A Polar Mesoscale Cyclone Formed over the East China Sea and Developed into a Secondary Cyclone over the Northwestern Pacific

— An Observational Case Study on 19–22 February 1975 —

Kozo NINOMIYA

Nonaffiliated, Tokyo, Japan

(Manuscript received 28 June 2016, in final form 5 January 2017)

Abstract

Polar mesoscale cyclones (PMCs) frequently develop over the Japan Sea. Genesis of PMCs over the East China Sea is rare, but can occur under certain synoptic-scale conditions. In this observational case study, the feature of a PMC generated over the eastern East China Sea on 20 February 1975 is studied using observation data including those obtained during Air-mass Transformation Experiment, satellite cloud images, and objective-reanalysis data.

The PMC with a comma-cloud formed within cyclonic polar-air streams induced by an upper cold trough and a synoptic-scale parent cyclone that developed near Japan. Within 3-hour period after the generation of the PMC, its central pressure deepened from 1016 to 1012 hPa. Strong surface winds occurred in the trailing portion of the comma-cloud. The large-scale conditions for the PMC's genesis were characterized by the southward intruding of the cold core in the upper cold trough beyond 34°N to the East China Sea, positive vorticity advection at 500 hPa, and the moist-neutral layer formed over the warm Tsushima Current in the eastern East China Sea.

The PMC, after passing over Kyushu, developed as it moved eastward along the Pacific coast of Japan. The PMC developed further into the secondary cyclone comparable to the parent cyclone, as it moved in the low-level baroclinic zone over the northwestern Pacific. The large-scale conditions for the development were characterized by the upper cold trough and the low-level baroclinic zone formed over the zone of maximum sea-surface temperature gradient along north of the Kuroshio extension.

Keywords  polar mesoscale cyclone; cyclogenesis; East China Sea

1. Introduction

Polar mesoscale cyclones (PMCs) and polar lows (PLs) develop frequently over the seas in higher latitudes, such as the Norwegian Sea, Barents Sea, northeastern Atlantic, and northeastern Pacific. Climatological features of PMCs / PLs over these areas have been studied extensively in many articles (e.g., Rasmussen et al. 2003a).

Meanwhile, climatology of PMCs over seas in northeast Asia and the northwestern Pacific have been discussed only in a few articles. Yamal and Henderson (1989a, b) documented the distribution of PLs in the cyclogenesis stage over these areas based on the satellite images for seven 5-month winter seasons (November to March), 1976–1977 to 1982–1983. During this period, ~1500 PLs were identified in total. Among them, ~90% were associated with a “comma-cloud” and ~10% were associated with a relatively smaller “spiraliform-cloud”. There were two maximum zones of comma-cloud generation; the primal zone stretching from northern Japan (43°N/150°E) to the Bering Sea (50°N/165°E) and
the secondary zone stretching eastward from northern Japan to the Pacific (40°N/170°W). Meanwhile the spiraliform-cloud’s generation was localized in the Japan Sea and the North Pacific nearby the Aleutians and Alaska. Genesis of PLs was rare over the Yellow Sea and the East China Sea. The comma-clouds were usually associated with deep baroclinicity close to the polar front, whereas the spiraliform-clouds developed within the cold air-mass over the zone of the large sea-surface temperature (SST) gradient.

Ninomiya (1989) documented the distribution of PMCs over seas in northeast Asia and the northwestern Pacific based on the satellite images for a 3-month period, from December 1986 to February 1987. In this period, PMCs were most frequently observed over the Japan Sea and the northwestern Pacific in 40–50°N/140–180°E, whereas any PMC was not found over the East China Sea. The large-scale cyclones traveling northeastward over the North Pacific usually reached their maximum intensity around the Aleutians to form the deep “Aleutian low”. Meanwhile, Siberian anticyclone predominated over the northeastern part of Asia Continent. The very strong pressure gradient between Aleutian low and Siberian anticyclone caused strong polar-air outbreak over East Asia. This is the major reason why PMCs over the Japan Sea and the northwestern Pacific develop at the relatively lower latitude (35–45°N).

These PMCs formed and developed in the vicinity of the cold core in the upper cold vortex or deep westerly trough. In many cases, PMCs over the Japan Sea formed and developed 500–1000 km to the northwest of the large-scale parent cyclones that developed in the vicinity of Japan. PMCs over the northwestern Pacific tended to develop 1000–2000 km to the west of the large-scale parent cyclones. PMCs developed usually over areas of large air–sea temperature difference, which caused large heat energy supply from the sea to the atmosphere. These climatological features of PMCs over the Japan Sea are consistent with results of many observational studies (e.g., Ninomiya 1991; Ninomiya et al. 1993; Tsuboki and Wakahama 1992; Fu et al. 2004), a climatological study (Yanase et al. 2016), and numerical simulation studies (e.g., Yanase et al. 2004; Yanase and Niino 2007).

