Flow Regimes of a Continuously Stratified Flow over a Mesoscale Mountain and their Impacts on Aviation Turbulence

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ABSTRACT

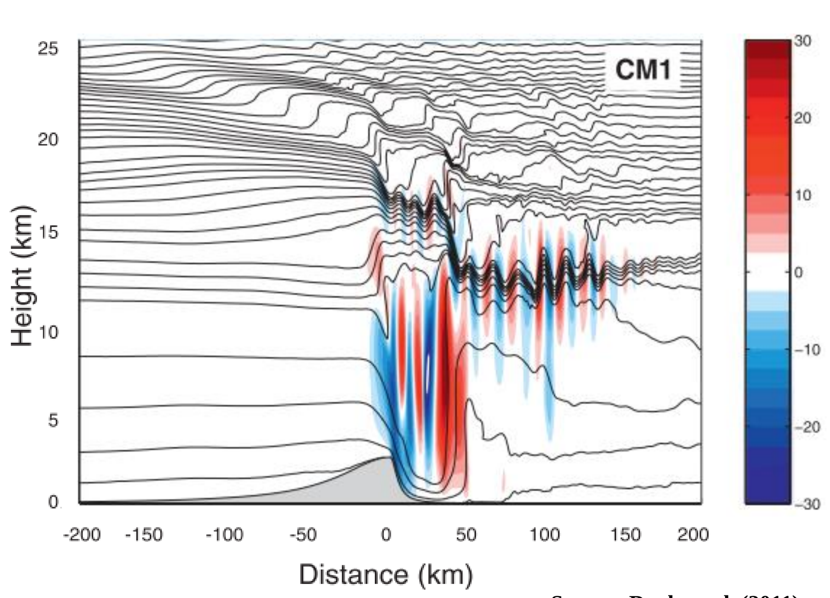
One important source of aviation turbulence is gravity wave breaking induced by airflow over mesoscale mountains, which is responsible for many severe turbulence encounters. The purpose of this study is to investigate gravity wave breaking over terrain in different parameter space. In order to gain a more in-depth understanding of the dynamics, we perform a series of systematic idealized simulations with idealized bell-shaped mountains by adopting the Cloud Model 1 (CM1) to avoid some unnecessary complications from the real atmosphere and test some hypotheses. For a uniform, but structured flow over a mesoscale mountain, two distinguished flow regimes are found: (I) upward propagating moist gravity waves (GW) regime and (II) evanescent fluid flow (EV), depending upon the hydrostatic control parameter (Na/U), similar to a uniform, unstructured flow. The flow associated with the GW regime tends to steepen, overturn, create a wave-induced critical level, trap the energy below it, and then generate a "dead" region with strong turbulence with well-mixed regions, and severe downslope winds. In addition to the turbulent region over the lee slope, it is found that in Regime I, strong turbulence regions may also occur in upper troposphere and lower stratosphere, depending upon the basic flow Froude number (Fr=U/Nh) and the hydrostatic control parameter (Na/U). In this study, we are particularly interest in flow response to orographic effects in the typical commercial aircraft cruise levels in the upper troposphere and lower stratosphere (i.e., approximately 8–14 km above the earth surface). In addition, we will investigate the effects of moisture and the PBL. Both two- and three-dimensional idealized simulations with PBL (coarse resolution) or Large Eddy Simulations (LES) with finer resolutions are also conducted.

