Climatology of Polar Mesocyclones over the Sea of Japan Using a New Objective Tracking Method

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ABSTRACT

Polar mesocyclones (PMCs) are mesoscale cyclonic vortices that develop poleward of the main polar front. This article reports on a new algorithm for the objective tracking of PMCs, including meso-β-scale vortices, which will facilitate the study of their climatology. The algorithm is based mainly on the vorticity field and consists of three parts: the identification of vortices, the connection of vortices at consecutive time steps, and discrimination between PMCs and synoptic-scale disturbances. The objective tracking method was applied to Mesoscale Analysis (MA) data provided by the Japan Meteorological Agency, which has a horizontal resolution of 5 km. The detected tracks of PMCs were confirmed by subjective analysis of the MA data and satellite images. The method used here to discriminate between PMCs and synoptic-scale disturbances differs from that used in previous studies, which is based on the difference between the sea surface temperature and the temperature at 500 hPa, but gives a consistent result. This objective tracking method was used to obtain the climatology of PMCs over the Sea of Japan, which were classified into three groups according to the regions where they attained their maximum intensity. In each region, the PMCs have different characteristics with respect to their direction of movement, size, and intensity, which are likely to be related to their environment or development mechanism.

1. Introduction

Polar mesocyclones (PMCs) are cyclonic vortices that develop poleward of the main polar front and have a horizontal size of meso-α (200–2000 km) to meso-β (20–200 km) scale according to the definition by Orlanski (1975). PMCs include polar lows (PLs), which are intense maritime cyclones with horizontal scales between 200 and 1000 km (Rasmussen and Turner 2003). The Sea of Japan (Fig. 1) is one of the regions where PMCs frequently occur during winter, where they are caused by cold-air outbreaks from the Eurasian continent (Asai 1988, hereafter A88; Ninomiya 1989). A cloud band known as the Japan Sea polar airmass convergence zone (JPCZ; A88) is typically present over these two regions, and several studies indicate a link between PMCs and the JPCZ (Okabayashi and Satomi 1971; Shimizu and Uchida 1974; Asai and Miura 1981). Using satellite images, A88 analyzed the locations of PMC genesis over the Sea of Japan during the winter of 1983/84 and found that PMCs with horizontal scales of less than 300 km are concentrated in two regions: one between the northeastern base of the Korean Peninsula and the central part of Honshu Island, and the other to the west of Hokkaido Island (Fig. 2). A cloud band known as the Japan Sea polar airmass convergence zone (JPCZ; A88) is typically present over these two regions, and several studies indicate a link between PMCs and the JPCZ (Okabayashi and Satomi 1971; A88; Nagata 1993; Tsuboki and Asai 2004; Kato 2005; Watanabe and Niino 2014). Several mechanisms have been proposed for the development of PMCs. Asai and Miura (1981) and Nagata (1993) suggested that small PMCs are related to the horizontal shear of the JPCZ, whereas Tsuboki and...
Wakahama (1992) suggested that PLs are associated with baroclinicity. Diabatic heating caused by condensation also plays an important role in both small PMCs (Kato 2005) and PLs (Yanase et al. 2004). Furthermore, these individual processes can occur at the same time and in a complex manner (Lee et al. 1998; Fu et al. 2004; Shimada et al. 2014; Watanabe and Niino 2014). These differing developmental mechanisms are probably the cause of the various sizes and shapes of PMCs. Yanase and Niino (2007) demonstrate that the cloud patterns and development mechanisms of PLs change significantly when environmental baroclinicity changes. This suggests a strong connection between the features of PMCs and environmental conditions. Climatological studies may be useful if we wish to achieve a more comprehensive understanding of the diverse nature of the PMCs that develop over the Sea of Japan.

