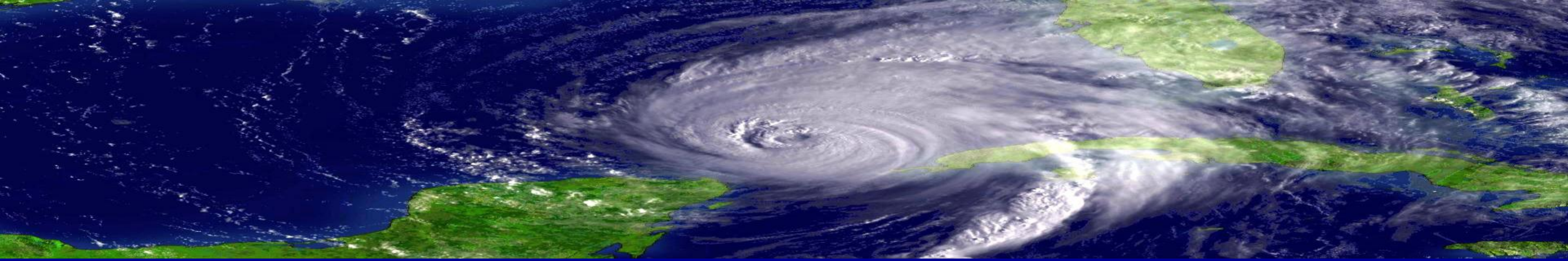


Supper parameterization of roll vortices in the hurricane boundary layer

Isaac Ginis and Kun Gao
University of Rhode Island

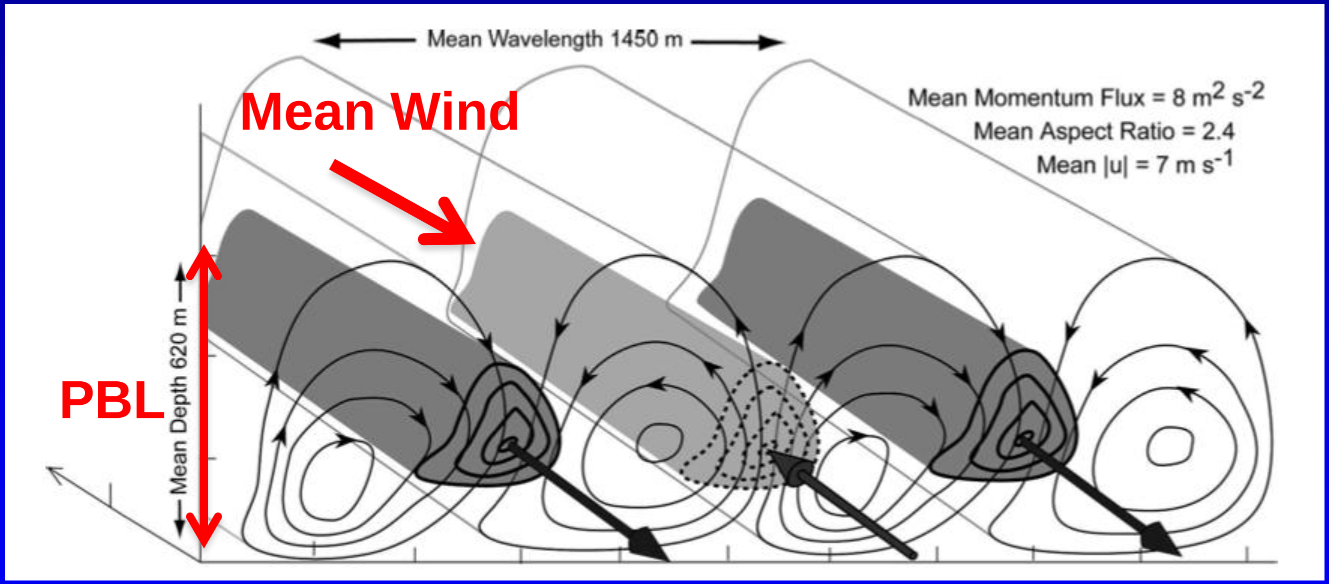
Collaborator: Ralph Foster (UW)

HFIP Regional Models Workshop
NCEP Sep 17-18, 2012

University of Rhode Island GSO Graduate School of Oceanography

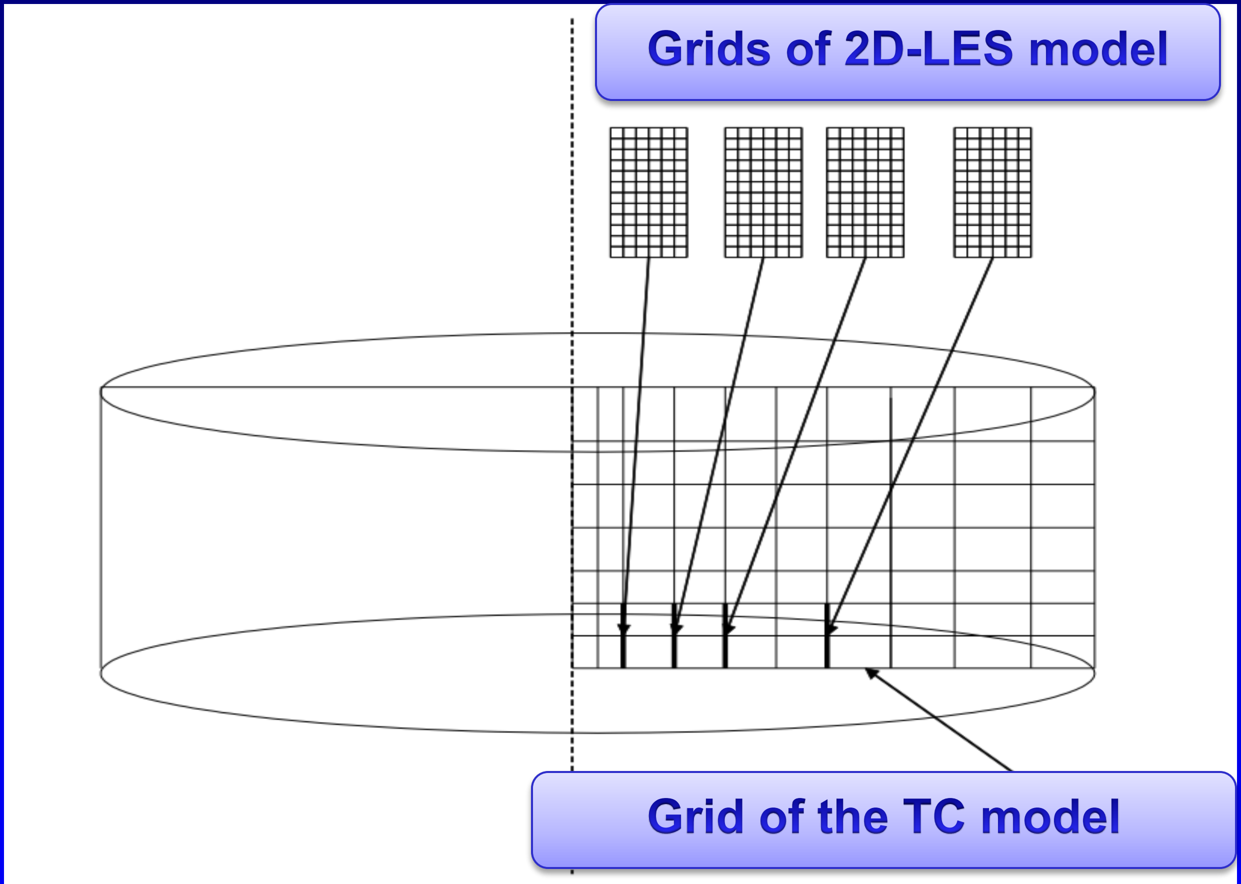
Motivation

Observations suggest roll vortices (rolls) are ubiquitous in tropical cyclones. Yet their effects are not explicitly represented in TC models.



