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Relationship between Mesoscale Vortices and a Band Cloud on the West Coast of Hokkaido: A Case Study of a Meso-γ-Scale Wave Train during Special Radar Observations

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Abstract

Meso-γ-scale vortices (a wave train) were observed on January 15, 1987 during special radar observations at Haboro, Hokkaido Japan. The life cycle of the wave train, accompanied by a meso-β-scale vortex and a Band Cloud, is documented in this paper. The meso-γ-scale vortices were generated in the cloud band of the meso-β-scale vortex, where the wind shear and temperature gradient were strong. The life time of the two vortices of the wave train was 1 hour. These vortices were composed of outer spiral band echoes of 20 km and 30 km in diameter with an echo free area, gusts and warm cores inside. However, the evolution of the echoes of the two vortices was not the same because of the difference between the land and sea surface conditions.

The wave train generated in the cloud band of the meso-β-scale vortex (lifetime of several hours), which was formed at the rear side of meso-α-scale low ($\sim$1 day), was influenced by a synoptic short-trough. The multi-scale structure of vortices which were formed from meso-α to meso-γ-scale in the cold air outbreak is pointed out in this study. Further, the process, which changed from a meso-β-scale vortex to a band cloud in connection with a change in the low level winds, is discussed.

1. Introduction

Mesoscale vortex-like disturbances which are important in forecasting heavy snowfalls have been mainly investigated in the Hokuriku coast (e.g., Miyazawa, 1967) and the Ishikari Bay (e.g., Kono and Magono, 1967) in Japan. Further, a broad cloud band which formed along the west coast of Hokkaido Island over the Japan Sea was labeled as a Convergence Band Cloud (Okabaya-

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shi and Satomi, 1971, hereinafter, CBC). CBCs are understood to be an intense type of orographically and thermally influenced front (Fujiyoshi et al., 1988 ; Tuboki et al., 1989 ; Kobayashi and Kikuchi, 1993), or convergence zone (Asai, 1988) occurring in the mid-winter season.

The relationship between a meso-α-scale low (polar low) over the east coast of the Asian Continent and its parent large scale low was pointed out by Ninomiya (1989). The meso-scale cyclones with spiral-shaped clouds and precipitation bands and strong winds in the polar air streams over the northern Japan Sea have been studied by Ninomiya (1991, 1994) and Ninomiya et al. (1993, 1996). Ninomiya (1991) classified these low depressions into two categories: "Meso-α-scale low over the eastern coast of the Asian Continent" and "Meso-β/γ-scale vortex over the west coast of Hokkaido."

Recently, the dynamic structure of meso-γ-scale vortices over the Ishikari Bay has been studied with Doppler radar (Uyeda, 1993 ; Fujiyoshi, 1993). Many questions, however, remain regarding the relationship between mesoscale (meso-α to meso-γ) vortices and CBCs, specifically in terms of, time and spatially. Due to an absence of radar data in the northwestern part of Hokkaido where mesoscale vortices and CBCs frequently generate, a detailed structure of mesoscale vortices and CBCs has not been discussed.

Based on these circumstances, observations arranged specially in the northwestern part of Hokkaido have been carried out at Haboro, from December 1986 to January 1987, on Rebun Island and at Soya Cape, January 1990, and on Rebun Island, January 1991. Radar observations were carried out for the first time at Haboro (Kobayashi et al., 1989). Simultaneous radiosonde observations were made at Funadomari on Rebun Island and Soya Cape in order to study the kinematic and thermodynamic structures of a cold air mass when the CBC was generated on the west coast of Hokkaido (Fujiyoshi et al., 1996). Continuously, Doppler radar and radiosonde observations were carried out at Sukoton Cape in Rebun Island (Takemoto, 1992).

Formation processes of meso-β/γ-scale vortices in the northwestern part of Hokkaido and time changes of mesoscale vortices and CBC are unknown to date. Further, the relationship between meso-α-scale lows mentioned by Ninomiya et al. (1993) and meso-β/γ-scale vortices have not been clarified yet.

It this paper, therefore the radar echo structures of meso-β/γ-scale vortices and CBC generated in the northwestern part of Hokkaido is analyzed using radar data obtained during the observations at Haboro. The purpose of this paper is to describe the detailed echo structures of meso-β/γ-scale vortices and the relationship between mesoscale vortices and CBC at the initial stage of disturbances.

