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The Generative Mechanism of Cloud Streets

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Cloud streets were successfully simulated by numerical model (RAMS) including an isolated mountain near the coast, large sensible heat flux from the sea surface, uniform stratification and wind velocity with low Froude number (0.25) in the inflow boundary.

The well developed cloud streets between a pair of convective rolls are simulated at a level of 1 *km* over the sea. The following five results were obtained: 1) For the formation of the pair of convective rolls, both strong static instability and a topographically induced mechanical disturbance are strongly required at the same time. 2) Strong sensible heat flux from the sea surface is the main energy source of the pair of convective rolls, and the buoyancy caused by condensation in the cloud is negligibly small. 3) The pair of convective rolls is a complex of two sub-rolls. One is the outer roll, which has a large radius, but weak circulation, and the other is the inner roll, which has a small radius, but strong circulation. The outer roll gathers a large amount of moisture by convergence in the lower marine boundary, and the inner roll transfers the convergent moisture to the upper boundary layer by strong upward motion between them. 4) The pair of inner rolls form the line-shaped cloud streets, and keep them narrow along the center-line of the domain. 5) Both by non-hydrostatic and by hydrostatic assumptions, cloud streets can be simulated. In our case, non-hydrostatic processes enhanced somewhat the formation of cloud streets. The horizontal size of the topography does not seem to be restricted to within the small scale where non-hydrostatic effects are important.

1. Introduction

Cloud streets are frequently observed during cold air mass advection over warm sea surface in winter season. Thick and long cloud streets can be sometimes seen in the lee of some islands or mountains near the coast.

Figure 1 shows the satellite image of cloud streets for 0300 Z, 29 December 1991. The Sea of Japan, bordered by the Korea Peninsula and Japan Island, can be seen in the central part of the photograph. The well-developed cloud streets over the ocean are classified into two types. Some occur in groups of thin cloud streets, the others are independent thick cloud streets with a long line shape. The former is, for example, observed over the Huang Hai sea and the East China sea (point A). The latter is seen in the lee of Japan Islands (B - C) and in the lee of Korea Peninsula (point D). At point A, there are relatively low mountains in the windward region near coastline, however, point B, C, and D are located in the lee of high mountainious region (Aso, Fuji, and Paektu mountain, respectively). The origins of the cold-air mass in the regions of point C and D are different. The air mass at point D is dry because it comes from the ice-covered continental region, and the air mass at point C is the wetter than point D because it comes from the Sea of Japan. Although the origin of the air mass at point C and point D are different from each other, well-developed cloud streets with a long line shape are observed in the lee of both regions. This study will focus

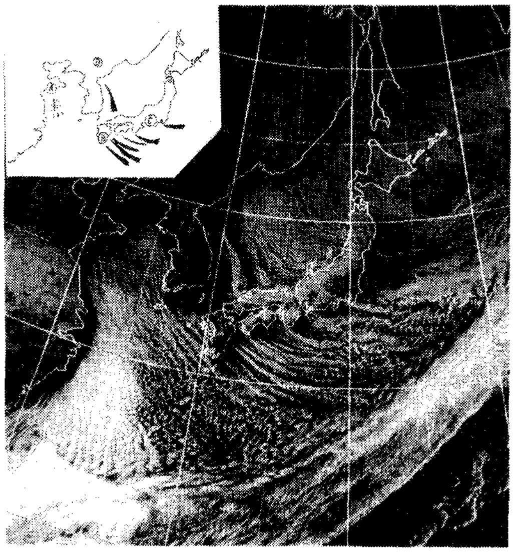

Fig. 1. Satellite image for 03 Z 29 December 1991.

on the formation mechanism of these well-developed cloud streets with a long line shape. When cold air advects from the Korea Peninsula to the Sea of Japan, the thermodynamic properties of the atmospheric boundary layer are changing because of large sensible and latent heat fluxes from the East sea. As the cold air traverses the warm sea, the mixed layer becomes deeper; as a result, convective rolls, which must be related to the formation and maintenance of cloud streets, are formed over the East sea.

