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A Numerical Study on the Mechanism of Lee Vortex in the Lee of Large Scale Mountain

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Understanding the nonlinear flow caused by orographic effects can be valuable in siting of new businesses, industries, and transportation facilities. In spite of recent work on large-amplitude waves and wave breaking, the studies of flow around large scale mountains have just begun.

The generative mechanism of lee vortices in the lee of large scale mountain is investigated by Ertel's theorem. The CSU RAMS is used as a numerical model.

According to the numerical results, the isentropes are depressed behind the large scale mountains. This means the vortex lines must run upward and downward along the depression surface because vortex lines adhere to isentropic surfaces. Therefore, the vertically oriented vorticity can be formed in the lee of the large scale mountain. This vorticity plays an important role for orographic precipitation, because strong vertical velocity and cloud bands are developed along isothermal deformation surface.

1. Introduction

Mountains have a significant influence on the weather over the East Asia on many spatial and temporal scales. On the large scale, a massive mountain chain such as the Tibet plateaus affects the weather over much of China, Korea and Japan by modifying the positions and amplitudes of the longwave troughs and ridges. In turn, this modification can alter the tracks of middle latitude cyclones and cause temperature and precipitation anomalies. In addition, mountainous regions create warm anomalies in summer, inducing monsoon circulations that impact the wind and precipitation patterns over East Asia.

The physical basis of the large-scale orographic influence is not fully known. It may involve the excitation of internal gravity waves by individual terrain features and the breaking of these waves in the troposphere and lower stratosphere. Cumulatively, these breaking waves exert a drag (e.g., Sawyer 1959; Lilly 1972; Palmer *et al.* 1986; McFarlane 1987; Durran 1995), which affects the large-scale meteorological patterns.

Korea peninsula consists of 70 percentage of mountains, and that mountains induce a variety of local weather phenomena. In response to the diurnal radiative cycle, slope winds develop local departures from the synoptic-scale flow.

During the daytime on sunny days, upslope flows develop along the heated slopes. The rising buoyant plumes are significant sources of turbulences for general aviation and become the sites for convective development. Depending upon the large-scale wind direction and speed, convection can be initiated over the crests or on the lee slopes relative to the prevailing flow.

Thus, convective precipitation patterns and temporal evolution can exhibit considerable day-to-day variation. In stable situations, precipitation is enhanced by lifting on the windward slopes modified by microphysical and blocking effects (e.g., Smith 1989). Where there is a prevailing downslope flow, precipitation can be totally suppressed.

At night, cool air descends the slopes, forming drainage flows that accumulate cool air in valleys. These circulations influence local fog formation and, since cities have historically arisen in valleys, there is a significant impact on ground and air transportation. There is also the problem of air quality and human health. Because power plants and heavy industries tend to be sited in valleys, orographic circulations of this type may require use of relatively expensive low-sulfur coal and restrict certain industrial activities. Understanding the orographic effects of these flows can be valuable in siting of new businesses, industries, and transportation facilities. In spite of recent work on large-amplitude waves and wave breaking (Smith 1979, 1989b; Blumen 1990; Baines 1995), the studies of flow around large scale mountain have just begun. There remain several critical unsolved problems; 1) there is still considerable uncertainty concerning the influence of mountain drag on large scale flow, 2) the physics and dynamics of orographic precipitation are poorly understood, 3) researches are needed on the relationship between terrain and model resolution, 4) the role of evaporative cooling and radiative inversions in basins, valleys, and upstream blocked regions needs further study, and 5) the relative role of elevated heating, friction, beta effect, and mechanical lifting on large scale flow over large scale mountains is not well understood.

This study focuses on the first (effect of mountain drag on large scale flow) and second (orographic effect on precipitation) problems which are related to the origin of lee vortex. The generative mechanism of lee vortex in the lee of large scale mountain is investigated in the viewpoint of Ertel's theorem.

2. Model description

2.1. Numerical model

The Regional Atmospheric Modeling System (RAMS), developed at Colorado State University (CSU), was applied to clarify the effects of mountain drag on large-scale flow and orographic precipitation in the lee of large scale mountains.

The RAMS (version 3b) consists of the full set of nonhydrostatic compressible dynamic equations, a thermodyanmic equation, and micro-physics equations for liquid- and solid-phase clouds and precipitation. Since the general characteristics of CSU RAMS are summarized by Pielke *et al.* (1992), only the major options assumed in the present experiments are referred to here. Vertical and horizontal turbulent mixing is parameterization using the level 2.5 model of Mellor and Yamada (1982). The parameterization of cloud and precipitation in RAMS follows the outline by Kessler (1969), who divided total liquid water into two categories: cloud water and rain water. The governing equation for vapor depositional growth of cloud water is derived by the standard cloud physics (e.g., Pruppacher and Klett, 1978). The autoconversion of cloud droplets into rain is estimated based on a threshold average diameter (Manton and Cotton, 1977).

