GRAVITY WAVE INSTABILITY EVOLUTION IN VARIABLE STRATIFICATION AND SHEAR

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ABSTRACT

An anelastic numerical model is used to explore gravity wave instability dynamics in variable stratification and shear environments in the mesosphere and lower thermosphere (MLT). Recent computational advances facilitate the characterization of localized gravity wave packets in a deep atmosphere, enabling realistic amplitude evolution and enhanced sensitivity to transient nonlinear dynamics. The results reveal that gravity wave packets impinging on a sheet of high stratification and shear enable local Kelvin-Helmholtz instabilities (KHI) where GW vertical displacements approach their maxima and mean and gravity wave shears combine. The KHI arise at smaller scales and evolve to larger scales with time, as seen in lidar, radar, and airglow observations. Such events tend to be highly localized and thus yield local energy and momentum deposition expected to have strong influences throughout the mesosphere, thermosphere, and ionosphere (MTI) region. These simulations illuminate one of the major mechanisms driving turbulence and mixing in the MLT at scales that are challenging or impossible to describe quantitatively with existing measurement capabilities.

OBSERVATIONAL MOTIVATION

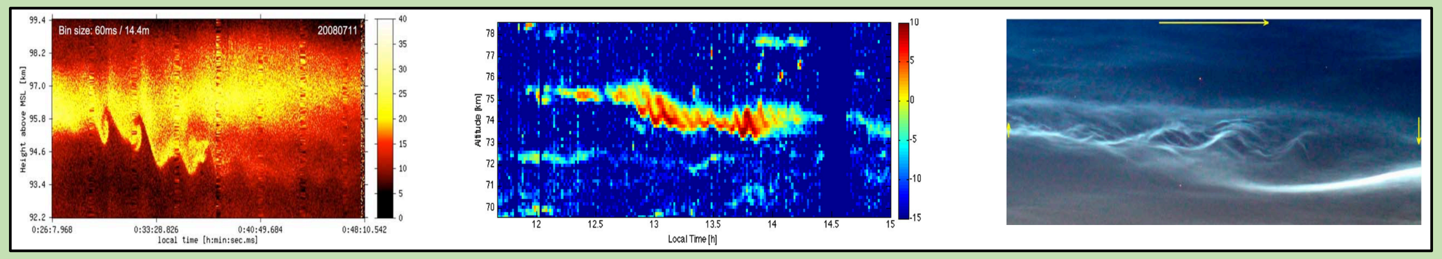


Figure I (a) (b) (c)
KHI in the mesosphere visible in sodium density LIDAR observations [Pfrommer et al. 2009], radar echo power [Lehmacher et al 2007], and high resolution noctilucent cloud imagery [Baumgarten and Fritts 2014]. The characteristic undulating layer structure in both images indicates the presence of a gravity wave propagating through the region, with KHI and secondary instabilities forming on the upper crest of the wave.

The goal of this investigation is to characterize gravity wave-induced small scale instability evolution in the MTI region. The investigation is guided by a small but qualitatively consistent observation set (Figure I) showing small scale KHI billows forming as the result of a gravity wave propagating through a region of high stratification. The limited observations of such dynamics can be explained by the highly transient nature of these events and the very fine resolution required to resolve sub-100m scales at high altitudes. In the absence of broader observations, it is desirable to find a suitable numerical scheme that can reproduce these dynamics in the context of a larger atmospheric domain. The limitations of other modeling schemes resulted in the selection of an anelastic, incompressible, finite-volume code for probing these dynamics.

COMPUTATIONAL MOTIVATION

Linear:
- Cannot capture self acceleration and other non-linear dynamics

Ray Tracing:
- Doesn't handle turning layers well

Boussinesq Spectral:
- Assumes constant density and vertical periodicity, requires unrealistic initial conditions

Anelastic Finite Volume:
- Captures self acceleration and non-linear dynamics
- Can characterize turning layers
- Has density scale with altitude, allowing for realistic GW amplitude evolution with propagation
- Enables deep atmospheric simulations with sufficient resolution to characterize instabilities until the onset of turbulence

CODE FRAMEWORK

- 2D, anelastic, incompressible, finite volume
- Background Sech and Tanh profiles for Stability (N^2) and mean wind (U):

$$N^2[z] = N_0^2 + (N_1^2 - N_0^2)\,\mathrm{Sech}^2\left[\frac{z-z_0}{d}\right] \qquad U[z] = U_1 + \frac{U_0-U_1}{2} + \frac{U_1-U_0}{2}\,\mathrm{Tanh}\left[\frac{z-z_0}{d}\right]$$