Even though deep cumulus convection has been intensively investigated during the past three decades, only a few systematic investigations have focussed on these cloud streets.

According to the conventional theory (Kuettner; 1971, Le Mone; 1973, Nicholls; 1978), the vertical shear and static instability play an important role for the formation of the thin cloud streets. For the thick cloud streets with long line-shape in the lee of the isolated mountain, however, the other mechanism seems to be important in addition to the conventional theory. This may be related to both strong static instability caused by large amount of heat flux from the sea surface in the marine boundary and mountain induced mechanical disturbance (Smolarkiewicz; 1988, 1990, Kimura; 1986, Olafsson and Bougeault; 1996) caused by flow separation around mountain. It is doubtful that the conventional theory alone accounts for cloud-street formation.

Although the cloud streets are a familiar phenomenon, the formation mechanism of cloud streets is not yet known. In this study, the numerical simulation of cloud-street formation with precipitation are carried out under both strong static instability in the marine boundary layer and topographically induced mechanical disturbance around a mountain, which may be more favorable conditions for the formation of cloud streets.

2. Model description

In this study, the effects of the two factors, strong static instability and topographically induced mechanical disturbance, are investigated by use of the CSU RAMS (Regional Atmospheric Modeling System) with high horizontal/vertical resolution, 1 *km* and 100 *m*, respectively. Since the general characteristics of CSU RAMS are summarized by Pielke et al. (1992), only the major options assumed in the present experiments are here. In the calculation, an uniform stratification and wind velocity with low Froude number (0.23) are assumed in the inflow boundary. Vertical and horizontal turbulent mixing is parameterized using the level 2.5 by Mellor and Yamada (1978). To emphasize the thermal and moisture effects of sea surface, strong heat and moisture flux are assumed in the marine boundary layer, based on the bulk method. The bulk exchange coefficients (C_hU) of marine surface layer for heat and moisture flux are

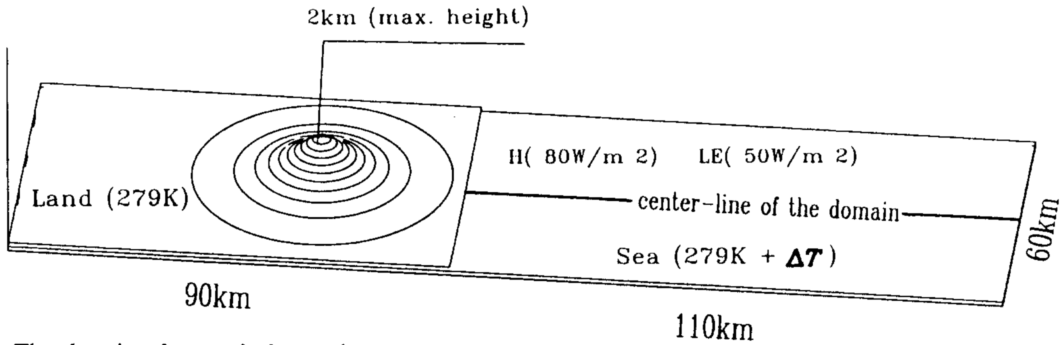

Fig. 2. The domain of numerical experiment.

assumed to be a constant value of 0.02. The bulk exchange coefficient (C_mU) for momentum flux over marine surface is assumed to be 0.015. However, there are no heat and moisture flux on the land surface because of assuming ice covered land. Longwave and shortwave radiation are not activated in this study, because these effects seem to be much less important than thermal forcing from the sea surface.

Figure 2 indicates the schematic domain of the numerical experiments. The domain sizes are 90 *km* by 60 *km* and 110 *km* by 60 *km* for land area and ocean area, respectively. The values of sensible heat flux (H) and latent heat flux (LE) shown in the figure are horizontal means calculated by numerical model over the sea surface.

