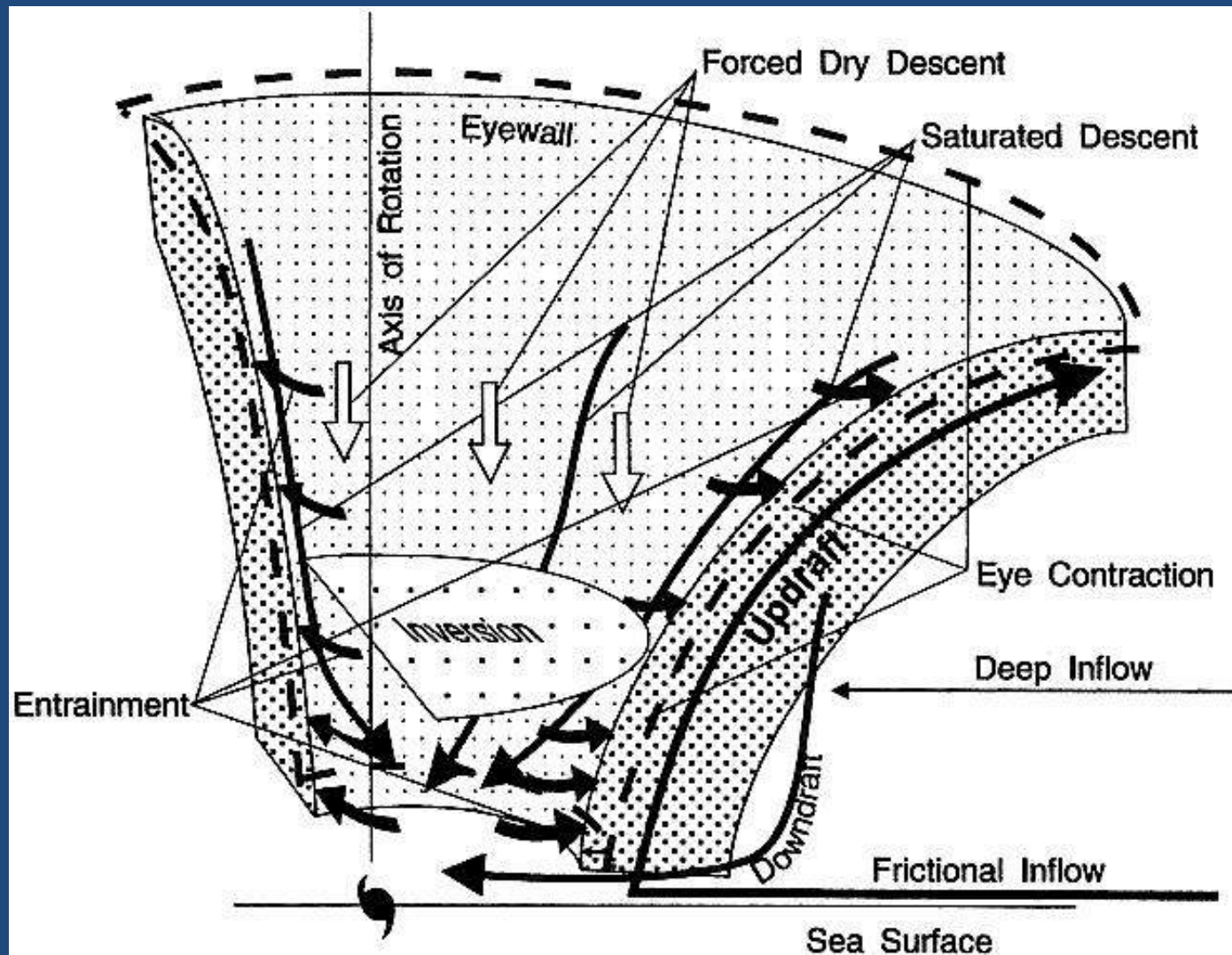


# The Tropical Cyclone Warm Core

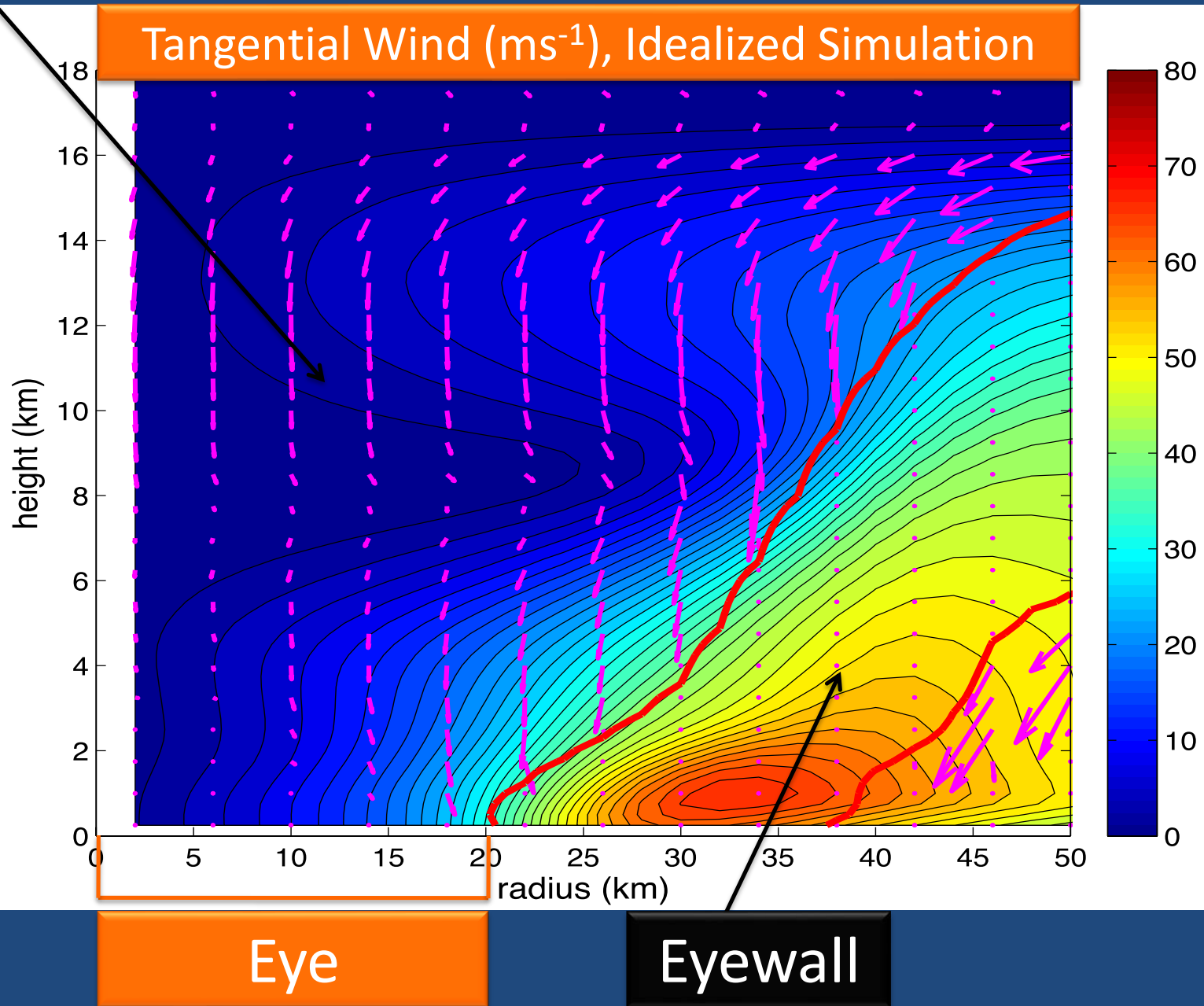
Daniel P. Stern

University Corporation for Atmospheric Research

# Structure of the Eye and Eyewall

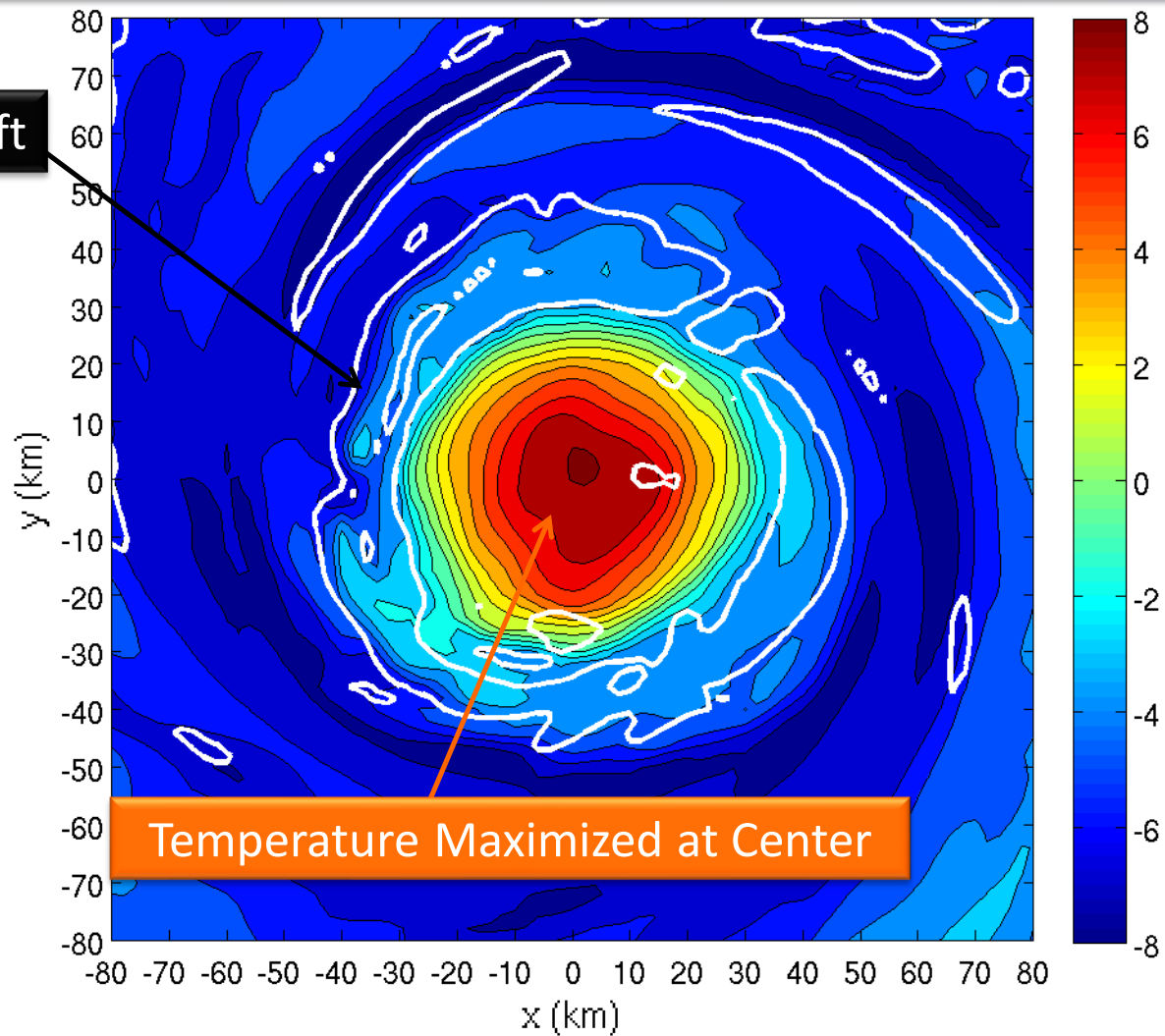


Most of the Eye Experiences Descent



## Temperature at $z=6$ km, Idealized Simulation

Eyewall Updraft



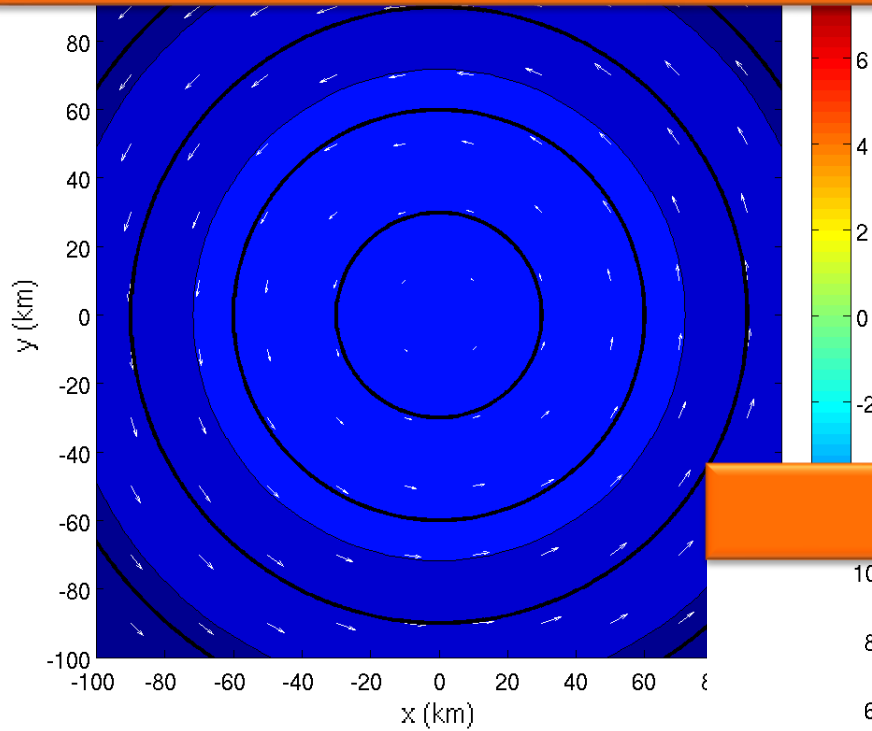
# Thermal Wind Balance and the Warm Core

$$\left(f + \frac{2v}{r}\right) \frac{\partial v}{\partial z} = \frac{g}{T_0} \frac{\partial T}{\partial r}$$

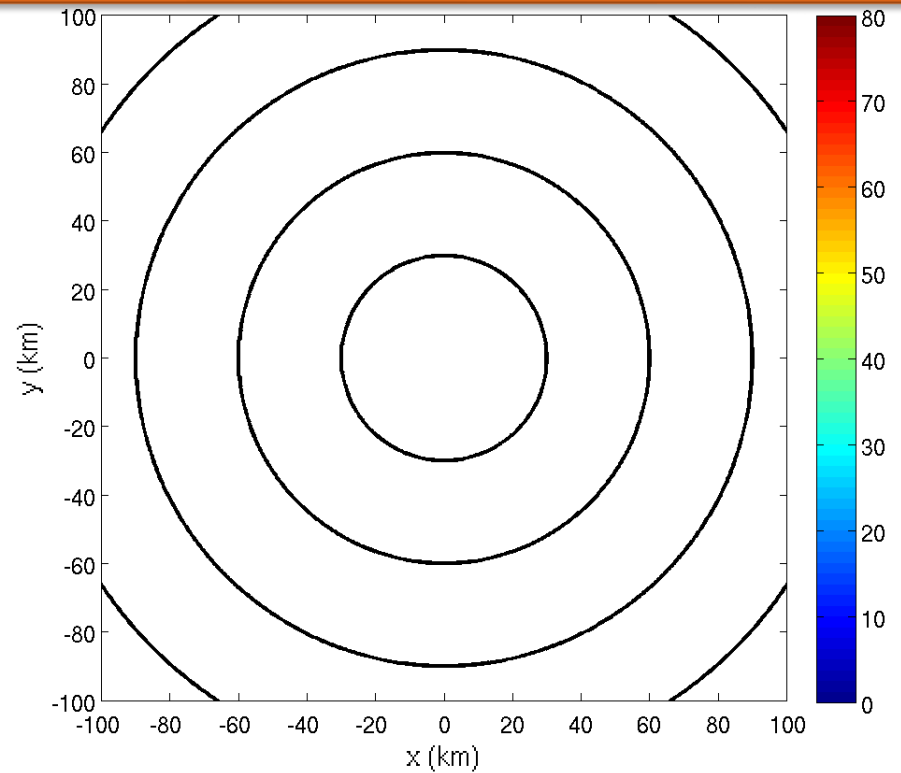
- Thermal wind balance requires that wherever the tangential winds decrease with height, the temperature must increase inwards.
- The temperature is therefore warmest at the center of tropical cyclones.
- So the temperature structure of the eye is closely linked to storm intensity and to the overall structure of the wind field.



## Temperature at $z=6$ km



## Wind Speed at $z=10$ m



# Observed Structure of the Warm Core

## Hurricane Cleo (1958)

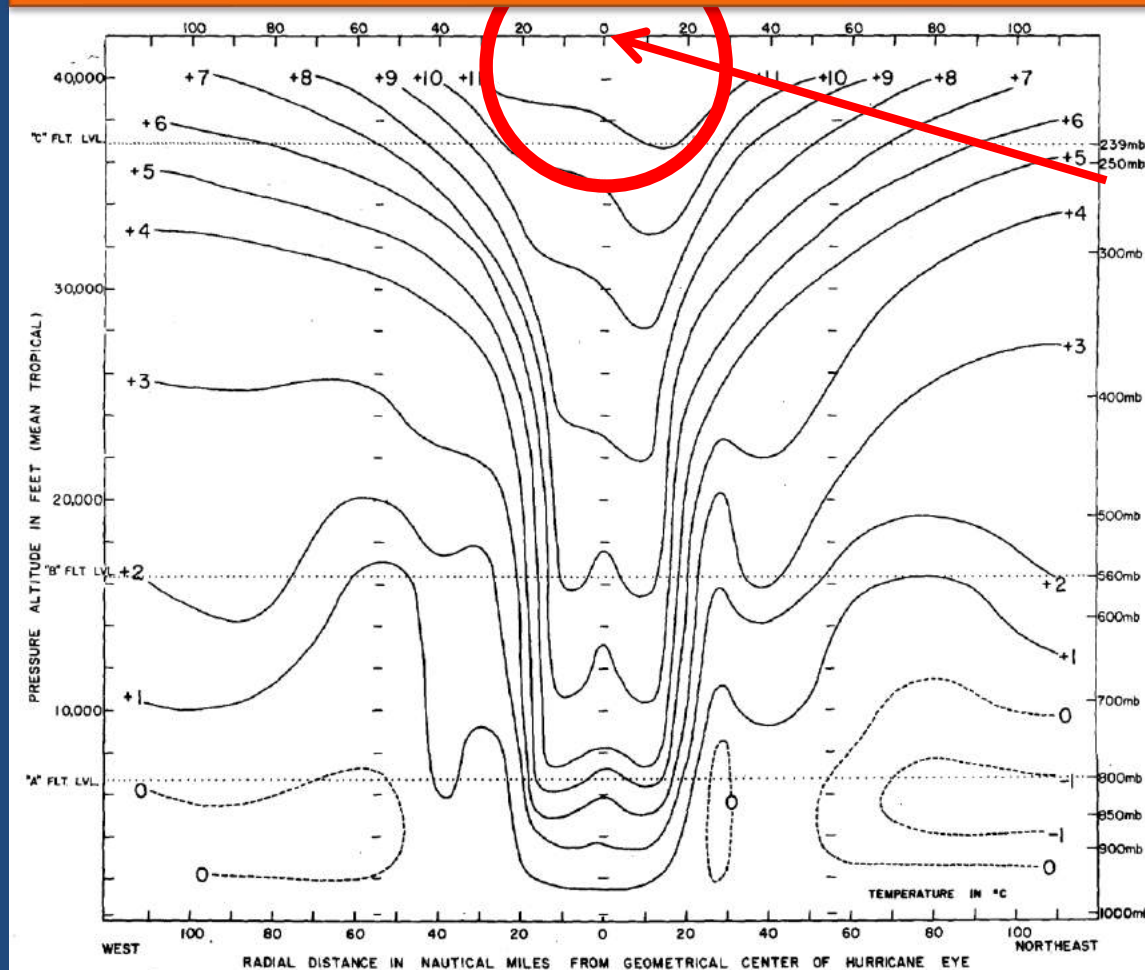


FIGURE 8.—Vertical cross-section of temperature anomaly from mean tropical atmosphere along first traverse of hurricane Cleo.

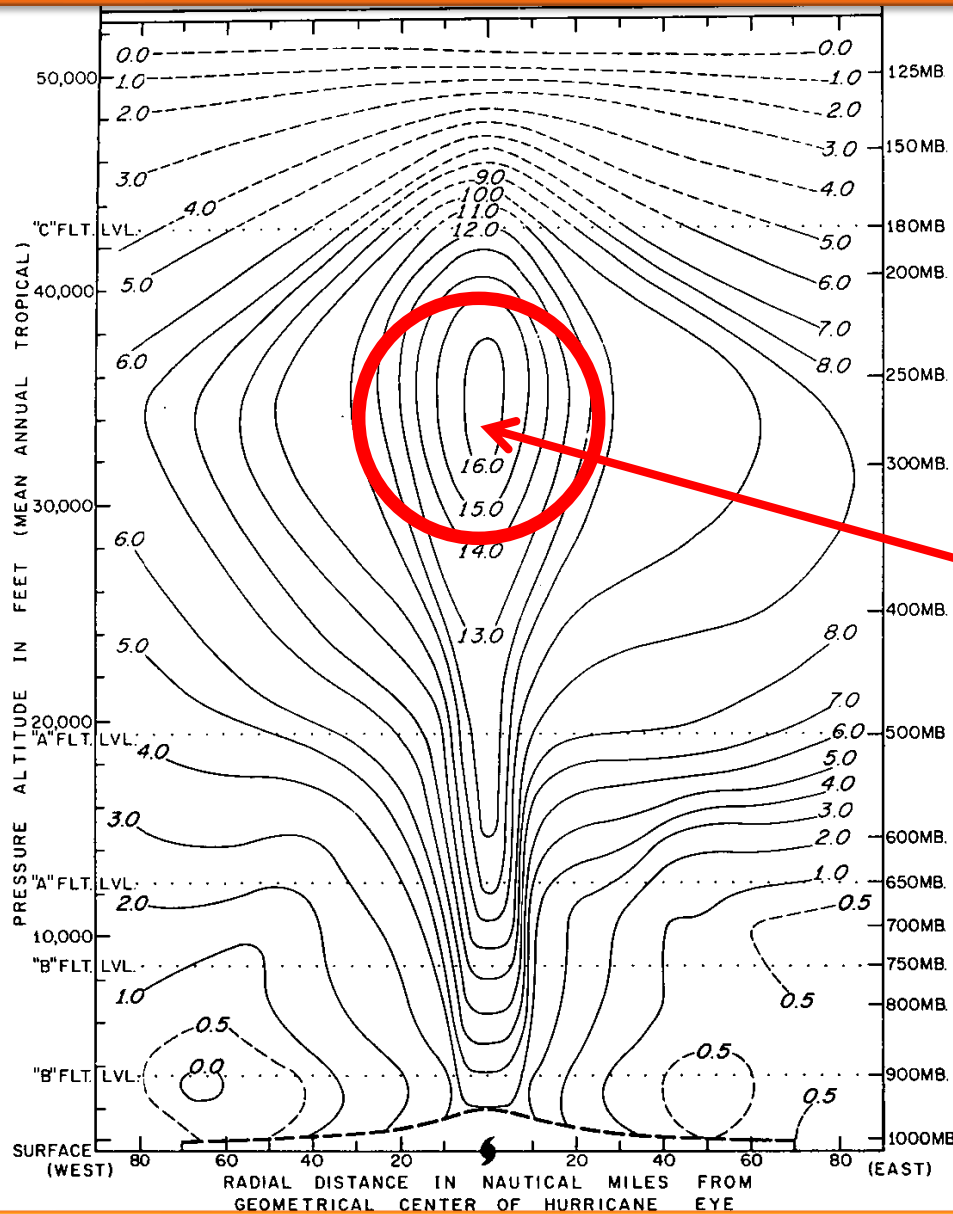
Best Track: 85kt

+11 °C at ~12 km

Perturbation Temperature (°C)

La Seur and  
Hawkins (1963)

# Hurricane Hilda (1964)



+16 °C at ~11 km

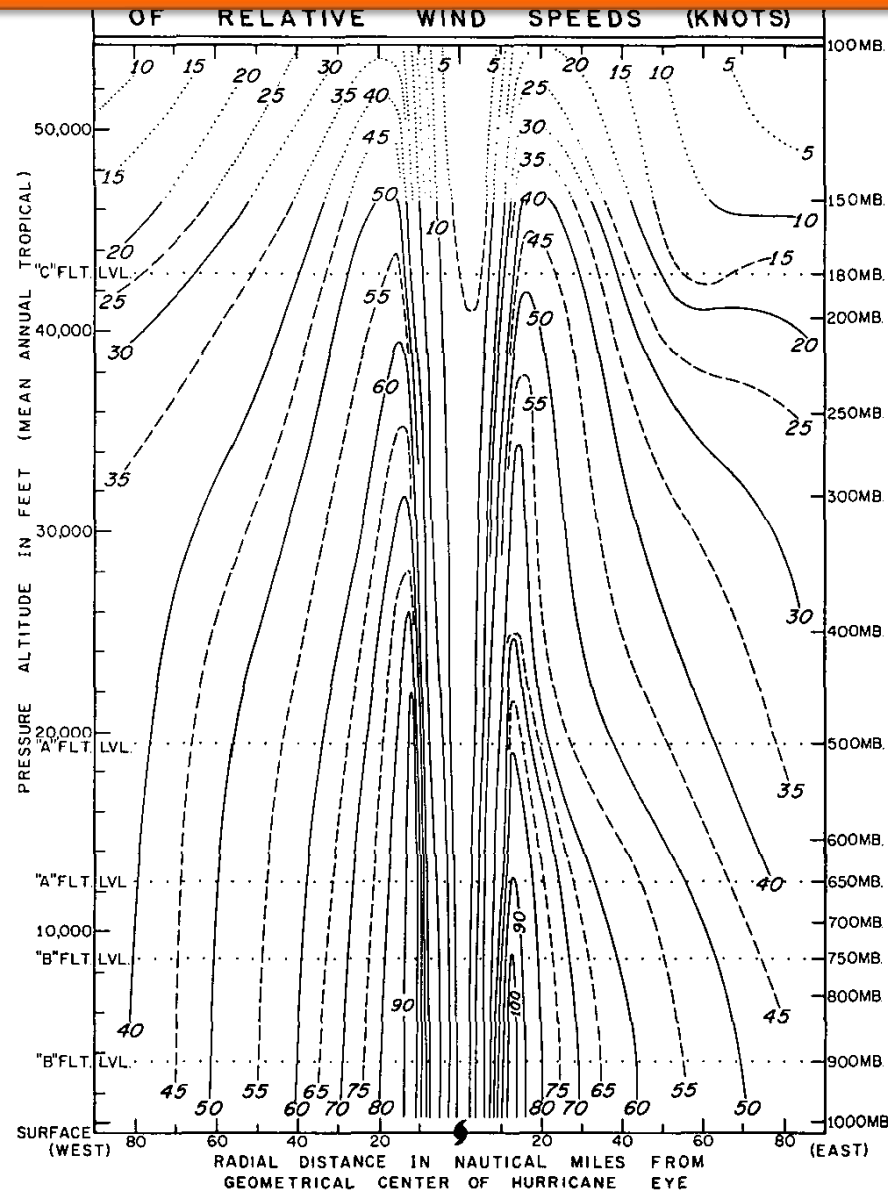
Best Track: 130 kt  
MSLP: 941 mb

Perturbation Temperature (°C)

Hawkins and  
Rubsam 1968



# Hurricane Hilda (1964)

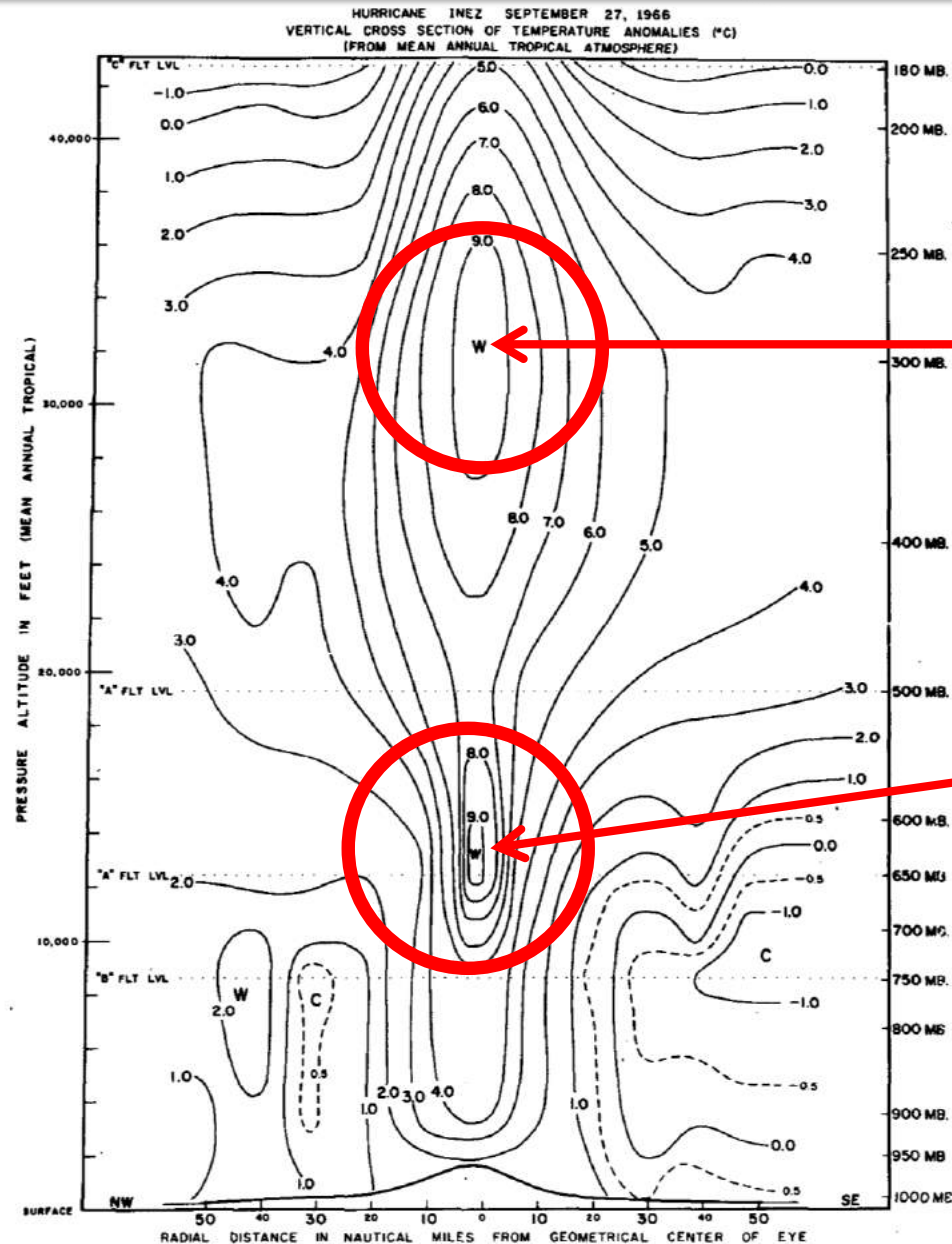


Best Track: 130 kt

Wind Speed (kt)

Hawkins and  
Rubsam 1968

## Hurricane Inez (Sept 27<sup>th</sup>, 1966)



**Best Track: 110 kt**  
**MSLP: 962 mb**

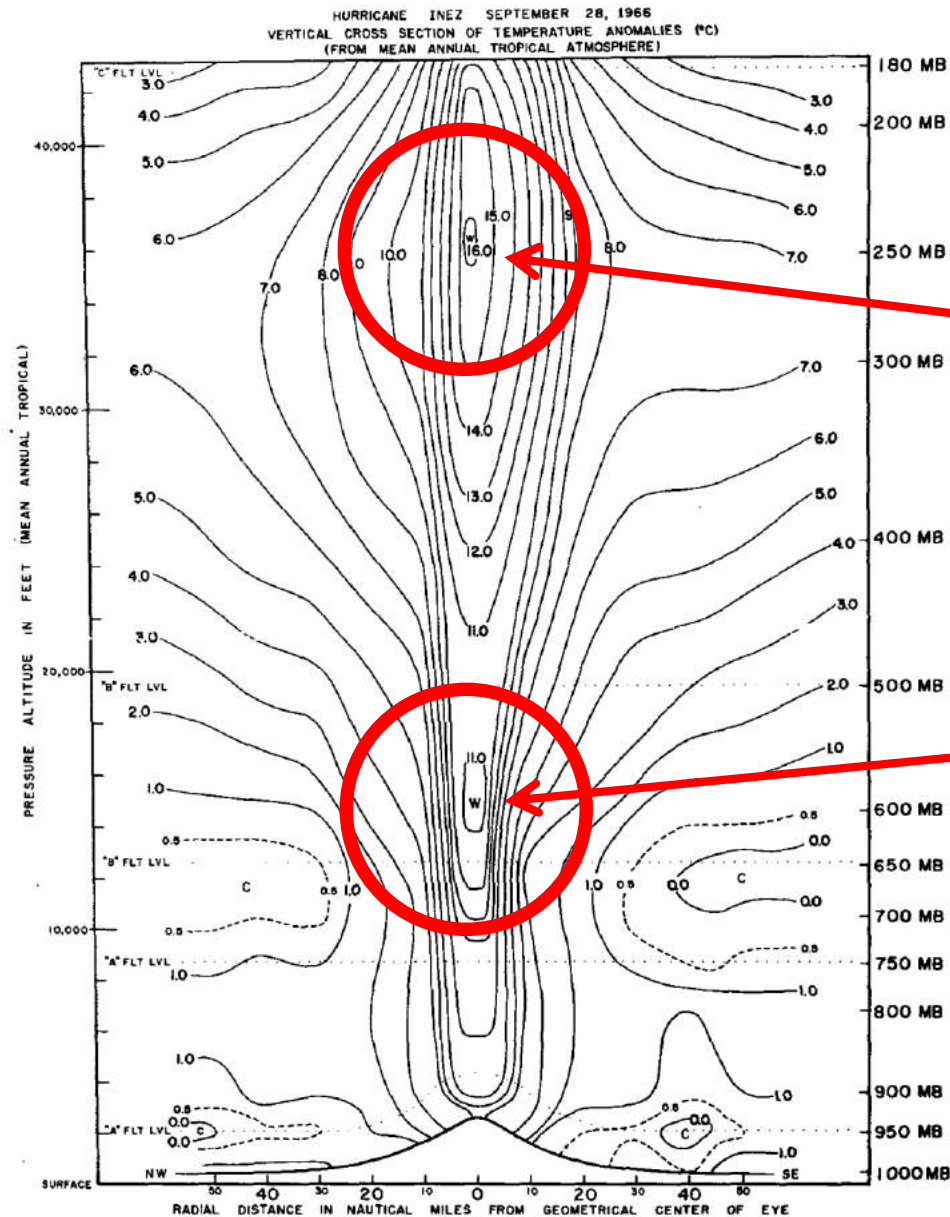
**+9 °C at ~10 km**

**+9 °C at ~4 km**

Hawkins and  
Imbembo 1976

FIG. 6. Centers of anomalous warmth, located near the 600 and 300 mb levels. The isolated lower center is thought to be rather unusual.

