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The DOI for this manuscript is

DOI:10.2151/jmsj.2017-007

J-STAGE Advance published data: January 16, 2017

The final manuscript after publication will replace the preliminary version at the above DOI once it is available.
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 –

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

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Abstract

Polar mesoscale cyclones (PMCs) frequently developed over the Japan Sea. Genesis of PMCs over the East China Sea is rare, but could occur under the 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 by using observation data including those obtained during Air-mass Transformation Experiment, satellite cloud images and objective-reanalysis data.

The PMC with comma-cloud formed within cyclonic polar-air streams induced by an upper cold trough and a synoptic-scale parent cyclone which developed near Japan. Within 3-hour after generation of the PMC, its central pressure deepened from 1016 hPa to 1012 hPa. Strong surface winds occurred in the trail of the comma-cloud. The large-scale conditions for the generation stage 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. It developed further in the low-level baroclinic zone over the Northwestern Pacific, into the secondary cyclone comparable to the parent cyclone. 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.
1. Introduction

Polar mesoscale cyclones (PMCs) / polar lows (PLs) develop frequently over the seas in higher latitudes, such as the Norwegian Sea, the Barents Sea, the Northeastern Atlantic, and the 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 the Northeast Asia and the Northwestern Pacific have been discussed only in a few articles. Yarnal 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), 1976-77 to 1982-83. During this period, ~1500 PLs were identified in total. Among them, ~90% were associated with relatively larger “comma-cloud” and ~10% were associated with relatively smaller “spiraliform-cloud”. There were two maximum zones of comma-cloud generation; the primal zone elongated from northern Japan (43°N/150°E) to the Bering Sea (50°N/165°E) and the secondary zone elongated 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 the 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, 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 travelling northeastward over the Northern Pacific usually reached their maximum intensity around the Aleutians to form the deep “Aleutian low”. Meanwhile, Siberian anticyclone predominated over the northeastern part of the Asia Continent. The very strong pressure gradient between Aleutian low and Siberian anticyclone caused strong polar-air outbreak over the 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 northwest of the large-scale parent cyclones which developed in the vicinity of Japan. PMCs over the Northwestern Pacific tended to develop 1000-2000 km 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, they become 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. Up to the present, 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 \(\sim 140 \text{ W m}^{-2}\) and \(\sim 200 \text{ W m}^{-2}\) over the Japan Sea. Kondo (1976) evaluated \(SH\) and \(LH\) of \(\sim 80\) and \(\sim 120 \text{ W m}^{-2}\) over the northwestern East China Sea (34°N/124°E), and, \(SH\) and \(LH\) of \(\sim 140\) and \(\sim 220 \text{ W m}^{-2}\) over the eastern East China Sea (33°N/128°E). Meanwhile, \(SH\) and \(LH\) of \(\sim 100\) and \(\sim 300 \text{ W m}^{-2}\) were evaluated over the southern East China Sea (25°N/123°E). Kondo (1976) stated also that the “effective bulk coefficient \(C_H\) and \(C_E\)”, 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 up to the present. 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, since 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 southwestward 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 secondary cyclone” over the Northwestern Pacific. The
“secondary cyclone” means the PMC developed to the cyclone comparable to its
parent cyclone.

2. Data utilized in the present study

The main data utilized in the present study are;

(1) Routine observation data of Japan Meteorological Agency (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 about 4000 km. Figure 1a also shows a mesoscale comma-cloud (indicated by an arrow) associated with the PMC of 1016 hPa (Fig. 2a) over the East China Sea at 33°N/128°E. The PMC formed in the cyclonic streams prevailed in the poleward 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 later.
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 west of the parent cyclone. In Fig. 1b, the PMC was seen as the head of comma-cloud with trail at 36°N/139°E. Features of the mesoscale cloud-systems around the comma-cloud on DMSP image (Fig. 17) will be described later.

The PMC developed into the secondary cyclone of 992 hPa, 1200 km 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 signified yet as a depression on the surface weather map, though 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 the small depression of 1016 hPa with cyclonic circulation. At 03 UTC 20 (Fig. 5c), 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 DMSP VHR (visible high-resolution) cloud image at 03:21 UTC 20 February. (Latitude and longitude grid-lines are not presented in Fig. 6. The location of the PMC will be seen on the NOAA cloud image in Fig. 1a.) 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, b, c and 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.

