Tropical cyclone intensification

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A quote and questions

I. N. James, Introduction to Circulating Atmospheres, p93, when referring to the Held-Hou model for the Hadley circulation:

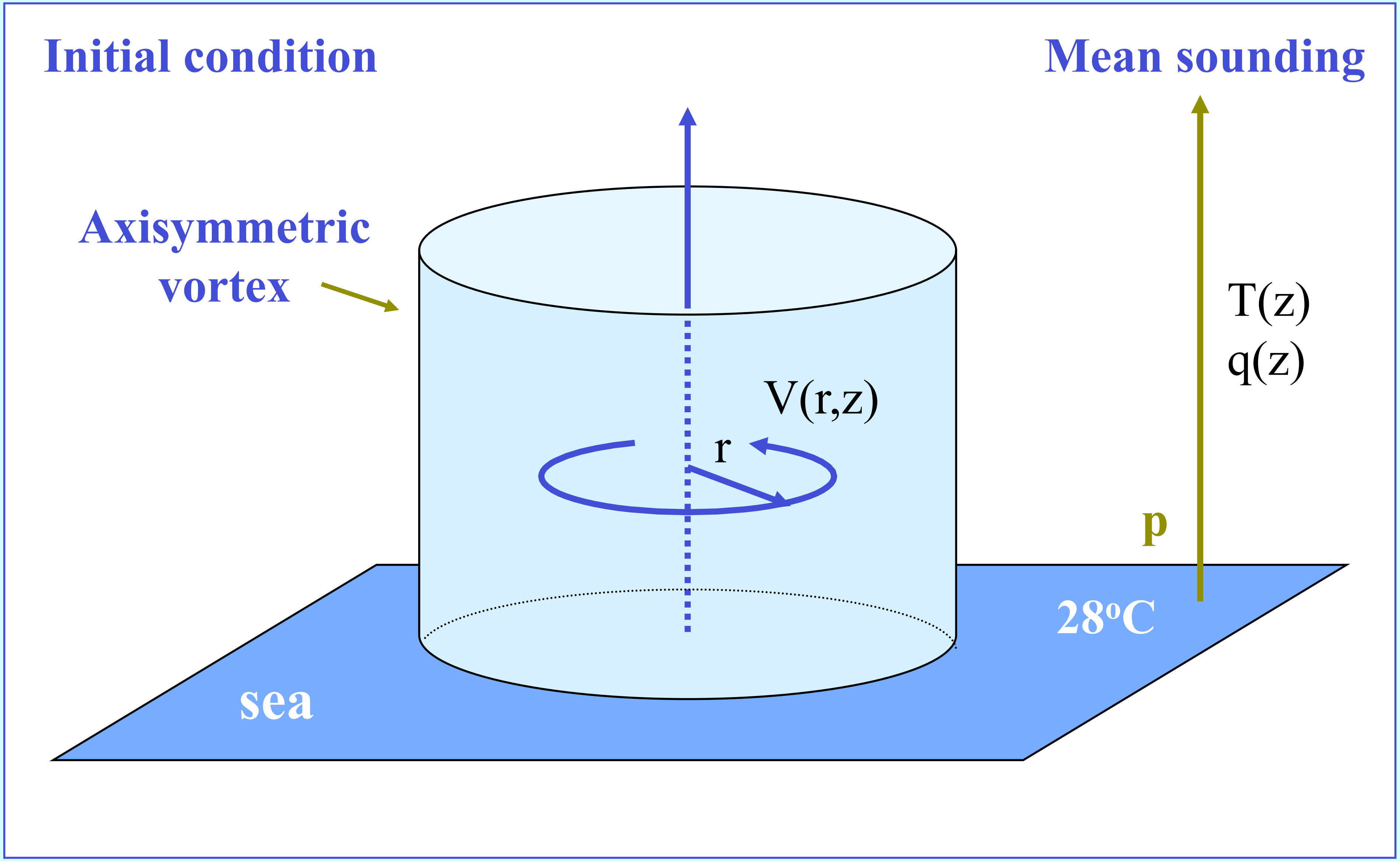
- " … . This is not to say that using simple models is folly. Indeed the aim of any scientific modelling is to separate crucial from incidental mechanisms. Comprehensive complexity is no virtue in modelling, but rather an admission of failure."

- What is the analogue of the Eady Problem for hurricanes?
- What are the basic dynamics of hurricane intensification?

