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Dynamical Approach to the Maintenance Process of the Long-Lasting Convergence Band Clouds along the West Coast of Hokkaido

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Abstract

A theoretical explanation of the maintenance process of the convergence band clouds along the west coast of Hokkaido (CBC) was performed through the two-dimensional dynamical model. The effects of diabatic heating from the sea surface contribute to the frontgenesis along the coast line and non-geostrophic wind circulations which correspond well with the analytical field were formed. So, we concluded that the CBCs were possible to consider as one kind of a coastal front dynamically.

1. Introduction

Larger cloud bands formed along the west coast of Hokkaido Island in the winter monsoon seasons are very important to the heavy snowfalls around Sapporo city and are called the convergence band clouds (hereinafter referred to CBC ; Okabayashi and Satomi, 1971 ; Kobayshi et al., 1987). Recently, numerical experiments for CBC have been studied by Nagata (1987) and Sasaki and Deguchi (1988). Nagata indicated that the thermal effect was more important than the effect of friction to form the convergence zone in the Japan Sea using a very-fine-mesh model of J.M.A..

Moreover, Doppler radar observations have been carried out in the Ishikari Plain and front-like structures of CBCs were reported (Fujiyoshi et al., 1988 ; Tsuboki et al., 1989). Bosart (1975) analyzed the coastal frontgenesis at New England area in the United States. He emphasized both importance of the direction of a coast line and the differential friction between the sea and the land. That is to say, it means that the frontgenesis is advanced when a favor-

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able angle between the direction of a pressure gradient and that of the surface temperature gradient is formed. Moreover, the northerly wind caused by the land friction plays a role of non-geostrophic circulation. The direction of the geostrophic wind is decided by the favorable synoptic weather situation. Actually, in many cases of the New England, the coastal front is observed in December. There is a difference between the coastal fronts in the eastern coast of the United State and that in the western coast of Hokkaido Island, but both cases have a similar relationship between the direction of surface temperature gradient and the geostrophic wind direction. The purpose of this paper is to confirm the dynamical explanation of the presence of the convergence zone near the west coast of Hokkaido (coastal frontgenesis) in midwinter seasons.

2. Meteorological conditions of the long-lasting CBC

From the analysis of the life cycle of CBC, it was understood that the CBC was maintained for long time under an almost uniform synoptic weather situation after the mature stage of CBC which was elongated for 200 to 300 km (Kobayashi et al., 1987). Figure 1 shows a GMS image and T_{BB} distributions of a long-lasting CBC case. Especially, it is well recognized that CBC developed from the west side of Sakhalin to the Shakotan Peninsula in the mature stage from the low T_{BB} area. And this case of CBC was maintained for three days. An important feature of long-lasting CBCs is wind field in the mesoscale,

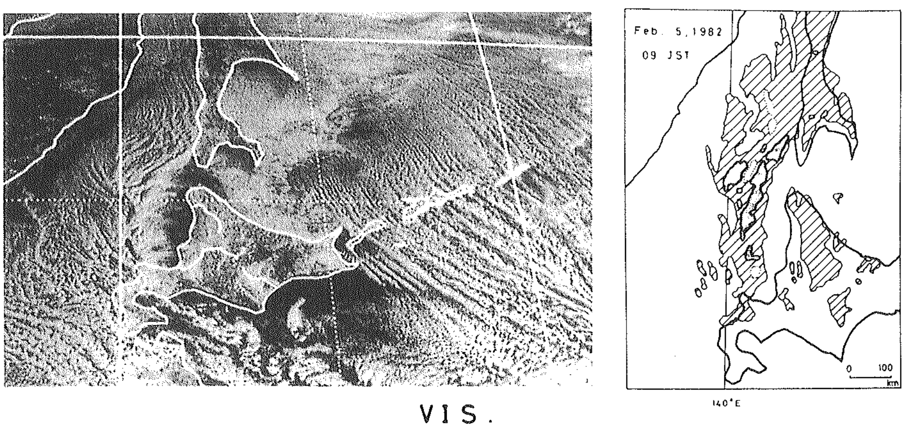

Fig. 1. GMS image and T_{BB} distributions of long-lasting CBC to the west coast of Hokkaido at 09 JST Feb. 5, 1982. Areas of $T_{BB} < -22$, -30 and -40°C are indicated by hatched, stippled and solid, respectively (Kobayashi et al., 1987).

namely, three different air currents are observed in northern Hokkaido as shown in Fig. 2. Northwesterly monsoon winds blow under a synoptic situation which is relatively warm and moist, and northeasterly wind which is about 1 km height and southeasterly cold land breeze with a shallow (~100 m) colder and drier current which is formed under the nocturnal cooling in central Hokkaido.

