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Author(s)	TSUBOKI, Kazuhisa
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Numerical Experiments of Mesoscale Cyclone Formed off the West Coast of Hokkaido

Kazuhisa Tsuboki

Institute for Hydrospheric-Atmospheric Sciences, Nagoya University, Nagoya, 464-8601, Japan

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Abstract

An intensive observation of snow storms was performed in January and February 1992 (Kikuchi, 1993) in the Ishikari District of Hokkaido, Japan. During the intensive observing period, a mesoscale cyclone was observed off the west coast of Hokkaido during the period from 30 January to 1 February 1992. We made numerical experiments of the mesoscale cyclone using JSM. The prediction experiment simulated development of the mesoscale cyclone. When the mesoscale cyclone generated, the lower troposphere was cold over Hokkaido and warm over the Sea of Japan. The cold air flowed southeastward and made a convergence with the northwesterly monsoon wind. The mesoscale cyclone was formed along the convergence zone. The mesoscale cyclone was a shallow disturbance which was confined to below 850 hPa.

When the sensible heat flux from the surface is switched off, the mesoscale cyclone was not simulated. The experiment in which both latent and sensible heat fluxes were switched off gave the similar result. In these experiments, the horizontal temperature gradient between the land and sea was significantly weakened and the convergence zone was not formed. The static stability in the lower troposphere became more stable. As a result, the mesoscale cyclone was not formed.

Even though the moist processes were switched off, the mesoscale cyclone was simulated. This indicates that the moist processes are not essential for the development of the mesoscale cyclone. We could infer that a hydrodynamic instability of the dry air is essential for the mesoscale cyclogenesis.

1. Introduction

Satellite images occasionally show the occurrence of a mesoscale vortex in the winter monsoon air streams off shore along the west coasts of Hokkaido and Sakhalin. The vortex, with a characteristic diameter of 200-500 km, usually accompanies a broad single cloud band, namely a "band cloud", and causes locally severe snow storms along the coastal regions. The band cloud is a distinctive characteristic of the mesoscale vortices. The mesoscale vortex accompanies a lowered surface pressure and a cyclonic low-level wind circulation. We, therefore, refer to it as the mesoscale cyclone.

At the end of the 1940s, surface observations revealed the occurrence of mesoscale cyclones along the west coast of Hokkaido and a mesoscale high which developed by the radiative cooling over the island of Hokkaido. Based on the ground observations and rawinsonde analysis, Suginaka (1964) pointed out the importance of a cold low at 500 hPa and discussed how the upper low is associated with the generation or intensification of a lower small cyclone.

Since 1963 radar data at Sapporo District Meteorological Observatory is available and the radar has been used for the investigation of heavy snowfall. Saito et al. (1967) observed a radar echo which is associated with the mesoscale low and concluded that a mesoscale high and a convergence of warm, moist air in the cyclonic streams behind a synoptic-scale low are important for the local heavy snowfall. Kono and Magono (1967) used a radar to find two types of small cyclonic rotation over the Ishikari Bay of the Japan Sea: local topographic low and vortex mesoscale disturbance. The former extended to less than ~3 km in altitude and the latter extended to ~550 hPa. Harimaya (1970) studied a mesoscale vortex disturbance using radar data and found that it was generated when the upper cold air mass passed the northern part of Hokkaido and an advection of vorticity occurred over the west coast of Hokkaido.

From satellite image, Okabayashi (1969a, 1969b) found that the mesoscale cyclone accompanies the band cloud. Okabayashi and Satomi (1971) used satellite and radar to find that the discontinuous line is coincided with the band cloud and that small vortices, with a diameter of 50 km, develop along the band cloud. They concluded that these small vortices develop with moving southward and become a mesoscale cyclone.

Magono (1971), and Yamaguchi and Magono (1974) explained the mechanism of the mesoscale cyclone by an analogy to the classical frontal model of cyclones given by Bjerknes and Godske (1936). Kobayashi et al. (1989) used a radar to observe a meso-β scale (20-200 km) vortex-like disturbance which formed at the edge of a band cloud and reported that the wind field of the confluence of three different air currents was important to generate the cyclone. The mesoscale cyclone is usually generated when the synoptic pressure gradient is rather small and the northwesterly monsoon wind is light. The observational studies suggested that the mesoscale cyclone is generated along a discontinuous line between radiatively cooled air over the land and warmer over-sea air. Recently, Doppler radar observations revealed the radar echo and kinematic structures of the band cloud (Fujiyoshi et al., 1988a, 1988b; Tsuboki et al., 1989).

Since the mesoscale cyclone develops rapidly over the sea, it is difficult to reveal mechanisms of cyclogenesis and development from observation. Tsuboki and Wakahama (1992) proposed baroclinic instability with shallow shear layer as a mechanism of cyclogenesis and showed that scale selection, growth rate and vertical structure obtained from a theory correspond to those of observed cyclones. The theory was, however, a linear instability analysis and described only the cyclogenesis. In order to study development process and structure of the mesoscale cyclone, a special observation and simulation by a numerical model are necessary.