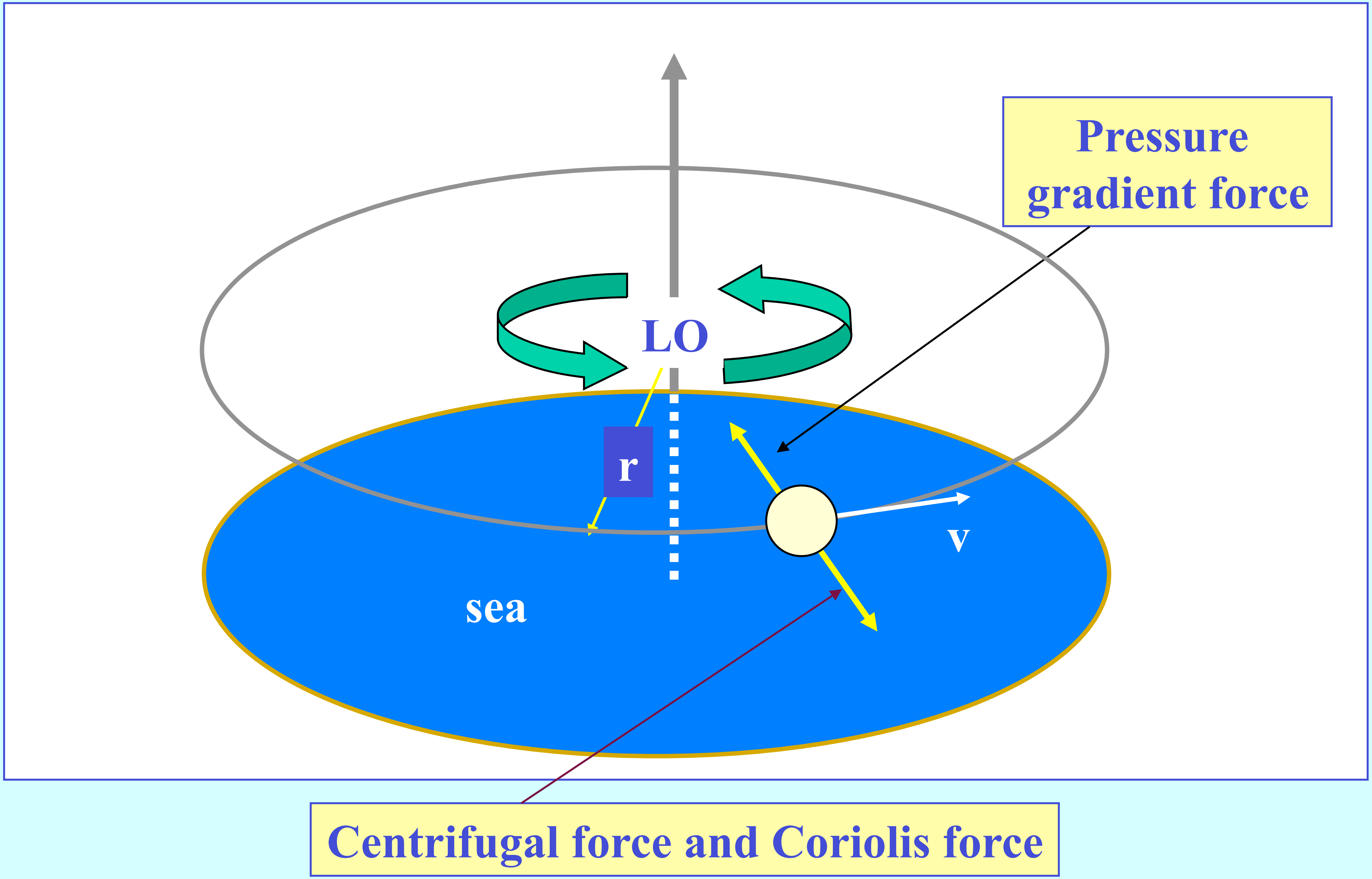
Topics

1. How do tropical cyclones intensify?
   - The basic thought experiment for intensification
   - Important physical principles
3. Paradigms for intensification
4. Recent discoveries using idealized model simulations with simple physics
   - Dynamics of vortex spin up
   - Is WISHE relevant?
   - Axisymmetric view of spin up – comparison with the other paradigms
5. New frontiers