Many PMCs/PLs in the polar region are associated with convection promoted by the relatively warm sea surface. After making landfall, PMCs/PLs were situated over a cold land surface, which cause the convection to weaken, with a resulting rapid decay of PMCs/PLs within a short period of time (Rasmussen et al. 2003b). Similarly, Japan Sea PMCs weakened rapidly during their passage over Japan. To date, little attention has been given to PMC’s redevelopment over the northwestern Pacific after the passage over Japan.

It was already mentioned that PMCs tend to develop over seas where large heat energy is supplied from the sea to the atmosphere. Hirose et al. (1996) evaluated the sensible (SH) and latent heat fluxes (LH) of ~140 W m⁻² and ~200 W m⁻² over the Japan Sea. Kondo (1976) evaluated SH and LH of ~80 W m⁻² and ~120 W m⁻² over the northwestern East China Sea (34°N/124°E), and evaluated SH and LH of ~140 W m⁻² and ~220 W m⁻² over the eastern East China Sea (33°N/128°E). Meanwhile, SH and LH of ~100 W m⁻² and ~300 W m⁻² were evaluated over the southern East China Sea (25°N/123°E). Kondo (1976) stated that the “effective bulk coefficient $C_H$ and $C_L$”, which are applicable for the climatological estimation over the East China Sea in winter, are $1.9 \times 10^{-3}$.

PMCs seldom generated over the East China Sea, while PMCs frequently developed over the Japan Sea. The lower tropospheric wind field over the Japan Sea during polar-air outbreak is characterized by the cyclonic circulation, whereas that over the East China Sea is usually characterized by the anticyclonic circulation (Ninomiya 1972). On the monthly mean 500 hPa map in winter, a deep trough predominated in 140–160°E and extended southward to Japan (Ninomiya 1989), which means frequent approach of the cold trough or cold vortex to the Japan Sea. Meanwhile, in 120–130°E, the cold core in the upper cold vortex or westerly trough seldom extended southward beyond 34°N to the East China Sea. These are inferred to be the major reasons why PMCs seldom developed over the East China Sea.

The main purpose of this observational case study is to depict PMC genesis over the East China Sea, which has not been reported to date. The PMC over the East China Sea on 20 February 1975 was found from available data sets for the present study. This case presented a unique opportunity to study the genesis of a PMC over the East China Sea, because dense observation data of “Air-Mass Transformation Experiment’ 75” (AMTEX’75) can be utilized for the analysis. AMTEX’75, a sub-program of Global Atmospheric Research Program, was carried out in February 1975 over the East China Sea around the Southwest Islands of Japan that extends southwestern from 29°N/130°E to 24N°/123°E (Fig. 8), to study processes of air-mass transformation and related cyclogenesis. This case also presented an opportunity to study the development of the PMC into “the sec-
ondary cyclone” over the northwestern Pacific. The “secondary cyclone” means the PMC that developed to a cyclone comparable to its parent cyclone.

2. Data utilized in the present study

The main data utilized in the present study are as follows;
(1) Routine observation data of the Japan Meteorological Agency (JMA).
(2) Data from AMTEX’75 (Management Committee for AMTEX, 1975a, b).
(3) NOAA (National Oceanic and Atmospheric Administration) – 4 cloud images (Environmental Data Service, NOAA, 1975).
(4) Defense Meteorological Satellite Program (DMSP) images (see Kidder and Haar 1995) provided by 20th Weather Squadron of U.S.A. Air Force at Yokosuka for AMTEX’75.
(5) Japanese 55-year Reanalysis (JRA-55) data on 1.25° latitude / longitude grid at a 6-hour interval (Ebita et al. 2011; Kobayashi et al. 2015).
(6) Map of 8-day (21–28 February 1975) averaged sea-surface temperature (SST) in “10-day averaged SST map” issued by JMA.
(7) Weather maps issued by JMA.

3. Synoptic-scale overview

NOAA-4 VIS (visible) cloud image (Fig. 1a) and the surface weather map (Fig. 2a) at 00 UTC 20 February show two major frontal cloud bands extended southwestward from the synoptic-scale cyclones at 45°N/175°W (976 hPa) and 35°N/145°E (1000 hPa; the parent cyclone of the PMC). The distance between these cyclones was approximately 4000 km. Figure 1a also shows a mesoscale comma-cloud (indicated by an arrow) associated with the PMC of 1016 hPa over the East China Sea at 33°N/128°E (Fig. 2a). The PMC formed in the cyclonic streams prevailed in the pole-
ward area of the cold front associated with the parent cyclone. The mesoscale features of the comma-cloud on DMSP image (Fig. 6) will be described in Section 4.

NOAA-4 VIS cloud image (Fig. 1b) and the surface weather map (Fig. 2b) at 00 UTC 21 February show that the parent cyclone (988 hPa) moved to 38°N/154°E. The PMC developed into a depression of 998 hPa at 35°N/140°E, 1200 km to the west of the parent cyclone. In Fig. 1b, the PMC was seen as the head of the comma-cloud with the trail at 36°N/139°E. Features of the mesoscale cloud-systems around the comma-cloud on DMSP image (Fig. 17) will be described in Section 6.