Total precipitation in 3-hour of 6 mm and 9 mm were observed at Station 843, and Station 817. 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 $\sim 30 \text{ m s}^{-1}$ 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 $25^\circ\text{N}/123^\circ\text{E}$ to $29^\circ\text{N}/129^\circ\text{E}$, and further to the Northwestern Pacific. Tsushima Current branched from Kuroshio at $28^\circ\text{N}/128^\circ\text{E}$, 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 $129^\circ\text{E}$, 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. However, in other years, area of SST colder than $7^\circ\text{C}$ protruded from the Yellow Sea to the northwestern East China Sea (e.g., Ninomiya, 1972; Kondo, 1976).

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

There was a cold trough over the northeastern part of China. A cold core of $-42^\circ$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 east of the cold trough (Fig. 9d). The parent cyclone was associated with 700 hPa $\omega$ of $-40$ hPa h$^{-1}$, and 925 hPa $\zeta$ of $15 \times 10^{-5}$ s$^{-1}$ (Figs. 9c and d). However, the cyclonic circulation associated with the parent cyclone did not prevail over the East China Sea yet, and large anticyclone covered 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 $-39^\circ$C was approaching toward northern part of the Yellow Sea (Fig. 9a). A zone of 500 hPa $\zeta$ of $10 \times 10^{-5}$ s$^{-1}$ formed along the western-southern periphery of the cold vortex (Fig. 9b), and 700 hPa $\omega$ of $-30$ hPa h$^{-1}$ appeared at 35°N/120°E (Fig. 9c). In association with this upward motion, 925 hPa $\zeta$ of $10 \times 10^{-5}$ sec$^{-1}$ was seen at 35°N/120°E, nearby a weak depression of 1024 hPa within the anticyclone (Figs. 9b and 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 $\omega$ and 925 hPa $\zeta$ were intensified to $-40$ hPa h$^{-1}$ and $25 \times 10^{-5}$ s$^{-1}$ at 34°N/123°E, respectively. However, the PMC was not identified yet as a surface depression (map 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 around $34^\circ$N/$125^\circ$E on 19 February, $SH$ and $LH$ of $\sim 80$ and $\sim 75$ W m$^{-2}$ were estimated. Meanwhile $SH$ and $LH$ of $\sim 120$ and $\sim 190$ W m$^{-2}$ were estimated at $33^\circ$N/$128^\circ$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. It should be noted that 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 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 in 990-740 hPa. It should be noted that the relatively deep moist-neutral layer had formed already at 12 UTC 19, prior to the genises of the PMC, at this station which was located to the east of the warm SST area in Tsushima Current. The tropopause was identified at 400 hPa. Vertical wind shear was large in 700-400 hPa,
but very weak in 850-700 hPa.

Station Mosulop and observation ship Ryofuu were located on ~127°E meridian at a distance of 400 km between them. Vertical distributions of \(-\partial Z/\partial y\) and \(-\partial T/\partial y\) at ~127°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 thermal wind is proportional to \(-\partial T/\partial y\). Figure 11 showes 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, \(-\partial Z/\partial y\) did not largely increased with height, that was consistent with the weak wind shear in the lower troposphere seen in Fig. 10a. Realatively large \(-\partial T/\partial y\) 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 observation ship Ryofuu at borth 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 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 \(\zeta\) and 700 hPa \(\omega\) 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 $\zeta$ of $\sim 20 \times 10^{-5}$ s$^{-1}$ at 33°N/127°E, and the minimum 700 hPa $\omega$ of $\sim -30$ hPa h$^{-1}$ at 33°N/127.5°E. JRA-55 maps of 500 hPa height, 500 hPa temperature, and 500 hPa $\zeta$ at 00 UTC 20 February are presented in Figs. 13a, b and c, respectively. In these maps, 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 $-42^\circ$C was situated over 43°N/120°E. The cold trough extended southeastward from the cold core, and cold area of $-39^\circ$C elongated over the Korea Peninsula (Figs. 13a and b). The parent cyclone developed 1300 km east of the cold trough, and the PMC was generated close to the cold trough. In Fig. 13c, large 500 hPa $\zeta$ of $\sim 20 \times 10^{-5}$ s$^{-1}$ appeared over the parent cyclone, whereas a belt of large $\zeta$ of $\sim 10 \times 10^{-5}$ 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 map of $\text{MST}(600-925)/3.25$, 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 $\text{MST} = h/c_p = (c_p T + g z + L q) / c_p$, 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 and 4). Figure 14b showed a deep moist-neutral layer with the relatively large southwesterly wind-shear in 970-600 hPa. Wind-shear was very small in 600-350 hPa. Wind-shear increased above the tropopause at 350 hPa.