2.2. Numerical experiments

In this study, the flow pasts an idealized large-scale mountain having two peak under a low

Froude number ($Fr = U/NH = 0.25$, $U = 10 ms^{-1}$, $N = 0.02 s^{-1}$, $H = 2 km$), where U is the cross-mountain wind speed, N is the Brunt-Väisäla frequency, and H is the maximum mountain height. The atmosphere was simulated up to 12 *km* height and divided into 51 layers with a high resolution near the ground surface and progressively less resolution with height. Rayleigh damping is applied to the upper twelve layers in order to avoid reflection of gravity waves. The horizontal domain is 3000 *km* (x-direction) by 3000 *km*(y-direction) with the resolution of 30 *km*. The total number of grid point is 101×101×51. The time step of integration is 60 *s* for a long time step and 30 *s* for the sound wave term, respectively. To allow gravity waves to pass through the lateral boundaries, the radiation condition by Orlanski (1976) was adopted for the simulation.

2.3. Initial Conditions

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. The wind fields are given as a constant through all levels ($u = 10 ms^{-1}$, $v = 0$, $w = 0$) except for the lowest level given as 2 ms^{-1}.

3. Results of numerical experiments

Figure 1 shows the simulated cloud obtained by the three dimensional numerical model after 72 hours integration. The arrow indicates the direction of inflow with 10 ms^{-1}. The solid lines represent the contours of topography with the interval of 200 *m* and the mesh surface located in the lee of mountain indicates the isosurface of cloud-mixing ratio ($0.25 gkg^{-1}$). In this figure, well developed two large cloud-bands are observed in the lee of two peaks, respectively. One more interesting thing here is thin cloud line which has normal direction to the inflow at downstream region. The two cloud bands and thin cloud lines come from orographic effect, because homogeneous heat and moisture fluxes are assumed in this study.

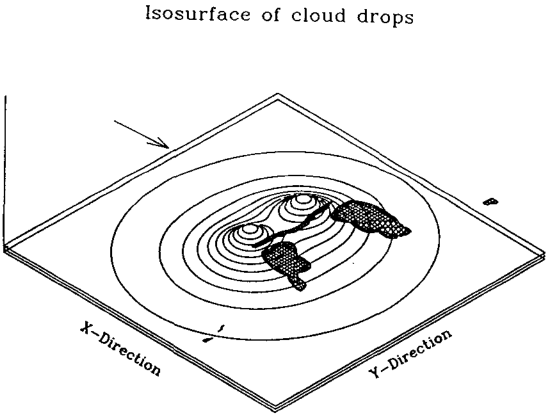

Fig. 1. The three dimensional distributions of simulated cloud band caused by large-scale mountain effect.

Figure 2 indicates two dimensional structure of streamlines. (a) is horizontal cross section of streamline at the height of 1 *km* and (b) is vertical cross streamline along x-direction between the two mountain peaks. figure 2a shows one pair of lee-vortex in the lee of two peaks and convergence zone between the vortex pair. The convergence zone between the pair of vortex can be seen more clearly in Fig. 2b. There are strong circulations with the large radius at downstream region, and strong convergence zone exist in the lee of peak. The pair of vortex and convergence zone play an important role for the formation of cloud caused by orographic effect (see Fig. 1). The convergence zone gathers moisture at low level (below 1 *km*) and transfers the converged moisture to upper atmosphere (2 *km* level). And then, each vortex transfers the moved moisture to the lee of each mountain peak. Therefore, the vortex in the lee of the mountain is very important for The formation of large-scale mountain induced cloud formation. the mechanism of large-scale mountain induced cloud formation should be also related to the origin of vortex problems like mesoscale cases. That is "where does the vortex come from ?".

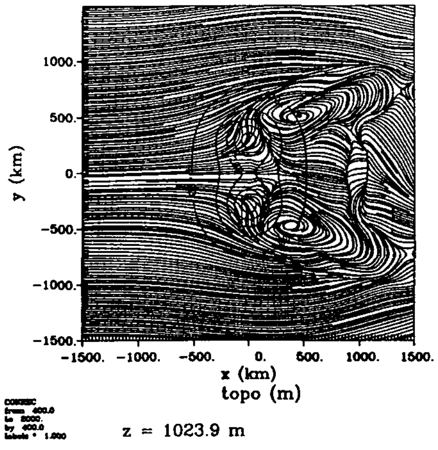

Fig. 2a.

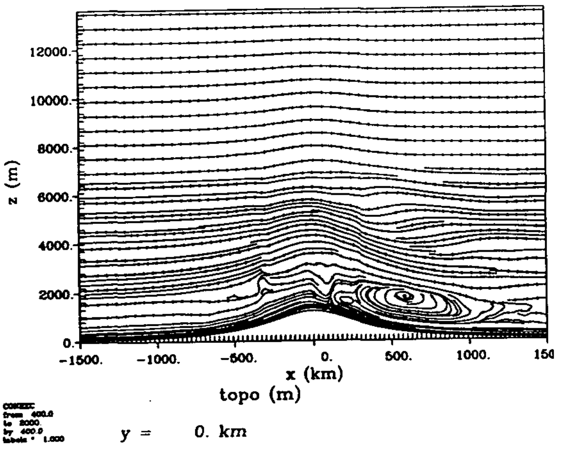

Fig. 2b

Fig. 2. The horizontal (a) and vertical (b) cross sections of streamlines.

