Structure and Environment of Polar Mesocyclones over the Northeastern Part of the Sea of Japan

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ABSTRACT

Polar mesocyclones (PMCs) are mesoscale cyclonic vortices that develop poleward of the main polar front. The Sea of Japan is one region where PMCs frequently occur during winter. In this paper, the general characteristics of the structure and environment of PMCs that form over the northeastern part of the Sea of Japan and move southward are examined using composite analysis and numerical simulation. The composite analyses show that the synoptic-scale environment of the PMCs is characterized by a zonal temperature gradient at lower levels and a trough accompanied by cold air at upper levels. These elements of the environmental field form a reverse shear. The mesoscale structure of the PMCs exhibits characteristics of baroclinic development, while it is also accompanied by condensational heating. The numerical simulation in which the composite fields are used for the initial and boundary conditions successfully reproduces a realistic PMC. In this numerical simulation, the mesoscale structures are almost smoothed out in the initial and boundary fields, indicating that the PMCs spontaneously form and develop when the large-scale environment becomes favorable. Sensitivity experiments in which moisture is removed demonstrate that condensational heating is crucial for the genesis and development of the PMC. The sensitivity experiments also show that the warm sea surface temperature in the Strait of Tartary and the Sea of Japan to the west of Hokkaido Island, and the topography of the Sikhote-Alin mountain region provide favorable conditions for the development of the PMCs.

1. Introduction

Polar mesocyclones (PMCs) and polar lows are often observed over high-latitude oceans in winter. The term “polar mesocyclone” is the generic term for all meso-\(\alpha\)-scale (200–2000 km) and meso-\(\beta\)-scale (20–200 km) cyclonic vortices that develop poleward of the main polar front (Rasmussen and Turner 2003). The term “polar low” is used for intense PMCs with horizontal scales between 200 and 1000 km and with surface wind near or above gale force (Rasmussen and Turner 2003). They are observed over high-latitude oceans in both hemispheres, including the North Atlantic Ocean (e.g., Harold et al. 1999), North Pacific Ocean (e.g., Yarnal and Henderson 1989), and the Southern Ocean (e.g., Carleton and Carpenter 1990). All these regions are characterized by cold air outbreaks from land or sea ice over relatively warm open oceans.

A number of case studies and numerical experiments have demonstrated that various mechanisms affect the development of PMCs, including baroclinic instability (e.g., Reed and Duncan 1987), thermal instabilities such as conditional instability of the second kind (CISK) (e.g., Rasmussen 1979), or wind-induced surface heat exchange (WISHE) (e.g., Emanuel and Rotunno 1989). These mechanisms can operate at the same time (e.g., Yanase and Niino 2007). In addition, many studies indicate that upper-level troughs are important for triggering PMCs (e.g., Montgomery and Farrell 1992). Heat and moisture fluxes from the sea surface also contribute to the development of PMCs by forming a less stable atmosphere (e.g., Bresch et al. 1997).

The Sea of Japan (Fig. 1) is one region where PMCs frequently occur (Asai 1988; Ninomiya 1989). It is unique in that it is located at relatively low latitude (around 40°N) compared with other regions where PMCs frequently occur. In winter, cold air accumulates over the Eurasian continent and breaks out over the Sea of Japan, where the sea surface temperature (SST) is relatively high due to the Tsushima Current, which is a branch of the Kuroshio. This results in an unstable convective layer near the sea surface that is favorable for the genesis and development of PMCs.

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Several statistical analyses have shown that PMCs are mainly concentrated in two regions of the Sea of Japan: the western part and the northeastern part (Asai 1988; Yanase et al. 2016, hereafter Y16; Watanabe et al. 2016, hereafter WNY). Kolstad (2011) demonstrates that a favorable condition for PMCs associated with a cold air outbreak and upper-level trough frequently appears over the northeastern part of the Sea of Japan. There are two dominant directions of travel of PMCs over this part of the Sea of Japan: southward and eastward (Y15; WNY). In this study, we focus on the southward-moving PMCs over the northeastern part of the Sea of Japan. The structure and development mechanisms of such PMCs have been examined in a number of case studies using observational data (Tsuboki and Wakahama 1992; Ninomiya 1994; Fu et al. 2004), objective analysis data (Shimada et al. 2014), and numerical simulations (Yanase et al. 2004; Wu and Petty 2010; Wu et al. 2011).

These PMCs often develop in a baroclinic environment. Ninomiya (1994) reported a southward-moving PMC that formed in association with local frontogenesis within a polar airstream caused by a synoptic-scale low over the Pacific Ocean. Using the quasigeostrophic potential vorticity equation, Tsuboki and Wakahama (1992) examined the linear stability of radiosonde-observed meridional and zonal winds with vertical shear that changes direction with height, and found two unstable modes. They suggested that these unstable modes might correspond to the observed PMCs.