(N_0, N_1, U_0, U_1, z_0, d) = (background N, peak N, wind below shear layer, wind above shear layer, shear layer center, shear layer depth)

- Collocated stability and shear maxima at 80km, with minimum Richardson Number (Ri) of

$$Ri_{min} = \left(\frac{N^2[z_0]}{\left(\frac{\partial U}{\partial z}\right)^2[z_0]}\right) = 4\,N_1^2\left(\frac{d}{U_1-U_0}\right)^2$$

- Raised viscosity (ν) such that Reynolds Number

$$\mathrm{Re} = \Delta U d/(50\,\nu_{molecular}) \sim 20$$

motivated by observed scales in *Fritts and Baumgarten* 2014
- 80km vertical domain, 15m resolution

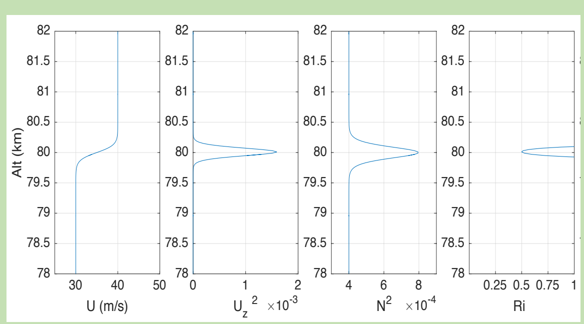


Figure II
Background profiles used to initialize simulations. The collocated shear and stability (N^2) maxima lead to a stable minimum Richardson Number (Ri) of 0.5.

SIMULATION PARAMETERS

- GW initialized in stratosphere and propagates to shear and stability layer at 80km
- Gravity Wave has intrinsic phase speed C = 30 m/s,

$$\lambda_z = 10\mathrm{km},\ \lambda_x = \{10\mathrm{km}, 20\mathrm{km}\} \rightarrow \gamma = \frac{\lambda_x}{\lambda_z} = \{1,2\}$$

 I: horizontally localized packet with Gaussian amplitude distribution and 10 λ_x domain
 II: full domain width packet with periodic boundary conditions, 1-2 λ_x domain

- With initial Ri-stable background profiles, all instabilities that form on the layer are caused by the gravity wave

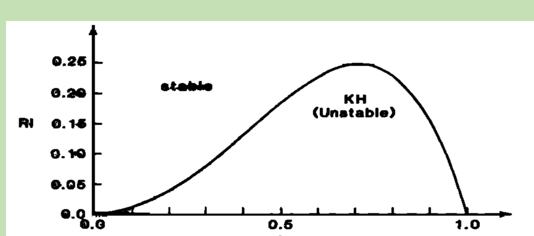
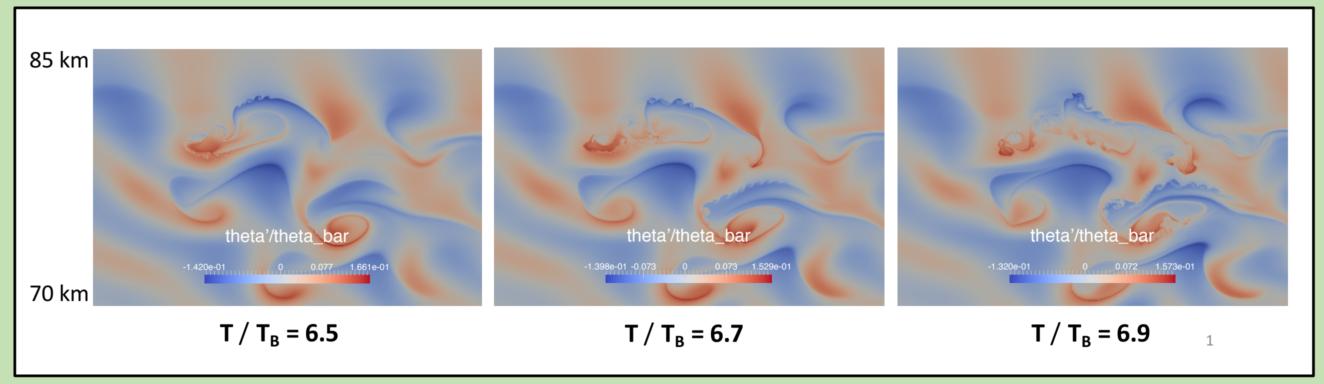