Several climatological studies of PMCs over the Sea of Japan have been performed using satellite images and weather charts (A88; Ninomiya 1989; Ookubo 1995). Ninomiya (1989) analyzed several PLs using nephanaalysis (analysis chart focusing on the types and amounts of clouds) and weather charts, and described their characteristic environments. Using serial satellite images, Ookubo (1995) demonstrated that there are two types of PMCs: one moves east-northeastward and the other moves southeastward. However, as these studies relied on the subjective detection of PMCs, they were unable to deal with a large amount of data. For example, A88 and Ninomiya (1989) analyzed a period of only one winter, and Ookubo (1995) analyzed only nine PMCs. Recently, a number of objective tracking algorithms have been developed and applied to objective analysis datasets and dynamic downsacle datasets (Zahn and von Storch 2008; Irving et al. 2010; Uotila et al. 2011; Bromwich et al. 2011; Xia et al. 2012; Chen and von Storch 2013; Zappa et al. 2014; Yanase et al. 2016, hereafter Y16). Tracking algorithms are useful in obtaining reliable climatological data for PMCs because they can objectively and automatically detect a large number of PMCs. As for the climatology of PLs over the Sea of Japan, Chen and von Storch (2013) analyzed the entire North Pacific using a regional climate model with a horizontal resolution of 0.4°, and Y16 examined the Sea of Japan in detail using the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015) with a horizontal resolution of about 60 km. These studies, however, examined only meso-α-scale PLs because of the limited horizontal resolution of the data.

Climatological studies of PMCs using satellite images suggest that many PMCs smaller than 200 km develop over the Sea of Japan (A88) and over the northeastern Atlantic (Harold et al. 1999; Condron et al. 2006; Blechschmidt 2008). Small PMCs have also been observed over the Great Lakes (Hjelmfelt 1990; Laird et al. 2001). Moreover, the ability to objectively detect PMCs is strongly influenced by the size of the PMCs, and a large number of PMCs smaller than 200 km are missed (Condron et al. 2006). Figure 3a presents a visible image of PMCs taken by the Japanese Multifunctional Transport Satellite 2 (MTSAT-2), which shows three meso-β-scale vortices existing simultaneously in the JPCZ. Although JRA-55 marginally resolves the JPCZ, it spreads over a wide band-shaped region and the vortices are not reproduced clearly (Fig. 3b). On the other hand, Fig. 3c shows a corresponding plot based on Mesoscale Analysis (MA) data provided by the Japan Meteorological Agency (2013; see below for details), which indicates that MA has the potential to resolve meso-β-scale PMCs (Fig. 3c).

In this study, we present a new algorithm for the detection and tracking of PMCs, including meso-β-scale
vortices, using MA. Using this algorithm, we also show some climatology of PMCs over the Sea of Japan. The remainder of this paper is organized as follows. Section 2 describes the datasets, the tracking algorithm, and the validation of the objective tracking. Section 3 shows the tracks of the PMCs and briefly discusses the climatology of the PMCs over the Sea of Japan. Section 4 compares the PMCs detected by the algorithm with those in previous studies and briefly considers the environment of the PMCs. Finally, section 5 provides a summary and conclusions.

2. Data and methodology

a. Data

We used MA data in the tracking analysis of the PMCs. The MA is a product of objective analysis using the Japan Meteorological Agency’s (JMA) mesoscale model, which is based on the JMA nonhydrostatic model (Saito et al. 2006), as a forecasting model. For the data assimilation, MA uses the four-dimensional variational scheme, the JMA-Nonhydrostatic-model-based Variational Analysis Data Assimilation (JNoVA; Honda et al. 2005). The domain of MA is a rectangular area of 3600 km × 2880 km in Lambert conformal conic map projection covering Japan and its surroundings. The original MA dataset has a horizontal resolution of 5 km with 50 vertical levels, and a temporal resolution of 3 h. In the present analysis, we used a dataset prepared by converting the original MA data into geographic coordinates with a horizontal grid spacing of 0.1° in latitude, 0.125° in longitude, and 16 pressure levels by a linear interpolation. This resolution is sufficient to examine the characteristics of meso-β-scale PMCs. As most PMCs occur during the cold season, we analyzed six cold seasons from November 2009 to March 2015. (Note that JNoVA was introduced in April 2009.) Hourly infrared (IR) and visible satellite images from MTSAT-2 were used to validate the detected PMCs. The NOAA 0.25° daily optimum interpolation sea surface temperature (OISST; Reynolds et al. 2007) data were used to examine the environment of the PMCs.

