Recent Changes in Explosively Developing Extratropical Cyclones over the Winter Northwestern Pacific

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ABSTRACT

This study investigated recent changes in the characteristics of explosively developing extratropical cyclones over the northwestern Pacific region in winter from 1979/80 to 2010/11 by using reanalysis data from the Japanese 25-yr Reanalysis/Japan Meteorological Agency Climate Data Assimilation System (JRA-25/JCDAS). The results showed that the frequency of explosive cyclones increased in the northwestern Pacific region east of Japan. This increase was accompanied by a decrease in the number of slowly developing cyclones, indicating an increase in the cyclone growth rate. Moreover, most of the increased explosive cyclones east of Japan originated southwest of Japan. A comparison of the dynamical features and energy budgets of two composite cyclones in the earlier and later halves of the study period suggested that the increase was due to an enhancement of the low-level baroclinicity to the east of Japan and an increase in humidity associated with sea surface temperature warming and enhanced evaporation along the eastern shore of the Asian continent.

1. Introduction

The northwestern Pacific is one of the most prominent regions with large cyclone activity in the Northern Hemisphere, along with the northwestern Atlantic. These areas are known as storm-track regions, which are defined as regions of maximum transient eddy variation (e.g., Blackmon et al. 1977) or as frequent pathways of extratropical cyclones (e.g., Whittaker and Horn 1984). Among these extratropical cyclones, explosively developing examples are called bombs (Sanders and Gyakum 1980; Roebber 1984). Explosive cyclones frequently appear over storm-track regions, particularly during winter, and sometimes disrupt human activities by heavy precipitation, snowfall, severe winds, and high waves.

Changes in cyclone activity due to global warming are one of the most interesting issues for human society. Many studies have examined this issue by simulating enhanced greenhouse warming using general circulation models (GCMs). One of the major results of these experiments is a decrease in the total cyclone number during Northern Hemisphere winter (e.g., Lambert 1995; Geng and Sugi 2003; Bengtsson et al. 2006; Lambert and Fyfe 2006; Pinto et al. 2007). Geng and Sugi (2003) noted that this decrease was caused mainly by a decrease in the low-level baroclinicity associated with greater (lesser) warming at higher (lower) latitudes. Another result from GCM simulations is the intensification of cyclones (e.g., Lambert 1995; Yin 2005; Lambert and Fyfe 2006). However, Ulbrich et al. (2009) mentioned that this result depended on the definition of extreme events; that is, the number of extreme cyclones increased when “extreme” was defined on the basis of the core pressure but decreased when extreme was defined using the Laplacian of the surface pressure or vorticity around the core.
Moreover, some studies suggested a northward shift of storm tracks in the Northern Hemisphere on the basis of GCM simulations (e.g., Yin 2005). According to Bengtsson et al. (2006) and Ulbrich et al. (2008), however, the shift was longitudinally restricted, that is, weakening of cyclone activities over the Mediterranean and strengthening over the British Islands, and weakening over the western Pacific and strengthening around the Aleutian Islands.

On the other hand, recent changes in cyclone activity have also been investigated on the basis of reanalysis data. In the Northern Hemisphere, cyclone intensification was reported over the North Pacific (e.g., Graham and Diaz 2001; Wang et al. 2006), over the North Atlantic (e.g., Geng and Sugi 2001; Harnik and Chang 2003), and over both regions (e.g., Lambert 1996; Chang and Fu 2002; Paciorek et al. 2002). Some of these studies suggested a noticeable intensification after 1970 (Lambert 1996; Chang and Fu 2002), and others suggested a relationship between the cyclone intensity and the sea surface temperature (SST) (Lambert 1996; Graham and Diaz 2001). The hemispheric decrease in total cyclone number during Northern Hemisphere winter, which is one of the major results in the enhanced greenhouse warming simulation, is not evident in the reanalysis data. A northward shift of cyclone activity was found in the Northern Hemisphere (McCabe et al. 2001) or in more restricted regions over the Euro-Atlantic sector (Trigo 2006; Wang et al. 2006).

In this study, we analyze reanalysis data to examine recent changes in explosively developing cyclones over the winter northwestern Pacific and to explore the mechanisms of the observed changes. We mainly used the Japanese 25-yr Reanalysis/Japan Meteorological Agency (JMA) Climate Data Assimilation System (JRA-25/JCDAS; Onogi et al. 2007), whereas most previous studies used reanalysis data of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) or the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40). We expect the JRA-25/JCDAS data to be of high quality, especially around Japan. Moreover, the target phenomena in this study are explosively developing cyclones that are characterized by rapid development, whereas most previous studies focused on extreme cyclones that are characterized by their intensity (e.g., the lowest central pressure or highest vorticity). Although explosive and extreme cyclones are similar and sometimes overlap each other, the occurrence of explosive cyclones could be more sensitive to climate changes because cyclone development is directly affected by changes in the basic field.