# Hurricane Inez (Sept 28<sup>th</sup>, 1966)



Best Track: 130 kt  
MSLP: 932 mb

+16 °C at ~11 km

+9 °C at ~4 km

FIG. 14. Temperatures were near normal below 550 mb, except in the eye.  
Note the separate center of warmth in the eye around 600 mb.

Hawkins and  
Imbembo 1976

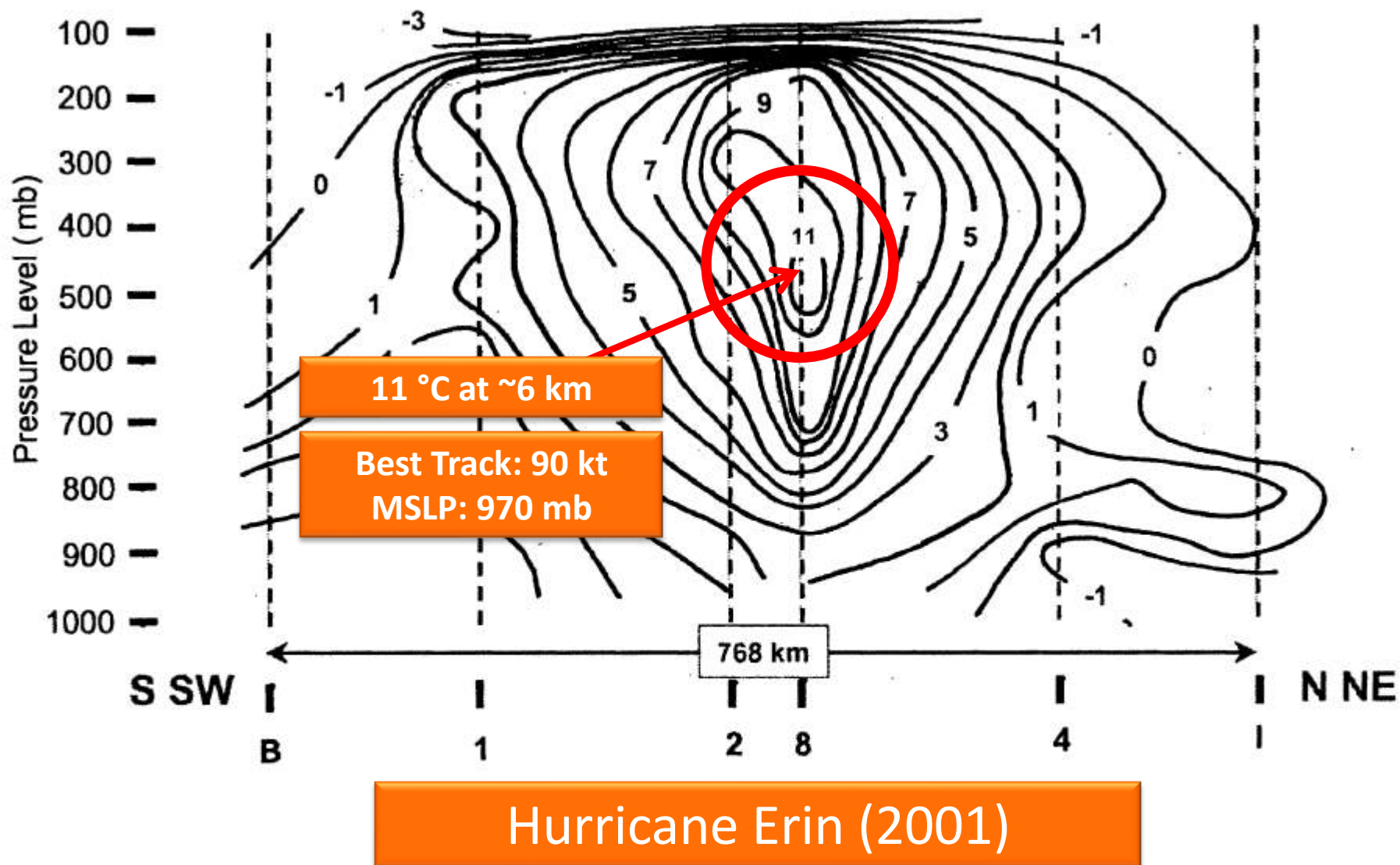


FIG. 6. Cross section through Erin's core showing temperature perturbation. Analysis was made by compositing dropsondes along/nearby the dashed line shown in Fig. 1. The vertical slide is oriented from southwest to northeast. Maximum perturbation temperature of +11°C and distance scale are shown. Initial release times of dropsondes are 1629, 1648, 1704, 1750, 1928, and 1936 UTC for B, 1, 2, 4, 8, and I, respectively.

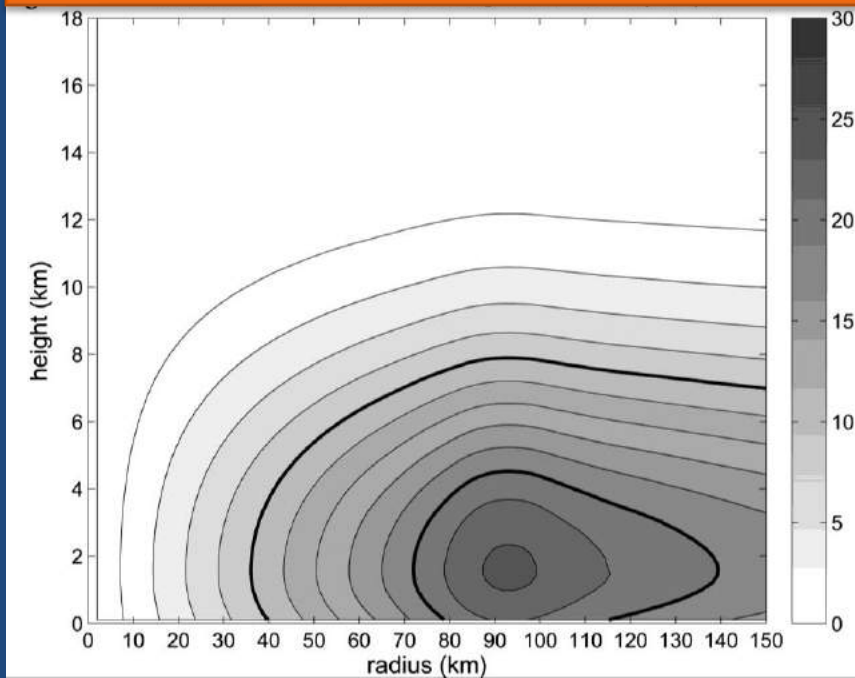
# Idealized Hurricane Simulations

- Weather Research and Forecasting (WRF) Model
- 3 nested grids: 18/6/2 km
- Doubly periodic boundary conditions
- 40 vertical levels
- $f$ -plane (i.e., constant Coriolis, 20 °N)
- YSU Planetary Boundary Layer (PBL) parameterization
- SST = 28C, “moist-tropical” sounding (Dunion 2011)
- Initialized with weak tropical cyclone-like vortex

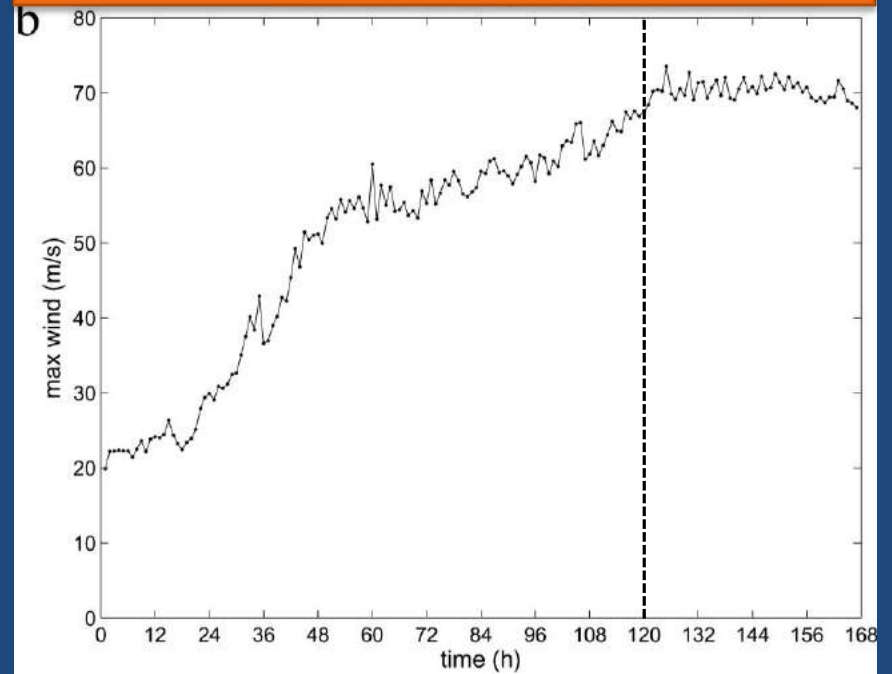


# Control Simulation

## Initial Az. Mean Tangential Wind

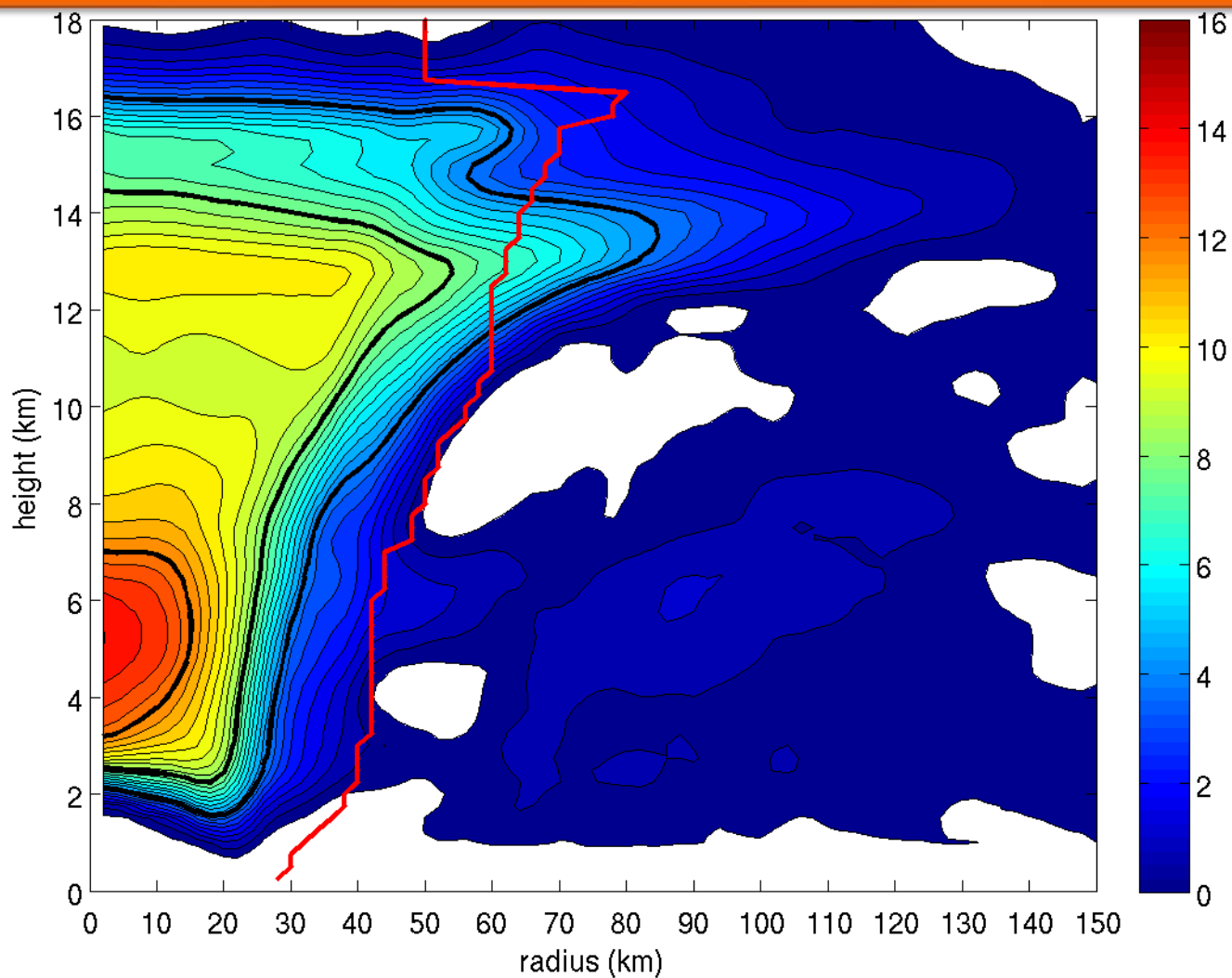


## Max Wind Speed at 10-m Height





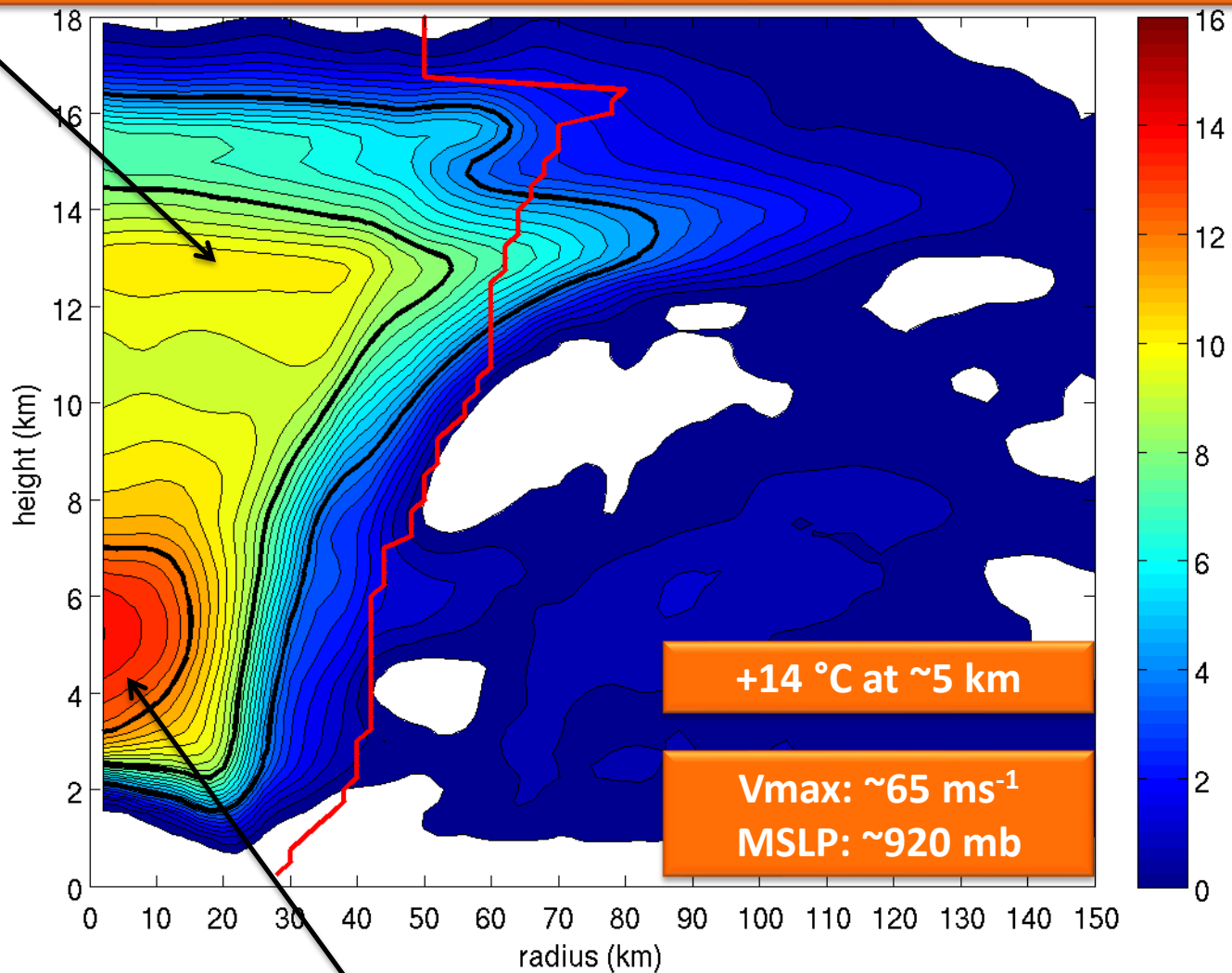
## Perturbation Temperature ( $^{\circ}\text{C}$ ) at $t=120$ h



— RMW

Secondary Maximum

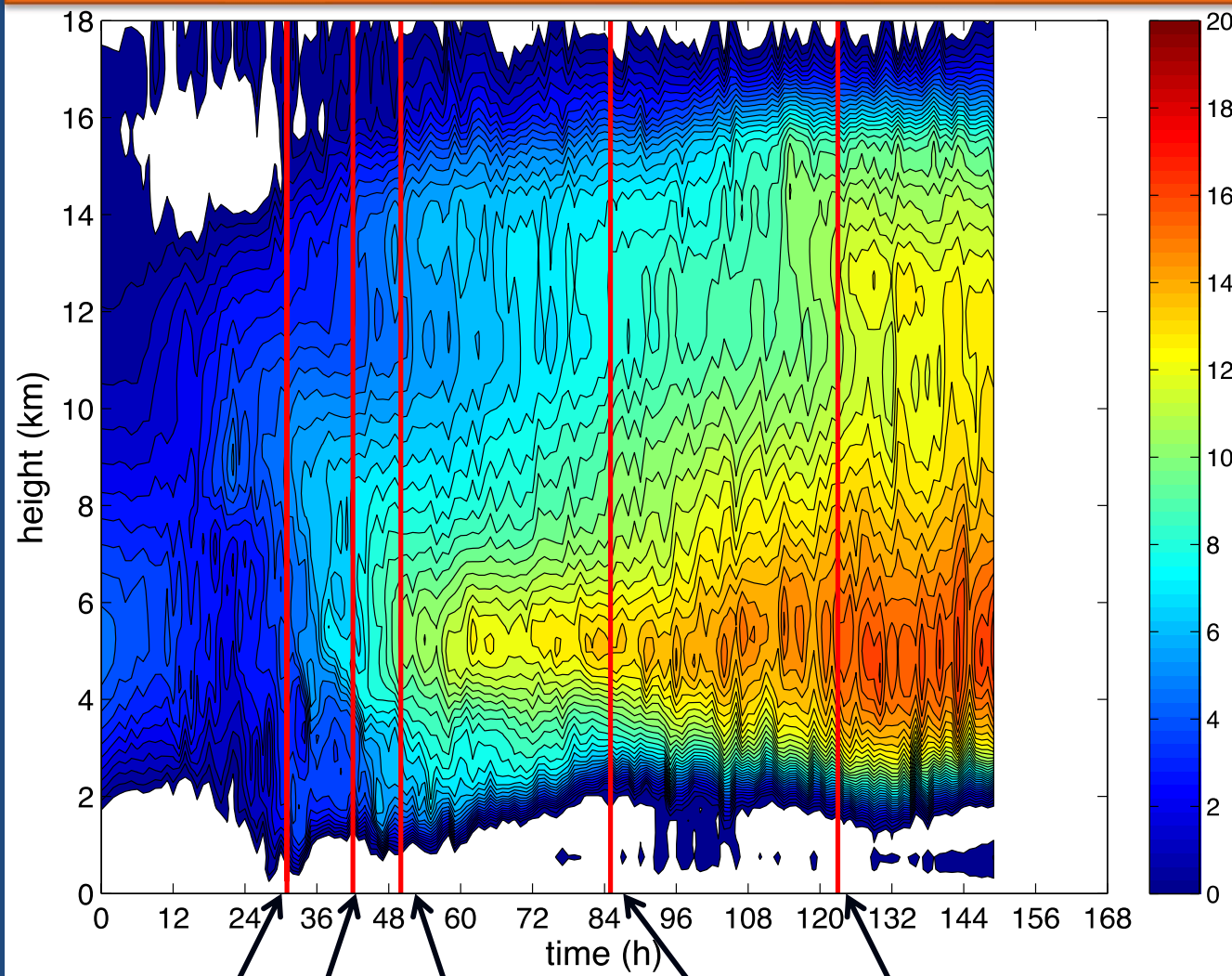
## Perturbation Temperature ( $^{\circ}\text{C}$ ) at $t=120$ h



— RMW

Mid-level Maximum

# Perturbation Temperature at Center of Eye



Height

Time

Cat 1

Cat 2

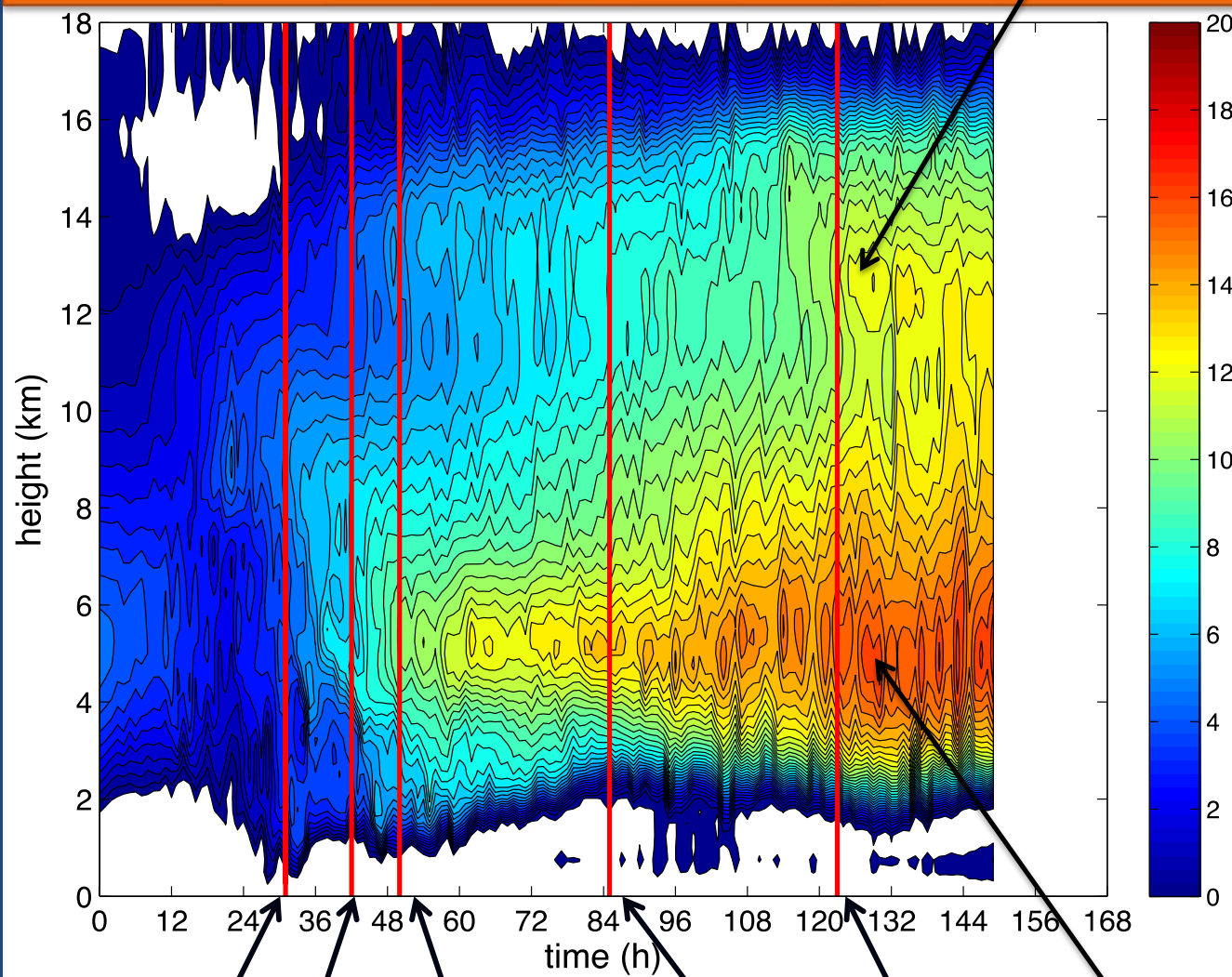
Cat 3

Cat 4

Cat 5

Secondary Maximum

## Perturbation Temperature at Center of Eye



Height

Time

Cat 1

Cat 2

Cat 3

Cat 4

Cat 5

Mid-level Maximum

Why is the warm core maximized at mid-levels in simulations?

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- To answer this, we examine a potential temperature budget.



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# Why is the warm core maximized at mid-levels in simulations?

- To answer this, we examine a potential temperature budget.
- Where is the largest warming found?
- What terms are important/dominant in warming the eye?
- Does the answer to the above questions depend on the intensity of the storm?