It is considered therefore that the maintenance process of CBC was characterized by following conditions for simplicity: 1) the presence of relative low pressure area along the coast line, 2) three different wind directions which make a cyclonic flow pattern, especially a balance of wind between the northwesterly monsoon wind and the southeasterly low level land breeze, 3) the development of the wind shear line which has a front like structure and 4) the stagnation of the band echoes near the coast line which bring about the merging of band echoes (Kobayashi et al., 1992). The conditions of 1) and 2) are char-

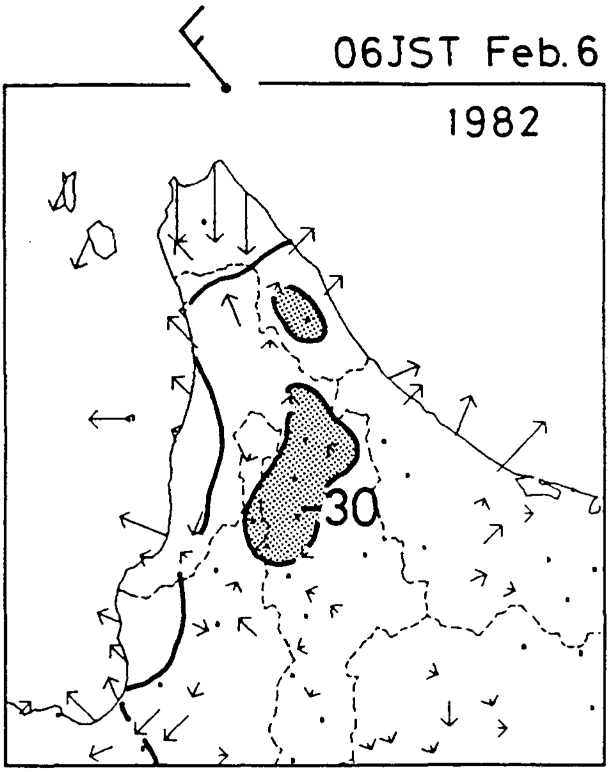

Fig. 2. AMeDAS wind and temperature fields (isotherms of −20°C and −30°C) in the northern part of Hokkaido at the mature to dissipating stage of CBC.

acterized by the long-lasting field near the sea surface for the CBC and the conditions of 3) and 4) are characterized by the features of band echoes. A synoptic situation over Hokkaido is considered to be quasi-stationary, and the CBCs are influenced by the mesoscale surface conditions, such as a differential heating, a differential wind field and friction between sea and land. Thinking that CBCs formed along the coast line and the isotherms on the sea surface are almost parallel to the coast line, a stationary model of two dimensions is allowed to be studied in this case. Moreover, considering that the general monsoon wind blows perpendicular to the coast line, we investigated the effects of diabatic heating from the sea surface mainly.

3. Outline of the model

Based on the mesoscale structures of the wind, by the pressure and temperature fields mentioned in the previous chapter, a two dimensional model was proposed. The model idealized in this case is presented schematically in Fig. 3. In the model, a horizontal homogeneous cold air mass passed over the homogeneous sea, and the air above the sea surface were heated below and a convective layer which is capped by an inversion layer is formed. The height of the convective layer is decided as H. Actually, the thickness and temperature of the convective layer increases as it progresses downstream, but a constant H