An intensive observation of snow storms was performed in January and February 1992 (Kikuchi, 1993) in the Ishikari District of Hokkaido, Japan. During the intensive observing period, a mesoscale cyclone was observed off the west coast of Hokkaido during the period from 30 January to 1 February 1992. The purpose of this study is to clarify effects of diabatic heating by condensation and surface heat fluxes to the development of the mesoscale cyclone. We performed numericl experiments of the mesoscale cyclone and used the simulated data to study the mesoscale cyclone.

2. Data and numerical model

The following data for the period from 30 January to 1 February 1992 were provided by the Japan Meteorological Agency (JMA) and were used for data analyses and numerical modelings ;

1. objective analysis data of the Japan area (JANAL) with a resolution of 40 km (60°N), and 18 levels every 12 hours,
2. daily analysis of sea surface temperature (SST) with a resolution of 1.0 degrees in both latitude and longitude,
3. and the Geostationary Meteorological Satellite (GMS) infrared (IR) Tbb (the equivalent black body temperature) data.

The JANAL data were interpolated into model grids and used for initial and boundary conditions of numerical simulations. The SST data gave a lower boundary condition in sea areas.

We adapted the Japan Spectral Model (JSM) of version of 1988 for a numerical experiments of the mesoscale cyclone. JSM which was developed by JMA for operational forecasts is a spectral limited-area model (Segami et al., 1989). The model is formulated in terms of the primitive equations in sigma coordinates. The spectral method with a time-dependent lateral boundary condition (Tatsumi, 1986) is adopted in the model. The vertical levels were 23 sigma levels in this study. The model expresses horizontal fields of model variables by the double Fourier series. The transform grids were 129 and 129 points in the zonal and meridional directions, respectively. The horizontl spacing of model grids was chosen to be 30 km for the present study. The domain of experiments is the same that shown in Fig. 1 of Segami et al. (1989). The map projection was the North Polar Stereo graphic Projecion. The distribution of the sea surface temperature was fixed throughout the integration period.

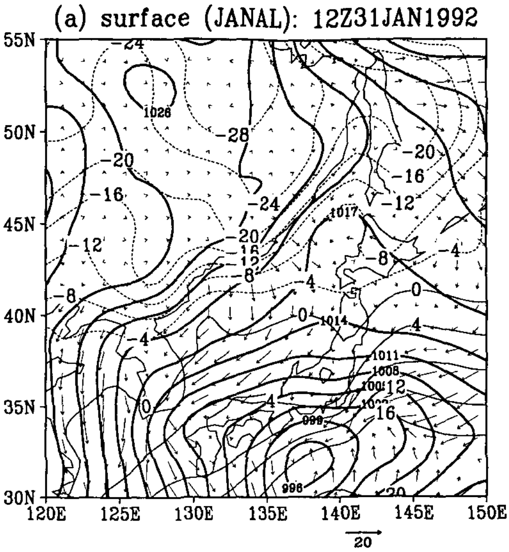
Moist processes in the model were the moist convective adjustment for subgridscale convection, large-scale condensation and evaporation of raindrops. Surface fluxes were calculated by a bulk method. The level two version of the turbulent closure model (Mellor and Yamada, 1974) was used for vertical diffusions. Temperature of ground was calculated by a four-layer model. Radiation was taken into account only for the calculation of ground temperature.

3. Cloud patterns of mesoscale cyclone

A band cloud which has a scale of a few hundred kilometers in length and a few tens kilometers in width formed at 1200-1800UTC, 30 January 1992 along the west coasts of Hokkaido and Sakhalin. The mesoscale cyclone began to develop along the band cloud at 2100 UTC, 30 January. A vortex cloud pattern associated with the mesoscale cyclone developed around 0000 UTC, 31 January and its was in mature around 0600 UTC, 31 January. The horizontal diameter was approximately 300 km. The vortex cloud began to move south-westward around 1200 UTC, 31 January with distorting the vortex pattern. The vortex cloud pattern began to dissipate at 1800 UTC, 31 January. After the vortex cloud dissipated, another band cloud was formed along the west coast of Hokkaido.

4. Synoptic pattern

The surface weather chart at 0000 UTC, 30 January 1992 (not shown) shows a synoptic low to the east of Hokkaido and a high over the Eurasia Continent. A cold air outbreak occurred over Japan and its surrounding areas. A cold air was extending southeastward over Hokkaido at a level of 850 hPa, which is a characteristic pattern of synoptic temperature field when mesoscale cyclones develop.