b. Algorithm for tracking PMCs

Relative vorticity at the 950-hPa level is used to track the PMCs. The vorticity field is smoothed using a
running mean over 0.4° in latitude and 0.5° in longitude to focus on PMCs with horizontal scales larger than, or equal to, meso-β scale. The algorithm for the tracking of PMCs consists of three parts: the identification of vortices at each time step, the connection of vortices in consecutive time steps, and the exclusion of synoptic-scale disturbances.

1) IDENTIFICATION OF VORTICES AT EACH TIME STEP

The algorithm used to detect vortices is similar to that developed by Shimizu and Uyeda (2012) to detect convective cells in radar reflectivity scans. Their algorithm is based on an adaptive threshold scheme that is able to identify a convective cell that includes a single local maximum of reflectivity from the cell groups and is suitable for identifying PMCs embedded in a larger system such as the JPCZ.

Figure 4 shows a schematic diagram of the algorithm used to identify vortices. (right) The horizontal distribution of the vorticity field and (left) the vorticity along line A–B in the right panels. (a) The original vortex areas, which are defined as the green and red areas. (b) An example of a peak (peak 1) identified as a vortex. The gray area in (b) is where vorticity is lower than the temporary threshold $\zeta_{\text{min}}$, and will be distributed to either the yellow or red vortex area in the last step. (c) An example of a peak (peak 2) identified as a part of the neighboring vortex. (d) The final result of the identification process. The isolated vortex areas are defined as the green, red, and yellow areas in (d). The center of each vortex is shown by cross marks in (d). See text for details.
continued until all peaks having vorticity $\approx \zeta_{\text{max}}$ in multiple vortex areas are identified. There are two kinds of areas in a multiple vortex area: the first belongs to a vortex area defined by the threshold $\zeta_{\text{min}}$ that separates two peaks (e.g., red and yellow areas in Fig. 4b), and the other is the rest of the multiple vortex area (gray area in Fig. 4b). For a grid point within the latter area, the distances between the grid point and the edge of the vortex areas are calculated. The grid point is assigned to the vortex area whose edge is closest to it. In this way, each vortex and its vortex area are determined as in Fig. 4d. The center and intensity of each vortex are defined by the location and magnitude of the vorticity peak. The size of each vortex is defined by the area of the isolated vortex area. Note that Wernli and Schwierz (2006) applied similar method to sea level pressure (SLP) field to identify extratropical cyclones. Our method using the vorticity field is more suitable to identify PMCs because they are smaller than extratropical cyclones and sometimes are not accompanied by SLP minimum with closed SLP contours.

2) CONNECTION OF VORTICES AT CONSECUTIVE TIME STEPS

To connect vortices at consecutive time steps, a steering wind for each vortex is calculated to estimate the movement of the vortex. This steering wind is defined as a wind averaged over a box that encloses an area of 4° in latitude by 5° in longitude between 1000 and 700 hPa, where the center of the box is chosen to coincide with the vortex center. In some tracking schemes for synoptic-scale systems, the steering wind is taken to be some fraction of average wind partly due to the beta effect (e.g., Simmonds et al. 1999).

However, since the sizes of vortices considered here are small, the beta effect might be negligible. Therefore, the averaged wind is directly assumed to be a steering wind.

