Polar Low Development over the East Coast of the Asian Continent on 9–11 December 1985

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Abstract

Polar low development over the eastern coast of the Asian Continent (northeastern part of the Japan Sea) on 9–11 December 1985 is studied.

The low-level strong thermal gradient was maintained along the east coast of the Asian Continent. When a large-scale trough including a cold cut-off vortex approached the east coast, a synoptic-scale low developed over the northwestern Pacific to the east of Japan, and the cyclonic circulation of the synoptic-scale low predominated over the coastal zone.

The easterly winds in the northwestern quadrant of the synoptic-scale low advected the warm air from the Pacific to the Continent, while the westerly winds in the southwestern quadrant of the low advected the cold air from the Continent. Consequently, the N-S thermal gradient was enhanced in the western part of the low. This was the frontogenesis in horizontal shear flows, and a W-E oriented trough (shear line) formed in the lower troposphere in the western part of the synoptic-scale low.

The polar low of the meso- α -scale formed in the W-E trough under the influence of the cut-off cold vortex aloft. In the aforementioned process, the synoptic-scale low played the role of the parent circulation for the polar low formation.

1. Introduction

The development of mesoscale lows in polar air flows have been studied by many authors. In particular, polar lows over the Norwegian Sea and the Barents Sea, and the comma-cloud lows over the northeastern Pacific have been studied extensively. The results of various studies on these lows are well summarized in review papers by Rasmussen (1983) and Businger and Reed (1989). As for the development of the polar lows, the baroclinic instability in the lower atmosphere between the sea-ice area and the warm open sea area and/or CISK are considered to be important mechanisms.

The cloud images obtained by the Geostationary Meteorological Satellite (GMS) of the Japan Meteorological Agency (JMA) and radar observation data also show frequent formation of meso-scale lows with spiral cloud and/or precipitation bands over the Japan Sea and the northwestern Pacific. The horizontal and time scale of these lows are in a wide scale range from meso- α -scale to meso- γ -scale in the scale subdivision by Orlanski (1975).

Ninomiya (1989) studied the polar/comma-cloud lows (hereafter noted as p/c low) over the Japan Sea and the northwestern Pacific during three win-

ter months of 1986/1987. In his study, the p/c low is defined as “the meso- α -scale low that forms in the polar air streams north of the main polar front, which is accompanied by spiral- or comma-shaped clouds of 700–200 km extent in its formation and mature stages”. The typical examples, the occurrence frequency and distribution of the p/c lows, and the large-scale setting of the p/c low development were studied in his paper.

Miura and Asai (1987) studied, by using GMS cloud images, distribution of cloud vortices of ~ 200 , ~ 100 and ~ 50 km diameter over the Japan Sea during four winter months of 1983/1984. They showed that zones of frequent occurrence of vortices are seen east of the Korea Peninsula (*i.e.*, the western Japan Sea) and west of Hokkaido.

The mesoscale cloud/radar echo vortices over the Japan Sea sometimes cause intense snowfalls and strong gusts. Several authors (*e.g.*, Miyazawa, 1967; Tatsuno, 1974; Asai and Miura, 1981; Ninomiya, Hoshino and Kurihara, 1990; Ninomiya and Hoshino, 1990) studied the evolution process and structure of mesoscale lows with cloud/echo vortex over the Japan Sea coastal areas of the central part of Japan.

Various case studies (*e.g.*, Suginaka, 1964; Motoki, 1974; Muramatsu *et al.*, 1975; Yagi *et al.*, 1979;

Kibe, 1988 and 1989; Wakahara, 1989; Ohkubo *et al.*, 1989; Tsuboki and Wakahama, 1992) studied features of mesoscale lows over the northeastern Japan Sea. Some authors (*e.g.*, Wakahara, 1989) proposed detailed classification of these lows according to size, cloud features, place of formation, path and large-scale setting.

However, the present author thinks that the more simple classification is useful to understand the nature of these lows. The mesoscale low over the northeastern Japan Sea can be classified reasonably into the following two main categories. The first category includes the meso- α -scale lows which form within the lower tropospheric baroclinic zone between the very cold airmass over the Asian Continent and the warm airmass over the oceans. This category is defined as "the polar low formed over the east coast of the Asian Continent" in this paper. The second category includes the meso- β - and/or meso- γ -scale vortices which form in the boundary between the airmass transformed over the Japan Sea and the relatively cold flows from Hokkaido. They are named as "the mesoscale low over the west coast of Hokkaido" in this paper. The former and the latter will correspond to Type I and Type II meso-scale cyclones of Tsuboki and Wakahama (1992), respectively. Niomiya (1989) has shown that the "polar low over the east coast of the Asian Continent" tends to form, under the influence of the cut-off cold vortex aloft, within the cyclonic circulation of the synoptic-scale low which developed over the northwestern Pacific to the east of Japan.

As mentioned above, many case studies have been made on the polar low over the east coast of the Asian Continent and the mesoscale low over the west coast of Hokkaido. However, the present author thinks that a more systematic and comprehensive analysis on these lows is necessary to understand the nature of them. This is the motivation of the present and successive studies.

The present paper describes the evolution process and features of a typical case of the polar low over the east coast of the Asian Continent, which formed and developed on 9–11 December 1985.