INTRODUCTION

- **As gravity waves propagate upward, if the wind speed and atmospheric stability profiles are favorable, they can break.**
- **Mountain wave breaking is capable of generating clear air turbulence (e.g., Clark et al. 2000; Sharman and Lane 2016).**
- **Clear air turbulence usually occurs at high altitudes (8-14 km above the earth surface) making them one of the most common sources of aviation turbulence (Lane et al. 2012; Sharman et al. 2012).**
- **To a certain extent, turbulence can be measured as the ratio between buoyancy and wind shear, also known as the Richardson number:**

$$Ri = N^2/(\partial U/\partial z)^2$$

Gravity wave example:



Source: Doyle et al. (2011)

METHODOLOGY

- **Cloud Model (CM1) release 18**
  - **Two-dimensional mode: 1000x350 gridpoints (Δx = 1km; Δz = 100m)**
  - **Adaptive time stepping**
  - **Horizontal turbulence coefficient different from vertical (tconfig=2)**
  - **Model top: 35km; Sponge layer depth: 10km**

Terrain: two-sided 2D bell shaped mountain

$$h(x) = \frac{h_m}{(x/a)^2 + 1}$$

where the mountain height, $h_m = 2.5\,km$, and the halfwidth, $a = 40km$.

METHODOLOGY

Case	Wind speed (ms^{-1})	friction	moisture
CTL	20	NO	NO
CTL_u30	30	NO	NO
CTL_u40	40	NO	NO
CTL_f	20	YES	NO
CTL_m	20	NO	YES

CTL = Control   CTL_u30 = 30 ms^{-1} wind   CTL_u40 = 40 ms^{-1} wind
CTL_f = friction   CTL_m = moisture

New idealized potential temperature profile:

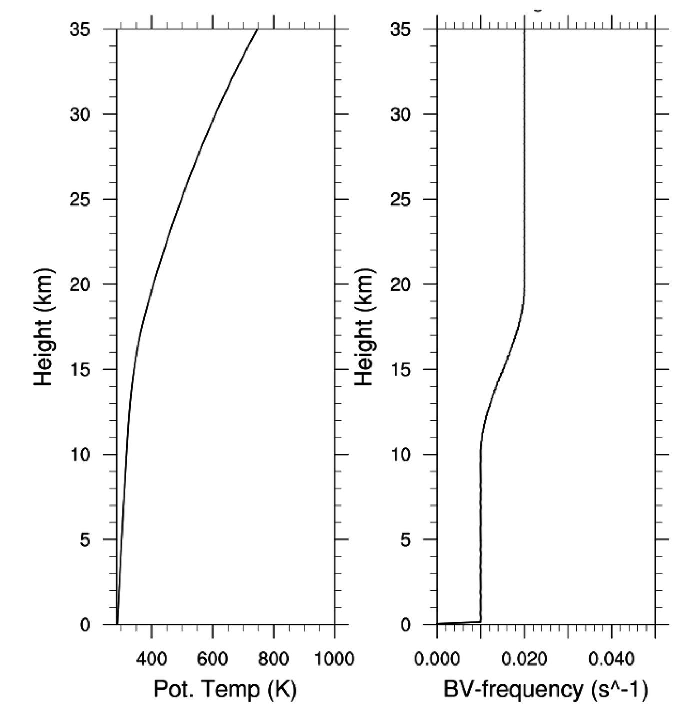
Surface to 10 km: Constant stability $N = 0.01\ s^{-1}$.

10 to 20 km: N increases from 0.01 to 0.02 s^{-1} via the following sine function,