Yoshida and Asuma (2004) and Kuwano-Yoshida and Asuma (2008) well described the characteristics of explosively developing cyclones in the northwestern Pacific. They investigated the statistical features and dynamical structures of explosive cyclones by classifying them into three types depending on where they were generated and developed. One was generated over the eastern Asian continent and developed over the Sea of Okhotsk or Japan Sea (OJ), another was generated over the same continent and developed over the northwestern Pacific Ocean (PO-L), and the third was generated and developed over the northwestern Pacific Ocean (PO-O). Their analyses revealed that the PO-O type had the largest growth rate among the three types, and it was accompanied by a distinct baroclinic zone in the mid-level and a large amount of precipitation around the center. Yoshiike and Kawamura (2009) investigated the relationship between large-scale wintertime circulation and explosive cyclones in the northwestern Pacific, and found that explosive cyclones tended to be concentrated farther along the Kuroshio and the Kuroshio Extension when the winter monsoon was strong.

Here, we also investigate explosive cyclones in the winter northwestern Pacific, but the main objective of this study is to reveal trends in explosive cyclones and clarify the dynamical mechanisms. We describe the data and methods in section 2, including the cyclone-tracking schemes and energy budget formulas. In the beginning of section 3, we report a notable change in the occurrence of explosive cyclones on the basis of the obtained track data. The rest of the section examines the mechanism of this change by conducting composite and energy budget analyses. Finally, we summarize the main results and discuss associated issues in section 4.

2. Data and analysis methods

a. Data

As mentioned in the introduction, the reanalysis dataset of JRA-25/JCDAS was used in this study to detect changes in explosively developing cyclones and to explain the underlying dynamical mechanisms. This dataset has temporal coverage from 1979 to the present with a time interval of 6 h and horizontal resolution of 1.25° × 1.25°; we used the data from 12 pressure levels ranging from 1000 to 100 hPa. Moreover, we used the ERA-40 and ECMWF Interim Re-Analysis (ERA-Interim) (Simmons et al. 2007) data for 1979–2002 and 1989–2011, respectively, to compare the results for the number of explosive cyclones. We used the high-resolution version of the ERA-40 data with grid intervals of approximately 1.125° on a Gaussian grid; the ERA-Interim data have horizontal grid intervals of 1.5°. Both ERA datasets were provided with a time step of 6 h.
Owing to the data availability of JRA-25/JCDAS, our analysis was restricted to the period from 1979 to 2011. To extract trends in the number of explosive cyclones during winter for this period, we divided the period into the first and last 16 yr (1979/80–1994/95 and 1995/96–2010/11, respectively) and compared the characteristics of explosive cyclones’ occurrence and structure in each period.

b. Detection of explosively developing cyclones

To investigate trends in explosively developing cyclones, we objectively identified and tracked all extratropical cyclones in the Northern Hemisphere. However, a wide range of methods have been developed for identification and tracking, and it is known that the choice of method tends to affect the results (e.g., Ulbrich et al. 2009). Thus, in this study, we adopted two commonly used methods based on the sea level pressure (SLP) and the low-level (850 hPa) vorticity fields. The use of the SLP for identification is historical and familiar. However, according to Hoskins and Hodges (2002), this field is strongly influenced by large scales that can mask weak synoptic scales. They mentioned that the vorticity would be a better field because it focuses on smaller scales and allows cyclones to be identified much earlier. However, this field is very noisy, and too many small-scale cyclones can be identified in high-resolution data.

For the SLP field, local minima were identified as cyclone centers. A grid point was considered a cyclone center if its SLP value was smaller than the values at each of its eight neighboring grid points. Because the SLP field is not reliable over high ground owing to vertical extrapolation, mountain regions with altitudes higher than 1500 m were excluded. For the 850-hPa vorticity field, we applied the same preprocessing as Hoskins and Hodges (2002), including a spatial bandpass filter with a total wavenumber between 6 and 42, and spectral tapering. Next, local maxima were identified as cyclone centers. A comparison of the identified cyclones’ distribution in the two fields revealed that cyclones in the filtered vorticity field tended to be distributed evenly throughout the hemisphere, and the total number was larger than in the SLP field. Cyclones in the SLP field were focused in specific regions, including the northwestern Pacific, where the number of cyclones was larger in the SLP field.