2. Data source

The following data are utilized in the present study;

GMS IR images: obtained at 6-hour intervals,

T_{BB} maps: map of cloud top temperature estimated from GMS IR data, prepared by the Meteorological Satellite Center,

Upper observation data: in TEMP A and B code,

Objective analysis data: prepared by the Numerical Prediction Division, JMA,

Surface data: in SYNOP code, digital record at 10-min. interval and self recording data,

AMeDAS data: hourly data from Automated Me-

Fig. 1. Geographic map of the East Asia and the northwestern Pacific. Some geographical areas and observation stations are indicated. H, S, and K.P. indicate Hokkaido, Saghalin and the Kamchatka Peninsula, respectively.

teorological Data Acquisition System (station interval ~ 20 km, about 2/3 of AMeDAS stations report surface wind velocity, temperature, precipitation and sunshine duration, and other 1/3 of them report precipitation only),

Radar data: radar echo maps obtained by Hakodate, Sapporo and Kushiro meteorological radar, and Surface, 850, 700 and 500 mb maps: in the Daily Weather maps issued by JMA.

3. Overview of polar low in 9–11 December 1985

Figure 1 shows the geographic map of the East Asia and the northwestern Pacific areas. Some geographical areas and observation stations, which are mentioned in the following sections, are indicated on the map. On the map, H ($\sim 45^\circ\text{N}/142^\circ\text{E}$), S ($\sim 50^\circ\text{N}/142^\circ\text{E}$) and K.P. ($\sim 55^\circ\text{N}/160^\circ\text{E}$) indicate Hokkaido, Saghaline and the Kamchatka Peninsula, respectively.

The surface map at 12 GMT 9 December 1985 is presented in Fig. 2. A synoptic-scale low (980 mb) in the developing stage was located over $\sim 45^\circ\text{N}/152^\circ\text{E}$. This synoptic-scale low formed around 00 GMT 8 December under the influence of a westerly trough aloft. The synoptic-scale low developed rapidly from 992 mb at 00 GMT 9 to 964 mb at 00 GMT 10 December. A polar low formed over the east coast of the Continent, within the cyclonic circulation of the synoptic-scale low on 9 December. On the surface map, the location of the synoptic-scale low (indicated by the blacked circle) and the

Fig. 2. The surface map at 12 GMT 9 December 1985. The center of the synoptic-scale low (indicated by the blacked circle) and the polar low (indicated by the comma) are shown at 12-hour intervals.

polar low (indicated by the comma) are shown at 12-hour intervals.

The GMS IR (infrared) images at 00 GMT 9, 12 GMT 9, 00 GMT 10, 12 GMT 10 and 00 GMT

11 December 1985 are presented in Fig. 3, Fig. 4, Fig. 5, Fig. 6 and Fig. 7, respectively.

The features of cloud systems of the synoptic-scale low and the major polar front in these images are described first. In Fig. 3 (00 GMT 9) the synoptic-scale low (992 mb, at $\sim 41^\circ\text{N}/147^\circ\text{E}$) and the major polar front are seen over the Pacific to the east of Japan. In Fig. 4 (12 GMT 9 December), the cloud area of the synoptic-scale low is seen around $46^\circ\text{N}/152^\circ\text{E}$ and a large cloud zone of the polar front extends from $30^\circ\text{N}/155^\circ\text{E}$ to $40^\circ\text{N}/170^\circ\text{E}$. As the occlusion process progressed, the cloud system of the synoptic-scale low was separated from the major polar front (Fig. 5, at 00 GMT 10 December). After the completion of the occlusion, the cloud zone of the secondary front formed within the southeastern quadrant of the occluded low (Fig. 6 and Fig. 7).

The evolution of the polar low is also seen in these IR images. At 00 GMT 9 December, a mesoscale cloud vortex of the polar low formed at $46^\circ\text{N}/140^\circ\text{E}$ (Fig. 3), within the cyclonic circulation of the synoptic-scale low.

The surface map at 12 GMT 9 December is shown in Fig. 2. At this time, the polar low is seen on the IR image (Fig. 4) as a cloud vortex centered at $46^\circ\text{N}/140^\circ\text{E}$. The thick cloud shield ($T_{BB} \approx -40^\circ\text{C}$, cloud top 600 mb) of 500 km extent is seen on the north side of the polar low, while thin cumulus bands are seen on the south side.

Fig. 3. The GMS IR image at 00 GMT 9 December 1985. The cloud vortex of the polar low is at $46^\circ\text{N}/140^\circ\text{E}$.

Fig. 4. The GMS IR image at 12 GMT 9 December 1985. The polar low is at $46^{\circ}\text{N}/140^{\circ}\text{E}$.

Fig. 5. The GMS IR image at 00 GMT 10 December 1985. The polar low is at $44^{\circ}\text{N}/138^{\circ}\text{E}$.

Fig. 6. The GMS IR image at 12 GMT 10 December 1985. The polar low is at 43°N/139°E.

Fig. 7. The GMS IR image at 00 GMT 11 December 1985. The polar low is at 42°N/141°E.

While the synoptic-scale low moved northeastward to $\sim 50^\circ\text{N}/150^\circ\text{E}$ at 12 GMT 10 December, the polar low remained over the northern Japan Sea. In the mature stage of the polar low (at 00 GMT 10, Fig. 5), the cloud system of the polar low ($44^\circ\text{N}/138^\circ\text{E}$) showed its largest extension. The thick cloud shield ($T_{BB} \approx -50^\circ\text{C}$, cloud top 450 mb) with ~ 300 km N-S and ~ 1000 km W-E extension was seen over the north side of the polar low. The thin cumulus spiral bands appeared over the center and the south side of the polar low. The IR image shows a cloud-free spot, similar to an “eye” in the very center of the cloud spiral.

After the mature stage of the polar low, the thick cloud shield over the north side of the polar low disappeared gradually (Fig. 6, 12 GMT 10 December). However, the well organized cumulus spiral bands and the “eye” were still sustained.