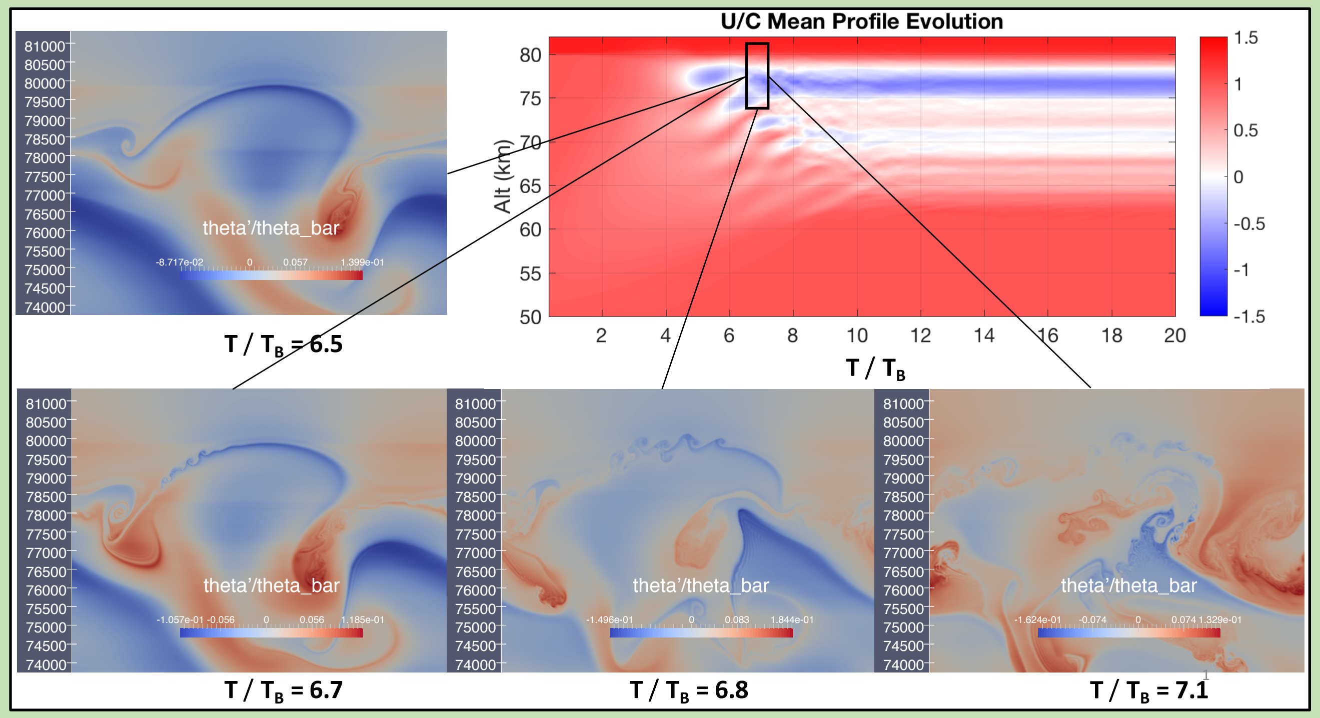
Figure III
Stability conditions for KH in a tanh(z) velocity profile and uniform stratification., where $\alpha = 2\pi h/\lambda_x$. Taken from Fritts and Rastogi 1985.

$\gamma = 1$ HORIZONTALLY LOCALIZED PACKET IN WIDE DOMAIN

The instability structures evolving from the shear layer are shown here in the potential temperature perturbation fields for a horizontally localized packet in a 10 λ_x horizontal domain. The evanescence of the wave above the layer leads to a complex multiscale environment with the reflected wave packet causing both upward and downward propagation below the layer. A chain of KHI billows forms on the crest of a rising cold perturbation, matching the characteristic structure of the observations in Figure I. The billow lifetime is short, evolving to larger horizontal scales and quickly becoming unstable in < 1 buoyancy period.