Figures 15a, b and c show JRA-55 latitude-vertical \((log p)\) cross sections at 130°E of \(\text{MST, } \zeta \), and \(\omega\) at 06 UTC 20 February 1975, respectively. At this time, the PMC (1008 hPa) was located at 32°N/131°E (figure is not presented), where a slightly unstable layer existed in 900-800 hPa (Fig. 15a). The large \(\zeta (\sim 15 \times 10^{-5} \text{ s}^{-1})\) 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 \(\text{“effective bulk coefficient } C_H \text{ and } C_E \text{ of } 1.9 \times 10^{-3} \text{ ”, and}\) ship-observation data around 33°N/128°E on 20 February, \(\text{SH and } LH\) 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. It is inferred that the northbound warm
Tsushima Current provided one of favorable conditions for the geneses 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 ~33.5°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 09UTC 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 precipitation increased when the PMC passed over the Northwestern Pacific 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 north of the trail of the PMC.

Figures 18a and b present NOAA-4 VIS images at 00 UTC 22 and 00 UTC 23 February, respectively. Figures 19a and b 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, since the parent cyclone moved northeast-ward faster than the PMC. The evolution of the PMC was examined by 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 $Ps$ associated with the PMC. Significant development of the PMC occurred during 00 UTC 21 - 00 UTC 22 over 140 - 145°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 b, 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 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 d, respectively. The parent cyclone and the associated cold front were identified on these maps. The PMC was accompanied with 925 hPa $\zeta$ of $\sim20\times10^{-5}$ s$^{-1}$ at 36°N/142°E and 700 hPa $\omega$ of $\sim-70$ hPa h$^{-1}$ at
At this stage, the 925 hPa $\zeta$ of the PMC was comparably large 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, b and c, respectively. The slow-moving U-shaped wide
trough was still situated over the Japan Sea. In this trough, the main trough with cold
core of $-42^\circ$C reached 38$^\circ$N/130$^\circ$E (Figs. 22a and b). The parent cyclone was located
2500 km east of the cold core, and the PMC was situated 1000 km east of the cold core.
In Figs. 22a and c, small 500-hPa depression enclosed by the 5220-m height-contour,
associated with 500 hPa $\zeta$ of $-20 \times 10^{-5}$ s$^{-1}$, formed over the PMC. The PMC developed
as a secondary cyclone to have 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 northeast-ward from the East China sea (29$^\circ$N/129$^\circ$E) to the
Northwestern Pacific. During 12 UTC 20 - 00 UTC 21, the PMC moved
eastnortheast-ward over the Kuroshio, in which the SST was $\sim$16$^\circ$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 northeast-ward, and reached
40$^\circ$N/156$^\circ$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 and 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 ~130°E evaluated at 00 UTC 20 are presented in the left panel of Fig. 24. Stations 646 and 678 are located on ~140°E meridian at a distance of 335 km between them. Vertical profiles of $-\partial Z/\partial y$ and $-\partial T/\partial y$ at ~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 $u$-component of the 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 b.

At ~130°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°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 and 23a).

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 up to the present. 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. The sea-level pressure over the northern part of Kyushu dropped ~5 hPa in 3-hour, in association with passage of the PMC. A surface trough with a shear-line extended westward from the center of the PMC. Strong northwesterly gust of ~20 m s$^{-1}$ in the shear-line 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 east of the trough, and the PMC generated close to the trough. Since the
feature of the cold trough was not depicted in detail by Nishijima (1993), following
description is added; The 500 hPa cold core of $-39^\circ$C in the trough was located over
Sakhalin of Russia ($48^\circ$N/$142^\circ$E) at 12 UTC 31 January 1992. The cold trough
extended southwest-ward from the cold core to Korean Peninsula. However, the cold
area of $-36^\circ$C did not reach to 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 $-36^\circ$C
in the trough extended to the East China Sea at 00 UTC 20 February 1975, whereas
the cold area of $-36^\circ$C did not reach to the East China Sea at 12 UTC 31 January
1992. It is inferred that the difference in southward extension of the upper cold trough
caused difference between the generation place of 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 56$^\circ$N/162$^\circ$W under a 500 hPa
cut-off low at 00 UTC 15. Intense cold-air outbreak took place in the back of 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$^\circ$N/138$^\circ$W. It developed into a secondary cyclone (1004
hPa at 37$^\circ$N/127$^\circ$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
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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 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-day.