# Potential Temperature ( $\theta$ ) Budget

$$\Delta\theta = TADV + HEAT + PBL + HDIF$$

*TADV* : Total Advection (Horizontal + Vertical)

*HEAT* : Diabatic Heating (e.g., heating from condensation/freezing, evaporative cooling, etc)

*PBL*: Tendency from Planetary Boundary Layer parameterization

*HDIF*: Tendency from Horizontal Diffusion + Rayleigh Damping

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We can further decompose *TADV* into:

Mean Vertical Advection:

$$-\bar{w} \frac{\partial \bar{q}}{\partial z}$$

Eddy Radial Advection:

$$-\frac{\overline{u'q'}}{r} - \frac{\overline{u'q'}}{r}$$

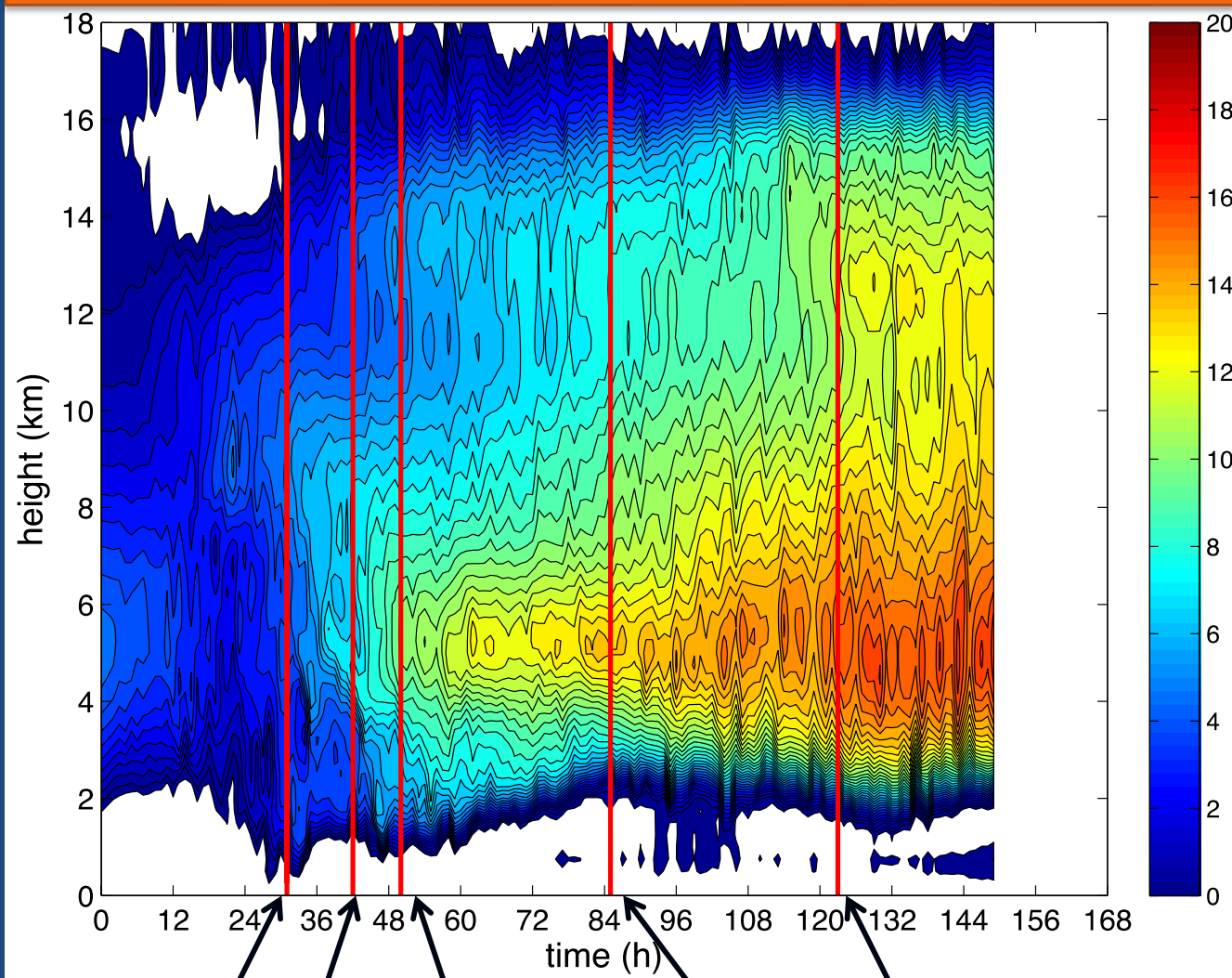
Mean Radial Advection:

$$-\bar{u} \frac{\partial \bar{q}}{\partial r}$$

Eddy Vertical Advection:

$$-\frac{\overline{w'q'}}{\partial z}$$

# Perturbation Temperature at Center of Eye



Height

Time

Cat 1

Cat 2

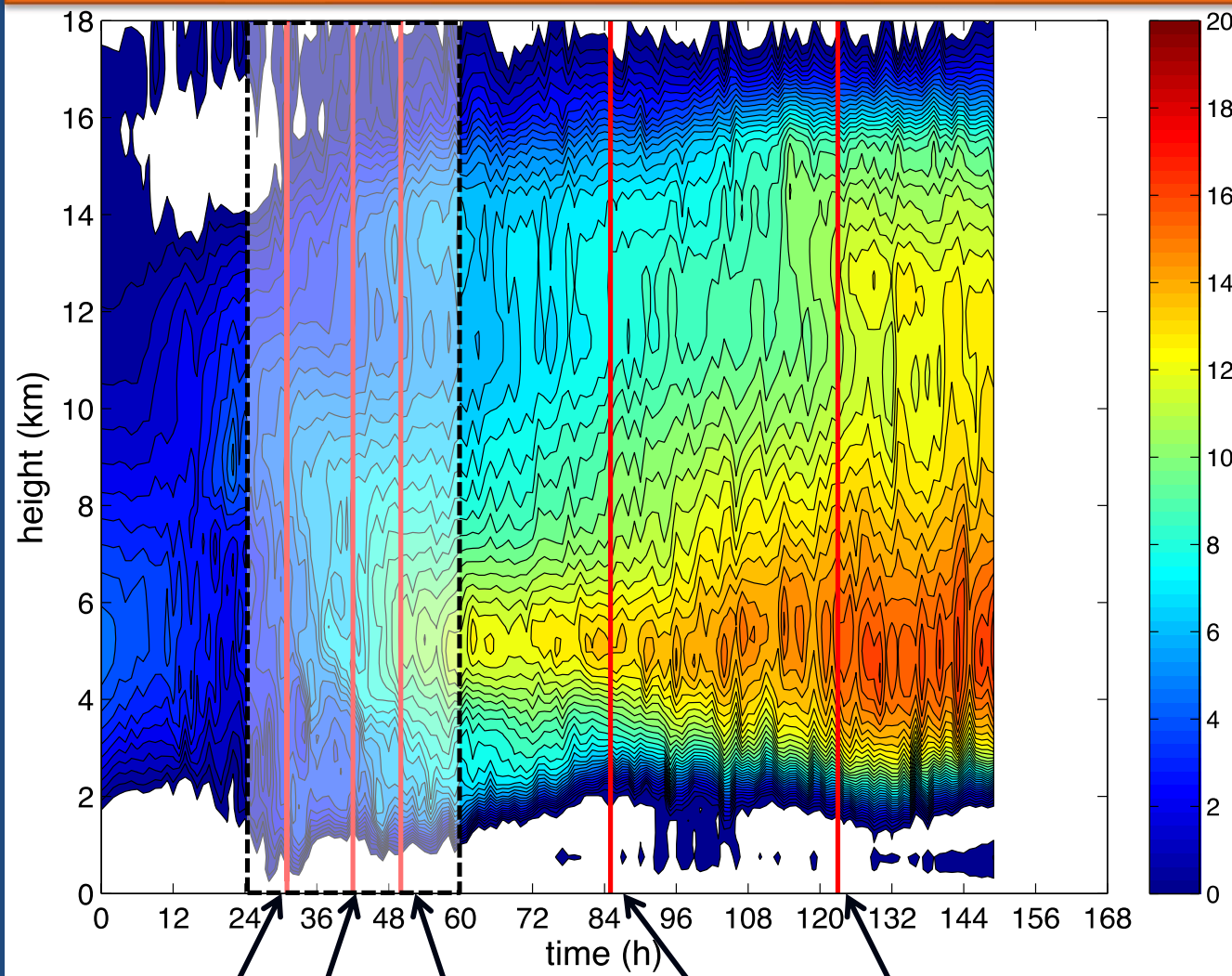
Cat 3

Cat 4

Cat 5



# Perturbation Temperature at Center of Eye



Height

Time

Cat 1

Cat 2

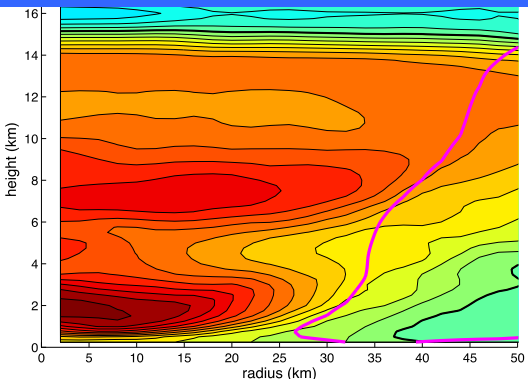
Cat 3

Cat 4

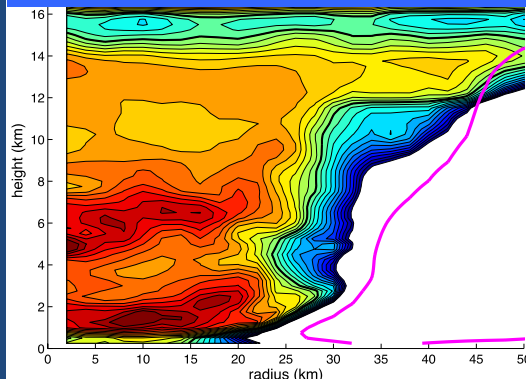
Cat 5

# Potential Temperature Budget, $t = 24-36$ h

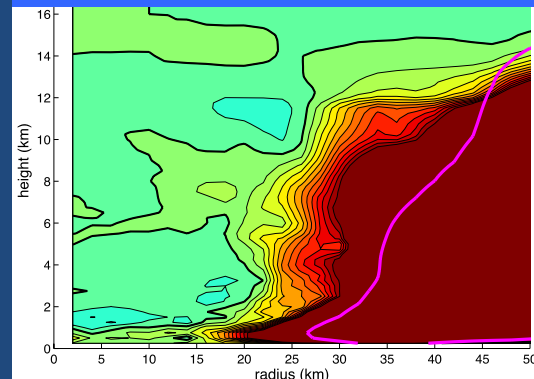
## 12h Change in Pot. Temp.



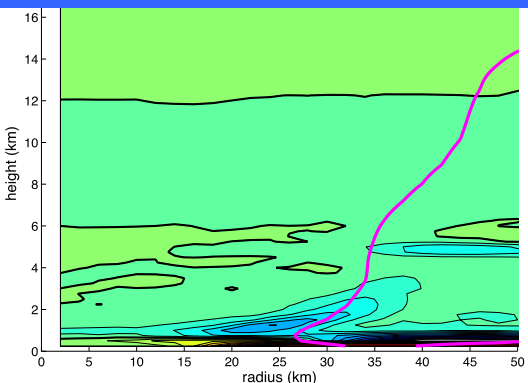
## Total Advection (K/12h)



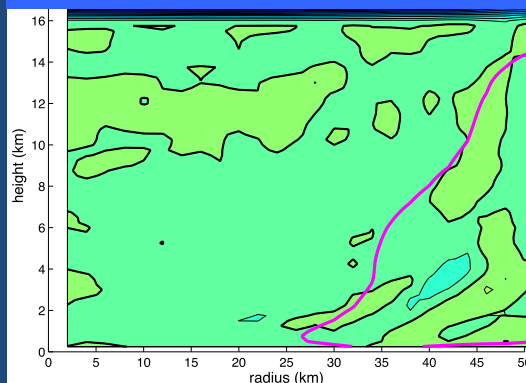
## Diabatic Heating



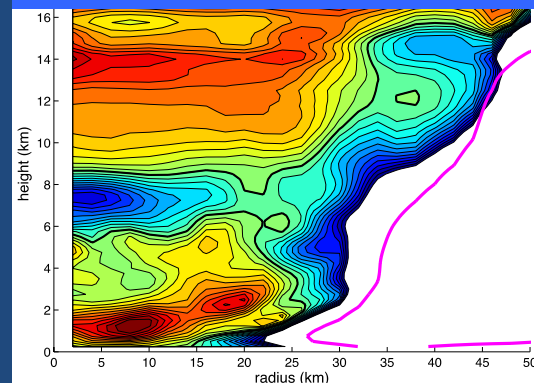
## PBL Tendency



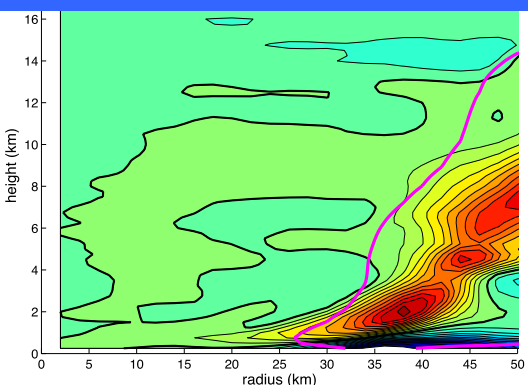
## Horizontal Diffusion



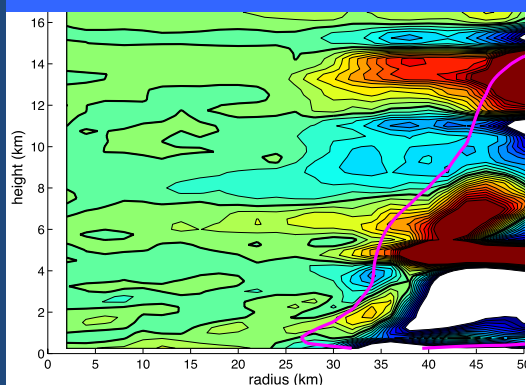
## Mean Vert. Adv.



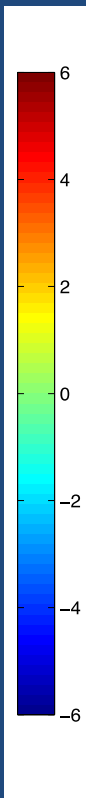
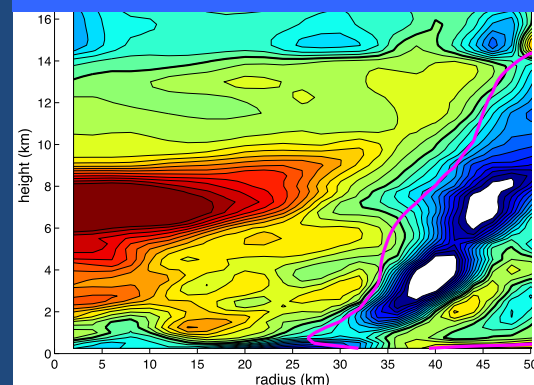
## Mean Radial Adv.



## Eddy Vert. Adv.

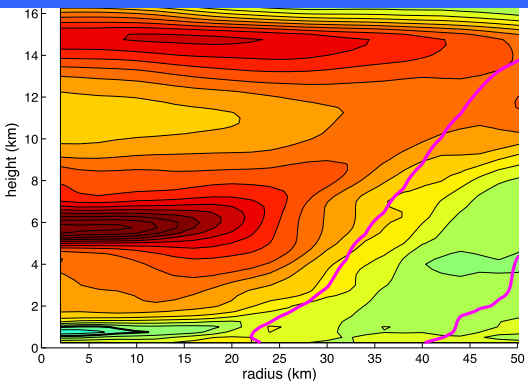


## Eddy Radial Adv.

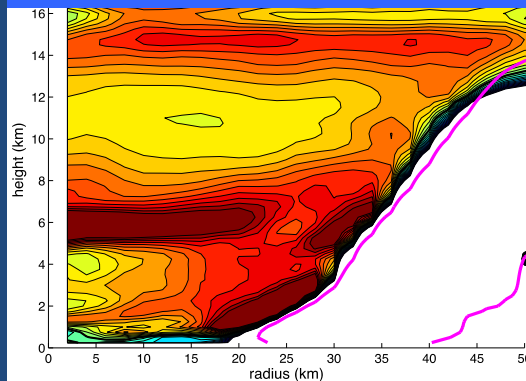


# Potential Temperature Budget, $t = 36-48$ h

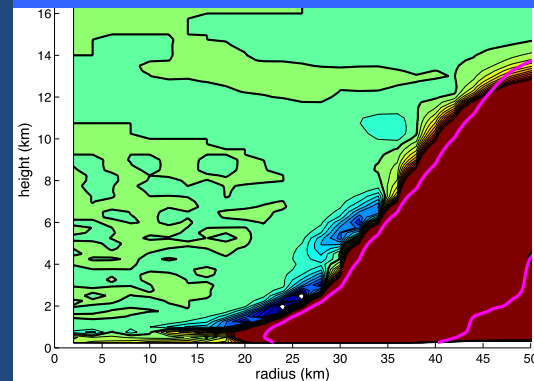
## 12h Change in Pot. Temp.



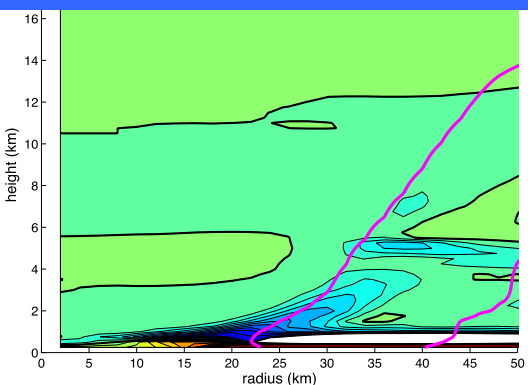
## Total Advection (K/12h)



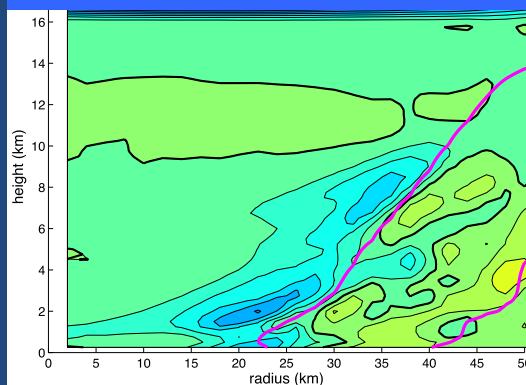
## Diabatic Heating



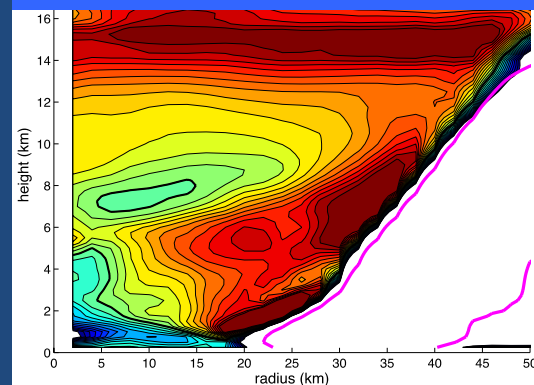
## PBL Tendency



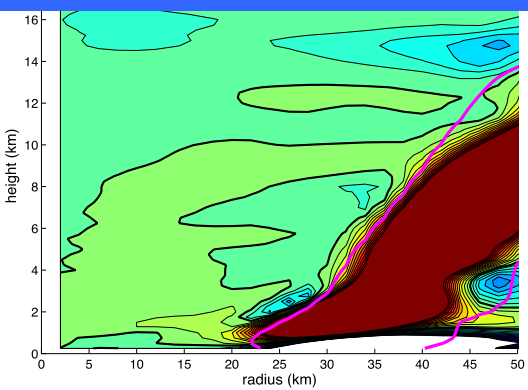
## Horizontal Diffusion



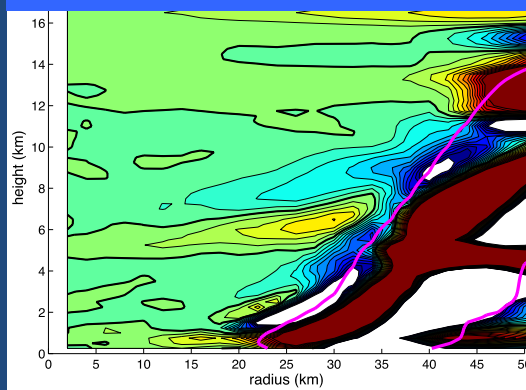
## Mean Vert. Adv.



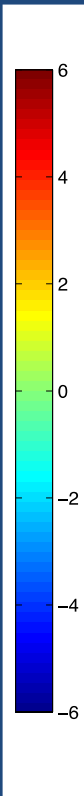
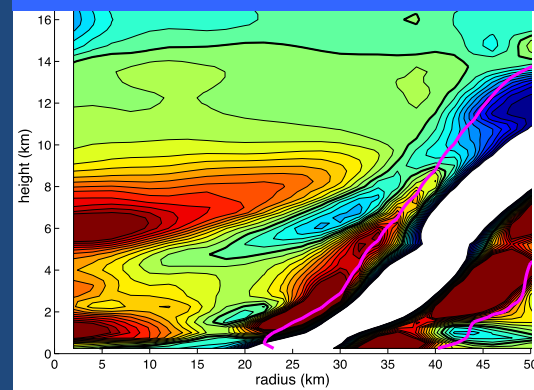
## Mean Radial Adv.



## Eddy Vert Adv.

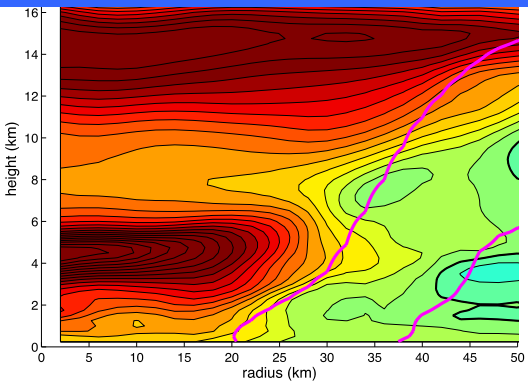


## Eddy Radial Adv.

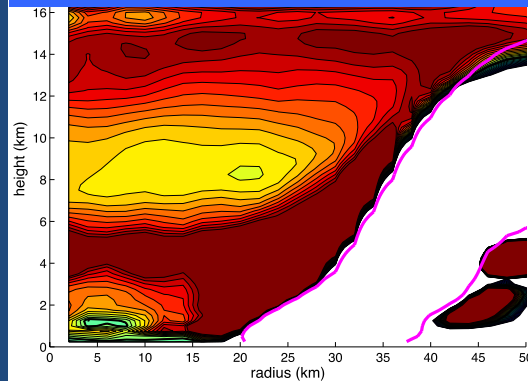


# Potential Temperature Budget, $t = 48-60$ h

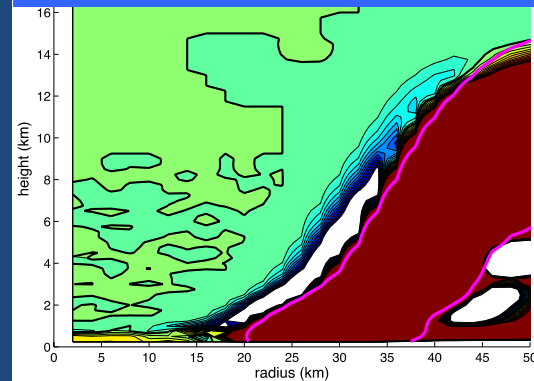
## 12h Change in Pot. Temp.



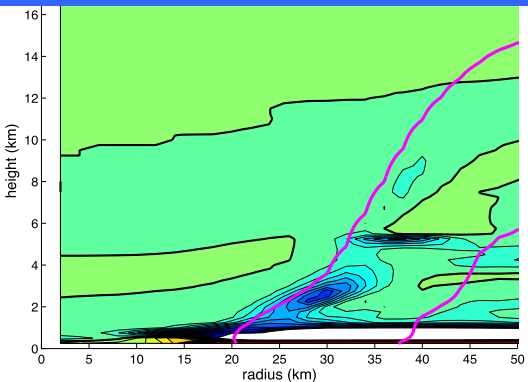
## Total Advection (K/12h)



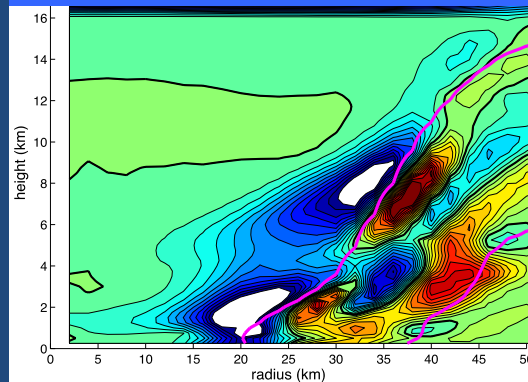
## Diabatic Heating



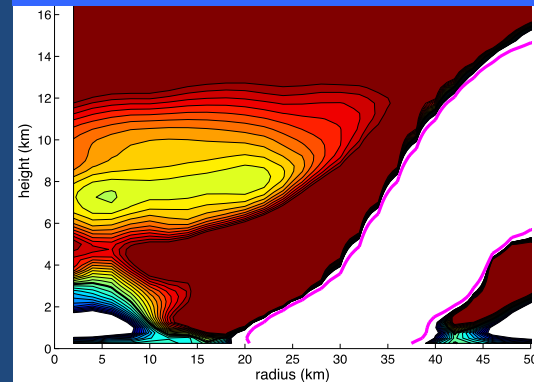
## PBL Tendency



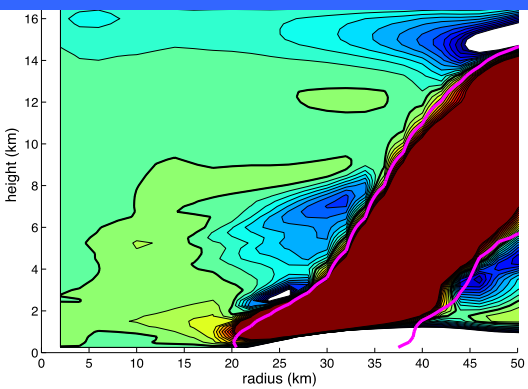
## Horizontal Diffusion



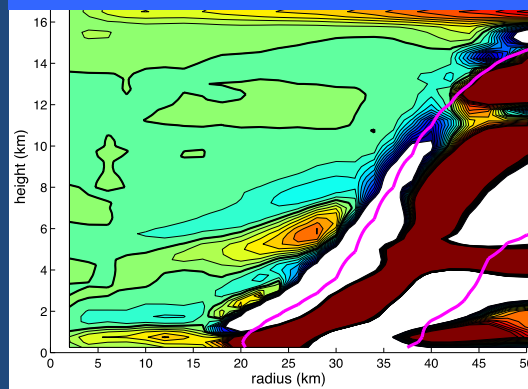
## Mean Vert. Adv.



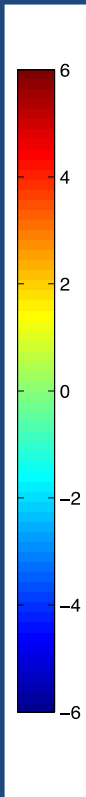
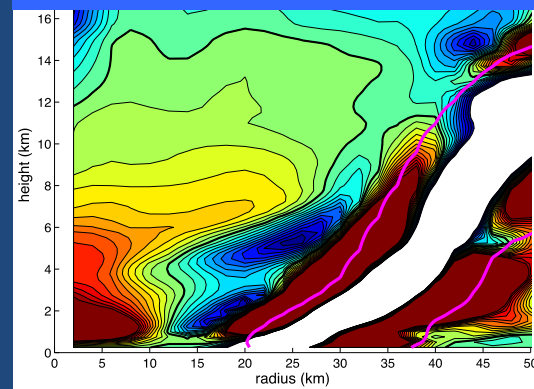
## Mean Radial Adv.



## Eddy Vert Adv.



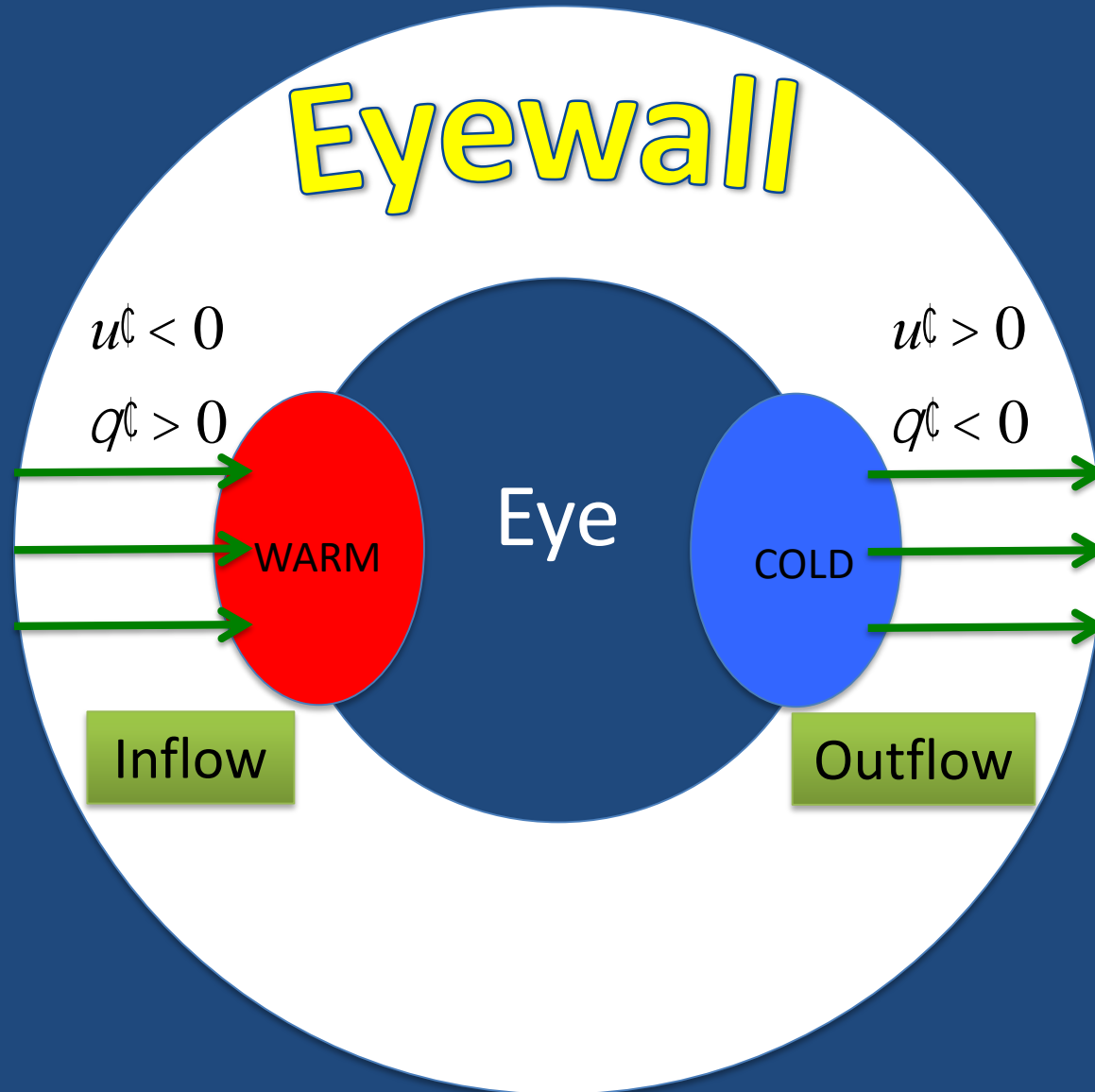
## Eddy Radial Adv.



# Why is the warm core maximized at mid-levels in simulations?

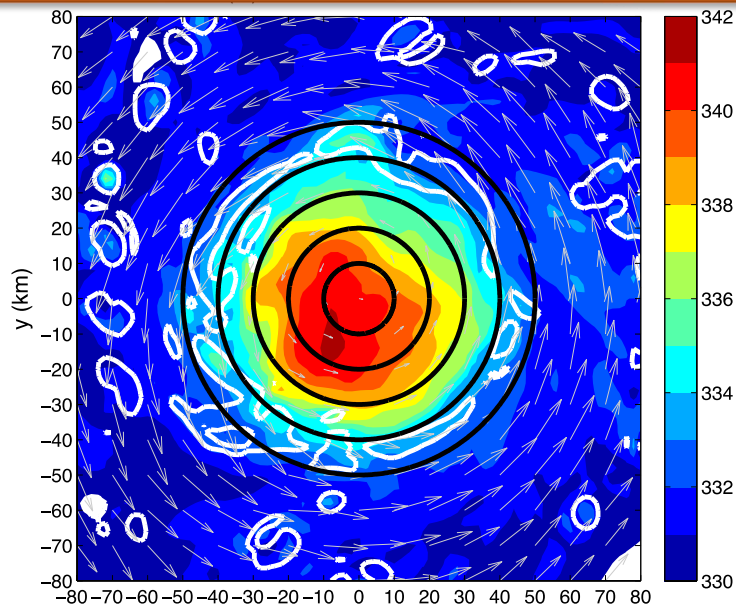
- During the period of RI, there is persistent warming at 5-7 km height.
- Both mean subsidence and eddy radial advection contribute to this warming.
- Strong subsidence at edge of eyewall is cancelled by evaporative cooling and horizontal diffusion.