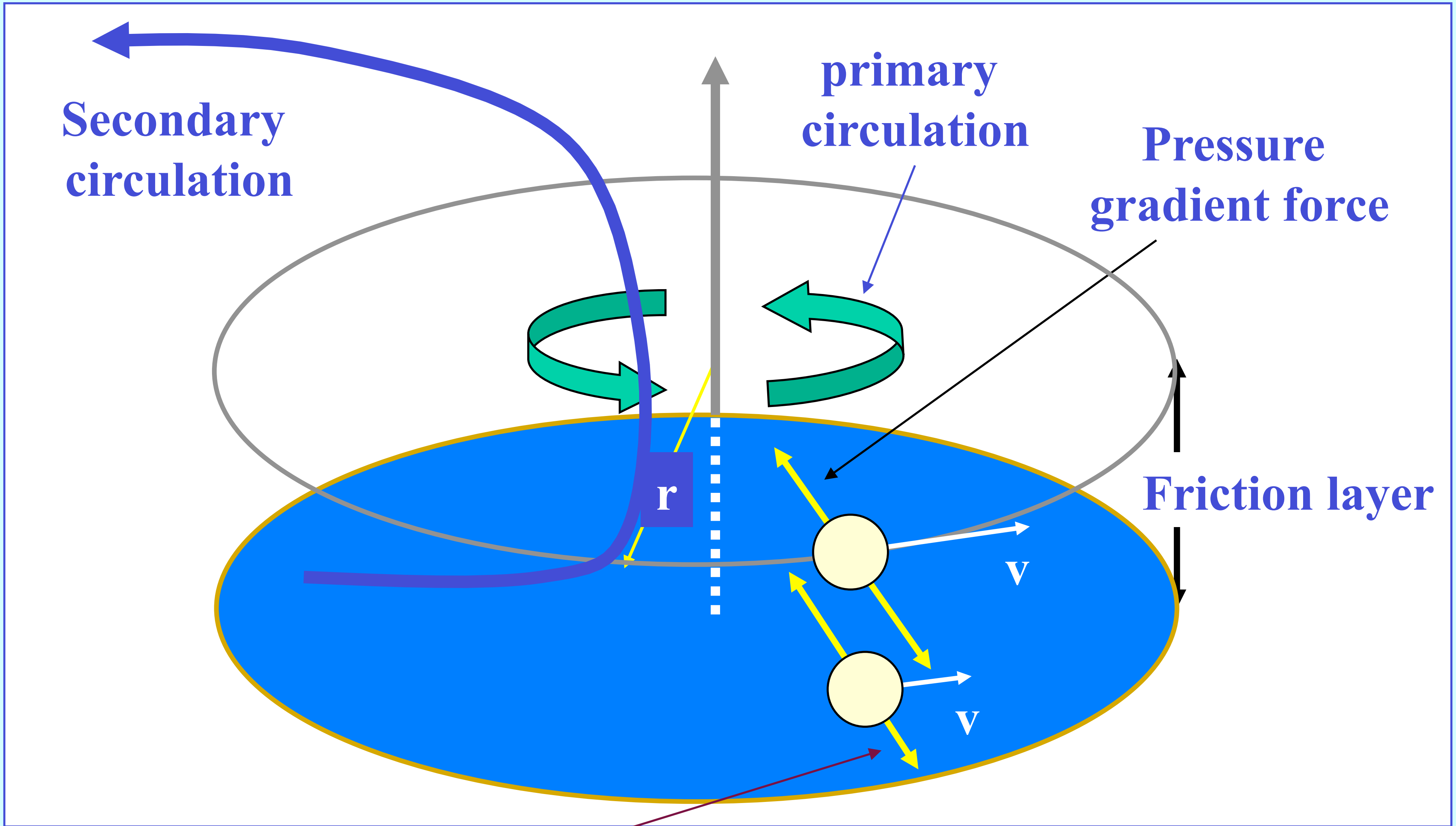
The basic thought experiment for intensification