The PMC developed into the secondary cyclone of 992 hPa, 1200 km to the west of the parent cyclone at 12 UTC 21 February (the surface weather map is not presented). Figure 3 shows the movement and evolution of the parent cyclone and the PMC during 00 UTC 20–12 UTC 23 February. Features of the PMC in the generation stage in 00 UTC 20–00 UTC 21 will be discussed in Sections 4 and 5. Features in the development stage after 00 UTC 21 will be studied in Sections 6 and 7.

4. Genesis of the PMC

The station maps (in Fig. 4) show the routine observation stations of JMA and observation stations of AMTEX’75. In addition, there were many observation data at several fishing ships in this area, which are utilized in the surface analysis in Fig. 5.

The surface weather maps in Fig. 5 depict features of the PMC in the generation stage. At 21 UTC 19 February (Fig. 5a), the PMC was not yet signified as a depression on the surface weather map, although a weak surface trough was seen at 33°N/127°E. At 00 UTC 20 (Fig. 5b), the PMC formed at 33°N/128°E as a small depression of 1016 hPa with a cyclonic circulation. At 03 UTC 20 (Fig. 5c), the central pressure of the PMC deepened to 1012 hPa, simultaneously with the intensification of the cyclonic circulation. At 05 UTC 20 (Fig. 5d), the PMC (1010 hPa) moved over Kyushu (33°N/131°E), and a surface trough elongated southwestward from the PMC. Strong winds prevailed in the vicinity of the surface trough. After 06 UTC 20, the PMC moved eastward along the Pacific coast of Japan (the surface map is not presented). At 00 UTC 21, the PMC of 998 hPa was located at 35°N/140°E (Fig. 2b).

Figure 6 shows a DMSP VHR (visible high-
resolution) cloud image at 03:21 UTC 20 February. See the location of the PMC on the NOAA cloud image in Fig. 1a, since latitude and longitude gridlines are not presented in Fig. 6. The PMC appeared as a comma-cloud with a head, notch and trail. A few northeast–southwest oriented narrow cloud-lines formed around the trail.

Time series of the surface observation data during 15 UTC 19–12 UTC 20 February at Stations 47–843, 845, 817 and 832 (see the station map in Fig. 4. “Regional code-number 47” was omitted in the map) are presented in Figs. 7a–d, respectively. At Stations 843, 845 and 832, the increase and decrease of surface air-temperature of ~ 3°C was seen, before and after the PMC’s passage, respectively. Meanwhile, the drop of the surface temperature of ~ 2°C occurred at Station 817 simultaneously with the peak of precipitation.

A total precipitation in 3-hour of 6 and 9 mm were observed at Station 843 and Station 817, respectively. That is, relatively intense precipitation occurred in the vicinity of the PMC during its passage over the sea or coastal area. However, the precipitation in 3-hour at Station 815 was 4 mm (not shown in Fig. 7). That is, the precipitation weakened during the PMC’s passage over Kyushu.

Wind speed increased to ~ 30 m s$^{-1}$ at Stations 845 and 832, in association with the passage of the surface trough (i.e., the comma-trail).

5. Large-scale condition for the genesis of the PMC

5.1 The sea-surface temperature (SST) distribution in the East China Sea

The map of 8-day averaged SST for 21–28 February 1975 is presented in Fig. 8. There are two warm sea-currents of Kuroshio and Tsushima Current in the East China Sea. Kuroshio flowed northeastward from 25°N/123°E to 29°N/129°E, and further to the northwestern Pacific. Tsushima Current branched from Kuroshio at 28°N/128°E, then flowed northward.
along the western coast of Kyushu, and further flowed into the Japan Sea through the Tushima Straits. The warmest SST spread over the Kuroshio around the Southwest Islands. Relatively warm SST spread over Tsushima Current around 129°E, and relatively cold SST spread over the western East China Sea. In Fig. 8, SST was not shown in the northwestern East China Sea and the Yellow Sea. In other years (e.g., 1968 (Ninomiya 1972) and 1974 (Kondo 1976)), the area of SST colder than 7°C protruded from the Yellow Sea to the northwestern East China Sea.

5.2 Synoptic-scale features preceding genesis of the PMC

JRA-55 maps of 500 hPa height and 500 hPa vorticity ($\zeta$) at 12 UTC 19 February are presented in Figs. 9a and 9b, respectively. The 500 hPa isotherms of $-42^\circ$C and $-39^\circ$C are shown by broken lines in Fig. 9a. Maps of 700 hPa vertical-$p$-velocity ($\omega$) and the sea-level pressure ($Ps$) at 12 UTC 19 February are presented in Figs. 9c and 9d, respectively. The hatched areas in Fig. 9d indicate the areas where 925 hPa $\zeta$ was larger than $10 \times 10^{-5}$ s$^{-1}$.

Fig. 6. DMSP VHR cloud image at 03:21 UTC 20 February 1975.