Diabatic processes also play an important role in the development of the PMCs. In their numerical study of a southward-moving PMC, Yanase et al. (2004) carried out several sensitivity experiments and showed that condensational heating was important for the short-term development of the PMC and that latent and sensible heat fluxes from the sea surface indirectly contributed to the development of the PMC by maintaining unstable stratification. Wu et al. (2011) applied a piecewise potential vorticity (PV) inversion method to a southward-moving PMC and showed that condensational heating produced a positive PV anomaly and intensified the PMC. In addition, it increased the influence of the upper-level PV anomaly on the low-level PMC by reducing static stability.

Several case studies have highlighted the importance of an upper-level vortex or a trough accompanied by cold air (Fu et al. 2004; Wu et al. 2011; Shimada et al. 2014), which brings less stable stratification that favors convection and a dynamic forcing that spins up a low-level vortex. Shimada et al. (2014) found that a meso-α-scale PV anomaly within a synoptic-scale PV anomaly intruded down to around the 700–600-hPa level during the development stage of the PMCs.

The development mechanism of a PMC varies from case to case and several individual processes can operate at the same time in a complex manner. These different development mechanisms result in PMCs with different characteristics. Yanase and Niino (2007) performed an idealized numerical simulation of PMCs and demonstrated that the cloud patterns and development mechanisms of PMCs change significantly when environmental baroclinicity changes. Moreover, the cloud pattern and dominant process can sometimes change even during the lifetime of a PMC (Fu et al. 2004; Shimada et al. 2014).

Such diversity in PMCs makes it difficult to acquire a comprehensive understanding of the general characteristics of PMCs from case studies alone. One promising approach to establish the general characteristics of PMCs is a statistical analysis in which the average characteristics of a number of PMCs are examined (Bracegirdle and Gray 2008; Kolstad 2011; Mallet et al. 2013; Rojo et al. 2015; Y15; Terpstra et al. 2016). Y15 used an objective tracking method for polar lows and performed a composite analysis for the polar lows over the Sea of Japan. They showed typical environmental fields for the polar lows, including an upper-level trough and a synoptic-scale low to the east of the polar lows.

Southward-moving polar lows often appear in a reverse shear condition, in which the direction of the steering wind at the lower levels is opposite to that of the thermal wind (Y15; Terpstra et al. 2016). The reverse shear condition accounts for a significant portion of the environment of polar lows (Kolstad 2006). Terpstra et al. (2016) showed that polar lows in a reverse shear conditions are associated with stronger surface heat and moisture fluxes and low static stability compared with...
forward shear conditions, implying that polar lows in reverse shear conditions are more convective.

Since Y15 used a reanalysis dataset with a coarse horizontal resolution (about 60 km), they analyzed only meso-α-scale polar lows. However, meso-β-scale PMCs are often observed over the Sea of Japan (WNY) and the general characteristics of PMCs including meso-β-scale ones have not been well elucidated.

Although a cold air outbreak is a synoptic phenomenon and spreads over the whole of the Sea of Japan, PMCs tend to form over specific regions, suggesting that local geography may provide favorable conditions for the PMCs. For example, the high SST of the northeastern part of the Sea of Japan (Fig. 1) due to the Tsushima Current might affect the formation of the PMCs in this region. Topography can also trigger the genesis of the PMCs (e.g., Moore and Vachon 2002). The Sikhote-Alin mountain region is located along the eastern coast of the Eurasian continent (Fig. 1). It deflects cold air outbreaks from Siberia and often causes a cloud band accompanied by strong cumulus convection over the northeastern part of the Sea of Japan (Ohtake et al. 2009). The Sikhote-Alin mountain region is thus also likely to affect the formation of PMCs in this region. However, these effects have not been examined in detail.

The purposes of the present study are 1) to examine the general characteristics of the southward-moving PMCs over the northeastern part of the Sea of Japan and 2) to assess the effects of local topography and SST around the northeastern part of the Sea of Japan. To this end, we perform a composite analysis and numerical simulations for the PMCs that are detected by an objective tracking method. This paper is organized as follows: the data and the methodology of the composite analyses and numerical simulations are described in section 2; the results of the composite analyses and numerical simulations are presented in sections 3 and 4, respectively; and finally, a discussion and conclusions are given in section 5.

2. Data and methodology

a. Data

Operational objective analyses in the six cold seasons (November–March) from November 2009 to March 2015 produced by the Japan Meteorological Agency (JMA) are used for tracking the PMCs and for the composite analysis. The mesoscale analysis (Japan Meteorological Agency 2013) uses the JMA Mesoscale Model and four-dimensional variational data assimilation. It has a rectangular domain of 3600 km × 2880 km covering Japan and its surroundings. The original mesoscale analysis has a grid spacing of 5 km on a Lambert conformal conic map projection with 50 vertical levels, and a temporal resolution of 3 h. In the present analysis, we use a dataset prepared by linearly interpolating the original data onto geographic coordinates with a horizontal grid spacing of 0.1° in latitude, 0.125° in longitude, and 16 pressure levels.

Since mesoscale analysis does not have diabatic heating as a variable, the formulation of Emanuel et al. (1987) is used to calculate diabatic heating:

\[
\frac{d\theta}{dt} = \omega \left( \frac{\partial \theta}{\partial p} - c_p T - \Gamma_m \frac{\partial \theta}{\partial p} \right),
\]

where \(\theta\) is potential temperature, \(\Gamma_m\) is the moist adiabatic lapse rate, and \(\Gamma_d\) is the dry adiabatic lapse rate. The diabatic heating is calculated in the region of relative humidity > 90% and it is zero otherwise because this formulation is only valid for saturated air.