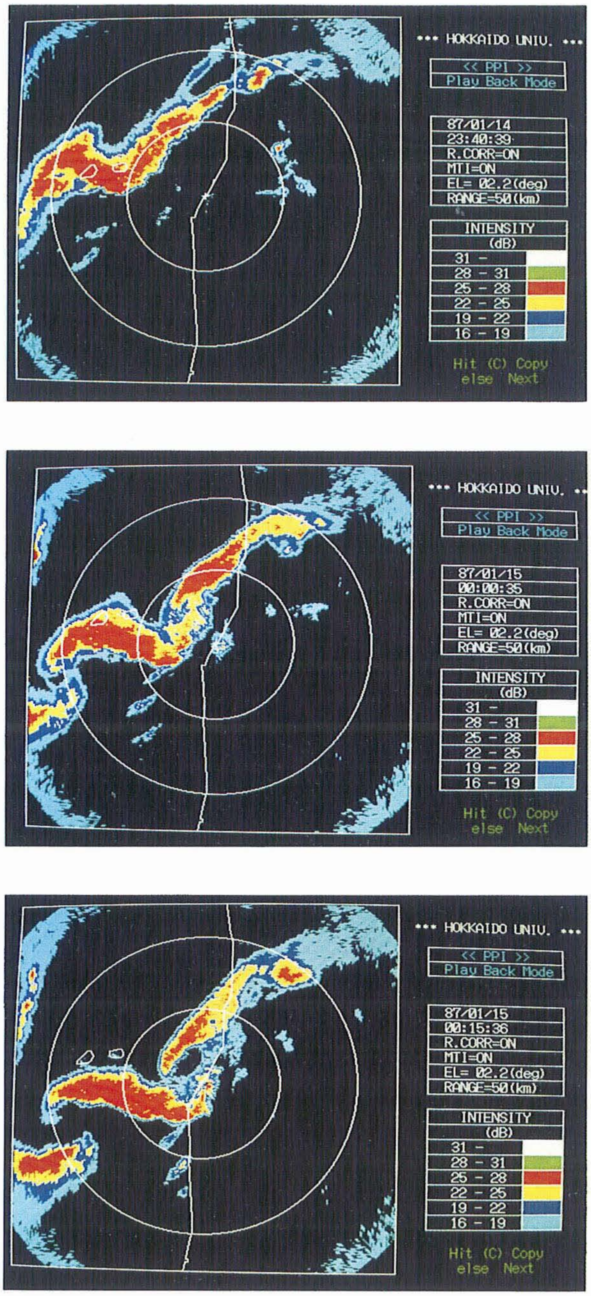
2. Radar observation at Haboro

Radar observations arranged specially were carried out from the middle of December 1986 to the middle of January 1987 in Haboro Town (44°21′N, 141°42′E) located on the west coast of Rumoi Sub-prefecture of Hokkaido Island about 150 km north from Sapporo. The mobile meteorological radar of the Meteorological Laboratory, Faculty of Science, Hokkaido University was set up on a cliff of 30 m in height along the coast line. Fortunately, there were no obstacles to hinder radar detection around the radar site (Kobayashi et al., 1989). The range covered by the radar used was 63.5 km in radius. Radar data were taken by the CAPPI and RHI modes at every 10 minute interval. For the analysis, the data were recorded on an average of over 1 km×1 km mesh in horizontal and 0.5 km in vertical.

3. A case study of mesoscale vortices and CBC on January 14-15, 1987

The event occurred on January 14-15, 1987 accompanying by multi-scale vortices and a CBC during a cold air outbreak period after a passage of the synoptic scale low on January 13. Figure 1 shows PPI displays of three different times on January 14-15. The meandering band echo was distinguished along SW to NE direction (Fig. 1a). As an amplitude of the band wave became large, two vortices generated in succession. The first vortex formed at 40 km offshore (Fig. 1b) and the second vortex formed just above the Haboro radar site (Fig. 1c). The meso-γ-scale wave train pattern was clear from these PPI displays. A GMS image and radar echo pattern at 01 JST January 15 are shown in Fig. 2. A meso-α-scale low was recognized as a cloud mass which developed on the east side of Hokkaido. On the contrary, a meso-β-scale vortex was generated in the west coast of Hokkaido. A V-shaped cloud was dominant in both the satellite image and radar echo pattern. Further, meso-γ-scale vortices (wave train) were formed at the south side band of the meso-β-scale vortex.

We will introduce the structure of meso-γ-scale vortices (wave train) and the relationship between the wave train and the meso-α- to meso-β-scale disturbances or CBC.

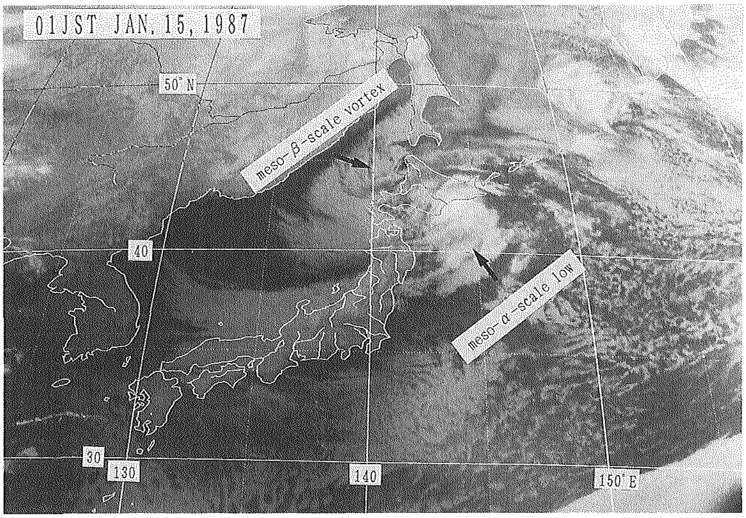


(a)

(b)

(c)

Fig. 1. Rader echo displays at Haboro on (a) 23 : 40 JST Jan. 14, (b) 00 : 00 JST and (c) 00 : 15 JST Jan. 15, 1987. Radar range circles are 20 km, 40 km, respectively.



