Mesoscale Model Initialization of a Linear Model for Mountain Waves

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Problem / Research Motivation

- Mountain wave drag must be parameterized in global weather and climate models due to insufficient model resolution.
- Parameterization schemes based on linear theory do not work when mountain flow regime is nonlinear, so effort must be made to improve parameterization schemes in nonlinear flows
- Aviation community needs accurate gravity wave and turbulence forecasts

Organization of Presentation

- Introduction, explain background of problem, introduction to the models used in this research.
- Compare numerical results to analytical solution
- Show results for nonlinear flow around an idealized hill. Compare momentum flux estimates.
- Discussion and conclusion

Intro & Background - Mountain Meteorology

- mountains are forcing mechanism for buoyancy oscillations (orographic gravity waves or mountain waves) in stably-stratified atmospheric flows
- mountains affect the atmospheric circulation from global to local scales
- lower atmospheric non-linear effects (flow-splitting, downstream vortices, upstream blocking) are important in mountain wave generation
- poor representation in global weather models, climate forecasting due to subgrid-scale forcing - attempt to calculate GW momentum flux contribution

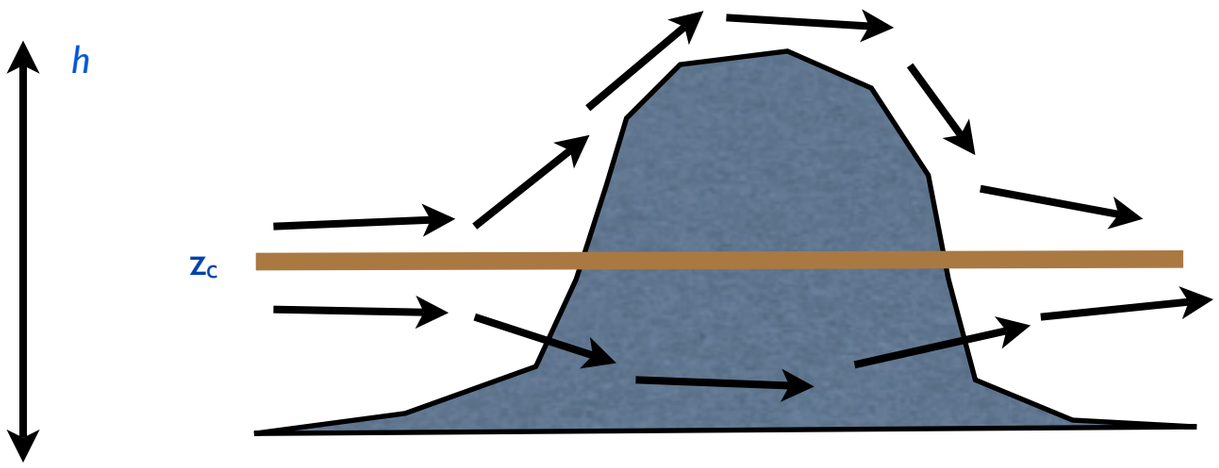
Linear vs. nonlinear Flow Regimes

$$Fr_h = \frac{U}{Nh_m},$$

Froude number

The Froude number Fr_h can be used to estimate the linearity of simple flows. When $Fr_h > 1$, the flow is linear and upstream air parcels ascend the obstacle. When $Fr_h < 1$, the flow is nonlinear

Sheppard's formula applies energy arguments to model a nonlinear flow over a hill. If an upstream air parcel has sufficient kinetic energy to ascend the hill's height h, then it does so and contributes to gravity wave generation. If not, the parcel goes around the hill.



dividing streamline height, z_c - upstream parcels above this level have sufficient KE to ascend the mountain