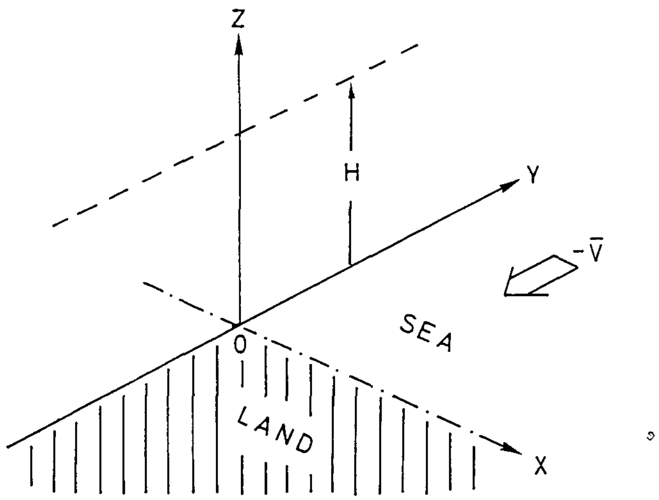

Fig. 3. The physical structure of the model. $-V$ indicates the geostrophic wind in the initial condition.

and a constant θ are assumed here. We assume that a basic condition of the geostrophic wind, V^*, and the potential temperature, θ^* is formed. An X-axis is placed along the coast line and a Y-axis is placed on the sea, and so the monsoon wind is decided as $V<0$ in these coordinates. Upon these basic conditions which represented the barotropic state, a perturbation caused by the mesoscale conditions was added. Considering the homogeneous condition along X-axis, the perturbation is varied with Y and Z coordinates. As a result, the perturbation equations of two $(y-z)$ dimensions were developed as follows (Williams, 1972 ; Økland, 1990).

The perturbation equations mentioned above, under the Boussinesq approximation and the hydrostatic assumption, are as follows.

$$\partial v/\partial y+\partial w/\partial z=0 \qquad (1)$$

$$-V^*\partial u/\partial y+v\partial u/\partial y+w\partial u/\partial z-fv=0 \qquad (2)$$

$$-V^*\partial v/\partial y+v\partial v/\partial y+w\partial v/\partial z+fu=\partial E/\partial y \qquad (3)$$

$$V^*\partial\theta/\partial y+v\partial\theta/\partial y+w\partial\theta/\partial z=Q/c_p \qquad (4)$$

$$\partial E/\partial z=g\theta/\theta^* \qquad (5)$$

Here, u, v and w are the perturbation velocity and θ is the perturbation temperature. Equation (1) is a continuous equation. Equations (2) and (3) denote the movement for v and w, respectively. A force caused by a balance of the thermal wind is also considered in the equation (3). Equation (4) is the first law of the thermodynamics. We assume that θ is only a function of y and is uniform through the vertical direction. In (4), a right hand term denotes the diabatic heating and Q is the heating rate per unit mass per second. Equation (5) is the pressure function,

$$E=c_p\theta^*\ (\theta/\theta^*)^{R/C_p}+gz.$$

After which, we change the equations to a non-dimensional form and expand each variable in a power series. In this theory, the appropriate scales of horizontal, vertical, the geostrophic wind velocity and the difference of the temperature are as follows:

$$L=200\text{ km}$$
$$H=2000\text{ m}$$
$$V=5\text{ m/s}$$
$$\theta=10\text{ K}$$

Equations (1)-(5) were written in the non-dimensional form:

$$\partial v/\partial y+\partial w/\partial z=0 \tag{6}$$

$$-\partial u/\partial y+R(v\partial u/\partial y+w\partial u/\partial z)-v=0 \tag{7}$$

$$-R^2\partial^2 v/\partial y\partial z+RR'\ (v\partial^2 v/\partial y\partial z+w\partial^2 v/\partial^2 z)+\partial u/\partial z=\partial\theta/\partial y \tag{8}$$

$$\partial\theta/\partial y-R\ (v\partial\theta/\partial y+w\partial\theta/\partial z)=q \tag{9}$$

where R and R' are the Rossby numbers ($R=U/fL$, $R'=V/fL$) and q is the heating rate in a non-dimensional form. Further, each variable is expanded in a power series with the Rossby number. Considering the scale mentioned above, the Rossby number is calculated to be smaller than unity.