3. Initial conditions

Initial velocity, potential temperature and specific humidity are assumed to be horizontally uniform with profiles. The surface specific humidity is 3.5 gkg^{-1}, decrease by 2 $gkg^{-1}km^{-1}$ with altitude in the lower boundary layer (below 1 *km*). A relatively weak (5 Kkm^{-1}) and a strong (10 Kkm^{-1}) stable layer are given below and above 1 *km* level, respectively. To consider the influence of strong heat flux from the sea surface, a relatively high SST (289 *K*) is given. On the contrary, the relatively cold land-surface temperature (279 *K*) is assumed to maintain the snow cover and dry condition of the land surface. The wind fields are given as a constant through all levels (u = 10 ms^{-1}, v = w = 0) except for the lowest level given as 2 ms^{-1}.

4. Results and discussion

Cloud streets were successfully simulated in the lee of an isolated mountain near the coast, under the assumption of large sensible heat flux on the sea surface. The well developed cloud streets are simulated between a pair of convective rolls at the level of 1km over the sea.

Figure 3 shows the simulated cloud streets obtained by the three dimensional numerical model after eight hours integration. The circles of solid lines represent the contours of topography with the interval of 500 *m* and the straight solid line located at the lee of mountain indicates the coastline. Figure 3a shows the x-z cross section of cloud-mixing ratio along the centerline through the whole domain. The maximum value of cloud-mixing ratio is 0.4 gkg^{-1}. Figures 3b and 3c indicate the horizontal distribution of cloud-mixing ratio and streamlines at the level of the maximum cloud-mixing ratio, which are about 1 *km* and 800 *m* high,

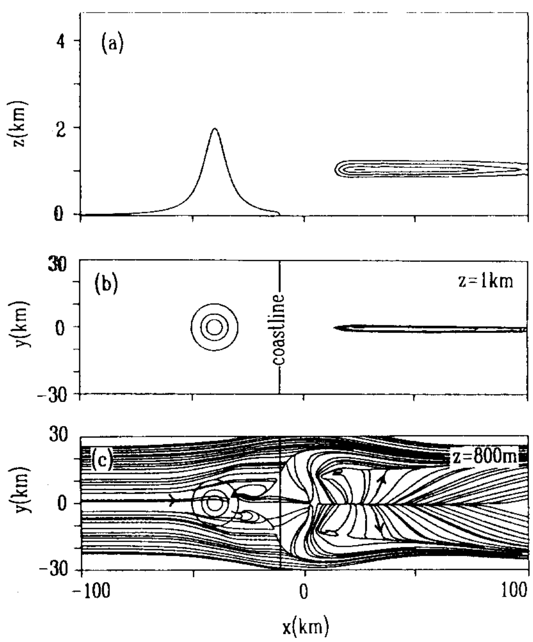

Fig. 3. The simulated cloud streets by three dimensional numerical model. (a) and (b) are vertical (x-z) and horizontal (x-y) cross section of cloud mixing ratio through the center-line of the domain. (c) Horizontal structure of streamline at the level of 800 *m*.

respectively. Figure 3b shows the thick and long cloud streets, which is similar to the satellite -image (see A, B, C, and D in Fig. 1). Figure 3c indicates a horizontal cross section of streamline in the level of that cloud streets. This figure shows clear divergence in the lee of the mountain, which must be a part of convective rolls. This means that the cloud streets are accompanied by convective rolls along the center line of the domain. The strong convective rolls in the layer of the cloud street must mainly contribute to the formation and maintenance of the cloud streets.

Figure 4 reveal the schematic diagram which explain the relationship between the well developed cloud streets and the pair of convective rolls for the formation and maintenance of cloud streets over the sea in the lee of the mountain. Two kinds of convective rolls are shown in this figure. One has large radius but weak circulation, and the other has small radius but strong circulation. The former is a pair of outer roll, which gathers large amount of moisture by the convergence in the lower marine boundary. The

