Systematic Analysis of Flow-Orography Interaction in Idealized Numerical Simulations

Šimon Bartoň, Dominika Hájková and Petr Šácha
Department of Atmospheric Physics, Faculty of Mathematics and Physics, Charles University; contact: simon.barton@matfyz.cuni.cz

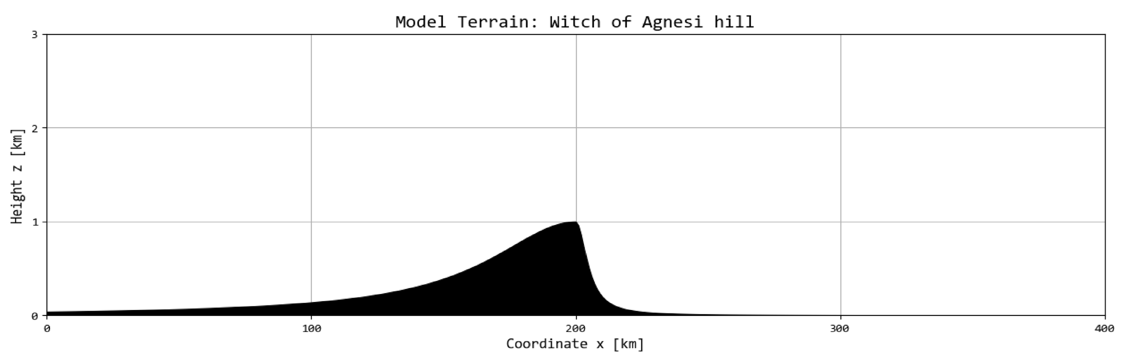
1 Outline

Current generation climate and global numerical weather prediction models still cannot resolve much of the spectrum and associated effects of orographic **internal gravity waves** (IGWs). Among those parameterized subgrid-scale processes is the IGW dissipation characterized by wave breaking and turbulent overturning that is intimately tied to IGW instabilities. These instabilities substantially impact atmospheric dynamics by redistributing momentum, generating clear-air turbulence, and altering atmospheric composition.

By varying orographic shapes and wind profiles in WRF model setting, we examine the **transition between the non-breaking and breaking regimes**. We diagnose these transitions through surface drag and momentum flux analyses, and based on stability indicators such as the **inverse vertical Froude number**.