The cyclone tracks were determined from the identified cyclone centers. For a tracking algorithm, we used the scheme of Wernli and Schwierz (2006) as a reference. Their scheme first estimated a cyclone’s location in the next time step \( x^*(t + 6) \) from the locations in the present \( x(t) \) and previous \( x(t - 6) \) time steps by reduced linear continuation of the track:

\[
x^*(t + 6) = x(t) + 0.75[x(t) - x(t - 6)].
\]

Among the cyclone centers in the next time step, the center located at \( x(t + 6) \) was regarded as the identical cyclone center if \( x(t + 6) \) was the closest to \( x^*(t + 6) \) and if the distance between \( x(t + 6) \) and \( x^*(t + 6) \) was less than a certain threshold (600 km). When we searched for the second point of a track, we took the initial position of the cyclone as the estimation point because no previous displacement was available. The assumed acceleration factor, 0.75, and the maximum distance between \( x^*(t + 6) \) and \( x(t + 6) \), 600 km, are considered the parameters in this scheme. They were chosen within a realistic range on the basis of previous studies (Wernli and Schwierz 2006; Hewson and Titley 2010). Cyclones with lifetimes shorter than 24 h were excluded from our analysis. Moreover, because this method detected multiple tracks for a merged cyclone, the track with the longest lifetime was chosen as a cyclone’s representative track. The relationship between cyclone mergers and the growth rate was discussed in Inatsu (2009).

To test the accuracy of the tracking scheme, we compared these numerically obtained tracks to manually derived tracks. The comparison was made for each connection between cyclones in consecutive time steps, given the distributions of cyclones in the SLP and filtered vorticity fields. The conditions for the test were similar to those in Hewson and Titley (2010) in the extended North Pacific region for 3 days from 20 October 2008 (12 time steps with 6-hourly JRA-25/JCDAS data). Only one case was clearly wrong out of 105 connections in the SLP field, and two cases were wrong out of 161 connections in the vorticity field. The one case in the SLP field was a weak cyclone over eastern China, which seemed to disappear but was tracked incorrectly toward the southwest. The two cases in the vorticity field were weak cyclones in subtropical regions, which could not be tracked owing to their very rapid acceleration. A large number of cyclones were distributed over the continent in the SLP field, and in subtropical regions in the filtered vorticity field, which would lead to tracking errors in these areas. Overall, however, the tracking accuracies based on both the fields were on the order of 99%, which is comparable to that using a sophisticated method by Hewson and Titley (2010), although their method took much weaker cyclones into account.

Finally, the explosively developing cyclones were identified among the tracked cyclones. The explosive cyclones in the SLP field were defined by the maximum growth rate, similar to that in Sanders and Gyakum (1980):

\[
-\frac{\text{SLP}(t + 12) - \text{SLP}(t - 12)}{24} \frac{\sin 60^\circ}{\sin \phi(t)} > 1,
\]

(1)
where $\phi$ is the latitude. The selected explosive cyclones accounted for about 20% of the total cyclones in the winter northwestern Pacific. The explosive cyclones in the filtered vorticity field were defined as in Eq. (1) except that the threshold of the maximum growth rate was set to $1.5 \times 10^{-6} \text{ s}^{-1} \text{ h}^{-1}$, assuming the same ratio of explosive cyclones as in the SLP field.

c. Energy budget analysis

To investigate the dynamical mechanisms of the obtained changes, the energy budgets of the explosive cyclones were analyzed using the JRA-25/JCDAS data. Before each analysis, 6-hourly data were decomposed into low-frequency basic fields and high-frequency anomaly fields by applying a Butterworth low-pass filter with a cutoff period of 10 days. The energy budgets were calculated from these fields using the formulas of Kosaka and Nakamura (2006, 2010) and Kosaka et al. (2009). Those studies defined the eddy kinetic energy and the eddy available potential energy as

\[
\begin{align*}
\text{KE} &= \frac{u'^2 + v'^2}{2} \\
\text{APE} &= \frac{R(T^2)}{2\sigma p},
\end{align*}
\]

respectively, where $\mathbf{v} = (u, v)$ denotes horizontal winds, $T$ is the temperature, $p$ is the pressure, $R$ is the gas constant, and $\sigma = RT/c_p - \partial T/\partial p$ is the stability parameter, where $c_p$ is the specific heat at a constant pressure of dry air. Primes denote the high-frequency anomaly from the low-frequency basic field that is denoted by a bar. Moreover, the baroclinic and barotropic energy conversions from the basic to anomaly fields, and the energy supply due to diabatic heating, were defined as

\[
\begin{align*}
\text{CP} &= \frac{f}{\sigma} v' T \frac{\partial \pi}{\partial p} + \frac{f}{\sigma} u' T' \frac{\partial \pi}{\partial p}, \\
\text{CK} &= \frac{v'^2 - u'^2}{2} \left( \frac{\partial \pi}{\partial x} - \frac{\partial \pi}{\partial y} \right) - u'v' \left( \frac{\partial \pi}{\partial y} + \frac{\partial \pi}{\partial x} \right), \\
\text{CQ} &= \frac{R T' Q'}{c_p \rho \sigma},
\end{align*}
\]

respectively, where $f$ is the Coriolis parameter and $Q$ is the apparent heat source defined by Yanai et al. (1992). These energetic values were integrated over the troposphere from the surface to the 100-hPa level; integrated values are denoted by brackets, for example, $[\text{KE}], [\text{CP}]$. The basic component on the right-hand side of the CP equation, which is analogous to the Eady growth rate maximum (Lindzen and Farrell 1980; Hoskins and Vales 1990),

\[
\text{BI} = \frac{f}{\sigma} \left( \frac{\partial \pi}{\partial p} \right),
\]

was used as a measure of the baroclinicity. Note that other terms in the energy budget, such as advection by the basic wind, geopotential flux convergence, and mechanical damping, were estimated, but are not shown because of their small or negative contributions to cyclone development.