$$u=u_0+Ru_1+\cdots$$
$$v=v_0+R'\ v_1+\cdots$$

here, each variable inserts equations (6)-(9) and zero order terms are chosen. Finally, the zero order equations are given as follows:

$$\partial v_0/\partial y+\partial w_0/\partial z=0 \tag{10}$$

$$-\partial u_0/\partial y-v_0=0 \tag{11}$$

$$\partial u_0/\partial z=\partial\theta_0/\partial y \tag{12}$$

$$\partial\theta_0/\partial y=q \tag{13}$$

We will calculate the perturbation solutions of zero order of u, v, w and θ. As to the surface weather condition, the differential heating q which is a function of y is inserted in the equation (13). In fact, once the diabatic heating of q is given, θ, u, v and w are calculated in turn numerically using the boundary conditions. The boundary conditions are thought to be $w=0$ at $z=0$ and $z=H$, respectively. And all variables of the perturbation are zero at minus infinity. As a result, we can calculate each variable from minus (the land) to plus (the sea) direction numerically.

4. Results

The behavior of the zero order solutions is investigated in this chapter. As a surface weather condition, the surface heating was given as a function of y. Figure 4 shows one case of a differential heating over the land and the sea. The surface heating is given as a probability function. The peak of the heating is placed at $y=0$. That is the idealized case of nonuniform sea surface temperature with the concentrated heat source over the sea. In fact, the Tsushima warm current is present along the west coast of Hokkaido (Fig. 5). Therefore,

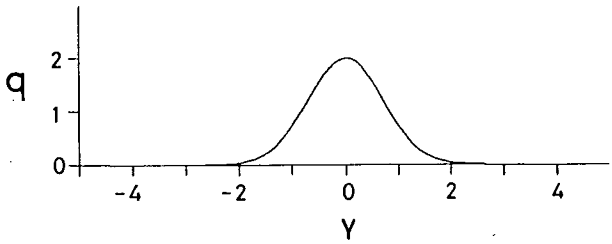

Fig. 4. The surface heating distribution as a function of y.

the sea surface temperature has its peak along the coast of Hokkaido where the surface temperature difference reaches about 10 K, and decreases toward the west of the Japan Sea where the difference is about 5 K in winter.

Figure 6 indicates the wind patterns of $v+w$ perturbation component (top), the u component (center) and the perturbation of θ (bottom), respectively. It is clear that the upward motions are formed at the location where the temperature gradient is maximal. Moreover, the convergence zone of the v component is formed near the surface. This means that the upward motion caused by the differential heating between the land and the sea is strengthened by the difference of sea surface temperature. It is recognized that there are upward motions over the sea and downward motions over the land. It is important that the seaward flow is formed at a low level and a maximum of speed appears at the coast line. The circulation is formed at the coast line where the gradient of heating is maximal and is developed all over the convective layer. The field of u component is shown perpendicular to the $y-z$ plane. The $-u$ (the northerly wind) component indicates that the concentrated flow such as a jet stream forms near the surface. It is thought that the u-component which is the non-geostrophic wind generated in the solution would satisfy the relation of the thermal winds. The gradient of u to the z direction is plus and the wind direction is opposite at the height of $H/2$. The potential temperature changes remarkably at the peak of the heating where it corresponds to the surface convergence zone and the strong updraft zone.

As a result, whereas, the geostrophic wind of V and isobars are parallel to the y axis at the initial condition, the deformation of isobars is caused by the non-geostrophic wind components. Figure 7 shows u and v patterns of $x-y$ plane near the surface. The u and v perturbation components are multiplied by the geostrophic wind of 5 m/s in order to understand the actual wind field. The curvature of the wind which is equal to the isobars is the steepest at the coast