After 12 GMT 10 December, the polar low weakened gradually as it moved ESE-ward from the east coast of the Continent. Figure 7 (00 GMT 11 December) shows the cloud features of the polar low in the decaying stage, which was located at $42^\circ\text{N}/141^\circ\text{E}$ over the Pacific coast of Hokkaido. A comma-shaped cloud band of ~ 400 km length and a few thin cumulus bands appeared on the west side of the polar low. The east-northeast side of the polar low was characterized by very little cloudiness.

After 00 GMT 11 December, the polar low moved eastward with speed of 800 km/day and weakened rapidly, although the GMS IR image is not shown for this stage.

4. Large-scale setting for polar low formation

The large-scale situation for 8–11 December 1985, during which the polar low developed, is studied in this section.

The map of the mean sea-surface temperature (SST) for 1–10 December 1985 is presented in Fig. 8. In the northwestern Pacific, the 10°C SST isotherm was approximately along the 40°N latitude circle, and the zone of large SST gradient ($\sim 10^\circ\text{C}/500$ km) was in $42\text{--}37^\circ\text{N}$. In the Japan Sea, owing to the northeast-bound warm Tsushima current, the warm SST area extended to the west coast of Hokkaido.

The thermal contrast between the very cold continent and the warm sea areas yields the strong thermal gradient in the lower troposphere over the east coastal zone of the continent (see Fig. 10 and Fig. 12).

The evolution process of the polar low, and the relation among the polar low, the synoptic-scale low, the 500 mb cut-off low and the 500 mb cold core will be studied first.

The 500 mb maps at 12 GMT 8, 12 GMT 9 and 12 GMT 10 December 1985 are presented in Fig. 9. The hatched area indicates the 500 mb cold area enclosed by the -42°C isotherm. The location and

Fig. 8. The mean sea-surface temperature for 1–10 December 1985.

the central pressure of the synoptic-scale low are indicated in Fig. 9. The location of the polar low is indicated by the “comma” in Fig. 9.

Figure 10 is the 500 mb longitude-time section for 00 GMT 8–12 GMT 11 December 1985. This longitude-time section is made by using data from the observation stations aligned along the path of the 500 mb cut-off low. The location of these stations is shown in Fig. 1.

A large-scale trough propagated from the Asian Continent to the northwestern Pacific with a speed of ~ 800 km/day. A 500 mb cold core and a cut-off low were seen in the trough. In 8–9 December, the 500 mb cold core and the cut-off low were in phase. However, after 10 December, the 500 mb cold core remained over Hokkaido ($\sim 140^\circ\text{E}$), while the cut-off low alone moved away to the northwestern Pacific ($\sim 160^\circ\text{E}$).

The synoptic-scale low (Fig. 2) formed and developed in front of the large-scale trough. On 9 December, the polar low formed within the cyclonic circulation of the synoptic-scale low and under the cold cut-off low aloft. The polar low reached to its mature stage around 00 GMT 10 December under the 500 mb cold core. At 12 GMT 10 December, the 500 mb cold core and the polar low remained around Hokkaido, while the 500 mb cut-off low and the synoptic-scale low moved to $50^\circ\text{N}/160^\circ\text{E}$. The polar low weakened when the 500 mb cold core weakened as it moved eastward.

The situation in the lower troposphere will be described next. Figure 11 shows the 850 mb longitude-time section for 00 GMT 8–12 GMT 11 December 1985. The strong thermal gradient in the W-E direction of $\sim 10\text{K}/300$ km is seen around 138°E , between the continent and the sea area. The polar low

Fig. 9. The 500 mb height field at 12 GMT 8, 12 GMT 9 and 12 GMT 10 December 1985. The hatched area indicates the 500 mb cold area colder than -42°C . The blacked circle and comma indicate the synoptic-scale low (center surface pressure is also given) and the polar low, respectively.

formed and remained for 36 hours within the zone of strong thermal gradient. It is also found in Fig. 11 that the polar low formed and developed within the low pressure area and the circulation of the synoptic-scale low.

Figure 12 shows the 850 mb map at 12 GMT 9 December 1985. A zone of strong thermal gradient over the northwestern Pacific bounded by the 0°C and 6°C isotherms corresponds to the major polar frontal zone. There is another zone of strong thermal gradient of 300–500 km width along the east-southeastern coast of the continent. The thermal gradient in this zone is $\sim 10^{\circ}\text{C}/300\text{ km}$.

Fig. 10. Longitude-time section of 500 mb height (solid line), temperature (broken line) and wind velocity (a full wind barb and a flag express 10 and 50 knots, respectively) for the period between 00 GMT 8 and 12 GMT 11 December 1985. The location of the polar low is shown by the comma. See Fig. 1 for the location of observation stations.

Fig. 11. Longitude-time section of 850 mb height (solid line), temperature (broken line) and wind velocity for the period between 00 GMT 8 and 12 GMT 11 December 1985. The location of the polar low is indicated by the comma.

Fig. 12. The 850 mb map at 12 GMT 9 December 1985. The solid and broken lines are the height contours and the isotherms, respectively. The thick broken line indicates the W-E trough (shear line).

On 9 December 1985, the synoptic-scale low developed over the northwestern Pacific to the east of Hokkaido in ahead of the large-scale westerly trough (Fig. 2 and Fig. 9). The cyclonic circulation in the rear of the synoptic-scale low predominated over the zone of strong thermal gradient along the coast of the continent.

The easterly winds in the northwestern quadrant of the synoptic-scale low advected warm air, while the westerly winds in the southwestern quadrant of the low advected cold air. Due to these thermal advections, the N-S thermal gradient was enhanced in the western part of the synoptic-scale low. At the same time, the synoptic-scale low elongated westward and a shear line (*i.e.*, a trough in W-E direction) formed to the west of the low's center (indicated by a heavy broken line in Fig. 12). The polar low formed in the W-E trough under the influence of the cold cut-off vortex aloft.