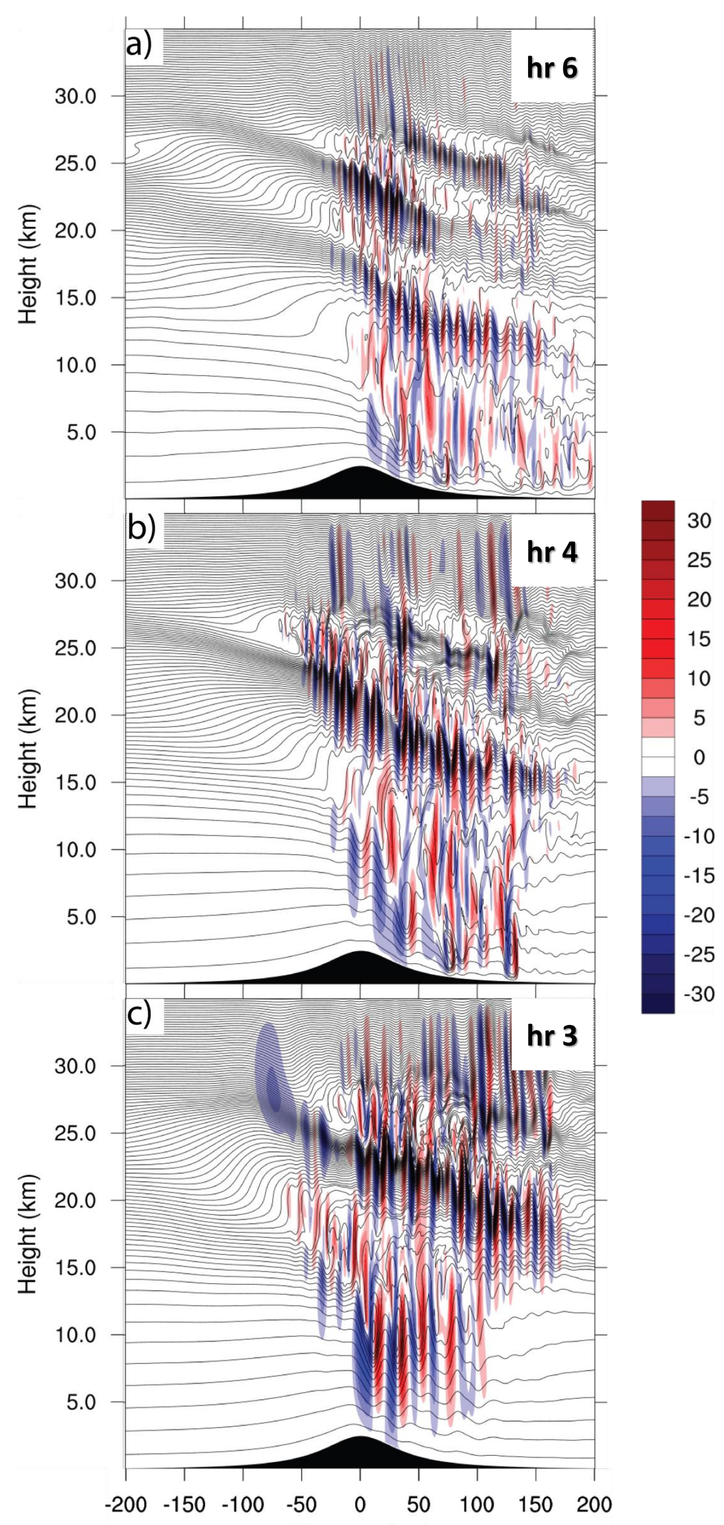
$$N(z) = N_0 \sin\left(\frac{\pi}{2}\left[\frac{1\text{m} - (h_2 - z)}{(h_2 - h_1)}\right]\right)^2$$

where z goes from $h_1 = 10$ km to $h_2 = 20$ km in 250 m intervals.