The global analysis (Japan Meteorological Agency 2013) uses the JMA Global Spectral Model and four-dimensional variational data assimilation. It has a TL959 spectral horizontal resolution (∼20 km), and 60 vertical levels up to 0.1 hPa. The temporal interval is 6 h. The global analysis is used as outer boundary conditions for the mesoscale analysis. In the present analysis, we use a dataset prepared by interpolating the original data into geographic coordinates with a horizontal grid spacing of 0.5° in both latitude and longitude.

b. Tracking and selection of the PMCs

The database of PMCs is compiled from mesoscale analysis in the six cold seasons (November–March) from November 2009 to March 2015 using a tracking algorithm. The tracking algorithm used in this study is almost the same as WNY apart from three minor modifications: 1) the vorticity field is smoothed using a running mean over a radius of 25 km, 2) the steering wind is defined as the average wind over a radius of 200 km between 1000 and 700 hPa, and 3) the estimated area used for the connection of vortices is defined as an area within 120 km from the estimated position based on the steering wind. The algorithm detects and tracks vorticity maxima in the relative vorticity field at 950 hPa and detects PMCs with horizontal scale between about 50 km and about 300 km.

In this study, we selected the southward-moving PMCs that reached to the south of 43°N (Fig. 2). This is because most of them attain their maximum intensity measured by vorticity at 950 hPa within 2° from 43°N. Hereafter such PMCs are referred to as NES-PMCs, where “NE”
denotes the northeastern part and “S” is the southward movement. Most of the PMCs and polar lows examined in the previous case studies correspond to the NES-PMC (Tsuboki and Wakahama 1992; Fu et al. 2004; Wu et al. 2011; Shimada et al. 2014). Note that southward-moving PMCs that made landfall at the north of 43°N were also found by the tracking algorithm and they have different characteristics (not shown). The analysis for such PMCs will be reported elsewhere in the future.

c. Composite analysis

The average characteristics of the NES-PMCs and the environmental fields are investigated by composite analysis using the mesoscale analysis and global analysis. A key time \( t = 0 \) h for each NES-PMC is defined as the time when it is closest to the latitude line of 43°N. Hereafter the time is measured relative to the key time. Lag composite fields in geographic coordinate are calculated using the global analysis to examine the synoptic-scale environmental field. Anomaly fields of this composite are defined by subtracting the 14-day running mean between \( t = -168 \) and \( t = +168 \) h from the total composite. In addition, composite fields in a vortex-centered coordinate at \( t = 0 \) h are calculated using the mesoscale analysis to examine the mesoscale environmental fields and the structure of NES-PMCs.

d. Numerical simulation

The JMA Nonhydrostatic Model (JMA-NHM; Saito et al. 2006) with one-way nesting is used for the present numerical simulations. The model domain is shown in Fig. 1. The parent domain has 350 × 250 horizontal grid points with grid spacing of 10 km and the nested domain has 401 × 401 horizontal grid points with grid spacing of 5 km. A total of 40 vertical grid points are distributed from the surface up to 15 540 m, with grid intervals that vary from 40 m at the surface to 802 m near the upper boundary. An explicit three-ice bulk scheme (Ikawa et al. 1991), which predicts mixing ratios of water vapor, cloud water, rain, cloud ice, snow, and graupel, and the number density of cloud ice, is used for microphysical modeling. The Kain–Fritsch convective parameterization scheme (Kain and Fritsch 1990; Kain 2004) and the Mellor–Yamada–Nakanishi–Niino level-3 boundary layer parameterization scheme (Nakanishi and Niino 2006) are used. The composite of the NOAA 0.25° daily Optimum Interpolation Sea Surface Temperature (OISST; Reynolds et al. 2007) data at \( t = 0 \) h is used for the SST and the distribution of sea ice (Fig. 1).

First, the simulation for the parent domain (10-km mesh), in which the total field of the composite of the global analysis is used for the initial and boundary conditions, is started at \( t = -48 \) h and is continued until \( t = +24 \) h. Then, the integration for the nested domain (5-km mesh), in which the results of the simulation for the parent domain are used for the initial and boundary conditions, is performed from \( t = -24 \) to \( t = +24 \) h.

A backward trajectory analysis is conducted to analyze the results of the numerical simulation. A fourth-order Runge–Kutta scheme with a time step of 30 s is adopted to calculate the movement of the parcel, in which the three-dimensional velocity is used to calculate the movement of the parcel. The three-dimensional velocity components at each point on the trajectory are calculated every 30 s by linearly interpolating spatially and temporally the model outputs stored every hour. The potential temperature, water vapor mixing ratio, and equivalent potential temperature of the parcels are also calculated using the same interpolation method.