Schematic diagram of roll vortices (Morrison, 2005)

Numerical Approach



Governing Momentum Equations

TC mean flow (axisymmetric):

$$\frac{\partial \bar{U}}{\partial t} + \bar{U}\frac{\partial \bar{U}}{\partial r} + \bar{W}\frac{\partial \bar{U}}{\partial z} - \frac{\bar{V}^2}{r} - f \cdot \bar{V} = -\frac{\partial \bar{P}}{\partial r} - \boxed{\frac{\partial \overline{W' \cdot U'}}{\partial z}} + K\frac{\partial^2 \bar{U}}{\partial z^2}$$

$$\frac{\partial \bar{V}}{\partial t} + \bar{U}\frac{\partial \bar{V}}{\partial r} + \bar{W}\frac{\partial \bar{U}}{\partial z} + \frac{\bar{U} \cdot \bar{V}}{r} + f \cdot \bar{U} = -\boxed{\frac{\partial \overline{W' \cdot V'}}{\partial z}} + K\frac{\partial^2 \bar{V}}{\partial z^2}$$

$$\frac{\partial \bar{U}}{\partial r} + \frac{\bar{U}}{r} + \frac{\partial \bar{W}}{\partial z} = 0$$

Rolls – 2D LES model:

$$\frac{\partial \eta'}{\partial t} + u'\frac{\partial \eta'}{\partial x} + w'\frac{\partial \eta'}{\partial z} = -\bar{u}\frac{\partial \eta'}{\partial x} - w'\frac{\partial \bar{\eta}}{\partial z} + T_{\eta'}$$

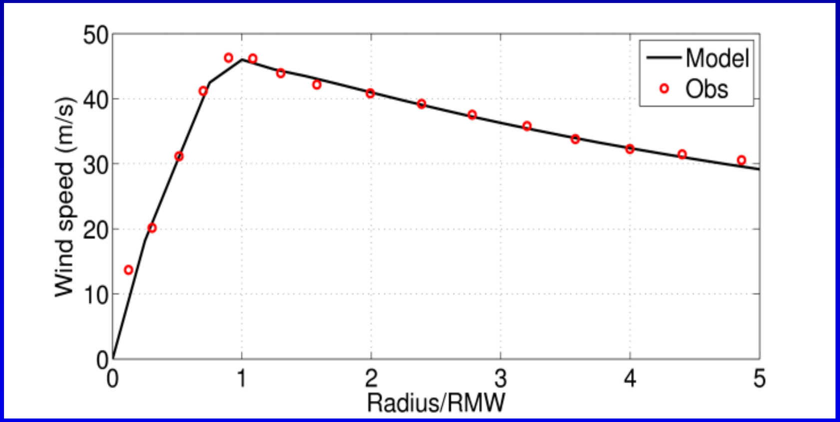
$$\frac{\partial v'}{\partial t} + u'\frac{\partial v'}{\partial x} + w'\frac{\partial v'}{\partial z} = -\bar{u}\frac{\partial v'}{\partial x} - w'\frac{\partial \bar{v}}{\partial z} + T_{v'}$$

$$\eta' = \frac{\partial w'}{\partial x} - \frac{\partial u'}{\partial z}$$

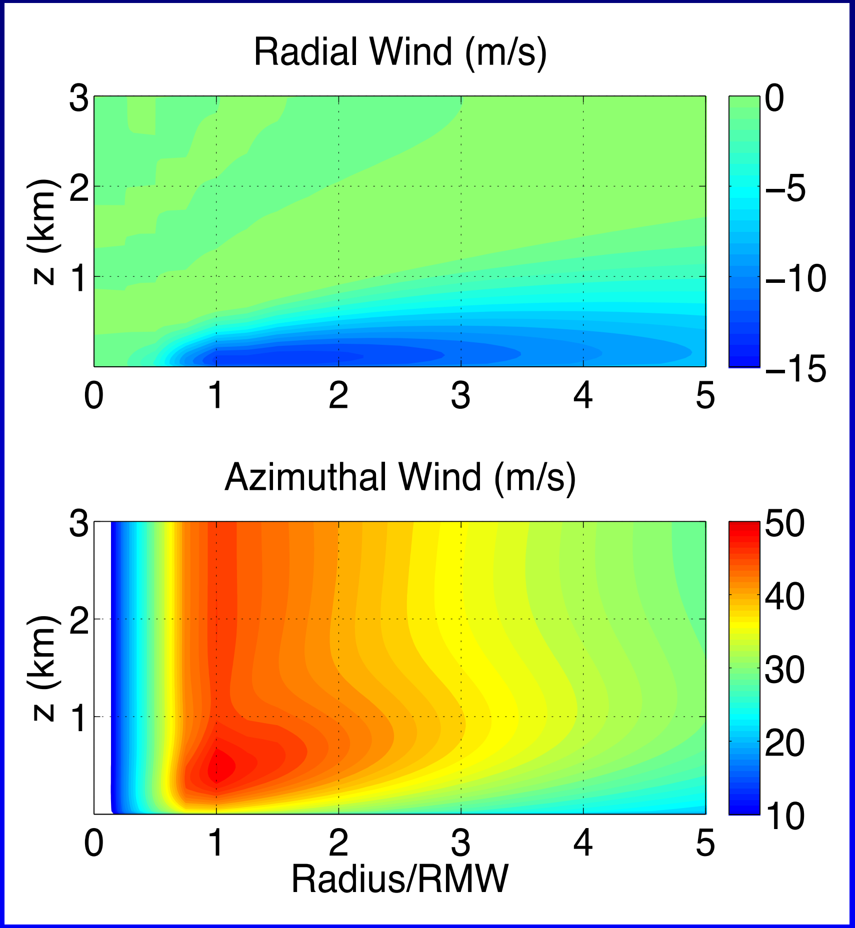
Ginis et al, 2004
Yu et al, 2012

Hurricane Boundary Layer Study

- Axisymmetric
- Wind on top under gradient wind balance



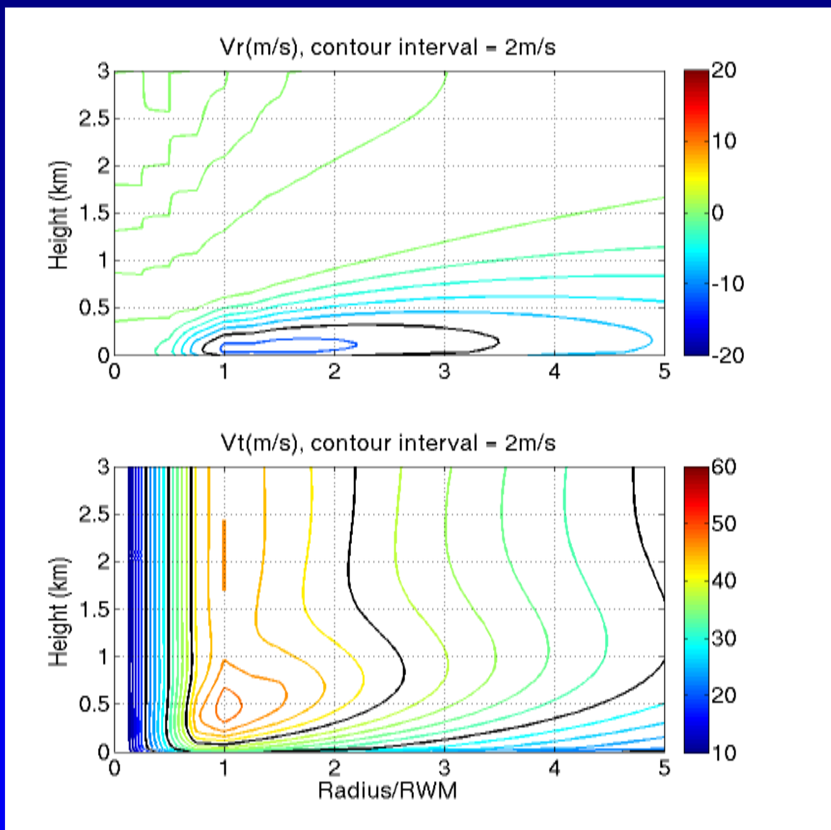
Holland wind model, parameters determined from HBL composite observation dataset (Zhang, 2011). This dataset derived based on 790 GPS dropsondes deployed in 13 hurricanes.