# What is Eddy Radial Advection?

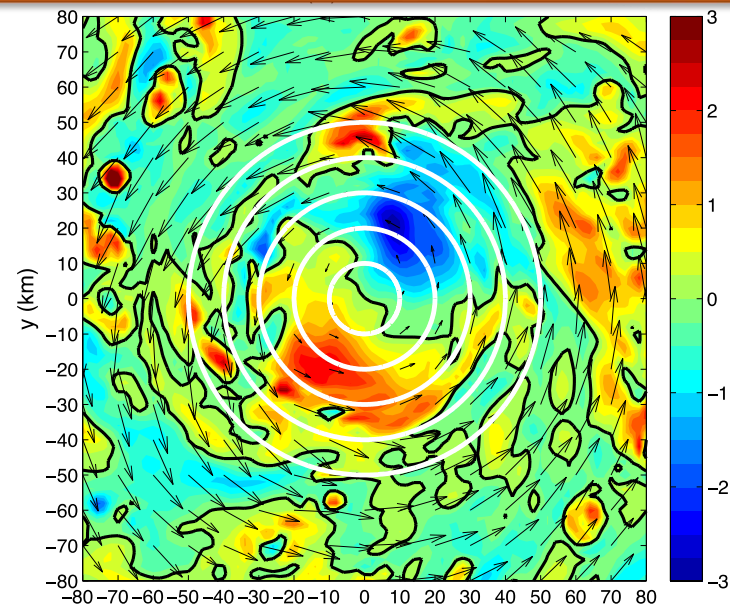




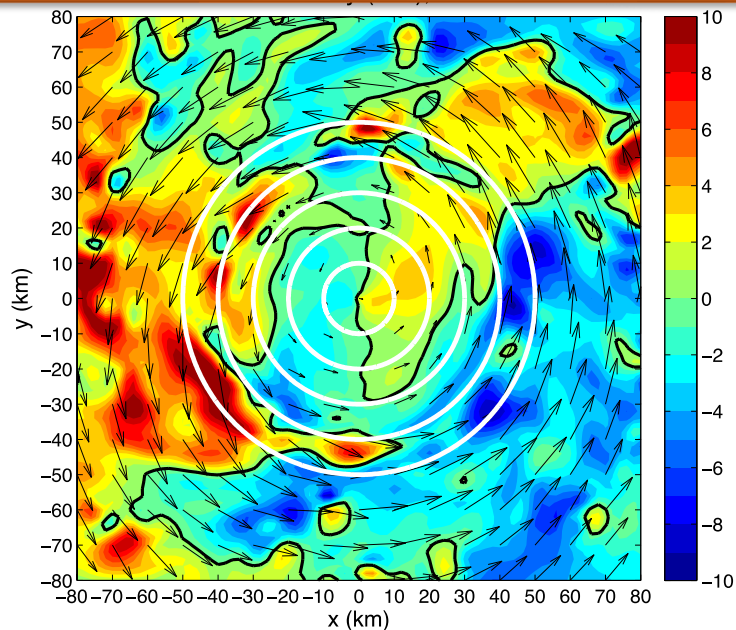
# Potential Temperature ( $\theta$ ) at $z=6$ km



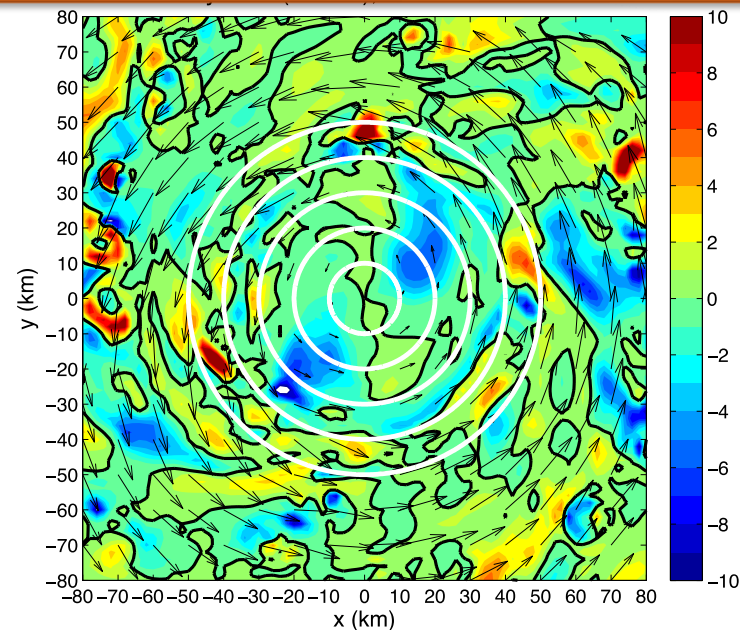
# Asymmetric $\theta$ at $z=6$ km



# Asymmetric Radial Velocity at $z=6$ km



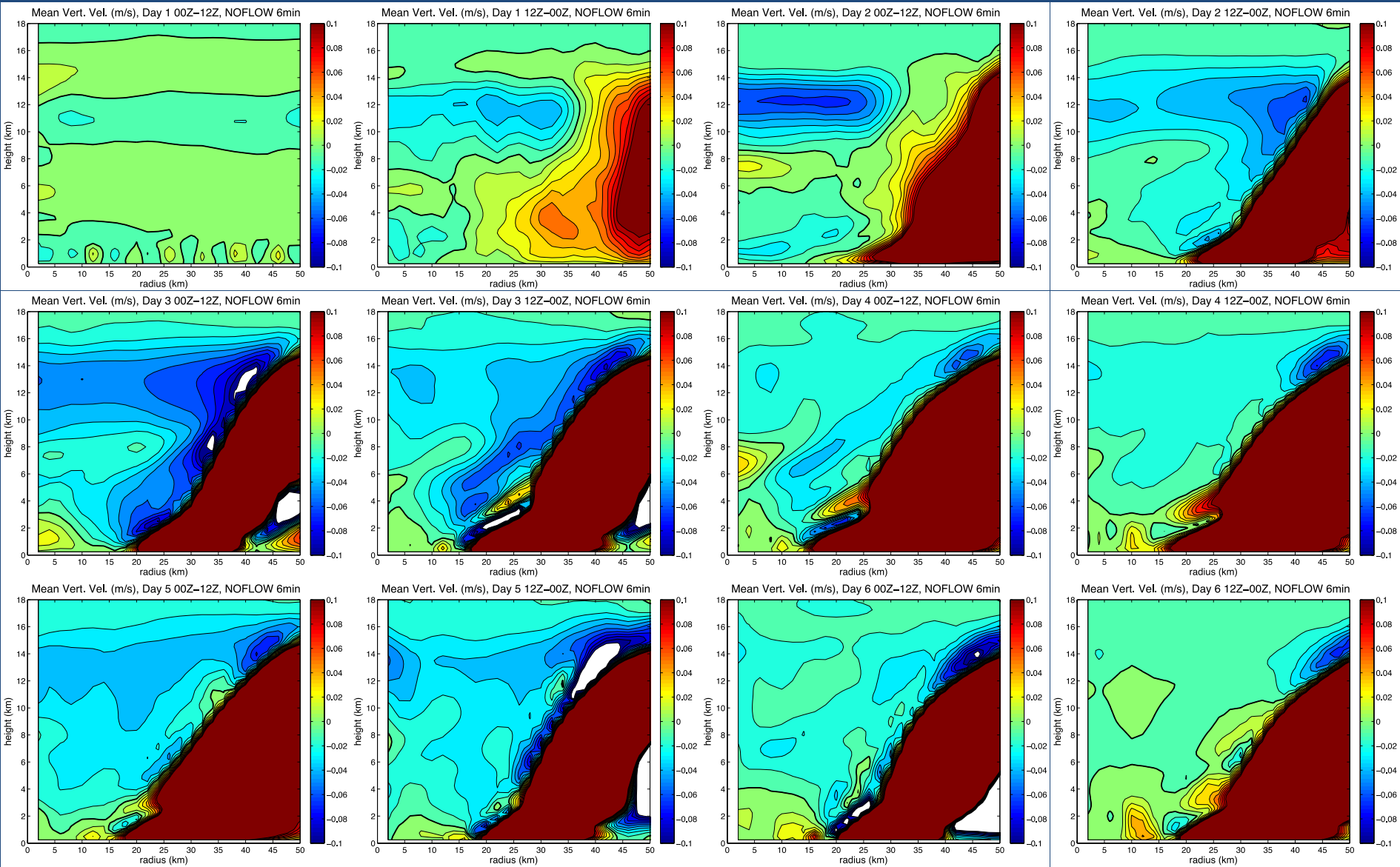
# Radial Eddy Flux of $\theta$ at $z=6$ km



# Why are there two warm core maxima?

- There are two distinct maxima in the distribution of warming from subsidence.
- To understand why, we examine the evolution of mean vertical velocity and static stability within the eye.

# 12-h Mean Vertical Velocity

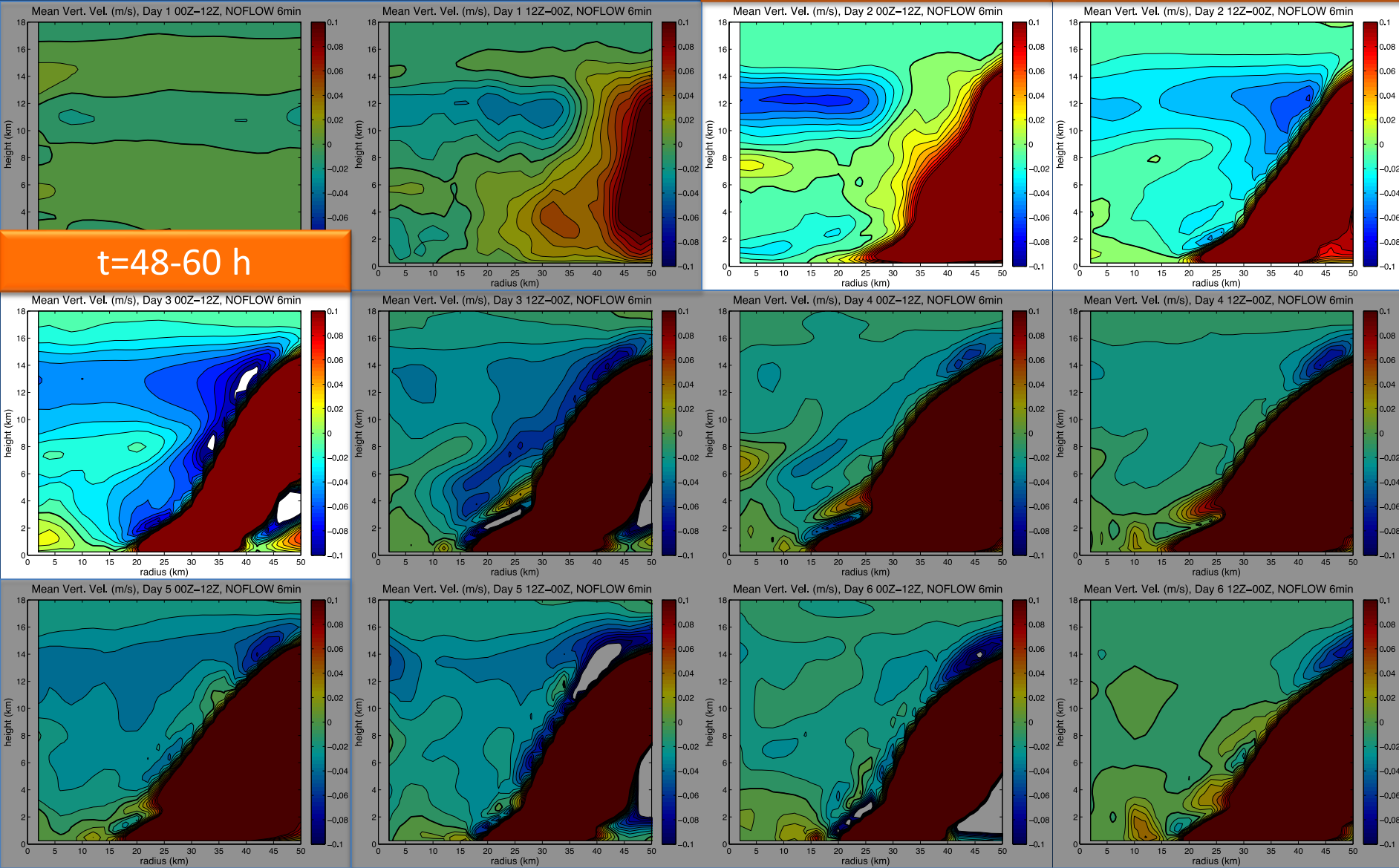


# 12-h Mean Vertical Velocity

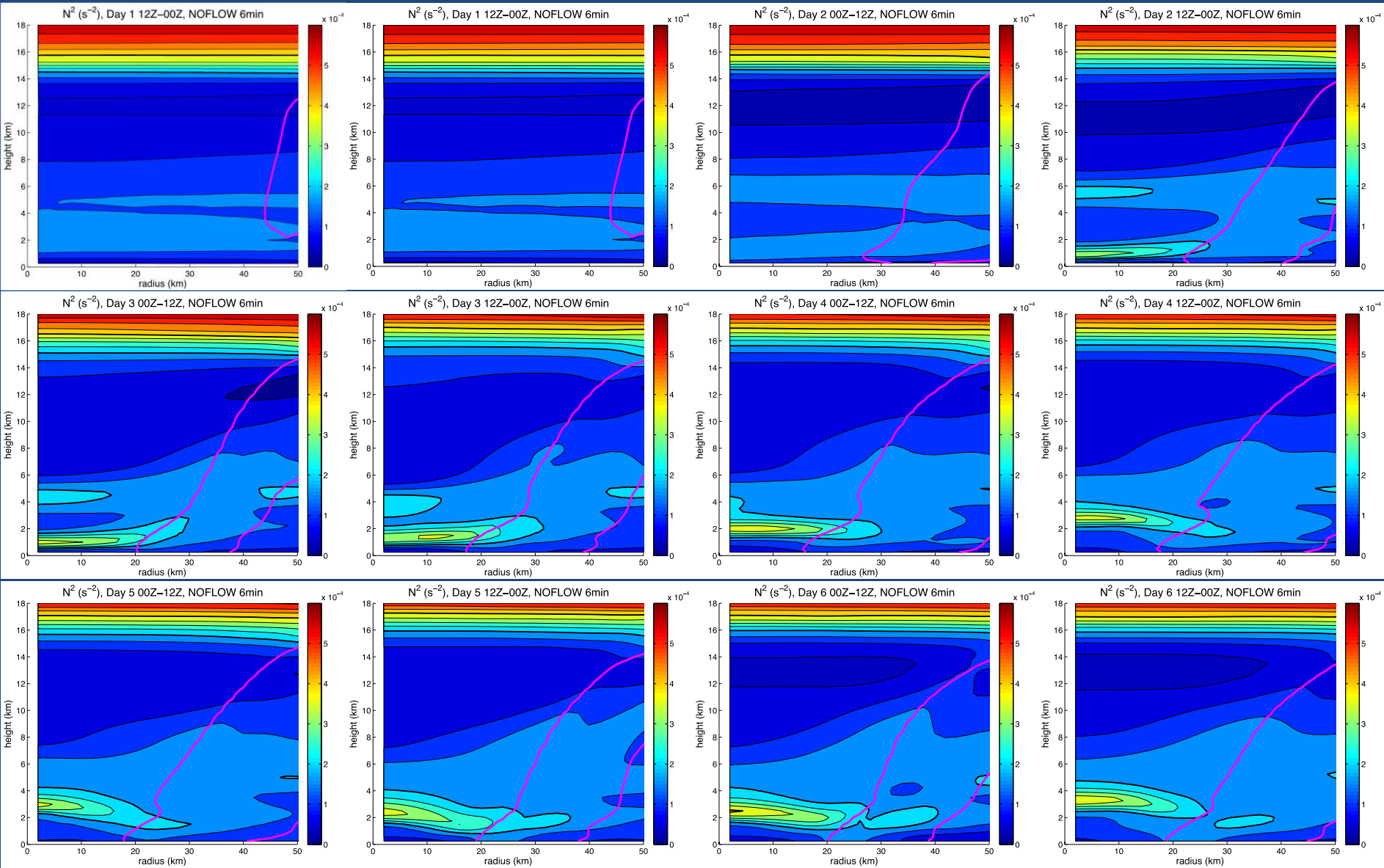
t=24-36 h

t=36-48 h

t=48-60 h



# 12-h Mean Static Stability



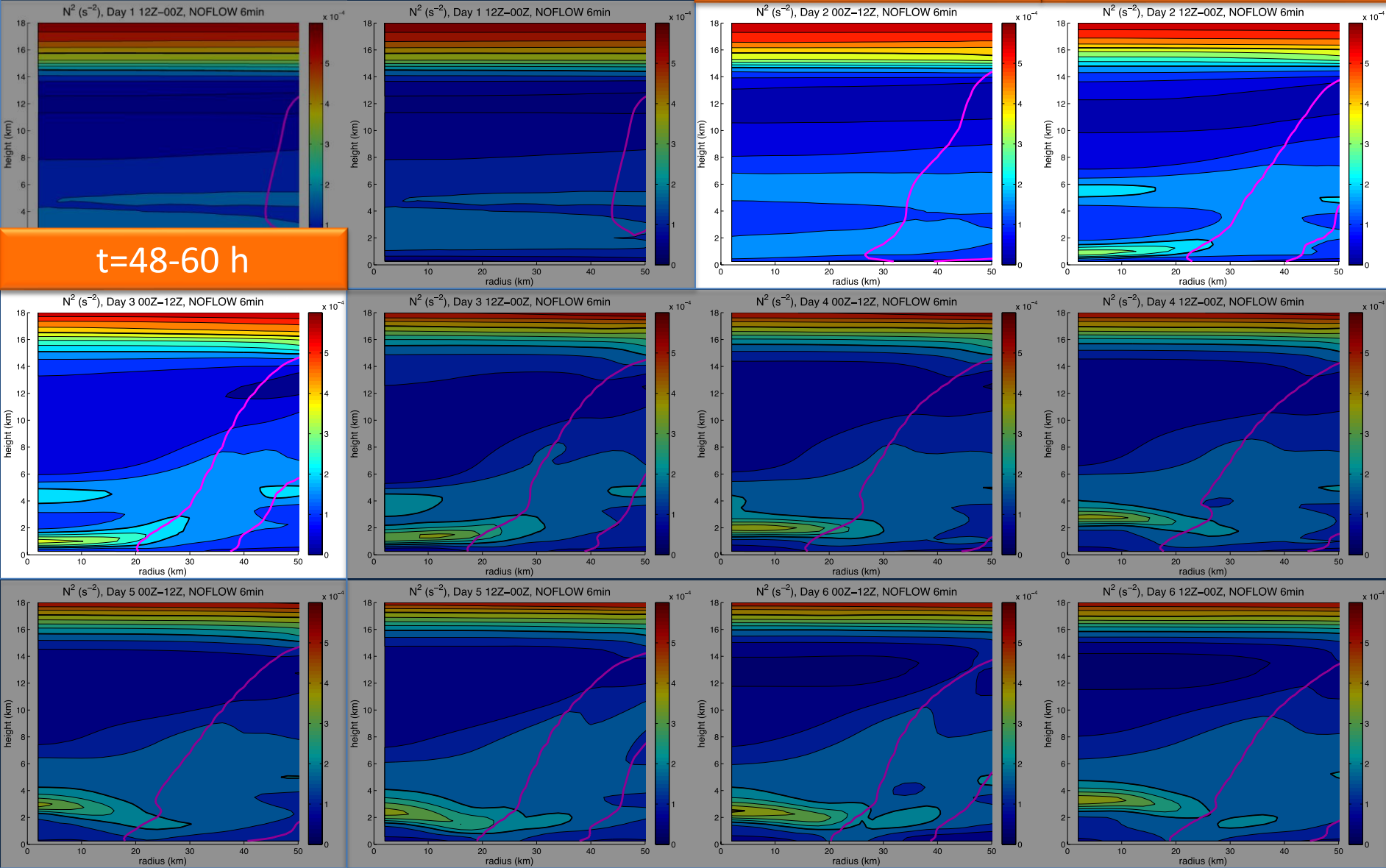


# 12-h Mean Static Stability

t=24-36 h

t=36-48 h

t=48-60 h

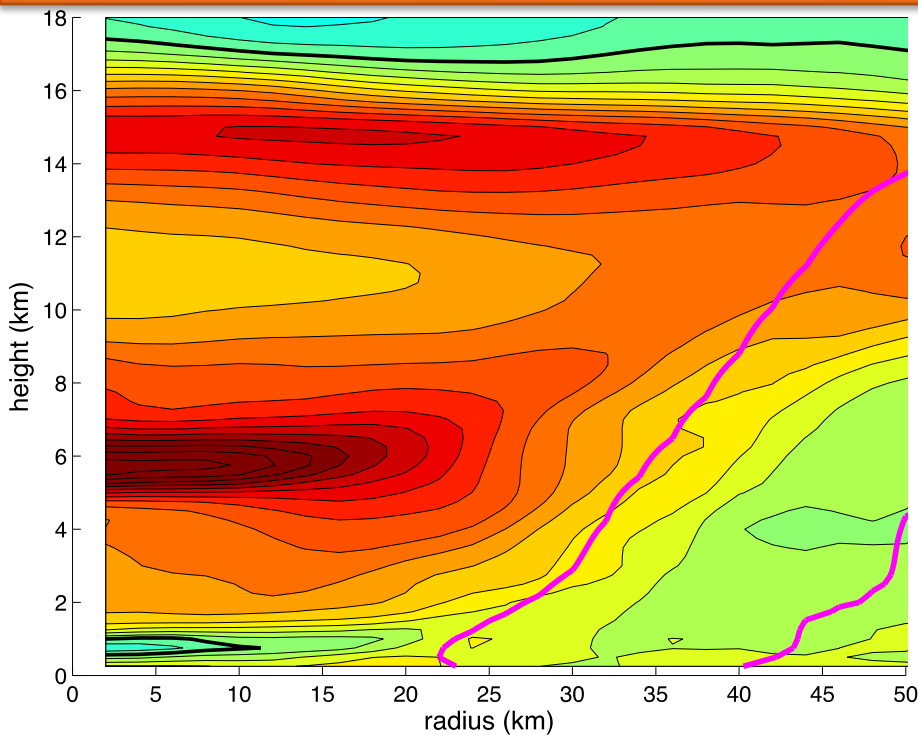


# Why are there two warm core maxima?

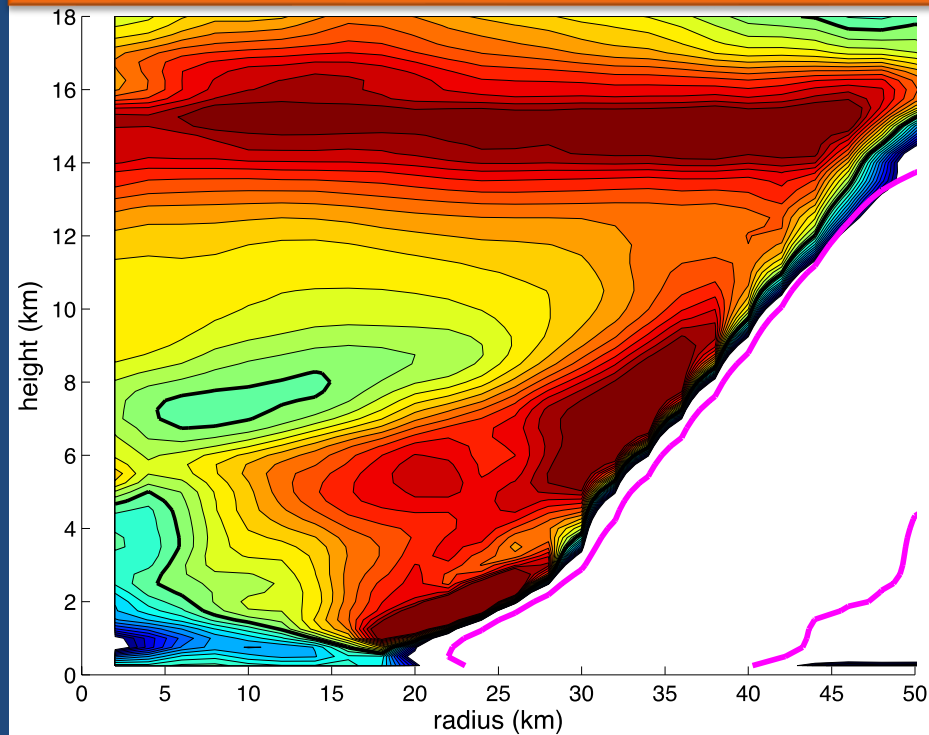
Mean Vertical Advection:

$$-\bar{w} \frac{\partial \bar{\theta}}{\partial z}$$

12h Change in Potential Temperature



12-h Mean Vertical Advection

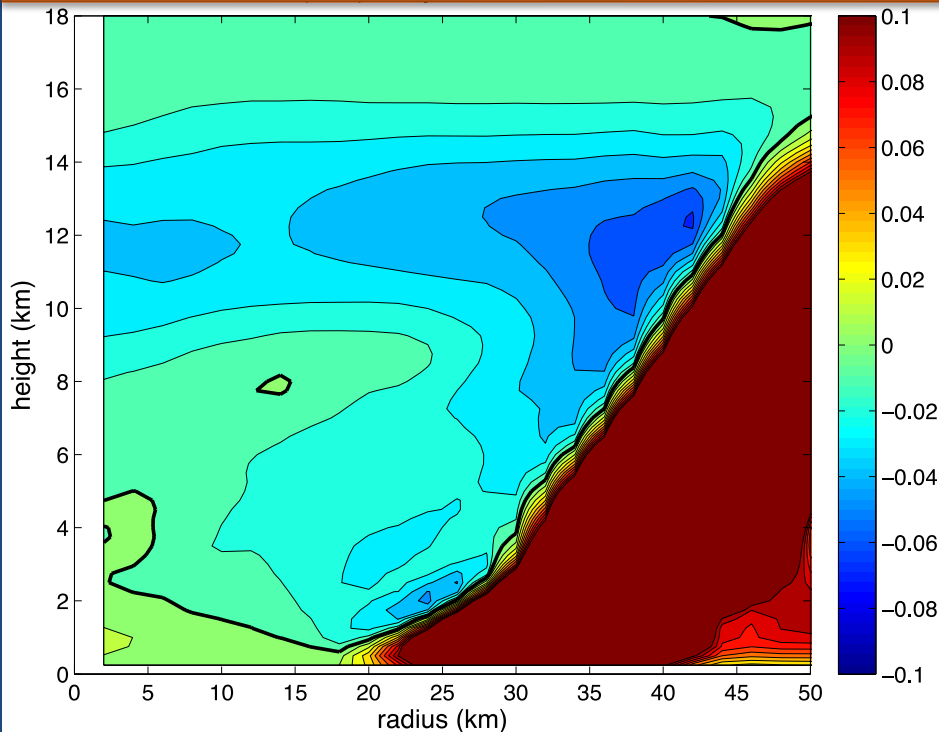




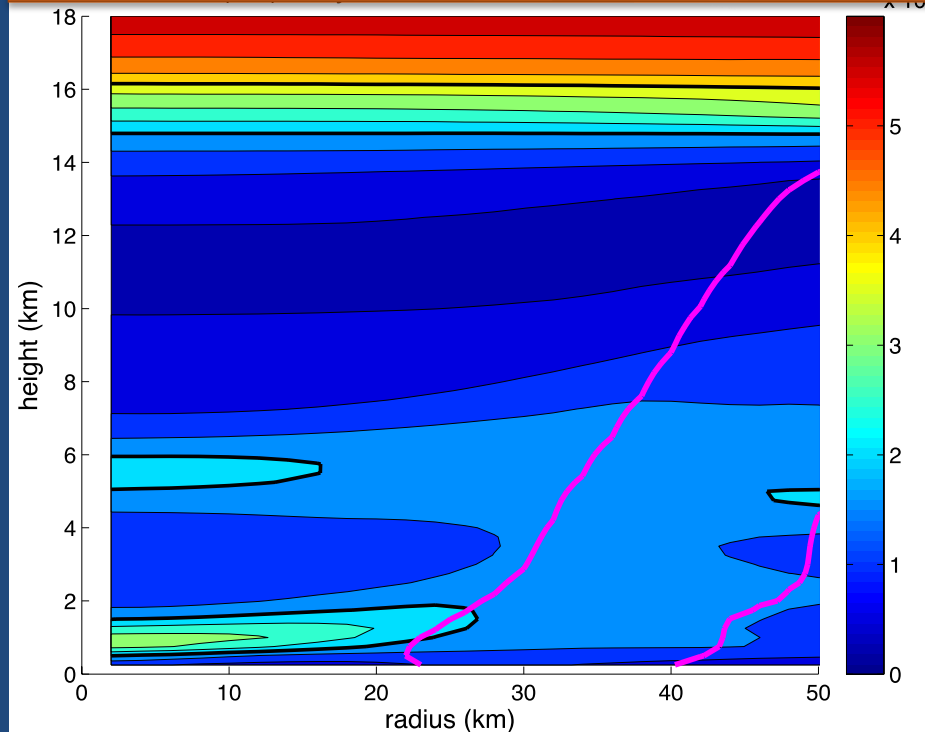
# The structure of mean descent and static stability determines the level of peak warming.

Static Stability: 
$$N^2 = \frac{g}{\bar{\theta}} \frac{\partial \bar{\theta}}{\partial z}$$

## 12-h Mean Vertical Velocity $\text{ms}^{-1}$



## 12-h Mean $N^2$ ( $\text{s}^{-2}$ )



Less warming is accomplished at the level of peak subsidence, because stability is weak.

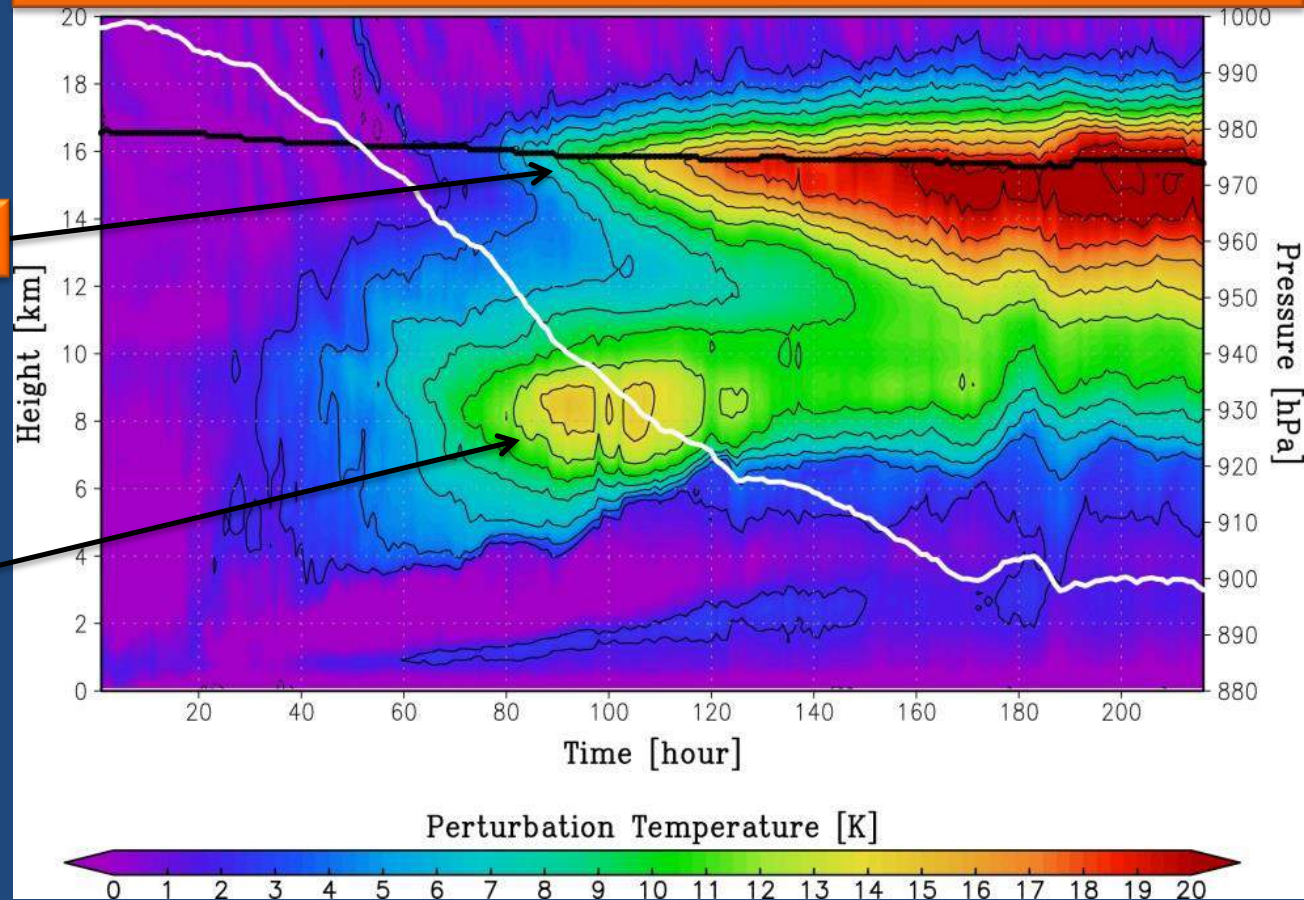
Warming is greatest near mid-level stability maximum and in tropical tropopause layer.