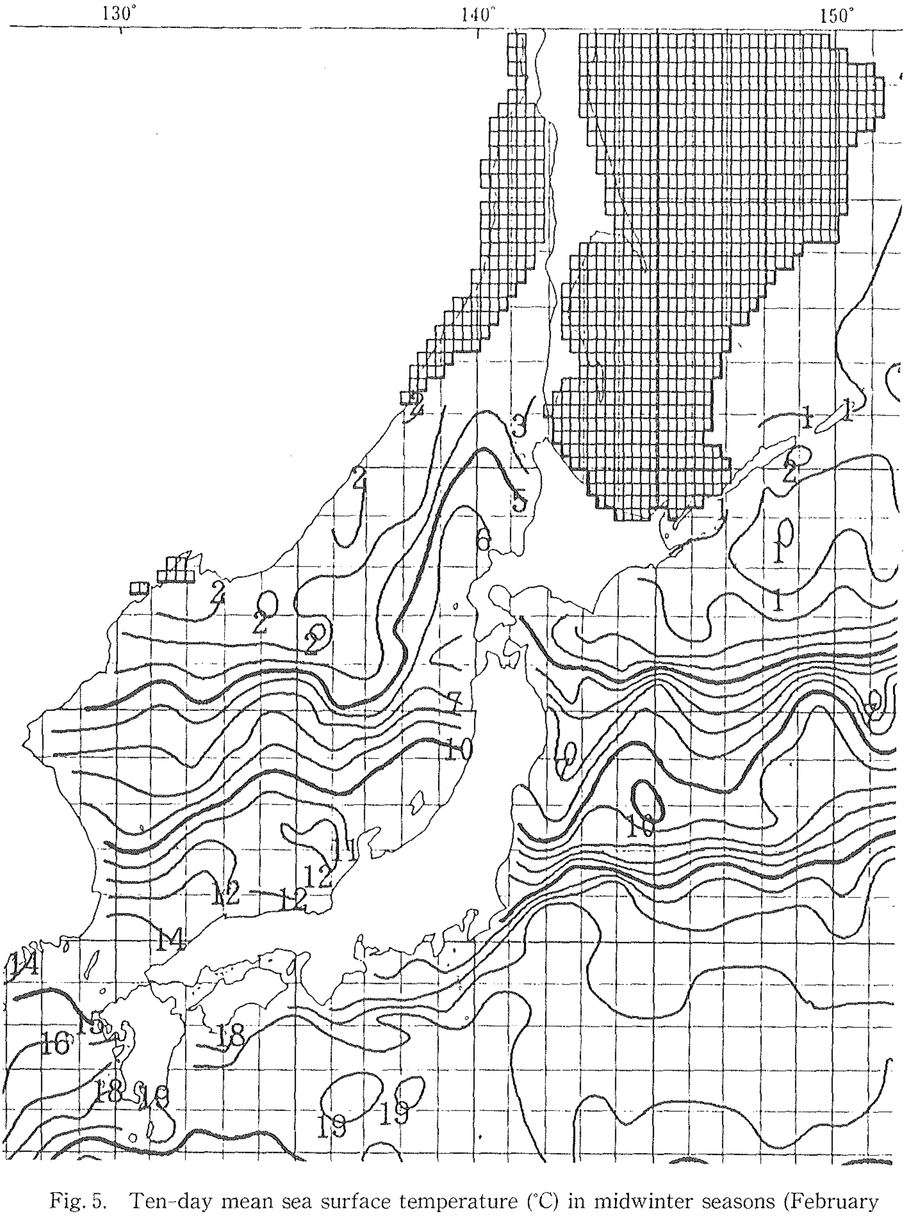

Fig. 5. Ten-day mean sea surface temperature (°C) in midwinter seasons (February 11-20, 1992). Netting area denotes the coverage of sea ice (after J.M.A.).