The position of a vortex at the next time step is estimated by assuming that the vortex is advected by the steering wind. For this estimated position, two requirements are imposed. First, the vortex at the next time step must be located within 1° in longitude and 0.8° in latitude of the estimated position (i.e., the estimated area; Fig. 5a). If there are more than two vortices in the estimated area, the vortex closest to the estimated position is linked to the previous vortex. If there is no vortex that satisfies the first requirement, the second requirement is considered, which is that a part of an isolated vortex area at the next time step overlaps with the estimated area (Fig. 5b). If there are more than two isolated vortex areas for which part of the area overlaps with the estimated area, the vortex at the previous time step is linked to the vortex with an isolated vortex area having the largest amount of overlap with the estimated area.

If a vortex does not have a corresponding vortex at the previous (next) time step, that time step is defined as the genesis (dissipation) time. If more than two previous vortices are connected to a single vortex at the next time step, they are recognized as being merged. The split of vortices is not explicitly considered in this scheme. When a vortex splits into two vortices, one of them is linked to the vortices at the previous time step and the other is regarded as a vortex that is generated at the time step. In this study, PMCs are defined as vortices with a lifetime exceeding 6 h (three time steps).
3) EXCLUSION OF SYNOPTIC-SCALE DISTURBANCES

As we do not use a spatial high-pass filter, the present tracking method also picks up disturbances such as synoptic-scale lows and cold fronts. Therefore, we introduce schemes that discriminate synoptic-scale disturbances from PMCs based on their size and shape.

The size of the vortex area and SLP are used to identify synoptic-scale lows (Fig. 6). First, the sizes of the original vortex areas are examined and SLP minima that are at least 0.5 hPa less than the surroundings are detected. Then, a vortex that is located in an original vortex area larger than 40,000 km² and that is within 300 km of an SLP minimum is considered a synoptic-scale low (black cross in Fig. 6). Although some large PMCs can be erroneously classified as synoptic-scale lows using these thresholds, almost all synoptic-scale lows are properly classified here. If a vortex is in an original vortex area larger than 40,000 km² but is located farther than 300 km from an SLP minimum, the vortex is not considered a synoptic-scale low (white cross in Fig. 6). The present scheme is able to distinguish between a synoptic-scale low and a vortex embedded within it. Such multiscale structures are sometimes observed over the Sea of Japan (e.g., Ninomiya et al. 1990; Ninomiya and Hoshino 1990; Ninomiya 1994; Tsuboki and Asai 2004).

Next, the shape of the original vortex area is used to identify cold fronts (Fig. 7). First, the southern and northern edges of each original vortex area are detected. The distance between the two edges (L in Fig. 7) and the clockwise angle between the line connecting the two edges and north (θ in Fig. 7) are calculated. If the distance is greater than 400 km and the angle is between −20° and +60°, the original vortex area is further examined. First, the ridge of the vorticity field in the original vortex area is detected in the following way. A grid point on the ridge is determined by choosing the point where the vorticity is one of the three largest of the nine neighboring grid points. Then, the grid points chosen in this way are fitted by a smooth quadratic curve. If the average curvature of the quadratic curve is less than 0.1 (the curvature is positive when the quadratic curve is convex westward) and the coefficient of determination ($R^2$) is greater than 0.8, the vortices in the original vortex area are considered part of a cold front.

Finally, all time steps from the lifetime of the PMC are examined according to the two schemes. If the number of time steps when the vortex is considered a synoptic-scale low or a cold front is more than one-seventh of the whole lifetime of the PMC, then the PMC is excluded as a synoptic-scale disturbance.

c. VALIDATION OF THE TRACKING ALGORITHM

When the present tracking method was applied to the MA data, 642 PMCs were detected over the six cold seasons. Merged PMCs were counted as one PMC within this number and 120 mergers were found. However, most of the mergers occurred at the early stages of a vortex and 23 mergers among them were merger of vortices having lifetime longer than 3 time steps (9 h).