3. Composite analysis

a. Overview of the NES-PMCs

Figure 2 shows the tracks of the NES-PMCs. A total of 23 NES-PMCs were found in the six cold seasons. The numbers of the NES-PMCs in November, December, January, February, and March are 2, 3, 9, 7, and 2, respectively. They were generated to the west and northwest of Hokkaido Island, moved southwestward at the beginning, and then changed direction to southeastward. Finally, they made landfall on Hokkaido Island or Honshu Island and dissipated. The horizontal scales of them are between about 150 and 300 km and about half
of them are meso-β scale (i.e., smaller than 200 km). Y15 also performed a composite analysis on the environment of polar lows in this area. A total of 19 out of the 23 NES-PMCs detected in the present study are not listed in Y15 because our tracking method is able to detect smaller or weaker PMCs. On the other hand, some large polar lows included in Y15 are excluded from this study because they are classified as synoptic-scale disturbances by our tracking method.

b. Synoptic-scale environment

We first show the low-level synoptic-scale environment of the NES-PMCs. In the total field of sea level pressure (SLP) (left column of Fig. 3), a high pressure system over Siberia (the Siberian high), and a low pressure system over the North Pacific Ocean (the Aleutian low) are visible between $t = -48$ and $t = 0$. This is a typical pressure pattern when the East Asian winter monsoon prevails over the Sea of Japan.

In the anomaly field, the synoptic-scale structure is more obvious. At $t = -48$ h (Fig. 3a), a negative SLP anomaly extends westward from the Aleutian low to the northeast of Hokkaido Island. The western part of this anomaly corresponds to the preceding extratropical cyclone. A positive SLP anomaly is seen to the north of the negative SLP anomaly. This pattern of negative and positive SLP anomalies produces an easterly component of wind between them, resulting in a northeasterly wind to the northwest of Hokkaido Island in the total field. This northeasterly wind advects warm air onto the Sea of Okhotsk and a warm anomaly forms there, while the northwesterly wind to the south advects cold air from the Eurasian continent onto the Sea of Japan giving a cold anomaly to the southwest of Hokkaido Island (Fig. 3b). This creates a zonal temperature gradient in the total field between the west of Hokkaido Island and Kuril Island, where the temperature increases eastward. This configuration is similar to an occluded front.

A new negative SLP anomaly appears over the Japanese islands at $t = -24$ h (Fig. 3c). The cold air intrudes farther to the east behind the negative SLP anomaly (Fig. 3d). In the total field, a trough extends from the Aleutian low to the Sea of Japan and the wind direction at the west of Hokkaido Island changes from northwesterly to northwesterly with decreasing latitude. NES-PMCs appear and develop in this trough where cyclonic flow is dominant (Fig. 3e).

At $t = 0$ h (Fig. 3e), the negative SLP anomaly intensifies to the east of Japan. This SLP anomaly corresponds to a synoptic-scale low and NES-PMCs are located in its northwest quadrant. Strong northwesterly wind behind the synoptic-scale low advects cold air over the Sea of Japan (Fig. 3f). The NES-PMCs develop at the northern boundary of the cold anomalies. Finally, NES-PMCs make landfall on Honshu Island and dissipate, while the synoptic-scale low continues to develop over the northwestern Pacific Ocean and the center of the cold anomaly moves over the Pacific Ocean (not shown).

The upper-level environment is characterized by a trough accompanied by cold air. At $t = -48$ h, a negative height anomaly and positive vorticity at 500 hPa exist above the northern part of the Japanese islands (Fig. 4a). They are related to the preceding extratropical cyclone over the same region. A new trough with cold air exists over the Eurasian continent (Figs. 4a,b). At $t = -24$ h, the new trough moves into the Sea of Japan (Figs. 4c,d). As the trough passes over the northeastern part of the Sea of Japan, the NES-PMCs form and develop beneath the trough, where the upper-level wind is weak (Figs. 4e,f). The NES-PMCs are located slightly north of the center of the upper-level negative height anomaly. The trough continues to progress eastward and finally moves over the northwestern Pacific Ocean (not shown).

c. Mesoscale structure of NES-PMCs

Next, we show the mesoscale structure of the NES-PMCs (Fig. 5). A zonal temperature gradient is evident around the NES-PMC (Fig. 5a). A thermal ridge is collocated with the surface trough extending from west, which is seen to the west of Hokkaido in the synoptic-scale field (Fig. 3e). Cold advection intensifies to the south of the warm area. Consequently, the temperature contours show marked westward protrusion. In this configuration, the westward warm advection intensifies the warm anomaly in the north of the NES-PMC, while the eastward cold advection intensifies the cold anomaly in the south of the NES-PMC, indicating baroclinic generation of available potential energy. A warm core is seen at the center of the NES-PMCs. The surface trough locally deepens in association with this warm core (Fig. 5a). Moreover, the wind direction changes significantly from northeasterly to northwesterly with decreasing latitude in association with the surface trough, indicating that the NES-PMCs develop in the region of large cyclonic horizontal shear.