Since the polar low formed as a sub-circulation system in the synoptic-scale low, the latter is considered as the parent circulation (low) of the polar low. The polar low genesis in the synoptic-scale parent low will be discussed in more detail in the following sections.

5. Vertical extension of the polar low's cyclonic circulation

The 850, 700 and 500 mb maps at 00 GMT 9, 12 GMT 9, 00 GMT 10, 12 GMT 10 and 00 GMT 11 December 1985 are presented in Fig. 13. In each map, the center of the polar low, which is determined from the IR cloud image, is indicated by the

comma.

Around 00 GMT 9 December, the polar low formed within the cyclonic circulation on the west side of the parent low, which prevailed over the zone of strong thermal gradient in the lower troposphere. At this time, the cut-off cold low aloft was centered at $\sim 45^\circ\text{N}/135^\circ\text{E}$. The cyclonic circulation of the cut-off low was seen at 700 and 500 mb levels. The polar low formed ~ 400 km to the east of the cut-off low aloft. In the formation stage, the cyclonic circulation of the polar low was limited to the lower troposphere.

At 12 GMT 9 December, the cloud vortex of the polar low was clearly seen on the IR cloud image (Fig. 4). At this time, the polar low was located ~ 200 km to the east of the cut-off low aloft. The W-E shear line in the western part of the parent low was evident at this stage. The cyclonic circulation of the polar low was found at both 850 and 700 mb levels.

Around 00 GMT 10 December, the polar low was in the mature stage. The cloud system of the polar low attained the largest extension, and spiral cloud bands were found (Fig. 5). At the 850 mb level, the warm advection by the easterly winds in the north side of the shear line, and the cold advection by the westerly winds in the south side of the shear line were most evident in this stage. The polar low was located under the cut-off low aloft. The cyclonic circulation of the polar low reached to 500–400 mb. The aforementioned features indicate the important role of the coupling between the vortex aloft and the low-level circulation system in the development of the polar low.

As the cut-off low aloft and the parent low moved northeastward and passed away from the coastal zone, the polar low weakened gradually. At 12 GMT 10 December, the cut-off low and the parent low were at $\sim 50^\circ\text{N}/160^\circ\text{E}$ (the bottom map in Fig. 9). On the IR cloud image (Fig. 6), the extension of the cloud system of the polar low reduced significantly. The cyclonic circulation of the polar low was no longer evident at the 500 mb map. At 00 GMT 11 December, the polar low weakened rapidly as it moved toward the Pacific coast of Hokkaido. The cyclonic circulation of the polar low was limited in the lower troposphere.

As described above, the cyclonic circulation of the polar low was confined within the lower troposphere, except during its mature stage when the cyclonic circulation reached to the middle troposphere.

6. Polar low genesis in synoptic-scale parent low

In Section 4, we described the features of the wind and thermal fields at 12 GMT 9 December 1985 and discussed the favourable conditions for the polar low formation. We will study further the process of the

Fig. 13. The 500, 700 and 850 mb map at 00 GMT 9, 12 GMT 9, 00 GMT 10, 12 GMT 10 and 00 GMT 11 December 1985. The thick solid lines indicate the geopotential height contours (60 gpm interval). A supplemental contour with 30 gpm interval is given by a thin solid line. The broken lines indicate the isotherms (6°C interval). The polar low is indicated by the comma. The thick broken line indicates the W-E trough (shear line).

polar low genesis.

Figure 14 shows the 500, 700 and 850 mb maps at 00 GMT 10 December 1985. At 500 mb, a meso- α -scale low enclosed by the 5060 gpm contour was embedded in the large-scale trough. In the lower troposphere (850 and 700 mb), the W-E shear line was seen within the synoptic-scale parent low. It is an important fact that the warm air advection and the westward protrusion of the warm air occurred on the north side of the shear line by the easterly winds from the oceanic areas to the Continent. The

cold air advection and the eastward protrusion of the cold air occurred on the south side of the shear line by the westerly winds from the continent to the oceanic areas.

The vertical distribution of the wind and the temperature distribution on the skew log p-T diagram obtained at stations 31-960, 31-909 and 47-401 (see Fig. 1 for the stations) at 12 GMT 9 and 00 GMT 10 December 1985 are presented in Fig. 15. The stations 31-909 and 47-401 were located in the easterly flow on the north side of the shear line, while the

00 GMT 10 DEC 1985

Fig. 14. The 500, 700 and 850 mb map at 00 GMT 10 December 1985. The contours and isotherms are given by the solid and broken lines, respectively. The center of the polar low is indicated by the comma. The thick broken line in 850 mb map indicates the W-E trough (shear line).

station 31-960 was located in the westerly flow on the south side of the shear line.

It is obvious that, in 1000–600 mb layer, the higher temperature was associated with the easterly wind from the oceanic areas to the continent, and the lower temperature was associated with the westerly wind from the continent to the oceanic areas. The aforementioned features in the thermal field are different from the features in the simple winter monsoon, in which the strong thermal gradient is main-

Fig. 15. Top panel: The temperature and wind data at station 31-960, 31-909 and 47-401 (see station map in Fig. 1) at 12 GMT 9 December 1985. The thin broken line in the skew log p-T diagram is the moist adiabatic ascent line with θ_e (equivalent potential temperature) of 277K. Winds are given in knots with north "upwards". The hatched layer shows the moist layer in which the dewpoint depression is smaller than 3°C. Bottom panel: The temperature and wind data at station 31-960, 31-909 and 47-401 at 00 GMT 10 December 1985.

tained in the lower troposphere in the northwesterly flow over the sea areas due to the airmass transformation process (Ninomiya, 1968).