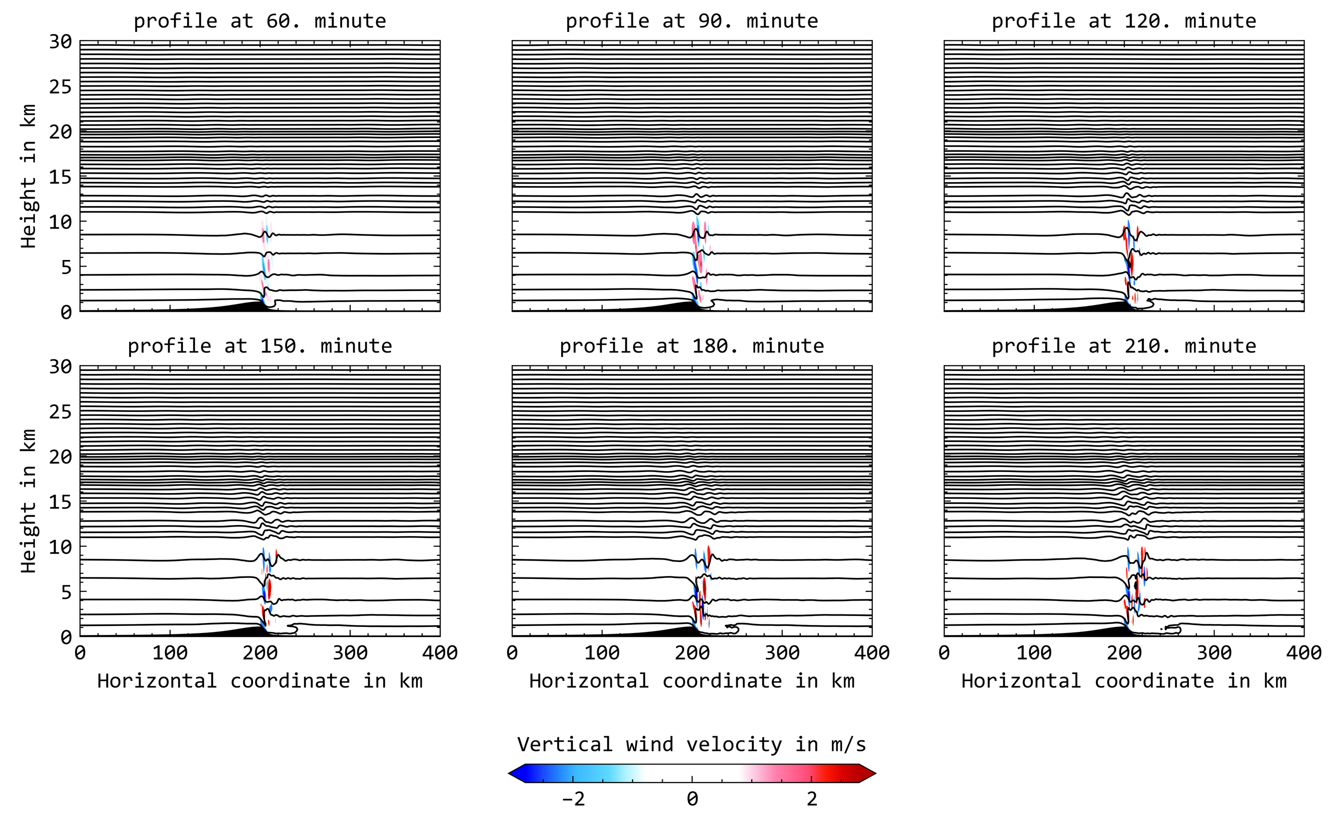
2 Model setttting

WRF model version 4 is used for numerical simulations, particularly its idealized 2D version, test case `em_hill2d_x`. The model setting is as follows: domain width: 400 km, domain height: 30 km, equidistant horizontal grid size: 1000 m, 150 hybrid sigma-pressure levels in the vertical direction, simulation length: 4 hours. The asymmetric hill surface is given by the Witch of Agnesi curve. The hill height varies from 200 to 1000 m throughout the simulations. Turbulent processes are parametrized using constant eddy diffusion coefficients that equal either 0 or 100 m^2/s.



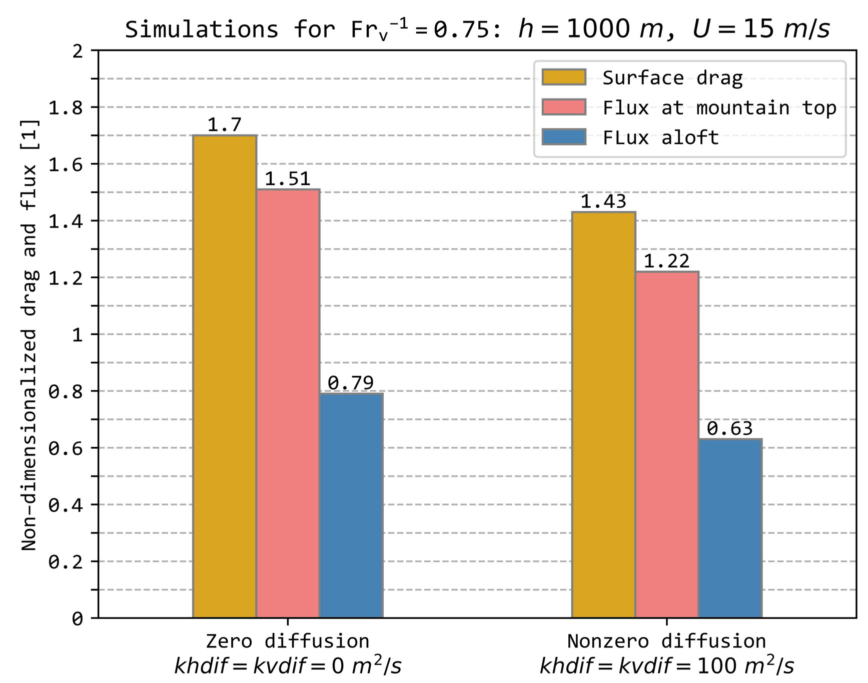
3 Results: IGW field and instability development

The development of an IGW instability is plotted below for a constant wind of 8 m/s and hill 1000 m high. Potential temperature isolines reached the convective instability threshold and the flow is overturning, although the model does not have sufficient resolution to fully resolve the turbulent cascade (leaving aside it is inherently a 3D phenomenon). **The limits of what the model is able to resolve are crossed**.