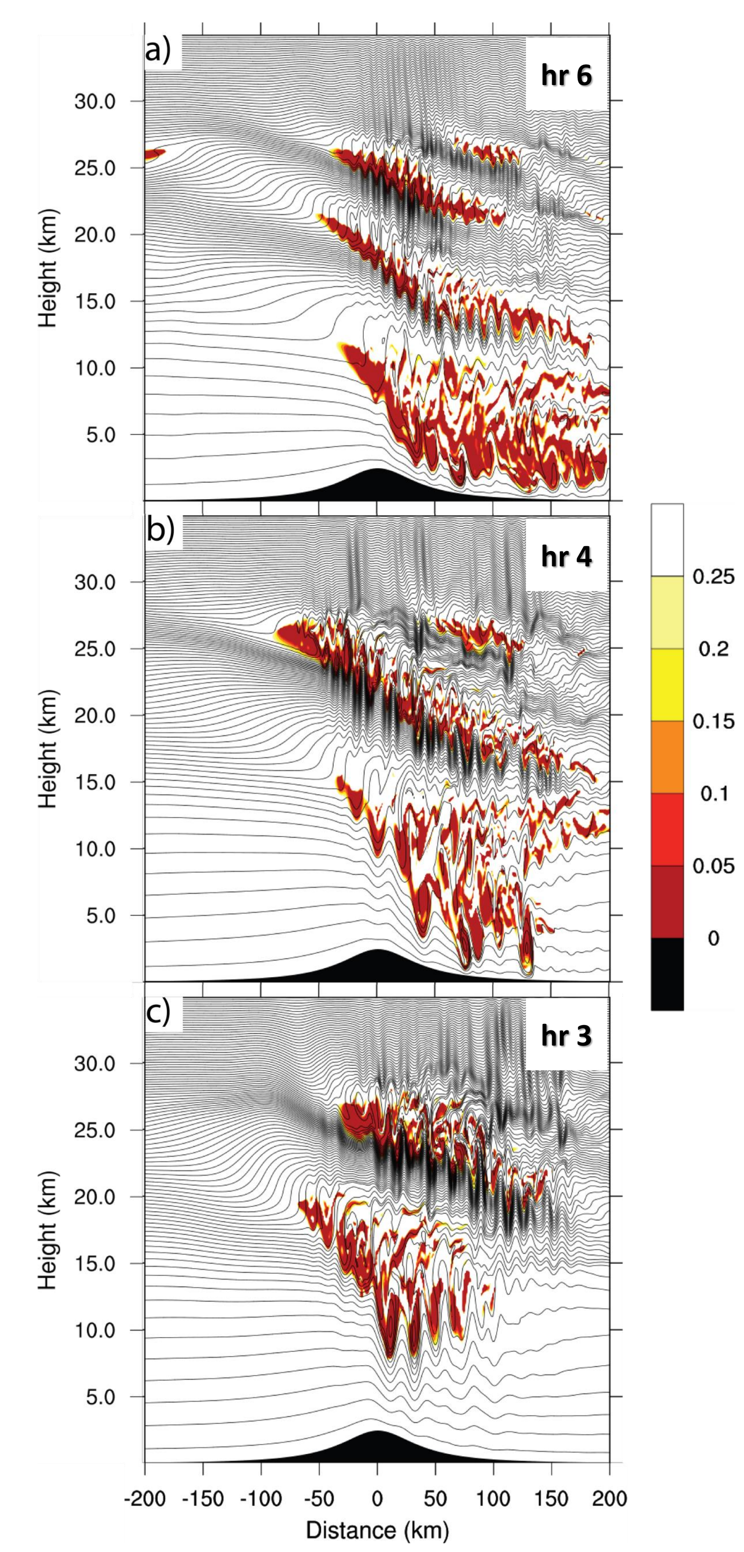
20 km to model top: Constant stability $N = 0.02\ s^{-1}$.