The moist layers in which the dew-point depression is smaller than 3°C over stations 31-909, 31-960 and 47-412 are indicated by the hatched layers in Fig. 15. The thick moist layer over station 31-909 indicates the upward motion in the easterly wind and the warm advection zone to the north of the W-E trough (shear line).

It is also found that the shield of thick cloud

Fig. 16. Top panel: the 500 mb height (thick solid line) and vorticity (thin solid line, unit; $\times 10^{-6} \text{ sec}^{-1}$) field at 12 GMT 9 December 1985. The hatched area indicates the positive vorticity. Bottom panel: the 850 mb temperature (thick solid line) and 700 mb vertical- p -velocity (ω , thin solid line, unit; mb/hour) at 12 GMT 9 December 1985. The hatched area indicates negative ω (upward motion).

(Fig. 5) formed over the north side of the shear line, where warm air was advected by the easterly winds. The area of small cloudiness (the thin cumulus spiral bands are clearly seen in this area) covered the south side of the shear line, where the cold air was advected by the westerly winds. This fact indicates that the upward motion occurred in the warm air over the north side of the shear line, and the downward motion occurred in the cold air over the south side of the shear line.

The polar low formed in the W-E trough, under the influence of the upper cut-off low, as a subcirculation system of the synoptic-scale parent low.

Next, the vorticity and the vertical velocity fields shall be mentioned. Figure 16 shows the 500 mb height, the 500 mb vorticity (ζ), the 850 mb temper-

ature and the 700 mb vertical- p -velocity (ω) fields at 12 GMT 9 December 1985. These maps are obtained from the initial field of the Fine-mesh Limited area Model (FLM) with 127 km mesh.

At 12 GMT 9 December 1985, a zone of large positive vorticity ($\sim 60 \times 10^{-6} \text{ sec}^{-1}$) elongated along the southern rim of the 500 mb cut-off low from $\sim 125^\circ\text{E}$ to $\sim 155^\circ\text{E}$. The zone of the 700 mb upward motion extended along the north-northeast side of the zone of maximum vorticity. The zone of the 700 mb upward motion (bottom panel in Fig. 16) agrees well with the cloud distribution on the IR image (Fig. 4). The major maximum of the upward motion ($\omega = -22 \text{ mb/hour}$) at $47^\circ\text{N}/156^\circ\text{E}$ was associated with the synoptic-scale low, while the secondary maximum of the upward motion ($\omega = -9 \text{ mb/hour}$) at $47^\circ\text{N}/139^\circ\text{E}$ corresponded to the polar low.

At 00 GMT 10 December (a figure is not presented), the zone of maximum vorticity elongated along the south-southeast side of the large-scale trough. The zone of maximum upward motion formed along the north of the zone of maximum vorticity from $\sim 46^\circ\text{N}/137^\circ\text{E}$ to $\sim 50^\circ\text{N}/170^\circ\text{E}$. The major area of the 700 mb upward motion ($\omega = -13 \text{ mb/hour}$), which was associated with the synoptic-scale low, was seen over $49^\circ\text{N}/163^\circ\text{E}$. The secondary maximum of the upward motion ($\omega = -7 \text{ mb/hour}$), which corresponded to the polar low, was seen over $47^\circ\text{N}/138^\circ\text{E}$.

The aforementioned distribution of ζ and ω is commonly found for the case of the polar low formation over the east coast of the Asian Continent.

From the above analysis, we shall infer the following process of polar low formation within the parent low.

The large-scale features in the lower troposphere over the east coast of the Asian Continent and the circulation of the synoptic-scale parent low are schematically illustrated in Fig. 17. The panel A of Fig. 17 presents the features of the zone of large thermal gradient in the lower troposphere along the east coast of the Asian Continent in the "undisturbed state". The zone of large thermal gradient forms in the boundary between the cold continental airmass and the warm oceanic airmass. The high pressure (anticyclone) appears over the Continent and the low pressure appears over the northwestern Pacific. In the coastal zone, the surface winds are northerly as indicated by V_{sfc} in the figure. The "thermal wind" (the vertical shear of the geostrophic wind) is, however, southerly, because of the cold airmass in the west and the warm airmass in the east, as indicated by V_t in the figure.

The panel B in Fig. 17 shows the features in the coastal zone under the influence of the synoptic-scale low. When the synoptic-scale low developed over the northwestern Pacific, east of Japan, in front of the large-scale trough, the cyclonic circulation of the

Fig. 17. A: Schematic illustration of the zone of strong thermal gradient in the lower troposphere along the boundary between the continent and the ocean in "the undisturbed period". V_{sfc} and V_t indicate schematically the surface wind and the thermal wind. B: Schematic illustration of the zone of large thermal gradient under the influence of the cyclonic circulation of the synoptic-scale low. The warm air advection appears in the northwestern quadrant of the low and the cold air advection appears in the southwestern quadrant of the low. Under this situation, the W-E trough (shear line) forms in the western part of the low. The polar low forms within the W-E trough.

synoptic-scale low predominated over the coastal zone. The easterly wind in the northwestern quadrant of the low advected the warm air from the Pacific to the Continent. The upward motion occurred in this warm air. The westerly wind in the southwestern quadrant of the low advected the cold air from the Continent. The downward motion occurred in the cold air.