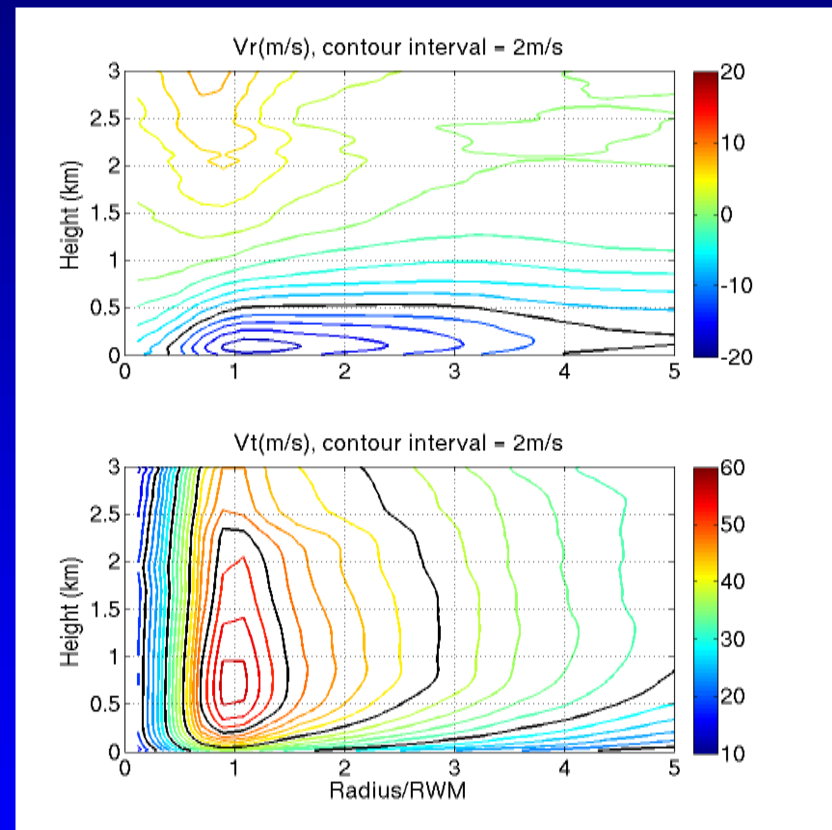
Balanced state without rolls
(RMW = 40 km)

Hurricane Boundary Structure

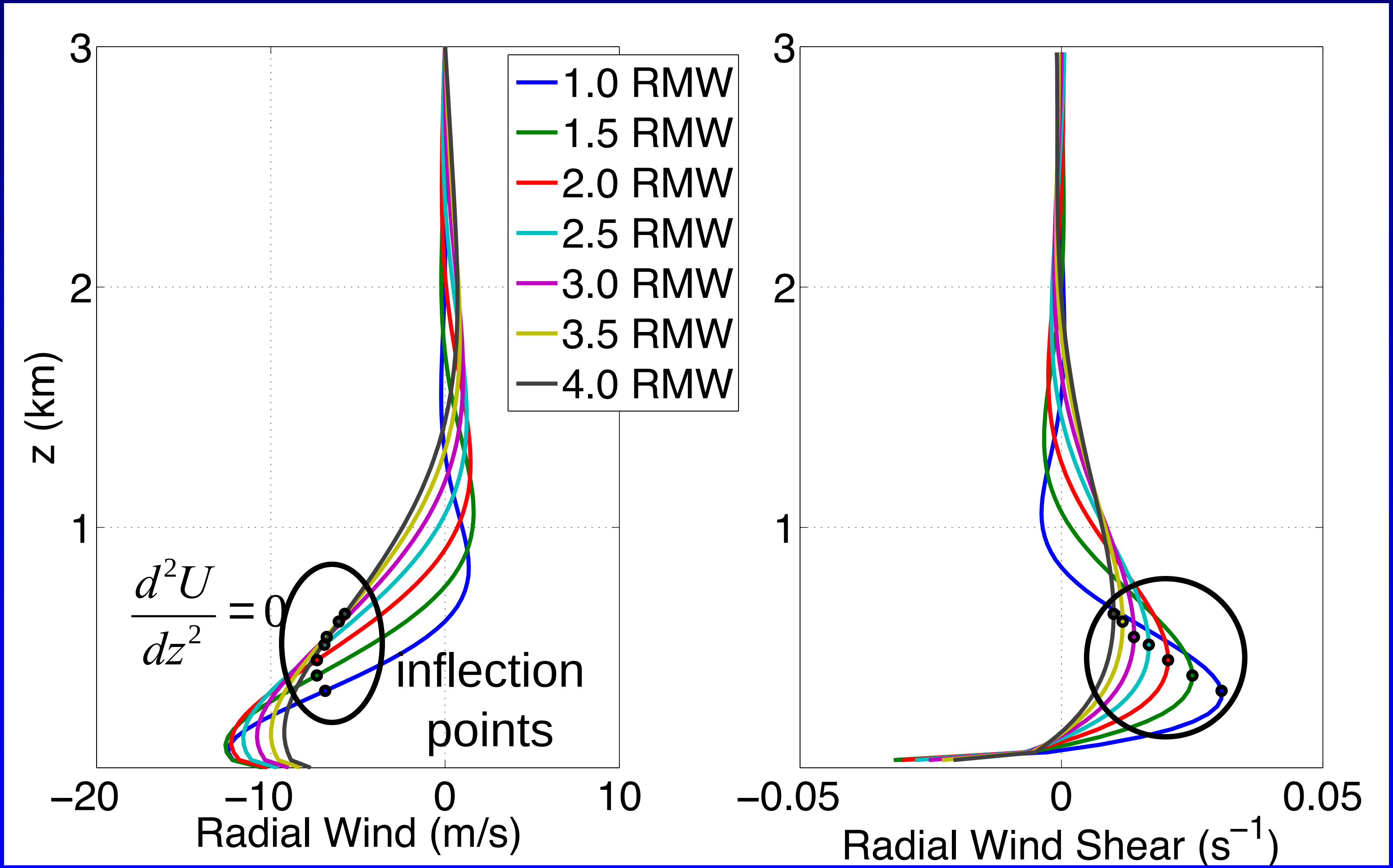
Model



Observation-based composite
(Zhang, 2011)