In the following section, the energy budgets are shown as composites from several events. The composite fields were constructed for two sets from cyclones in the earlier and later years of the study period, respectively. For each composite set, two composites were constructed: one by the simple Eulerian mean and the other by the Lagrangian mean with the cyclone center superimposed on the same location. The Lagrangian mean might be the better approach for illustrating the sharp structure of the transient fields. To avoid excessive smoothing in the Eulerian mean, the composite cyclones were confined to a specific region as discussed later.

3. Results

a. Climatological features of the storm track

As mentioned in the introduction, the northwestern Pacific is one of the major storm-track regions in the Northern Hemisphere. Figure 1 shows the climatological distributions of fields associated with cyclone activities over the northwestern Pacific averaged for winters (December–February, DJF) from 1979/80 to 2010/11. Figure 1a illustrates the baroclinicity described in Eq. (4) at the 850-hPa level. Large BI values extend from the west around Mongolia and from the southwest around Taiwan toward the east over the northwestern Pacific; the maximum is located east of Japan. A cyclone’s development is well known to be greatly affected by the SST distribution (Fig. 1c) in the northwestern Pacific. The sharp SST gradient at the oceanic front of the Kuroshio anchors the low-level baroclinic zone (Nakamura et al. 2004; Taguchi et al. 2009). Moreover, the warm SST itself affects the rapid development of cyclones by supplying heat and moisture from the ocean (Kuo et al. 1991; Neiman and Shapiro 1993). Figure 1b shows the climatology of poleward heat flux associated with high-frequency eddies ($v' T'$) at the 850-hPa level, and Fig. 1d shows the precipitation including snowfall. Both figures show distributions similar to that of the BI (Fig. 1a), but the maximum regions are shifted eastward from the BI maximum. Under the strong advective effect of the Asian jet, the amplitude of transient eddies, in the form of the meridional heat flux and precipitation, tends to be
maximized to the east of the core of the baroclinic zone (Nakamura et al. 2002).

b. Changes in explosive cyclone frequency

When we detected explosively developing cyclones by the method described in section 2b using JRA-25/JCDAS SLP data, we identified 770 tracks in 32 winters (DJF) from 1979/80 to 2010/11 over the northwestern Pacific (30°–60°N, 120°E–180°). On the other hand, 604 tracks were found in the filtered vorticity field. These numbers roughly correspond to the number of explosive cyclones obtained by manual tracking (e.g., Sanders and Gyakum 1980) and by objective tracking (e.g., Yoshida and Asuma 2004). Here, we describe the mean features and changes in the frequency of explosive cyclones using the SLP field at first, and the vorticity field after that.

Figure 2a shows the winter mean number densities of points at which the growth rate of the central pressure [left-hand side of Eq. (1)] reaches its maximum in the lifetimes of explosive cyclones. The density is concentrated in the northwestern Pacific region extending from the Japan Sea toward the east; the maximum is located east of Japan. This distribution is consistent with that found in previous studies (e.g., Yoshida and Asuma 2004) and corresponds well with the BI distribution (Fig. 1a). The change in the number density between the first (1979/80–1994/95) and last (1995/96–2010/11) 16 yr is shown in Fig. 2b. The density increased east of Japan (35°–41.25°N, 135°–160°E), where it was originally high, and decreased over the Pacific farther to the northeast. Given the northeastward migration of extratropical cyclones in this region, the decrease over the Pacific may be due to an upstream increase, which implies changes in the timing of the maximum growth rate in the earlier stage of a cyclone’s life.

Figure 3 shows the interannual variations in the number of explosive cyclones exhibiting a maximum growth rate over the region east of Japan (shown by a box in Fig. 2b) during winter (DJF). The variation in the JRA-25/JCDAS SLP data (Fig. 3a) indicates that the number of explosive cyclones increased from about 6.5 to 8.5 per winter over the two periods. Despite the large interannual variability, the increase was about twice the standard deviation of the sample mean, indicating statistical significance at a confidence level greater than 95% based on the two-sample $t$ test. The interannual variation was investigated in other datasets (ERA-40, thin solid line; ERA-Interim, thin dashed line), using the SLP field. The number of explosive cyclones in both datasets shows the variations and increasing trends similar to that in JRA-25/JCDAS, although neither dataset covers the entire analysis period.

