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Numerical Simulation on Stratified Flow over an Isolated Mountain Ridge*

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Abstract: The characteristics of stratified flow over an isolated mountain ridge have been investigated numerically. The two-dimensional model equations, based on the time-dependent Reynolds averaged Navier-Stokes equations, are solved numerically using an implicit time integration in a fitted body grid arrangement to simulate stratified flow over an isolated ideally bell-shaped mountain. The simulation results are in good agreement with the existing corresponding analytical and approximate solutions. It is shown that for atmospheric conditions where non-hydrostatic effects become dominant, the model is able to reproduce typical flow features. The dispersion characteristics of gaseous pollutants in the stratified flow have also been studied. The dispersion patterns for two typical atmospheric conditions are compared. The results show that the presence of a gravity wave causes vertical stratification of the pollutant concentration and affects the diffusive characteristics of the pollutants.

Key words: internal gravity wave; stratified flow; complex topography; numerical method

Introduction

The response of a stably stratified flow over an isolated mountain ridge has been studied extensively in the last four decades. Most of what is generally known about atmospheric flow over topographic features is related to the generation of mountain waves[1-4], down slope winds[5,6], and upstream blocking[7,8]. The flow around topographic features is characterized by the parameter $F = U/NH$, where N is the Brunt-Väisäla frequency, defined as $N^2 = -(g/\rho)(\mathrm{d}\rho_{\mathrm{B}}/\mathrm{d}Y)$, H is the height of the mountain, and U is the uniform upstream velocity. In general, the flow is linear if F is sufficiently large. Nonlinearities (steepening, wave breaking and mixing, columnar disturbances, etc.) become increasingly important as F approaches unity.

The present study concerns the local scale atmospheric motion over an isolated mountain ridge. We have chosen to use a numerical model for solving the time-dependent Navier-Stokes equations. The model presented here has been developed by implementing the density equation and defining a reference state for the atmosphere that corresponds to hydrostatic equilibrium. In this study we perform two-dimensional (2-D) numerical simulations of atmospheric flow with uniform inflow over an isolated mountain ridge. Uniform flow over a 2-D obstacle represents the simplest related model system. It is not immediately obvious therefore that such a simplified description will have any environmental relevance. However, in some cases the lower atmosphere exhibits nearly ideal physical properties: almost uniform wind from a constant direc-

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tion in a stable stratification with an approximately constant Brunt-Väisäla frequency[9]. We present results of simulations that have been carried out to test the validity of these modifications and to test the ability of the model to reproduce flow features for various atmospheric conditions.

In addition, complex mountain topographies cause complicated flow patterns and mountain climate characteristics. Some flow phenomena, such as dividing streamlines and mountain waves, will lead to different patterns of plume dispersion and diffusion. Accordingly, a combination of these unsteady flow fields and the complex topography can lead to the frequent occurrence of high pollution concentration conditions. The dispersion characteristics of gaseous pollutant is studied in this work using a continuum approach, to better understand the characteristics of the pollutant transport mechanism.

1 Numerical Model Equations

The basic atmospheric flow equations are solved using the Boussinesq approximation. The governing equations for unknown variables $u_i = (u, v)$, ρ, p, and C consist of the continuity, Navier-Stokes, density, and concentration equations. The details are seen in Ref. [10].

2 Numerical Results for 2-D Atmospheric Flows over Topography

In order to validate the mathematical models and numerical method, the scheme has been tested for several 2-D flow patterns over topographic features and the results have been compared either with known analytical solutions or other published data. The following test cases are considered: near-neutral flow, hydrostatic flow, and non-hydrostatic flow. In the first case the isothermal atmosphere is used. In the latter two cases we restrict our consideration to the model atmosphere, that is to say isothermal in the motionless state. For hydrostatic flow, linear hydrostatic waves exist in the flow field, which have a periodic structure in the vertical direction, and which quickly decay in the horizontal direction with increasing distance from the mountain symmetry plane. Non-hydrostatic flow is expected to occur over smaller mountains. Non-hydrostatic motion (Lee waves) occurs under very small overflow velocities. The classical Lee waves are quasi-periodic waves extending downstream from a mountain.

Test cases have been performed with an ideally bell-shaped mountain profile given by $h(x) = h_m a^2 / (x^2 + a^2)$, h_m being the maximum elevation and a the mountain half-width. For this mountain profile, analytical solutions for the vertical velocity can be found for the case of near-neutral flow[11]. For hydrostatic flow and non-hydrostatic flow, solutions for the flow field can be found in Refs. [12-14].

2.1 Near-neutral flow

For near-neutral flow, an analytical solution for the vertical velocity can be found in Christianc[11]. The calculated results are plotted in Fig. 1. The solution for the vertical velocity obtained from the numerical model for an incoming horizontal wind of 10 m/s compares very well with the analytical solution. The solution was calculated with a =10 km, and h_m =500 m using a constant density profile.

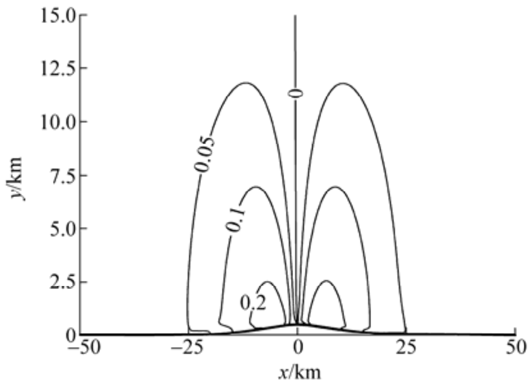

Fig. 1 Vertical velocity in near-neutral atmospheric conditions (m·s^{-1})

2.2 Hydrostatic flow

For hydrostatic flow: $h_m / a \ll 1$ and $Na/U \gg 1$ or $F > 1.18$[15]. A hydrostatic stationary test was run assuming a =16 km and h_m =800 m, at the resolution Δx = 2.8 km and Δy = 200 m and with an initial horizontal velocity of U = 32 m/s. For this test case the temperature was chosen so that N = 0.02 s^{-1} and F = 2.0. The same test conditions were also used in early studies[13,14].

The horizontal velocity, vertical velocity, and potential temperature contours obtained at time t=86 000 s are plotted in Figs. 2-4. The results agree well with