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 \(\sim 10 \, \text{K (1000 km)}^{-1}\), 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. 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 PMC.

9. Concluding remarks

Genesis of PMCs over the East China Sea is rare, but could 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 up to the present.
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 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 up to the
present. The analysis showed that the PMC developed, as it moved eastward over
Kuroshio to the south of Japan. It developed further over the Northwestern Pacific, into a secondary cyclone of the parent cyclone, as it moved northeast-ward in the low-level baroclinic zone that formed over the zone of strong SST-gradient 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, 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 PMC.

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 the environmental conditions on the genesis and development of PMCs in various cases.

Acknowledgements

The analysis using JRA-55 data was made by 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 advices.
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Figures caption

Fig. 1. NOAA-4 VIS cloud images for 00 UTC 20 (a), and 00 UTC 21 February 1975 (b). The comma-cloud is indicated by an arrow.

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Fig. 3. Movement and evolution of the parent cyclone (triangle) and the PMC (circle). The Blacked and open symbols are for 00 and 12 UTC, respectively. The central sea-level pressure of the parent cyclone and the PMC are shown at 24-hour interval.

Fig. 4. Map of observation stations. JMA stations are indicated by ●, and JCG (Japan Coastal Gard) stations by ▲. Observation ship Ryoufuu and buoy are indicated by ■ and □.

Fig. 5. Mesoscale surface analyses for 21 UTC 19 (a), 00 UTC 20 (b), 03 UTC 20 (c) and 05 UTC 20 February 1975 (d). The solid and dashed lines indicate isobars and isotherms.

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

Fig. 7. Time series of the surface data (Ps; sea-level pressure, wind velocity, T; temperature, Prec; hourly rainfall) during 15 UTC 19 - 12 UTC 20 February 1975, at Stations 843(a), 845 (b), 817 (c), and 832 (d). The height of the station is shown in the parentheses after the station number.

Fig. 8. Map of the 8-day averaged SST (°C) for 21–28 February 1975. Reproduced from “10-day averaged SST map” issued by JMA.

Fig. 9. JRA-55 maps of 500 hPa height (a), 500 hPa $\zeta$ ($10^{-5}$ s$^{-1}$) (b), 700 hPa $\omega$ (hPa h$^{-1}$) (c) and Ps (hPa) (d) at 12 UTC 19 February 1975. The 500 hPa isotherms of $-42^\circ$C and $-39^\circ$C are shown by dashed lines in Fig. 9a. The hached areas in Fig. 9d indicate the areas where 925 hPa $\zeta$ was larger than $10\times10^{-5}$ sec$^{-1}$.

Fig. 10. The upper observation data at Station Mosulop (a) and Station 807 (b) at 12
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Fig. 11. Vertical distributions of $-\partial Z/\partial y$ (○), and $-\partial T/\partial y$ (●) evaluated from the data at Station Mosulop and observation ship Ryoufu at 12 UTC 19 February 1975.

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Fig. 13. JRA-55 maps of 500 hPa height (a), 500 hPa temperature (°C) (b), 500 hPa $\zeta$ ($10^{-5}$ s$^{-1}$) (c), and $\text{MST}(600-925)/3.25$ (difference of MST between 600 and 925 hPa; unit in K (100 hPa)$^{-1}$ ) (d) at 00 UTC 20 February 1975. The center of the parent cyclone and the PMC are indicated by ▲ and ●.

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Fig. 15. JRA-55 latitude-vertical ($\log p$) cross sections at 130°E of MST in K (a), $\zeta$ in $10^{-5}$ s$^{-1}$ (b), and $\omega$ in hPa h$^{-1}$ (c) at 06 UTC 20 February 1975.

Fig. 16. The longitude-time section of the observed sea-level pressure along ~33.5°N. The dashed line indicates minimum sea-level pressure.

Fig. 17. DMSP VHR cloud image at 03:03 UTC 21 February 1975. The large arrow indicates the comma-cloud (PMC). The small arrow with “a” shows the mesoscale
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