# Other Simulation Studies

## Perturbation Temperature at TC Center

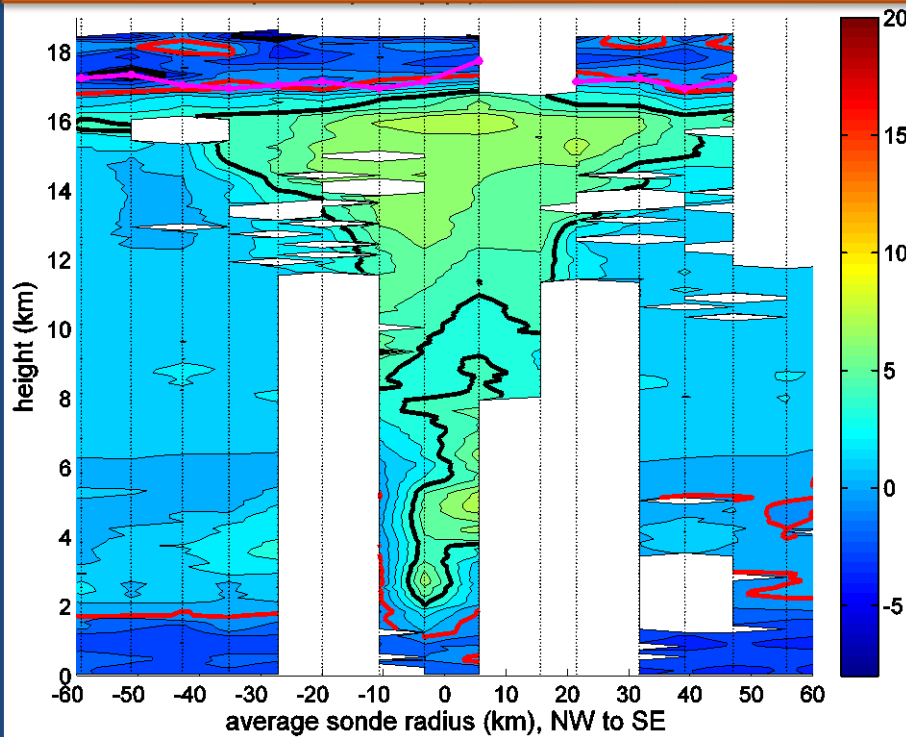
Near-Tropopause Maximum

Mid-level Maximum

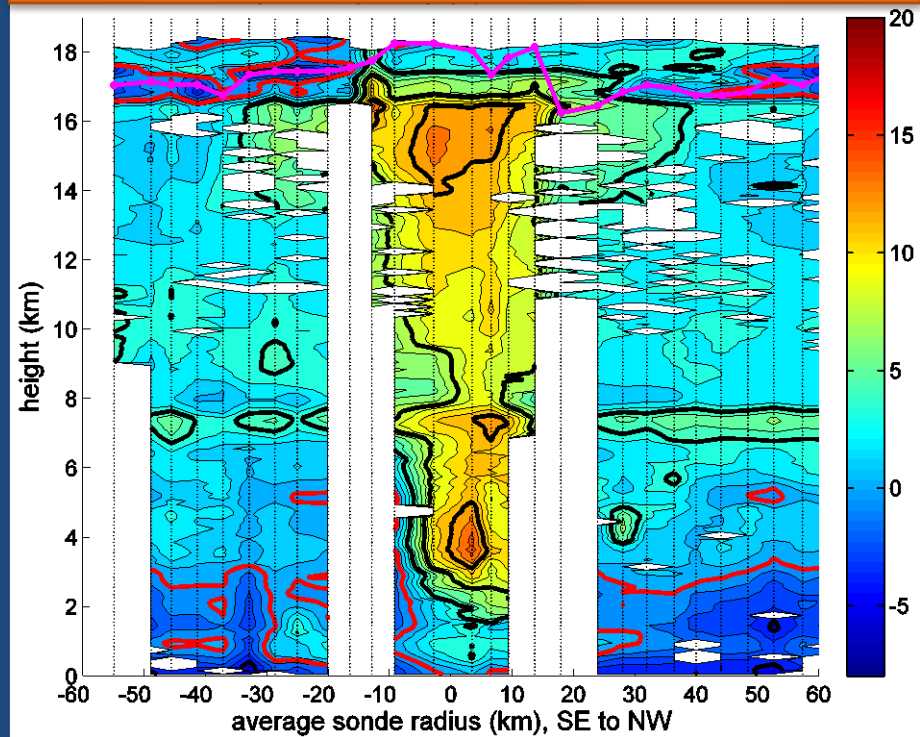


# Observations of Hurricane Patricia (2015)

October 22<sup>nd</sup>, (115 kt)



October 23<sup>rd</sup>, (~160 kt)



Pert Temp=0

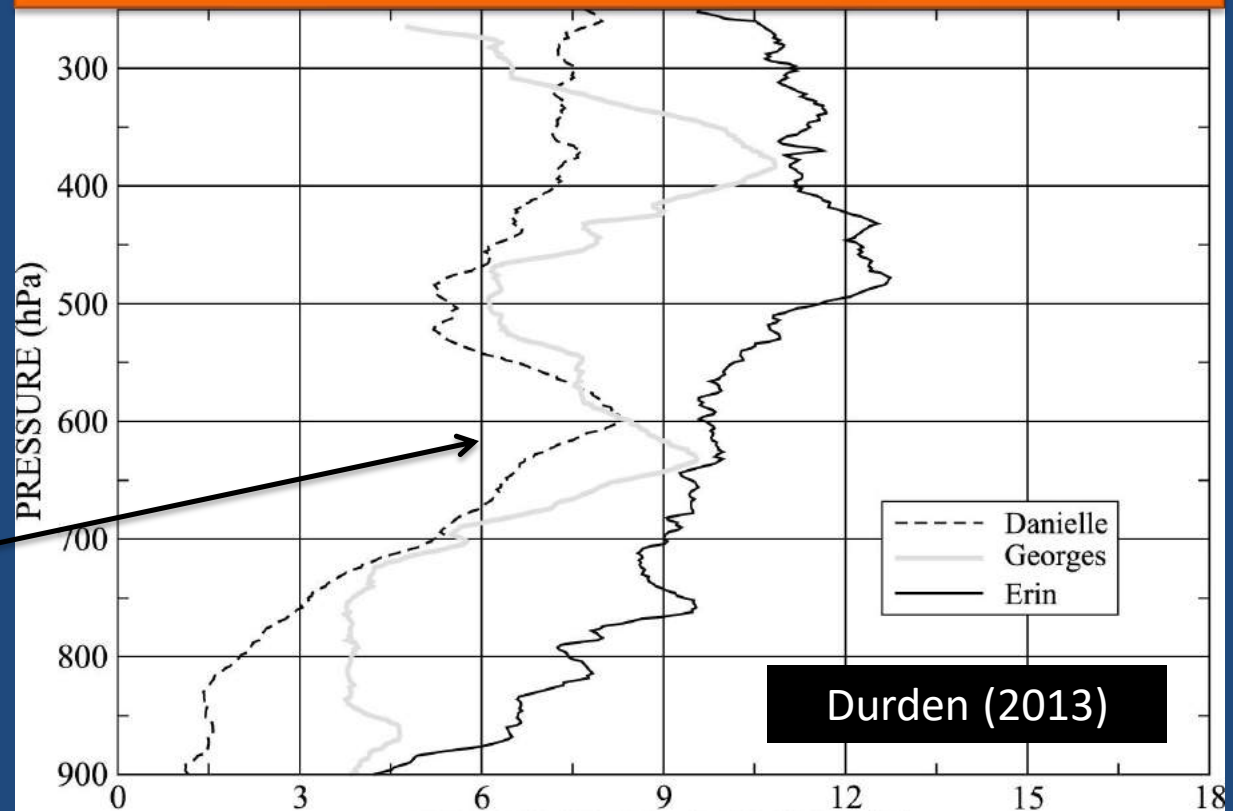
Tropopause

Evidence of both mid-level and near-tropopause maxima on consecutive days

Stern and Doyle (2016),  
Hurricanes Conference

# More Warm Core Observations

## Dropsondes from NASA ER-2



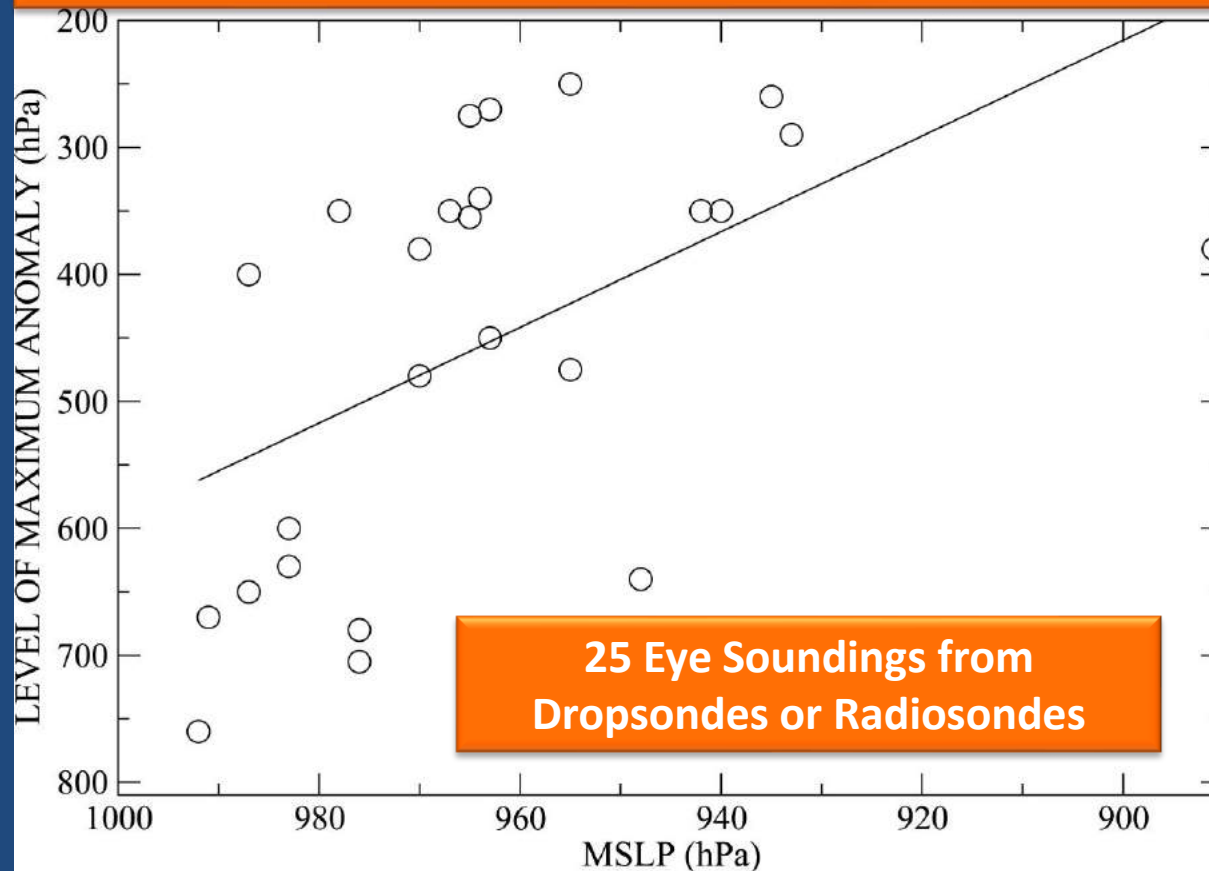
Mid-level Maxima

## Perturbation Temperature (°C)

There is a lot of variation in structure, though mid-level maxima are relatively common.

# Is the Height of the Warm Core Related to Intensity?

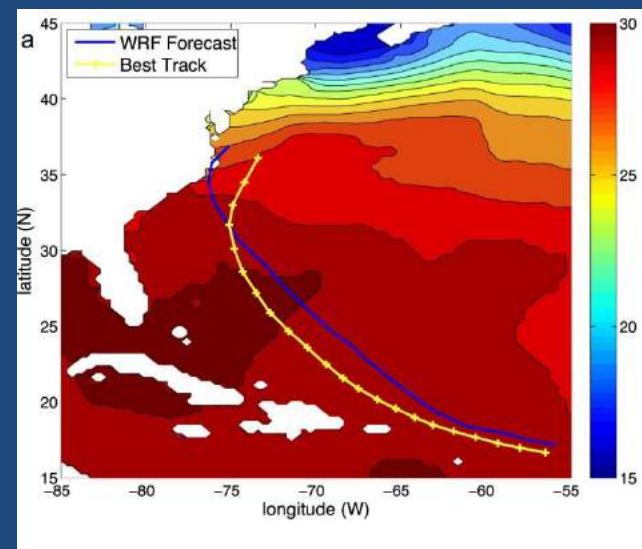
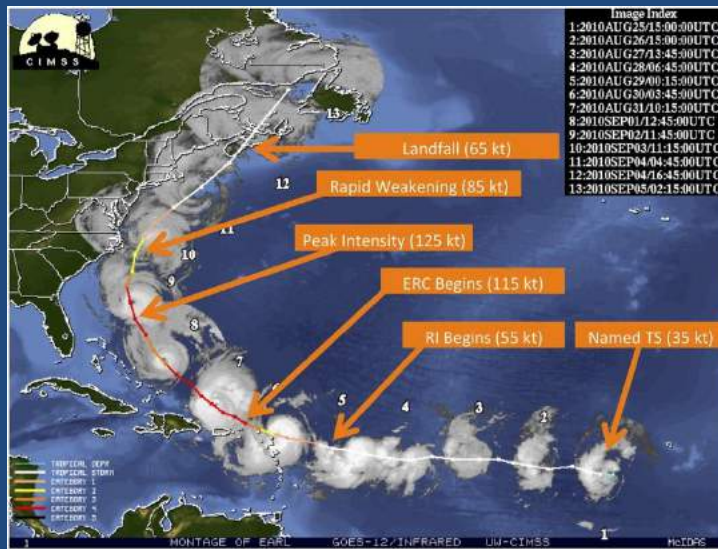
## Height of Max Pert. Temp vs. Intensity



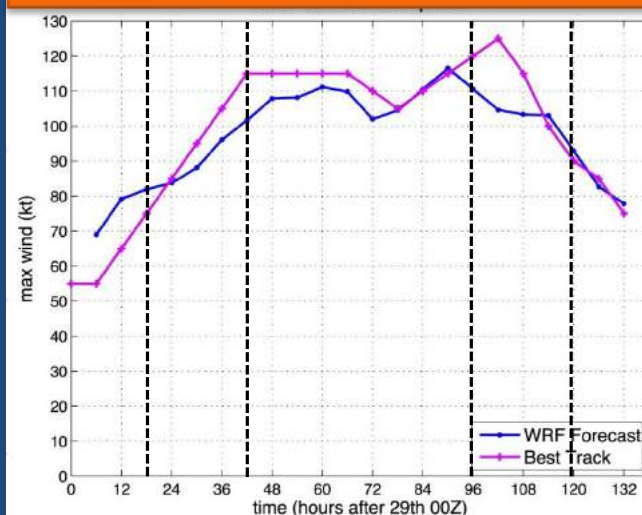
Some evidence that the height of peak warming increases with intensity, but there is very large scatter.



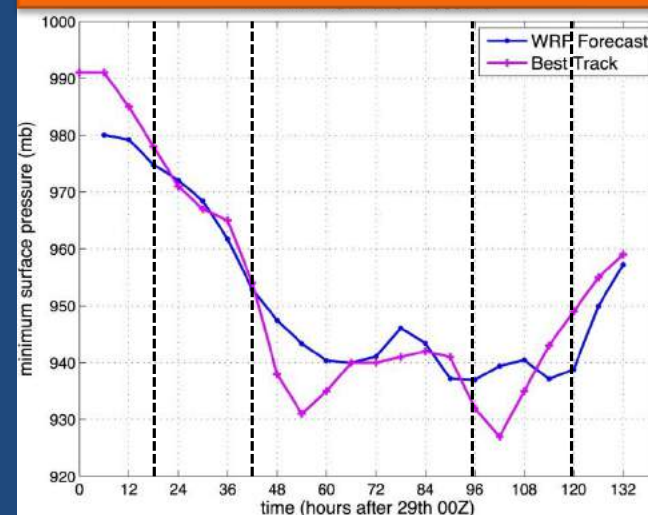
# Observations and Simulations of Earl (2010)



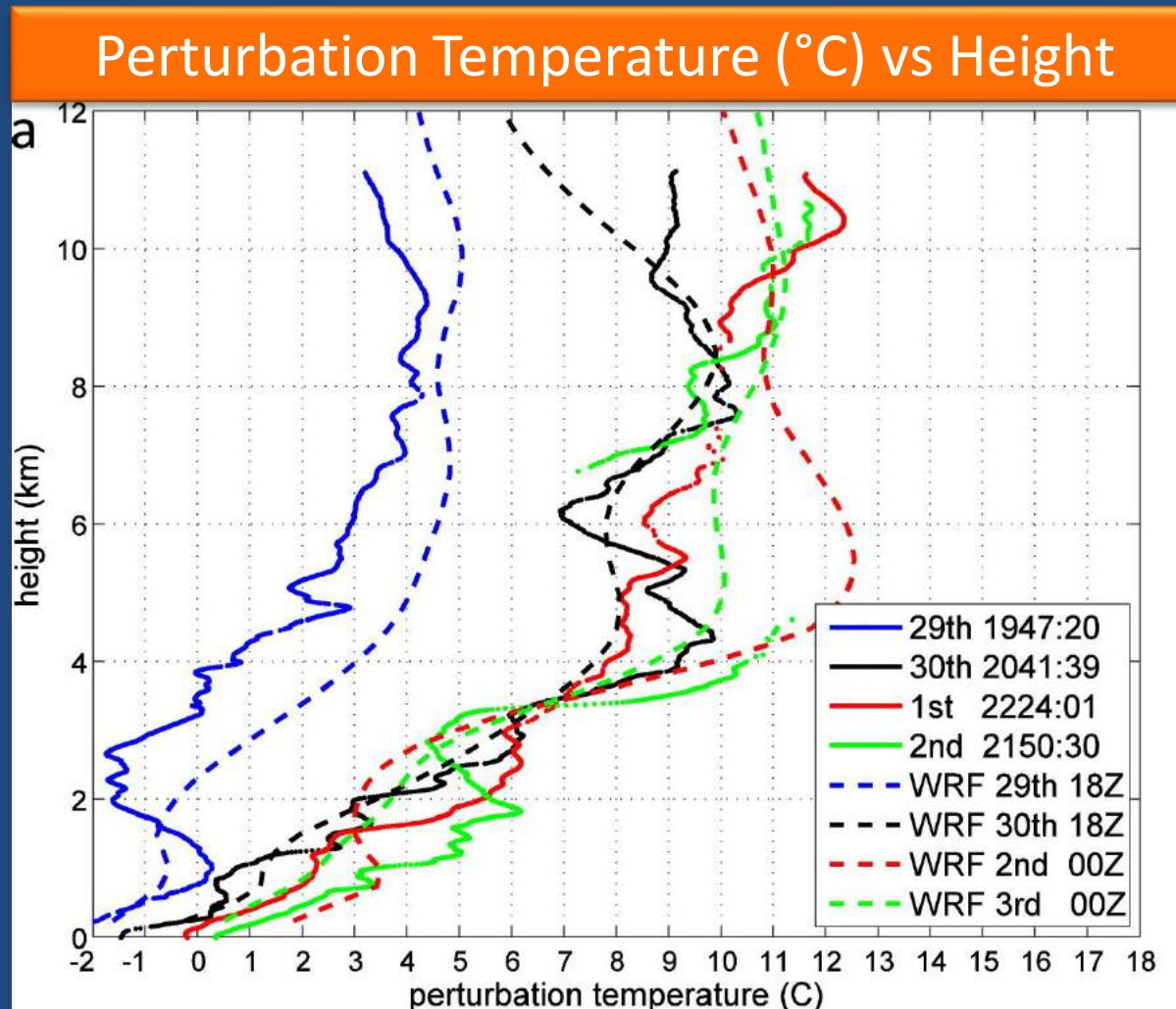
## Max 10-m Wind Speed (kt)



## Minimum Surface Pressure



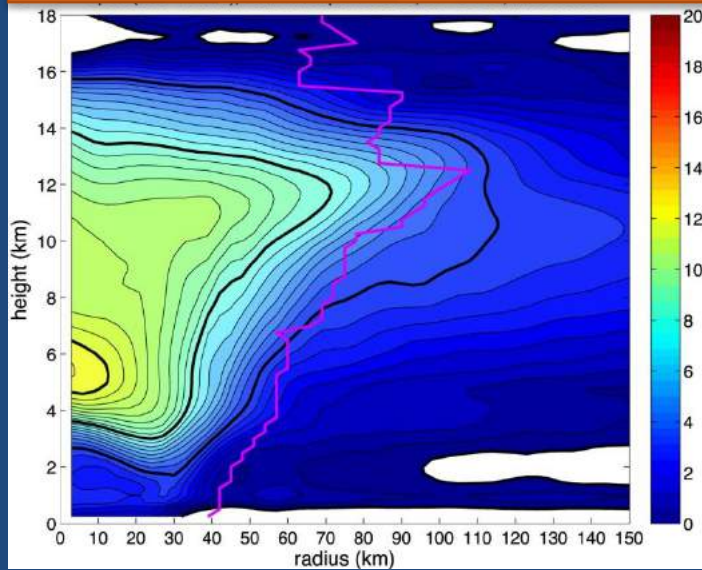
# Observations and Simulations of Earl (2010)



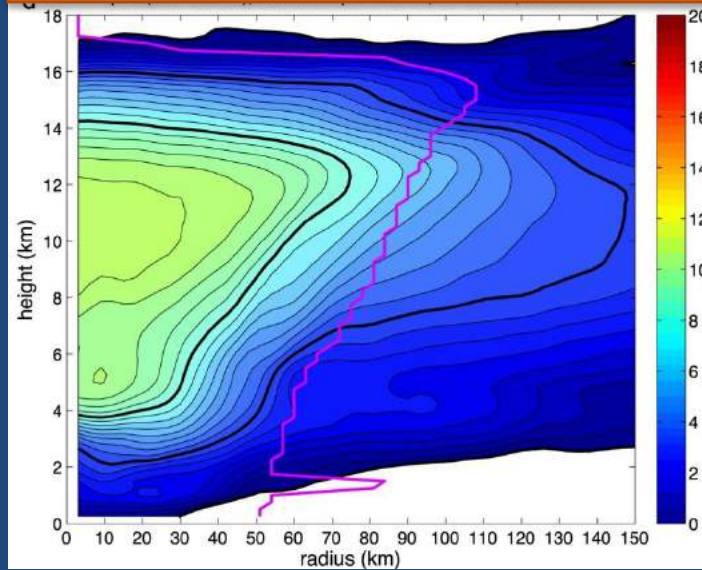


# Relating the Warm Core to the Wind Field

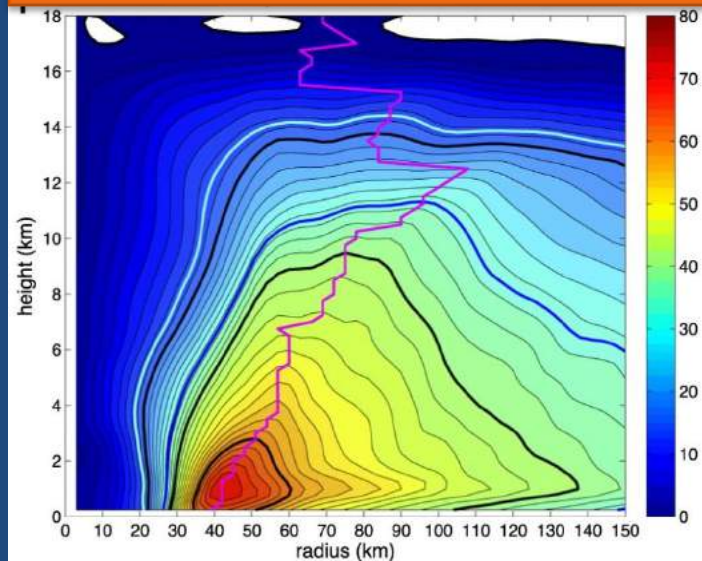
Pert. Temp., 00 UTC Sept 2<sup>nd</sup>



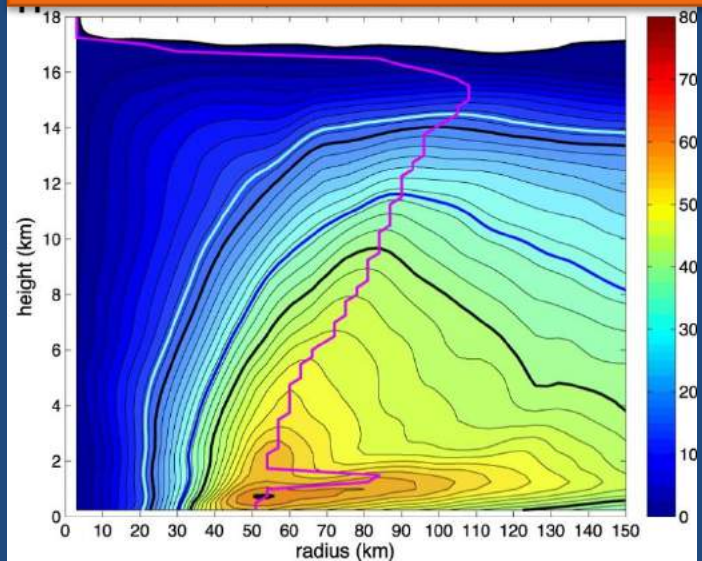
Pert. Temp., 00 UTC Sept 3<sup>rd</sup>



Vt (ms<sup>-1</sup>), 00 UTC Sept 2<sup>nd</sup>

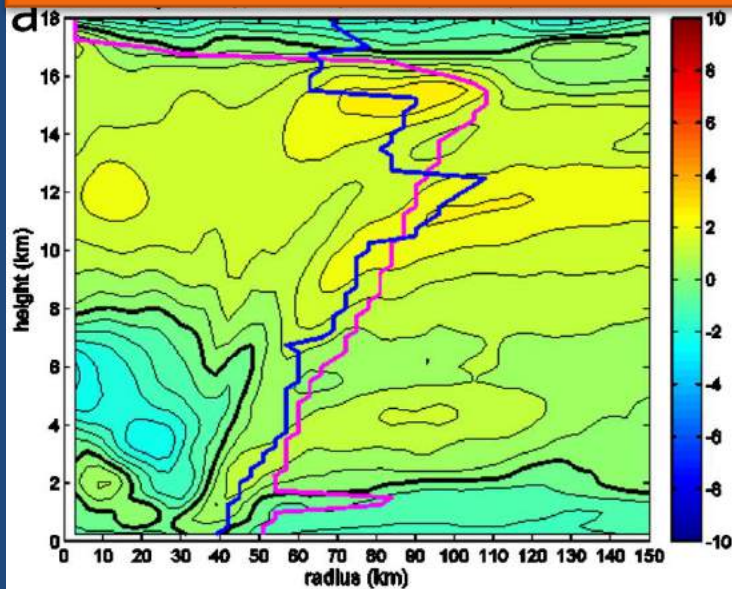


Vt (ms<sup>-1</sup>), 00 UTC Sept 3<sup>rd</sup>

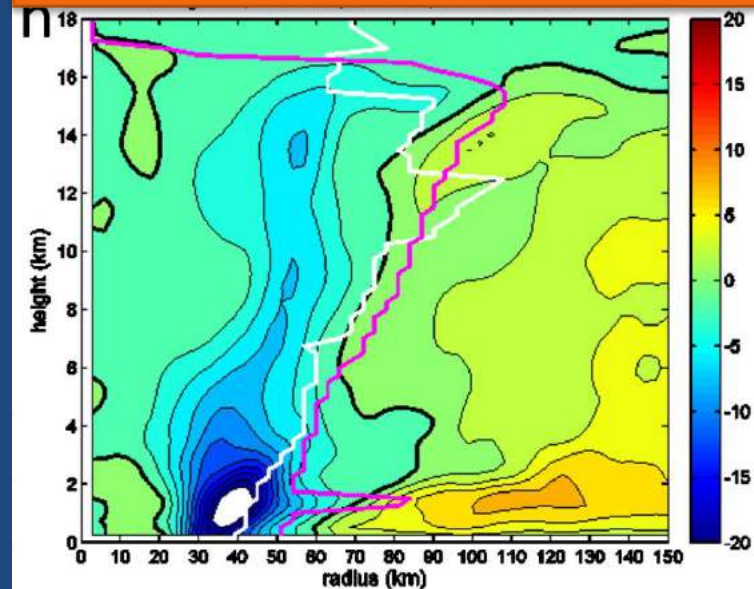


# Relating the Warm Core to the Wind Field

## 24-h Change in Temperature



## 24-h Change in Tangential Wind



- Mid-level cooling and upper-level warming in eye results in shift in warm core.
- Minimum pressure stays nearly constant.
- Wind field expands, but maximum winds weaken substantially.
- There is not an obvious direct relationship between these fields.

# What Does Thermal Wind Balance Tell Us?

## Thermal Wind Balance

$$\left(f + \frac{2v}{r}\right) \frac{\partial v}{\partial z} = \frac{g}{T_0} \frac{\partial T}{\partial r}$$

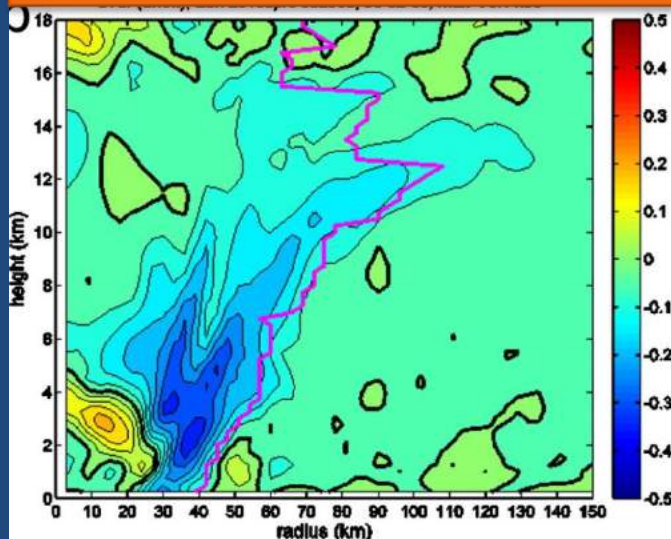
Neglecting  $f$

$$\frac{\partial T}{\partial r} \approx \frac{2T_0}{g} \frac{v_g}{r} \frac{\partial v_g}{\partial z}$$

Schubert et al. (2007)

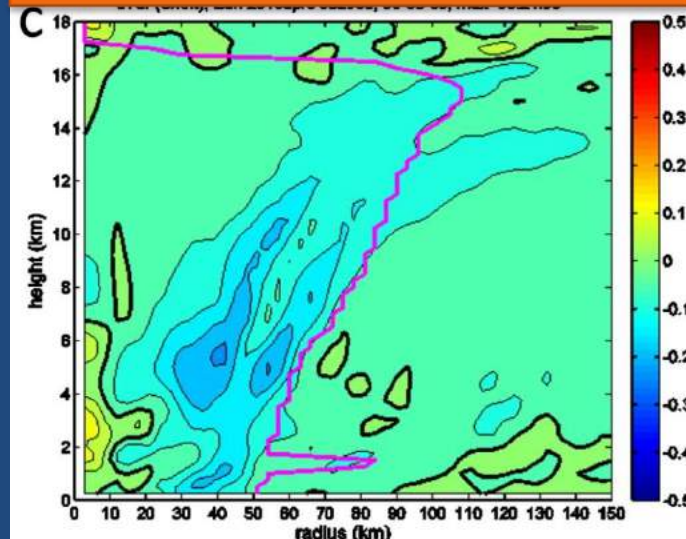
- The radial temperature gradient is proportional to vertical gradient of the squared gradient wind speed, divided by radius.