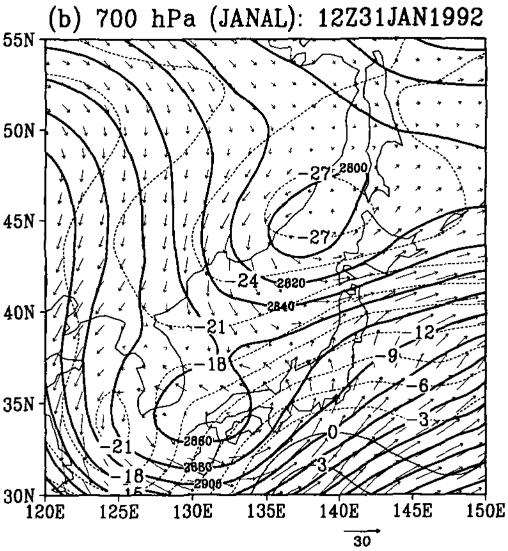


Fig. 1. (a) Surface pressure (thick lines in hPa), surface temperature (thin lines in °C) and surface wind vectors, and (b) height (thick lines in meter), temperature (thin lines in °C) and wind vectors of 700 hPa at 1200 UTC, 31 January 1992 obtained from the JMA objective analysis of the Japan area.

The surface pressure and temperature patterns at 1200 UTC, 31 January 1992 obtained from JANAL (Fig. 1a) show a synoptic-scale low is located to the south of Japan and a high over the continent. The cold air outbreak was occurring over the Sea of Japan. The pressure gradient was rather weak over Hokkaido and weak mesoscale low was formed off the west coast of Hokkaido. An upper cold trough was present above the northern part of the Sea of Japan at 700 hPa (Fig. 1b). This indicates that an intense cold air advection occurred over Hokkaido.

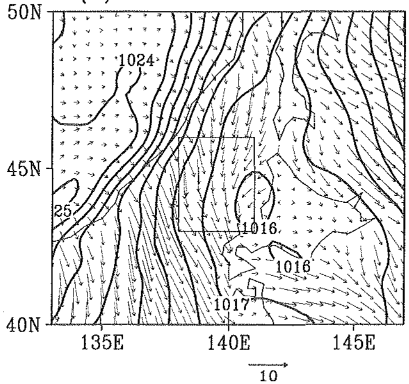
5. Prediction experiment of mesoscale cyclone

The observed mesoscale cyclone began to develop around 2100 UTC, 30 January 1992. The prediction experiment of the mesoscale cyclone was started from an initial value of 0000 UTC, 30 January 1992 and integrated for 48 hours. The experiment properly simulated processes of cyclogenesis and development of the mesoscale cyclone. Figure 2 shows that surface pressure and wind patterns associated with development of the mesoscale cyclone. The simulated mesoscale cyclone began to develop at 0900 UTC, 30 January along the west coast of Hokkaido (Fig. 2a). The surface wind vector shows that convergence occurs between the northerly and the northeasterly from Hokkaido. The mesoscale cyclone developed and attained its central pressure of 1014 hPa at 2100 UTC, 30 January (Fig. 2b). It was in mature stage around 0900 UTC, 31 January (Fig. 2c) and began to move south-westward. The location, horizontal scale and movement of the simulated cyclone well correspond to the cloud patterns observed by GMS.

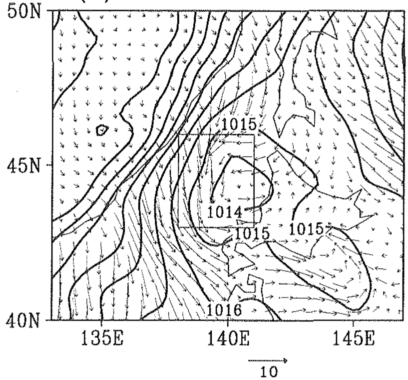
The environmental temperature field of the mesoscale cyclognesis characterized by a shallow cold air over Hokkaido and Sakhalin and a relatively warm air over the Sea of Japan. Development process of temperature field associated with the mesoscale cyclone is significant in 1000 hPa temperature field (Fig. 3). Before the mesoscale cyclone developed, the cold air over Hokkaido made a covergence with the northerly monsoon wind along the west coast of Hokkaido (Fig. 3a). When the vortex formed (Fig. 3b), the cold air flowed from the land to the sea on the north side of the vortex center and the warm air flowed from the sea to the land. When the mesoscale cyclone was mature, a warm core formed at the center of the vortex owing to the diabatic heating of condensation (Fig. 3c).