The aforementioned process is regarded as the frontogenesis in the horizontal shear flow. Figure 18(1), (2) and (3) illustrate the frontogenesis in the deformation (confluence), shear and convergence fields, respectively, where the solid lines with arrows represent stream lines and the broken lines

show isotherms. While the deformation (Fig. 18(1)) and the convergence (Fig. 18(3)) increase the thermal gradient in A-a direction, the shear flows (Fig. 18(2)) increase the thermal gradient in B-b direction because of the warm advection in the right side and the cold advection in the left side. If we rotate Fig. 18(2) anticlockwise by 90° , we will get the same situation as panel B of Fig. 17.

Due to the frontogenesis in the shear flows, the N-S thermal gradient increased on the west side of the synoptic-scale low. Simultaneously, the W-E trough (shear line) developed in the western part of the synoptic-scale low. At this stage, the polar low formed and developed in the W-E trough under the influence of the cut-off cold low aloft. The synoptic-scale low played the role of the parent circulation of the polar low.

Next, we shall discuss the influence of the cut-off cold low aloft on the formation of the polar low. In general, the vertical stretching of the vortex tube due to the upward motion associated with the cut-off low and the decrease of the vertical stability associated with the passage of the cut-off low are the important processes in the coupling of the upper- and low-level circulation systems.

In this case, the initial field of the FLM shows the upward motion in front of the cut-off low. The vertical-p-velocity at 700 mb (ω_{700}) at 12 GMT 09 December 1985 was shown in Fig. 16. The ω_{700} of -9 mb/hour is seen in front of the cut-off low. The ω_{700} of -2 , -9 , -7 and -5 mb/hour are seen over the west coast of Hokkaido at 00 GMT 09, 12 GMT 09, 00 GMT 10 and 12 GMT 10 December 1985, respectively (figures are not shown).

The vertical stability $-\partial\theta/\partial p$ in 850–500 mb layer at 31–909 and 47–401 (see the location in the station map in Fig. 1) in 08–11 December 1985 are presented in Table 1. The vertical stability decreases with the passage of the cut-off cold low aloft.

The aforementioned features indicate that the cut-off cold low aloft played an important role in the formation of the polar low.

7. Surface analysis of the polar low

After 12 GMT 10 December 1985, the polar low weakened as it moved toward the west coast of Hokkaido and further to the Pacific coast. The surface map at 18 GMT 10 December is shown in the left panel of Fig. 19. At this time, the synoptic-scale low moved away to $50^\circ\text{N}/160^\circ\text{E}$, and the polar low was seen as an isolated small low in the northerly streams of the polar air. The local surface map over Hokkaido is presented in the right panel of Fig. 19, where the data from synoptic observation stations are plotted. The diameter of the outermost closed isobar of the polar low was about 200 km.

In the following analysis, the data from dense AMeDAS stations are used. The AMeDAS surface

Fig. 18. Schematic illustration of the frontogenesis process. The solid lines represent the flow pattern. The broken lines show the isotherms.; (1) Frontogenesis due to deformation. (2) Frontogenesis due to horizontal shear. (3) Frontogenesis due to convergence. (Adopted from Ogura, 1984)

Table 1. The vertical stability $-\partial\theta/\partial p$ in 850–500 mb layer at 31-909 and 47-401 (see the station map in Fig. 1) in 08–11 December 1985. Unit is in K/100-mb.

	31-909	47-401
12 GMT 08	5.6	5.4
00 GMT 09	5.3	3.5
12 GMT 09	3.6	2.0
00 GMT 10	2.2	1.9
12 GMT 10	x	2.5
00 GMT 11	x	2.8

analysis was made every hour. As examples, the AMeDAS surface maps at 18 and 20 GMT 10 December are presented in Fig. 20. The polar low was seen on these maps as a meso- α -scale cyclonic circulation system. The hourly location of the polar low determined by the surface analysis is shown in Fig. 21 by the comma. In Fig. 21, some stations are also indicated.

As shown in Fig. 21, the polar low passed by the synoptic station 47-421 (Suttsu) around 18 GMT 10 and 47-423 (Muroran) around 20 GMT 10 December. The sea-level pressure (P_s) at station 47-421, 47-423 and 47-412 (Sapporo) during 00 GMT 10–12 GMT 11 December are presented in the top panel of Fig. 22. The minimum pressure at stations 47-421 and 47-423 indicates the passage of the polar low nearby the respective station. The pressure dip is not seen at station 47-412, which was ~ 100 km from the path of the polar low. Therefore $P_{s421} - P_{s412}$ (the difference between P_s at 47-421 and 47-412) and $P_{s423} - P_{s412}$, which are shown in the bottom panel of Fig. 22, will represent the sea-level pressure change due to the passage of the polar low at the respective station. The depth of the polar low changed from -6 mb at station 47-421 to -3 mb at station 47-423. This means that the polar low weakened

Fig. 19. Left panel: The surface map at 18 GMT 10 December 1985. Right panel: The surface map over Hokkaido at 18 GMT 10 December 1985.

rapidly during a few hours passage over the land of Hokkaido.

The time sequence of the surface data (P_s : sea-level pressure, T : temperature, T_d : dewpoint temperature, R : precipitation, G : peak gust speed, V : 10-minute averaged wind speed and the wind direction) at station 47-421 (Suttsu) are presented in Fig. 23. Figure 24 shows the surface hourly data at AMeDAS station A21226 (Ohokishi). In Fig. 24, a full wind barb and a flag indicate a wind speed of 2 and 10 m/sec, respectively.

The features of the polar low in the decaying stage over Hokkaido are easily seen in Fig. 20, Fig. 23 and Fig. 24. On the AMeDAS surface maps (Fig. 20), the polar low appeared as the cyclonic circulation of ~ 200 km diameter. The wind speed was large in the southeastern quadrant (southerly wind) of the polar low. The time sequence data (Fig. 23 and Fig. 24) also show strong southerly wind during a few hours preceding the passage of the polar low.