To evaluate the validity of the tracking algorithm, we subjectively examined all of the detected PMCs by using the vorticity and the SLP field from MA and satellite IR images. We first checked whether a detected PMC was subjectively judged to be a PMC using the MA data, and then checked whether the PMC was evident in the IR images. PMCs were then classified into one of three groups: those that were judged to be PMCs using the MA data and were also found in the satellite images at least once during their life time (class A), those that were not judged to be PMCs from the MA data but were not found in the satellite images (class B), and those that were not judged to be PMCs (class C). Figure 8a shows the total monthly number of PMCs in each class: 381 PMCs (59%) in class A and 81 PMCs (13%) in class B, with 72% of the PMCs at least judged to be a PMC by subjective detection using the vorticity and SLP field. Some of the class-B PMCs were covered by upper-level
cloud in the satellite image, but others were so weak that they were not accompanied by obvious cloud features. Class C contained 180 PMCs (28%) that were either part of a cold front or a weak peak in a synoptic-scale low. The proportion of class-C PMCs was large in November and March (Fig. 8a) when synoptic-scale lows are common over the Sea of Japan. Vorticity peaks associated with these synoptic-scale lows were sometimes erroneously classified to PMCs. To reduce false detections, we introduced criteria for the intensity and lifetime of the PMCs. To reduce false detections, we introduced criteria for the intensity and lifetime of the PMCs. We selected PMCs that satisfied either of the following criteria (hereafter referred to as strong criteria): 1) the lifetime exceeded 9 h and the vorticity exceeded $3.0 \times 10^{-4}$ s$^{-1}$ for at least two time steps, or 2) the lifetime exceeded 6 h and the vorticity exceeded $4.5 \times 10^{-4}$ s$^{-1}$ once during the lifetime. A total of 290 PMCs satisfied the strong criteria (Fig. 8b). The numbers of PMCs classified into classes A, B, and C were 226 (78%), 25 (8.6%), and 39 (13%), respectively, and 87% of the PMCs agreed with the subjective detection using the vorticity and SLP field. Thus, the strong criteria reduce the number of false detections, especially in November and March. In the following section we focus on those PMCs that satisfied these criteria to obtain more robust results.

We also subjectively checked the vortices identified as synoptic-scale disturbances by our algorithm using MA and satellite images. A total of 212 of such vortices were found over the six cold seasons. By the subjective analyses, 22 vortices among them were considered to be the vortices that our algorithm should have classified into PMCs.
There were some class-A PMCs that did not satisfy the strong criteria, implying that PMCs found in satellite images sometimes had only a weak surface vorticity signature or none. Thus, our method is likely to miss some PMCs. To evaluate the detection rate, we compared our results with PMCs detected in satellite images. First, we compiled a database of PMCs using MTsat-2 visible images during daytime (at 0000, 0600, and 0900 UTC) for a cold season from November 2011 to March 2012. When compiling this database, we also referred to a database of PMCs archived by Gurvich (2013) based on Moderate Resolution Imaging Spectroradiometer images. Since we did not track PMCs here, a persistent PMC may be counted several times in successive images. A total of 185 PMCs were detected in this period. Then the PMCs in the database were compared with those detected from the MA data using our detection methodology. If a vortex detected from the MA data was located within 150 km from a PMC in the database, the PMC was considered to be detected by our method. In this operation the persistency of the vortices in the MA data was not considered. Among 185 PMCs, 113 PMCs were detected by our method. Although the database contains some very weak PMCs, our method turns out to detect about 61% of PMCs observed in the visible satellite images.