RESULTS - WINDS

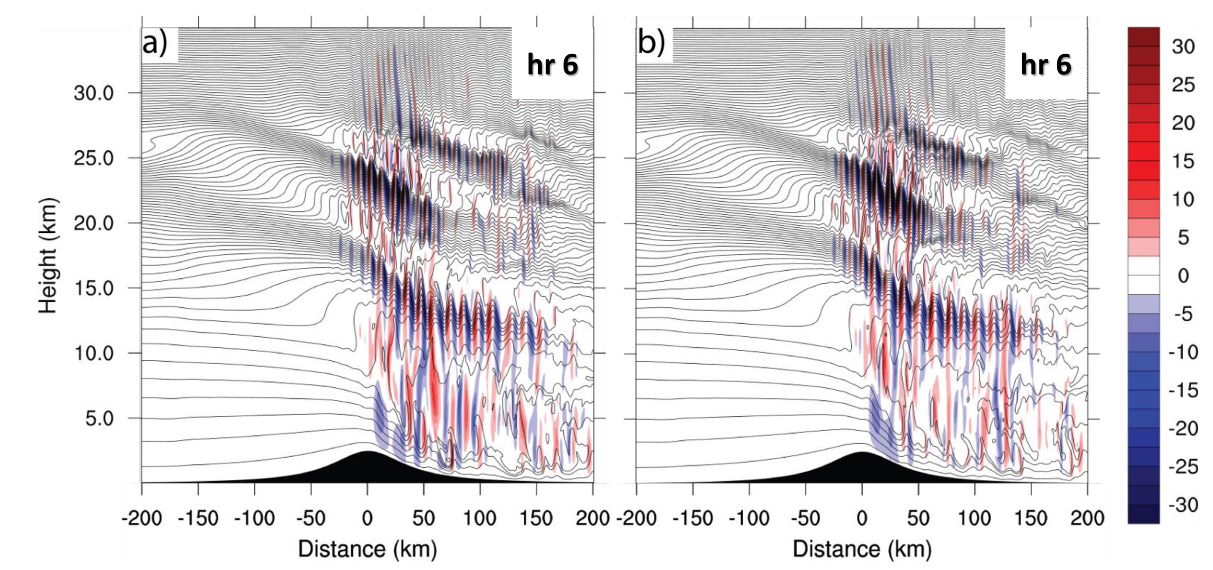


Vertical velocity (ms^{-1}) in color and potential temperature contours for (a) CTL, (b) CTL_u30, and (c) CTL_u40 at nondimensional time $\frac{Ut}{a} = 10.8$.



Richardson number in color and potential temperature contours for (a) CTL, (b) CTL_u30, and (c) CTL_u40 at nondimensional time $\frac{Ut}{a} = 10.8$.