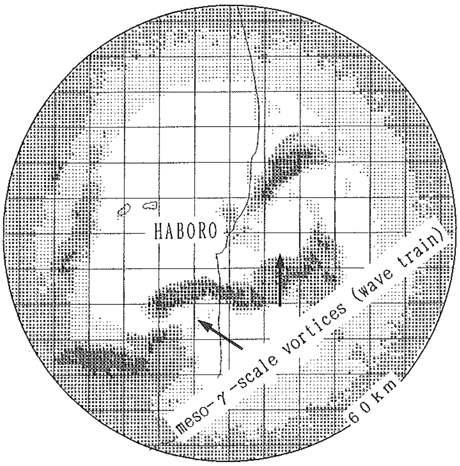


Fig. 2. GMS-IR image and rader echo pattern at 01 JST Jan. 15, 1987.

3.1 Synoptic situation and generation of meso-α-scale low

A surface pressure pattern of west-high and east-low continued for almost 2 days after the passage of the synoptic-scale low. A meso-α-scale low of 1004 hPa was generated on the east side of Hokkaido at the passage of a short-trough over the northern part of Japan as shown in Fig. 3. Figure 4 indicates trajectories of the synoptic low (open circle with dashed line), the meso-α-scale low (solid circle with solid line) and the upper level (700 hPa) cold airmass (small

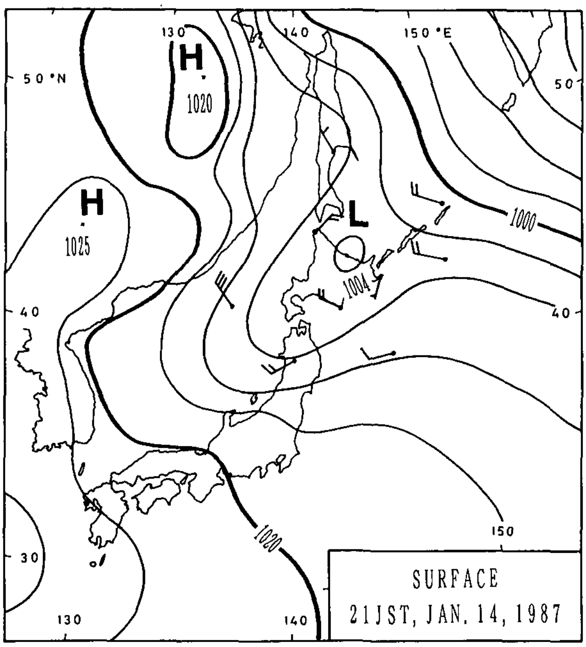


Fig. 3. Surface weather chart at 21 JST Jan. 14, 1987.

cross with large circle). The generation of the meso-α-scale low was accompanied by the passage of an upper level cold airmass, which was the same situation as with the polar low over the east coast of the Asian Continent shown by Ninomiya (1991). The lifetime of the meso-α-scale low was for more than a day.

Figure 5 shows successive GMS-IR images from 21 JST January 14 to 06 JST January 15. It was recognized that there was a cloud mass accompanied by a 1004 hPa low over the east side of Hokkaido. The system of the cloud mass was generated abruptly after 21 JST and moved eastward. The meso-β-scale vortex was characterized by a V-shaped cloud pattern spread over the northern part of the Japan Sea (01 JST). The generation of the meso-β-scale vortex was simultaneous with that of the meso-α-scale cloud system. The lifetime of the meso-β-scale vortex was less than several hours, because the vortex was not clear at 21 JST and 03 JST in the figure. This meso-β-scale disturbance was formed at the rear of the meso-α-scale low where the wind shear in the horizontal or vertical directions should be formed between the westerly monsoon wing and the northeasterly wind caused by the synoptic scale forcing, and where a temperature gradient was the strongest (mentioned in the