In the present tracking algorithm, we use several thresholds, which are empirically determined based on subjective analyses of MA and satellite images. The results of the tracking depend on these thresholds. In general, more (less) PMCs are detected with moderate (strict) thresholds, while more (less) false detections are found. The threshold for the intensity of a vortex \( \zeta_{\text{max}} \), which is used for identifying vortices at each time step, has large influence on the result. We checked the sensitivity of the results to \( \zeta_{\text{max}} \) by changing \( \zeta_{\text{max}} \) from 3.0 \( \times 10^{-4}\text{s}^{-1} \) and 1.5 \( \times 10^{-4}\text{s}^{-1} \) from the original value of 2.0 \( \times 10^{-4}\text{s}^{-1} \). With \( \zeta_{\text{max}} \) of 3.0 \( \times 10^{-4}\text{s}^{-1} \), 171 PMCs that satisfy the strong criteria were detected. The numbers of class-A, -B, and -C PMCs became 141 (82%), 13 (7.6%), and 17 (10%), respectively. Although the larger \( \zeta_{\text{max}} \) reduces the proportion of false detection, it also reduces the number of class-A PMCs. With \( \zeta_{\text{max}} \) of 1.5 \( \times 10^{-4}\text{s}^{-1} \), more PMCs were detected. However, most of them are class-C PMCs. The number of PMCs that satisfy the strong criteria increased to 326 and the numbers of class-A, -B, and -C PMCs became 241 (74%), 35 (9.2%), and 55 (17%), respectively. The number of class-A PMCs was slightly larger than that for \( \zeta_{\text{max}} \) of 2.0 \( \times 10^{-4}\text{s}^{-1} \), while the number of class-C PMCs was also increased. Since the thresholds depend on the characteristics of the dataset including horizontal resolutions and physical processes incorporated in the parent model, we need to set appropriate thresholds first for each dataset based on subjective analyses. Once appropriate thresholds are set, however, the present method is effective for obtaining the climatology of the PMCs.

3. Climatology of the PMCs

In this section we show the climatology of the PMCs identified using our new tracking method. The greatest numbers of PMCs form during December and January (Fig. 8b). However, as the interannual variation is very large (not shown), analysis is required over a longer time period to provide robust results.

The tracking analysis gives the geographical distribution of the PMCs. Figure 9 shows the tracks and locations at maximum intensity of the PMCs (Fig. 9a) and the average number found within a 1° \( \times 1° \) grid in the cold season (Fig. 9b). The tracks of the PMCs are concentrated mainly in two regions: the western part of the Sea of Japan from the base of the Korean Peninsula to the center of Honshu Island (the WJ region), and the western part of the northern Sea of Japan to the west of Hokkaido Island (the NJ region). Several PMCs were also found in the central part of the Sea of Japan around 40°N, 138°E (the CJ region). The PMCs were classified into one of these three regional groupings according to the location where they reached their maximum intensity (Fig. 9b). The numbers of PMCs in the WJ, NJ, and CJ regions were 146, 98, and 46, respectively. We examined the typical characteristics of the PMCs in each region, such as their direction of movement (Fig. 10), maximum intensity (Fig. 11), and size (Fig. 12).

In the WJ region, most of the PMCs form leeward of the mountains to the north of the Korean Peninsula (see also Fig. 1) and move southeastward (Fig. 10). There are also PMCs that move eastward or east-northeastward along the coast of Honshu Island (Fig. 10). Many PMCs attain their maximum intensity at the beginning of their lifespan, whereas other PMCs intensify during their lifetime and reach peak intensity near Honshu Island (Fig. 9). The maximum vorticity of PMCs in this region is small in comparison with other regions (Fig. 11), although a few intense PMCs (e.g., maximum vorticity \( >8.0 \times 10^{-4}\text{s}^{-1} \)) were also observed. The average size of PMCs in this region was intermediate among the three regions (Fig. 12), although occasional large PMCs (\( >30000\text{km}^2 \)) were also observed.

PMCs in the NJ region reached their maximum intensity near Hokkaido Island (Fig. 9) and followed two major directions of movement: southward and eastward (Fig. 10). Most PMCs in this group made landfall on Hokkaido Island, although some of the southward-moving
PMCs moved into the CJ region along the western coast of northern Honshu Island (Fig. 9a). The maximum vorticity of PMCs in this region was the largest and sometimes exceeded 8.0 × 10^{-4} \, \text{s}^{-1} (Fig. 11). The average size of PMCs was smaller than in the other regions, and most were smaller than 20000 \, \text{km}^2 (Fig. 12).