$\partial T / \partial r$  ( $^{\circ}\text{C km}^{-1}$ ), 00 UTC 2<sup>nd</sup>



Weakening of  
temp. gradient

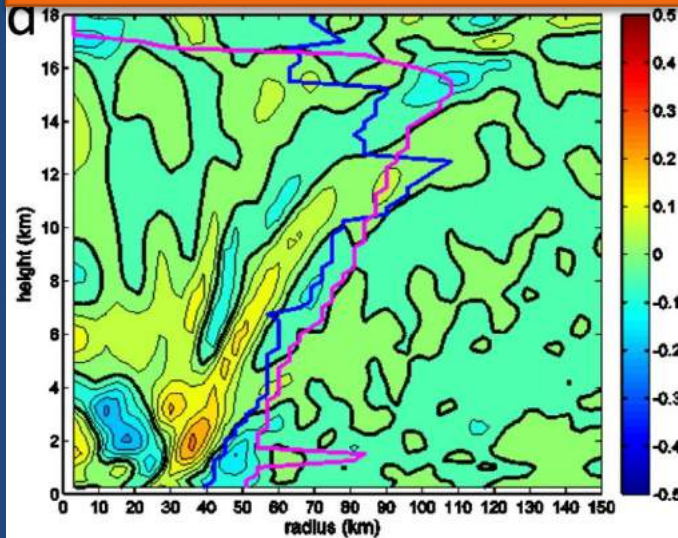
$\partial T / \partial r$  ( $^{\circ}\text{C km}^{-1}$ ), 00 UTC 3<sup>rd</sup>



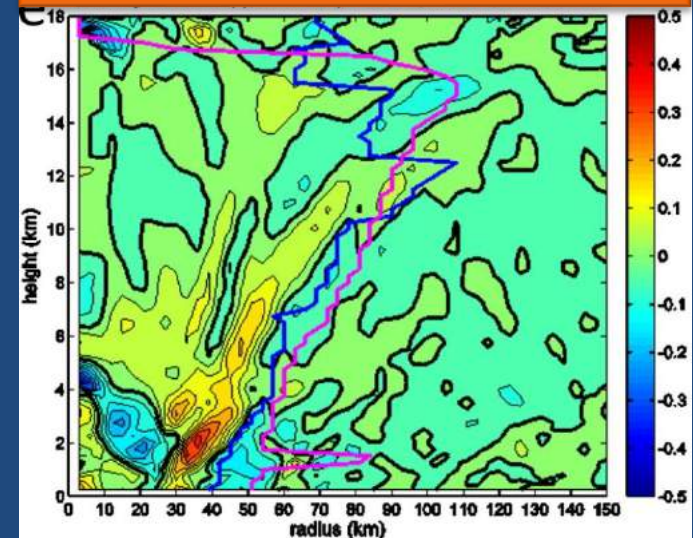


# What Does Thermal Wind Balance Tell Us?

24-h Change in:  $\frac{\partial T}{\partial r}$



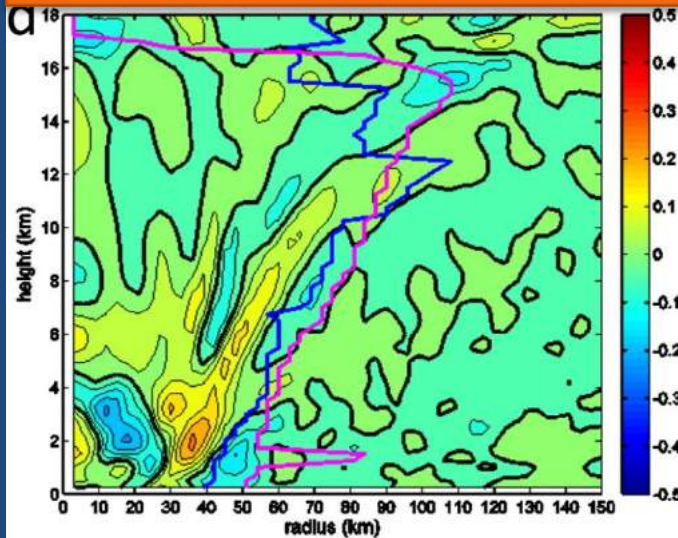
24-h Change in:  $v_g \frac{\partial v_g}{\partial z}$



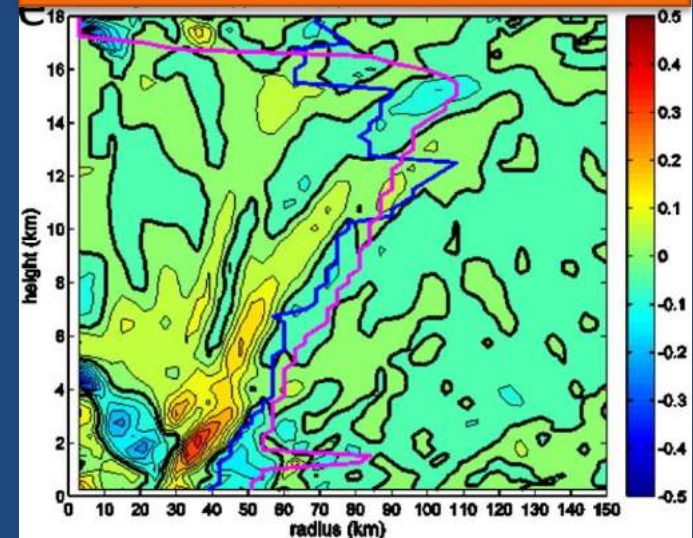
- The close correspondence demonstrates that the approximations to the actual thermal wind balance equation are appropriate.
- Note that this does not actually evaluate whether the flow itself is balanced.

# What Does Thermal Wind Balance Tell Us?

24-h Change in:  $\frac{\partial T}{\partial r}$



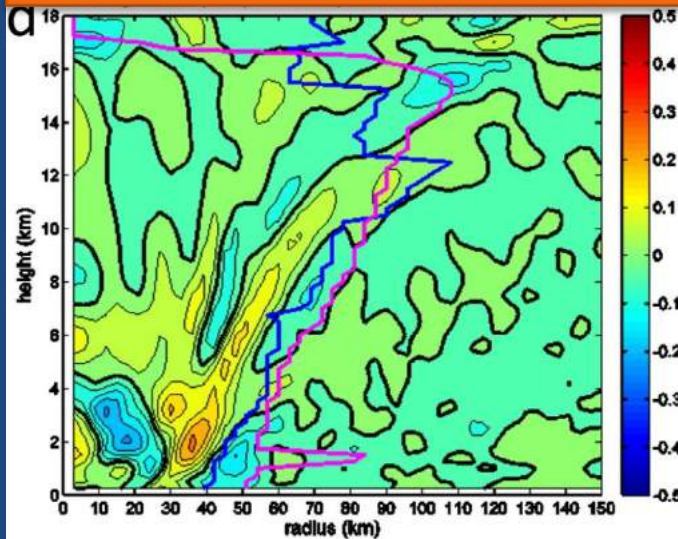
24-h Change in:  $v_g \frac{\partial v_g}{\partial z}$



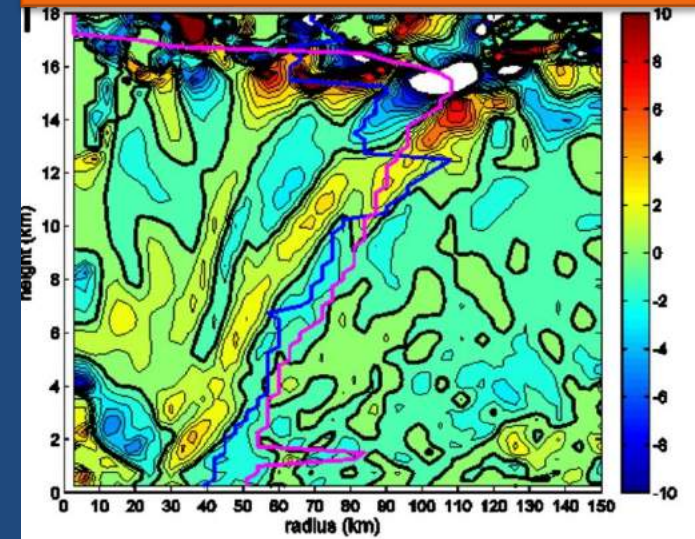
- Weakened (negative) temperature gradient (positive change) corresponds to a decrease in the magnitude of the vertical gradient of the squared gradient wind (positive change).
- This is somewhat difficult to interpret.

# What Does Thermal Wind Balance Tell Us?

24-h Change in:  $\frac{\partial T}{\partial r}$



24-h Change in:  $\frac{\partial v_g}{\partial z}$

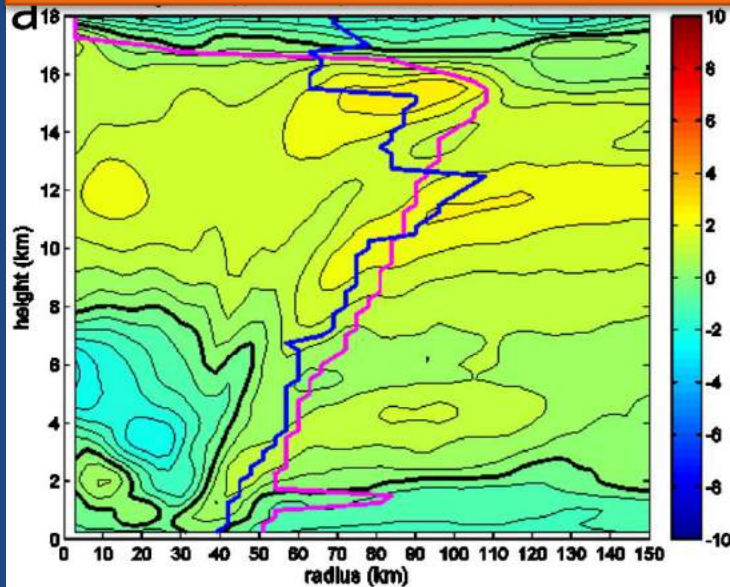


- The change in radial temperature gradient corresponds relatively well to the vertical gradient in the gradient wind itself.
- This is easier to interpret, but there are still complicated spatial variations.

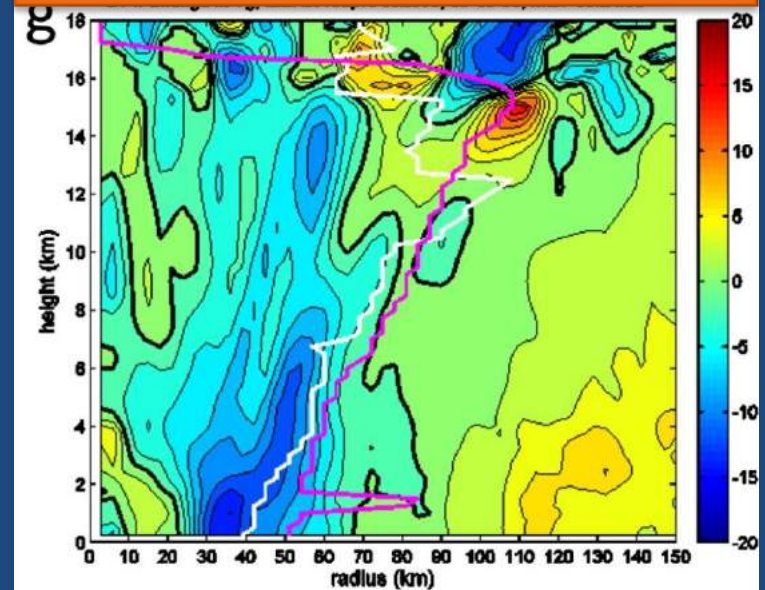


# What Does Thermal Wind Balance Tell Us?

## 24-h Change in Temperature



## 24-h Change in Gradient Wind

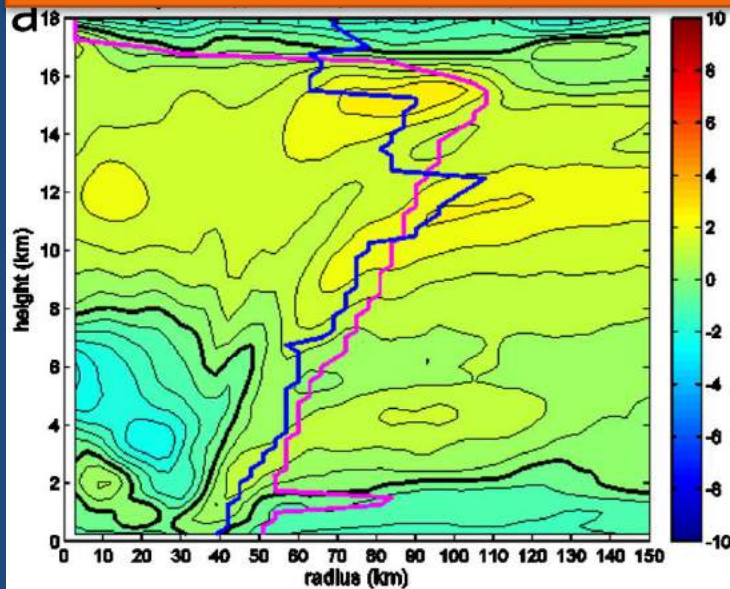


- The gradient wind speed decreases throughout the depth of the eyewall
- The weakened temperature gradient and the cooling of the mid-level eye/eyewall corresponds with the fact that the gradient wind weakens *less* at mid-levels than in the lowest 2 km.

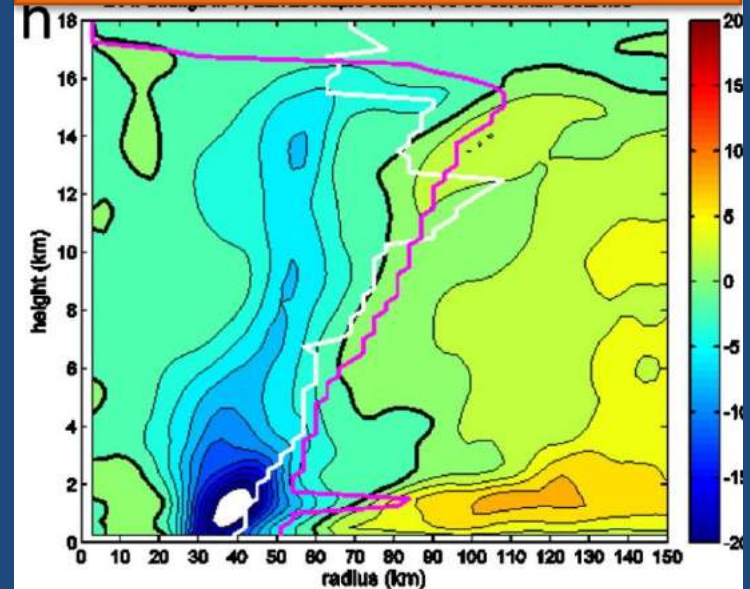


# What Does Thermal Wind Balance Tell Us?

24-h Change in Temperature



24-h Change in Tangential Wind



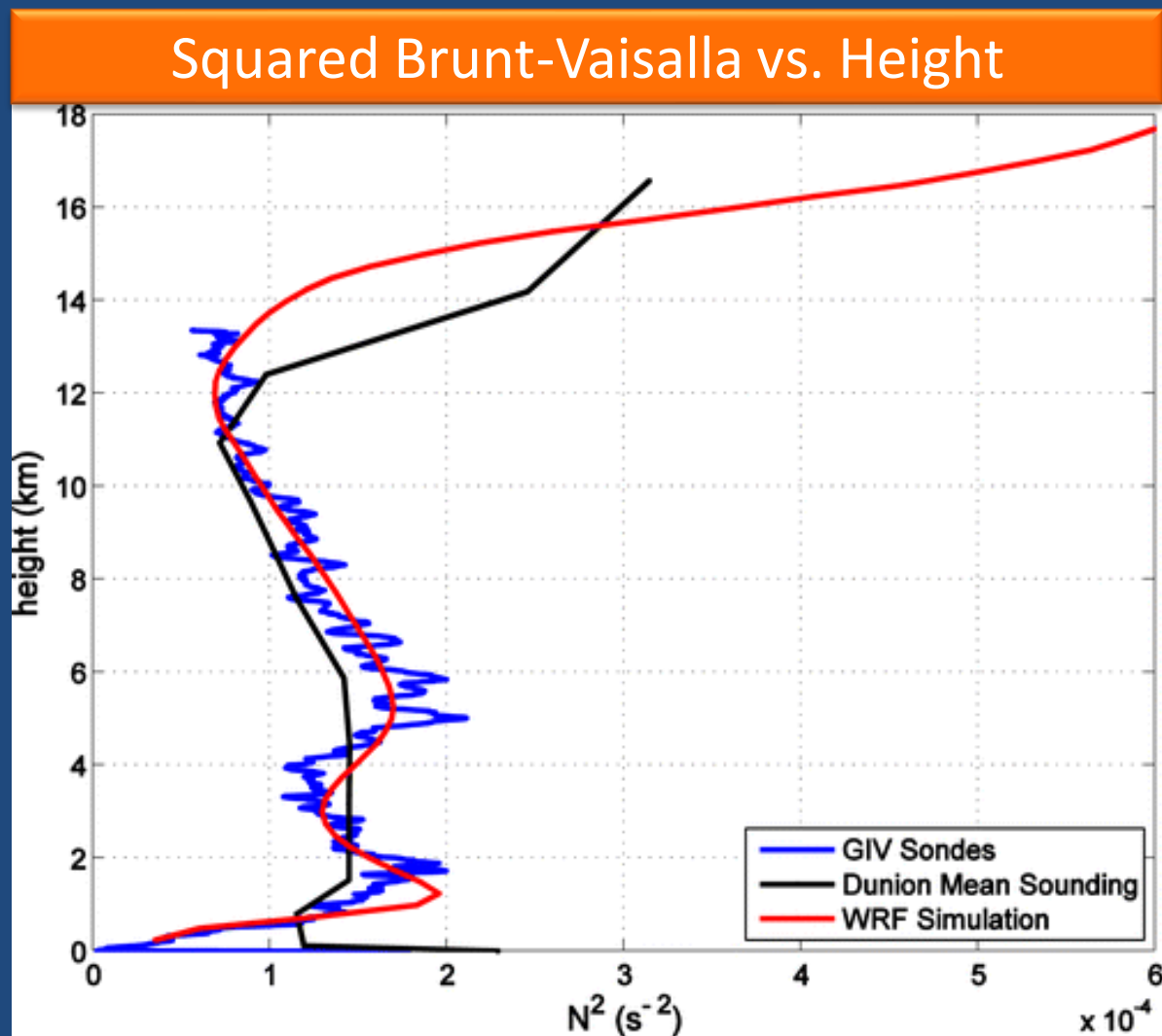
- The greatest weakening of tangential wind is in the boundary layer, and is substantially unbalanced.
- Therefore the subtle shifts in the warm core have little direct relationship to the changes in intensity.
- Temperature changes are related to wind changes, but in a very complex manner.

# Summary

- Idealized simulations and recent observations suggest that there is substantial variability in the distribution of warming in the eye.
- Dual mid-level and near-tropopause maxima are common, and this structure is related to the climatological profile of static stability in the tropics.
- Budget analyses indicate that mean subsidence and eddy radial advection are important in warming the eye.
- Although changes in the temperature and wind fields are related through thermal wind balance, there is not a clear connection between the vertical structure of the warm core and intensity or intensity change.

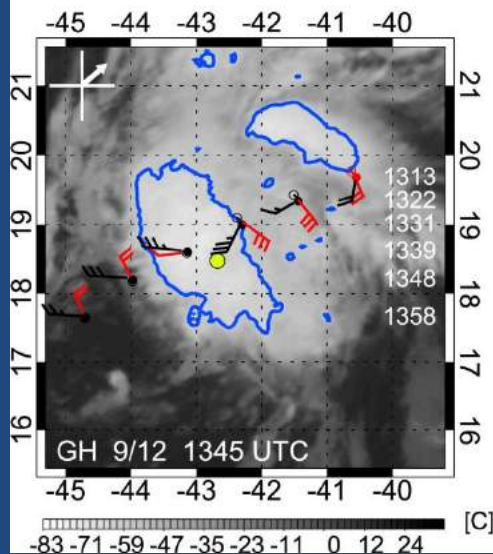
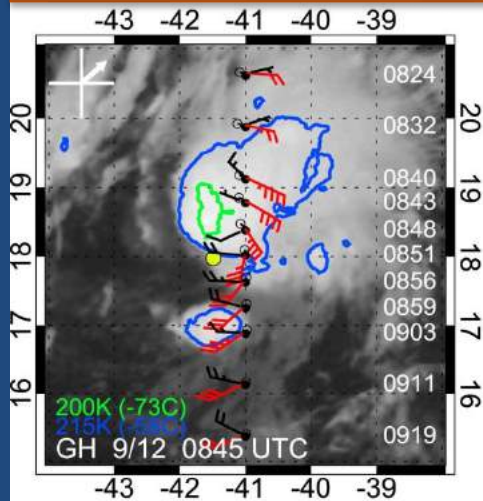
# Bonus Slides!

# Environmental Static Stability Influences Warm Core Structure

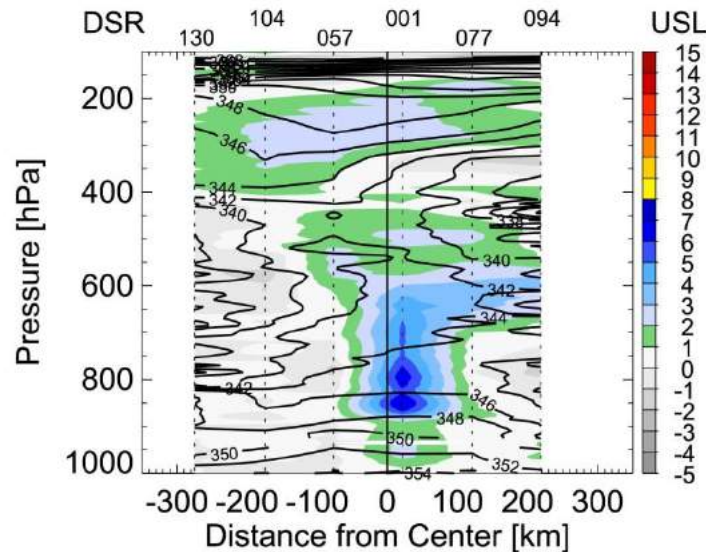
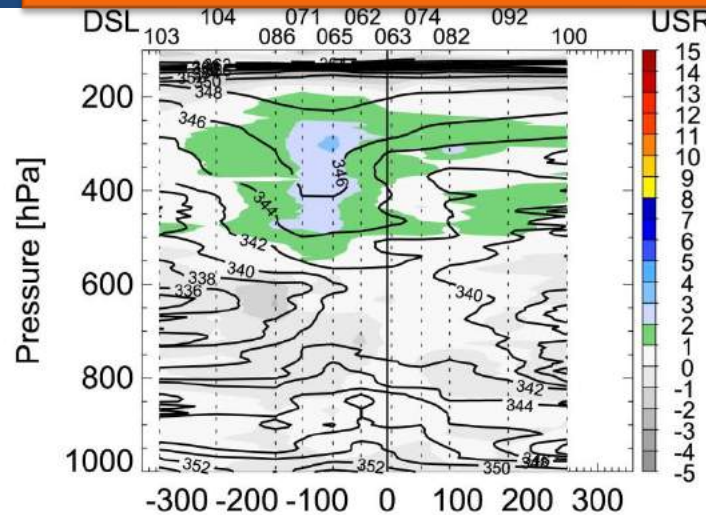


# Dropsonde Observations from Hurricane Edouard (2014)

IR Satellite



Perturbation Temp (°C)



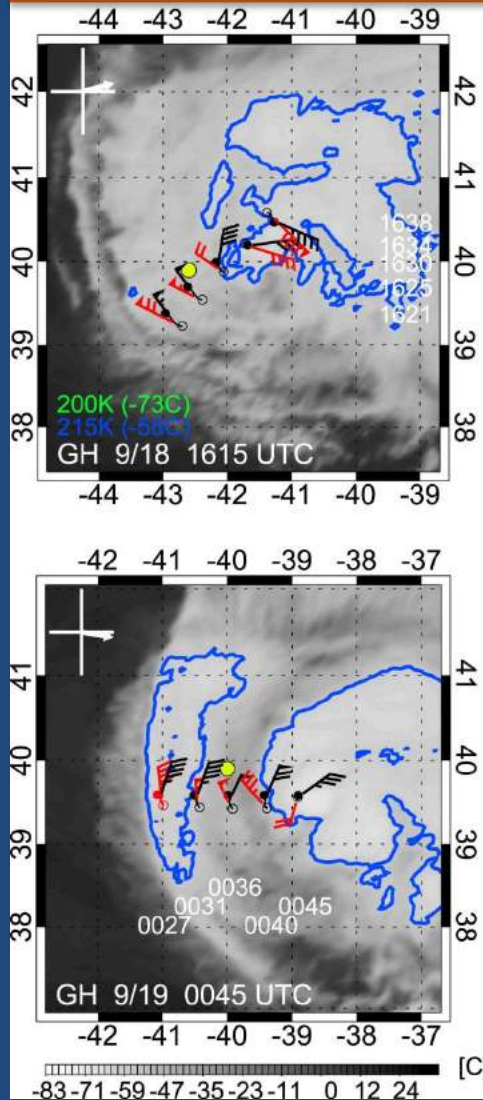
**Best Track: 35 kt**  
**MSLP: 1005 mb**

**Best Track: 40 kt**  
**MSLP: 1000 mb**

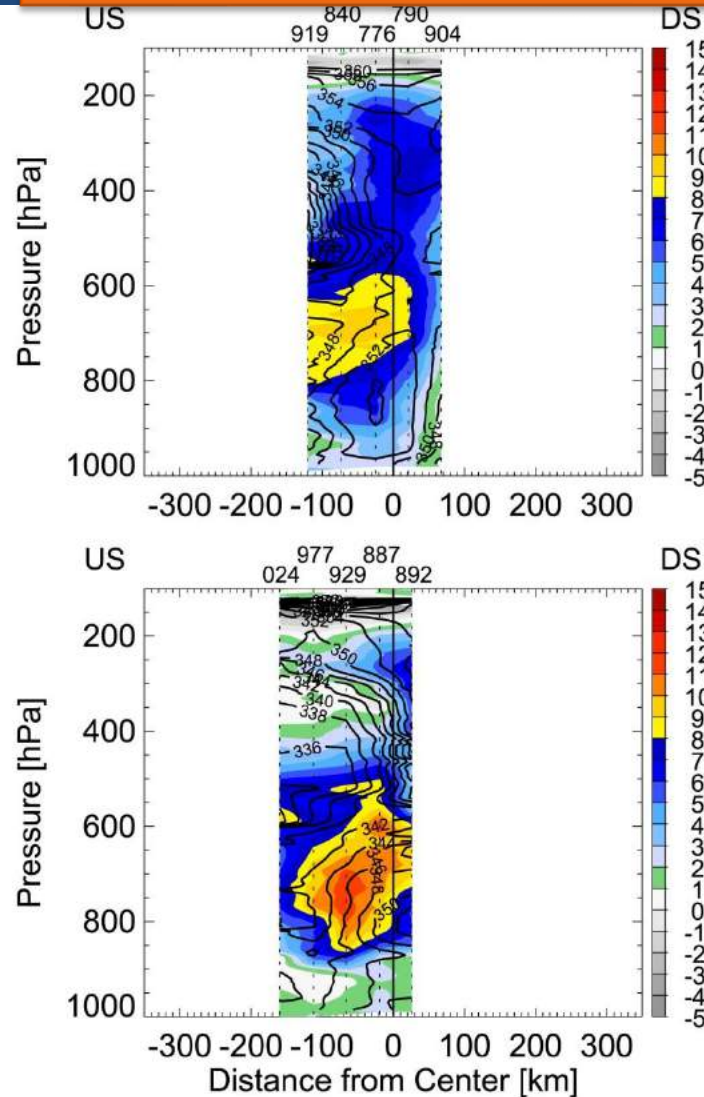


# Dropsonde Observations from Hurricane Edouard (2014)

IR Satellite



Perturbation Temp (°C)



**Best Track: 70 kt**  
**MSLP: 971 mb**

**Best Track: 60 kt**  
**MSLP: 980 mb**

# Summary and Conclusions #1



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# Summary and Conclusions #1

- The warm core in idealized simulations is typically maximized in the mid-troposphere (4-8 km)
- This is because during intensification, the warming tendency from advection is maximized at mid-levels.
- Mean descent is maximized well above the height of maximum warming.
- Because static stability is a minimum in the upper-troposphere, the large descent there does not lead to as much warming as in the mid-troposphere.

# Trajectory Analysis



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- A trajectory is the path of a hypothetical “air parcel”, found by integrating the velocities in time.

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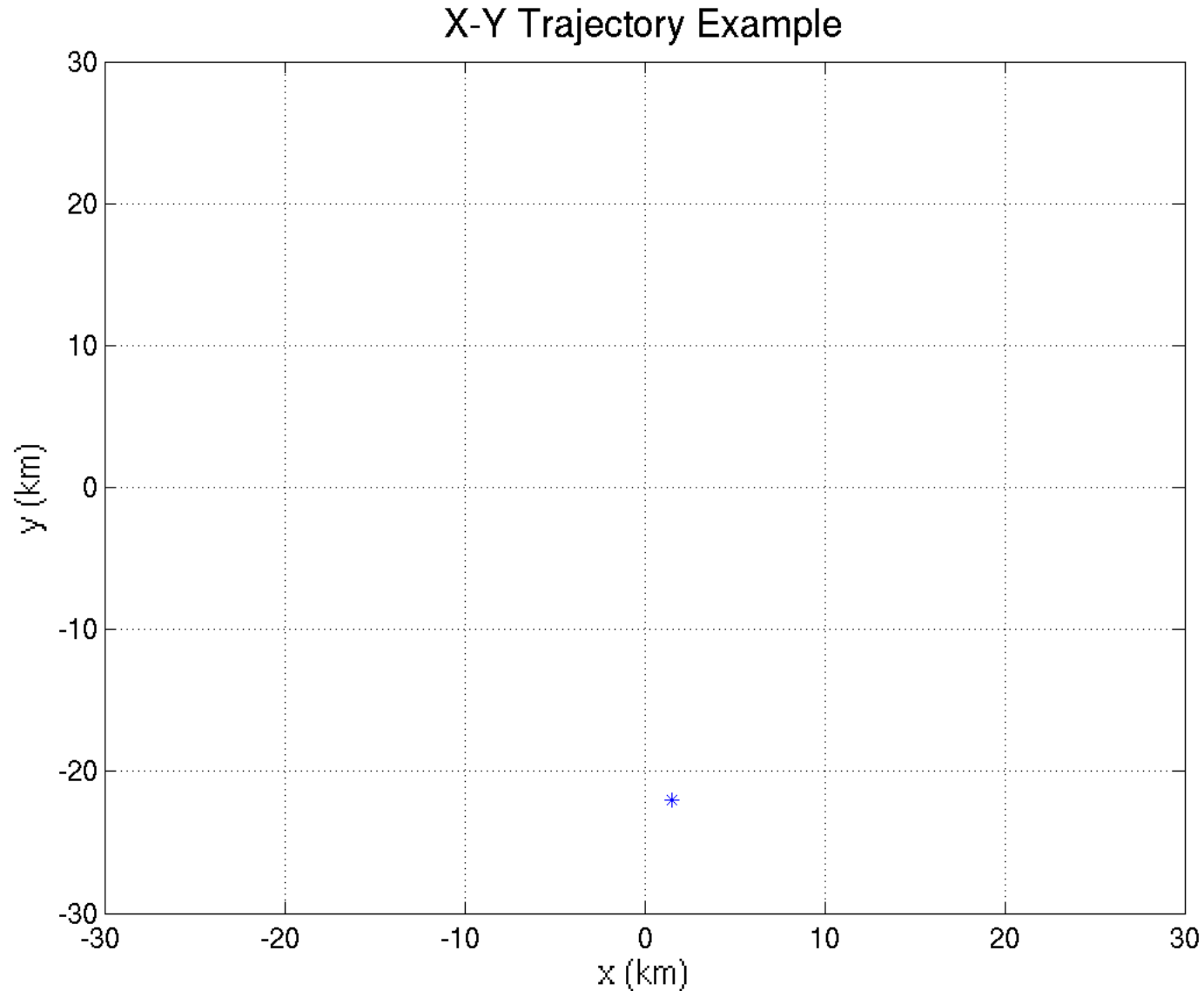
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- Forward trajectories tell us where air at a given point ends up at a future time.
- Backward trajectories tell us where air at a given point originated from at a past time.