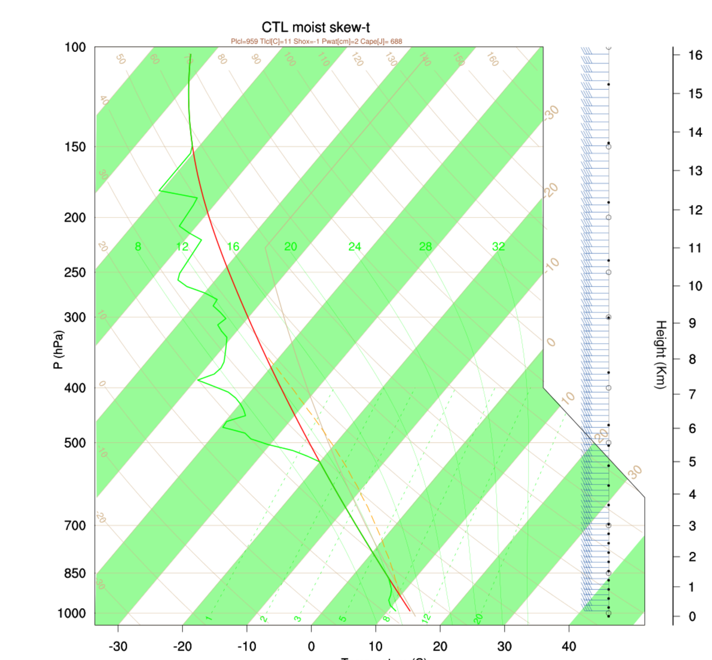
RESULTS - FRICTION



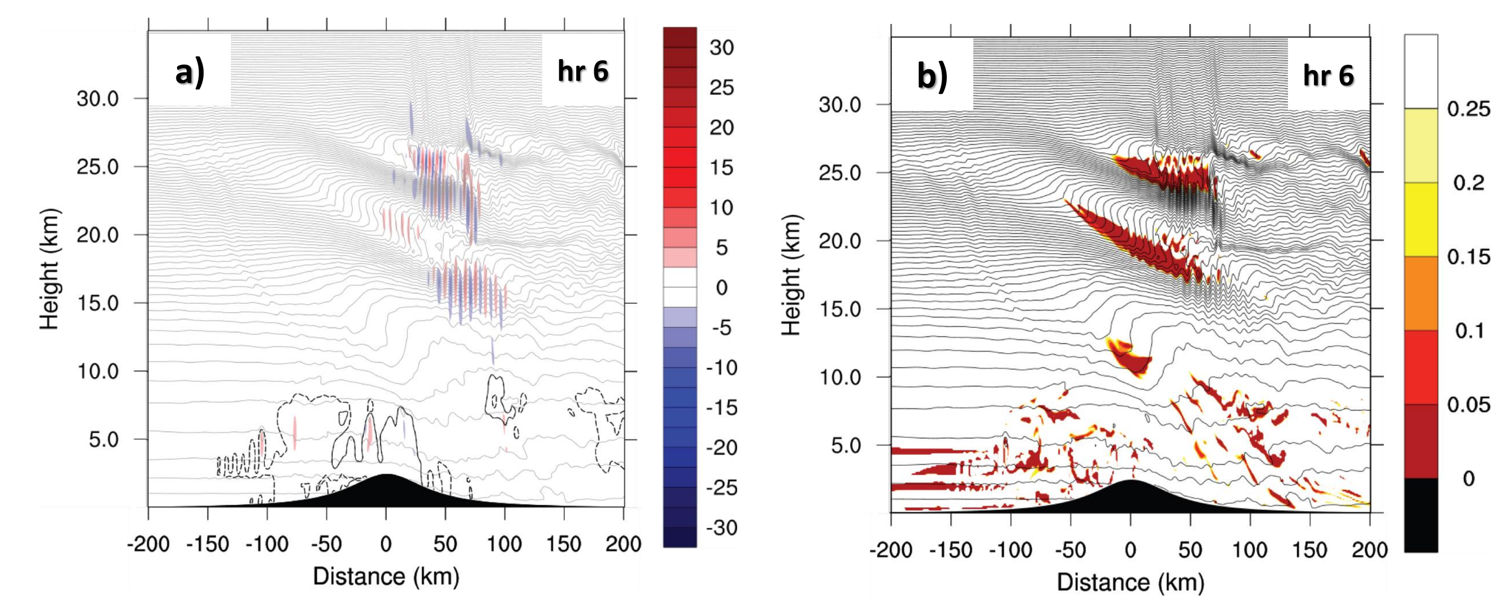
Vertical velocity (ms^{-1}) in color and potential temperature contours for (a) CTL and (b) CTL_f at nondimensional time $\frac{Ut}{a} = 10.8$.

- **Vertical velocity magnitudes are lower below the first vertical wavelength when friction is included.**

RESULTS - MOISTURE



- **Moisture profile obtained from the 2100 UTC March 25 2006 MGAUS sounding**
- **Moisture significantly changes the vertical velocity field and gravity wave structure in the troposphere.**
- **Above the tropopause, gravity wave structure remains unchanged.**



Potential temperature contours for CTL_m at nondimensional time $\frac{Ut}{a} = 10.8$. Panel (a) shows vertical velocity (ms^{-1}) shaded and cloud envelope (combined hydrometeor values greater than 0.1 g kg^{-1}) in thick dashed lines. Panel (b) shows Richardson number shaded.

CONCLUSIONS

- **Increasing basic wind speeds tend to:**
  - **Increases the vertical wavelength, consistent with linear theory**
  - **Decreases turbulence in lower layer and downstream**
  - **Increases vertical velocity magnitude**
  - **Transition to evanescent flow, consistent with Sever & Lin (JAS 2017).**
- **Adding friction yields no notable results. Large-eddy simulation (LES) is required to advance our understanding of friction.**
- **Moisture tends to reduce the wave amplitudes and reduce turbulence. However, severe turbulence is now present upstream, which is induced by convection.**
- **Above 15 km or tropopause, not many differences are observed when moisture is included.**

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