. In the present study, the diabatic heating term is estimated from the difference between ITT and the sum of horizontal and vertical advection terms.

Variances of high-pass-filtered temperature (T') and wind velocities (u' and v'), as well as covariances between them, have been used as storm track indices (Nakamura 1992; Chang 2001; Schemm et al. 2021). In the present study, they are calculated by a high-pass filter with a cutoff period of 8 days. Eddy heat flux ($\overline{v'T'}$) based on the high-pass-filtered variables is also used as a measure of storm track activity.

As a measure of background baroclinicity, the Eady growth rate (EGR; Lindzen and Farrell 1980) is evaluated locally as

$$\text{EGR} = 0.31 \frac{f}{N} \frac{d\mathbf{v}}{dZ}, \quad (8)$$

where f is the Coriolis parameter, N is the Brunt–Väisälä frequency, and Z is the geopotential height.

3. Results

a. Enhanced bomb cyclone activity

Bomb cyclone activity in January estimated by LDR24P1 based on the JRA-55C data shows a significant positive trend over the central North Pacific (Fig. 1a). The trend is explained largely by a sudden increase in the activity around 1987 (Figs. 1b,c). Seasonality of the difference in LDR24P1 between the earlier period (from 1958/59 winter to 1985/86 winter) and the later period (from 1986/87 winter to 2011/12 winter) shows that the enhancement of LDR24P1 occurs in December through February (Fig. 1d). The enhancement is consistent with Nakamura et al. (2002), who showed that “midwinter suppression” of the Pacific storm track activity found by Nakamura (1992) had diminished after 1987. The

frequency of LDR24 less than 0.8 hPa h^{-1} decreases, while that larger than 0.9 hPa h^{-1} increases (Figs. 1e,f).

Another analysis based on the tracking and NDR24 yields similar results. NDR24P1 increases over the central North Pacific in January, although its distribution is rather noisier, and its maxima are shifted slightly upstream compared to their counterpart LDR24P1 (Figs. 2a–c). This is probably because NDR24P1 is based only on SLP at the cyclone centers whereas LDR24 is calculated at whole grids and includes advection effect. The increase of NDR24P1 within the central North Pacific domain (155°E – 180° , 38° – 50°N ; the red rectangle in Fig. 2c) is caused by increment of cyclones with NDR24 larger than 1.2 Bergeron within the central North Pacific after 1987 (Figs. 2d–g). As shown in Table 1, the total frequency of the cyclone tracks with $\text{NDR24} \geq 1.2$ Bergeron and mean NDR24P1.2 within the domain averaged in the later period increases more than that in the earlier period with a 95% significance level by Student's t test. By contrast, the mean NDR24 for each track is almost same between the later and earlier periods. As shown in Table 2, the frequency of bomb cyclones in the entire North Pacific is consistent with the result of previous studies (Roebber 1984; Gyakum et al. 1989; Yoshida and Asuma 2004). The percentage of bomb cyclones to all cyclones with $\text{NDR24} \geq 1$ Bergeron within a midlatitude domain (155°E – 180° , 38° – 50°N) become 29.8% in the later period, up from 28.1% in the earlier period, whereas the corresponding change in the entire North Pacific in January is 24.0%, up from 23.3%. These results suggest that the increase of stronger bomb cyclones with $\text{NDR24} \geq 1.2$ Bergeron over the central North Pacific is essential to the rapid change of bomb cyclone activity in the late 1980s.

Tracks of bomb cyclones traveling over the midlatitude domain defined above are compared between the two periods before and after the 1986/87 transition. Figure 3 shows the track frequency of cyclones whose NDR24 values exceeded 1.2 Bergeron in the central North Pacific domain. Each of these bomb cyclones has been tracked from its formation until its central pressure reached the minimum. In the later period (Fig. 3a), bomb cyclones in the central North Pacific domain tend to travel along the southern coast of Japan, and some of them can be traced back to their formation in the East China Sea. This is consistent with Reale et al. (2019), who showed that the genesis of western North Pacific explosive cyclones is likely to occur along the region from the East China Sea to the Kuroshio Extension for the period of 1979–2008. In the earlier period (Fig. 3c), their formation was more likely over the Sea of Japan rather than in the East China Sea. These differences are statistically significant (Fig. 3e). In contrast, no significant increase can be found in the number of cyclones passing through a subtropical domain (155°E – 180° , 23° – 35°N , rectangular domain in Figs. 3g,h). This means that the meridional shift of the cyclone tracks cannot be the cause of the increasing cyclones over the midlatitude domain. It has been known that bomb cyclones developing in the northwestern Pacific have different structures and development mechanisms depending on their origins and tracks (Yoshida and Asuma 2004; Kuwano-Yoshida and Asuma 2008). Our results suggest that the development mechanism of bomb cyclones