# An Example Trajectory





# Questions We Can Answer with Trajectories

- Are air parcels within the eye isolated from the eyewall, or is there instead frequent mixing?

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- Are air parcels within the eye isolated from the eyewall, or is there instead frequent mixing?
- How far do parcels descend while remaining within the eye?
- Do the answers to these questions depend on shear and/or intensity?

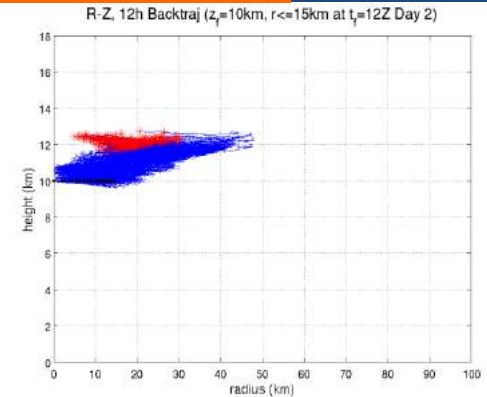
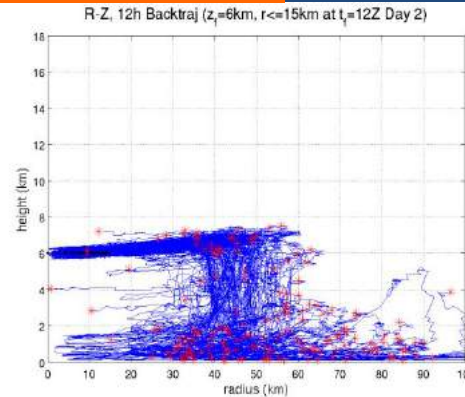
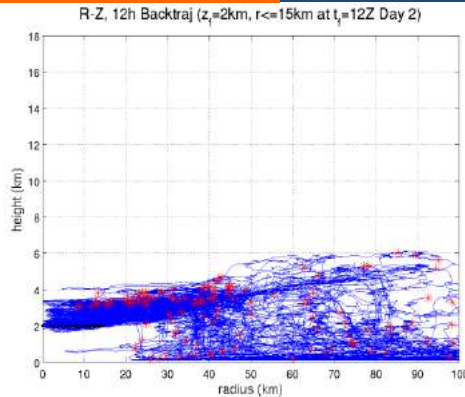
# 12-h Backward Trajectories: NOFLOW

Z=2km

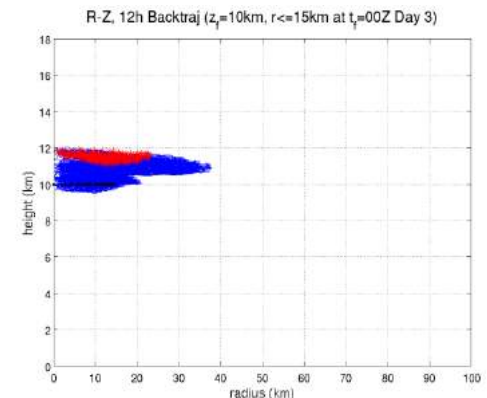
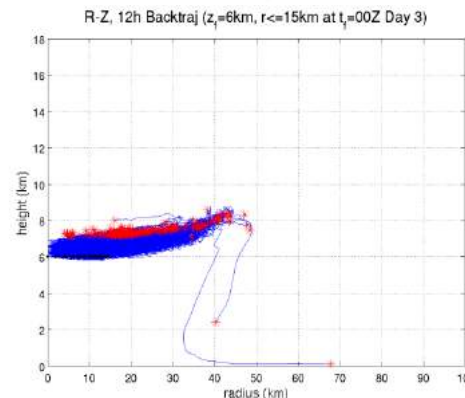
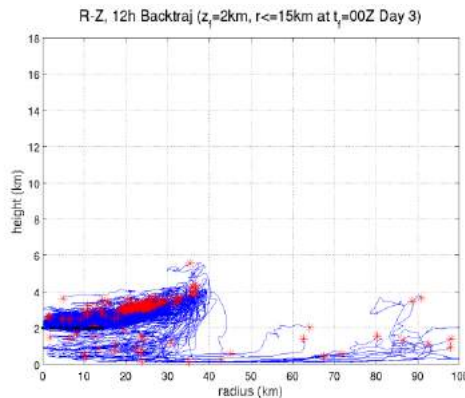
Z=6km

Z=10km

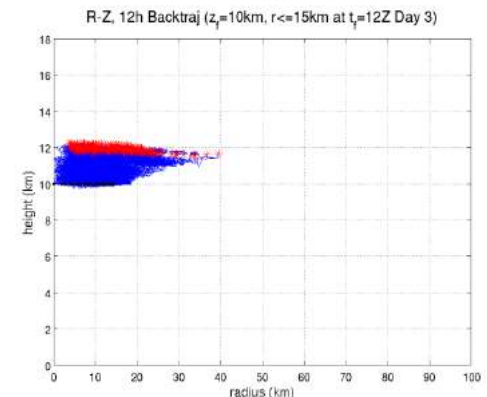
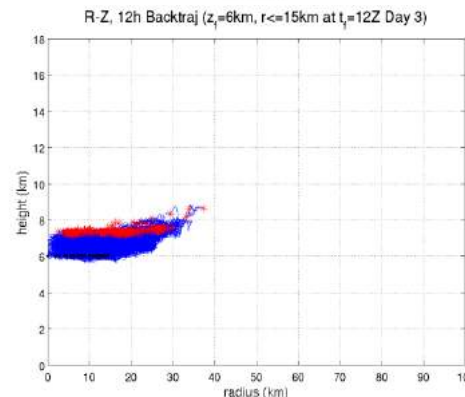
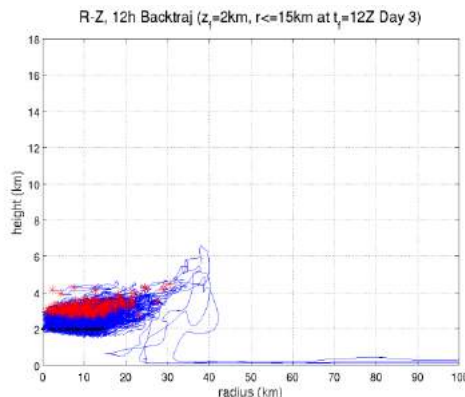
Day 2 00Z-  
12Z



Day 2 12Z-  
00Z



Day 3 00Z-  
12Z



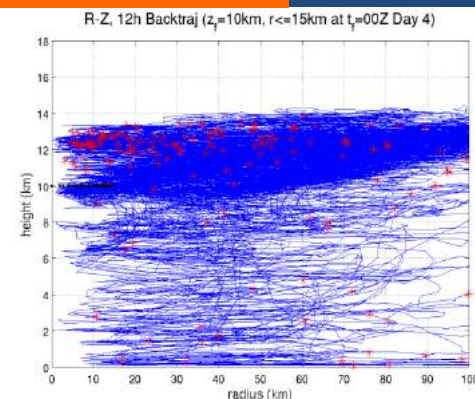
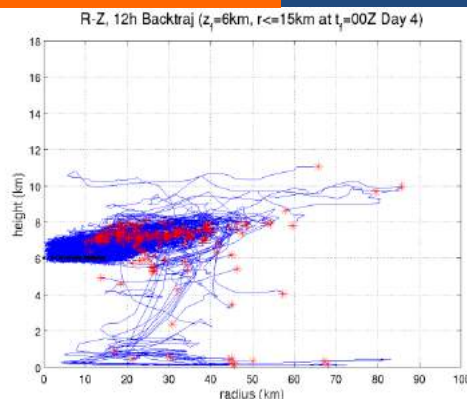
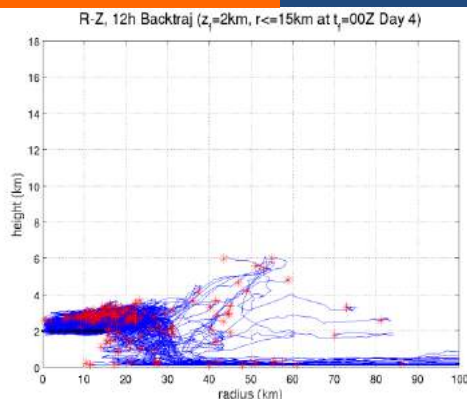
# 12-h Backward Trajectories: SHEAR10

Z=2km

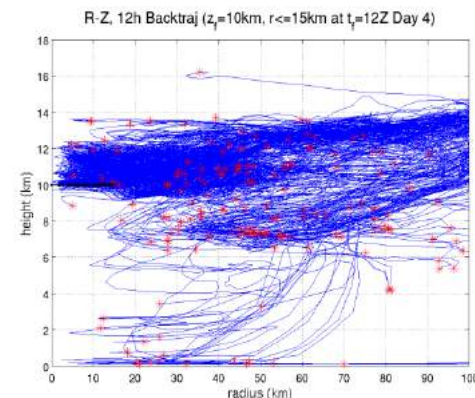
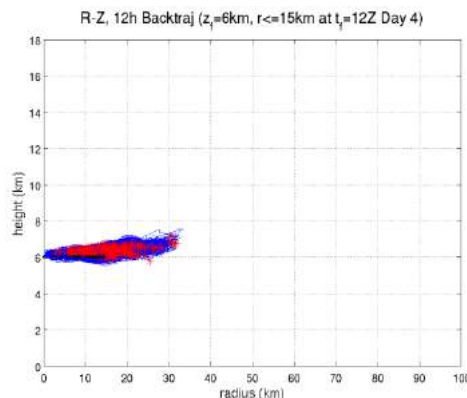
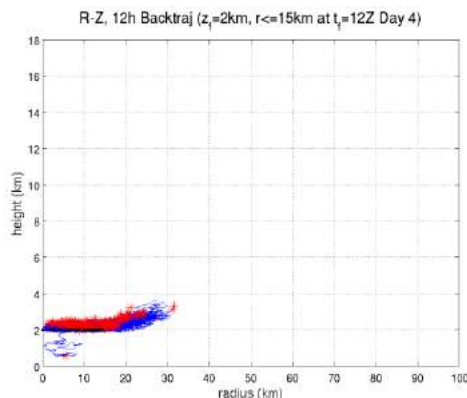
Z=6km

Z=10km

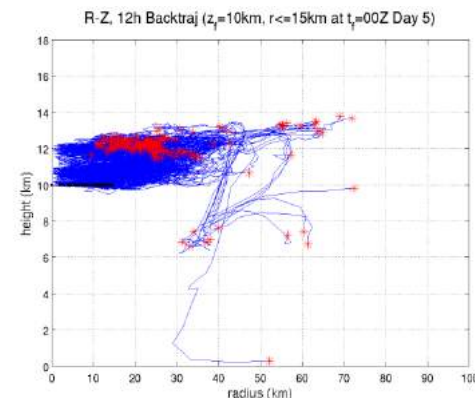
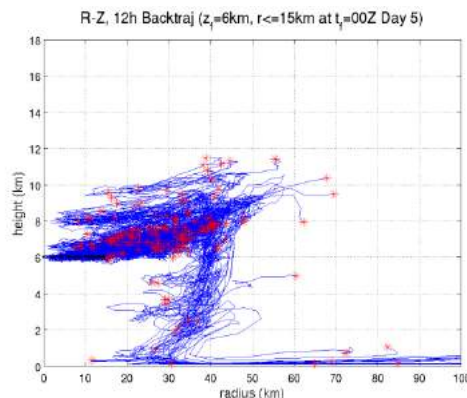
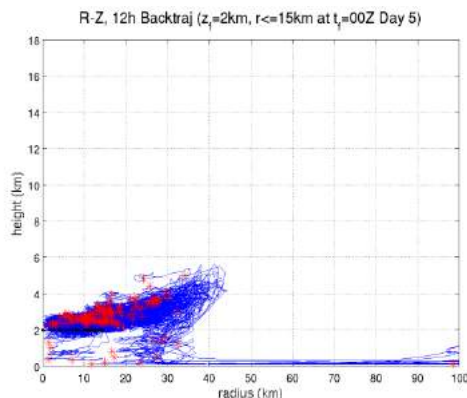
Day 3 12Z-  
00Z



Day 4 00Z-  
12Z



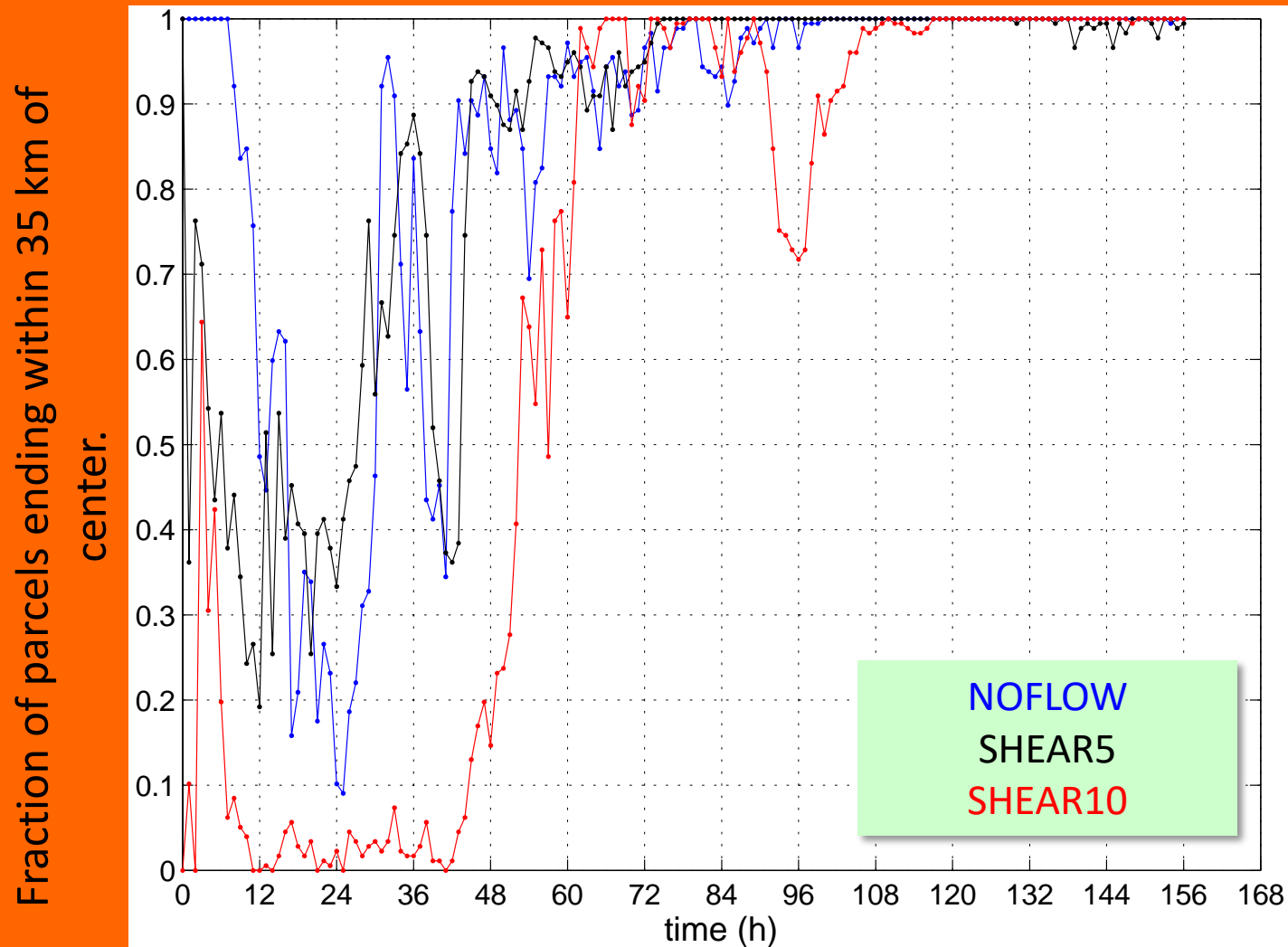
Day 4 12Z-  
00Z





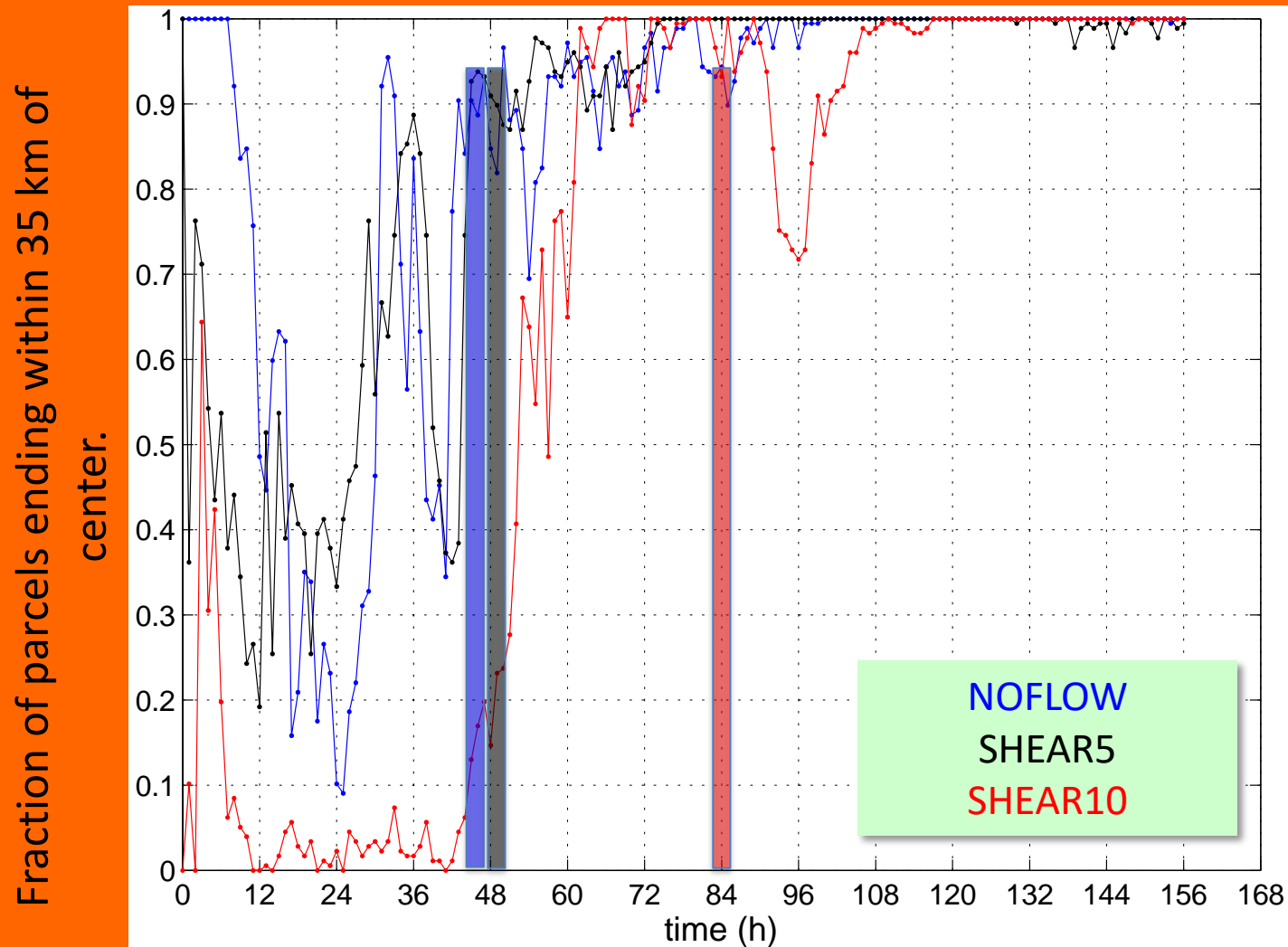
# How does eye/eyewall mixing vary with intensity?

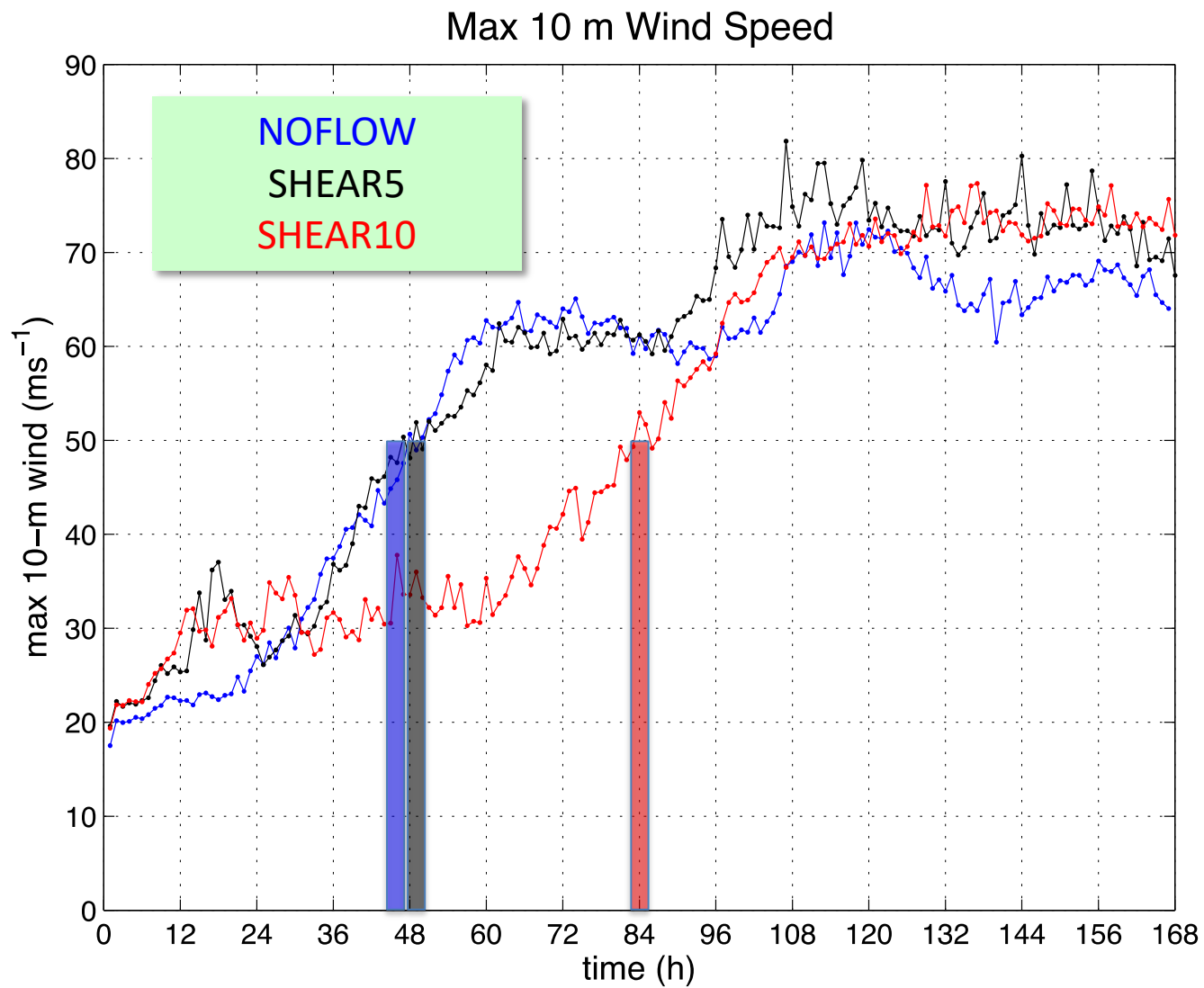
12-h Forward Trajectories, seeded each hour.



# How does eye/eyewall mixing vary with intensity?

12-h Forward Trajectories, seeded each hour.





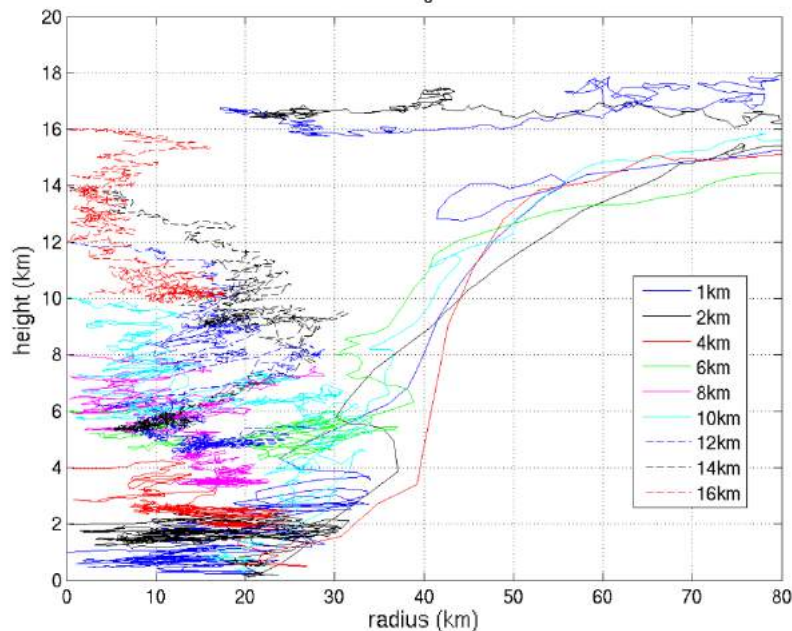
# How Far Can Parcels Descend within the Eye?

# How Far Can Parcels Descend within the Eye?

- 4-day forward trajectories released at storm center at different heights in NOFLOW
- Parcels can remain inside the eye for at least several days.

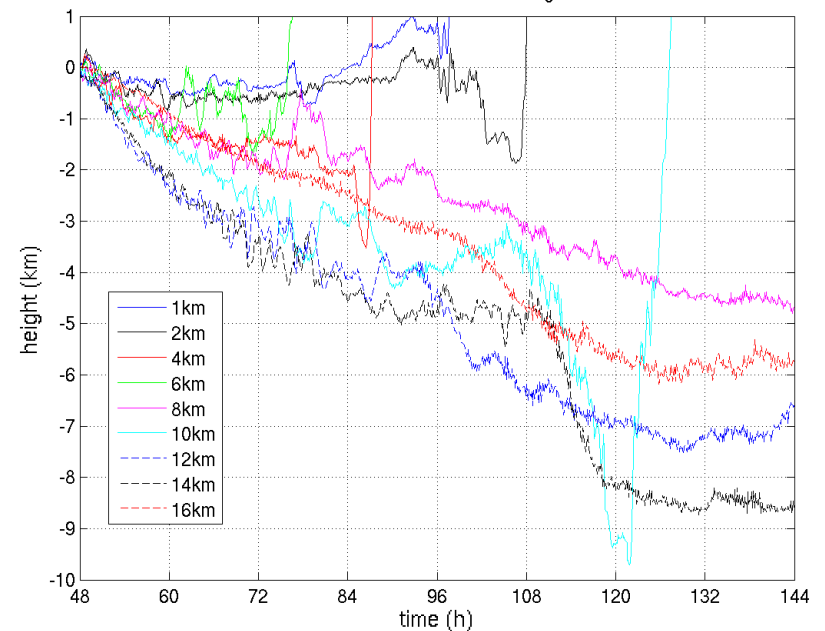
## Radius-Height

R-Z 4-Day Traj,  $r_0=0$  at Day 3 00Z

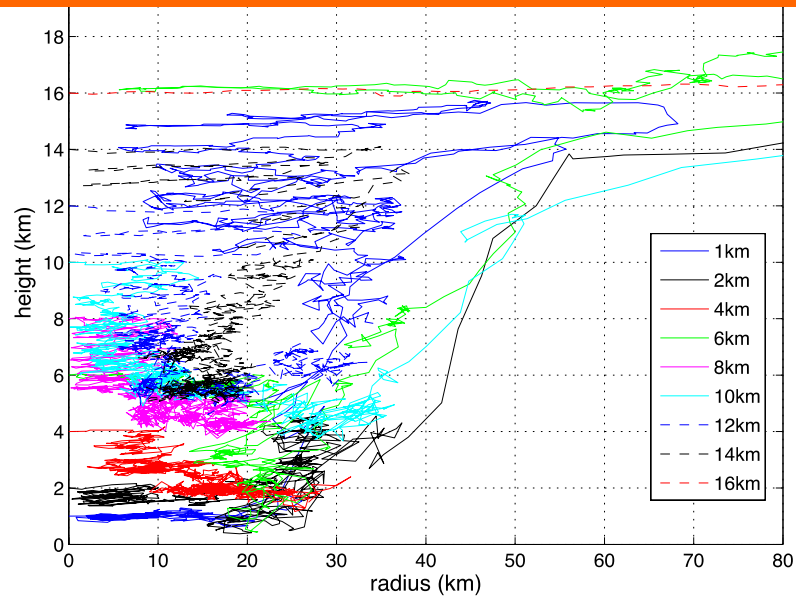


## Vertical Displacement vs. Time

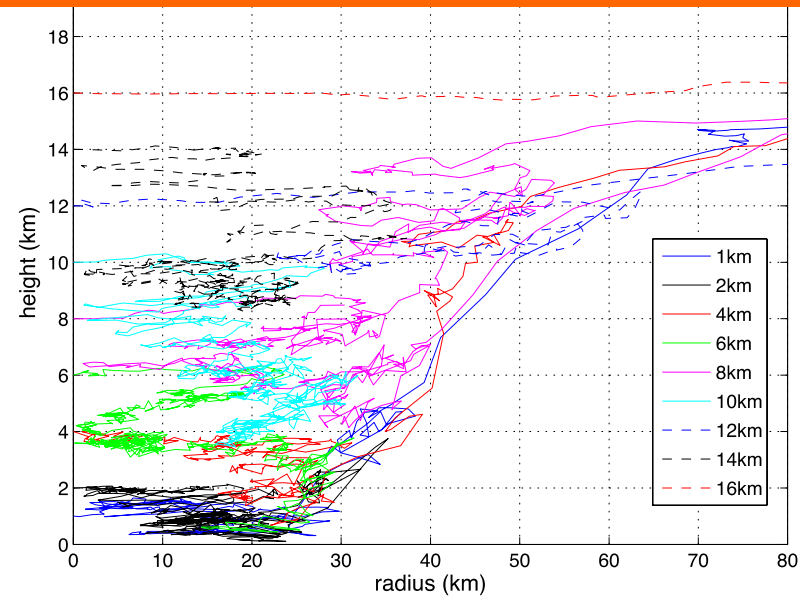
Displacement vs. Time, 4-Day Traj,  $r_0=0$  at Day 3 00Z