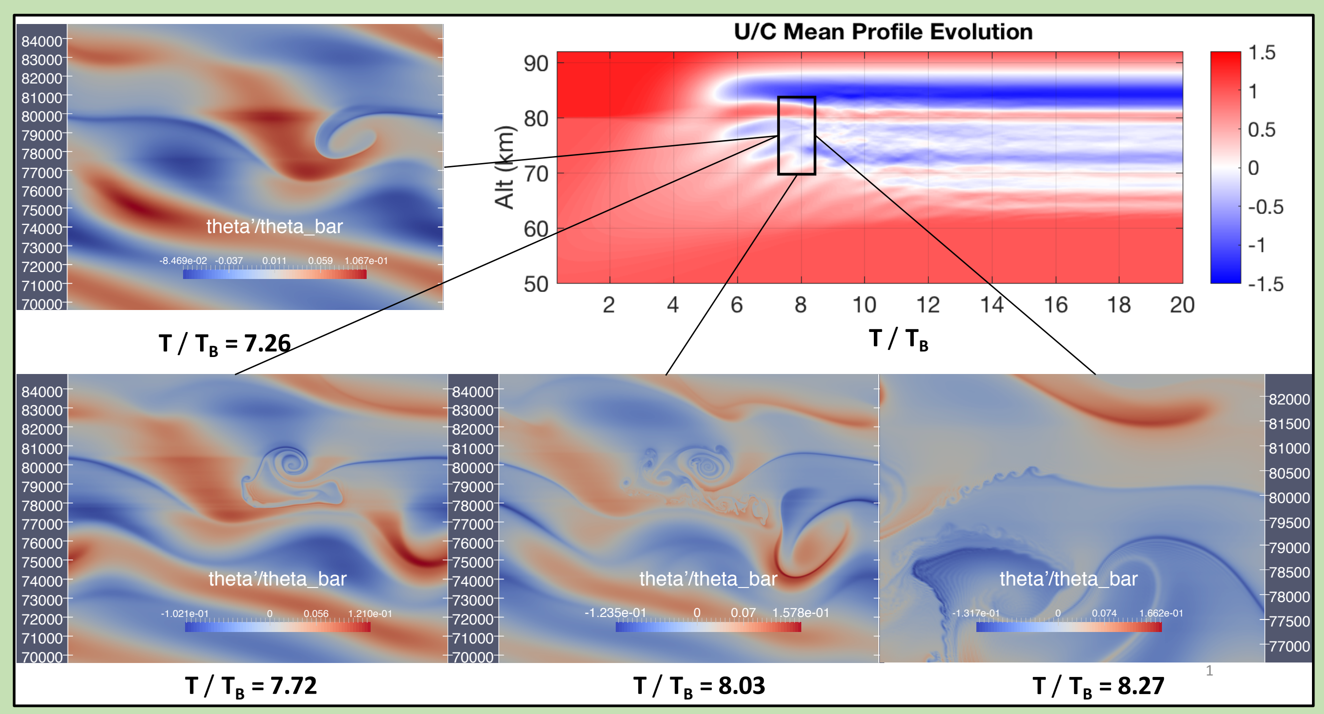
$\gamma = 1$ HORIZONTALLY UNIFORM PACKET IN PERIODIC DOMAIN



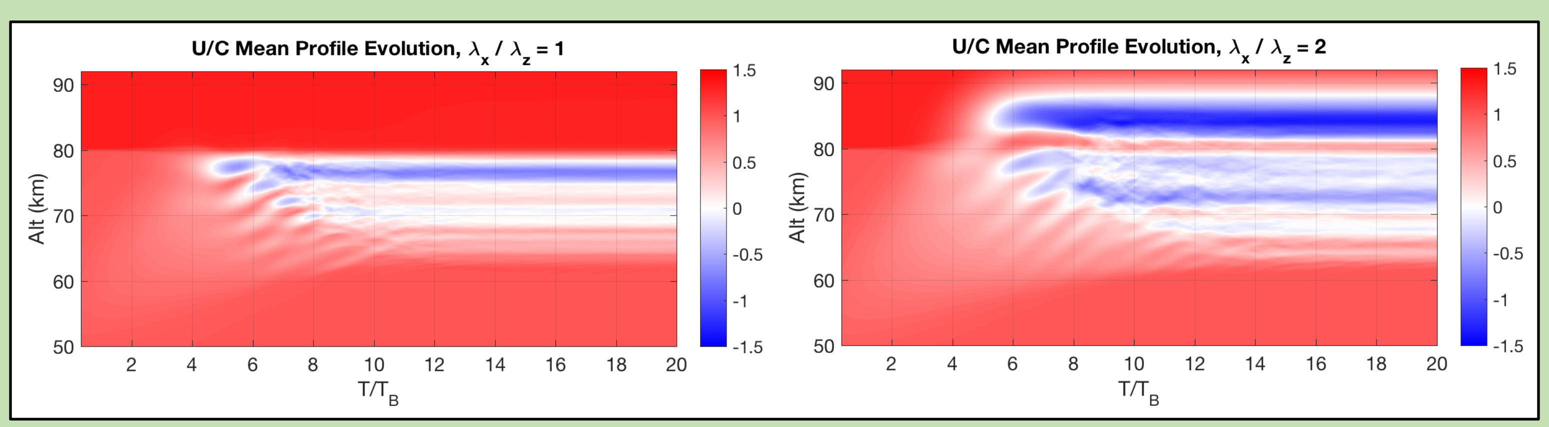
The instability structures evolving from the shear layer are shown here in the potential temperature perturbation fields for a horizontally uniform packet in a 1 λ_x periodic horizontal domain. As with the localized packet, a chain of KHI billows forms on the crest of a rising cold perturbation, quickly evolving to larger scales and becoming unstable in < 1 buoyancy period. The region of KHI formation and decay is identified in the normalized mean wind profile evolution, where the KHI formation appears to coincide with the initial reflection of the wave packet. The downward propagation of the packet continues until it appears to break and decelerate the mean flow near an altitude of 70km.