The primary circulation



Frictionally-induced secondary circulation



Centrifugal force and Coriolis force are reduced by friction

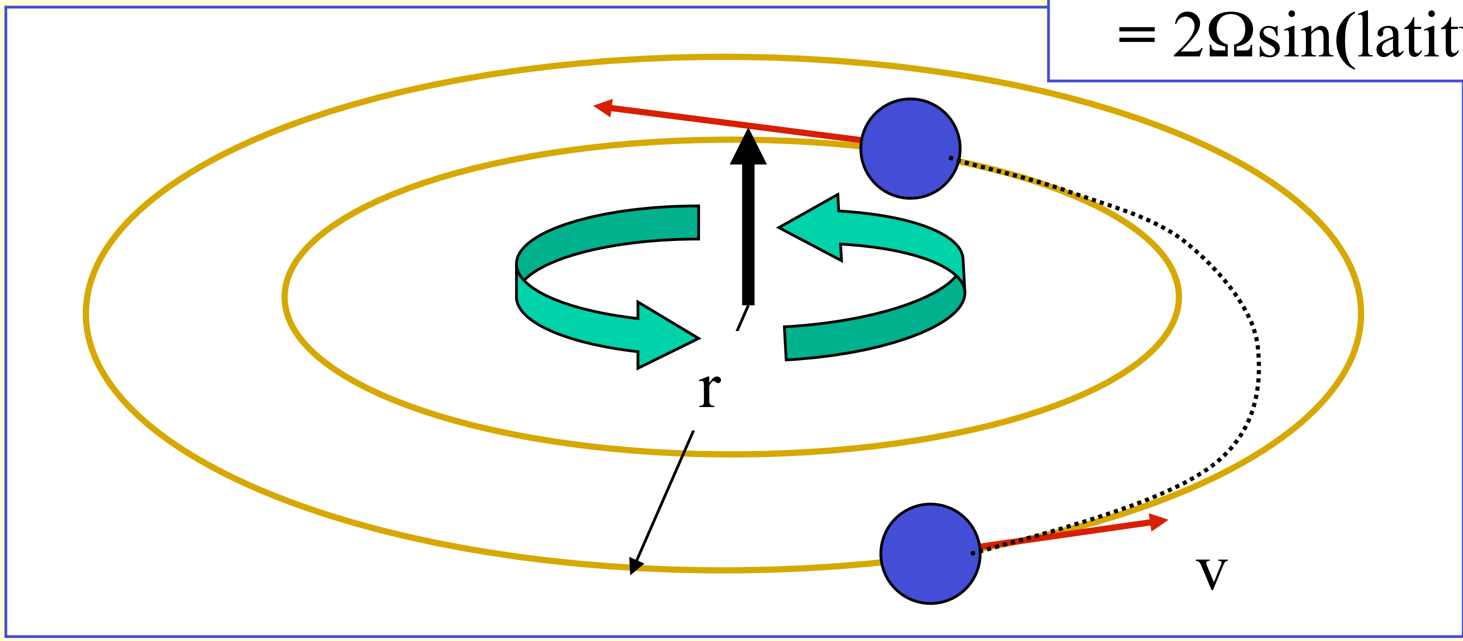
“Tea cup” Experiment

Hurricane intensification

- **Basic principle**
  - **Conservation of absolute angular momentum:**

$$M = rv + r^2f/2$$

f = Coriolis parameter
$= 2\Omega \sin(\text{latitude})$



$v = M/r - rf/2$ ⇨ **If r decreases, v increases!**

⇨ **Spin up requires radial convergence**

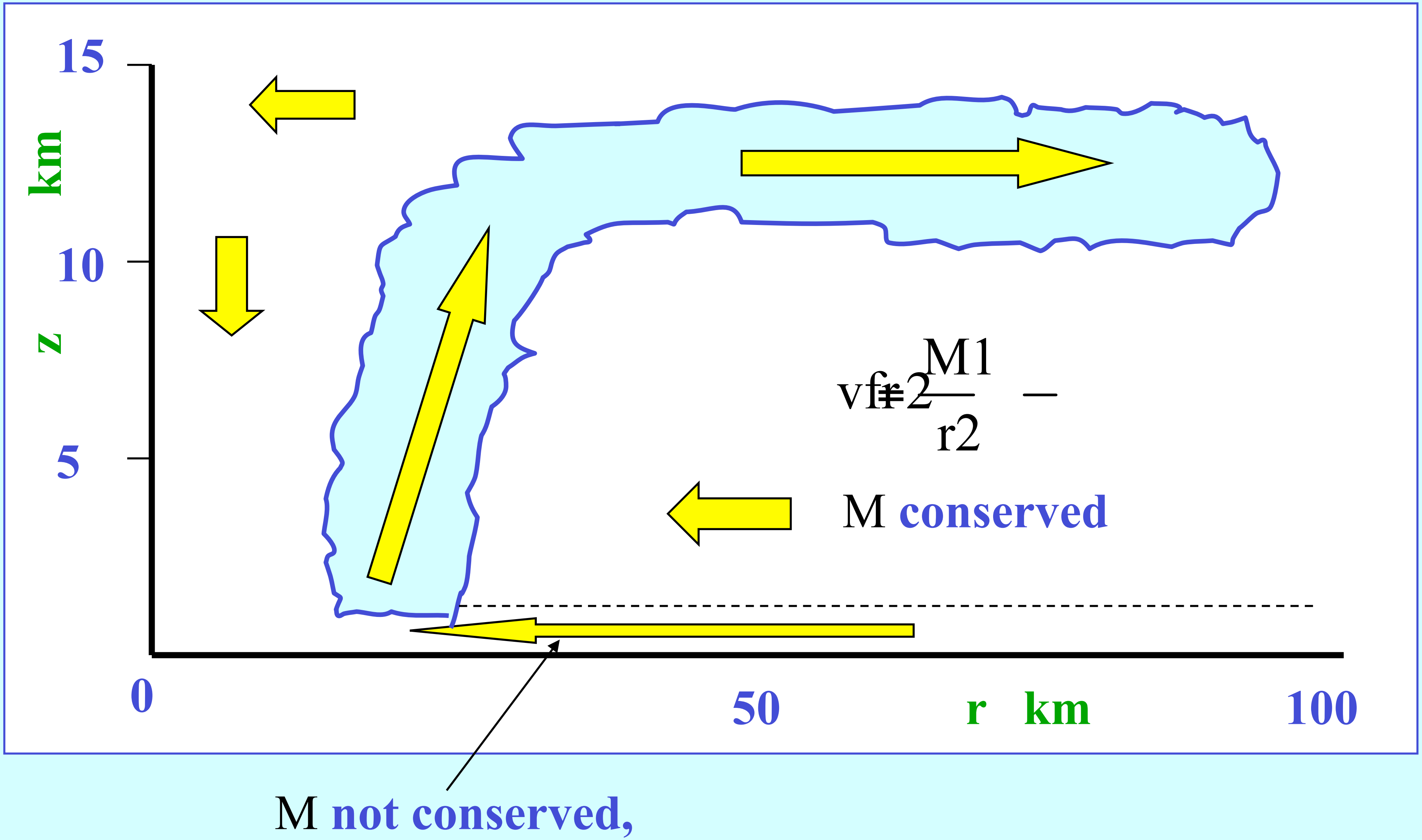
Paradigms for intensification

1. **Conventional view articulated by Ooyama (1969, 1982), Willoughby (AMM 1998, WMO, 1995) involving convectively-induced convergence together with absolute angular momentum conservation above the boundary layer.**

2. **Thermodynamic view (E-theory) articulated by Emanuel (1989, 1994, 1995, 1997) involving the WISHE mechanism.**

3. **Asymmetric view (M-theory) invoking "Vortical Hot Towers" or VHTs (Hendricks *et al*. 2004, Montgomery *et al*. 2006, Nguyen *et al*. 2008, Shin and Smith 2008, Montgomery *et al*. 2009, Smith *et al*. 2009, Hoang *et al*. 2009).**

Conventional view



Thermodynamic view: A steady hurricane model

15 MARCH 1986 KERRY A. EMANUEL

1986 **Journal of the Atmospheric Sciences**

An Air–Sea Interaction Theory for Tropical Cyclones. Part I: Steady-State Maintenance