Fig. 7. Time series of the sea-level pressure ($Ps$), wind velocity, temperature ($T$), and hourly rainfall ($Prec$) during 15 UTC 19–12 UTC 20 February 1975, observed at Stations 843(a), 845 (b), 817 (c), and 832 (d). The height of each station is shown in the parentheses after the station number.
There was a cold trough over the northeastern part of China. A cold core of −42°C within the trough was located over 45°N/117°E (Fig. 9a). The synoptic-scale parent cyclone of 1012 hPa formed at 33°N/140°E, 1500 km to the east of the cold trough (Fig. 9d). The parent cyclone was associated with 700 hPa $\omega$ of $\sim -40$ hPa h$^{-1}$ and 925 hPa $\zeta$ of $\sim 15 \times 10^{-5}$ s$^{-1}$ (Figs. 9c, d). However, the cyclonic circulation associated with the parent cyclone did not yet prevail over the East China Sea, and large anticyclone covered the eastern part of China and the western East China Sea in 110–125°E (Fig. 9d).

Since the PMC formed under the influence of the cold trough within the following 12 hours, situations around the cold trough are noted in detail. The cold area of −39°C was approaching toward the northern part of the Yellow Sea (Fig. 9a). A zone of 500 hPa $\zeta$
of \( \sim 10 \times 10^{-5} \) s\(^{-1}\) formed along the western–southern periphery of the cold vortex (Fig. 9b), and 700 hPa \( \omega \) of \( \sim -30 \) hPa h\(^{-1}\) appeared at 35°N/120°E (Fig. 9c). In association with this upward motion, 925 hPa \( \zeta \) of \( \sim 10 \times 10^{-5} \) s\(^{-1}\) was seen at 35°N/120°E, nearby a weak depression of 1024 hPa within the anticyclone (Figs. 9b, d).

After 6-hour, at 18 UTC 19 February, the cold area of \(-39^\circ\)C in the cold trough approached to the Yellow Sea. Simultaneously, 700 hPa \( w \) and 925 hPa \( z \) were intensified to \( \sim -40 \) hPa h\(^{-1}\) and \( \sim 25 \times 10^{-5} \) s\(^{-1}\) at 34°N/123°E, respectively. However, the PMC was not yet identified as a surface depression (maps at 18 UTC 19 are not presented).

Using the “effective bulk coefficient \( C_H \) and \( C_E \) of \( 1.9 \times 10^{-3} \)” (Kondo 1976) and ship-observation data on 19 February, \( SH \) and \( LH \) of \( \sim 80 \) and \( \sim 75 \) W m\(^{-2}\) were estimated around 34°N/123°E, and \( SH \) and \( LH \) of \( \sim 120 \) and \( \sim 190 \) W m\(^{-2}\) were estimated around 33°N/128°E.

The upper observation at Station Mosulpo (at Cheju Island of Korea, see Fig. 4) at 12 UTC 19 February is presented in Fig. 10a. Figure 10a showed a shallow dry-neutral layer (i.e., dry-mixed layer) in 1000–900 hPa. This dry-neutral layer was capped by an inversion layer in 900–870 hPa. That is, the moist-neutral layer did not form yet at 12 UTC 19 at this station, which was located to the east of the cold SST area. Note that a deep moist-neutral layer formed in 1013–600 hPa at this station at 00 UTC 20 February (figure is not presented), simultaneously with the generation of the PMC.

In the synoptic-scale field, vertical wind shear indicates the horizontal gradient of temperature (i.e., baroclinicity) through the thermal wind relation. At Station Mosulpo / 12 UTC 19, vertical wind shear was large above the tropopause at 400 hPa, whereas vertical wind shear was very weak in 900–700 hPa (Fig. 10a).

The upper observation at Station 807 at 12 UTC 19 February (Fig. 10b) showed a moist-neutral layer (i.e., dry-mixed layer) in 990–740 hPa. Note that the relatively deep moist-neutral layer had already formed at 12 UTC 19, prior to the genesis of the PMC, at Station 807 which was located to the east of the warm SST area. The tropopause was identified at 400 hPa. Vertical wind shear was large in 700–400 hPa, but very weak in 850–700 hPa.

Station Mosulpo and the observation ship Ryofuu were located on \( \sim 127^\circ\)E meridian at a distance of 400 km between them. Vertical distributions of \(-\partial Z/\partial y\) and \(-\partial T/\partial y\) at \( \sim 127^\circ\)E evaluated at 12 UTC 19 are presented in Fig. 11. The \( u \)-component of geostrophic wind is proportional to \(-\partial Z/\partial y\) and that of the thermal wind is proportional to \(-\partial T/\partial y\). Figure 11 showed the large \(-\partial T/\partial y\) in the upper troposphere, which was sustained in the southern periphery of the cold core. Consequently, \(-\partial Z/\partial y\) increased rapidly with height in the upper troposphere, which means increase of \( u \)-component of the geostrophic wind. Meanwhile \(-\partial T/\partial y\) was small in 900–800 hPa. Consequently,
−∂Z/∂y did not largely increase with height, which was consistent with the weak wind shear in the lower troposphere seen in Fig. 10a. Relatively large −∂T/∂y was seen in 1000–900 hPa layer (Fig. 11). It is added that the moist-neutral layer in the lower troposphere was not seen at the observation ship Ryoufuu at both 12 UTC 19 and 00 UTC 20 (figure is not presented).