Radial (Cross-Roll) Wind Profiles
Inflection Point Instability



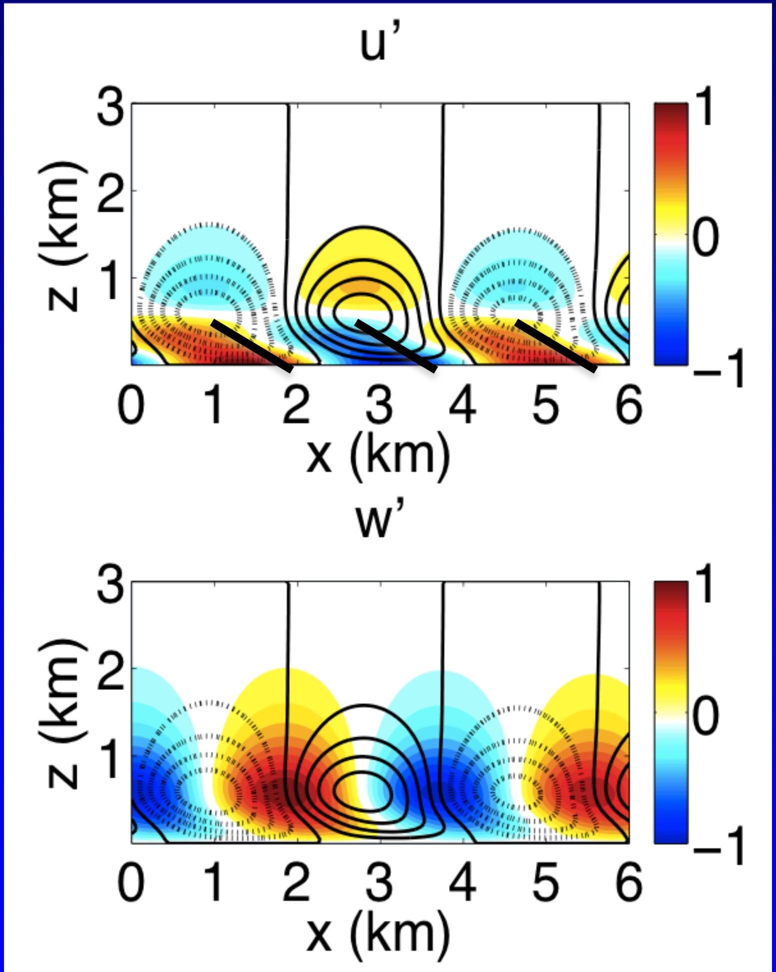
Radial wind and wind shear profiles at selected locations

Linear Phase (small perturbations)

Perturbations at least one order smaller than the mean flow.

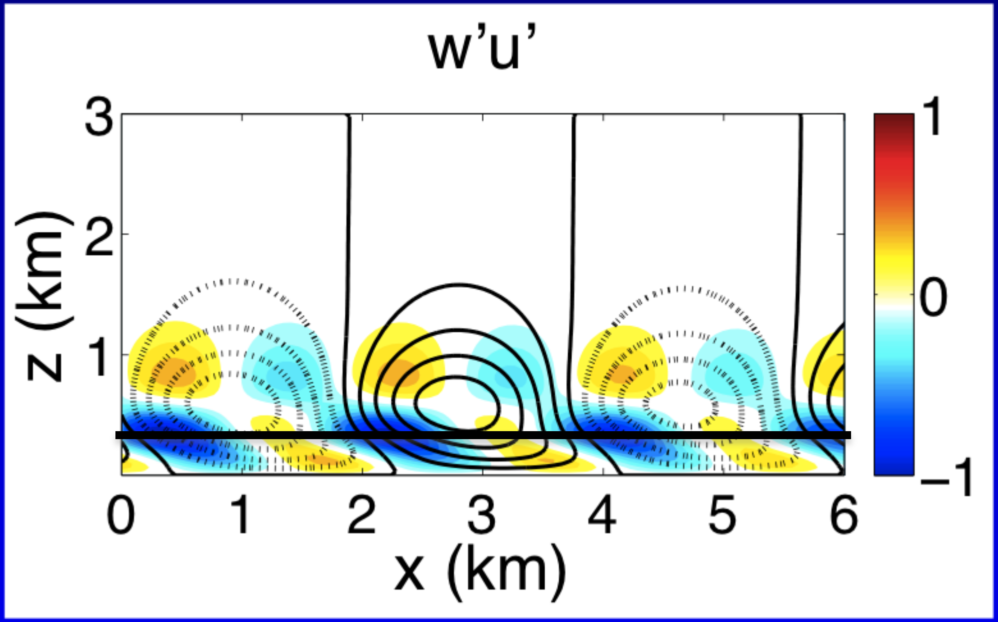
Mean flow remains unchanged.

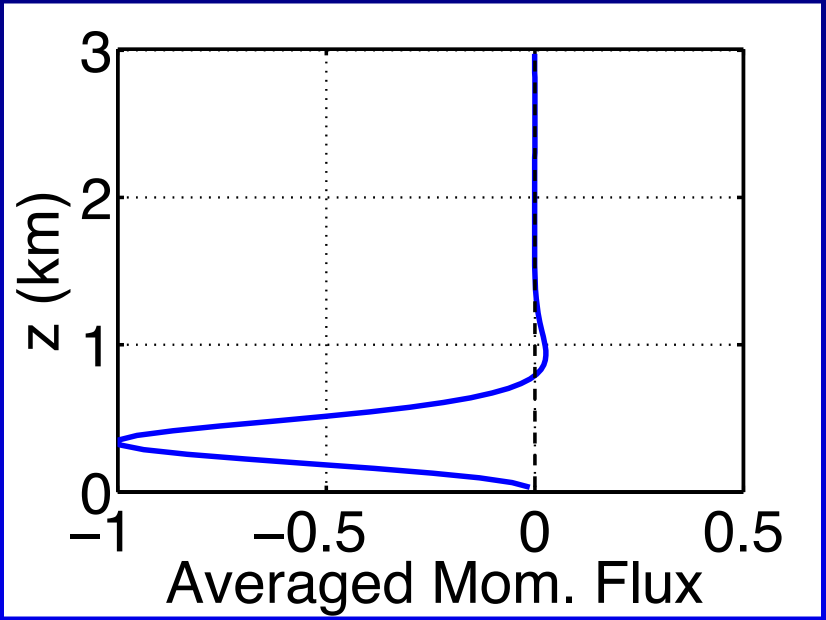
Perturbations grows exponentially with time.



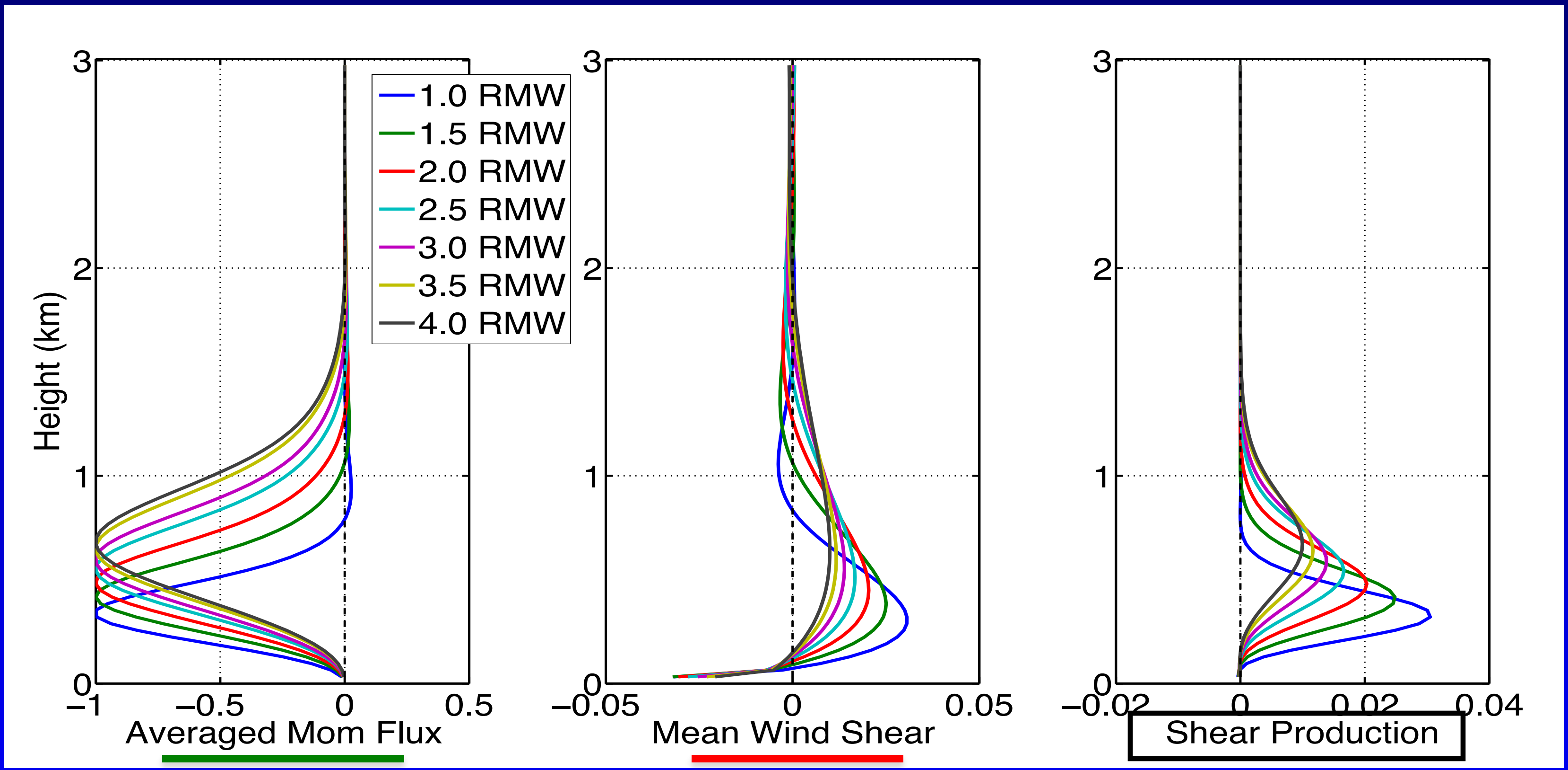
Structure of rolls at 1.0RMW
Color : normalized wind components
Contours : stream function