$\gamma = 2$ HORIZONTALLY UNIFORM PACKET IN PERIODIC DOMAIN

The instability structures evolving from the shear layer are shown here in the potential temperature perturbation fields for a horizontally uniform packet in a 1 λ_x periodic horizontal domain. Unlike the $\gamma = 1$ packets in the simulations above, the $\gamma = 2$ wave packet is able to propagate above the shear layer. The wave propagates through the layer and breaks above until a large KHI billow forms at the shear layer and remains stable for > 1 buoyancy period. A small chain of billows also forms below the layer at $T/T_B = 8.27$. The mean wind profile evolution shows again that the KHI formation occurs as the wave packet begins to reflect and propagate downward, with several distinct regions of decelerated mean flow developing as the reflected packets break at lower altitudes. The nuanced stratification in the resulting mean flow implies some degree of broadening wavenumber spectra and the generation of multiple downward propagating packets with different characteristics.



MEAN FLOW EVOLUTION



The mean flow evolution from the $\gamma = 1$ and $\gamma = 2$ packets is shown for the horizontally uniform wave packets in periodic domains. The breadth of variations between the final flow fields speaks to the complexity of the fine structure interactions occurring in this multiscale environment.

CONCLUSIONS

Anelastic, finite volume code is well-suited to quantifying GW instability dynamics in the MTI region

Gravity waves passing through a stratified region flatten the layer and reduce the Ri to drive the evolution of instability structures

Coherent KHI form in layers with both propagating and non-propagating wave characteristics

Simulations can reproduce and describe MTI KHI structures that match observations and add context to broaden understanding of these dynamics

Ubiquity of these layer structures suggests significant implications for GW behavior throughout the MTI region

ACKNOWLEDGEMENTS

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REFERENCES

Baumgarten, Gerd, and David C. Fritts, 2014: Quantifying Kelvin-Helmholtz instability dynamics observed in noctilucent clouds: 1. Methods and observations. Journal of Geophysical Research: Atmospheres 119.15: 9324-9337.

Fritts, D. C., & Rastogi, P. K., 1985: Convective and dynamical instabilities due to gravity wave motions in the lower and middle atmosphere: Theory and observations. Radio Science, 20(6), 1247-1277.

Fritts, D. C., L. Wang, and J. Werne, 2013: Gravity Wave – Fine Structure Interactions, Part 1: Energy dissipation evolutions, statistics, and implications, J. Atmos. Sci., 70(12), 3710-3734, doi: 10.1175/JAS-D-13-055.1.

Fritts, D. C., L. Wang, M. Geller, D. Lawrence, J. Werne, and B. Balsley, 2015: Numerical Modeling of Multi-Scale Dynamics at a High Reynolds Number: Instabilities, Turbulence, and an Assessment of Ozmidov and Thorpe Scales. J. Atmos. Sci. doi:10.1175/JAS-D-14-0343.1, in press.

Lehmacher, G. A., Guo, L., Kudeki, E., Reyes, P. M., Akgiray, A., & Chau, J. L., 2007: High-resolution observations of mesospheric layers with the Jicamarca VHF radar. Advances in Space Research, 40(6), 734-743.

Pfrommer, T., P. Hickson, and C.-Y. She, 2009: A large-aperture sodium fluorescence lidar with very high resolution for mesopause dynamics and adaptive optics studies, Geophys. Res. Lett., 36, L15831, doi:10.1029/2009GL038802.