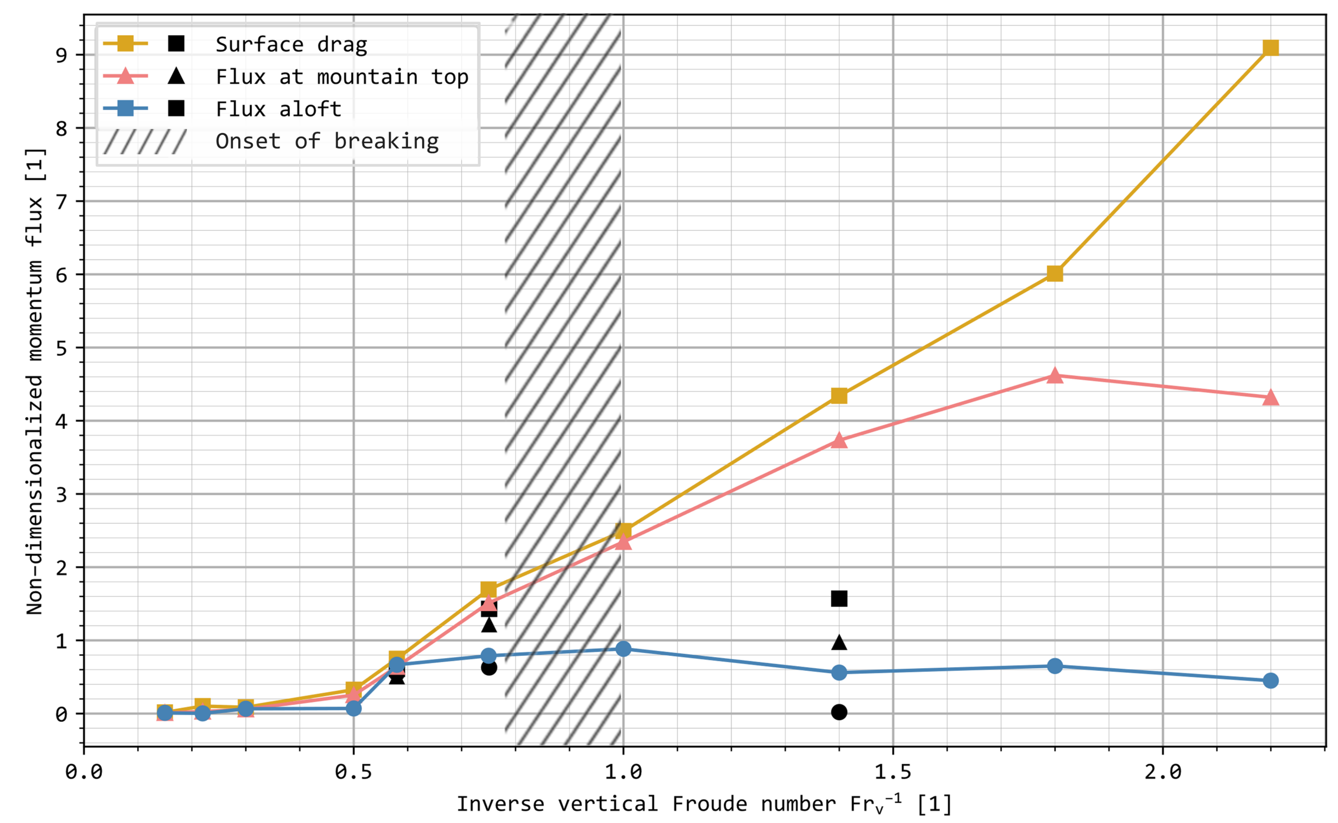
4 Results: sensitivity to the turbulence treatment

The following figure compares surface drags and momentum fluxes at the mountain top and aloft resulting from two simulations with the same setting characterized by the same ${Fr_v}^{-1} = 0.75$. The simulations differ in the turbulence parameterization, i.e. the value of the constant eddy diffusion. The lower values of the drag and fluxes for nonzero diffusion coefficients arise as turbulence causes more effective mixing than in the case of only partially resolved overturning.



5 Results: dependence of the momentum flux on the inverse vertical Froude number

To reach different states described by the inverse vertical Froude number (${Fr_v}^{-1}$), we run simulations with varied orography and wind speed. Eddy diffusion constants are set to zero. The following figure plots the dependence of surface drag and momentum flux at the mountain top and aloft on the inverse vertical Froude number. The hatched region marks its values typically linked to the onset of breaking.



The black markers at the points of ${Fr_v}^{-1} = 0.58$ and 0.75 stand for drag and fluxes for simulations with *nonzero* diffusion coefficients. Their values are lower indicating a greater portion of the momentum flux carried by the waves dissipates in the turbulence region. The rightmost triplet of black markers stands for drag and fluxes for a simulation with half the hill height and half the background wind velocity in contrast to the colored markers in the same column.

6 Conclusion and Outlook

- Limitations of the model in simulating the GW dissipation for partially resolved overturning. Dependence of linearity of the system on the free parameters and turbulence parameterization
- Do different approaches of obtaining ${Fr_v}^{-1}$ yield different critical values? Now only variation of the response to the hill–flow interaction despite identical inverse vertical Froude number is modeled
- Parameterizations of IGWs, subgrid-scale orography and turbulence should not be considered separately
- **Outlook**: estimates of critical values of ${Fr_v}^{-1}$ for the transition to nonlinear flow regimes and the sensitivity of this critical value to the turbulence parameterization
- High-resolution 3D simulation in **WRF model: idealized LES** to study the influence of turbulence parameterizations

Acknowledgements

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