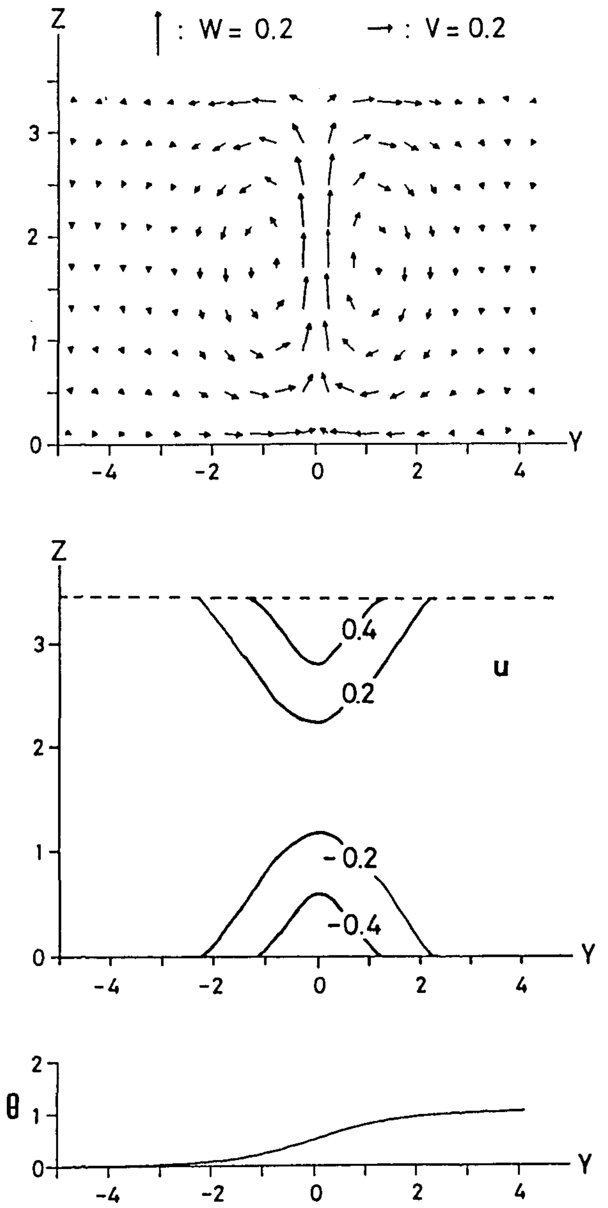

Fig. 6. The perturbation solutions of the v and w wind components (top), u component (center) and the potential temperature (bottom) under the condition of the heating in the Fig. 4.

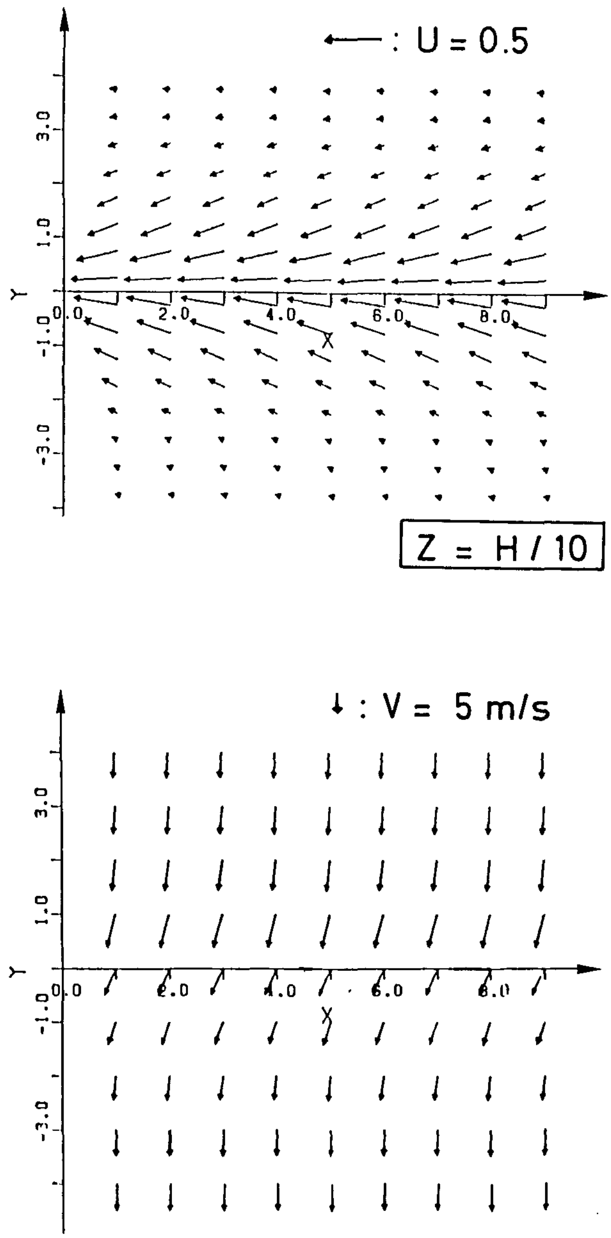

Fig. 7. The surface wind field of the $x-y$ plane (top). The wind field multiplied by the geostrophic wind of 5 m/s is also shown (bottom).