5.3 Synoptic-scale features around the PMC in generation stage

JRA-55 maps of Ps and 10-m-level wind velocity at 00 UTC 20 February are shown in Figs. 12a and b, respectively. The parent cyclone (1004 hPa) was located over the northwestern Pacific at 34°N/145°E, and cyclonic circulations prevailed over the Japan Sea and the northeastern part of the East China Sea. The PMC was not yet identified as a depression closed by the isobar of 1016 hPa (Fig. 12a). Maps of 925 hPa ζ and 700 hPa ω at 00 UTC 20 February are shown in Figs. 12c and d, respectively. The parent cyclone and the associated cold front were clearly identified on these maps. The PMC was also identified as the maximum 925 hPa ζ of ~20 × 10⁻³ s⁻¹ at 33°N/127°E, and the minimum 700 hPa ω of ~−30 hPa h⁻¹ at 33°N/127.5°E.

JRA-55 maps of 500 hPa height, 500 hPa temperature, and 500 hPa ζ at 00 UTC 20 February are presented in Figs. 13a–c respectively. In these maps, the location of the parent cyclone and the PMC were indicated by ▲ and ●, respectively. A slow-moving U-shaped wide trough was situated over the Japan Sea. In this wide trough, the main trough with a cold core of −42°C was situated over 43°N/120°E. The cold trough extended southeastward from the cold core, and the cold area of −39°C elongated over the Korea Peninsula (Figs. 13a, b). The parent cyclone developed 1300 km to the east of the cold trough, and the PMC was generated close to the cold trough. In Fig. 13c, large 500 hPa ζ of ~20 × 10⁻³ s⁻¹ appeared over the parent cyclone, whereas a belt of large ζ of ~10 × 10⁻³ s⁻¹ elongated along the southwestern periphery of the cold core. The 500 hPa vorticity field over the PMC was characterized by the positive vorticity advection.

Figure 13d shows a map of MST(600–925)/3.25, difference of “moist static temperature (MST)” between 600 and 925 hPa (unit in K (100 hPa)⁻¹) at 00 UTC 20 February. “Moist static temperature” is defined by MST = h/c_p = (c_p T + g z + L q)/c_p, where h, T, z, q, g, c_p and L is moist static energy, temperature, geopotential height, specific humidity, acceleration of gravity, specific heat of air at the constant pressure and latent heat of water, respectively. Both the parent cyclone and the PMC were in area of moist-neutral stratification.

The upper observation data nearby the PMC are examined next. The upper observation at Station 807 at 00 UTC 20 February (Fig. 14a) showed a deep moist-neutral layer in 970–470 hPa. At this station, vertical wind shear was large above the tropopause at 470 hPa, whereas wind shear is small in the lower troposphere.

Observation data at Station 778 at 12 UTC 20 February is presented in Fig. 14b. At 12 UTC 20, the PMC was situated in the vicinity of Station 778 (Figs. 3, 4). Figure 14b showed a deep moist-neutral layer with the relatively large southwesterly wind shear in 970–470 hPa. Wind shear was very small in 600–350 hPa. Wind shear increased above the tropopause at 350 hPa.

Figures 15a–c show JRA-55 latitude-vertical (log p) cross-sections at 130°E of MST, ζ, and ω at 06 UTC 20 February 1975, respectively. At this time, the PMC (1008 hPa) was located at 32°N/131°E (figure is not shown).
presented), where a slightly unstable layer existed in 900–800 hPa (Fig. 15a). The large $\zeta$ ($\sim 15 \times 10^{-3} \, \text{s}^{-1}$) associated with the PMC was seen within a shallow layer between 1000 and 800 hPa (Fig. 15b), whereas strong $\omega$ of $\sim -30 \, \text{hPa h}^{-1}$ was seen in 900–500 hPa (Fig. 15c).

Using the “effective bulk coefficient $C_H$ and $C_E$ of $1.9 \times 10^{-3}$”, and the ship-observation data around 33°N/128°E on 20 February, $SH$ and $LH$ of $\sim 120$ and $\sim 190 \, \text{W m}^{-2}$ were estimated. As mentioned in the introduction, the Japan Sea PMCs developed usually over areas of large air–sea temperature difference, which caused large heat energy supply from the sea to the atmosphere. In this case, the PMC formed over the warm SST area in the eastern East China Sea, but did not formed over the cold SST area in the western East China Sea. The northbound warm Tsushima Current provided one of the favorable conditions for the genesis of PMC over the eastern East China Sea.