FIG. 1. (a) LDR24P1 climatology in January from 1959 to 2012 (contour; hPa day^{-1}) and linear trend [shaded; $\text{hPa day}^{-1} (54 \text{ yr})^{-1}$]. (b) LDR24P1 difference in January between the two periods before and after the transition around 1987 (shaded; hPa day^{-1}). (c) Time series of LDR24P1 in January averaged within 160°E – 170°W , 30° – 50°N (thin line), superimposed on the time averages (bold lines) and half the standard deviation (dashed lines) for the two periods. (d) Latitude–time section of LDR24P1 averaged between 160°E and 170°W from October to May showing the climatological seasonality in the later (thin solid lines) and earlier (dotted lines) periods, superimposed on the tendency shown as their difference (shaded). (e) Frequency distributions of LDR24 in January averaged within 165°E – 175°W , 40° – 47°N for the later (solid line) and earlier (dashed line) periods. (f) Difference of the frequency distributions in (e) between the two periods.

over the central North Pacific may be different between the two decadal periods. By contrast, the cyclones whose NDR24 values never exceeded 1.2 Bergeron in the central North Pacific domain have overall decreased from the earlier period into the later period (Figs. 2d,e and 3b,d,f), except around 43°N , 175°E .

b. Long-term changes in the background state

One of the possible factors for the changes in the bomb cyclone activity is sea surface temperature (SST). The SST difference between the two periods is characterized by statistically significant

warming widely over the tropical Indian Ocean and the subtropical northwestern Pacific (Fig. 4a). Slight cooling along the sub-Arctic frontal zone east of Japan (Fig. 4a) led to the enhancement of SST gradient and associated near-surface baroclinicity between 35° and 40°N , which is favorable for cyclone development and thus consistent with the enhanced bomb cyclone activity shown in Fig. 3e. The warming in the East China Sea and Sea of Japan resembles the third leading mode of decadal-scale SST variability over the western North Pacific (Nakamura and Yamagata 1999), which changed its polarity around 1986. The long-term warming in these maritime regions, as well as along the Kuroshio and its

FIG. 2. (a) Maps of NDR24P1 (shading; hPa day⁻¹) and LDR24P1 (contour; hPa day⁻¹) in January averaged in the later period. (b) As in (a), but for the earlier period. (c) Their differences between the two periods as (a) minus (b) (dotted hatch for the significance with 95% confidence). (d) Frequency distributions of NDR24 (hPa h⁻¹) in January within 155°E–180°, 38°–50°N, marked with red rectangle labeled as “CNP” (number month⁻¹), averaged for the later (solid line) and earlier (dashed line) periods. (e) Their difference between the two periods. (f) Time series of NDR24P1.2 averaged within the rectangle in (c) in January, superimposed on the time averages for the earlier and later periods (solid line) and half the standard deviation (dashed line). (g) Time series of total frequency for NDR24 ≥ 1.2 Bergeron within the rectangular domain in (c) in January. “BEFORE” and “AFTER” in the labels correspond to the earlier (from 1958/59 winter through 1985/86 winter) and later (from 1986/87 winter through 2011/12 winter), respectively.

extension, is more than twice as fast as the average global ocean warming (Wu et al. 2012).

Another possible factor may be long-term changes in the upper-level westerly jet stream (Fig. 4b). Climatologically in January, the jet stream flows slightly to the north of 30°N over the North Pacific. The 300-hPa westerlies in the later period are slightly enhanced around 40°N over the Asian continent, Japan, and the eastern North Pacific, whereas they slow down slightly over the central North Pacific. The results may suggest

that the jet stream has expanded northward slightly into the later period. Most of the changes in the upper-level westerlies are, however, not statistically significant except over the Kamchatka Peninsula, and therefore their influence on midlatitude bomb cyclone activity must be limited.

As shown in Fig. 4c, lower-tropospheric temperature also underwent significant warming extensively, whereas its horizontal distribution is different from the SST warming. The lower-tropospheric warming peaks over the East China Sea,

TABLE 1. Total frequency (number) and mean NDR24 (Bergeron) of tracks whose NDR24 are larger than 1.2 Bergeron, and mean NDR24P1.2 (hPa day⁻¹) within 155°E–180°, 38°–50°N (marked with red rectangle in Fig. 2c) in January for 1959–86 and 1987–2012. Values in parentheses are standard deviations. Bold font indicates that the difference between 1987–2012 and 1959–86 exceeds the 95% confidence level by Student's *t* test.

	1959–86	1987–2012
Total frequency	5.69 (3.38)	8.87 (5.28)
Mean NDR24	1.54 (0.14)	1.58 (0.16)
NDR24P1.2	0.0090 (0.0057)	0.0141 (0.0084)

the Sea of Japan, and northeastern China, in addition to the north Indian Ocean. The former warming may be related to the decadal weakening of the East Asian winter monsoon (Nakamura et al. 2002; Wang et al. 2009). The positive anomaly of southerly 850-hPa temperature advection and negative anomaly of surface heat flux from the ocean in the later period relative to the earlier period (Figs. 4d–g) suggest that the SST warming over the marginal seas was forced by the weakening of the East Asian winter monsoon (Ding et al. 2014; Miao et al. 2018).

