Nonhydrostatic atmospheric modeling using a Cartesian terrain-intersecting grid

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1. Introduction

One of the most significant concerns of nonhydrostatic atmospheric modeling is handling of steep mountains. Models using terrain-following coordinates typically introduce significant pressure gradient force errors over steep slopes. The conventional step mountain method suffers from serious problems when reproducing mountain-induced gravitational waves because of less accuracy in the representation of topography.

Here, a cut-cell representation of topography is applied to a two-dimensional nonhydrostatic atmospheric model to achieve highly precise simulations over steep mountains.

2. Model descriptions

The cut cell method is based on a finite-volume discretization and generally maintains discrete conservation. Here, piecewise linear segments are embedded in Cartesian grids to represent topography. A disadvantage of this method is that small cut cells require small time steps to satisfy the CFL condition. To keep the computational time reasonable, we use a cell-merging approach in which small cells are merged with neighboring cells either vertically or horizontally.

Another difficulty in cut cell modeling is in the calculation of pressure gradient near the boundary. We introduce a unique arrangement of variables (Fig. 1) that simplifies the pressure gradient computations near the boundary and eliminates the computational cost of combining cells for the velocity variables (Yamazaki and Satomura, 2010). Fully compressible quasi-flux form equations (Satomura and Akiba, 2003) are used as the governing equations. The leap-frog scheme with the Asselin filter is used for time integration.

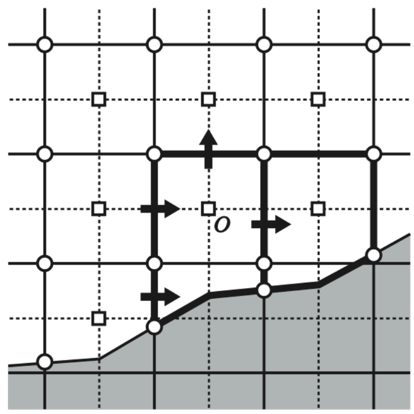

Fig. 1. Cartesian grids in the presence of topography. Shaded region represents the topography in the model. Thick lines describe the boundaries of merged cells. Squares and circles represent scalar points and velocity points, respectively. Arrows indicate fluxes through the cell *O*.

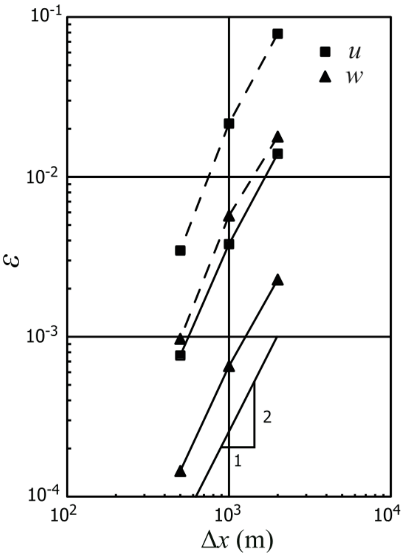

Fig. 2. Variation of global error in *u* and *w* with horizontal grid intervals for flow over a bell-shaped mountain. Solid and dashed lines indicate L_1 and L_2 norms of the errors, respectively.

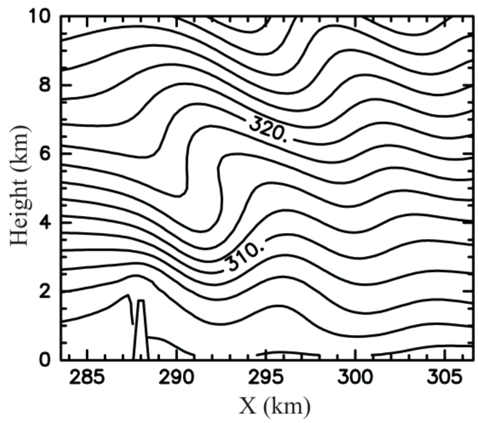

Fig. 3. The potential temperature over a cliff after 45 minutes of integration. The contour interval is 2 K.

3. Results

To verify the performance of the model, we performed two-dimensional numerical simulations of flows over a wide range of slopes from a gently sloping bell-shaped mountain to an extremely steep cliff.

The accuracy of the model was confirmed by simulating flow over a gently sloping bell-shaped mountain. The vertical velocity and momentum flux in the model agree well with those in the linear theory. A grid refinement study was performed by varying the horizontal grid intervals and showed that our model produces results of global second-order accuracy (Fig. 2).

The ability of the model to simulate flow over extremely steep topography was demonstrated using a cliff with slopes over 80 degrees (Fig. 3). Referring to the analytical solution of flow over a thin barrier (Huppert and Miles, 1969), the result showed that our model successfully reproduces flow over the cliff.

Acknowledgements

This study was supported in part by a Grant-in-Aid for JSPS Fellows. Part of this work was also supported by the MEXT Special Coordination Funds for Promoting Science and Technology "International Research for Prevention and Mitigation of Meteorological Disasters in Southeast Asia." Some Figures were drawn by the GFD-DENNOU Library.

References

Huppert, H. E. and J. W. Miles, 1969: Lee waves in a stratified flow. Part 3. Semi-elliptical obstacle. *J. Fluid. Mech.*, 35, 481-496.

Satomura, T., and S. Akiba, 2003: Development of high-precision nonhydrostatic atmospheric model (1): Governing equations, *Annuals of Disas. Prev. Res. Inst., Kyoto. Univ.,* **46B**, 331-336. (avaiable online at http://www.dpri.kyoto-u.ac.jp/dat/nenpo/no46/46b0/a46b0t32.pdf)

Yamazaki, H., and T. Satomura, 2010: Nonhydrostatic atmospheric modeling using a combined Cartesian grid, *Mon. Wea. Rev.,* doi:10.1175/2010MWR3252.1. (in press)