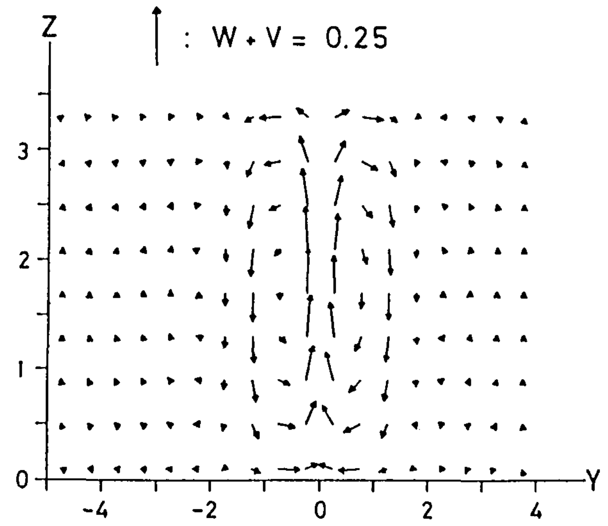

Fig. 8. The first order solutions of the v and w wind components.

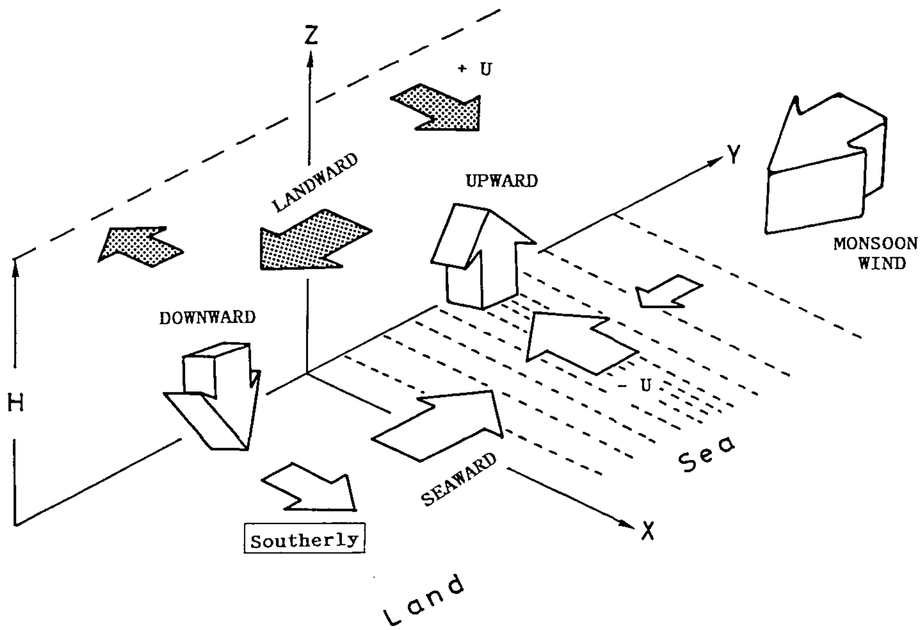

Fig. 9. The schematic figure of non-geostrophic winds shown by wide arrows. Dashed lines indicate sea surface isotherms.

which means that a low pressure area has formed over the coast line. In fact, the calculated value of the vorticity is in an order of 10^{-5} at $y=0$ and the pressure drop is calculated to one order of 10^{-1}. It corresponds well with the pressure trough and the cyclonic wind field which is observed along the west coast of Hokkaido.

The first order solutions are also investigated in each case as shown in the Fig. 8. It is recognized that the second circulations in $y-z$ plane are formed. The second circulation stems from the support of the main circulation of the zero order solutions. It is assumed that the second circulation expresses a local motion which is generated from the main circulation field.