The lower-tropospheric warming that peaks over the East China Sea enhances the Eady growth rate just to the north (Fig. 5a), where the formation of some of the bomb cyclones in the central North Pacific has become more frequent in the later period (Fig. 3e). As the difference between the two periods, 850-hPa equivalent potential temperature (EPT) has significantly increased along the east coast of Southeast Asia and the South and East China Seas (Fig. 5d), indicative of long-term warming and moistening in the lower troposphere. The increase in 850-hPa EPT has strengthened its meridional gradient significantly over southern China and the East China Sea, along the northern branch of the climatological maximum of the EPT gradient extending from southern China to the southern coast of Japan (Fig. 5b). Baroclinic instability associated with moisture supply is known to contribute to bomb cyclone development (Mak 1982; Yoshida and Asuma 2004; Kuwano-Yoshida and Asuma 2008; Binder et al. 2016; Kuwano-Yoshida and Minobe 2017).

Comparison between Figs. 5c and 5d reveals that the increase in 850-hPa EPT seems attributable not only to the warming but also to the corresponding moisture increase around the South and East China Seas, where a converging tendency was observed in the vertically integrated moisture flux from the western Pacific (Fig. 5g). In particular, the weakened monsoonal northerlies as shown in Figs. 5e and 5h (Nakamura et al. 2002; Wang et al. 2009) contributed to the warming and converging tendency in moisture flux, acting to increase 850-hPa EPT just south of the moist baroclinic zone characterized by climatologically pronounced EPT gradient. Meanwhile, the wetter tendency around the South China Sea occurred under the suppressed local evaporation (Fig. 5f) under the weakened monsoonal northerlies (Fig. 5e). The enhanced moisture supply must be due to the strengthened easterly trade winds over the western North Pacific (Fig. 5g). These interdecadal tendencies seem consistent with the interannual variability of the tropical Indian Ocean related to recent wintertime precipitation increase in the middle and lower Yangtze River Valley since the late 1970s (Li et al. 2015).

c. Modulated development of bomb cyclones

To understand modulations in the life cycle and developing mechanisms involved in increasing bomb cyclones, two kinds of composite analyses have been conducted. Bomb cyclones whose NDR24 values exceeded 1.2 Bergeron within the central North Pacific domain (155°E–180°, 38°–50°N) in January were sampled for our composite analyses. The domain corresponds to the Pacific storm track, where 104 and 81 bomb cyclones have been sampled in the later and earlier periods, respectively. One of the composite analyses was performed in the geographically fixed coordinate (GEO) to analyze large-scale environment. The time when NDR24 of a given bomb cyclone exceeded 1.2 Bergeron for the first time in that domain is defined as $T = 0$ h. The other was carried out in the surface cyclone center relative coordinate (CENTER) to focus on cyclone structure. In the CENTER composite, to extract the cyclone structure during explosive development in the domain, every detected cyclone whose NDR24 exceeded

TABLE 2. Monthly frequencies of all cyclones and bomb cyclones, and bomb cyclone percentage to all cyclones for the entire North Pacific (100°E–120°W, 20°–65°N) and all cyclones passing over the central North Pacific (155°E–180°, 38°–50°N) and the bomb cyclones with NDR24 ≥ 1 Bergeron in the central North Pacific averaged over 1958/59–1985/86 and 1986/87–2011/12.

Area	Period	Type	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Entire North Pacific	1958/59–1985/86	All	47.7	45	48.1	47.3	43.5	51.2	51.4	52.5
		Bomb	7.8	9.9	11.1	11.0	9.2	8.4	4.8	2.8
		Bomb ratio	16.3%	22.0%	23.0%	23.3%	21.2%	16.4%	9.4%	5.3%
	1986/87–2011/12	All	46.9	45.2	45.3	45.2	42.5	48.5	51.1	53.2
		Bomb	7.1	9.2	11.1	10.8	9.2	9.1	4.3	1.8
		Bomb ratio	15.1%	20.4%	24.5%	24.0%	21.6%	18.8%	8.4%	3.3%
Central North Pacific	1958/59–1985/86	All	12.4	12.8	16.3	16.0	14.1	15.0	11.7	10.8
		Bomb	1.5	2.7	4.8	4.5	3.9	3.8	1.4	0.79
		Bomb ratio	12.1%	21.1%	29.4%	28.1%	27.7%	25.3%	12.0%	7.3%
	1986/87–2011/12	All	11.3	12.0	16	16.1	14.6	14.7	12.4	10.9
		Bomb	1.2	2.2	4.8	4.8	4.5	3.7	1.7	0.73
		Bomb ratio	10.6%	18.3%	30.0%	29.8%	30.8%	25.2%	13.7%	6.7%

FIG. 3. Frequency distribution of the cyclone tracks from their formation to the minimum pressure for each track in January (shaded; number month⁻¹). (left) The cyclones whose NDR24 exceeded 1.2 Bergeron within the rectangular domain 155°E–180°, 38°–50°N and (right) those whose NDR24 never exceeded 1.2 Bergeron within the rectangular domain averaged (a),(b) between 1987 and 2012 and (c),(d) between 1959 and 1986, and (e),(f) the difference between the periods 1987–2012 and 1959–86. (g),(h) As in (e) and (f), but for 155°E–180°, 23°–35°N. Bold lines indicate the 95% confidence level in (e)–(h).