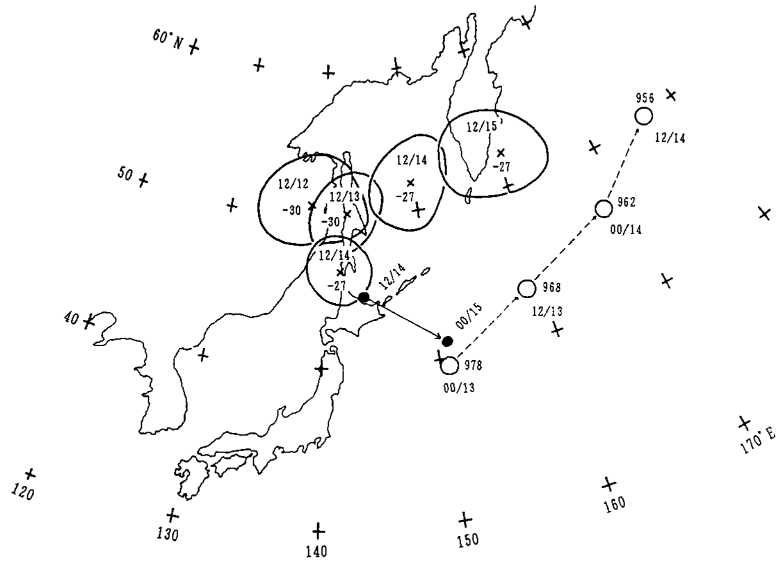


Fig. 4. Movement of synoptic low center (open circle with dashed line, from 09 JST Jan. 13 (00/13) to 21 JST Jan. 14 (12/14)), meso-α-scale low (solid circle with solid line, on 21 JST Jan. 14 (12/14) and 09 JST Jan. 15 (00/15)) and cold airmass at 700 hPa (small cross with large circle, from 21 JST Jan. 12 (12/12) to 21 JST Jan. 15 (12/15)).

section 3.3 and chapter 4).

After the V-shaped cloud system disappeared, a curved-shaped cloud band elongated to southward and the CBC was formed along the west coast of Hokkaido (03 and 06 JST). The CBC disappeared at 09 JST. The lifetime of the CBC, therefore, was several hours.

3.2 Radar echo structure of meso-β-scale vortex and meso-γ-scale vortices (wave train)

Smaller scale vortices were observed in the cloud band of the meso-β-scale vortex during the special radar observation period. Figure 6 indicates the time sequence of PPI radar echo patterns from 23 JST January 14 to 03 JST January 15, 1987. The band echo, elongated SW to NE direction (23 : 01 JST, in the figure), corresponded to the south side band cloud of the meso-β-scale V-shaped cloud as shown in Fig. 2. As the cloud band of the meso-β-scale vortex was moving southward, the band echo began to meander (23 : 31 JST) and vortex-like echo pattern was formed in the constricted area of the band echo. At 00 : 00 JST, the first vortex was formed about 40 km offshore from the radar site and

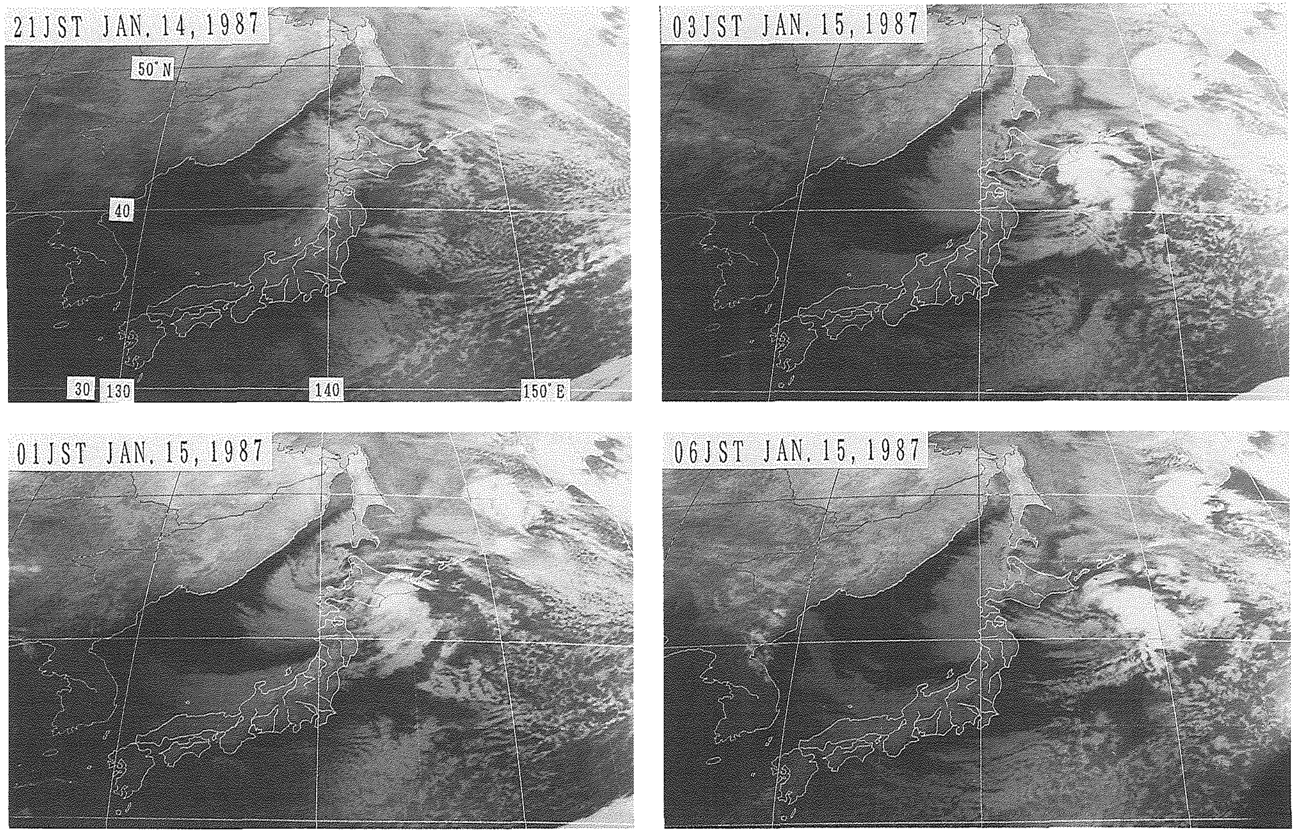


Fig. 5. Sequential displays of GMS-IR images from 21 JST Jan. 14 to 06 JST Jan. 15, 1987.