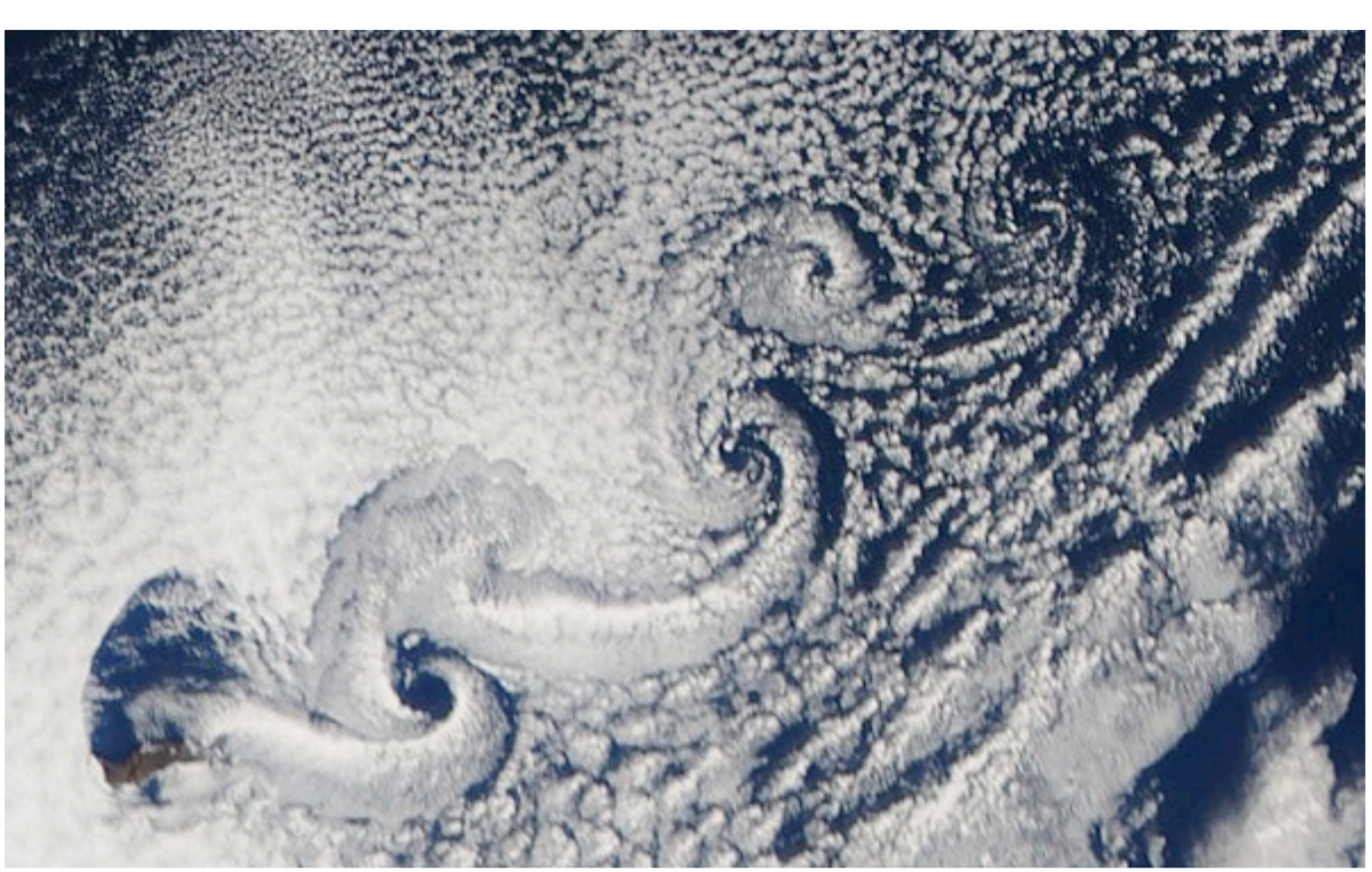
$$\frac{z_c}{h} = 1 - Fr_h$$

Sheppard's formula

Mountain Waves, Nonlinear Flows

In many instances, nonlinear effects are dominant in the lower atmosphere, and so linear theory (which assumes upstream flow ascends the mountain) is less applicable for mountain wave prediction

Vortex shedding in the lee of Galapagos island on September 14, 2006. Image courtesy of NASA high-res MODIS satellite imagery.



Research Tools

Weather, Research, and Forecasting (WRF) Model

Fully compressible, non-hydrostatic, nonlinear model in terrain-following coordinate system for real and idealized mesoscale meteorological simulations.

Fourier Transform method

Linear semi-analytical wavefield model, developed at Naval Research Laboratory, DC using ray methods. Initialized with traditional lower boundary vertical displacement, but two new features presented in this dissertation:

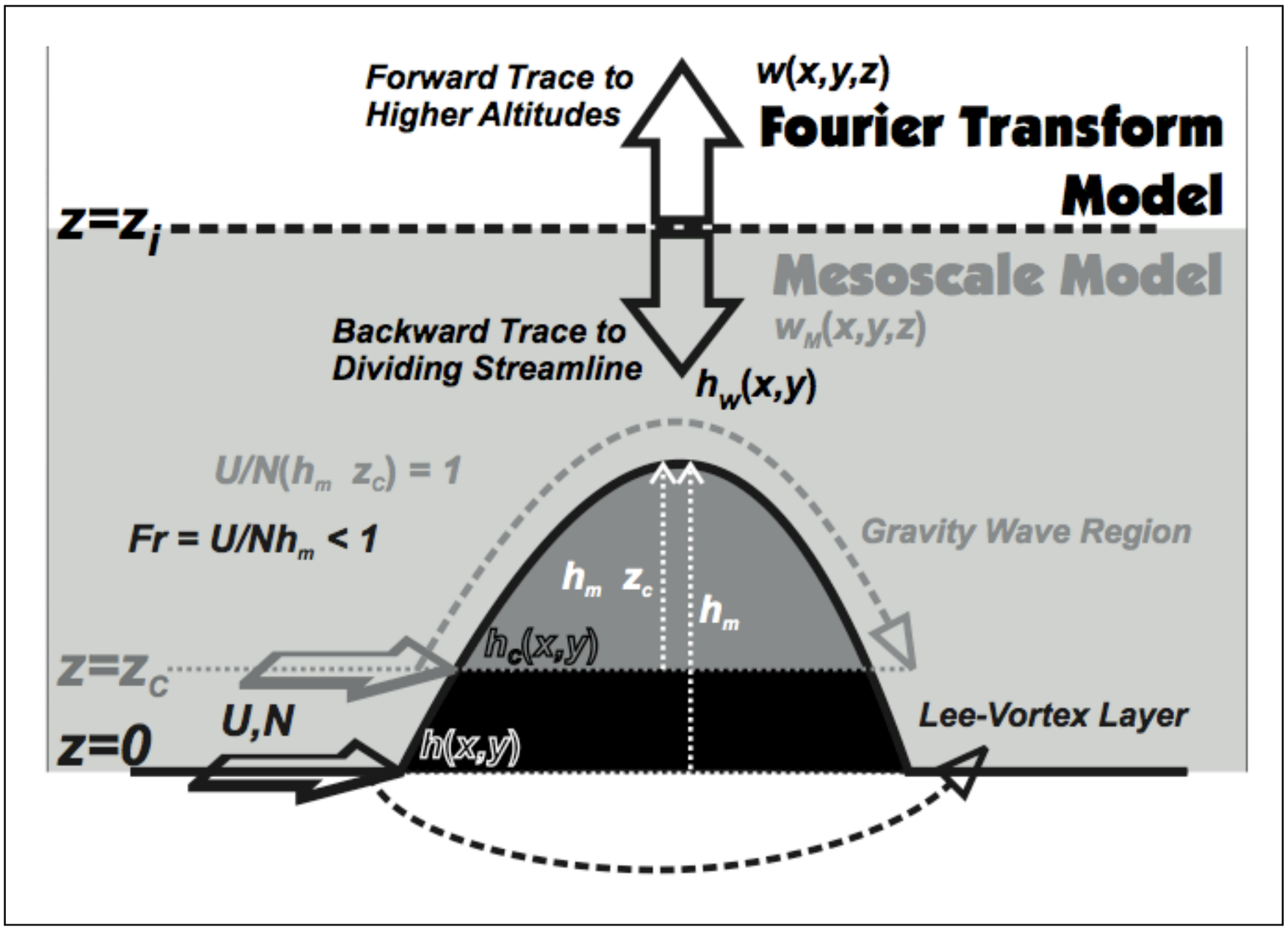
- hybrid WRF initialization scheme. FT is initialized with horizontal cross-section of w field from WRF above lower tropospheric nonlinear flow. Want to obtain more accurate wavefield with this initialization. We denote results using this technique as FT/WRF (traditional method is denoted as FT).

- calculation of local phase-averaged momentum fluxes $\rho \langle uw \rangle$ and $\rho \langle vw \rangle$ for local and area-averaged flux calculations from both initialization techniques. Most important terms for gravity wave drag in modeling - vertical variations driving effects on the flow

Fourier Transform Initialization

WRF initialization level (FT_w)

linear surface vertical displacement initialization (FT_o)

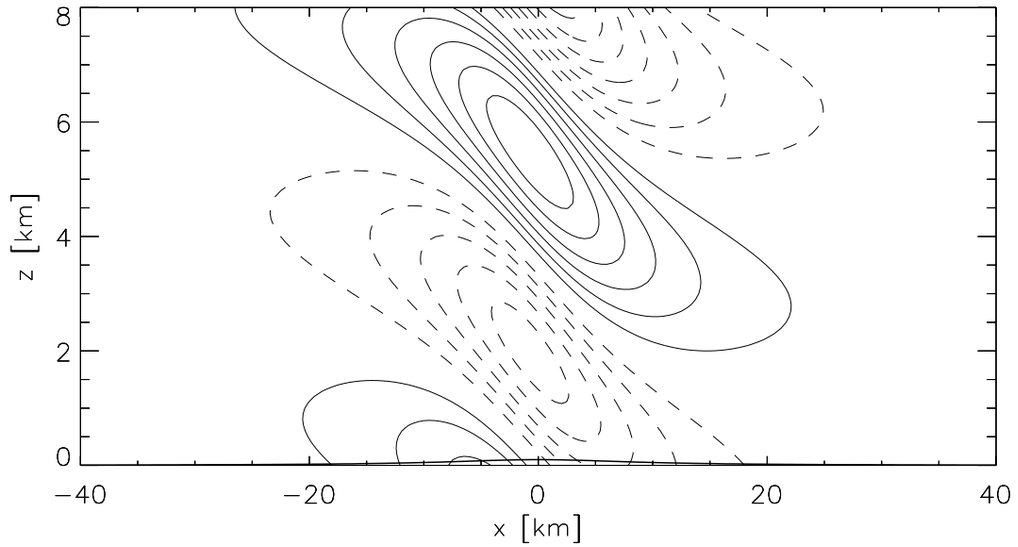


Schematic of the hybrid WRF-FT initialization scheme (FT_w). WRF is run to a steady-state, and then FT_w is initialized at a level above the lower level nonlinear processes (figure from Lindeman et al, 2008)