At the upper levels, a meso-α-scale area of positive vorticity associated with the upper-level trough passes slightly south of the NES-PMCs (Fig. 5b). A northerly wind exists at the low-level, while the northerly wind decreases with height due to the thermal wind associated with zonal temperature gradient (Fig. 5a). This is a reverse shear condition and is often found as an environment of southward-moving polar lows (Y15; Terpstra et al. 2016). In the meridional–vertical cross section through the center of the NES-PMCs, a positive PV
FIG. 3. Composite fields of the global analysis. (left) The total and anomaly fields of SLP and total field of the horizontal wind vectors at 850 hPa (green arrows: m s$^{-1}$). The total and anomaly fields are shown by contours with an interval of 4 hPa and by color shading (hPa), respectively. (right) As in (left), but for temperature at 850 hPa. The total and anomaly fields are shown by contours with an interval of 5°C and by color shading (°C), respectively: (a),(b) $t = -48$ h; (c),(d) $t = -24$ h; and (e),(f) $t = 0$ h. Black dots indicate statistical significance at the 0.05 level for the anomaly. The red dots indicate the locations of PMCs.
Fig. 4. As in Fig. 3, but for (left) 500-hPa geopotential height and (right) temperature at 500 hPa. The total and anomaly fields of 500-hPa geopotential height are shown by black contours with an interval of 100 m and color shading (m), respectively. The green lines in the left column are the $0.5 \times 10^{-5}$ s$^{-1}$ contours of relative vorticity for the total field.
anomaly accompanied by dry air intrudes down to 600 hPa to the south of the low-level NES-PMCs, while the large vorticity area associated with the NES-PMC is vertically aligned up to 600 hPa (Fig. 5d). The configuration of the upper-level PV anomaly and lower-level PMC are favorable for the baroclinic development (Farrell 1984). As the NES-PMCs move southward, however, the upper-level positive vorticity moves eastward (not shown). Thus, the phase of the upper-level vorticity and low-level NES-PMC is not locked and the favorable configuration for baroclinic development is sustained only for a limited period of time.

Cold air at the upper levels is also a characteristic feature associated with the NES-PMCs’ development. Since the core of the cold air passes right above the developing NES-PMCs (Fig. 4f) and there is a warm region around the NES-PMCs at lower levels (Fig. 5a), the stability of the atmosphere decreases around the NES-PMCs (Fig. 5c). The less stable stratification strengthens the effectiveness of the upper-level forcing at lower levels. In this less stable atmosphere, updrafts exist in association with NES-PMCs. The updrafts are collocated with an area of large diabatic heating, indicating that these updrafts are associated with condensational heating.

4. Numerical simulation

a. Numerical simulation for an environment obtained from composite analysis

In this section we examine the results of numerical simulations in which the composite field is used for the initial and boundary conditions. Since we use the coarse
The composite of the global analysis, the mesoscale structures are almost smoothed out in the initial and boundary conditions (not shown). Nevertheless, the PMC is successfully reproduced in both 10-km mesh (parent) and 5-km mesh (nested) simulations. The tracks of the PMCs in the two simulations are almost the same and the nested simulation covers the whole lifetime of the PMC. Thus, only the results of the nested simulation are discussed below.

Figure 6 shows the time evolution of the simulated PMC. A weak synoptic-scale SLP trough embedded in the Aleutian low moves southward before $t = -24$ h (not...
shown). When the western end of the SLP trough reaches the Strait of Tartary (or Mamiya Strait; see Fig. 1), a shear zone between northeasterly and northwesterly wind at around 45.5°N appears in the trough (not shown). The PMC starts to develop at the western part of the shear zone (Figs. 6a,b). The high vorticity area is collocated with strong updraft (not shown), indicating that the PMC is generated through stretching of the surrounding vorticity associated with the shear zone in the SLP trough. The PMC intensifies rapidly between \( t = 0 \) and \( t = +6 \) h, while moving southwestward. The PMC at \( t = +6 \) h (Fig. 6c) has a 4-hPa pressure drop at its center and is accompanied by surface wind stronger than 17 m s\(^{-1}\). At this stage the PMC is surrounded by a comma-shaped cloud (Fig. 7a). Then it changes its direction of travel to southeastward (Figs. 6c,d) and the cloud structure changes into spiraliform with a cloud-free eye (Fig. 7b).

Overall, the numerical simulation successfully reproduces a PMC that meets the definition of NES-PMCs. This confirms that the environment obtained by the composite analysis contains the important ingredients for generating NES-PMCs. As the mesoscale disturbances do not exist in the initial field, this PMC spontaneously forms and develops in the large-scale environment. The PMC reproduced in this numerical simulation is considered to have representative characteristics of NES-PMCs. Therefore, the structure and development mechanisms of the NES-PMCs are examined using these results.