As mentioned above, this study focuses on the effect of large-scale mountain drag on large-scale flow and orographic effect on precipitation in viewpoint of Ertel's theorem. Next section speculates the origin of lee vortex in the lee of large-scale mountain using Ertel's theorem.

4. Mechanism of lee vortex in the lee of large-scale mountain

Ertel's theorem is that for an inviscid adiabatic fluid the potential vorticity is conserved :

$$\frac{d}{dt}\left(\frac{1}{\rho}\omega\cdot\nabla\Theta\right)=0 \qquad (4.1)$$

where ω is vorticity, ρ is the height-dependent density of the base state, and Θ is the potential temperature. In our initial state, $\omega\cdot\nabla\Theta=0$ is assumed for all domain, and by eq.(4.1), it must remain so for all t, i.e.,

$$\omega\cdot\nabla\Theta=0 \qquad (4.2)$$

The geometrical interpretation of eq.(4.2) is that vortex lines must lie in the surface of constant Θ. Moreover, if the floomega is steady, the trajectories, which also remain on isentropic surface, are identical to streamlines.

Figure 3 shows the three dimensional structure of isentropic surface (a) and vertical velocity (b). Except for isentropic surface and vertical velocity, the others are the same as Fig. 1. In Fig. 3a, strong isentropic deformation can be seen in the lee of the mountain, and the deformations are more extended along downstream at each peak of the mountain, According to the Ertel's theorem, it is apparent that the strong isentropic deformation indicates vertical vorticity generation in the lee of the mountain. In Fig. 3b, there exists strong vertical velocity along the isothermal deformation surface at downstream region. Comparing Fig. 3a and 3b, we can see the Ertel's theorem can explain the origin of large- scale mountain induced vortex. This large-scale mountain induced vortex plays an important role for the formation and development of cloud (see Fig. 1), and that clouds contribute to the orographic precipitation.

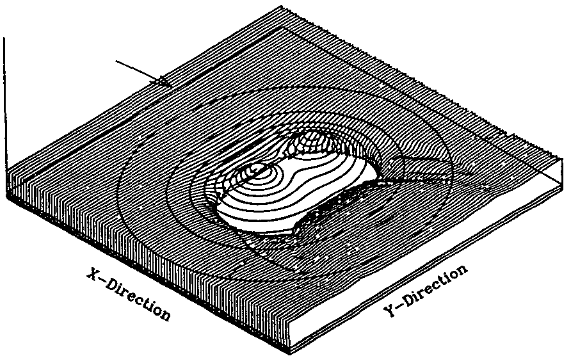
Isosurface of potential temperature

Fig. 3a.

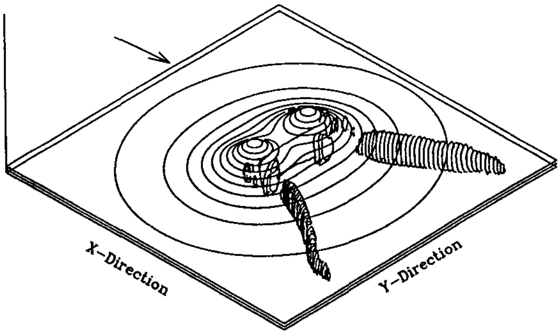
Isosurface of vertical velocity

Fig. 3b

Fig. 3. The three dimensional structure of isentropic surface (a) and vertical velocity (b).

5. Conclusion

As *Fr* decreases to the point where flow around the obstacle occurs, the computed flow becomes complex and difficult to interpret. In this nonlinear flow regime a variety of temporal and spatial scales appear in the solutions, and a physical interpretation of the results may easily be obscured by the truncation errors of finite -difference approximations, or more generally, by subgrid-scale effects. Fine mesh can reduce the truncation error, but round-off error will be increased. That round-off error makes physical analysis of numerical result as no meaning. However, the simulation of large-scale mountain induced vortex can be more free from the round-off error.

Ertel's theorem is used to analyze the generative mechanism of lee vortices in the lee of large scale mountain. The CSU RAMS is used as a numerical model. The shape of the isentropic surface is thus crucial for understanding the vorticity distribution. The numerical results of isentropes are depressed behind the mountain. This means the vortex lines must run upward and downward along the depression surface because vortex lines adhere to isentropic surfaces. therefore, the vertically oriented vorticity can be formed in the lee of the large scale mountain. This vorticity plays an important role for orographic precipitation, because strong vertical velocity and cloud bands are developed along isothermal deformation surface.

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