To obtain an overall picture of the change, the frequency distributions of all cyclones east of Japan are
depicted with respect to the maximum growth rate for the earlier period (filled bars) and later period (open bars) in Fig. 4. Note that explosive cyclones, which account for 20% of the total cyclones in the extended northwestern Pacific, as mentioned in section 2b, account for about 50% of the cyclones in Fig. 4, indicating rapid cyclone development in this region east of Japan. In the SLP field (Fig. 4a), the maximum growth rate clearly increased from the earlier to the later periods without any significant change in the total number of cyclones (280 and 268 in the earlier and the later period, respectively); the number of slowly developing cyclones (less than 1.0 hPa h\(^{-1}\)) decreased, and that of rapidly developing cyclones (greater than 1.0 hPa h\(^{-1}\)) increased.

Similar features and trends were identified in the filtered 850-hPa vorticity field. Number densities of explosive cyclones' maximum growth rates in the vorticity field (Fig. 2c) show a similar distribution to that in the SLP field (Fig. 2a), although the overall density is smaller in the vorticity field and the local maximum over the Japan Sea seen in the SLP field is obscure in the vorticity field. These differences would be owing to the spatial filter applied to the vorticity field, which smoothed out small scales in the northwestern Pacific. Nevertheless, the change in the number density based on the vorticity field (Fig. 2d) presents the increasing trend east of Japan, similar to that based on the SLP field (Fig. 2b). Figure 3b shows the interannual variation in the number of explosive cyclones based on the vorticity field in the JRA-25/JCDAS data. We can also see the variation and increasing trend similar to that in the SLP field, although the mean frequency was smaller in this field. A \( t \) test

![Figure 2](image1.png)

**Fig. 2.** Number densities of points where the growth rate reaches its maximum in explosive cyclones' lifetimes on the basis of (a),(b) the SLP field and (c),(d) the filtered vorticity field at the 850-hPa level in the JRA-25/JCDAS data for (a),(c) an average in winters (DJF) from 1979/80 to 2010/11 and (b),(d) the difference between the earlier (1979/80–1994/95) and later (1995/96–2010/11) periods, with 0.01 contour intervals without 0 contour lines. Number density was calculated as values per 14,800 km\(^2\) for one winter, which were smoothed by a nine-point average.

![Figure 3](image2.png)

**Fig. 3.** Interannual variation in the number of explosive cyclones exhibiting maximum development east of Japan (35°–41.25°N, 135°–160°E, boxes in Figs. 2b,d) during winter (DJF), based on (a) the SLP field in the JRA-25/JCDAS (thick line), ERA-40 (thin solid line), and ERA-Interim (thin dashed line) data, and (b) the filtered 850-hPa vorticity field in the JRA-25/JCDAS data. Horizontal lines and shadings indicate means over each period and the standard deviations of the means, respectively, on the basis of the JRA-25/JCDAS data.
revealed that the confidence level of the increase was greater than 95%. Moreover, the change in the cyclones’ frequency distribution in the filtered vorticity field is shown in Fig. 4b. The increase in the maximum growth rate is also apparent, while the total number did not change significantly (197 and 206 in the earlier and later period, respectively); the boundary of the growth rate is approximately $1.5 \times 10^{-6}$ s$^{-1}$ h$^{-1}$. We also confirmed a similar trend in the nonfiltered vorticity field, although weak cyclones in this field should be neglected in tracking owing to too many identified cyclones, as mentioned in section 2b.

Here, we showed an increase in the cyclone growth rate and an associated increase in the number of explosive cyclones east of Japan using the SLP and low-level vorticity fields in the JRA-25/JCDAS data, and also using the SLP field in two ERA datasets. The same analysis for other seasons showed that the increase was most prominent in winter. This result is consistent with the recent enhancement in storm-track activity during winter over the northwestern Pacific (Nakamura et al. 2002; Inatsu and Kimoto 2005), although the storm-track enhancement was reported for much broader areas.

c. Mechanisms of the change

In this section, we examine the mechanisms of the increase in the growth rate and in the number of explosive cyclones east of Japan by composite and energy budget analyses. The results shown below are only for the SLP field, although similar results were obtained for the filtered vorticity field as well.

Figure 5 shows the number densities of the genesis (shading) and tracks (contours) for all cyclones that passed over the region to the east of Japan (EJ: $35^\circ$–$41.25^\circ$N, $135^\circ$–$160^\circ$E) during winter. The EJ area is smaller than the region shown in Figs. 2b and 2d for an analysis reason described later. The track density shows two major routes leading to the EJ area: one is through the southern coast of Japan and the other is through the Japan Sea. The former route appears to be followed by cyclones generated over the East China Sea or on the route along the southern coast of Japan. The latter is followed by cyclones generated mainly over the Japan Sea.