Height deviation z' and temperature deviation T' along 44°N (Fig. 4) show the vertical structure of the simulated mesoscale cyclone in mature stage. The

(a) JSM: 09Z30JAN1992



(b) JSM: 21Z30JAN1992



(c) JSM: 09Z31JAN1992

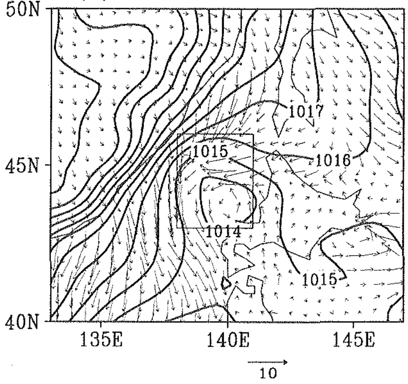


Fig. 2. Surface pressure patterns and surface wind vectors at (a) 0900 UTC, 30 January 1992, (b) 2100 UTC, 30 January 1992, and (c) 0900UTC, 31 January 1992 obtained from the prediction experiment. The squares in each figure indicate area of averaging of variables.

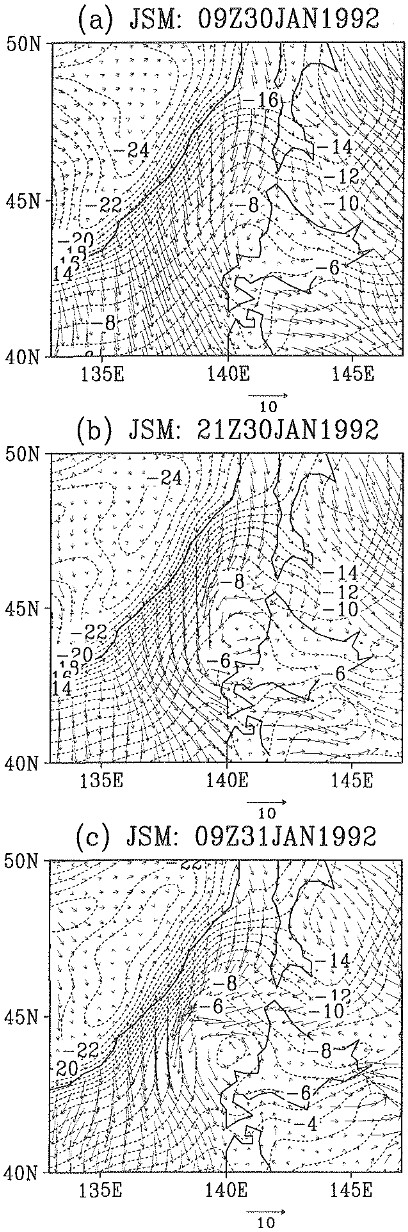


Fig. 3. Temperature (contours in °C) and wind vectors of 1000 hPa at (a) 0900 UTC, 30 January 1992, (b) 2100 UTC, 30 January 1992, and (c) 0900 UTC, 31 January 1992 obtained from the prediction experiment.

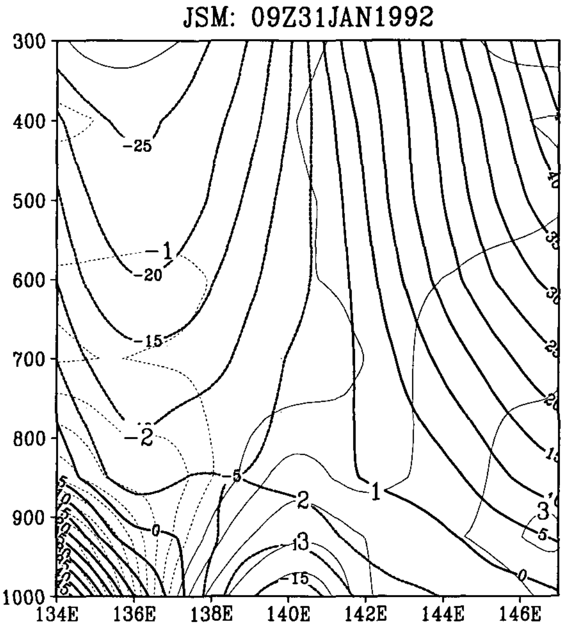
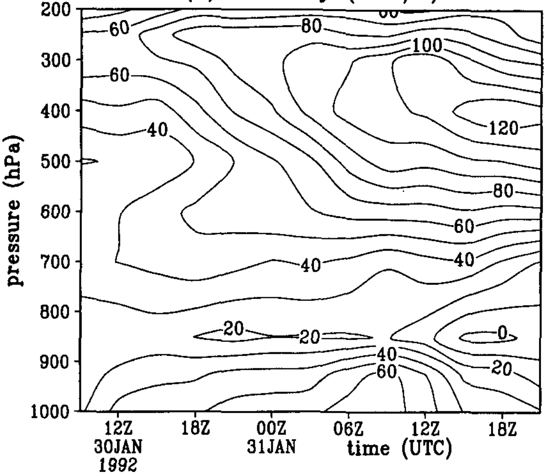


Fig. 4. Vertical cross sections of temperature deviation (thin lines in °C) and height deviation (thick lines in meters) at 0900 UTC, 31 January 1992. The deviations are differences from the averaged values between 134°E and 147°E.

deviation is difference from isobaric average between 134°E and 147°E at 0900 UTC, 31 January 1992. A negative z' centered at 140°E is the mesoscale cyclone. The negative z' corresponds to a positive T' ; this indicates the warm core of the mature vortex. These disturbances of z and T are shallow and confined to below 850 hPa. The mesoscale cyclone, therefore, a shallow low which confined to below the level. Another significant negative z' is present to the west of the mesoscale cyclone above 850 hPa. This low is the eastward-moving upper cold low. The mesoscale cyclone developed when the upper cold low came to the Sea of Japan.