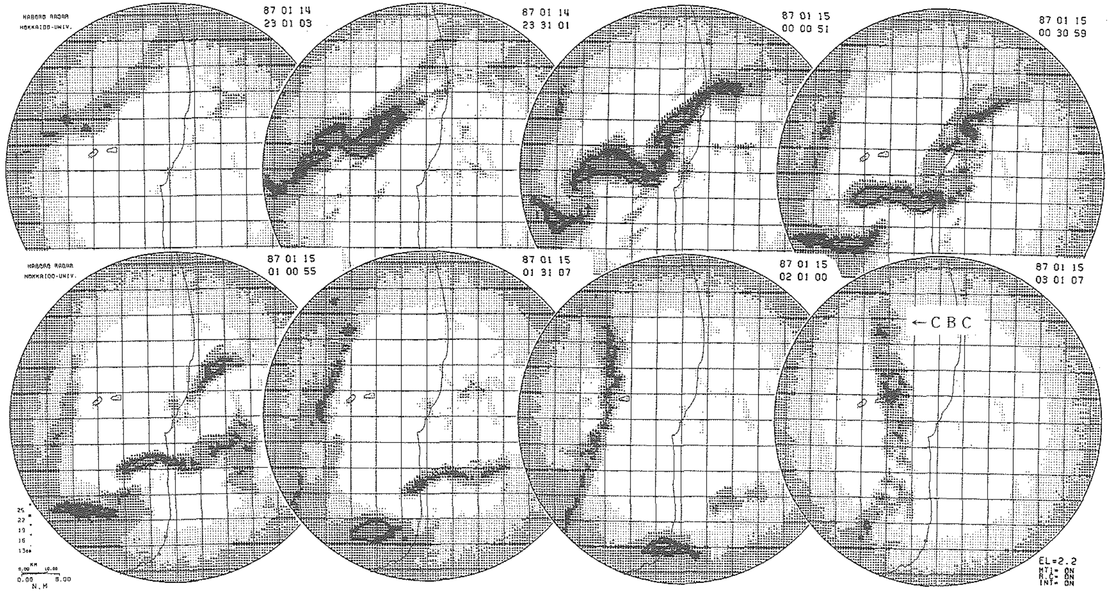


Fig. 6. Time sequence of PPI radar echo patterns through a life cycle of the wave train. Solid lines denote the intense reflectivity regions more than 25 dBZ.

for 10 minutes later, the second vortex developed just above the radar site. Two vortices linked together and the echo pattern took on the shape of a wave train (00 : 30 JST). The diameter of the echo free area, i.e., "cyclone eye" observed in each vortex was spreading at this time. The diameters of the vortices were about 20 km and 30 km, respectively, and the diameters of the echo free areas were 10 km and 20 km in their mature stage.

Nagata (1993) simulated meso-β-scale vortices developing along the Japan-Sea Polar-airmass Convergence Zone (JPCZ) cloud band. The formation process of the meso-γ-scale wave train was quite similar to the simulated meso-β-scale vortices which developed in a belt of concentrated positive vorticity accompanied by a dry eye and spiral bands. As the dominant mechanism of the meso-β-scale vortices in JPCZ was barotropic shear instability, we need to show whether the smaller scale wave train over the west coast of Hokkaido have the same mechanism as meso-β-scale vortices in JPCZ.

In the dissipating stage, the diameters of both the echo area and the echo free area began to spread (01 : 00 JST). The lifetime of each vortex was about 1 hour, and the movement directions of vortices were SE (first vortex) and ESE (second vortex) which were not similar to that of the band echo. After 01 : 30 JST, the vortices disappeared and the band echo moved out of the range. Corresponding to this, a developing band echo having a south to north direction was detected in the radar range. The south to north band echo corresponded with a part of the CBC shown in Fig. 5 (03 JST). As the band echo was formed by a convergence between the northwesterly wind and the northeasterly wind and new echo cells formed on the south side of the band, the band echo propagated southward (Kobayashi et al., 1992). After the mature stage of the CBC (02 JST), the band echo stagnated and began to move eastward under the balance of the westerly monsoon wind and the easterly land breeze.

Figure 7 indicates CAPPI radar echo patterns of 2, 3 and 4 km level above the sea surface. The first vortex which formed over the sea had a more intense echo area compared to the second vortex developed over the land. Moreover, whereas the echo top of the first vortex was 4 km, that of the second vortex was less than 3 km. As a result, the dynamical properties of the two vortices, such as the scale, duration and movement, were similar, however, the thermodynamical properties, echo intensity and echo top, were quite different. The reason for the latter is thought to be caused by a difference in heat and moisture transfer from the sea and land surface.