1.2 Bergeron within the domain are sampled. Thus, sample sizes are 245 in the later period and 166 in the earlier period, respectively, and analyzed only at $T = 0$ h, when NDR24 exceeded 1.2 Bergeron within the domain. In the GEO composites that are based on the relative time from $T = 0$ h, the number of samples is fixed even if any of the cyclone centers are not detected.

Figure 6 shows GEO composite maps of 850-hPa EPT difference from the earlier period into the later, on which the LDR24 values 12 h before and the center positions of the bomb cyclones observed in the later period are superimposed. At $T = -72$ h (Fig. 6a), EPT increase is obvious over the

southern East China Sea and the South China Sea, acting to enhance the low-level EPT gradient in the moist baroclinic zone over the East China Sea as preconditioning favorable for cyclone development. At $T = -48$ h (Fig. 6b), the enhanced EPT spreads from the region around the Philippines farther poleward to the East China Sea and western Japan, where cyclone centers are clustered with a well-defined positive LDR24 peak. At $T = -24$ h (Fig. 6c), the LDR24 peak associated with the cyclone centers strengthens just east of Japan, into which a tongue of the enhanced EPT extends northeastward from the region around the Philippines. At

FIG. 4. (a) January climatology of SST (thin lines for every 5°C) in the whole period, superimposed on the difference (shaded) between 1987–2012 and 1959–86 with its 95% confidence level (dotted) and the difference of LDR24P1 (0.6 hPa day^{-1} ; bold contour). (b) As in (a), but for 300-hPa wind speed difference (shaded; m s^{-1}) and climatology (contour), and wind vector difference (arrow). (c) As in (b), but for 850-hPa temperature (every 5 K) with its 95% confidence level (bold line). (d) As in (b), but for the surface sensible heat flux (positive if upward; W m^{-2}). (e) As in (b), but for horizontal temperature advection (shaded; $10^{-5}\text{ K m s}^{-1}$) and horizontal wind (arrow; m s^{-1}) at 850 hPa, and their climatologies in (f) 1987–2012 and (g) 1959–86, respectively.

$T = 0\text{ h}$ (Fig. 6d), the LDR24 peak with the bomb cyclone centers reaches the central North Pacific, but it is almost detached from the enhanced EPT tongue.

As evident in the corresponding difference composites of precipitable water (Fig. 7), moisture increase substantially

contributes to the enhanced EPT into the later period. At $T = -72\text{ h}$ (Figs. 7a,b), the moisture increase is particularly pronounced around the Philippines, while the modest moisture increase over southern and central China is associated with anomalous poleward moisture flux. Afterward, the tongue of

FIG. 5. (a) Difference of 850-hPa Eady growth rate in January between 1987–2012 and 1959–86 (shading; day^{–1}) and its climatology (solid line; contour: 1, 1.2, 1.4). Bold solid lines indicate the 95% confidence level. (b) As in (a), but for the horizontal gradient of 850-hPa equivalent potential temperature [K (100 km)^{–1}]. (c) As in (a), but precipitable water (mm) and (d), as in (a), but for 850-hPa equivalent potential temperature (K). (e) The differences in horizontal advection of equivalent potential temperature (shading; 10^{–5} K m s^{–1}) and in horizontal wind (arrow; m s^{–1}) both at 850 hPa. (f) As in (a), but for surface latent heat flux (W m^{–2}). (g) The differences of vertically integrated moisture flux (vector; mm m s^{–1}) and its convergence (shading; mm day^{–1}) between the later and earlier periods. (h) As in (a), but for 850-hPa streamfunction (10^{–6} m² s^{–1}).

FIG. 6. (a) GEO composite map of LDR24 12 h before (thin lines for every 0.1 hPa h^{-1}) at $T = -72 \text{ h}$ for bomb cyclones in January whose NDR24 values exceeded 1.2 Bergeron for the first time in each track ($T = 0 \text{ h}$) within 155°E – 180° , 38° – 50°N in the later period, superimposed on the composite difference of the 850-hPa equivalent potential temperature (shading; K) in January between 1987–2012 and 1959–86 with its 95% confidence level (bold lines). The cyclone centers in the later period are marked with open circles. (b) As in (a), but for $T = -48 \text{ h}$. (c) As in (a), but for $T = -24 \text{ h}$. (d) As in (a), but for $T = 0 \text{ h}$.

enhanced precipitable water extends into the developing bomb cyclones due to anomalous poleward moisture flux (Figs. 7c–h). These results indicate that extratropical cyclones formed in the moist baroclinic zone over the East China Sea migrate northeastward into the central North Pacific in developing explosively associated with warm, moist airflow from the subtropics.