Figure 8 shows the temperature field at 850 hPa. At \( t = +6 \) h (Fig. 8a), a warm area is collocated with the SLP minimum, whereas cold air intrudes eastward to the south of the warm area, similar to the composite field (Fig. 5a). At this time a positive PV anomaly also intrudes down to 600 hPa to the south of the PMC (not shown). This temperature structure and the upper-level PV anomaly indicate a baroclinic development of the PMC. Note that condensation mainly occurs at the western part of the warm area before \( t = +6 \) h (Fig. 7a), indicating diabatic generation of available potential energy there. On the other hand, the intrusion of the cold air to the south of the PMC becomes indistinct and the baroclinicity around the PMC weakens at \( t = +18 \) h (Fig. 8b). At this time the center of the upper-level PV anomaly moves over the Pacific Ocean. In association with the change in environmental baroclinicity, the cloud structure changes from comma shaped to spiraliform (Fig. 7). This is consistent with a case study by Shimada et al. (2014) and an idealized experiment by Yanase and Niino (2007).

A notable feature of the PMC is the warm area around its center. To examine the formation processes of the warm area, we have conducted a backward trajectory analysis. A total of 427 parcels were distributed on the model grid point around the center of the warm area.
with temperature above \(-11.5^\circ\text{C}\) at 850 hPa at \(t = +6\) h (the area enclosed by the dotted line in Fig. 8a), and their backward trajectories are obtained for a period of 24 h.

Figure 9 shows the trajectories of the parcels. Most of the parcels are located in the northern part of the Strait of Tartary at \(t = -18\) h. The rest of the parcels are located above the Sikhote-Alin mountain region and in the southern part of Sakhalin. These 353 parcels travel at low levels over the Strait of Tartary and the Sea of Japan to the west of Hokkaido Island, where the SST is relatively high. The other 74 parcels are initially located to the west of Hokkaido Island and they stay almost above 1000 m. Note that no parcel comes from the lower levels over the inland of the Eurasian continent due to the blocking of cold air by the Sikhote-Alin mountain region, which is higher than 1000 m. We also calculated the trajectories started from lower levels in the PMC and obtained similar characteristics (not shown).

The trajectory of the parcel whose equivalent potential temperature increase is the largest is depicted by red dots in Fig. 9. It is located over the western coast of the Eurasian continent at \(t = -18\) h and moves over the sea ice until \(t = -8\) h. Then it travels over the open ocean that has high SST. The parcel remains below 600 m through this period except for a few hours when it is finally elevated by the updraft associated with condensational heating. The potential temperature and water vapor mixing ratio of the parcel hardly increase when it is over the sea ice (Fig. 10). Once it moves over the open ocean, however, they increase gradually due to the sensible and latent heat fluxes from the sea surface. The potential temperature and water vapor mixing ratio of the parcel rise by 11.6 K and 1.8 g kg\(^{-1}\), respectively, from \(t = -8\) to \(t = +3\) h. This corresponds to a 16.6-K increase of equivalent potential temperature. On average, the equivalent potential temperature of the 353 parcels that travel over the Strait of Tartary and the Sea of Japan to the west of the Hokkaido Island rises by 11.4 K between \(t = -18\) and \(t = +6\) h. Although parcels initially located to the west of Hokkaido Island remain above the mixing layer and they contribute to the formation of the warm area by adiabatic heating, their number is relatively small. Thus, unlike the ordinary extratropical cyclone that has a warm sector mainly caused by warm advection, the warm area of the PMC is caused mainly by the sensible and latent heat fluxes from the sea surface.

b. Sensitivity experiments

The results of the composite analysis and the numerical simulation indicate that the development of the PMC is related to condensational heating. The trajectory analysis demonstrates that the warm sea surface in the Strait of Tartary appears important for the formation of the warm area and development of the PMC. It also indicates that the blocking of cold air by the Sikhote-Alin mountain...
region contributes to the formation of the warm area. To examine the contribution of the condensational heating, the high SST, and the topography, we have performed a set of sensitivity experiments.

The settings of the sensitivity experiments are summarized in Table 1; hereafter the full-physics experiment described in section 4a is referred to as CNTL. We design two DRY experiments (DRY_T24 and DRY_T0) to examine the contribution of condensational heating at initial and development stages of the PMC. In these two experiments, calculations in the parent domain are the same as CNTL, but moisture is removed from the calculation in the nested domain after \( t = 24 \) h and \( t = 0 \) h in DRY_T24 and DRY_T0, respectively. To evaluate the sensitivity to the high SST in the Strait of Tartary, we run an experiment (CSST) in which the SST in the Sea of Japan north of 40°N is decreased to the zonal average between 145°E and 150°E and the Strait of Tartary north of 46°N is covered by sea ice (Fig. 11a). To evaluate the effect of the Sikhote-Alin mountain region, we perform an experiment (No_Mt) in which the elevation of mountains higher than 100 m is reduced to 100 m (Fig. 11b).

In the DRY_T24 experiment, although the SLP trough extends into the Strait of Tartary as in CNTL, the shear zone does not intensify within the SLP trough (not shown). Consequently, the PMC does not form in DRY_T24. In fact, although a weak SLP trough is found around 42°N and 139°E at \( t = +6 \) h, no PMC exists (Fig. 12a). This experiment demonstrates that, in the absence of condensational heating, the stretching of vorticity does not occur and the PMC therefore cannot form.