KERRY A. EMANUEL

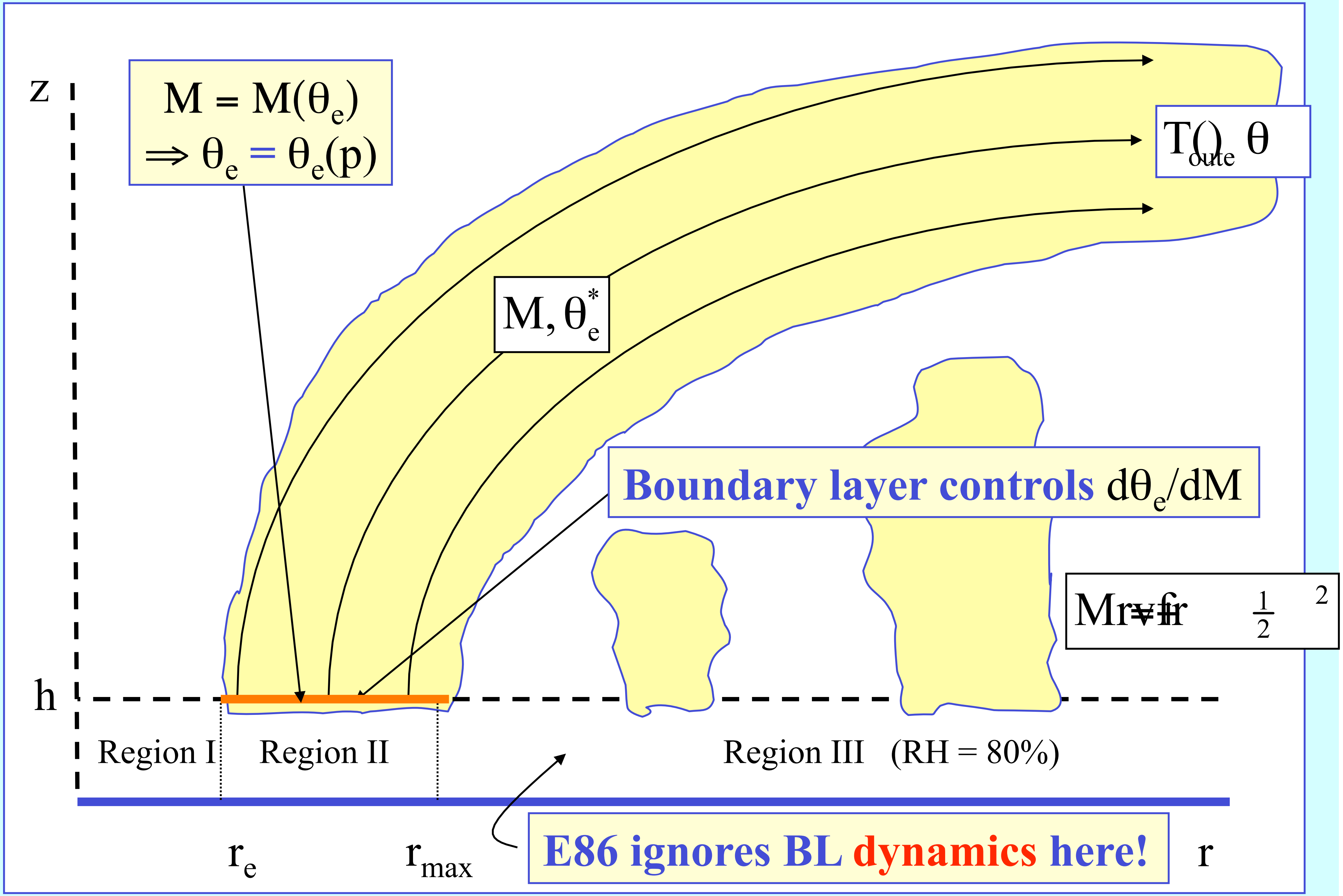
Center for Meteorology and Physical Oceanography, Massachusetts Institute of Technology, Cambridge, MA 02139

(Manuscript received 19 February 1985, in final form 29 October 1985)

ABSTRACT

Observations and numerical simulations of tropical cyclones show that evaporation from the sea surface is essential to the development of reasonably intense storms. On the other hand, the CISK hypothesis, in the form originally advanced by Charney and Eliassen, holds that initial development results from the organized release of preexisting conditional instability. In this series of papers, we explore the relative importance of ambient conditional instability and air–sea latent and sensible heat transfer in both the development and maintenance of tropical cyclones using highly idealized models. In particular, we advance the hypothesis that the intensification and maintenance of tropical cyclones depend *exclusively* on self-induced heat transfer from the ocean. In this sense, these storms may be regarded as resulting from a finite amplitude air–sea interaction instability rather than from a linear instability involving ambient potential buoyancy. In the present paper, we attempt to show that reasonably intense cyclones may be maintained in a steady state without conditional instability of ambient air. In Part II we will demonstrate that weak but finite-amplitude axisymmetric disturbances may intensify in a conditionally neutral environment.

Emanuel's 1986 steady hurricane model



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(www.interscience

Thermodynamic view has problems!