Development of mesoscale cyclone is shown by time-height cross sections of vorticity and divergence averaged in the area where the cyclone developed (Fig. 5). The averaged vorticity increased with time below 850 hPa and attained its maximum of $60\times10^{-6}s^{-1}$ around 0900 UTC, 31 January 1992 (Fig. 5a). This shows development of the mesoscale cyclone. The disturbance of the cyclone was shallow throughout its whole life time and became maximum around 0900 UTC, 31 January. During the development of the cyclone, divergence was

(a) vorticity (E-6/s)



(b) divergence (E-6/s)

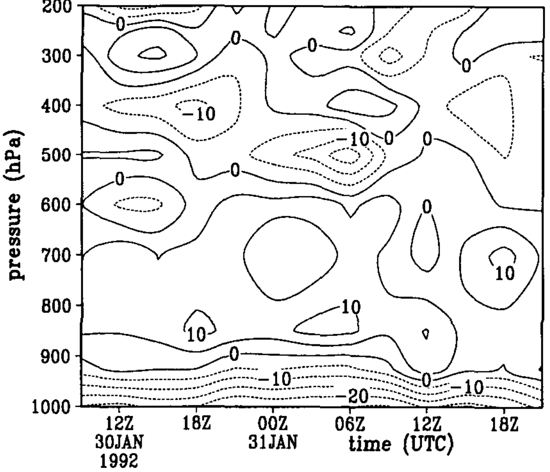


Fig. 5. Time-hight cross sections of averaged (a) vorticity (10^{-6} s^{-1}) and (b) divergence (10^{-6} s^{-1}) in the area of square in Fig. 2 obtained from the prediction experiment.

significantly negative below 900 hPa and weakly positive above the level. This low-level negative divergence and positive divergence above sustained upward motion of the mesoscale cyclone.

The time-height cross section of potential temperature (Fig. 6) shows that a mixing layer developed with time below a level of 850 hPa. A deep significant stable layer was present above the level. Consequently, the mesoscale cyclone

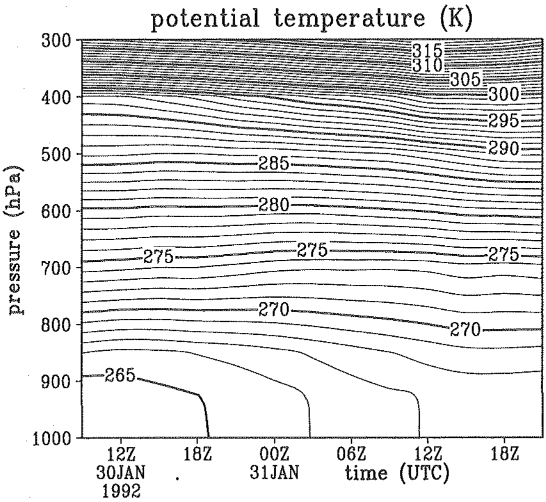


Fig. 6. Time-height cross section of averaged potential temperature (K) in the area of square in Fig. 2.

was confined within the mixing layer and was a shallow disturbance.

6. Effect of diabatic heating

Since mesoscale cyclones over the northern part of the Sea of Japan developed always over a warm sea. Their development, therefore, significantly influenced by latent and sensible heat fluxes from the surface. Since the temperature difference between the cold air and the warm sea is large, these heat fluxes are significantly large when mesoscale cyclone develop. The latent heat flux supplies moisture to the atmosphere and condensation will heat the air in the mesoscale cyclone. In order to examine effects of these diabatic heating, we performed the following numerical experiments of sensitivity tests;

1. only the sensible heat flux from the surface was switched off,
2. both the sensible and latent heat fluxes from the surface were switched off,
3. and moist processes of grid-scale condensation, moist convective adjustment and evaporation of raindrop were switched off.

All the three numerical experiments used the same initial and boundary conditions that used in the prediction experiment. They started at 0000 UTC, 30 January 1992 and integrated for 48 hours.