6. Development of the PMC into the secondary cyclone

The longitude-time section of observed sea-level pressure along $\sim 33.5^\circ$N latitude (approximately along the path of the PMC, in Fig. 4) is presented in Fig. 16. During 00–09 UTC 20 February, the central pressure of the PMC decreased from 1016 hPa to 1008 hPa, whereas the low-pressure area of the PMC remained narrow. After 12 UTC 20, the area of the PMC expanded with the deepening of the pressure from 1008 hPa at 09 UTC 20 to 996 hPa at 03 UTC 21, as the PMC moved eastward to 140°E.

The change of precipitation in the evolution process of the PMC is noted. The maximum 3-hour precipita-

Fig. 12. JRA-55 maps of $Ps$ (hPa) (a), 10-m-level wind velocity (b), 925 hPa $\zeta$ ($10^{-5} \, \text{s}^{-1}$) (c), and 700 hPa $\omega$ (hPa h$^{-1}$) (d) at 00 UTC 20 February 1975.
tion increased when the PMC passed over the north-western Pacific to the south of Japan (i.e., 8 mm at Station 778; 17 mm at Station 655; 18 mm at Station 648). The precipitation increased simultaneously with the deepening of the PMC.

During 00 UTC 20–00UTC 21 February, the cloud area of the PMC expanded with the deepening of the PMC. Figure 17 shows DMSP VHR cloud image at 03:03 UTC 21. The cloud system of the PMC, as the head of comma-cloud with trail, is indicated by the large arrow on Fig. 17. There were smaller mesoscale cloud-systems within the polar-air outbreak occurred after the PMC’s passage. A cloud band along the eastern off coast of the Korea Peninsula, and a “6-shaped cloud” over the western Japan Sea are also indicated by small arrows in Fig. 17. Several cloud streets formed in the polar-air streams to the north of the trail of the PMC.

Figures 18a and 18b present NOAA-4 VIS images at 00 UTC 22 and 00 UTC 23 February, respectively. Figures 19a and 19b show surface weather maps at 00 UTC 22 and 00 UTC 23, respectively. The PMC developed over the northwestern Pacific into the secondary cyclone of the parent cyclone. At 00 UTC 23, the distance between the parent cyclone and the secondary cyclone (PMC) was 1300 km at 00 UTC 22, and 1700 km at 00 UTC 23, because the parent cyclone moved northeastward faster than the PMC. The evolution of the PMC was examined using JRA-55 data. Figure 20 presents change and movement of the maximum 925 hPa $\zeta$, maximum 10-m-level $\zeta$, minimum 700 hPa $\omega$, and minimum $P_s$ associated with the PMC. Significant development of the PMC occurred during 00 UTC 21–00 UTC 22 over 140–145$^\circ$E.
7. Synoptic-scale condition for the development of the PMC

JRA-55 maps of $Ps$ and 10-m-level wind velocity at 12 UTC 21 February are shown in Figs. 21a and 21b, respectively. The parent cyclone (988 hPa) was located over the northwestern Pacific at 41°N/156°E, and the PMC (992 hPa) was at 36°N/142°E. These two cyclones formed a east–west elongated low-pressure area extended from 40°N/165°E to 36°N/139°E. Low-level northeasterly winds prevailed in the...
northern periphery of the low-pressure area (Fig. 21b). Maps of 925 hPa $\zeta$ and 700 hPa $\omega$ at 12 UTC 21 February are shown in Figs. 21c and 21d, respectively. The parent cyclone and the associated cold front were identified on these maps. The PMC was accompanied with 925 hPa $\zeta$ of $\sim 20 \times 10^{-5}$ s$^{-1}$ at 36°N/142°E and 700 hPa $\omega$ of $\sim -70$ hPa h$^{-1}$ at 37°N/143°E. At this stage, the 925 hPa $\zeta$ of the PMC was comparably large as compaed with that of the parent cyclone, and the 700 hPa $\omega$ of the PMC was stronger than that of the parent cyclone.

JRA-55 maps of 500 hPa height, 500 hPa temperature, and 500 hPa $\zeta$ at 12 UTC 21 are presented in Figs. 22a–c, respectively. The slow-moving U-shaped wide trough was still situated over the Japan Sea. In this trough, the main trough with the cold core of about –42°C reached 38°N/130°E (Figs. 22a, b). The parent cyclone was located 2500 km to the east of the cold core, and the PMC was situated 1000 km to the east
of the cold core. In Figs. 22a and 22c, small 500-hPa depression enclosed by the 5220-m height contour, associated with 500 hPa $\zeta$ of $\sim 20 \times 10^{-5}$ s$^{-1}$, formed over the PMC. The PMC developed as a secondary cyclone which had a deep structure extended into the middle troposphere.