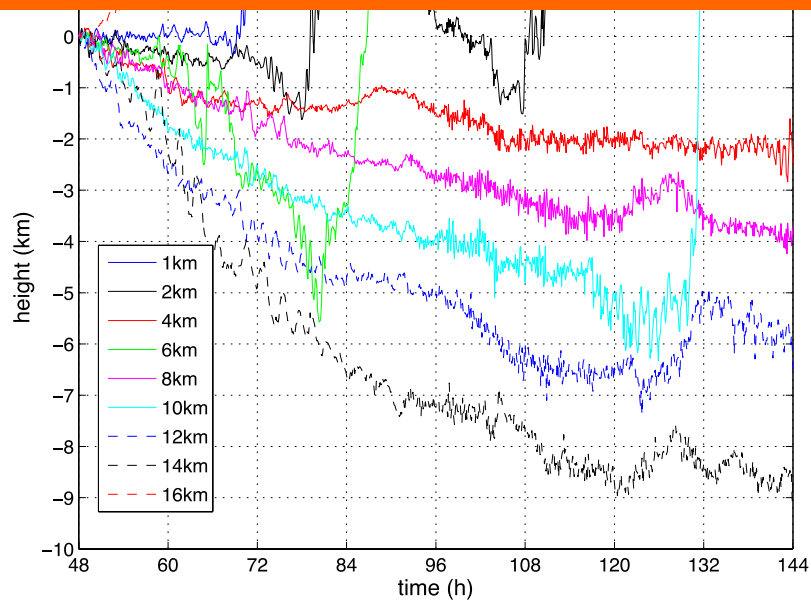
# Radius-Height: SHEAR5



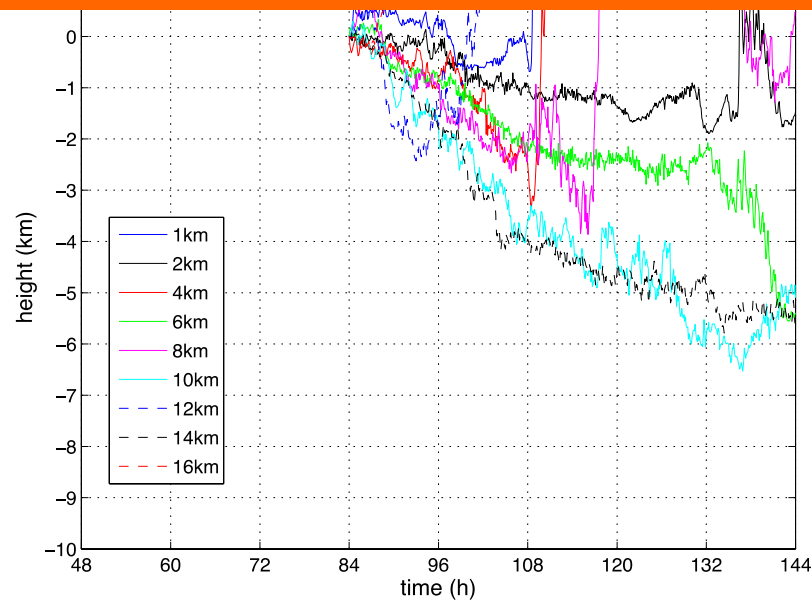
# Radius-Height: SHEAR10



# Vertical Displacement vs. Time: SHEAR5



# Vertical Displacement vs. Time: SHEAR10





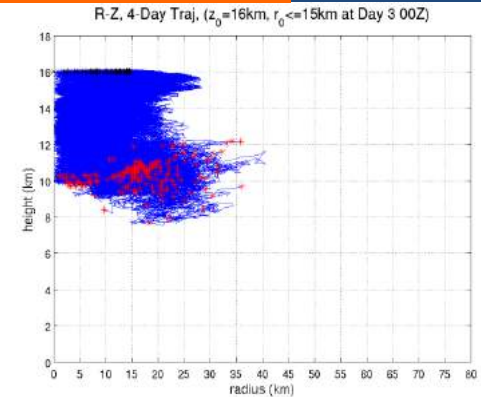
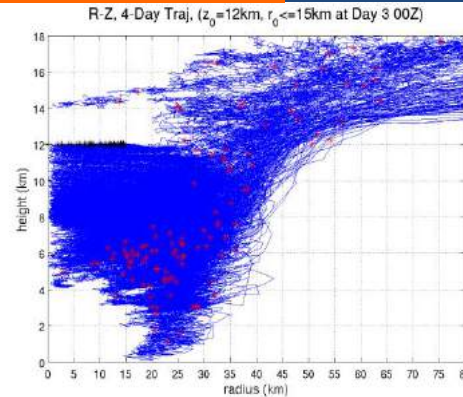
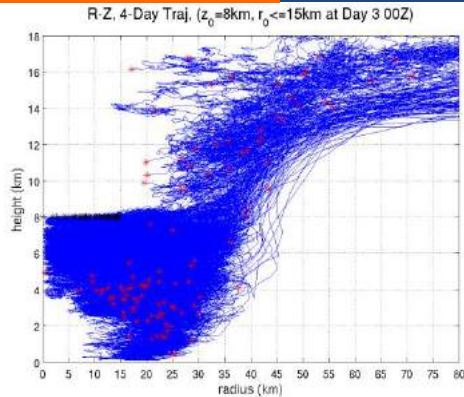
# 96-h Forward Trajectories

Z=8km

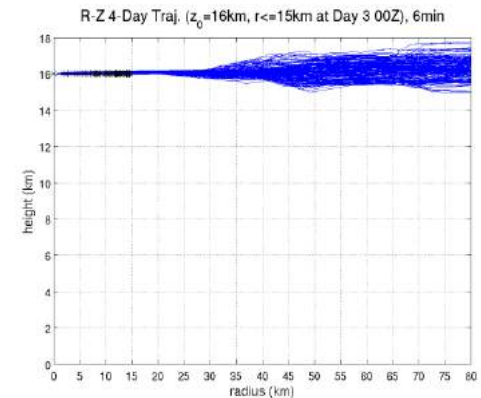
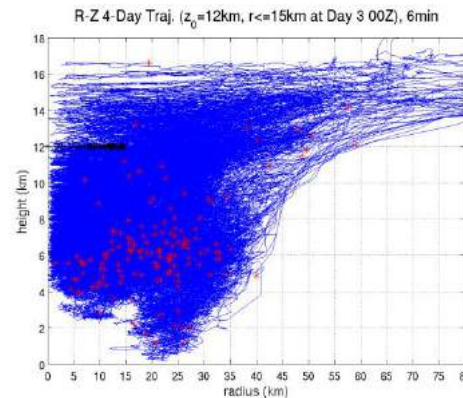
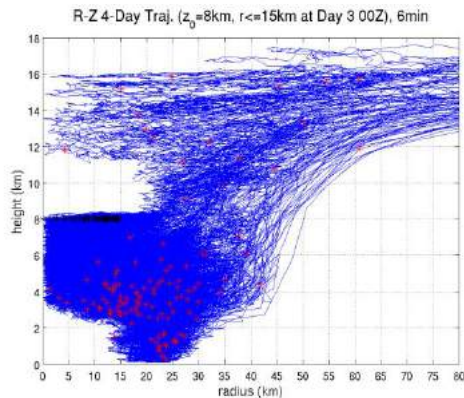
Z=12km

Z=16km

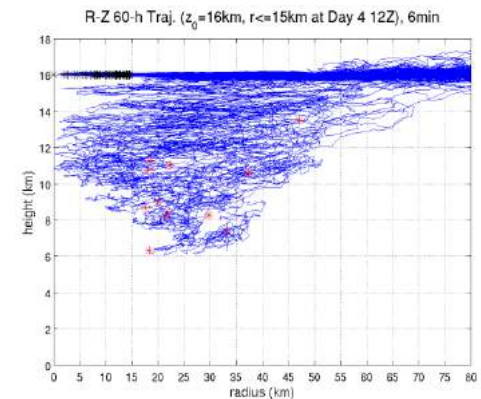
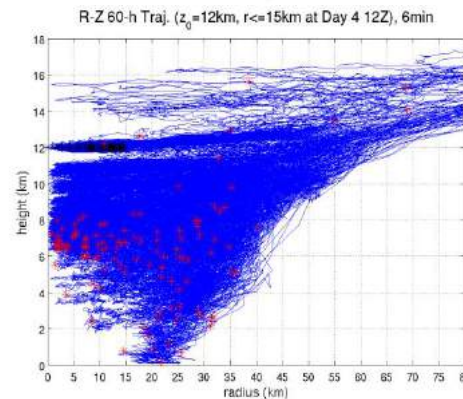
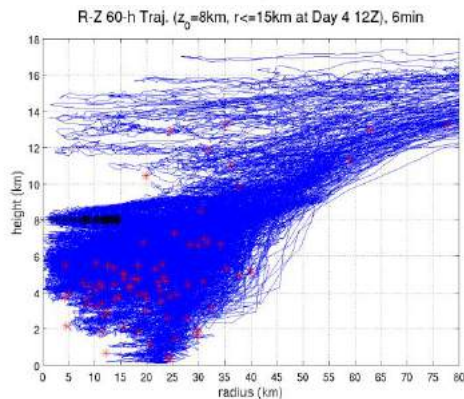
NOFLOW



SHEAR5



SHEAR10



# Summary and Conclusions #2

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- The presence of significant wind shear only slightly increases degree of stirring, for parcels within the eye.

# Summary and Conclusions #2

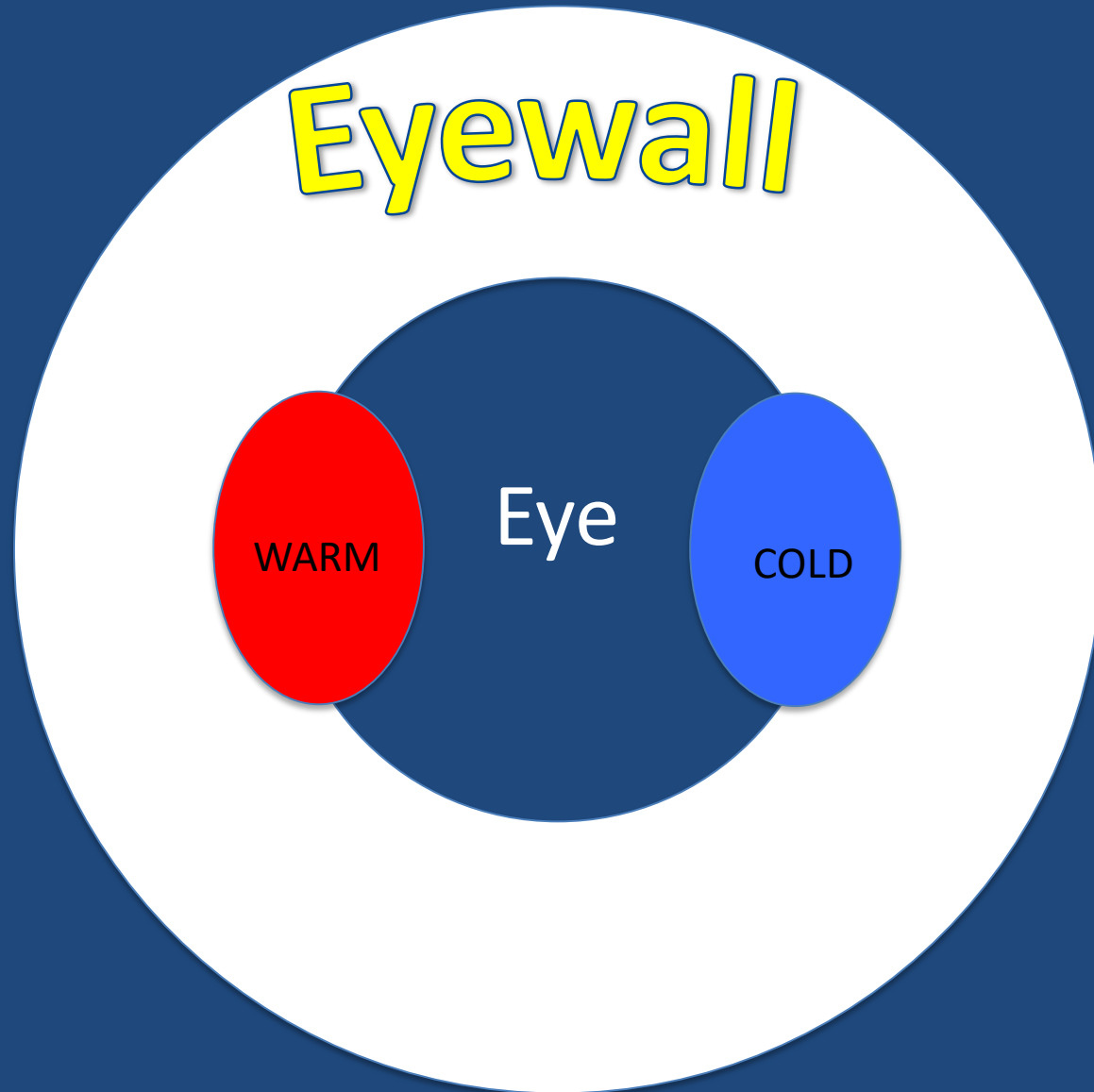
- The degree of eye/eyewall stirring is a strong function of storm intensity.
- Many parcels initially in the upper troposphere are able to descend by 5-10 km while remaining inside the eye.
- The presence of significant wind shear only slightly increases degree of stirring, for parcels within the eye.
- At the eye/eyewall interface, wind shear does greatly increase stirring. (not shown...in the Bonus Slides!)



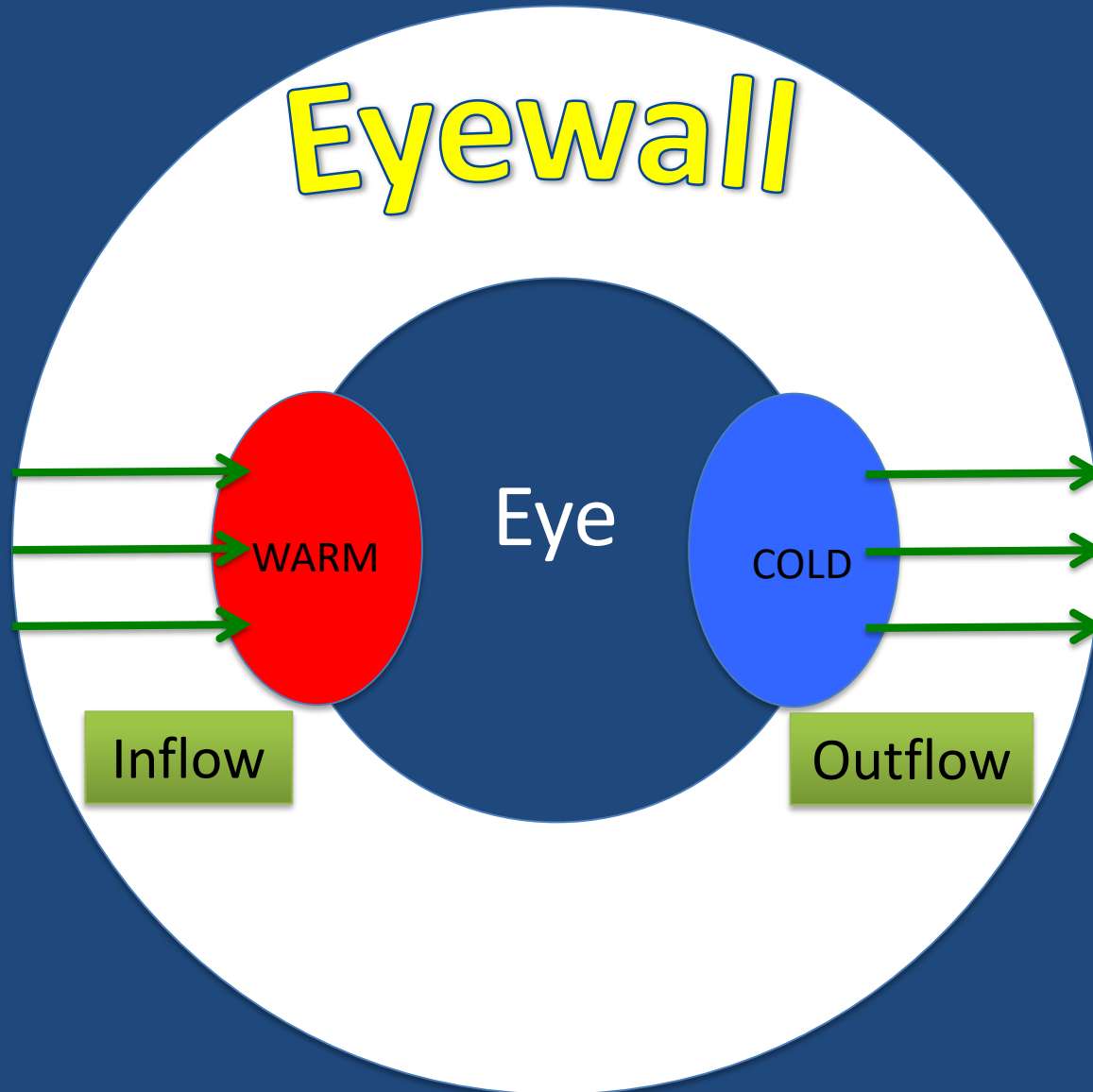
# What is Eddy Radial Advection?



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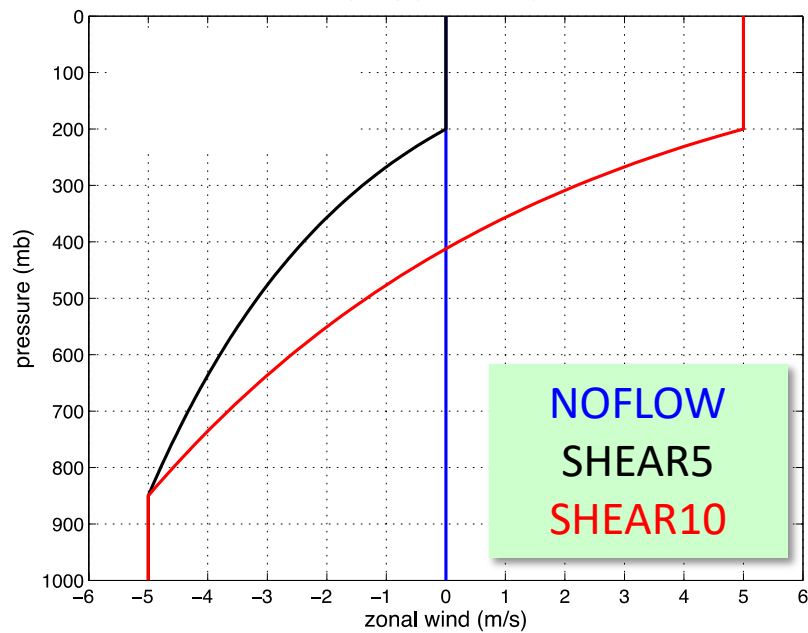
# What is Eddy Radial Advection?



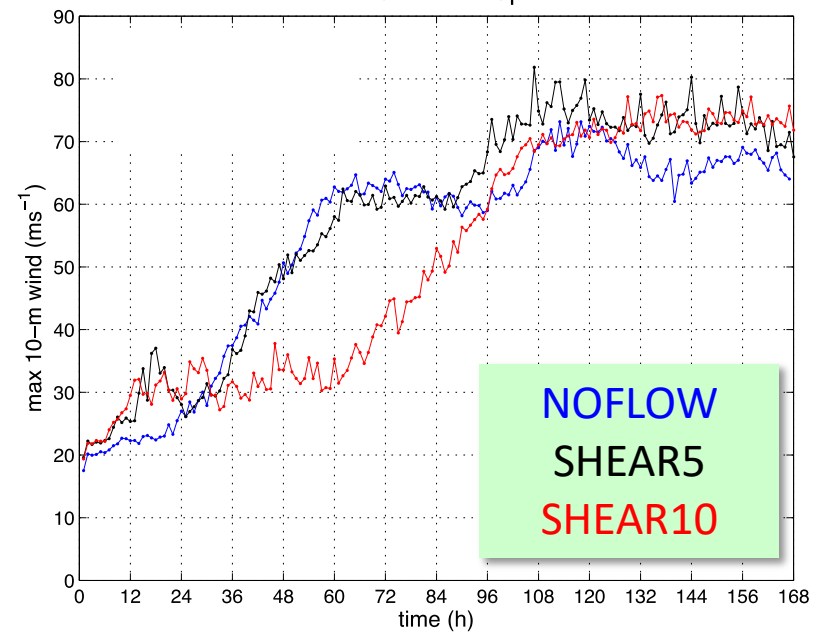
# What happens if we add shear?

- Real TCs are embedded in environmental flows that are vertically sheared.
- Shear is known to have a strong effect on storm intensity and structure.
- How does the warm core change when there is shear?

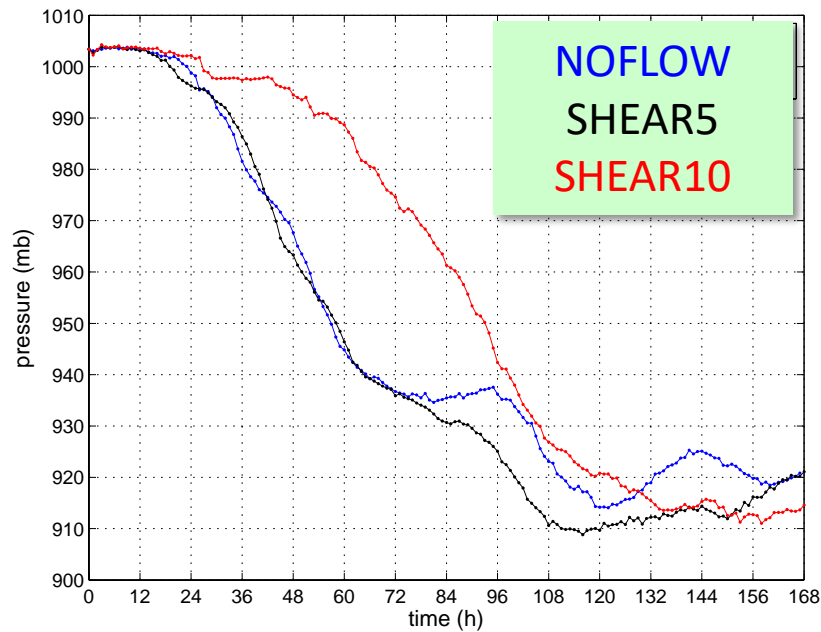
Initial Profiles of Mean Zonal Wind



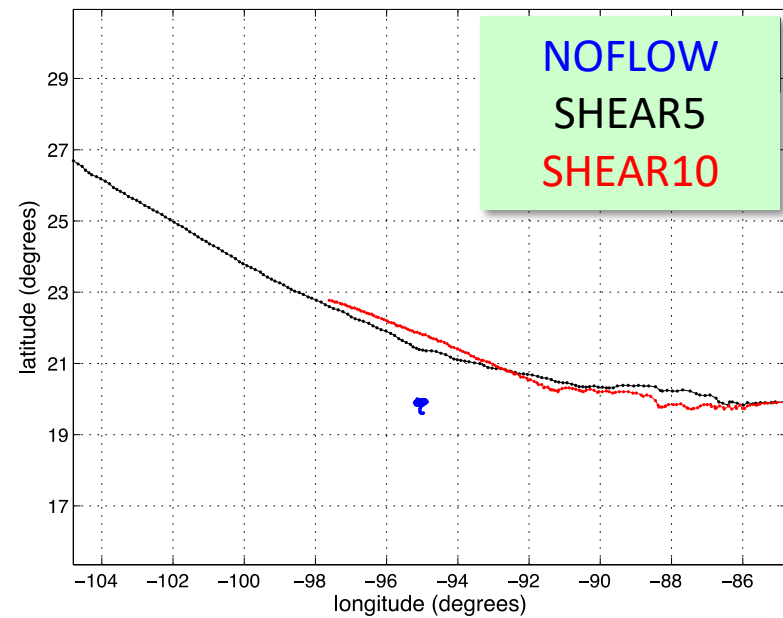
Max 10 m Wind Speed



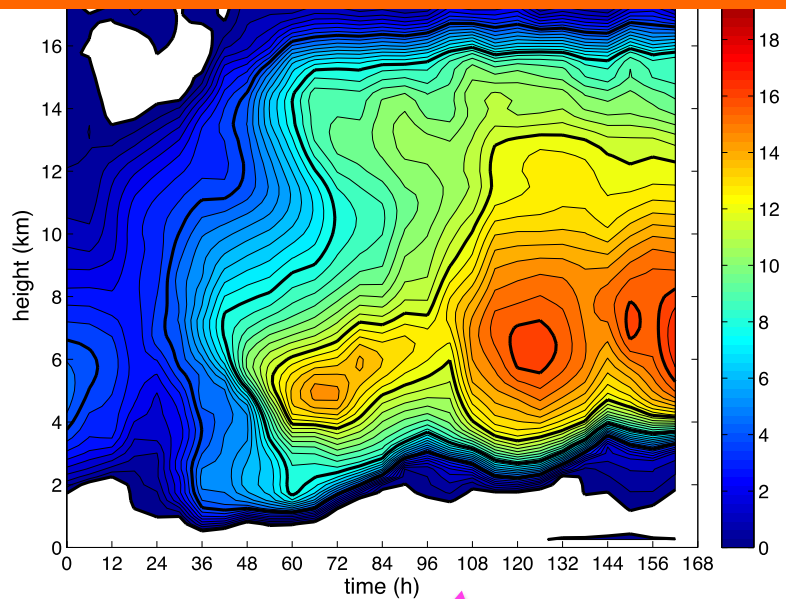
Minimum Surface Pressure



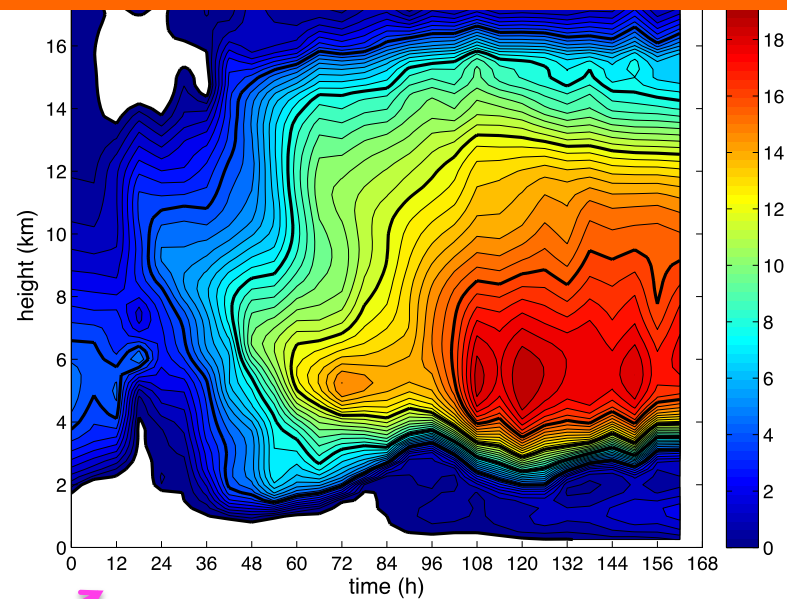
Track



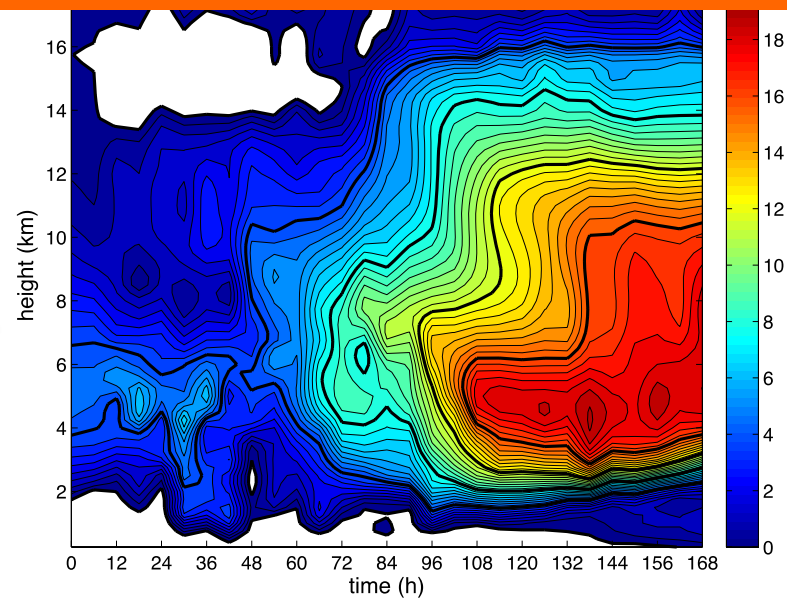
NOFLOW



SHEAR5



SHEAR10



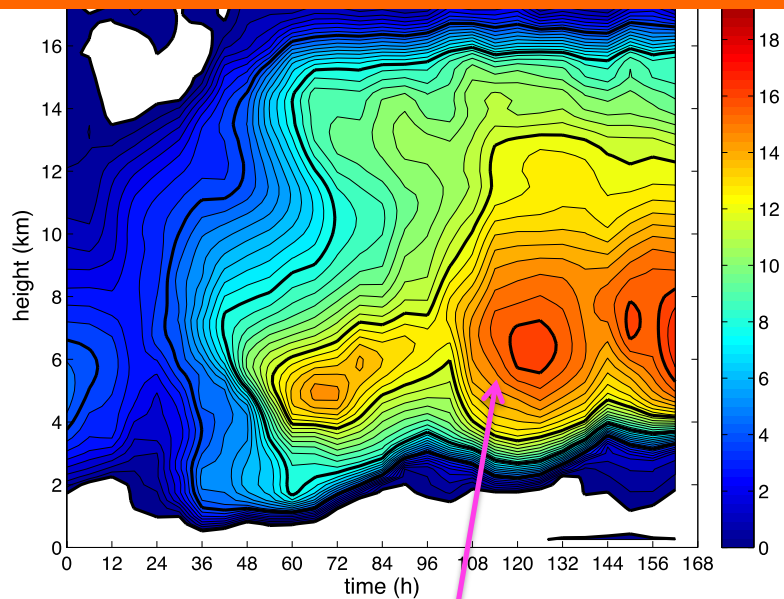
Perturbation  
Temperature at Center

Height

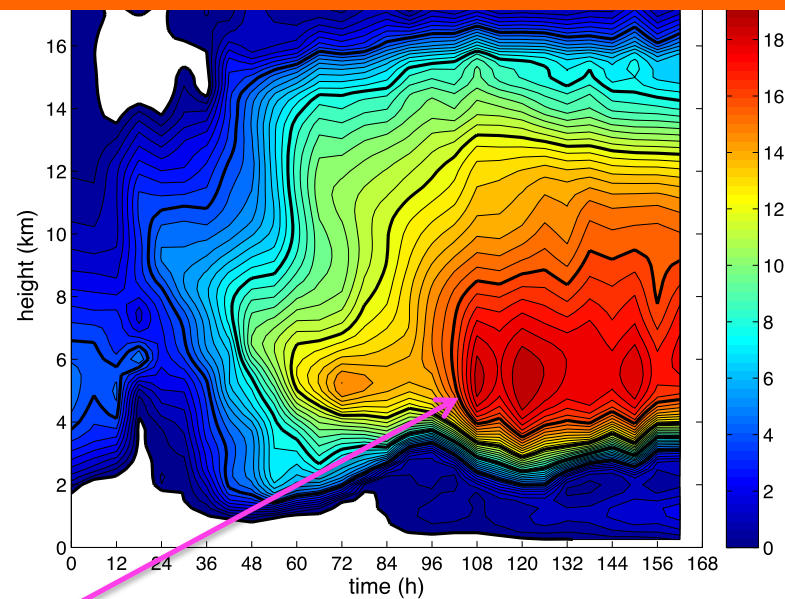
Time



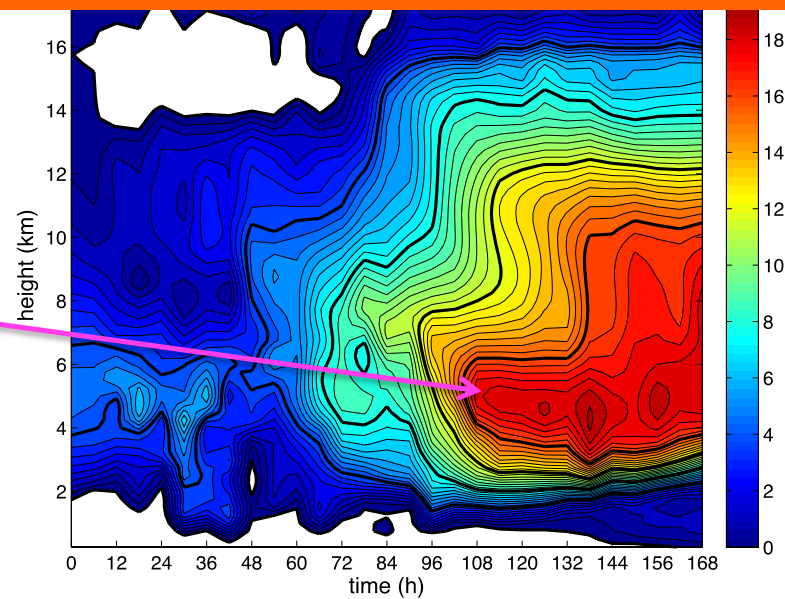
NOFLOW



SHEAR5



SHEAR10



Height of maximum is  
not altered by shear.

Height

Time