5. Discussion and concluding remarks

In this chapter, the maintenance process of CBC is analyzed and discussed mainly. The CBC corresponds with the convergence zone along the west coast of Hokkaido. Therefore, we must consider the dynamical explanation of the CBC formation. Considering that the CBC is a phenomenon formed in the mesoscale lower convective layer, it is conjectured that the effects of the heating and friction are important to generate the convergence field along the coast. Roeloffzen et al. (1986) investigated the coastal flows under the influence of the friction. They calculated the secondary flow patterns of existing any geostrophic wind. However, the wind speed used in their calculation was fixed as 20 m/s in their model which value is as strong as an actual monoon wind. In fact, the moderate wind speed is needed to form the convergence wind field. Hjelmfelt (1990) carried out a numerical study of the lake-effect snowstorms over Lake Michigan in the United States of America. He investigated the environmental conditions, that is, the wind speed, wind direction, differential temperature, stability and so on. His results suggested that the marginal value of the wind speed to generate the lake breeze was 3-5 m/s when the temperature difference between the lake surface and the land was 10°C. On the other hand, Nagata (1987) indicated that the thermal effect was more important than the effect of friction to form the convergence zone in the Japan Sea. Therefore, the differential heating was considered as the main thermal effect.

For the four meteorological conditions mentioned in chapter 2, the results could be checked as follows. (1) The low pressure zone on the coast line is formed by the u-component that originates when the thermal wind relation is satisfied. And the low pressure zone corresponds to the convergence and cyclonic vorticity fields. (2) Non-geostrophic circulation is generated, that is, the downward motion over the land and the upward motion over the sea are predominant. Moreover, the seaward low level flow (corresponding to the easterly wind) and the northerly wind are formed at the coast line. (3) The horizontal gradient of the potential temperature is concentrated in the area where the upward motion is strongest and the value of heating has its maximal value. In particular, the peak of the temperature gradient appears in the case of the differential heating over the sea considering the conditions of the actual Japan Sea. From these results, it may be realized that the horizontal deformation field is formed at the low level under the non-geostrophic circulation which strengthens the front. And so, this result expresses the dynamical effects and well explains the analyzed field. (4) However, in this linear and dry model, the heating accompanying the latent heat, the down draft in a cold dome and the cold land breeze could not be treated. For example, according to the satellite pictures of the organized CBC, the eastern edge of CBC is more distinct. Moreover, the merging process of band echoes in CBC also could not be explained from this result. It is suggested therefore that the effects of the thermodynamics in clouds would be important, after the developing of CBC clouds.

Generally, a term of the wind which makes the thermal wind component and the diabatic heating term contribute to frontgenesis (Williams, 1972). In our case, only the diabatic heating is given as an initial condition. As a result, it may be said that the dynamical effects to the coastal frontgenesis caused by the diabatic heating were made more clear in this model. Still, the direction of the uniform geostrophic wind is also important to deform the field. Figure 9 indicates the schematic picture of non-geostrophic wind circulations favourable for the maintaining CBC. It is obvious that a pair of upward motions over the sea and downward motions over the land, seaward motions at the surface and landward motions at the top along the coast line, and northerly u-component at the surface and southerly u-component at the top along the temperature gradient zone. However, no u-component appears over the land from this calculation. It is expected that u-component (southerly) over the land shown in the figure would supports and strengthen these circulations. Actually, the southeasterly surface cold breeze is observed along the west coast of Hokkaido in the mature stage of CBC. It is considered to play a role for the horizontal non-geostrophic coast-parallel wind which supports the horizontal circulation at the coast line. Therefore, considering the surface weather conditions over Hokkaido, it is recognized that the cold land breeze acts as a non-geostrophic wind over the land instead of the frictional driven surface wind.

Considering the mechanism of long-lasting effect of the CBC along the coast line, we investigated the dynamical effects by means of the diabatic heating. The two dimensional model is constructed and calculations are accomplished under a uniform synoptic situation and geostrophic wind field. The effect of diabatic heating constitute a non-geostrophic wind circulation on a $y-z$ plane, that is to say, the downward motion over the land and the upward motion over the sea. Especially, a differential heating between the regions at land-sea and over the sea is very important to produce the surface wind convergence and the surface temperature gradient. The calculation results coincide well with those of the analyses. And so, the CBC is explained dynamically as a boundary layer phenomenon under a balance of the horizontal pressure gradient and the pronounced horizontal thermal gradient. This dynamical feature is similar to that of coastal front.

Acknowledgments

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