A critique of Emanuel's hurricane model and potential intensity theory

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Balanced boundary layers used in hurricane models

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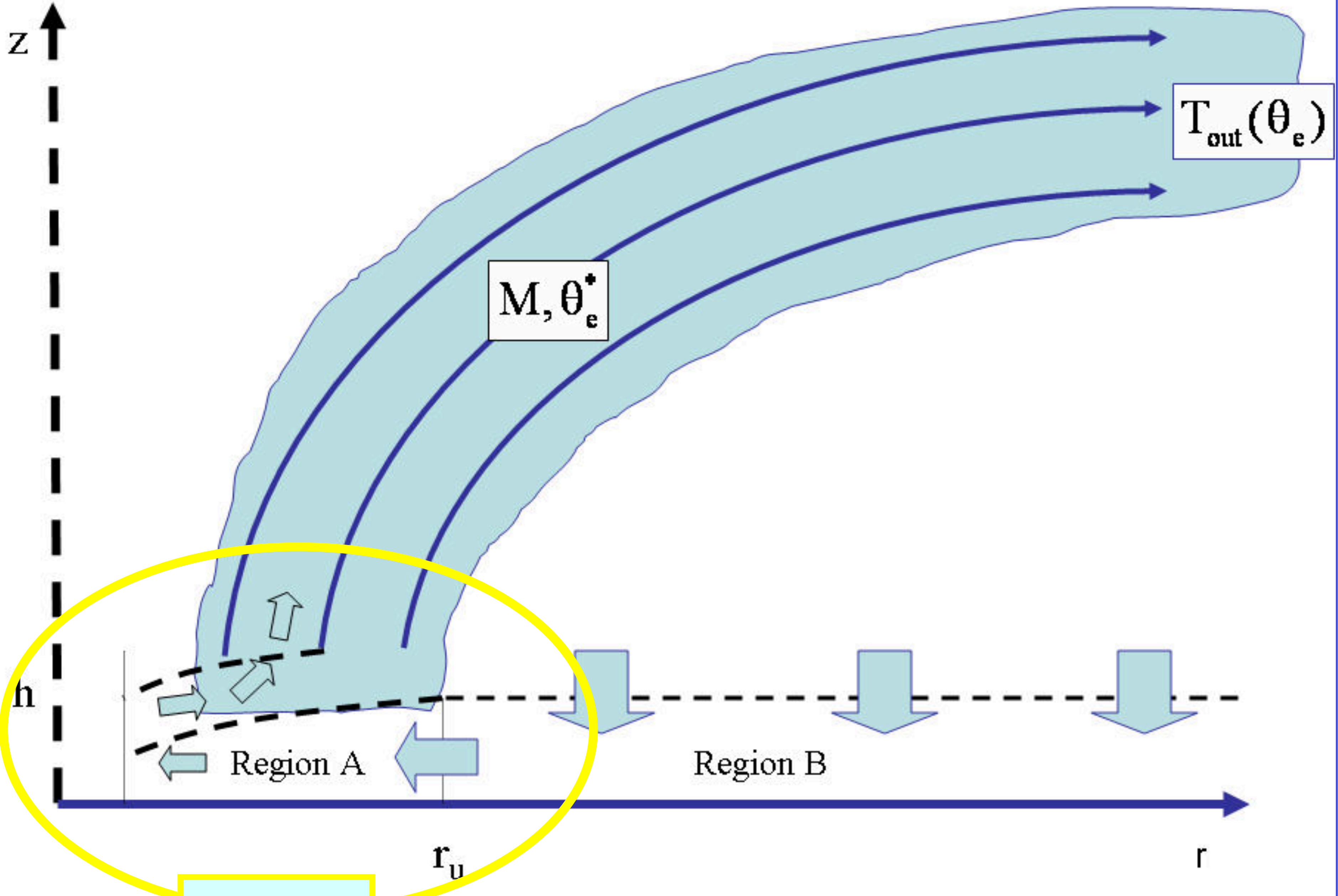
Available on my website



Revised

Cannot ignore unbalanced BL dynamics!

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Accepted subject to minor revision

Do Tropical Cyclones Intensify by WISHE?

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WISHE = Wind induced surface heat exchange

Basic air-sea interaction feedback loop:

Increase in surface wind speed =>
Increase in surface moisture transfer from the sea surface =>
Increase in "fuel supply" to the storm =>
Increasing wind speed …

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Asymmetric view

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Tropical-cyclone intensification and predictability in three dimensions

