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Numerical Representation of Mountains in Atmospheric Models

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NERC SCIENCE OF THE ENVIRONMENT

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Introduction

Orography creates downslope winds and affects local precipitation. Mountains also affect global circulation, acting as barriers to air flow which give rise to planetary waves.

The most common representation of terrain in atmospheric models is that of terrain following (TF) layers. An alternative is the cut cell method, which has been found to give more accurate results in a limited number of test cases from the literature.

This project assesses the accuracy of TF and cut cell style grids, using the same model to enable like-for-like comparison between grids.

Grids

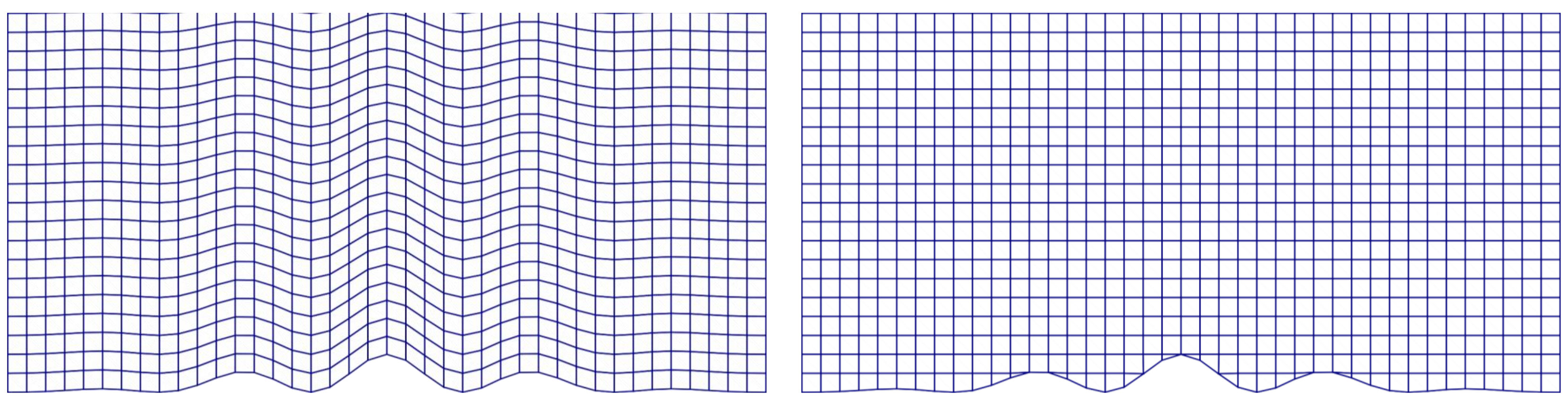

Figure 1 – Vertical cross sections of (left) Basic Terrain Following, and (right) cut cell style grids

Tests are performed on two different grids: Basic Terrain Following (BTF) and cut cell style. TF grids have the problem that, as model resolution increases, gradients tend to become steeper, which can lead to greater numerical errors (Steppeler et al. 2002). Cut cell grids are better able to represent steep slopes, but can result in very small cells that limit the model timestep unless the grid or the discretisation is modified to account for them (Jebens et al. 2011).

Tracer advection

Following Schär et al. (2002), a tracer is transported above orography by solving the advection equation for a prescribed horizontal wind. This challenges the accuracy of the advection scheme in the presence of grid distortions. A cubic upwind-biased scheme is used that is non-monotonic and is not flux corrected.

The tracer is seen moving east on the cut cell style grid in figure 2a, in which accuracy is greatest because the grid is uniform aloft. Although the continuous wind field is non-divergent the discrete wind field, without correction, is not. Comparing figures 2b and 2c we see that, by using Chorin's projection method to make the discrete wind field non-divergent, accuracy on the BTF grid increases dramatically.