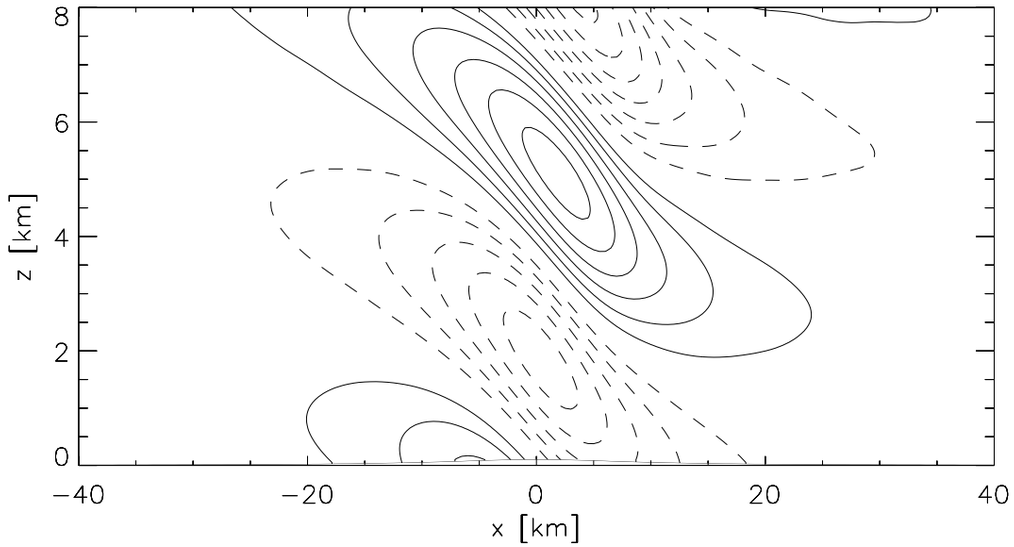
Both Fourier initialization methods resemble WRF and the analytical solution

for the linear uniform flow hydrostatic case

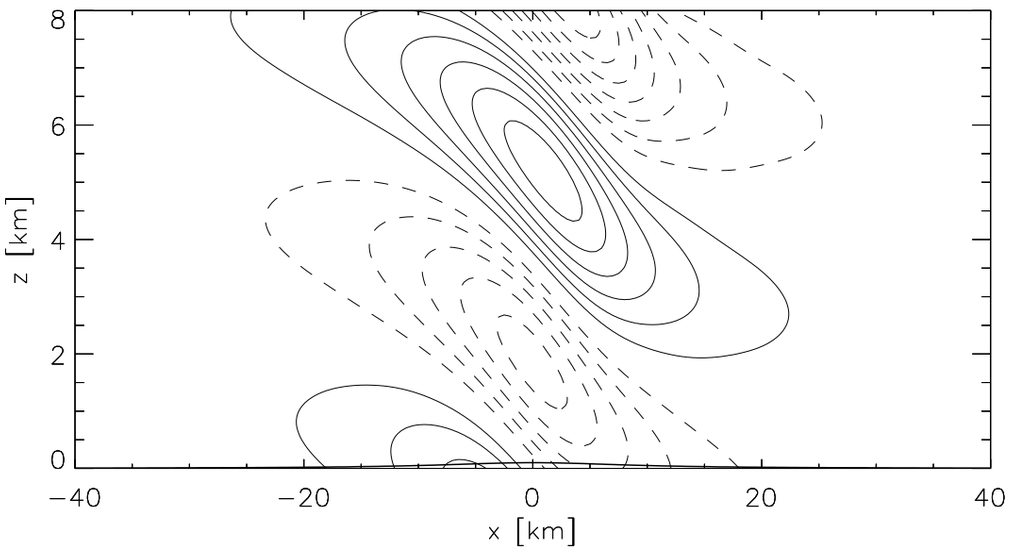
x-z cross-section of *w*, contour interval = 0.04 ms^{-1}