The time sequence of the surface temperature at Suttsu (47-421, Fig. 23) shows that the temperature

Fig. 20. The AMeDAS surface map at 18 and 20 GMT 10 December 1985. A full wind barb and flag indicate a wind speed of 2 and 10 m/sec respectively. The isotherms are given at 2°C interval. The thin and thick hatched area show the precipitation more than 1 and 2 mm/hour, respectively.

Fig. 21. Path of the polar low during 12 GMT 10–00 GMT 11 December 1985. Some stations indicated in the map.

rise around 12 GMT 10 December was not associated with a change in the wind direction but with an increase in the peak gust speed. This indicates the destruction of the cold stable boundary layer through the forced mixing by the rough winds of the polar low. Figure 24 (the data at Ohkishi, A21226) shows a temperature rise associated with the

southerly wind from the sea area, and a temperature fall associated with the northerly wind from the inland parts of Hokkaido. AMeDAS surface maps (Fig. 20) also show the strong thermal gradient between the area of strong winds from the sea and the

Fig. 23. The surface data at Suttsu (47-421) during 09 GMT 10–02 GMT 11 December 1985. P_s : the sea-level pressure, T : temperature, T_d : dewpoint temperature, R : precipitation, G : peak gust speed, V : 10-minute averaged wind speed, wind barb: wind direction.

area of winds from the cold inland areas.

Some reports (e.g., Ohokubo *et al.*, 1989) noted that the mesoscale low on the west coast of Hokkaido has the warm core. Some papers (Tsuboki and Wakahama, 1992) inferred that the low-level thermal gradient between the west coast of Hokkaido and the inland of Hokkaido is important for the development of the mesoscale low. In the present case of the polar low, the thermal gradient between the inner area of the polar low and the outer areas is seen in the boundary zone between the maritime air which intruded into the inland area and the cold air which flowed out from the inland high-pressure area of Hokkaido. It must be noted that the polar low weakened, in spite of the aforementioned thermal gradient in the lowermost layer, over the west coast and land area of Hokkaido as the parent low moved out from the polar low.

The AMeDAS observations indicate that precipitation (1–3 mm/hour) was associated, in general, with the southerly wind in the southeastern quadrant of the polar low (Fig. 20, Fig. 23 and Fig. 24). The distribution of precipitation by the polar low is also seen by radar observations. Figure 25 shows the three radar (Sapporo 47-412, Hakodate 47-430 and Kushiro 47-418) composited echo maps

Fig. 24. The hourly data of wind velocity (a full wind barb and a flag indicate a wind speed of 2 and 10 m/sec, respectively), temperature (T), and precipitation (R) at AMeDAS station Ohkishi (A21226) during 09 GMT 10–02 GMT 11 December 1985.

at 19:30 GMT 10 and 00 GMT 11 December 1985. The areas with precipitation rate of 0–1 mm/hour are shown by the hatched areas. Spiral precipitation bands are seen in southern parts of the polar low.

8. Concluding remarks

The present paper studied the development of a polar low during 9–11 December 1985 over the east coast of the Asian Continent.

In winter, the low-level strong thermal gradient is maintained in the coastal zone. When a large-scale westerly trough including a cut-off cold vortex approached the east coast, a synoptic-scale low developed over the northwestern Pacific to the east of Japan, and the cyclonic circulation of the synoptic-scale low predominated over the coastal zone. The easterly winds in the northwestern quadrant of the low advected the warm air from the sea areas, while the westerly winds in the southwestern quadrant of the low advected the cold air from the continent. These thermal advections increased the N–S thermal gradient in the western part of the low. This corresponds to frontogenesis due to the horizontal shear. Under this situation, the W–E oriented trough (shear line) formed in the lower troposphere over the western part of the low as illustrated in Fig. 17B. The polar low formed in the W–E trough under the influence of the cut-off cold vortex aloft. Thus, the synoptic-scale low played the role of the parent circulation of the polar low.

A similar process is commonly found for the polar low genesis over the east coast of the Asian Continent (on 14 January 1986, 4 January 1987 and 10 January 1987, for examples). The aforementioned process will explain the frequent occurrence of the polar low over the east coast of the Asian Continent

Fig. 25. Three-radar (Sapporo, Hakodate and Kushiro radars) composite echo map at 19:30 GMT 10 and 00 GMT 11 December 1985. The hatched areas show areas of precipitation rate of 0–1 mm/hour. The broken lines in the map show the boundary of the radar shadow for 2000 m echo height.

in the 40–55°N zone (Ninomiya, 1989). This process is different from that of the polar low around northwestern Europe and the comma cloud low in the northeastern Pacific.

It must be noted that the large-scale setting and the generation process of the “polar low over the east coast of the Asian Continent” are different from those of the “meso-scale low over the west coast of Hokkaido”, which is the meso- β - or meso- γ -scale low which forms in the boundary between the warm flows over the Japan Sea and cold flows from the inland area of Hokkaido (Tsuboki and Wakahama, 1992).

We need more systematic and comprehensive studies for the various cases of the polar low over the east coast of the Asian Continent for the further understanding of the polar low.