Roll-induced Momentum Flux





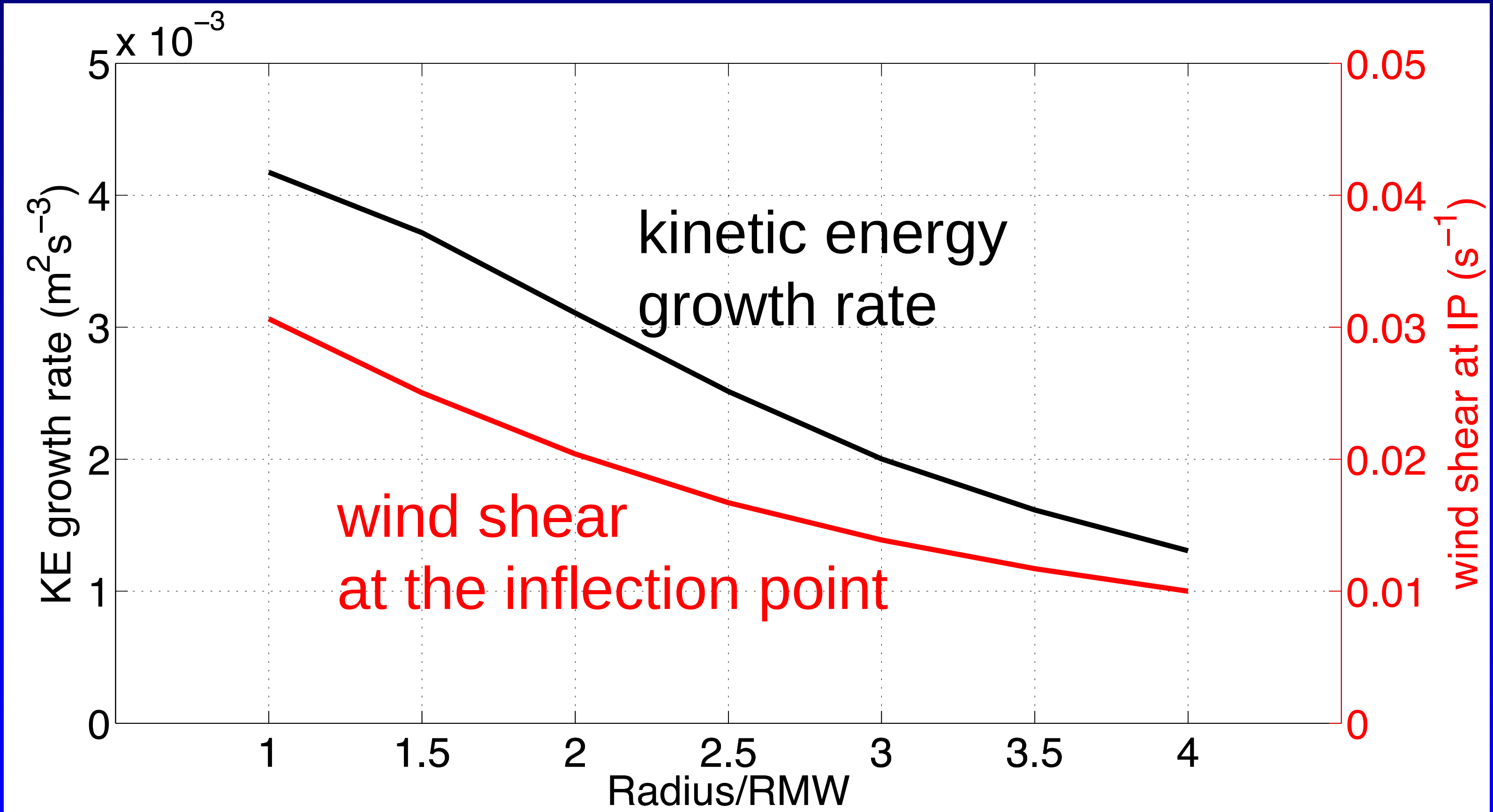
Shear Production (Energy Source)