An upper-tropospheric pressure trough can be another factor for bomb cyclone development (Takayabu 1991; Kuo et al. 1991; Chang 2005). Figure 8 shows GEO composite maps of 300-hPa geopotential height. Unlike in Figs. 6 and 7, however, Fig. 8 shows cyclone centers observed in the earlier period superimposed on the composited height field. At $T = -72 \text{ h}$ (Fig. 8a), a positive height anomaly is located over northeastern China and surface cyclones start forming to the southeast. Afterward, the positive height anomaly amplifies while moving eastward in association with the surface cyclones (Figs. 8b–d). The results suggest that in the later period bomb cyclones observed in the central North Pacific domain tend to develop under the influence of weaker upper-level troughs than in the earlier period. In other words, the bomb cyclone development

in the later period may require stronger involvement of moist processes than in the earlier period. This is consistent with Chang (2005) and Schemm et al. (2021), who showed that the East China Sea cyclones are unlikely to be accompanied by a corresponding upper-tropospheric anomalous circulation at their genesis, based on the period in the 1980s and later.

To delineate internal structures of bomb cyclones and elucidate contributions from dry and moist processes to their development, the CENTER composites for bomb cyclones whose NDR24 exceeded 1.2 Bergeron in the domain have been constructed (Figs. 9 and 10). As shown in Fig. 9a, the CENTER composites of SLP and precipitation for the later period depict characteristics of a developing cyclone, including a strong precipitation band along a warm front that extends southeastward from the cyclone center and another band along a cold front extending southwestward, indicating that the tracking method used in the present study works well. In the later period the precipitation bands along the warm and cold fronts tend to be stronger than their counterpart in the earlier period (Fig. 9b). In Fig. 9c, the shape of strong 850-hPa EPT gradients composited for the later period

FIG. 7. As in Fig. 6, but for SLP composite (thin lines for every 4 hPa) for 1987–2012, superimposed on the (left) corresponding composites of vertically integrated moisture flux (mm m s^{-1} ; vectors) and precipitable water (mm ; shading) and (right) their differences from 1959–86 into 1987–2012.

FIG. 8. As in Fig. 6, but for 300-hPa geopotential height composite (thin lines for every 200 m) in 1987–2012, superimposed on its difference from 1959 to 1986. Bold lines show the 95% confidence level. The cyclone centers in the earlier period are marked with open circles.

corresponds to the “T-bone structure” of fronts in the Shapiro–Keyser cyclone model (Shapiro and Keyser 1990). Compared with the earlier period (Fig. 9d), the EPT gradients tend to be stronger around the bent-back warm front west of the cyclone center and along the warm front. Besides, EPT tends to be higher along the enhanced low-level moisture flux from the southwest in the warm sector, which converges along the cold and warm fronts (Figs. 9e,f).

The corresponding CENTER composite maps for the upper troposphere are shown in Fig. 10. Both an upper-tropospheric pressure trough and cyclonic vorticity located northwest of the surface cyclone center tend to be significantly weaker in the later period than in the earlier period (Figs. 10a,b). Instead, upper-tropospheric divergence and midtropospheric ascent associated with the cyclone tend to be significantly stronger in the later period (Figs. 10c,d), especially around the warm front where precipitation tends to be enhanced (Fig. 9).

The structural modifications of bomb cyclones may suggest their modulated developing mechanisms (Yoshida and Asuma 2004; Kuwano-Yoshida and Asuma 2008). Our diagnosis with the surface pressure tendency equation [Eqs. (6) and (7)] reveals the importance of diabatic heating in the enhanced explosive cyclone development in the later period. As shown in Fig. 11a, the CENTER composite difference in

LDR24 shows a well-defined significant positive difference to the east and southeast of the cyclone center, with certain correspondence with the significant positive difference in the integrated temperature tendency [Eq. (7)]. Its east and southwestern portions are largely explained by the diabatic heating term in Eq. (7) (Fig. 11c), especially along the warm conveyor belt. A modest contribution of the temperature advection term acts constructively with the diabatic heating term downstream of the LDR24 maximum while destructively along the surface cold front (Figs. 11b,c).

The differences in large-scale environment and cyclone structure between the two periods may be analogous to those between bomb cyclones developing over the Pacific Ocean and those over the Okhotsk and Japan Seas (Yoshida and Asuma 2004; Kuwano-Yoshida and Asuma 2008). Comparison of monthly climatologies and composite maps between the two periods reveals that recent local warming and moistening in the lower troposphere over the South China Sea act to strengthen the EPT gradient mainly over the East China Sea. Under the warmer and moister environment in the later period, the explosive development of cyclones is likely in the central North Pacific even without a strong upper-tropospheric trough (Takano 2002). In the later period, bomb cyclone frequency can thus increase than in the earlier period

FIG. 9. (a) SLP (contoured for every 4 hPa) and precipitation (shading; mm day⁻¹) composited relative to the centers of bomb cyclones whose NDR24 values exceeded 1.2 Bergeron within 155°E–180°, 38°–50°N in 1987–2012. (b) As in (a), but for their differences from the corresponding composites for 1959–86. The local differences significant at the 95% confidence level are indicated with bold lines (SLP) and dots (precipitation). (c),(d) As in (a) and (b), respectively, but for 850-hPa equivalent potential temperature (shaded; K) and the absolute value of its horizontal gradient [contour; K (100 km)⁻¹]. (e),(f) As in (a) and (b), respectively, but for vertically integrated moisture flux (vectors; mm s⁻¹), its convergence (shading; mm day⁻¹) and precipitable water (contour; mm).