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References

- Asai, T. and Y. Miura, 1981: An analytical study of meso-scale vortex-like disturbances observed around Wakasa Bay area. *J. Meteor. Soc. Japan*, **59**, 832–843.
- Businger, S. and R.J. Reed, 1989: Cyclogenesis in cold air masses. *Weather and Forecasting*, **4**, 133–156.
- Kibe, S., 1988: Small scale low in the vicinity of the west coast of Hokkaido Island. *Tenki*, **35**, 146–151 (in Japanese).
- Kibe, S., 1989: Structure and classification of small-scale low over the west coast of Hokkaido. *Technical Note, Sapporo District Meteorological Observatory, Special Issue*, **38**, 12–32 (in Japanese).
- Miura, Y. and T. Asai, 1987: Formation process of the mesoscale vortex generated under the winter monsoon. *Proc. Third Conference on Mesoscale Processes*, Aug. 25–26, 1987, Vancouver, Canada, 139–140.
- Miyazawa, S., 1967: On vortical mesoscale disturbances observed during the period of heavy snow or rain in Hokuriku district. *J. Meteor. Soc. Japan*, **45**, 166–176.
- Motoki, T., 1974: A small cyclonic echo pattern formed in the Ishikari Plain. *Tenki*, **21**, 245–250 (in Japanese).
- Muramatsu, T., S. Ogura and N. Kobayashi, 1975: The heavy snowfall arisen from small scale cyclone on the west coast of Hokkaido Island. *Tenki*, **22**, 369–379 (in Japanese).
- Ninomiya, K., 1968: Heat and water budget over the Japan Sea and the Japan Islands in winter season. *J. Meteor. Soc. Japan*, **46**, 343–372.
- Ninomiya, K., 1989: Polar/comma-cloud lows over the Japan Sea and the northwestern Pacific in winter. *J. Meteor. Soc. Japan*, **67**, 83–97.
- Ninomiya, K., K. Hoshino and K. Kurihara, 1990: Evolution process and multi-scale structure of a polar low developed over the Japan Sea on 11–12 December 1985. Part I: Evolution process and Meso- α -scale structure. *J. Meteor. Soc. Japan*, **68**, 293–306.

- Ninomiya, K. and K. Hoshino, 1990: Evolution process and multi-scale structure of a polar low development over the Japan Sea on 11~12 December 1985. Part II: Meso- β -scale low in meso- α -scale polar low. *J. Meteor. Soc. Japan*, **68**, 307-318.
- Ogura, Y., 1984: *General Meteorology*. Tokyo University Press, 314 pp (in Japanese).
- Ohkubo, H., K. Wakahara and K. Taniuchi, 1989: Case study of A-type cloud vortex snow storm. *Technical Note, Sapporo District Meteorological Observatory, Special Issue*, **38**, 65-79 (in Japanese).
- Orlanski, I., 1975: A rational subdivision of scale for atmospheric processes. *Bull. Amer. Meteor. Soc.*, **56**, 527-530.
- Rasmussen, E., 1983: A review of meso-scale disturbances in cold air masses. *Mesoscale Meteorology*, 247-283, Radel Pub. Co.
- Suginaka, S., 1964: Small low and local heavy snowfall around the west coast of Hokkaido, *Tenki*, **11**, 183-188 (in Japanese).
- Tatsuno, I., 1974: Analysis of a mesoscale disturbance. *Kisho kenkyu Note*, **120**, 59-70 (in Japanese).
- Tsuboki, K. and G. Wakahama, 1992: Mesoscale cyclogenesis in winter monsoon air stream (to be published).
- Wakahara, K., 1989: Review on small-scale low over the west coast of Hokkaido. *Technical Note, Sapporo District Meteorological Observatory, Special Issue*, **38**, 1-12 (in Japanese).
- Yagi, S., T. Yoshida, N. Maeda, A. Kamoshida, Y. Tanaka, H. Kikuchi and T. Nakajima, 1979: Analysis of small scale low in the west coast of Hokkaido. *Tenki*, **26**, 87-97 (in Japanese).

1985 年 12 月 9-11 日のアジア大陸東岸における Polar Low の発達

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北日本周辺の寒気内小低気圧は次の 2 種類に大別される; (1) アジア大陸東岸で発生する meso- α -scale の polar low、(2) 北海道西岸で海上の暖気と北海道内陸からの寒気流の境界で発生する meso- β ~ γ -scale low。

本報告では (1) の典型例として 1985 年 12 月 9-11 日の polar low 発生・発達を調べ、下記の発生発達過程を見出した。(1) アジア大陸東岸の下部対流圏では準定常的に強い気温傾度が維持されている。(2) 寒冷渦を含む大規模トラフが接近し、その前方の日本東方海上で総観規模低気圧が発達する。(3) 大陸東岸で低気圧の循環が強まり、北西象限の東風による暖気移流、南西象限の西風による寒気移流が強まる。このシアーによる frontogenesis の状況下で対流圏下層で低気圧は西側に伸び東西に伸びるトラフ (シアーライン) が形成される (第 17 図参照)。(4) 北側の暖気移流域では上昇流と厚い雲域が、南側の寒気移流域では下降流と少雲量域があらわれる。(5) 同時的に、寒冷渦の近傍かつ W-E トラフの内部で polar low が発生する。(6) 以上のように、総観規模低気圧は polar low の parent low の役割をはたしている。(7) 発生期、polar low の循環は対流圏下層でのみ見られる。最盛期には eye を持つ spiral cloud bands が形成され低気圧性循環は対流圏中層におよぶ。(8) 上層寒冷渦前面の上昇流、寒冷渦通過に伴う鉛直安定度の減少が polar low 発生に有利な条件となる。(9) parent low が北西太平洋に去り、polar low が大陸東岸を離れるにしたがい polar low は急速に衰える。(10) polar low が北海道に上陸した時、その中心部と東外縁部との間に強い気温傾度が見られた。これは polar low の気流によって海上から侵入した暖気と北海道内陸の寒気との間の気温傾度であるが、この時点で polar low は衰弱している。