The influence of SST over the northwestern Pacific on the development of the PMC is examined. The map of the 8-day averaged SST for 21–28 February (Fig. 8) shows that Kuroshio flows northeastward from the East China sea (29°N/129°E) to the northwestern Pacific. During 12 UTC 20–00 UTC 21, the PMC moved eastnortheastward over the Kuroshio, in which the SST was $\sim 16$°C. During this period, $SH$ and $LH$ of $\sim 170$ and $\sim 250$ W m$^{-2}$ were estimated over Kuroshio south of Japan by using JRA55 data. After 00 UTC 21, the PMC moved northeastward, and reached 40°N/156°E at 00 UTC 23. During this period, the PMC moved over the zone of strong SST gradient ($\sim 5$ K (100 km)$^{-1}$) elongated along the northern side of Kuroshio extension. The low-level baroclinic zone (figure is not presented) formed over the zone of strong SST gradient.

The upper observations at 12 UTC 21 February nearby the developing PMC are examined. Observation at Station 646 (Fig. 23a) showed a deep moist-neutral layer in 920–500 hPa. At this station, the tropopause was identified at 470 hPa. Vertical wind shear was large in the lower layer (1000–800 hPa) and above 400 hPa, whereas wind shear was small in 700–400 hPa. Observation at Station 678 (Fig. 23b) showed a moist-neutral layer with the large westerly wind shear in 1000–800 hPa. Wind shear was small in 800–500 hPa, whereas wind shear increased above 500 hPa. In the lower troposphere, temperature at Station 646 was lower than that at Station 678. This lower temperature at Station 646 was associated with northerly winds (Figs. 21b, 23a).

Stations 807 and 827 are located on ~130°E meridian at a distance of 225 km between them. Vertical distributions of $-\partial Z/\partial y$ and $-\partial T/\partial y$ at $\sim 130$°E evaluated at 00 UTC 20 are presented in the left panel of Fig. 24. Stations 646 and 678 are located on $\sim 140$°E meridian at a distance of 335 km between them. Vertical profiles of $-\partial Z/\partial y$ and $-\partial T/\partial y$ at $\sim 140$°E evaluated at 12 UTC 21 are presented in the right panel of Fig. 24. The feature seen commonly at 00 UTC 20 and 12 UTC 21 February was the large $-\partial T/\partial y$ in the upper troposphere, which was sustained in the southern periphery of the cold core. Consequently, $-\partial Z/\partial y$ increased rapidly in the upper troposphere. This means increase of the $u$-component of geostrophic wind with
height. Meanwhile $-\partial T/\partial y$ was small in 700–600 hPa at 00 UTC 20 and 12 UTC 21, which was consistent with the weak wind shear in the middle troposphere seen in Figs. 23a and 23b.

At $~130^\circ$E/00 UTC 20, $-\partial T/\partial y$ in the lower troposphere was relatively small, whereas $-\partial T/\partial y$ in the lower troposphere at $~140^\circ$E/12 UTC 21 was relatively large. That is, the synoptic-scale feature in the development stage of the PMC was characterized by the low-level baroclinicity. This large $-\partial T/\partial y$ in the lower troposphere was owing to the lower temperature associated with northerly wind in 1000–850 hPa at Station 646 (Figs. 21b, 23b).

8. Discussions

8.1 Comparison with a PMC generated over the Tsushima Straits

It would be desirable to compare the PMC in the present report with other PMCs over the East China Sea. However, PMC genesis over the East China Sea has not been studied to date. Therefore, the PMC in the present study is compared with a PMC generated in the vicinity of the Tsushima Straits, reported by Nishijima (1993). At 12 UTC 31 January 1992, the PMC was seen on the surface weather map as a depression of 1006 hPa at 34°N/131°E within cyclonic circulations induced by its parent cyclone of 992 hPa at 33°N/137°E. The PMC moved southward over Kyushu in the following a few hours. Decrease of the sea-level pressure of $~5$ hPa in 3-hour was seen in the northern part of Kyushu, in association with passage of the PMC. A surface trough with a shearline extended westward from the center of the PMC. Strong northwesterly gust of $~20$ m s$^{-1}$ in the shearline was observed in western Kyushu. The satellite cloud images showed a small spiraliform-cloud,
and radar images showed a 6-shaped precipitation system. This PMC weakened during its passage over Kyushu. The PMC formed under the influence of a fast moving V-shaped cold trough over the Korean Peninsula (37°N/127°E) at 12 UTC 31 January 1992. The parent cyclone developed 1000 km to the east of the trough, and the PMC generated close to the trough. Because the feature of the cold trough was not depicted in detail by Nishijima (1993), the following description is added. The 500 hPa cold core of −39°C in the trough was located over Sakhalin of Russia (48°N/142°E) at 12 UTC 31 January 1992. The cold
trough extended southwestward from the cold core to Korean Peninsula. However, the cold area of −36°C did not reach the East China Sea.

The PMC in the present report and the PMC in Nishijima (1993) resembled each other in their environmental situations. However, the 500 hPa cold area of −36°C in the trough extended to the East China Sea at 00 UTC 20 February 1975, whereas the cold area of −36°C did not reach to the East China Sea at 12 UTC 31 January 1992. The difference between the southward extension of these upper cold troughs caused difference between the generation place of the respective PMCs.