When the sensible heat flux from the surface was switched off, the flow from Hokkaido and its convergence with the northerly monsoon wind occurred

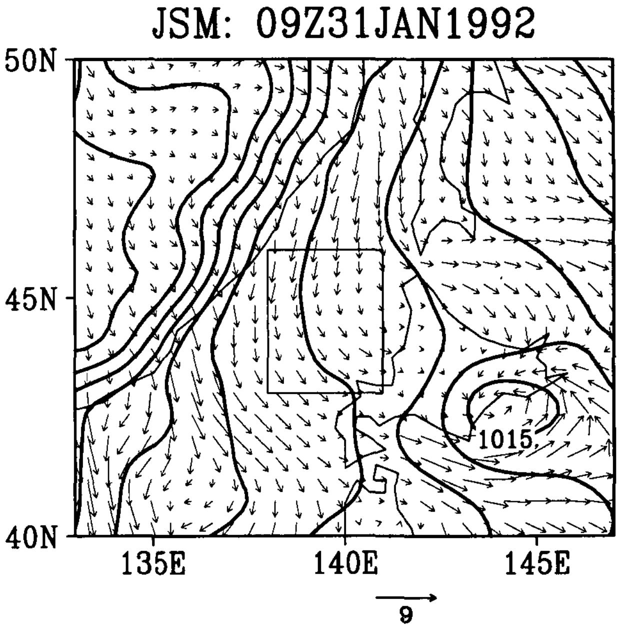
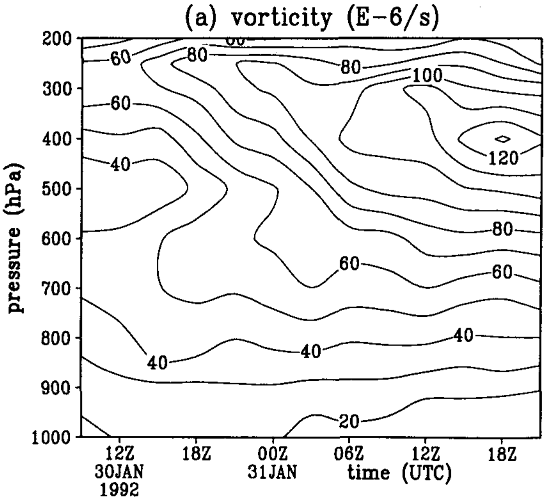


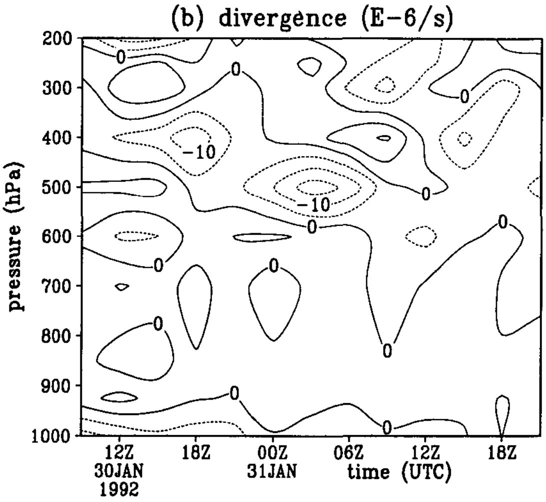
Fig. 7. Surface pressure pattern and surface wind vectors at 0900 UTC, 31 January 1992 obtained from the sensitivity experiment in which both latent and sensible heat fluxes from the surface were switched off.

around 0900 UTC, 30 January as simulated in the prediction experiment. They, however, disappeared after that time. The air above the sea was not warmed and the east-west temperature gradient between the land and sea did not formed. Consequently, no cyclone disturbance developed. Since no heating occurred in the lower troposphere, the cold core of the upper cold low reached to the surface.

The sensitivity experiment in which both the latent and sensible heat fluxes were switched off showed the similar results. The surface pressure and the surface wind vectors (Fig. 7) showed that no cyclone disturbance formed off the west coast of Hokkaido at 0900 UTC, 31 January 1992. Time-height cross sections of vorticity and divergence averaged in the area which indicated in Fig. 7 show that vorticity did not increased with time in the lower troposphere and that the low-level negative divergence was significantly weak and disappeared with time (Fig. 8). Time-height cross section of potential temperature is also significantly different from that of the prediction experiment in the lower troposphere. The averaged potential temperature in the area showed no devel-



(a) vorticity (E-6/s)



(b) divergence (E-6/s)

Fig. 8. Time-height cross sections of averaged (a) vorticity (10^{-6} s^{-1}) and (b) divergence (10^{-6} s^{-1}) in the area of square in Fig. 7 obtained from the sensitivity experiment in which both latent and sensible heat flux from the surface were switched off.

opment of the mixing layer in the lower troposphere (Fig. 9). Stratification of the lower troposphere was significantly stable.