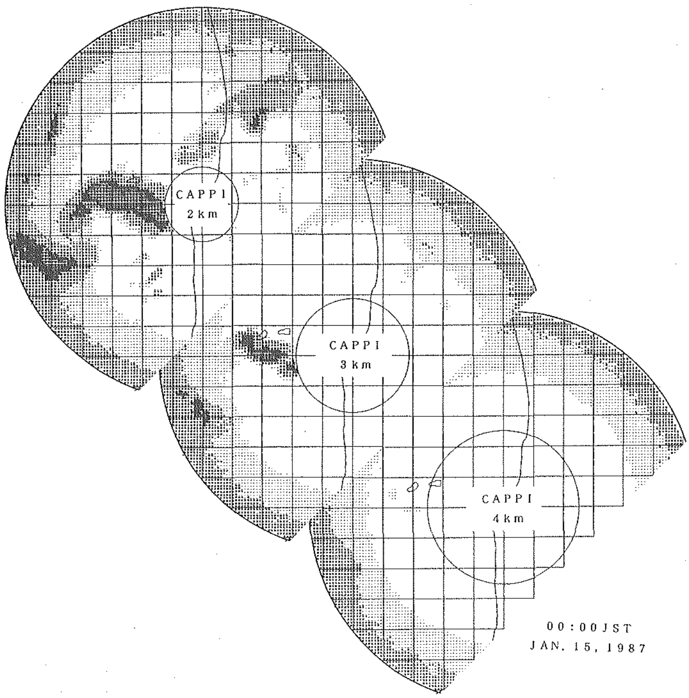


Fig. 7. Three different levels of echo patterns on 00 JST Jan. 15, 1987.

3.3 Surface weather conditions

Surface weather elements were also influenced by the upper level cold airmass, the synoptic scale forcing, mesoscale disturbances and local scale conditions. Figure 8 indicates surface wind and temperature fields at every 3 hour interval. Looking at the northern part of Hokkaido, the northeasterly wind which was colder than the monsoon wind made a distinct shear line between the northeasterly and westerly winds (21 JST). The shear line moved southward accompanied by the band cloud into the Ishikari Plain along the west coast of Hokkaido until 03 JST (see Figs. 5 and 6). After 03 JST, a radiational cooling during night time occurred over the northern part of Hokkaido. In a mesoscale high pressure area, the temperature dropped below −20°C and the divergent flow pattern from the meso-high was seen around coast line as land breeze, especially the southeasterly wind appeared along the west coast and the southerly wind appeared at Soya Cape. In this case, it was thought that the different two types of colder airmass formed the following two horizontal shear lines after the upper level cold vortex passed: 1) Shear-I, between the north-

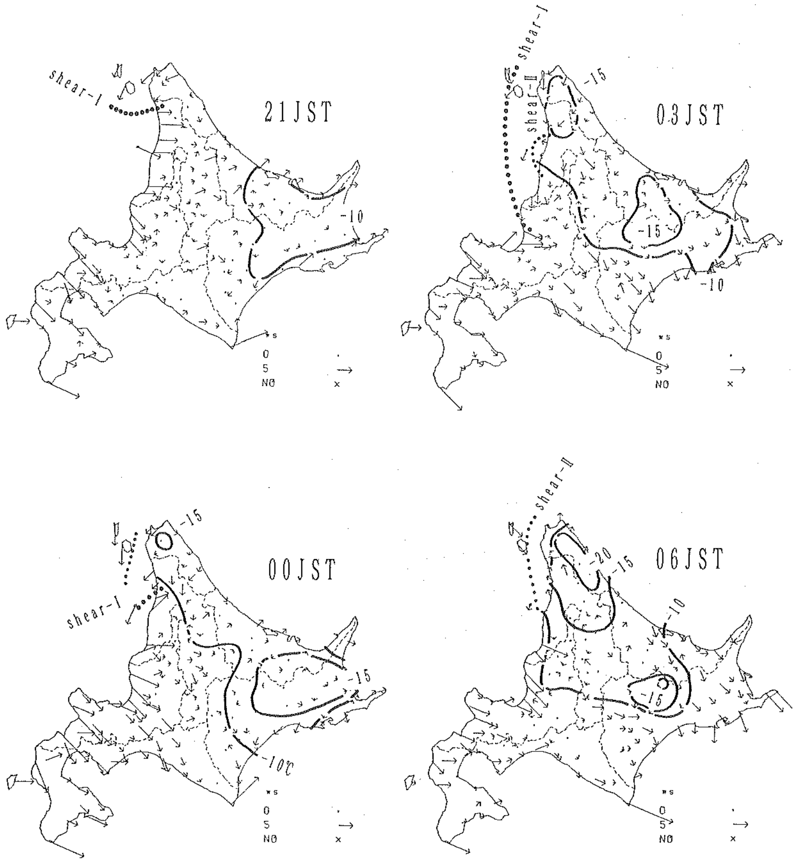


Fig. 8. AMeDAS wind and temperature fields from 21 JST Jan. 14 to 06 JST Jan. 15, 1987. Solid lines denote isotherms at 5°C interval. Dotted lines show shear lines.

easterly colder wind and the southwesterly wind, played a role in the meso-β-scale vortex formation. 2) Shear-II, between the northwesterly monsoon wind and the southeasterly land breeze along the west coast, played a role in the maintenance process of CBC.