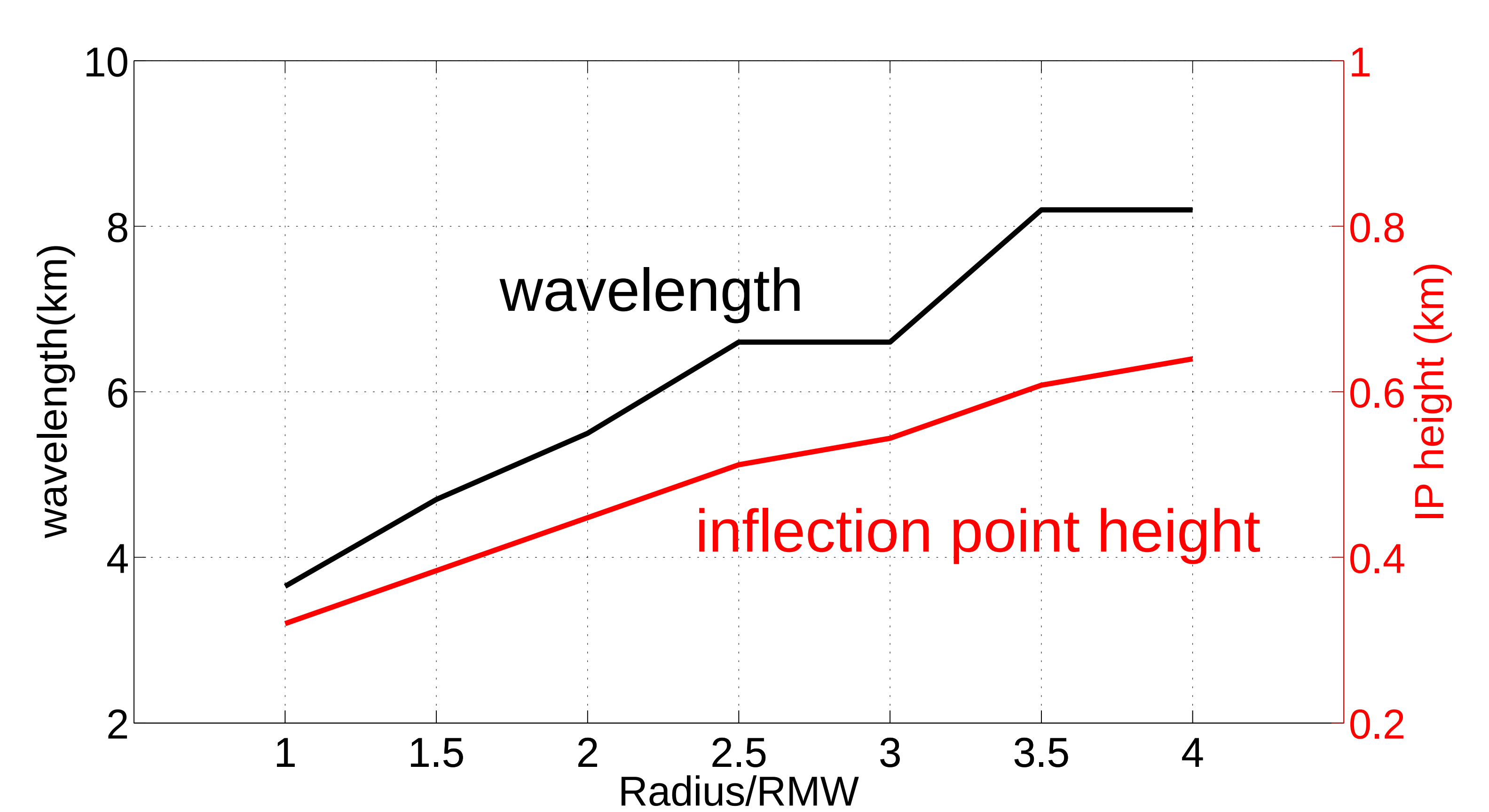
$$\frac{d}{dt}\overline{e'} = \boxed{-\overline{w'u'}\frac{\partial \overline{u}}{\partial z}} + \frac{g}{\theta_0}\overline{w'\theta_v'} - \overline{D}$$

cross-roll wind shear production

Growth Rate
(Neutral Stratification)



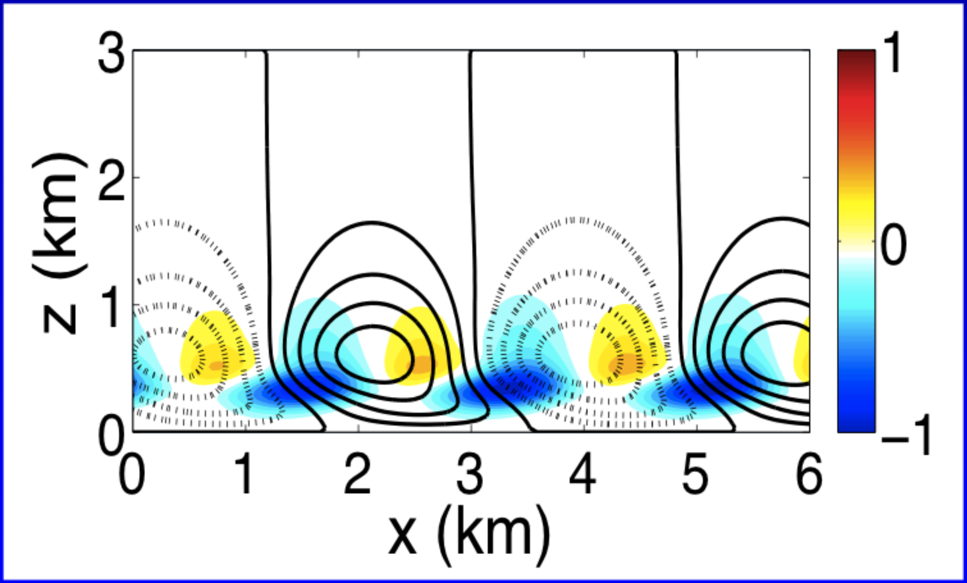
Wavelength



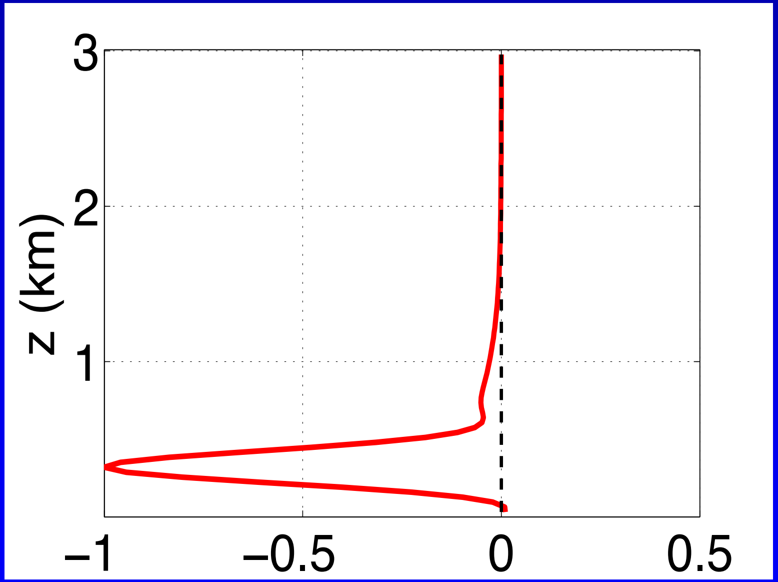
10
8
6
4
2
wavelength(km)
1
0.8
0.6
0.4
0.2
IP height (km)
wavelength
inflection point height
1
1.5
2
2.5
3
3.5
4
Radius/RMW

Effect of Stable Stratification

$$\frac{d}{dt}\overline{e'} = -\overline{w'u'}\frac{\partial \overline{u}}{\partial z} + \boxed{\frac{g}{\theta_0}\overline{w'\theta_v'}} - \overline{D}$$

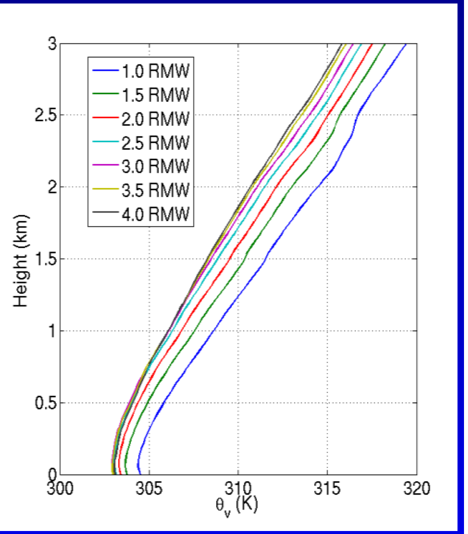


Potential temperature flux (normalized)