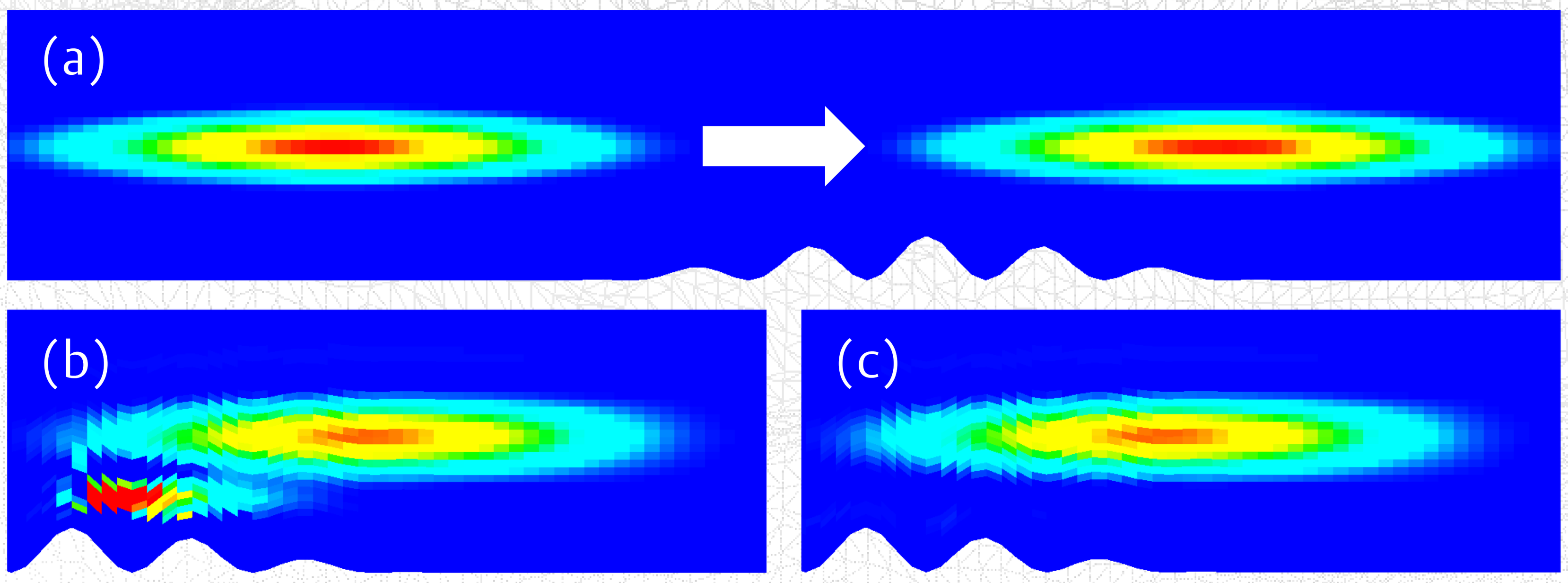

Figure 2 – Tracer advection on (a) cut cell style grid at $t = 1000$ s and $t = 7000$ s, (b) BTF grid with no wind field correction, and (c) BTF grid with a non-divergent discrete velocity field. (b) and (c) show tracer at $t = 7000$ s

Orographically induced gravity waves

Following Schär et al. (2002), uniform flow over an idealised two-dimensional mountain ridge induces gravity waves in a stable atmosphere. A Lorenz grid is used in which values of potential temperature, density, and the Exner function of pressure are collocated at cell centres.

Potential temperature anomalies are similar on both grids (figures 3a and 3b). Examining the cut cell style grid more closely in the lee of the mountain, figure 3c shows that the bottommost layer is anomalously warm and the layer above it is anomalously cold. This is a typical manifestation of the Lorenz computational mode in which discrete hydrostatic balance is preserved despite anomalies in the vertical thermal profile.