Figure 9 shows continuous weather records at Haboro during the passage of the wave train. The wind direction changed systematically; southwesterly gust winds up to 13 m/s were recorded with the south edge of the band echo at 00:00 and 00:17 JST. Northerly or northeasterly gusts up to 15 m/s were recorded with the north band of the wave train from 00:40 to 01:30 JST. Additionally, the wind speed weakened one time in the echo free area of the second vortex center. This tendency was very similar to the mesocyclone in

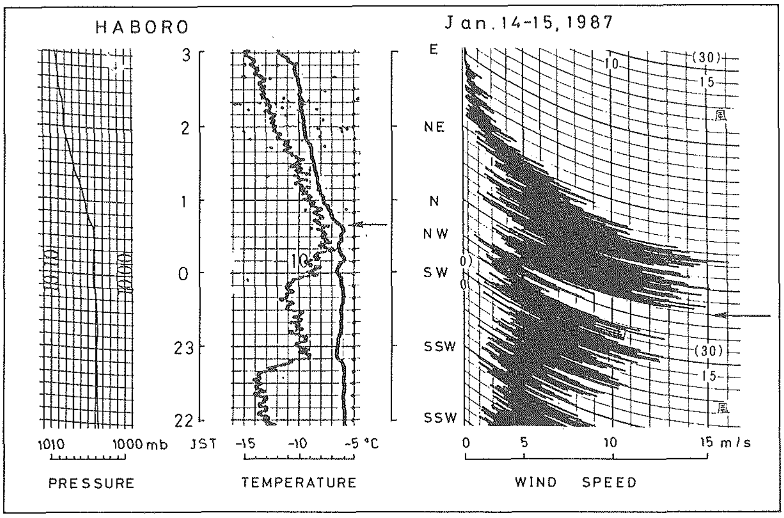


Fig. 9. Surface weather records of pressure (hPa), temperature (°C) and wind speed (m/s) and wind direction at Haboro. Arrows indicate the time of the gust wind.

the case of January 12, 1987 (Kobayashi et al., 1989). The temperature drop was 2°C/20 min after the passage of the band echo. This temperature change means the existence of two different kinds of airmass, that is, the northeasterly cold wind airmass and the southwesterly warm monsoon airmass. However, the thermal structure of the vortex inside, the warm core structure, was not clear (0.3°C) compared to the mesocyclone of January 12 (see Fig.8, Kobayashi et al. (1989)). Considering the second vortex formed over the land, it is supposed that weak thermal structure inside is the result of no heat being supplied from either the sea surface or the cloud inside.

In conclusion, it is considered that the meso-γ-scale vortices, accompanied with gusts and warm cores, were generated in the frontal zone which was represented by the shear line of surface winds having opposite directions and by the strong temperature gradient.

4. Discussion

4.1 Vertical structure of the cold airflows

We will discuss the vertical structure of two types of cold airflows; the northeasterly colder wind affected by the synoptic forcing and the coldest divergent flow from a meso-high formed in the inland of Hokkaido. Figure 10

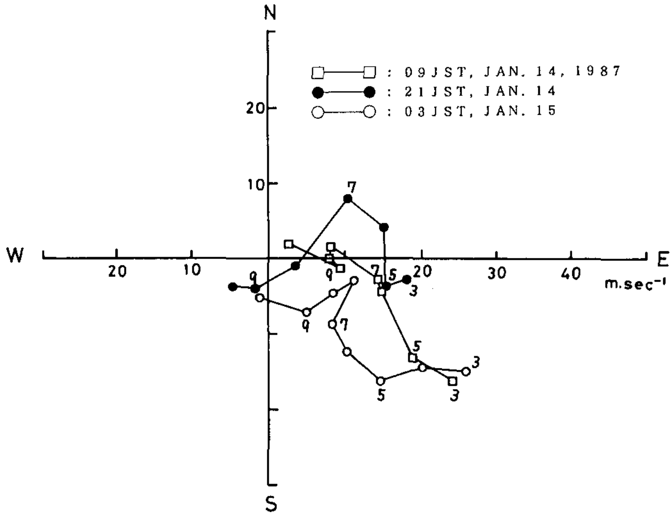


Fig. 10. Wind sounding hodographs at Wakkanai from 09 JST Jan. 14 to 03 JST Jan. 15, 1987.

shows hodographs at Wakkanai before and after the vortex formation. While the westerly wind was dominant in most layers as 09 JST, January 14 (open square), the northeasterly wind invaded below the 900 hPa level at 21 JST (solid circle) just before the meso-β-scale vortex formation. It is understood that the wind direction was backing to 700 hPa and formed a strong vertical wind shear. The northeasterly wind having a thickness of less than 1 km from the surface blows most likely through the Soya Strait (Kobayashi et al., 1987 ; Fujiyoshi, 1989). It is surmised, therefore, that the meso-β-scale disturbance was influenced by both horizontal and low-level vertical wind shears which formed the surface convergence. In addition, it is thought that the synoptic situation (Fig. 3) also supported meso-β-scale disturbance.