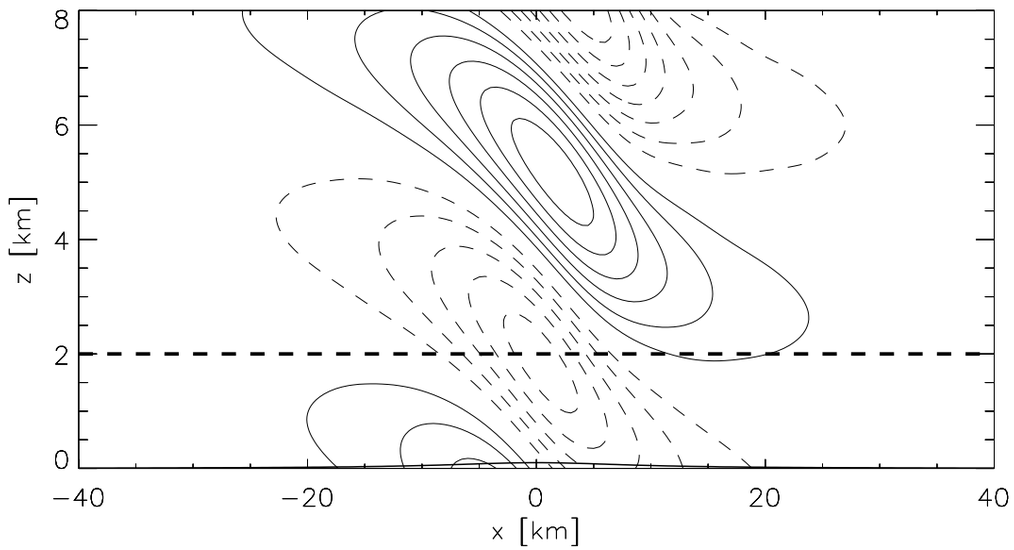
analytical



WRF



FT



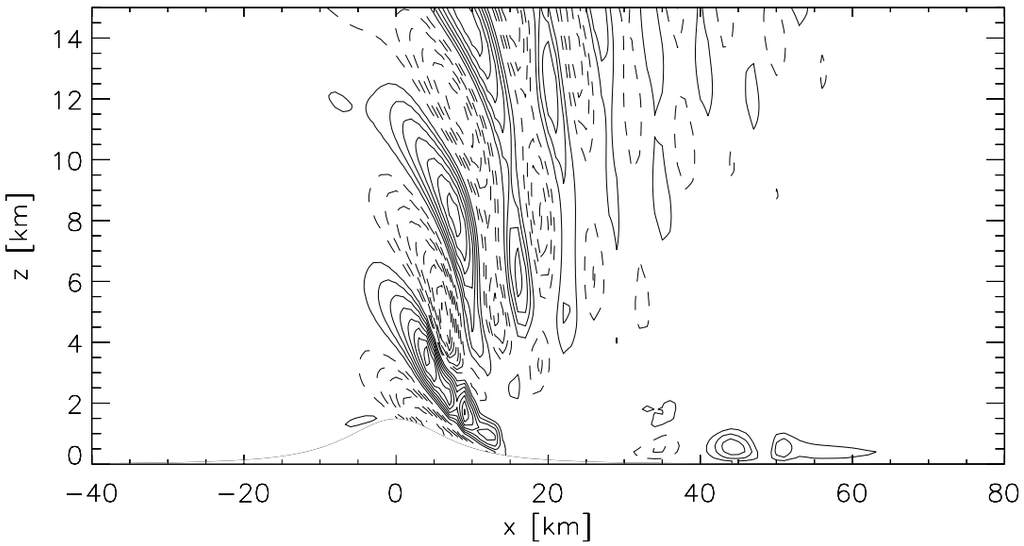
FT/WRF

initialization level WRF -------

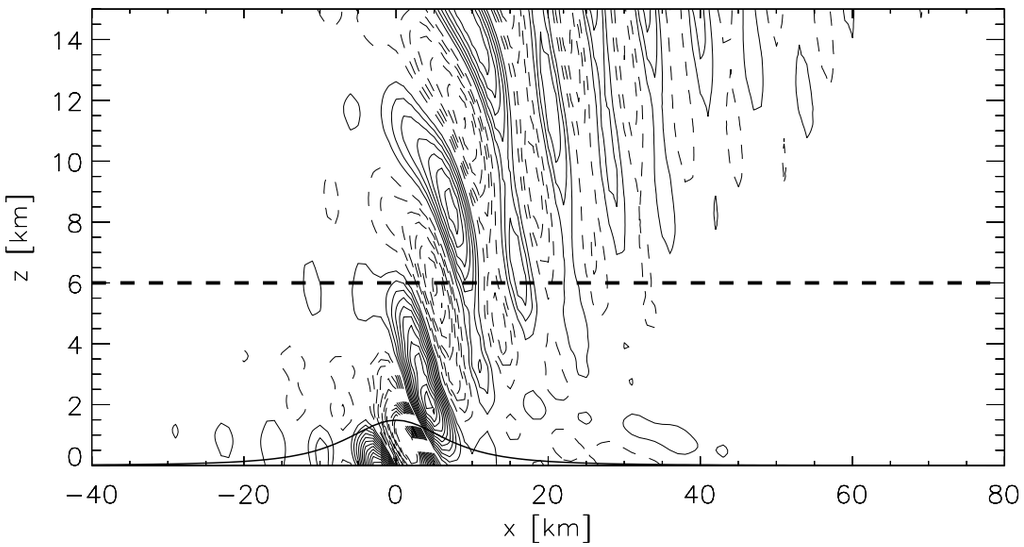
WRF - Weather, Research, and Forecasting Model
FT/WRF - Fourier Transform model initialized with w from WRF
FT - Fourier Transform model initialized with vertical displacement