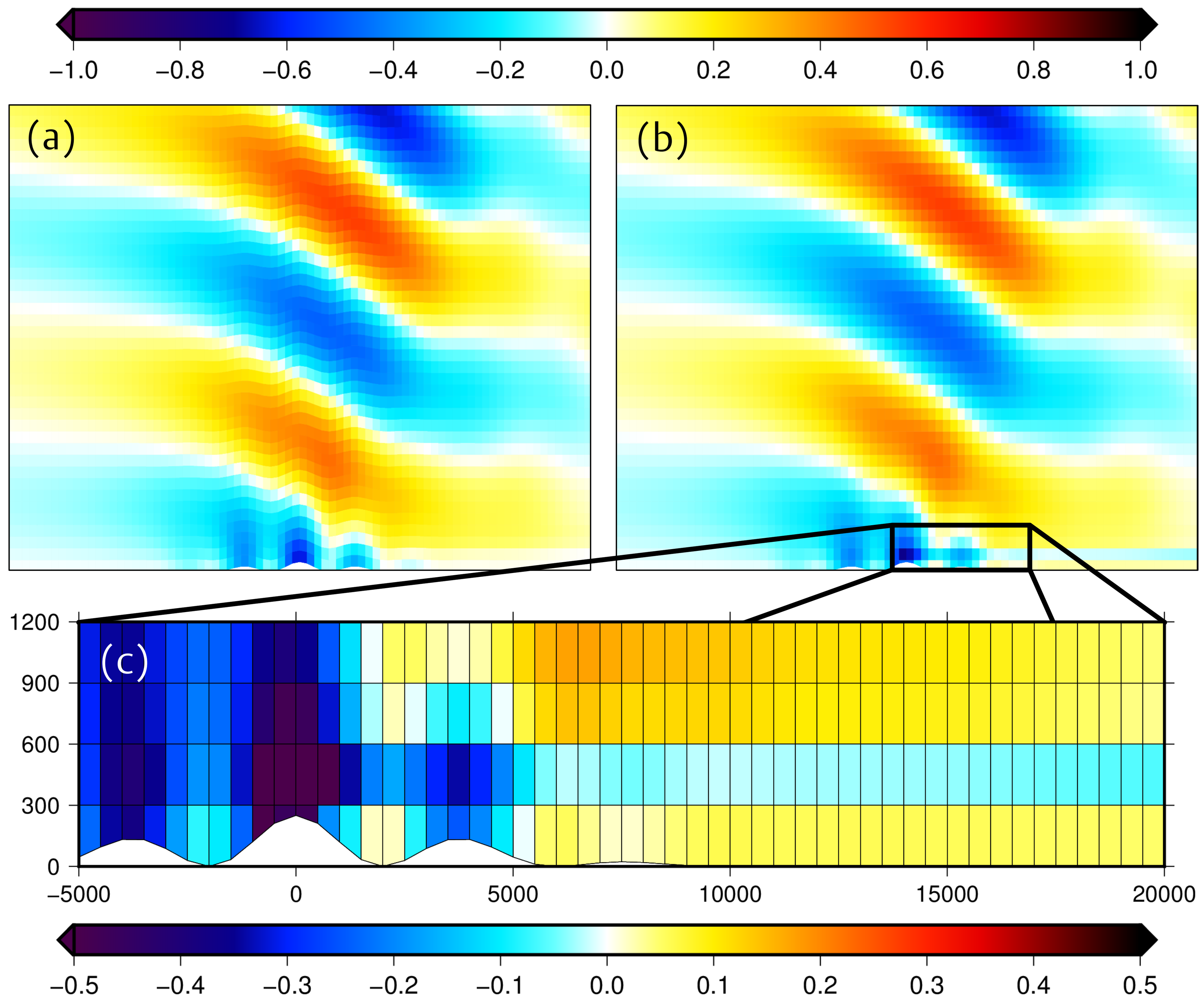

Figure 3 – Potential temperature anomalies in the gravity waves simulation after 18000 s on (a) BTF grid and (b) cut cell style grid; potential temperature scale ranges between ±1 K. (c) Enlargement of the lowest 1200 m on the cut cell style grid; note that the scale ranges between ±0.5 K.

Summary

- Accuracy of tracer advection on non-uniform TF grids is greatly improved by making the discrete wind field non-divergent.
- Terrain following grids give better accuracy when simulating orographically induced gravity waves.
- The Lorenz computational mode was found in the gravity waves test only on the cut cell style grid. This motivates the formulation of a Charney–Phillips staggering for unstructured grids in which potential temperature values are stored at cell faces instead of cell centres.

References

1. Jebens, S., O. Knoth and R. Weiner, 2011: Partially implicit peer methods for the compressible Euler equations. *J. Comp. Phys.*, **230**, 4955–4974.
2. Schär, C., D. Leuenberger, O. Fuhrer, D. Lüthi and C. Girard, 2002: A new terrain-following vertical coordinate formulation for atmospheric prediction models. *Mon. Wea. Rev.*, **130**, 2459–2480.
3. Steppeler, J., H.-W. Bitzer, M. Minotte and L. Bonaventura, 2002: Nonhydrostatic Atmospheric Modeling using a z-Coordinate Representation. *Mon. Wea. Rev.*, **130**, 2143–2149.

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