The Bowen ratio in the northern part of the Sea of Japan is usually larger than one when a cold air outbreak occurs. Significant part of diabatic heating in the lower troposphere is due to sensible heat flux from the sea. If the sensible

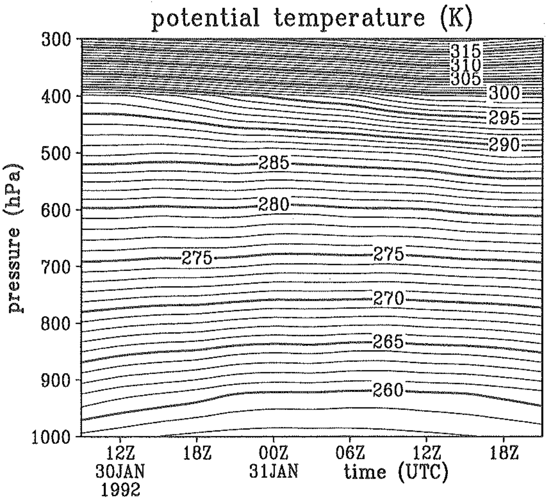


Fig. 9. Time-height cross section of averaged potential temperature (K) in the area of square in Fig. 7.

heat flux is switched off, the lower troposphere became more stable and diabatic heating due to convection which is sub-grid scale condensation in model will be suppressed. Consequently, diabatic heating is effectively reduced by switching off the sensible heat flux. The result of the two sensitivity tests, therefore, gave a similar results with respect to the mesoscale cyclone.

The third sensitivity test was a numerical experiment with no moist processes, which is referred to as the "dry model". Figure 10 shows surface pressure and surface wind field at 0900 UTC, 31 January 1992 obtained from the sensitivity test of the dry model. Even though no moist processes worked in the dry model, the mesoscale cyclone of which central pressure was 1015 hPa was simulated. This indicates that the mesoscale cyclone is different from tropical cyclones in which moist processes are essential for their development. The time-height cross section of averaged potential temperature in the area of question in this experiment (Fig. 11) shows that a mixing layer developed with time below 850 hPa owing to heating by the sensible heat flux from the sea. The mesoscale cyclone developed in the mixing layer of which static stability was small. In the dry model, the warm core which was simulated in the prediction experiment was not significant. This indicated that the warm core of the mesoscale cyclone was attributed to diabatic heating due to water vapor condensation.

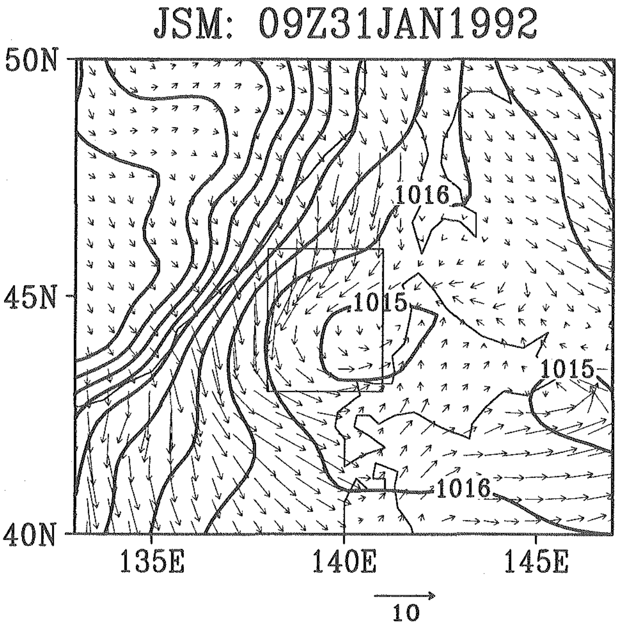


Fig. 10. As in Fig. 7, but for the dry model.

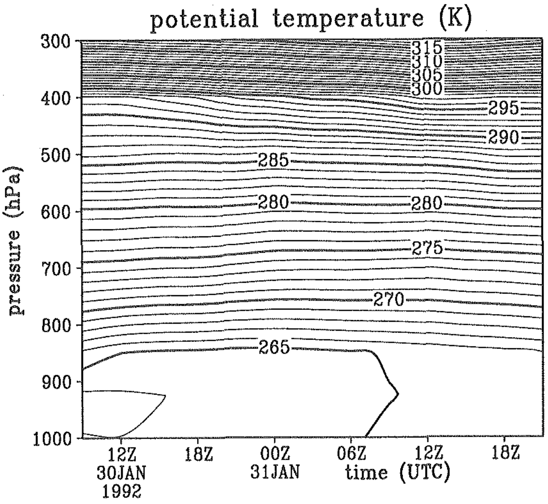


Fig. 11. As in Fig. 9, but for the dry model.

7. Discussion

Mesoscale cyclones formed off the west coast of Hokkaido are usually develop along a convergence zone which occasionally forms along the west coast of Hokkaido. The convergence zone is considered to be formed by a frontogenesis process in a zone of significant horizontal temperature gradient near the surface between the land and sea. Observational studies (Fujiyoshi et al., 1988 ; Tsuboki et al., 1989) showed that a cold easterly makes convergence with the northwesterly monsoon wind when a band cloud which develops along the convergence zone is formed.