In the DRY_T0 experiment (Fig. 12b), the track of the PMC is similar to that in CNTL (cf. Fig. 6c). However, the average vorticity within 150 km of the center of the PMC between 950 and 850 hPa (Fig. 13) and surface winds (Fig. 12b) weaken within 6 h after condensational heating is switched off. This indicates that the condensational heating directly sustains the strong circulation of the PMC. These two DRY experiments demonstrate that the condensational heating is crucial for both the generation and development of the NES-PMC.

![Fig. 9. Backward trajectories over 24 h of the parcels placed at \( t = 6 \) h in the area shown in Fig. 8a. Colors on each trajectory indicate parcel height. The SST (black contours; interval 1°C) and topography (color shading) are also drawn. Sea ice is shown in gray. The red dots indicate 6-hourly locations of the parcel examined in Fig. 10.](image)

![Fig. 10. Time series of potential temperature, equivalent potential temperature (left axis), and mixing ratio (right axis) of the parcel shown by the red dots in Fig. 9.](image)

<table>
<thead>
<tr>
<th>Expt</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNTL</td>
<td>Control simulation including all the physical processes</td>
</tr>
<tr>
<td>DRY_T24</td>
<td>No moisture after ( t = -24 ) h</td>
</tr>
<tr>
<td>DRY_T0</td>
<td>No moisture after ( t = 0 ) h</td>
</tr>
<tr>
<td>CSST</td>
<td>The SST and distribution of sea ice over the Sea of Japan are changed</td>
</tr>
<tr>
<td>No_Mt</td>
<td>The Sikhote-Alin mountain region is removed</td>
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</tbody>
</table>
In the CSST experiment, although the movement of the SLP trough is similar to that in CNTL, the generation of the PMC is delayed and it is located farther southward (Fig. 12c). There is little development of the PMC (Fig. 13) and it is quite weak at $t = +6\,\text{h}$ (Fig. 12c). In this experiment, the Strait of Tartary, through which the parcels enter the PMC, is covered by ice and the SST to the west of Hokkaido Island is lower than in CNTL. These lower boundary conditions give weaker surface fluxes than in CNTL. The weaker surface fluxes result in a more stable atmosphere and less condensational heating. The stable atmosphere also reduces the effect of the upper-level PV anomaly. Therefore, there is little development of the PMC in the CSST experiment. In addition, we performed an experiment in which heat and moisture fluxes from sea surface are completely switched off over the Sea of Japan north of 40°N. The PMC does not form in this experiment (not shown). These findings suggest that the high SST of the Sea of Japan to the west of Hokkaido Island and the Strait of Tartary is crucial for the development of the NES-PMC to the west of Hokkaido Island.

In the No_Mt experiment, the PMC is generated at almost the same time as in CNTL. However, the development of the PMC is moderate compared with CNTL (Fig. 13) and it is weaker than CNTL at $t = +6\,\text{h}$ (Fig. 12d). In this experiment, cold air over the Eurasian continent passes over the lowered mountain region and breaks out over the Sea of Japan. Although the cold air from the Eurasian continent also receives fluxes from the sea surface, it is somewhat colder and less humid than the airflow passing over the Strait of Tartary. Therefore, the atmosphere in No_Mt is more stable than in CNTL and condensational heating is less active than in CNTL (not shown). The stronger cold air outbreak shifts the baroclinic zone to the east (not shown). As the low-level wind coming from the Eurasian continent has a westerly component and the baroclinic zone shifts to the east, the PMC in No_Mt takes an eastern path compared with CNTL. Consequently, it makes landfall earlier before it fully develops. Thus, the Sikhote-Alin mountain region provides favorable conditions for the development of the NES-PMC to the west of Hokkaido Island by blocking cold air from the Eurasian continent.

5. Discussion and conclusions

In this study, we have examined the general characteristics of the structure and environment of the PMCs that form over the northeastern part of the Sea of Japan and move southward to the south of 43°N (NES-PMCs) using composite analysis and numerical simulation. Our results agree with the findings of previous case studies, confirming that these characteristics are common to NES-PMCs.

The characteristics of the synoptic-scale environment obtained by the composite analyses are summarized as follows. Prior to the generation of the NES-PMCs, a zonal temperature gradient caused by a preceding synoptic-scale low already exists in the northeastern part of the Sea of Japan. Then, a new synoptic-scale low starts to develop over the northern part of the Japanese islands in association with the approach of an upper-level trough accompanied by cold air. The NES-PMCs...
form and develop in the northwest quadrant of this synoptic-scale low, where cyclonic flow associated with the surface trough is dominant. These characteristics are almost the same as the results of Y15. Our results confirm that this feature is unchanged even if meso-β-scale PMCs are included. Therefore, other processes might determine the horizontal scale of NES-PMCs and this should be examined in the future.

One of the characteristic features of the environment of the NES-PMCs is a reverse shear condition. The low-level zonal temperature gradient is an important factor in providing the reverse shear condition. The preceding
synoptic-scale low advects warm air to the north with a region of cold advection to the south. This rotates the temperature gradient anticlockwise and provides a zonal temperature gradient. A similar preceding cyclone was observed in many PMC cases with a reverse shear condition (e.g., Bond and Shapiro 1991; Ninomiya 1994).