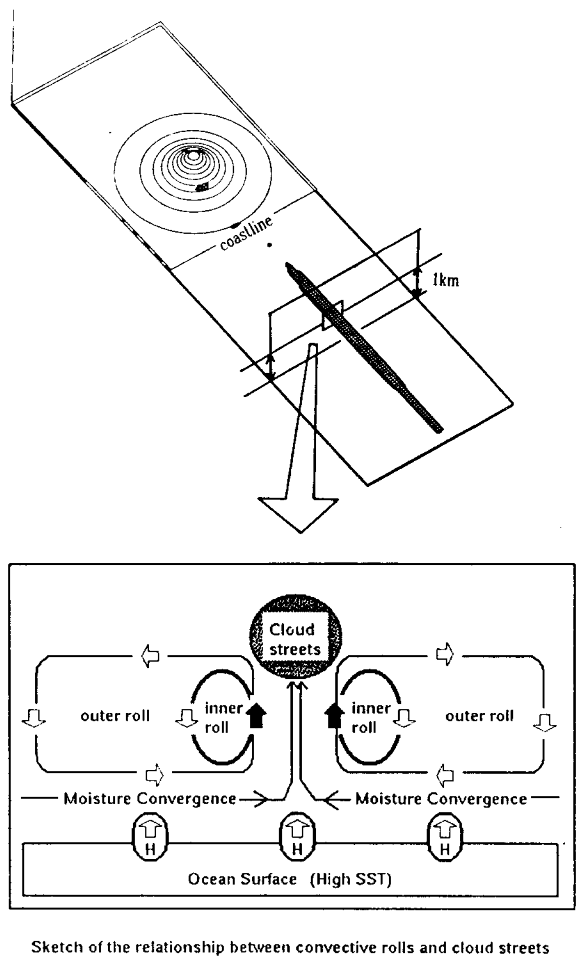

Fig. 4. The mechanism of cloud-street formation under strong static instability and topographically induced mechanical disturbance. Two kinds of convective rolls are shown in this figure. One (pair of outer roll) has large radius but weak circulation, and the other (pair of inner roll) has small radius but strong circulation.

latter is a pair of inner roll, which transfers the convergenced moisture to upper boundary layer from marine boundary layer by strong upward wind speed between them. The inner rolls form the thick and long line-shaped cloud streets, and keep it up narrow along the center-line of the domain because of small radius with strong circulation. Two kinds of convective rolls, therefore, play an important role for the formation and maintenance of cloud streets over ocean in the lee of the mountain. These pair of convective rolls can be formed under two necessary conditions: (1) strong static instability in the marine boundary layer, (2) topographically induced mechanical disturbance, which depend on Froude number. In the case of higher Froude number ($Fr > 1$), however, we can not expect the effect of topographically induced mechanical disturbance because flow pass by mountain without flow separation.

5. Conclusion

The effects of the two factors, strong static instability and topographically induced mechanical disturbance, are investigated by use of the CSU RAMS (Regional Atmospheric Modeling System) with high horizontal and vertical resolution. In the calculation, uniform stratification and wind velocity (low Froude number) are assumed at the inflow boundary. To clarify the importance of both the strong static instability and the topographically induced mechanical disturbance on the formation and maintenance of cloud streets, three kinds of numerical experiments with different sea-surface temperature were carried out, including a numerical experiment without mountain.

Cloud streets were successfully simulated in the lee of an isolated mountain near a coast, with the addition of a large sensible heat flux at the sea surface. Well developed cloud streets occur in the simulation between a pair of convective rolls below a height of 1 *km* over the sea. The following five results were obtained: 1) For the formation of the pair of convective rolls, both strong static instability and a topographically induced mechanical disturbance are required at the same time. 2) Strong sensible heat flux from sea surface is the main source of the convective rolls (the buoyancy caused by the condensation process in the cloud is negligibly small). 3) The pair of convective rolls contain two sub-rolls. One is the outer roll, which has a large radius but a weak circulation, and the other is the inner roll,

which has a small radius but a strong circulation. The former gathers large amount of moisture by convergence in the lower marine boundary layer, and the latter transfers the convergent moisture to the upper boundary layer by the strong vertical motion between the rolls. 4) The pair of inner rolls form the line-shaped cloud streets, and keep it up narrow line along the center-line of the domain. 5) Cloud streets can be simulated both by non-hydrostatic and by hydrostatic models, which implies that vertical inertia is not always important for the cloud-street formation. The horizontal scale of the topography does not seem to be restricted to within the small scale where non-hydrostatic effects are important.

Acknowledgements

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