Nonlinear Case: WRF - FT_w comparisons

WRF

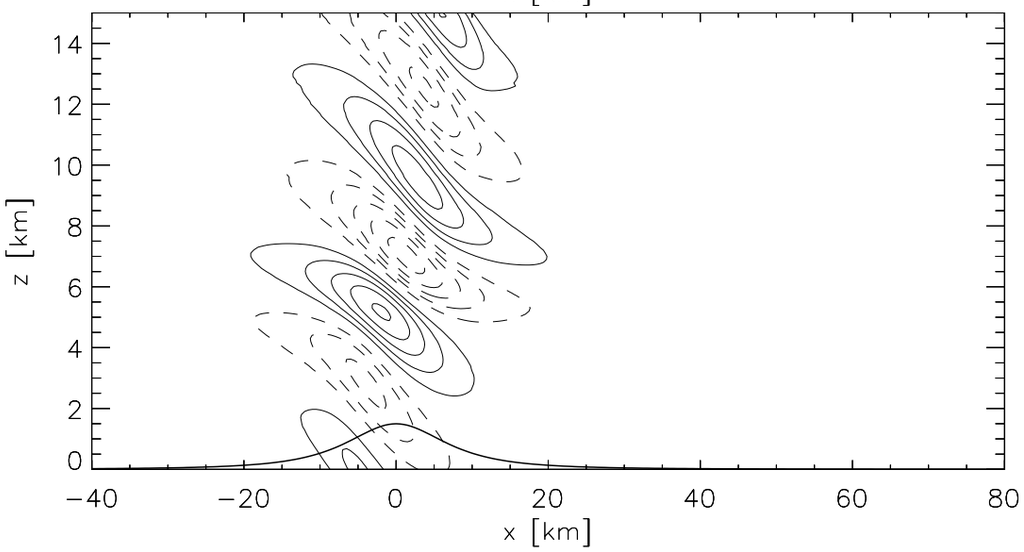


FT/ WRF



WRF initialization level

FT



$Fr_h = 2/3$

Wavefield as predicted by FT_w compares favorably with WRF - solutions diverge in lower atmosphere nonlinear flow

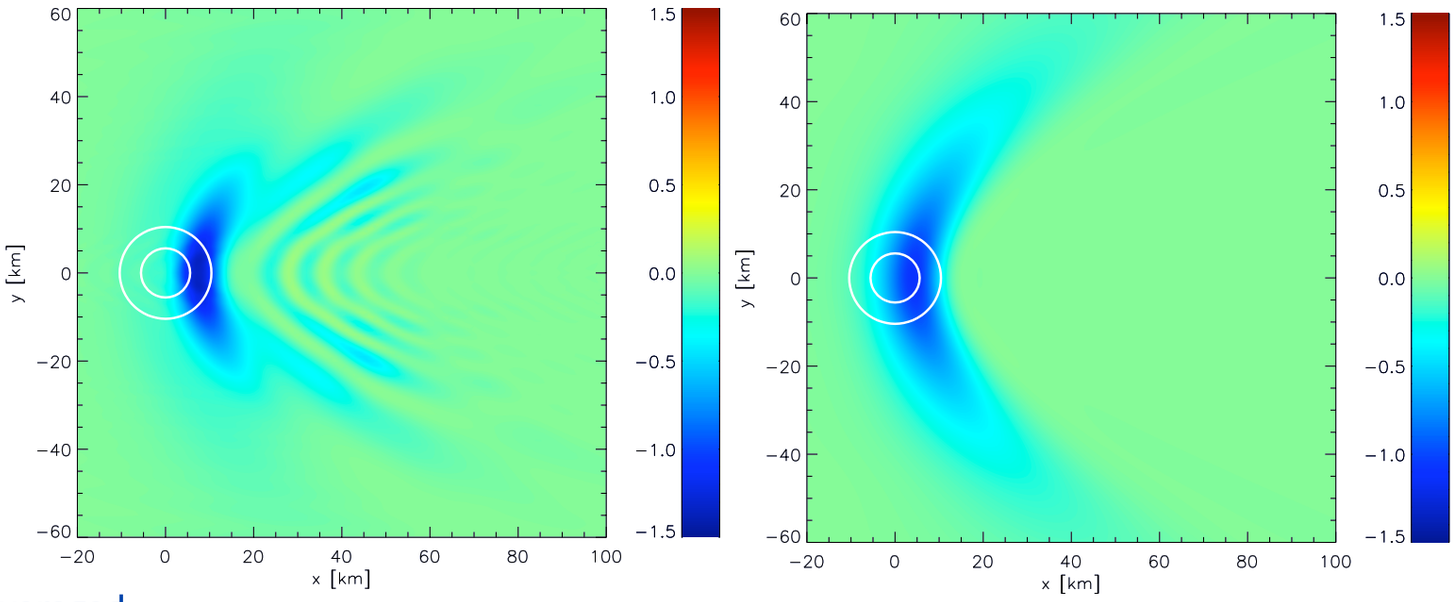
x-z cross-section of w.
Contour intervals = 0.3 ms^{-1}