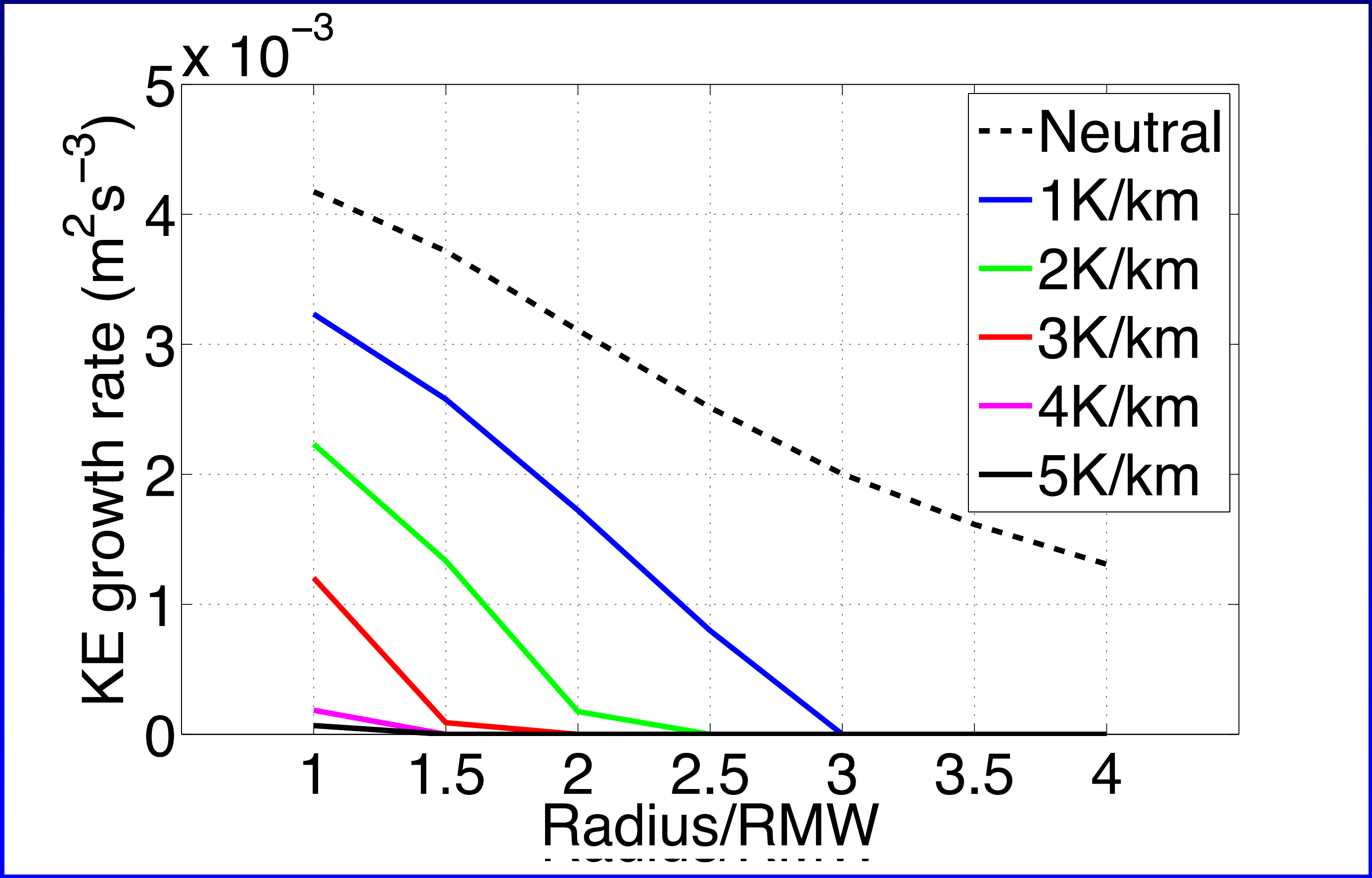


After averaging

Effect of Stable Stratification



Potential temperature profiles from observation-based HBL composite (Zhang, 2011)



Summary of Linear Phase Results

1. Rolls in HBL can be generated by *inflection point instability* under neutral or weak stratification

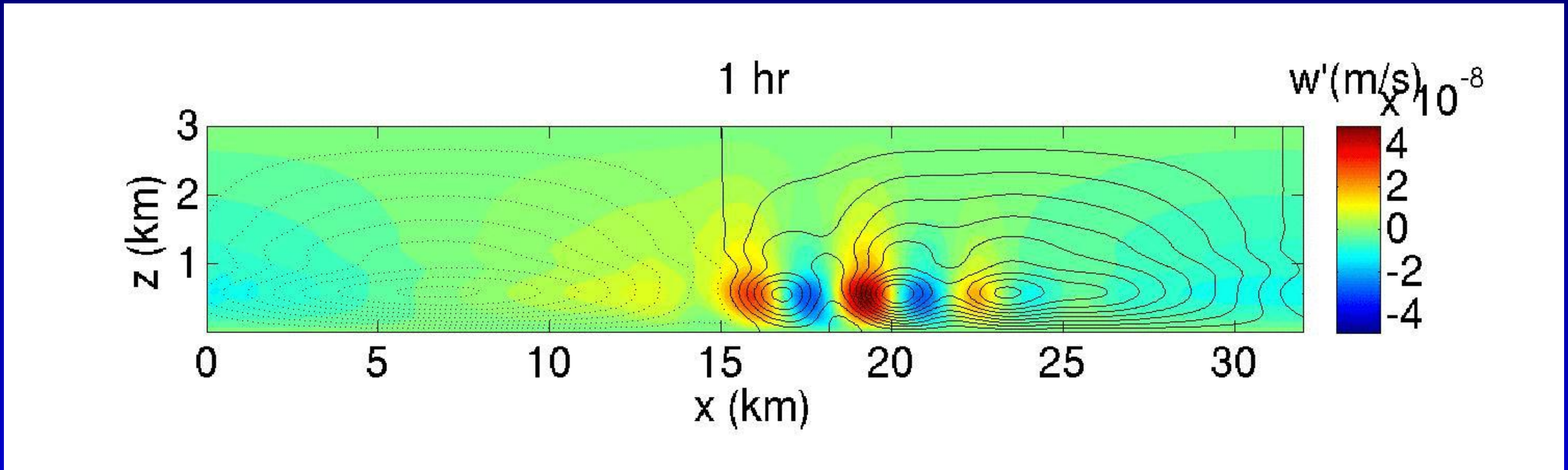
2. Rolls are *tilted* against the cross-roll mean wind to extract kinetic energy

3. Growth rate of the rolls *decreases and wavelength increases* with the radius under neutral stratification

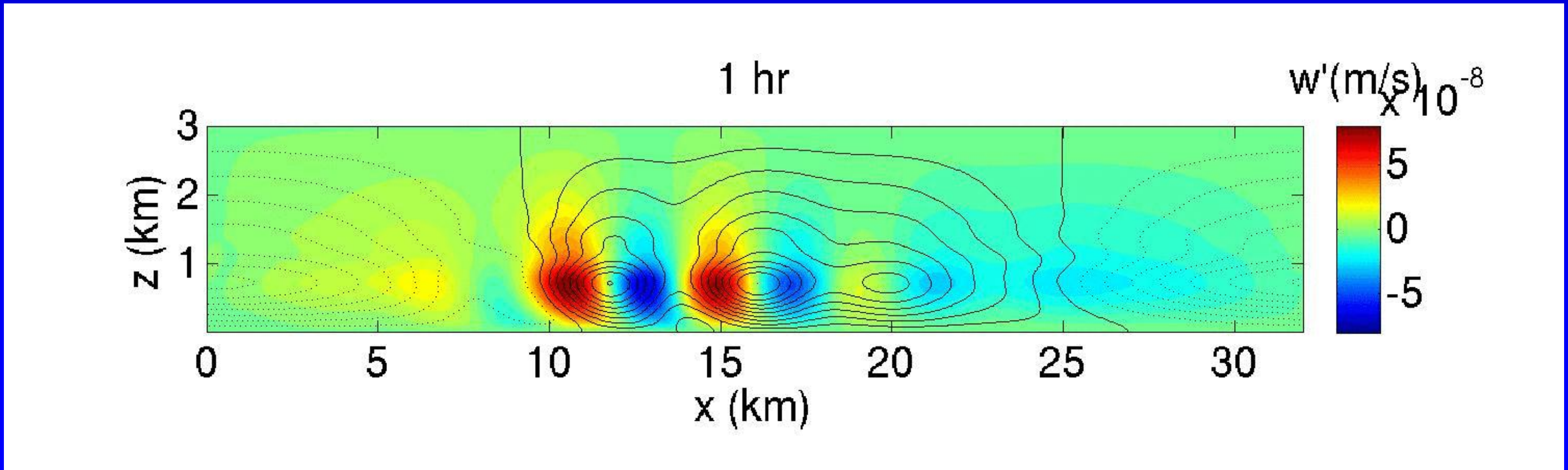
4. *Strong* stratification can *suppress* the growth of rolls.