The vertical structure of the thermodynamic condition at Wakkanai on 21 JST January 14 is shown in Fig. 11. As shown in the figure, a strong convective instability existed in the shallow layer near the surface (below 980 hPa), and weak convective instability existed at the 850 hPa level, respectively. If these convective instability layers were released, convective snow clouds would develop. In fact, mesoscale vortex echoes developed up to 2 km over the land area (Fig. 7). Fujiyoshi et al. (1996) pointed out that the static stability was higher at Soya Cape than at Rebun Island (below 1 km), and the level of the vortex cloud top was 2.5 km at Rebun Island.

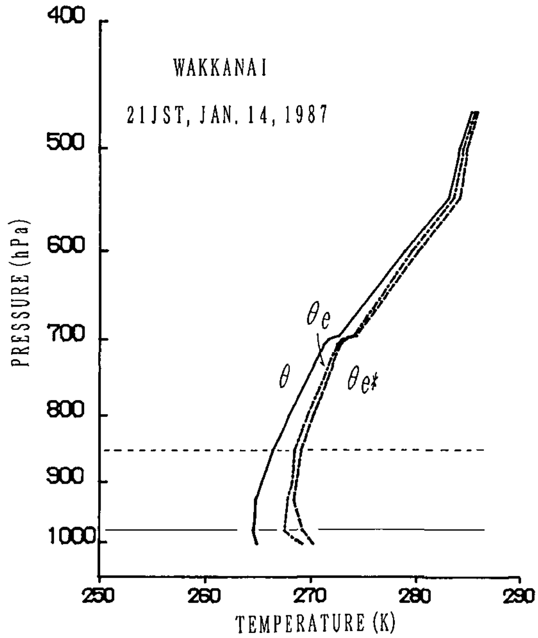


Fig. 11. Verticl distributions of saturated equivalent potential temperature (θ_e^*), equivalent potential temperature (θ_e) and potential temperature (θ) at Wakkanai on 21 JST Jan. 14, 1987. Solid and dashed lines denote the top of convective instability layers.

4.2 Relationship between mesoscale vortices and CBC

Concerning the formation of mesoscale vortices and CBCs at the northern part of Hokkaido, Kobayashi et al. (1987) showed a detailed structure of initial disturbances and the CBC using satellite images. They suggested that there were two different stages in the lifetime of CBCs: in the first stage, CBCs behaved as a meso-low, and in the second stage, CBCs maintained their life by the cold flow from the meso-high. This means that two different winds, a northeasterly wind and a divergent flow (land breeze), play an important role in forming organized mesoscale disturbances along the west coast of Hokkaido. Fujiyoshi (1989) pointed out the penetration of the northeasterly cold airmass through the Soya Strait from satellite images. Further, Fujiyoshi et al. (1996) observed the structure of the low level northeasterly flow at Wakkanai in relation to the formation of a CBC. In this case, a distinct life history of the mesoscale vortices and CBC was pointed out. Firstly the meso-α-scale low and the northeasterly wind made a short trough, next, the northeasterly wind made meso-β/γ-scale vortices against the monsoon wind. Finally, the CBC maintained by the divergent flow along the west coast of Hokkaido. It is important to recognize the relationship between multi-scale vortices and the CBC under the cold airmass outbreak. Further, more case studies of mesoscale disturbances formed in the northern part of Hokkaido must be accumulated.

5. Conclusions

Characteristic features of the mesoscale disturbances accompanied by the band cloud (CBC) and the relationship between mesoscale vortices and a CBC in the northern part of Hokkaido were documented in the case of January 14-15, 1987 using special radar observation data at Haboro. The detailed radar echo structure of the meso-γ-scale vortices (wave train) and the relationship between multi-scale vortices and a CBC along the west coast of Hokkaido were revealed for the first time. Conclusions are summarized as follows ; (1) The meso-γ-scale vortices were formed in the cloud band of a meso-β-scale vortex and the two vortices took on the shape of a wave train pattern. (2) The wave train had a lifetime of 1 hour approximately. These vortices were composed of the outer spiral band echoes of 20 km and 30 km in diameter, with an echo free area of 10 km and 20 km in the mature stage which contained gusts and warm cores inside. (3) The horizontal wind shear at the surface played a role in the formation of the wave train which had a different echo structure intensity and echo top over land and sea. (4) The Meso-β-scale vortex (lifetime of several hours), generated at the rear side of the meso-α-scale low ($\sim$1 day), formed under the condition of a synoptic short-trough, where the northeasterly colder wind was dominant on the west side of the Soya Strait. (5) The CBC ($\sim$ several hours) was formed after the dissipation of the meso-β-scale vortex along the west coast of Hokkaido. Winds having different direction, synoptic scale northeasterly wind below 850 hPa and the divergent flow from the inland meso-high which is a land breeze near the surface, are considered to be important for the formation of mesoscale disturbances and the maintenance process of CBCs, respectively.

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