WRF - Weather, Research, and Forecasting Model
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Horizontal cross-sections of local phase averaged momentum fluxes at 14 km

$Fr_h = 2/3$

ρ<uw>



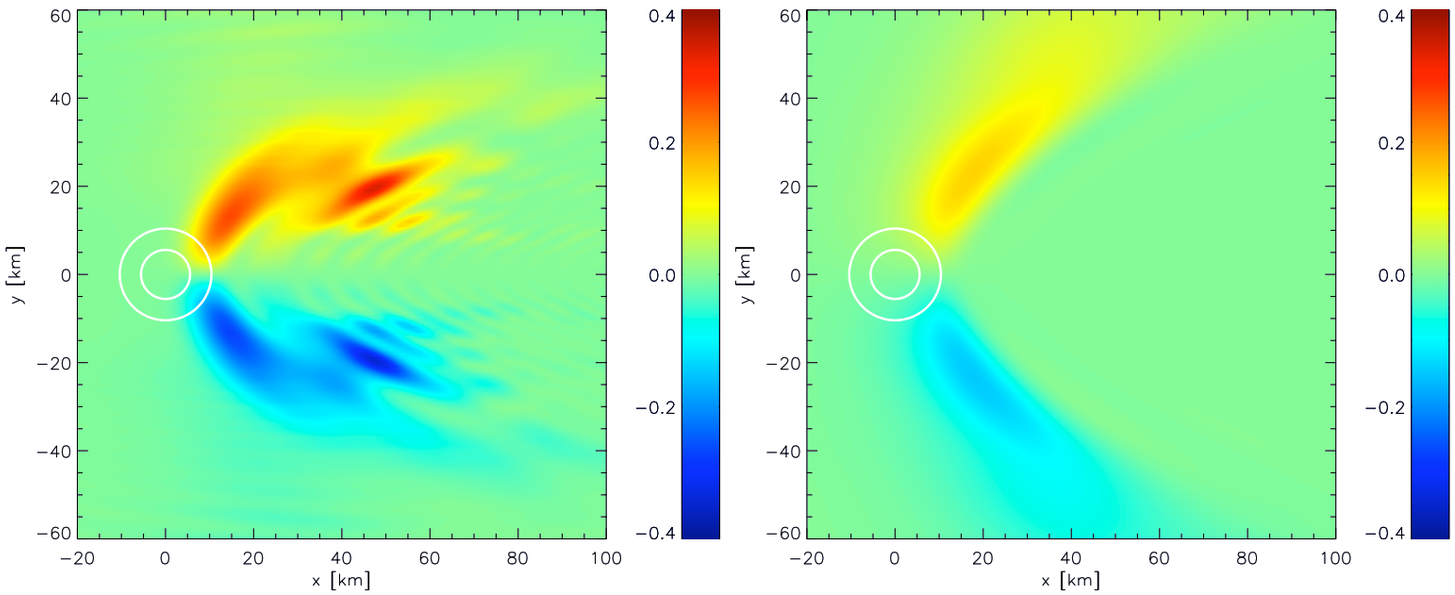
horizontally averaged ρ<uw>

0.0188 kg m^{-1} s^{-2}

0.0235 kg m^{-1} s^{-2}

We can determine where momentum flux concentrations are greatest

ρ<vw>



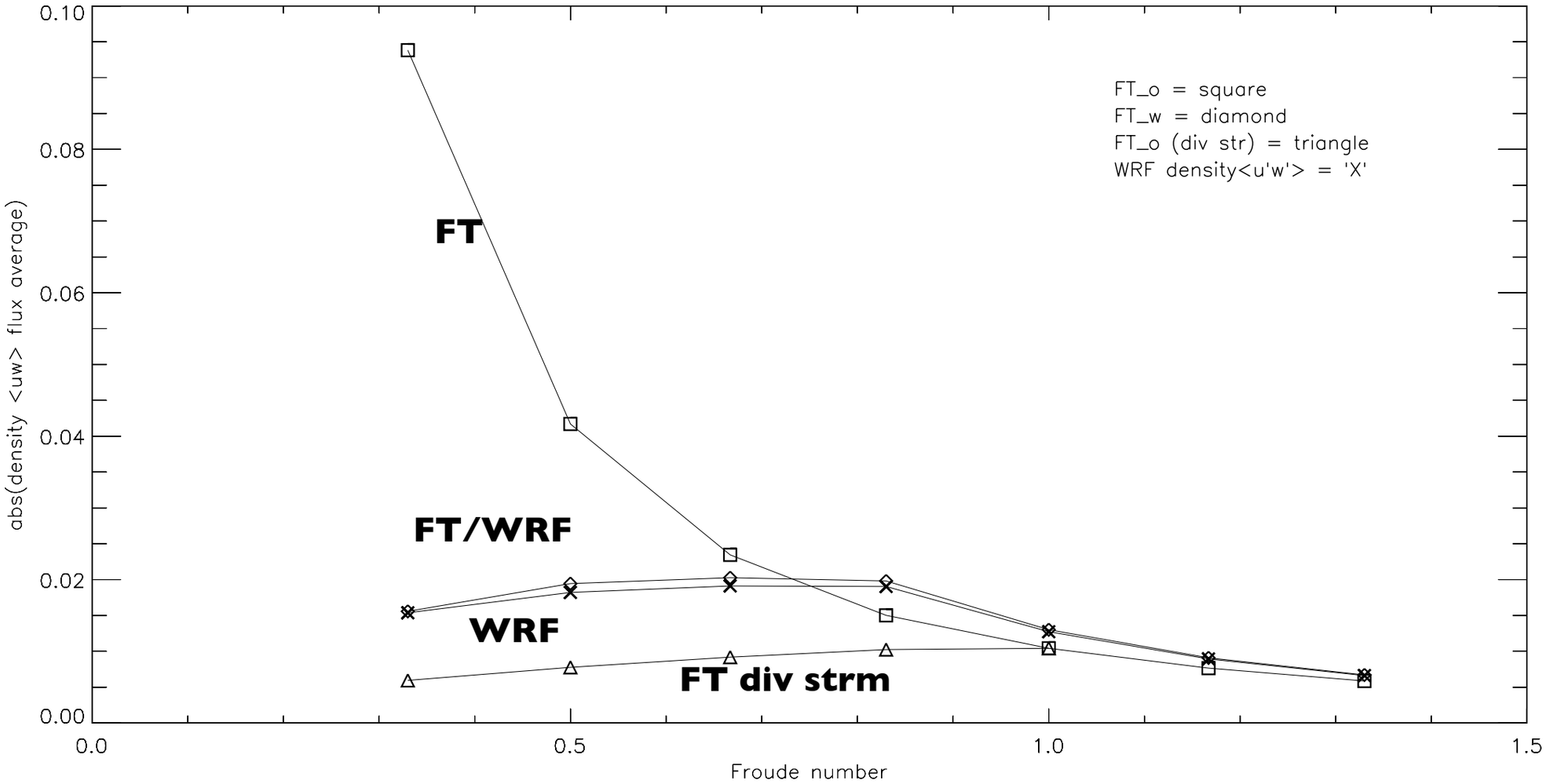
FT/WRF

FT

FT_w horizontal momentum flux average is less than FT_o

Average Horizontal Momentum Flux Concentration versus Froude number

FT increases dramatically with decreasing Fr



ρ<uw> units of kg m^{-1} s^{-2}

Plotted are the averaged horizontal ρ<uw> values for idealized cases where the Froude number is dependent on the mountain height. The averaged values are calculated from FT/WRF, FT, and FT using the dividing streamline height approximation. The globally-averaged WRF momentum flux (density multiplied by u and w perturbation quantities) is plotted for comparison (resembles FT/WRF).

WRF - Weather, Research, and Forecasting Model
FT/WRF - Fourier Transform model initialized with w from WRF
FT - Fourier Transform model initialized with vertical displacement

Conclusions / Future Work (con't)

Possible Research Directions, Applications, and Benefits