The mesoscale cyclone which simulated in the prediction experiment was formed along a convergence zone between a northeasterly and the northwesterly monsoon wind. The northeasterly from Hokkaido was simulated before the mesoscale cyclone developed. When the cyclone began to develop, condensation of water vapor occurred ; this intensified upward motion in the disturbance. As a result, the mesoscale cyclone developed more intensely.

The temperature gradient caused by the differential heating between land and sea is intensified by the frontogenesis process along the west coast of Hokkaido. Consequently, the convergence zone developed. When the sensible heat flux from the surface was switched off in the model, the temperature gradient was significantly weakened. Stratification in the lower troposphere became more stable and convective heating was reduced ; which resulted in reduction of condensation heating. If the stratification becomes more stable, the horizontal scale of unstable wave increases. It should be as small as the horizontal scale of the temperature gradient zone. In order the mesoscale cyclone to develop, a shallow weakly stratified layer is necessary. Studies of a linear stability analysis (Nakamura, 1988 ; Tsuboki and Wakahama, 1989) show that a short unstable wave could exist if the static stability of the lower troposphere is small. The sensible heat flux reduces the static stability of the lower troposphere and contributes to the formation of the mesoscale cyclone.

When the moist processes were switched off, the mesoscale cyclone was formed, although its intensity was rather weaker than that of the prediction experiment. This indicates that the moist processes are not essential for the development of the cyclone. We infer that the conditional instability of second kind which is considered to be a mechanism for tropical cyclones could not be important for the mesoscale cyclogenesis. A hydrodynamic instability of a dry atmosphere should be taken into account for a mechanism of the cyclogenesis.

In this paper, we pointed out that an upper cold low was located above the mesoscale cyclone. Its role on the cyclogenesis is not clear at present. It could be, however, important for the genesis and development of the mesoscale cyclone. Further investigation on the role of the upper cold low is necessary.

8. Summary and conclusions

In order to study snow storms, an intensive observation was performed in January and February 1992 (Kikuchi, 1993) in the Ishikari District of Hokkaido, Japan. During the intensive observing period, a mesoscale cyclone was observed off the west coast of Hokkaido during the period from 30 January to 1 February 1992. We made numerical experiments of the mesoscale cyclone using JSM to clarify the development process and structure of the mesoscale cyclone. We focused on effects of the diabatic heatings due to moist processes and surface heat fluxes. A prediction experiment and three experiments of sensitivity tests were performed from the same initial value of 0000 UTC, 30 January 1992 and the same boundary conditions which were given by the JANAL data.

The prediction experiment which included all modeled processes simulated the genesis and development of the mesoscale cyclone. The mesoscale cyclone began to develop around 21 hours from the initial time and was in mature stage around 33 hours. The central pressure of the mature cyclone was 1014 hPa. After the mature stage, the mesoscale cyclone moved south-westward and weakened. When the mesoscale cyclone generated, the lower troposphere was cold over Hokkaido and warm over the Sea of Japan. The cold air on the east side flowed southeastward and made a convergence. The mesoscale cyclone was formed along the convergence zone. In the mature stage, the mesoscale cyclone had a warm core in its central part and the maximum vertical velocity was about -10 hPa hour^{-1} at the central part. The mesoscale cyclone was a shallow disturbance which was confined to below 850 hPa.

Since the mesoscale cyclone was formed and developed over a warm sea, we examined effects of the surface heat fluxes to the cyclone. We made three numerical experiments of sensitivity tests: experiments with no sensible heat flux, no sensible and latent heat fluxes, and no moist processes (the dry model). When the sensible heat flux from the surface was switched off, the mesoscale cyclone was not simulated. The experiment in which both latent and sensible heat fluxes were switched off gave the similar result. The horizontal temperature gradient between the land and sea due to the differential heating is intensified by the frontogenesis process and the convergence zone is formed.

When the sensible and latent heat fluxes were switched off, the temperature gradient was significantly weakened and the convergence zone was not formed. The static stability in the lower troposphere became more stable. As a result, the mesoscale cyclone was not formed. The diabatic heating due to the surface heat fluxes and the moist processes reduce the static stability in the lower troposphere and create a shallow mixing layer. These make a shallow short unstable waves to be present.

Although the moist processes were switched off, the mesoscale cyclone was simulated. This indicates that the moist processes are not essential for the development of the mesoscale cyclone. We could infer that a hydrodynamic instability of the dry air is essential for the mesoscale cyclogenesis. Since the sensible heat flux from the surface warmed the lower troposphere, a mixing layer developed and the static stability was reduced. In such stratification of the atmosphere, a shallow short unstable waves could be present.

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