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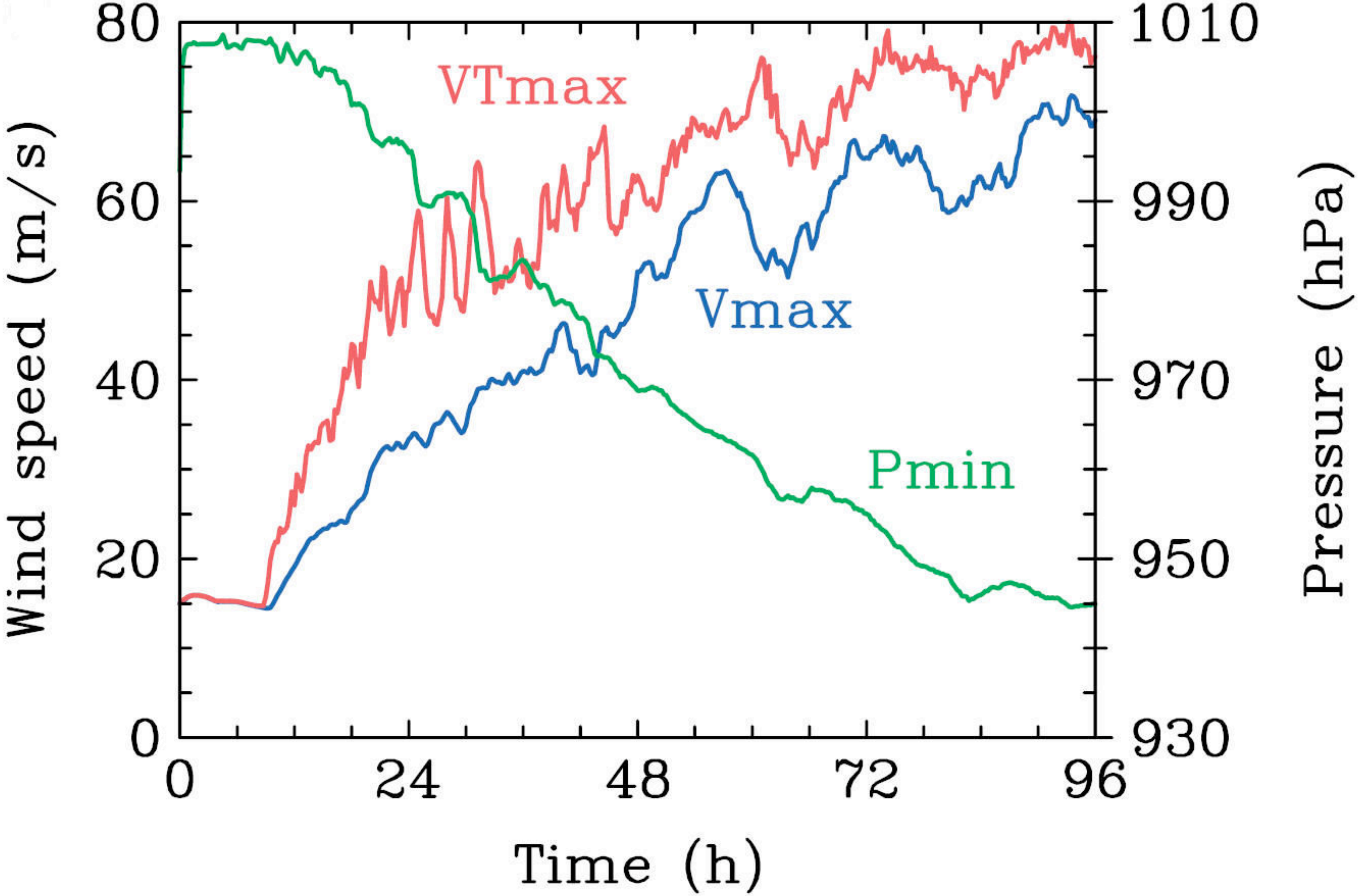
Available: http://www.meteo.physik.uni-muenchen.de/~roger

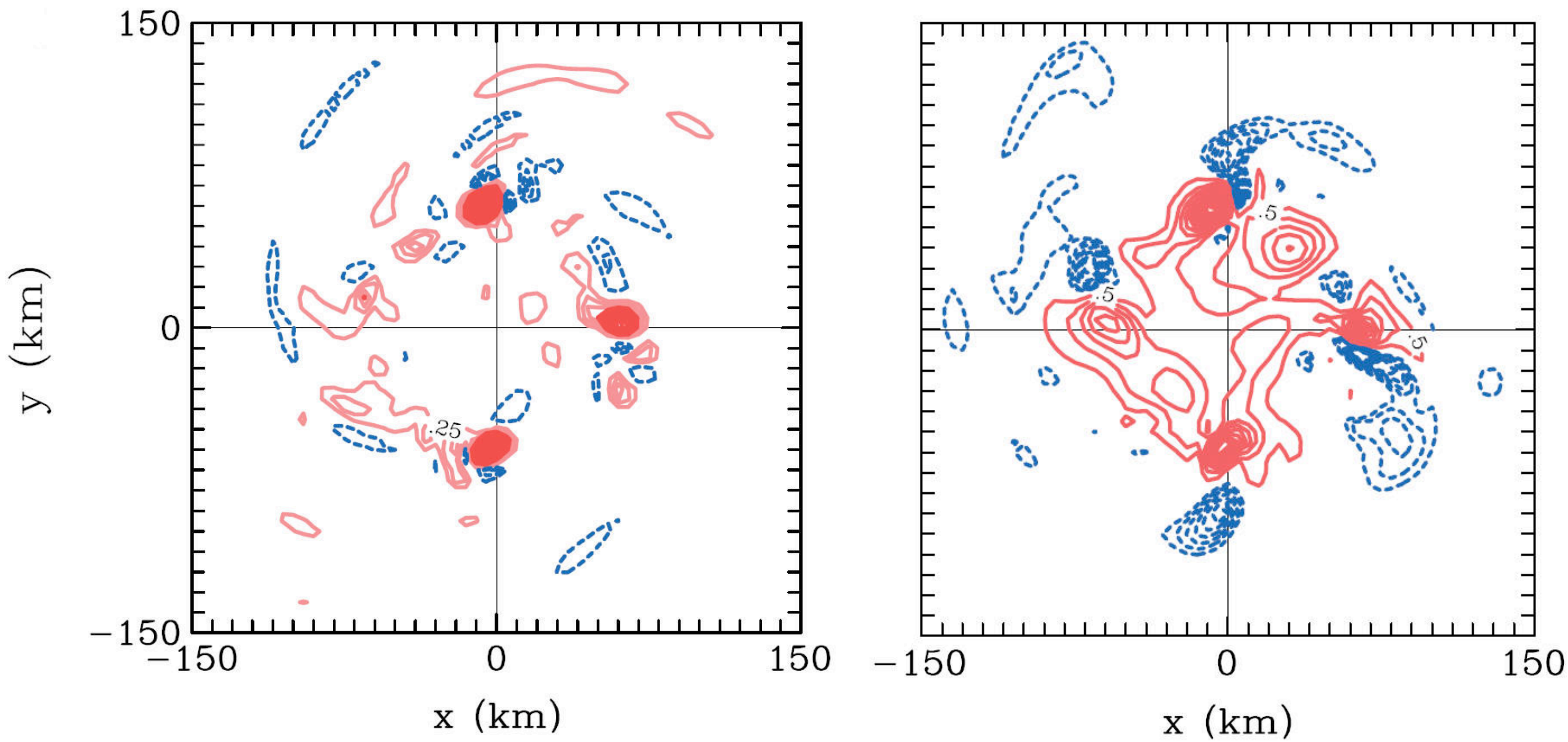
- **Idealized numerical model simulations with simple physics (MM5)**
- 5 **km** (1.67 **km**) **resolution in the finest nest,** 24 σ**-levels**