- The FT initialization technique featured in this dissertation has been shown to be versatile for low Froude number flows over complex orography. This analysis might be extended to non-uniform flows such as vertical wind shear, trapped waves, or external critical layers.

- Inclusion of other meteorological processes in WRF such as surface friction, Coriolis effects, diabatic processes, etc.

- Apply results of new FT techniques to mountain wave parameterization schemes - potential to improve accuracy of global weather model and climate forecasts

- Turbulence and aviation forecasts - able to geographically pinpoint where turbulent regions are likely to occur in the stratosphere and mesosphere

Related Literature

- Lindeman, J., D. Broutman, S.D. Eckermann, J. Ma, J.W. Rottman, Z. Boybeyi, 2008: Mesoscale model initialization of the Fourier transform method for mountain waves. Journal of the Atmospheric Sciences, accepted for publication

- Eckermann, S. D., Broutman, D., Ma, J., and Lindeman, J., 2006: Fourier-ray modeling of short wavelength trapped lee waves observed in infrared satellite imagery near Jan Mayen. Monthly Weather Review, 134, 2830-2848.

- Broutman, D., J. Ma, S.D. Eckermann, J. Lindeman, 2006: Fourier-Ray modeling of transient trapped lee waves. Monthly Weather Review, 134, 2849-2856

- Ahmad, N. and J. Lindeman 2007: Euler solutions using flux-based wave decomposition. International Journal for Numerical Methods in Fluids, 54, 47-72.

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