When explosive cyclones exhibiting the maximum development in the EJ area were classified by their genesis area into four regions (W, SW, S, and EJ; see Fig. 5), the number in each region was obtained for the earlier and later periods, as listed in Table 1. The number of explosive cyclones generated in the SW area clearly increased from the earlier to later period, and there are no other significant changes. This result is consistent with the recent increase in cyclones that follow a route through the southern coast of Japan (Inatsu and Terakura 2011). Further analyses to cyclone genesis showed no significant increase in the SW area (not shown), indicating that cyclones generated in the SW area developed increasingly to the east of Japan. Here, we focused on cyclones generated over the East China Sea (EC: $25^\circ$–$35^\circ$N, $120^\circ$–$130^\circ$E) that followed the route along the southern coast of Japan to the EJ area. The number of explosive cyclones following this route increased from 8 to 19 over the two periods (Table 1).

To investigate dynamical mechanisms of the increase in the cyclone growth rate, two sets of composite fields were constructed for these cyclones in the earlier and later periods. On the basis of the cyclones’ characteristics, the composite events were selected as those generated in the EC area, leaving the EC area across the eastern boundary, passing over the EJ area, exhibiting the maximum growth rate in winter (DJF), and being tracked for more than 60 h. From these events, time evolutions of the composite fields were constructed; the last time step of each cyclone in the EC area was adjusted to the same time (0 h). To maintain the sharp structure in the composite fields, the EC and EJ areas.
were confined to somewhat small regions. Moreover, cyclones occurring immediately after another cyclone (within 5 days) were excluded. As a result, 39 and 42 cyclones were selected to construct composite fields in the earlier and later periods, respectively, as listed in Table 2. Some dates in this table are in November because the listed date is the reference date when the cyclones started from the EC area, and event selection was based on the date of maximum development. The composite events are distributed evenly across the periods. Although a concentration appears in February, the situation is similar for the two periods. In Fig. 5, the averaged tracks of cyclones used for the composite are shown in the earlier (filled circles) and later (open circles) periods. Both tracks lie on the route along the southern coast of Japan. Note that these tracks are averages based on each track, a bit different from tracks of the minimum SLP in composite fields.

The composite fields were constructed separately for the 10-day low-pass-filtered basic fields, the remaining transient fields, and the energy budgets described in Eqs. (2) and (3). As mentioned in section 2c, each composite field was constructed using the Eulerian and the Lagrangian means. By comparing the structures and energy budgets between the two composite cyclones, we identified the dynamical mechanisms that would contribute to the increase in the growth rate and the number of explosive cyclones east of Japan.

Figure 6 shows the time evolutions of the transient components of the composite cyclones in the earlier (Figs. 6a,c,e) and later (Figs. 6b,d,f) periods based on the Eulerian mean for 30 h following the cyclones’ departure from the EC area. Note that cyclone centers in the 850-hPa geopotential height field (contours) are slightly shifted westward from the centers (marks) in the SLP field. In both composite cyclones, cyclone centers located over the East China Sea (Figs. 6a,b) move toward the northeast to the EJ area (Figs. 6e,f); the eddy energy [KE + APE] (contours with shadings) is supplied by baroclinic conversion [CP] (thick solid contours) and condensational heating [CQ] (thick broken contours), and is enhanced on the cyclones’ eastern flank. However, the energy supplies and resulting eddy energy in the later period’s composite are obviously larger than those in the earlier period’s composite, especially at 30 h.

Figure 7a shows time series of the minimum SLP (broken line) and eddy energy [KE + APE] (solid line) composited using the Lagrangian mean. Energetic values were averaged over a 30° × 30° domain around the cyclone centers at each time to obtain the time series. The minimum SLP dropped by about 30 hPa in the earlier period’s composite over 60 h, and by about 35 hPa in the later period’s composite over the same duration. In fact, the number of explosive cyclones was 36 in 42 composite events (86%) in the later period, which is larger than 27 in 39 composite events (70%) in the earlier period. Correspondingly, the eddy energy [KE + APE] in the later period’s composite increased more rapidly than that in the earlier period’s composite starting at 12 h, and the difference between the two composites reached its maximum at 30 h. The statistical confidence for the difference in the eddy energy between the two composites was more than 95% from 18 to 30 h, whereas that from the minimum SLP was relatively low (between 90% and 95%).

To investigate the cause of the difference in the growth rate between the two composite fields, the vertically integrated energy conversion terms are shown in Fig. 7b as [CP] (solid line), [CQ] (dashed line), and [CK] (broken lines).

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Table 1: Numbers of explosive cyclones generated at latitude $\phi_1$ and longitude $\lambda_1$ in each area shown in Fig. 5 that exhibited the maximum growth rate in the EJ region during winters (DJF) in the earlier (1979/80–1994/95) and later (1995/96–2010/11) periods.