8.2 Comparison with the PL/PMC over the northeastern and northwestern Pacific

In this subsection, the PMC in the present report is first compared with the PL over the northeastern Pacific in 16–17 March 1982 studied by Reed and Blier (1986). In their case, the parent cyclone (984 hPa) developed at 00 UTC 15 at 56°N/162°W under a 500 hPa cut-off low. Intense cold-air outbreak took place in the back of the cold front associated with the parent cyclone. The PL appeared on the surface weather map at 00 UTC 15 as a polar-trough at 42°N/138°W. It developed into a secondary cyclone (1004 hPa at 37°N/127°W) at 00 UTC 17 as it moved southeastward within deep baroclinic zone in the southern periphery of the cold vortex aloft, whereas the PMC in the present report developed as it moved northeastward over the low-level baroclinic zone in the northwestern Pacific.

The PMC in the present report is next compared with the weak PMC generated in 7–8 March 1992, within the orographically induced lee-side shear-zone south of the central part of Japan (Ninomiya 2014). The PMC was not accompanied by the significant upper westerly trough, nor by the significant parent cyclone. The PMC moved eastward over the low-level baroclinic zone in the northwestern Pacific. However, it did not develop into a relatively large PMC and weakened within 2 days.

8.3 Comment on conditions for genesis and development of PMCs

Observational studies on PMCs over the Japan Sea (e.g., Ninomiya 1989, 1991; Tsuboki and Wakahama 1992; Ninomiya et al. 1993; Fu et al. 2004) showed that PMC formed and developed in the lower tropospheric moist-neutral layer under the condition of strong baroclinicity. Yanase et al. (2004) concluded that, in a sensitivity experiment of a PMC developed under the strong baroclinicity, the condensational heating was an additional cause for the rapid development. Yanase and Niino (2007) concluded that the strong baroclinicity is an essential condition for the development of PMCs in idealized nonhydrostatic numerical experiments.

The baroclinic zone, with thermal gradient of ~ 10 K (1000 km)$^{-1}$, and moist-neutral layer in the lower troposphere often formed over the Japan Sea and the northwestern Pacific in winter. However, PMCs selectively generated and/or developed in the particular occasion at the respective place. Namely, PMCs developed on the northern side of the major front, in the vicinity of a upper-level cold vortex, in the low-level cyclonic polar-air streams induced by its parent cyclone. The present study showed that the location of the cold trough and the parent cyclone, relative to the baroclinic zone and the area of the large air-sea temperature difference, decided actual time and place of the genesis and development of individual PMCs.
9. Concluding remarks

Genesis of PMCs over the East China Sea is rare, but can occur under the certain synoptic-scale conditions. The first purpose of the present report is to study the PMC’s genesis over the East China Sea, which has not been studied to date. The present report analyzed the PMC’s genesis on 20 February 1975 by using dense observation data of AMTEX’75, routine observations by JMA, satellite cloud images, and JRA-55 reanalysis data. The analysis showed that the PMC with a comma-cloud generated in the moist-neutral layer formed over the warm Tsushima Current in the East China Sea, within the low-level cyclonic circulation induced by the upper cold trough and the parent cyclone, when the cold core in the upper cold trough intruded beyond 34°N to the East China Sea. The PMC deepened from 1016 hPa to 1012 hPa within 3-hour period after its generation, in association with the intensification of the low-level cyclonic circulation.

The second purpose of the present report is to study redevelopment of the PMC over the northwestern Pacific, on which little attention has been given to date. The analysis showed that the PMC developed as it moved eastward over Kuroshio to the south of Japan. It developed further into a secondary cyclone of the parent cyclone over the northwestern Pacific, as it moved northeastward in the low-level baroclinic zone that formed over the zone of strong SST gradient to the north of Kuroshio extension.

The synoptic-scale conditions of the present PMC were consistent with conclusions of many previous studies on the Japan Sea PMCs, in that the strong baroclinicity and the moist-neutral layer in lower troposphere are the favorable conditions for the genesis and development of the PMCs. In addition, the present study showed that location of the cold-core in the upper trough, and the low-level cyclonic polar-air streams induced by its parent cyclone, relative to the baroclinic zone and the moist-neutral layer over areas of the large air–sea temperature difference, decided the actual time and place of genesis and development of individual PMCs.

Studies on many cases of PMCs over the East China Sea, and the redevelopment of PMCs over the northwestern Pacific are needed to confirm the results of the present study. Numerical experimental studies will be also useful to examine the influence of environmental conditions on the genesis and development of PMCs in various cases.

Acknowledgments

The analysis using JRA-55 data was performed by the courtesy of the Atmospheric and Oceanic Research Institute (AORI) of the Tokyo University. I thank Dr. W. Yanase of AORI for his kind support for the analysis. I also thank the editor and anonymous reviewers for their valuable comments and advice.

References


Ninomiya, K., K. Wakahara, and H. Ohkubo, 1993: Meso-α-scale low development over the northeastern Japan Sea under the influence of a parent large-scale low