FIG. 10. (a) As in Fig. 9a, but for (a) 300-hPa geopotential height (contoured for every 100 m) for 1987–2012, superimposed on its difference from the corresponding composites for 1959–86 (shaded), (b) As in (a), but for 300-hPa relative vorticity (10^{-5} s^{-1}). (c) As in (a), but for 300-hPa wind divergence (10^{-5} s^{-1}). (d) As in (a), but for sign-reversed 500-hPa pressure velocity (Pa s^{-1}).

when bomb cyclone development required an intense upper-level trough.

4. Discussion

The analysis in the preceding section focuses on the North Pacific bomb cyclones in January, which is the only calendar month when their frequency is found to differ significantly between the two periods despite the long-term SST warming occurring throughout the year (not shown). To understand this seasonality, monthly climatologies for December and February are also analyzed (Fig. 12). In these months, LDR24P1 also increased significantly from the earlier period around the central North Pacific domain (Figs. 12a,b). Compared with the January difference (Fig. 1b), however, the differences in December and February are less pronounced, less extensive, and shifted downstream. Likewise, the corresponding interdecadal differences in 850-hPa EPT are noticeable only over the southern South China Sea and Southeast Asia but less pronounced over the East China Sea (Figs. 12e,f).

Correspondingly, no significant changes are found in the Eady growth rate along the baroclinic zone extending from South China to the southern coast of Japan in December and February (Figs. 12c,d) unlike in January shown in Fig. 5b.

We speculate that the seasonality in the bomb cyclone response to the SST warming might be, at least in part, due to a seasonality in warming tendency over the Asian continent. In December and February, the lower-tropospheric warming tendency over East Asia was stronger to the north of $\sim 20^\circ\text{N}$ than to its south (Figs. 12g,h). The associated reduction in dry baroclinicity over the East China Sea itself was unfavorable for cyclogenesis, acting to offset the effect of increased moisture on low-level EPT (Figs. 12e,f). By contrast, the corresponding January warming tendency was comparably strong both to the north and south of $\sim 20^\circ\text{N}$ along the continental coast with a peak warming over the East China Sea (Fig. 4b). Under this warming pattern in January, the meridional gradient in low-level EPT increased (Fig. 5b) with enhanced dry baroclinicity in the East China Sea (Fig. 5a).

FIG. 11. As in Fig. 10, but for the differences (shading; hPa h^{-1}) in the (a) vertically integrated virtual temperature tendency, (b) total temperature advection, and (c) diabatic heating terms of

In many of the previous studies, eddy heat fluxes evaluated locally as the covariance between high-pass-filtered temperature (T') and meridional wind fluctuations (v') were used to estimate storm track activity within an “Eulerian framework” (e.g., Chang 2001; Nakamura et al. 2002). Figure 13 shows maps of 850-hPa poleward eddy heat flux ($v'T'$) based on 6-hourly high-pass-filtered data in January accumulated separately when $\text{LDR24} \geq 1$, $1 > \text{LDR24} \geq 0$, and $\text{LDR24} < 0$ at each grid, whereas the corresponding maps of local frequencies for the individual categories are shown in Figs. 13b, 13d, and 13f, respectively. Climatologically (contours in Fig. 13), $v'T'$ associated with bomb cyclones ($\text{LDR24} \geq 1$) accounts only for 30% or less of the total flux. Nevertheless, the recent significant change in the eddy heat flux over the central North Pacific is mostly due to the contribution from bomb cyclones associated with their increased frequency (Figs. 13a,b). By contrast, no significant change is observed in the heat flux associated with the modestly positive LDR24 events (Fig. 13c) despite a significant decrease in their frequency (Figs. 13d,h), as the mean heat flux for the individual events becomes stronger in the later period (Fig. 13g). Meanwhile, the negative LDR24 events contribute slightly to the enhanced heat flux with a slight increase in their frequency (Figs. 13e,f). These results suggest that under the significant lower-tropospheric warming over the western North Pacific and the East and South China Seas, partly due to the weakening of the East Asian winter monsoon, bomb cyclone activity in January has increased into the later period especially over the central North Pacific, contributing to the diminished midwinter suppression in the storm track activity (Nakamura et al. 2002).

Unfortunately, JRA-55C analyzed in the present study is available only until December 2012, which prevents us from a straightforward comparison with Schemm et al. (2021). Instead, we use JRA-55, into which both satellite and conventional atmospheric observations have been assimilated until today. We have confirmed that JRA-55C and JRA-55 yield virtually the same LDR24P1 distribution (Figs. 1a and 14a, respectively), although JRA-55C is slightly drier in the tropics than JRA-55 (Fig. 14c). It is therefore suggested that the recent moistening may be slightly underestimated in JRA-55C. As shown in Fig. 14b, bomb cyclone activity after 2012 based on JRA-55 exhibits no significant difference from the period 1987–2012 (i.e., “later period” in the preceding sections). A markedly low LDR24P1 along the North Pacific storm track was observed in January 2014 (Fig. 14d) under the excessively strong westerlies (JMA 2015).