<table>
<thead>
<tr>
<th>Area</th>
<th>$\phi_1 \leq 35^\circ$</th>
<th>$\phi_1 &gt; 35^\circ$</th>
<th>$\lambda_1 \leq 140^\circ$</th>
<th>$\lambda_1 &gt; 140^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>28</td>
<td>27 (8)</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>SW (EC)</td>
<td>24</td>
<td>49 (19)</td>
<td>6</td>
<td>16</td>
</tr>
</tbody>
</table>

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line) for the two composite cyclones. For both composite fields, [CP] and [CQ] show positive contributions to the growth of the cyclones throughout the period shown, whereas [CK] shows a slight negative contribution after 24 h. A comparison of the two composite fields reveals that the contributions of [CP] and [CQ] are larger in the later period’s composite than in the earlier period’s composite, indicating that these terms contribute to the rapid growth in the later period’s composite. Although [CK] also shows a larger contribution in the later period’s composite after 42 h, it seems to contribute not to the rapid development but to maintaining the cyclones’ strength. Note that other terms in the energy budget, such as advection by the basic wind and geopotential flux convergence, show negative contributions to the cyclones’ development, and the larger contributions of [CP] and [CQ] in the later period’s composite are partially compensated by these effects.

The cause of the larger contributions of CP and CQ in the later period’s composite is examined by comparing the basic components of the two composite fields in Fig. 8. The differences in each basic field are shown at

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Fig. 6. Time evolutions of transient (10-day high-pass filtered) components of the 850-hPa geopotential height (contoured with 10-m intervals) and vertically integrated energy terms, [KE + APE] (contoured with $0.5 \times 10^6$ J m$^{-2}$ intervals; shading indicates values greater than $1.5 \times 10^6$ J m$^{-2}$), [CP] (contoured by thick solid lines with $0.5 \times 10^6$ J m$^{-2}$ 6-h intervals without 0 contours), and [CQ] (contoured by broken lines with $0.5 \times 10^6$ J m$^{-2}$ 6-h intervals without 0 contours), for composite cyclones in (a),(c),(e) the earlier period (1979/80–1994/95) and (b),(d),(f) the later period (1995/96–2010/11), for (a),(b) 0, (c),(d) 12, and (e),(f) 30 h following the departure of the cyclones from the EC area (shown in Fig. 5). Filled and open circles in each panel indicate mean cyclone positions in the SLP field shown in Fig. 5.
0 h when the composite cyclones started from the EC area toward the EJ area. The BI at 850 hPa (Fig. 8a) is larger in the later period’s composite east of Japan, which is consistent with the larger contribution of CP. The larger BI in the later period’s composite appears to be associated with the northeastward shift and the enhancement of the Aleutian low (Fig. 8c), which is accompanied by a corresponding shift in the westerly jet (Fig. 8d) and cold advection around the Kamchatka Peninsula (Fig. 8b). The larger BI is located between this cold anomaly and a warm anomaly over the central Pacific (25°N, 170°E). This warm anomaly seems to be connected with the warm SST anomaly (Fig. 8e) in the same region, suggesting that the larger BI in the later period’s composite is associated with the enhanced SST gradient.

On the other hand, the SST (Fig. 8e) also shows warm anomalies along the eastern shore of the Asian continent over the East China Sea and the Okhotsk Sea in the later period’s composite. The warm SST in these regions is associated with the large latent heat flux (Fig. 8f) probably through the enhanced temperature contrast between the sea surface and atmosphere. In particular, the large latent heat flux extending from the East China Sea along the southern coast of Japan supports the rapid development of cyclones in the later period’s composite through the effect of CQ. Note that the warm SST in the central Pacific would be associated with the small latent heat flux in the same region via the weak surface wind. These results suggest that the rapid development in the later period’s composite was associated with the larger low-level baroclinicity to the east of Japan and the larger latent heat flux along the southern coast of Japan, which correspond to the larger contributions of CP and CQ, respectively.

To confirm these results, we compare the winter (DJF) mean fields of the earlier and later periods in Fig. 9 for the same variables as in Fig. 1. The change in the BI distributions (Fig. 9a) shows a significant increase in the northern part of Japan and around the Okhotsk Sea, but the increase east of Japan seen in Fig. 8a is not clear. Moreover, the enhancement of the westerly jet east of Japan and the cold advection around the Kamchatka seen in the composite fields (Fig. 8) also could not be identified in the winter mean fields (not shown), although there were some similarities between them. The eddy heat flux (Fig. 9b) shows an increasing trend east of Japan, although the significance is below the confidence level. The large baroclinicity seen in the later period’s composite field can be considered to be reduced by the poleward eddy heat flux in the winter mean field. Our analysis suggests that the low-level baroclinicity would frequently be enlarged to the east of Japan in the later period, in which cyclones developed rapidly owing to the enhanced CP contribution, including the enhanced poleward heat flux, which in turn reduced the baroclinicity. In fact, the variance of the 10-day low-pass-filtered components demonstrated an increasing trend northeast of Japan for variables such as the geopotential height and temperature in the lower troposphere (not shown).