PMCs in the CJ region tended to move eastward or northeastward and reached their maximum intensity off the northwest coast of Honshu Island (Fig. 10). Their average maximum vorticity was intermediate among the three regions, and PMCs with maximum vorticity exceeding 8.0 × 10^{-4} \, \text{s}^{-1} were not observed in this region (Fig. 11). These PMCs were relatively large, with more than 25% being larger than 20000 \, \text{km}^2 (Fig. 12).

4. Discussion

a. Comparison with previous works

We now compare the results obtained using our tracking method with previous research into PMCs over the Sea of Japan, which was based mainly on the subjective analysis of satellite images. The geographical distribution of the detected PMCs (Fig. 9) agrees well with the results of A88 (Fig. 2). The two major directions of movement of PMCs around the center of Honshu Island, which are southeastward and east-northeastward (Fig. 10), also agree well with the results of Ookubo (1995). Thus, the tracking algorithm accurately reproduced the characteristics of the PMCs that were derived from the subjective analysis of satellite images.
Previous objective tracking methods for PLs used the difference between SST and temperature at 500 hPa (T500; hereafter SST $-$ T500 is referred to as $T_{\text{diff}}$) to discriminate between PLs and synoptic-scale disturbances (Zahn and von Storch 2008; Xia et al. 2012; Chen and von Storch 2013; Zappa et al. 2014; Y16). For example, Y16 uses $T_{\text{diff}} > 43$ K as a criterion for PLs. Figure 13 shows histograms of $T_{\text{diff}}$ averaged in a $1^\circ \times 1^\circ$ box around the center of a vortex at the time of its maximum intensity. In the plot, the PMCs and synoptic-scale disturbances were identified using our algorithm. The synoptic-scale disturbances occur even if $T_{\text{diff}}$ is small, whereas PMCs tend to develop for large $T_{\text{diff}}$. In total 80% of synoptic-scale disturbances developed with a $T_{\text{diff}}$ of less than 43 K, whereas more than half of the PMCs occurred when $T_{\text{diff}}$ was greater than 43 K. Although our algorithm for identifying PMCs is based solely on vorticity and SLP (and some of the large PMCs can be categorized as synoptic-scale lows), the result are consistent with those of previous studies that used the $T_{\text{diff}}$ as the discriminating criterion.

Although our algorithm identifies PMCs in an environment with small $T_{\text{diff}}$, such as those developing through barotropic instability. In the present study, a peak in the location of the maximum intensity is found near the base of the Korean Peninsula (Fig. 9b), which is indistinct in Y16 (see Fig. 7 in Y16). The PMCs that develop in this region are so weak that most do not pass the intensity threshold for PLs set in Y16. There is also a difference in the direction of movement of PMCs. In the present study, the proportion of eastward-moving PMCs in the present study (Fig. 10) is smaller than that in the generation of meso-$\beta$-scale PMCs. Our method is independent of thermal stratification and can deal with PMCs that develop mainly as a result of dynamic instability.

Y16 also analyzed PLs over the Sea of Japan. Since we analyzed PMCs including meso-$\beta$-scale PMCs and weaker PMCs, there are several differences between our results and those of Y16. The number of PMCs identified in this study is 7 times (twice) as large as those for strong (weak) threshold identified in Y16. This is because our result includes meso-$\beta$-scale PMCs. Moreover, our algorithm can identify and count individual PMCs appearing simultaneously in a larger system. Note also that our algorithm identifies PMCs in an environment with small $T_{\text{diff}}$, such as those developing through barotropic instability. In the present study, a peak in the location of the maximum intensity is found near the base of the Korean Peninsula (Fig. 9b), which is indistinct in Y16 (see Fig. 7 in Y16). The PMCs that develop in this region are so weak that most do not pass the intensity threshold for PLs set in Y16. There is also a difference in the direction of movement of PMCs. In the present study, the proportion of eastward-moving PMCs in the present study (Fig. 10) is smaller than that in the generation of meso-$\beta$-scale PMCs. Our method is independent of thermal stratification and can deal with PMCs that develop mainly as a result of dynamic instability.
As eastward-moving PMCs are relatively large, some are likely to be excluded as a synoptic-scale low by our algorithm.