5. Conclusions

Long-term changes in bomb cyclone activity in the winter-time North Pacific are investigated by using JRA-55C, a particular version of JRA-55 into which only the conventional observations have been assimilated. We have found that the

Eqs. (6) and (7), superimposed on the corresponding difference in LDR24 (contoured for every 0.05 hPa h^{-1}). The significant differences at the 95% confidence level are indicated with dots and bold lines, respectively.

FIG. 12. Monthly climatologies (thin contour) and their differences (shading) between the two periods in (left) December and (right) February. (a),(b) LDR24P1 (hPa day⁻¹), (c),(d) Eady growth rate at 850 hPa (day⁻¹; contour: 1, 1.2, 1.4), (e),(f) equivalent potential temperature at 850 hPa (K), and (g),(h) temperature at 850 hPa (K). Bold contours represent significant differences at the 95% confidence level.

bomb cyclone frequency in January increased suddenly around 1987 in the midlatitude central North Pacific. The increased frequency was contributed to by such cyclones that form over the East China Sea, then move along the southern

coast of Japan and finally undergo explosive development in the central North Pacific. The frequency increase was concomitant with the fast SST warming extensively in the South and East China Seas and the subtropical northwestern Pacific.

FIG. 13. (left) Monthly accumulated 850-hPa poleward eddy heat flux $\bar{v'T'}$ (K m s⁻¹) and (right) LDR24 frequency (day month⁻¹) in January for (a),(b) LDR24 ≥ 1, (c),(d) 1 > LDR24 ≥ 0, and (e),(f) LDR24 < 0. In each of the panels, thin contours indicate the climatology, while shading represents the differences between 1987–2012 and 1959–86. The differences significant at the 95% confidence level are marked with bold lines. Time series of (g) 850-hPa $\bar{v'T'}$ (K m s⁻¹) for 1 > LDR24 ≥ 0 and (h) frequency of 1 > LDR24 ≥ 0 (day month⁻¹) both averaged within 155°E–170°W, 30°–50°N, superimposed on the time averages for 1959–86 and 1987–2012 (solid line) and half the standard deviation (dashed line).

Correspondingly, lower-tropospheric EPT gradient was enhanced around the northern branch of the climatological baroclinic zone in the midlatitude East China Sea, in association with warming and moistening over the South and East China Seas under the weakened monsoonal northerlies and the SST warming in January after 1987.

The interdecadal environmental changes mentioned above are found to affect structure and amplification mechanisms of bomb cyclones. Moistening and warming in the warm sector of a cyclone through enhanced moisture transport from lower

latitudes with a warm conveyor belt act to strengthen precipitation mainly along the warm front. The resultant enhancement of diabatic heating is favorable for explosive cyclone development. As a result, a bomb cyclone has become more likely to develop without a strong upper-level cyclonic vortex propagating from Eurasia if compared with the period before 1987.

Our results seem consistent with climatological characteristics of bomb cyclones over the northwestern Pacific (Yoshida and Asuma 2004). Bomb cyclones developing along the

FIG. 14. (a) As in Fig. 1b, but using JRA-55. (b) Difference of LDR24P1 in January between averages from 2013 to 2020 and from 1987 to 2012 (shading; hPa day^{-1}) and average from 1987 to 2020 (contour). (c) Difference of precipitable water (shading; mm) and vertically integrated moisture flux (arrow; mm m s^{-1}) in January averaged from 1973 to 2021. (d) As in Fig. 1c, but for the eddy statistics based on JRA-55 from 1959 to 2020 with additional average and standard deviation between 2013 and 2020. Note that data before 1972 are the same data as in JRA-55C.

southern coast of Japan [Pacific Ocean (PO) type] tend to develop under a large contribution of latent heat release, while those over the Okhotsk and Japan Seas (OJ type) develop under a larger contribution of upper-level vorticity advection. The long-term SST warming in the subtropical northwestern Pacific and the East and South China Seas can set a condition favorable for the PO-type cyclone development in January. However, the corresponding impacts of the interdecadal SST warming on bomb cyclone activity in the central North Pacific tend to be less pronounced in December and February, which may be attributable, in part, to the tendency of interdecadal lower-tropospheric warming over East Asia in these calendar months to be more enhanced north of $\sim 20^\circ\text{N}$ than to its south. Thus, dry baroclinicity over the mid-latitude East China Sea tends to be reduced and thereby counteract the effect of low-level moistening. In January, by contrast, the lower-tropospheric warming was more meridionally uniform, yielding no substantial reduction in dry baroclinicity over the midlatitude East China Sea.