On the other hand, the changes in the SST (Fig. 9c) are similar to those in the composite fields (Fig. 8e) with considerable warming along the eastern shore of the Asian continent. The latent heat flux and precipitable water also exhibited changes similar to that in the SST (not shown). Moreover, the most notable change in this region appeared in the precipitation (Fig. 9d), which increased significantly from the southwest to the east of Japan. This result is consistent with the increase in the number of explosive cyclones from the SW area (Table 1). The moist environment is suitable for the rapid development of cyclones (e.g., Emanuel et al. 1987; Inatsu et al. 2003). Thus, it is suggested that cyclones generated
around the East China Sea would contain more water vapor in the later period owing to the warmer SST and greater evaporation, which causes more precipitation or condensational heating from the southwest to the east of Japan, resulting in more rapid cyclone development east of Japan. Moreover, the Kuroshio is located from the southwest to the east of Japan (e.g., Xie et al. 2002; Taguchi et al. 2009). The increases in the precipitation and SST shown in Fig. 9 could be associated with trends or decadal variations in the Kuroshio.

4. Summary and discussion

This study investigated recent changes in explosively developing cyclones over the northwestern Pacific for winters from 1979/80 to 2010/11 by comparing cyclone tracks in the earlier and later 16 yr based mainly on the JRA-25/JCDAS data. We found that the frequency of explosive cyclones increased east of Japan. This increase was accompanied by a decrease in the number of slowly developing cyclones, indicating an increase in the cyclone growth rate. Moreover, most of the increased explosive cyclones east of Japan originated southwest of Japan. To examine the dynamical mechanisms of the increase, two composite fields were constructed for cyclones, which were generated over the East China Sea and tracked to the east of Japan, in the earlier and later periods, and the energy budgets for these two composite fields were calculated. A comparison of the two composite fields revealed that the cyclone in the later period’s composite developed more rapidly than that in the earlier period’s composite in terms of the minimum SLP.
and eddy energy. Moreover, the energy budgets demonstrated that the energy supplies from baroclinic conversion and diabatic heating were larger in the later period’s composite, which would be associated with a larger low-level baroclinicity and larger latent heat flux in the basic fields. Similar features were also found in the winter mean fields, although the larger low-level baroclinicity was not clear owing to the restoring poleward heat flux by eddies. These results suggested that the increase in the growth rate and the number of explosive cyclones east of Japan are due to the enhanced low-level baroclinicity east of Japan and the increase in humidity associated with SST warming and enhanced evaporation along the eastern shore of the Asian continent.

Because such results derived from track data are known to be sensitive to the choices of tracking method and dataset, the increasing trend in the number of explosive cyclones was confirmed both in the SLP field and the filtered (and nonfiltered) 850-hPa vorticity field, and in the different datasets (ERA-40 and ERA-Interim). On the other hand, the explosive cyclone investigated in this study was defined as in Eq. (1), following Sanders and Gyakum (1980), where the growth rate was multiplied by the factor $\sin 60^\circ / \sin \phi(t)$. This factor seems to play a critical role in defining the distributions of explosive cyclones, although Sanders and Gyakum (1980) probably intended to reflect the fact that the variation is generally larger at higher latitudes. We also verified that similar changes appeared over the northwestern Pacific even when the factor was excluded from Eq. (1), although the mean distribution shifted slightly northward.

One of the purposes of this study was to identify recent changes associated with global warming. We obtained an increasing trend in the cyclone growth rate and the number of explosive cyclones east of Japan, which was probably associated with the increase in low-level baroclinicity and the increase in humidity. This result is consistent with the enhancement of storm-track activity found in a global warming experiment (Inatsu and Kimoto 2005). Moreover, the result is also consistent with Nakamura et al. (2002), although the significant weakening of the East Asian monsoon suggested in their study was not identified in this study. However, it is still unclear whether or not the obtained trends can be ascribed to global warming. The data length limitation of the reanalysis dataset prevents further investigation of the relationship between global warming and the recent observed trends in explosive cyclones. In particular, the SST in the northwestern Pacific is affected by decadal variability such as the El Niño–Southern Oscillation and Pacific decadal oscillation. It may be possible to interpret the obtained trend as a part of the long-term fluctuation associated with SST variation.

Acknowledgments. The JRA-25/JCDAS datasets were provided by the Japan Meteorological Agency (JMA)
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——, and ——, 2003: Possible change of extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols—Study with a high-resolution AGCM. J. Climate, 16, 2262–2274.