Formation and Evolution of Rolls

0.75*RMW



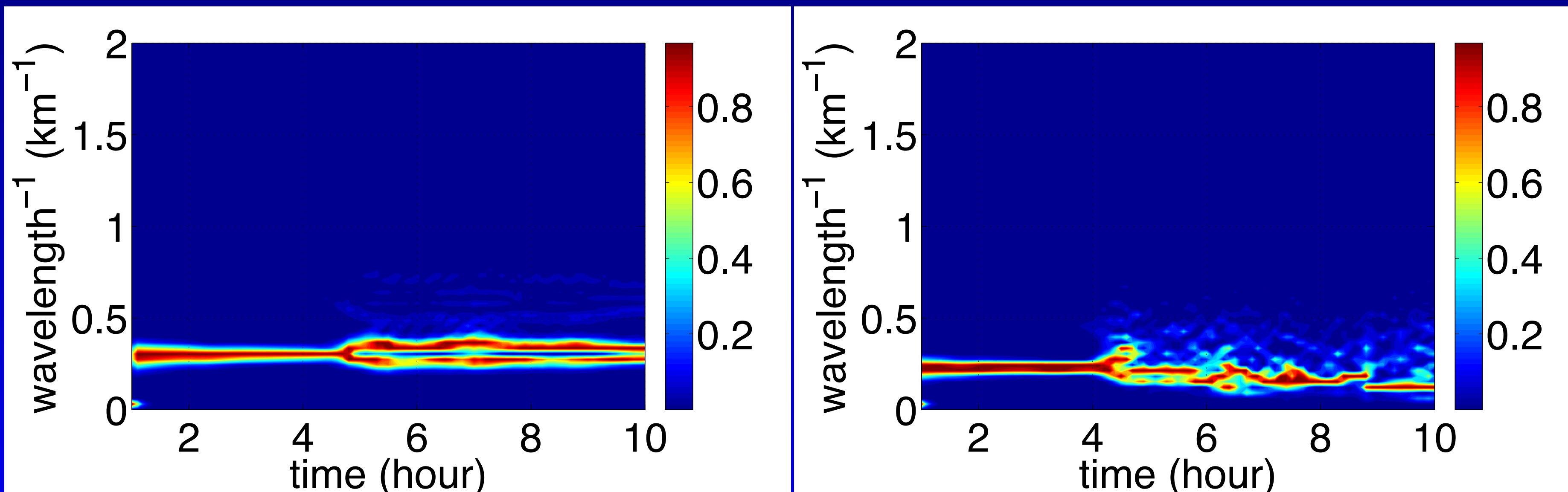
1.0*RMW



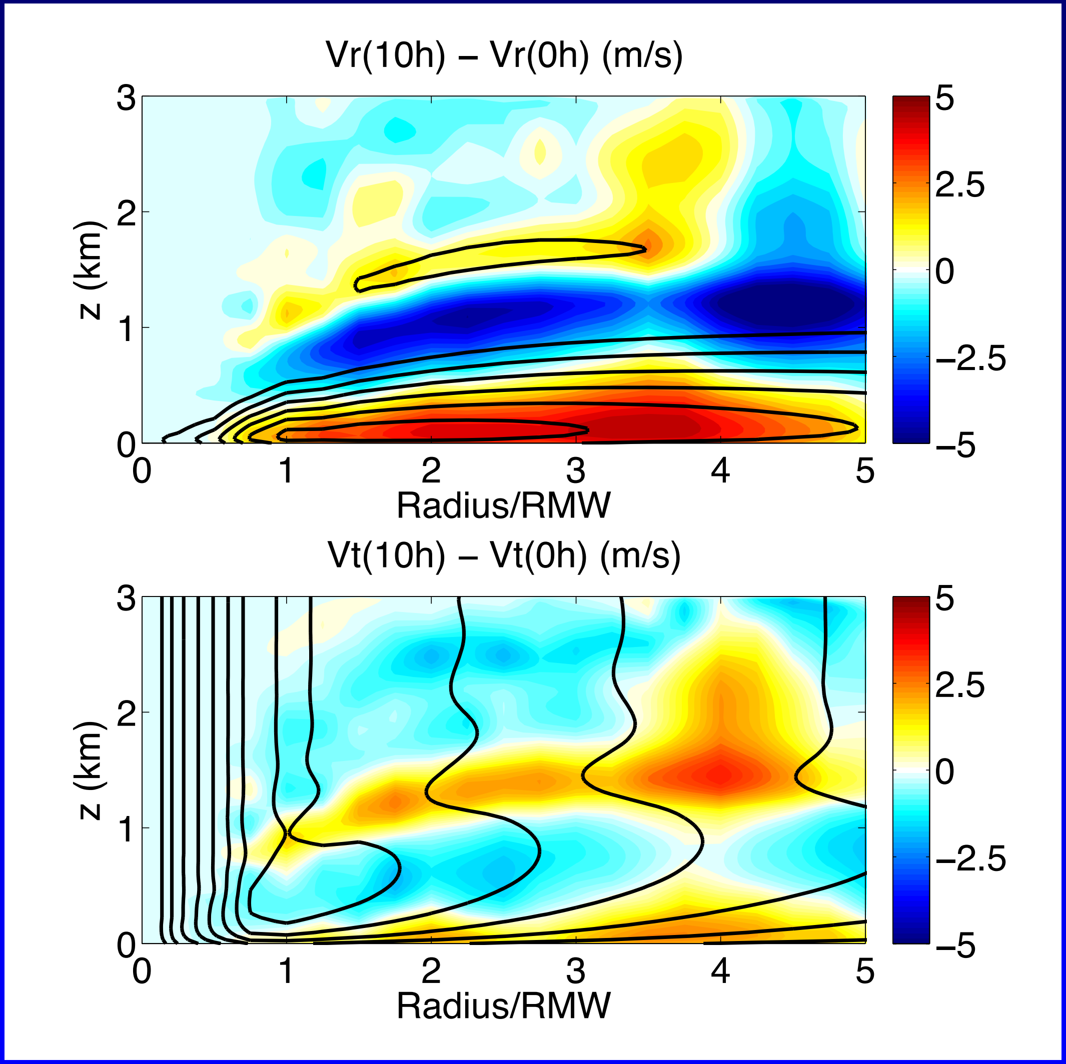
Formation and Evolution of Rolls

0.75*RMW

1.0*RMW



Changes of the Mean Flow



Radial

Tangential

Mean flow at 10hr – initial mean flow
(Black contours shows the initial mean flow)

Summary of Nonlinear Phase Results

- Nonlinear phase results show two types of roll structures: well-organized, coherent structure and multi-scale structure.
- The overall effect of roll-induced flux is to enhance momentum mixing in the HBL that could significantly modify the mean wind.
- The roll-induced mixing could lead to reduction of inflow wind speed and increase depth of inflow layer.

Future work

- Investigate the reason why rolls exhibit different types of evolution at different locations
- Investigate the effect of negative stratification
- Test the sensitivity to sub-grid-scale mixing
- Include background stratification in the non-linear simulations
- Explore how rolls contribute to the mixing of heat and moisture in the HBL