Some of the previous studies suggested that baroclinic energy conversion is the most relevant mechanism for the midwinter suppression of the North Pacific storm track activity (e.g., Chang 2001), and the interdecadal weakening of the East Asian winter monsoon and upper-level westerly jet stream modulated the background state to be favorable for baroclinic eddy development within the dry dynamics (e.g., Nakamura and Sampe 2002). Although thorough investigation of processes involved

in the midwinter suppression of the North Pacific storm track activity is beyond the scope of the present study, we have revealed that the interdecadal increase in the lower-tropospheric poleward eddy heat flux was associated mostly with increased bomb cyclone activity over the central North Pacific in January, which corresponds to the diminished midwinter suppression of the North Pacific storm track activity found by Nakamura et al. (2002). As pointed out by Chang (2001), cold monsoonal northwesterlies behind each of the cyclones traveling along the midwinter North Pacific storm track effectively induce shallow convective heating over the warmer sea surface, and the convective heating acts to reduce eddy available potential energy and thus contribute to the activity minimum. We have demonstrated the particular importance of diabatic heating for explosive cyclone development even in midwinter, especially in the recent period after 1987. Our findings suggest that not only the weakened winter monsoon but also the rapid SST rise in the East and South China Seas and subtropical northwestern Pacific may lead to the diminished midwinter suppression of the North Pacific storm track activity via moist diabatic processes by activating bomb cyclones in midwinter.

Although the present study has indicated contributions from bomb cyclones to the long-term modulations of low-level poleward eddy heat flux ($\bar{v'T'}$) in midwinter, further investigation is needed for deeper understanding of their role in the midwinter suppression of the North Pacific storm track activity, based on

other eddy statistics such as $u'v'$ and $u'T'$, and from an energetic perspective. Possible contributions from cyclones other than the bomb cyclones from the East China Sea, including those originating from downstream of the Kamchatka Peninsula (Schemm et al. 2021) to the long-term modulations of the mid-winter suppression will be also assessed in our future study. Additionally, how the future changes in the basic state and seasonal march under the global warming can affect bomb cyclone activity and storm track activity is a scope of our future study.

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Data availability statement. JRA-55C is available from the Data Integration and Analysis System (DIAS) at <https://diasjp.net/>.

APPENDIX

Tracking Algorithm

In this study, tracks of surface centers of moving cyclones are objectively identified in the JRA-55C global atmospheric reanalysis data (Kobayashi et al. 2014), and those tracks are utilized for investigating the activity of bomb cyclones as described in section 2. The tracking procedure is the following.

For tracking cyclones centers, SLP and its Laplacian (hereafter, ∇^2 SLP) are utilized. The combination of SLP and ∇^2 SLP (or surface vorticity) has been adopted to identify cyclone tracks in previous studies (e.g., Murray and Simmonds 1991; Pinto et al. 2005; Simmonds et al. 2008; Hewson and Tittley 2010). Before the tracking starts, a Gaussian spatial filter whose half-amplitude length is 300 km is applied to ∇^2 SLP to obtain a smoother field. Grid points whose altitudes are higher than 1500 m are not used for the tracking.

At a given instance, local SLP minima are first sought as candidates for cyclone centers, among which only the SLP minimum with the lowest pressure in the vicinity of a 400-km circle has been identified. The SLP minimum must accompany a local maximum of ∇^2 SLP within 650 km, which must be stronger than $100 \text{ Pa (100 km)}^{-2}$ and highest within a radius of 400 km. This condition is imposed to discard cyclones with insignificant amplitudes. Next, those SLP

FIG. A1. (a) Snapshot of SLP (black contours, every 4 hPa and thick for every 20 hPa) and identified surface cyclone centers (red open circles) at 1200 UTC 17 Dec 2011 based on the JRA-55C reanalysis. (b) Wintertime (DJF) climatological-mean density of surface cyclone centers [% (1000 km)^{−2}] in 1958/59–2011/12. Unit is set to be the same as in Neu et al. (2013). Meridians of 100°E and 120°W are highlighted, which indicate the western and eastern boundaries of the domain identified centers must pass.

minima identified above are compiled as tracks. The nearest SLP minima at successive time steps are connected only when the distance is not more than 800 km. Any track must persist at least over 24 h (four time steps) and must extend at least for 600 km over its life span. In addition, any cyclone track must pass through a domain around the North Pacific storm track (100°E–120°W, 20°–65°N).

The criteria and parameters mentioned above have been chosen to identify features as migratory synoptic-scale cyclones represented on a surface weather map. Indeed, identified cyclone centers are consistent with a SLP field as a snapshot (Fig. A1a). The distribution of cyclone center density is similar if longer thresholds for movement are imposed (e.g., 1000 km).

The climatological-mean wintertime density of cyclone centers is shown in Fig. A1b. Cyclone density is large over the area north of ~30°N over the North Pacific, associated with the climatological-mean Aleutian low. A narrow band of large density is located along the southern coast of Japan and extending northeastward, which is consistent with typical northeastward-moving cyclones along the Kuroshio from a synoptic viewpoint.

Because the identification algorithm described above includes a certain degree of arbitrariness, the tracking result

should be compared with those in previous studies. As shown in Fig. A1b, the North Pacific cyclone density based on our tracking algorithm is clearly within a range of variations among those algorithms in the IMILAST project (Neu et al. 2013). It is notable that the result with our algorithm is consistent especially with that with algorithms using both SLP and ∇^2 SLP (or surface vorticity).

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