Another important factor for the reverse shear condition is an upper-level trough just above the NES-PMCs. Since the wind is weak in the upper-level trough, the wind speed decreases with height and a reverse shear condition is provided around the NES-PMC. To satisfy these two factors, the upper-level trough must follow the preceding synoptic-scale low into the formation area of the NES-PMCs. This is often satisfied when shortwave troughs consecutively move within a synoptic-scale cold vortex, and a cold vortex is found in a number of NES-PMC cases (Fu et al. 2004; Wu et al. 2011; Shimada et al. 2014).

The synoptic-scale structures are also related to phenomena with larger spatial scale and low frequency; these phenomena are thus likely to affect the climatology of the PMCs. Indeed, several studies on polar lows over the North Atlantic suggest a relationship between polar lows and low-frequency atmospheric circulation features (e.g., Mallet et al. 2013; Rojo et al. 2015). Our composite analysis has shown that there are positive anomalies of SLP and 500-hPa geopotential height to the north and negative anomalies to the south of the NES-PMC formation area (Figs. 3 and 4). This configuration is similar to the negative phase of the Arctic Oscillation (Thompson and Wallace 1998). Therefore, NES-PMCs seem to occur more frequently during the negative phase of the Arctic Oscillation. As our analysis is restricted to six winters for which the quality of the dataset is homogeneous, it is difficult to discuss a long-term variation. It would be desirable to analyze the long-term climatology of the PMCs when high-resolution reanalysis data or dynamic downscaling data become available.

The mesoscale structure of the NES-PMCs shows characteristics of baroclinic development, including warm and cold areas around the NES-PMC and the upper-level vorticity that is located to the upshear side of the surface NES-PMC. However, they move independently and this favorable configuration for the baroclinic development is short lived. The relationship between the upper-level positive vorticity and the low-level NES-PMC indicates that the development of the NES-PMC is similar to a finite-amplitude growth in Montgomery and Farrell (1992), in which a polar low develops due to the interaction between finite-amplitude upper-level and low-level disturbances. Since the NES-PMCs develop in the region of large cyclonic horizontal shear, the horizontal shear provides a possible mechanism for the initiation of the low-level disturbances.

In the numerical simulation, when the environmental baroclinicity is large, the NES-PMC has a comma-shaped cloud. On the other hand, as the environmental baroclinicity decreases, the cloud structure of the NES-PMC changes into a spiraliform with a cloud-free eye. This change often occurs during the lifetime of an observed NES-PMC (Fu et al. 2004; Shimada et al. 2014). Since the environment used in the numerical simulation is the composite field, this is likely to be a general feature of the NES-PMCs.

The condensational heating is shown to be crucial for the generation and development of the NES-PMC. During the initial stage of the NES-PMC, the updraft due to condensational heating generates an initial disturbance by stretching the surrounding vorticity associated with the shear zone. During the development stage, condensational heating directly sustains the strong circulation of the NES-PMC. In terms of the energy conversion, these processes correspond to the diabatic generation of available potential energy and its conversion to kinetic energy. The diabatic intensification in the baroclinic environment is similar to the idealized numerical experiment by Terpstra et al. (2015). They showed that less stable atmosphere is favorable for the intensification. Thus, the critical importance of condensational heating for the development of the NES-PMC seems to be related to the fact that the NES-PMCs develop directly below the upper-level cold trough, where the stratification is least stable. On the other hand, the finite-amplitude growth due to the interaction
between the diabatically generated low-level vortex and the upper-level vortex, which is not included in Terpstra et al. (2015) also contribute to the development of the NES-PMCs.

The sensitivity experiments demonstrate that the high SST in the Strait of Tartary and the Sea of Japan to the west of Hokkaido Island favor the development of the NES-PMC. The warm area collocated with the NES-PMC is caused by the large fluxes from the warm sea surface in this region. The less stable environment that favors condensational heating is also maintained by the surface fluxes. The Sikhote-Alin mountain region blocks the cold air over the Eurasian continent so that the parcels entering into the NES-PMC can travel a longer distance over the warm sea and are supplied with more heat and moisture through surface fluxes. Thus, in addition to synoptic-scale environments, these features of the local geography contribute to the frequent occurrence of the PMCs to the west of Hokkaido Island.

In this study, we have identified favorable environments for PMCs. Moreover, we have succeeded in reproducing a realistic PMC in a numerical simulation using the composite fields for the initial and boundary conditions, indicating that the potential for the occurrence of PMCs can be estimated from the large-scale environment. It would be worthwhile to examine the accuracy of the estimation of PMC genesis from the large-scale environment by comparing coarse reanalysis datasets and high-resolution datasets such as downscaling simulations or regional reanalysis data. In addition, we may be able to estimate the future change in PMCs using climate prediction datasets, which do not explicitly resolve PMCs.

The approach adopted in this study using composite analysis and numerical simulations is found to be effective for revealing the general characteristics of PMCs. We are currently applying a similar approach to other PMCs over the Sea of Japan. The results will be reported elsewhere in the near future.

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The OISST dataset was provided by NOAA (https://www.ncdc.noaa.gov/oisst/).

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