**b. Environment of PMCs**

The characteristics of PMCs depend on environmental factors such as the baroclinicity and vertical stability of the atmosphere where the PMCs form and develop (Yanase and Niino 2007). Here, we examine the vertical stability of the atmosphere in which the PMCs developed. Figure 14 shows a scatterplot of the maximum intensity and $T_{\text{diff}}$ averaged in a $1^\circ \times 1^\circ$ box around the center of the PMC. Although weak PMCs are distributed across a wide range of $T_{\text{diff}}$ values, the more intense PMCs tend to occur in environments with a large $T_{\text{diff}}$. PMCs in the WJ region sometimes occur under less unstable conditions ($T_{\text{diff}} < 35$ K), but most are weak. Although these PMCs are likely to be formed by the dynamic instability such as barotropic instability associated with horizontal shear in the JPCZ, they do not intensify further when the stratification is not favorable to their development. In the NJ region, intense PMCs (i.e., maximum vorticity $>8.0 \times 10^{-4} \text{s}^{-1}$) tend to occur under highly unstable conditions ($T_{\text{diff}} > 45$ K). Very cold air ($T_{500} < -40^\circ\text{C}$) frequently intrudes into this region, and this is favorable for the development of PMCs. In the CJ region, there is no obvious relationship between PMC intensity and the vertical stability of the atmosphere, which indicates that the diabatic contribution is likely to be less important for the development of the PMCs in this region and other factors such as baroclinicity might be important.

**5. Summary and conclusions**

To improve our understanding of the climatology of PMCs over the Sea of Japan, we developed a new algorithm for the objective tracking of PMCs. The algorithm is based primarily on the vorticity field and consists of three parts: the identification of vortices, the connection of vortices in consecutive time steps, and the exclusion of synoptic-scale disturbances. First, we identify the location, intensity, and area of a vortex from a vorticity field at each time step, in which isolated vortex areas that include a single local maximum of vorticity are identified from a multiple vortex area. This method is suitable for identifying multiple PMCs embedded in a larger system such as the JPCZ. Second, the movement of a vortex is estimated by the steering wind. Two vortices in consecutive time steps are connected when they satisfy the criteria of the distance between the estimated position and the position of the vortex at the next time step. Finally, we distinguish PMCs from synoptic-scale disturbances using the size and shape of the PMCs.

We have successfully obtained reliable tracks of PMCs using this tracking algorithm. With additional criteria for the lifetime and intensity of PMCs, 86% of the detected PMCs agreed with the PMCs that were subjectively detected using the vorticity and SLP field, and 78% of the detected PMCs were identified using satellite images. The geographical distribution of the PMCs generated using the algorithm agrees well with previous studies based on satellite images. Our method for discriminating between PMCs and synoptic-scale disturbances does not depend on
the environmental stratification and have demonstrated that the PMCs tend to occur in less stable environments than extratropical cyclones, which has been assumed in the previous climatological studies. Moreover, our method can deal with PMCs that develop mainly through horizontal shear instability.

Using our new tracking method, we analyzed the climatology of PMCs over the Sea of Japan. PMCs were classified into three groups according to the region where they attained their maximum intensity. PMCs in each region have different characteristics with regard to their direction of movement, size, and intensity. These characteristics are likely to be related to either the environmental conditions at the time of formation or the developmental mechanism. To consider this point in more detail, we are currently performing a composite simulation or regional reanalysis data to examine a long-term climatology of PMCs. We may also apply this method to other regions where PMCs frequently form, in order to study similarity and differences of their characteristics among different regions around the world.

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