Evolution of Intensity



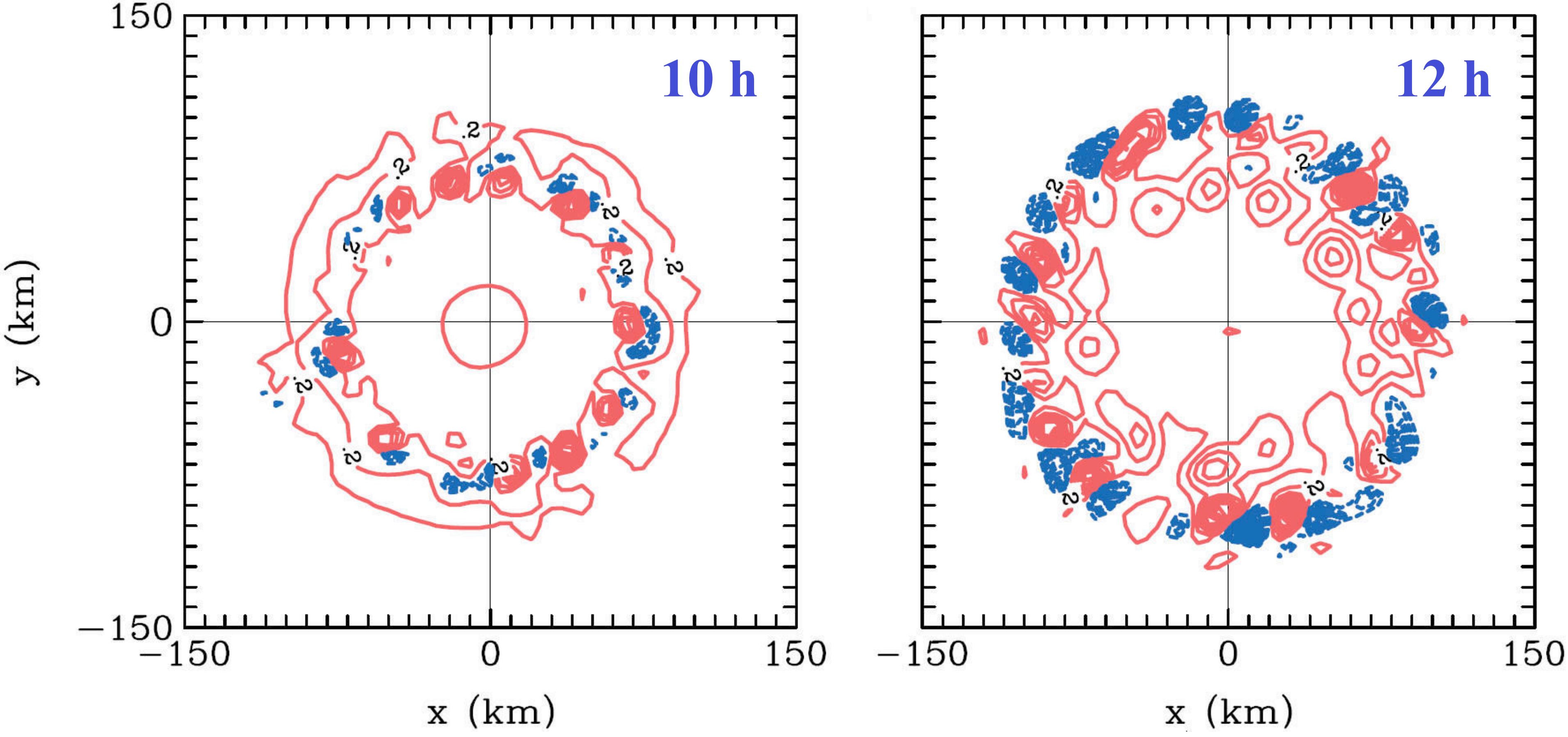
Vertical velocity\vorticity pattern at 24 h

850 mb ~ 1.5 km **850 mb**

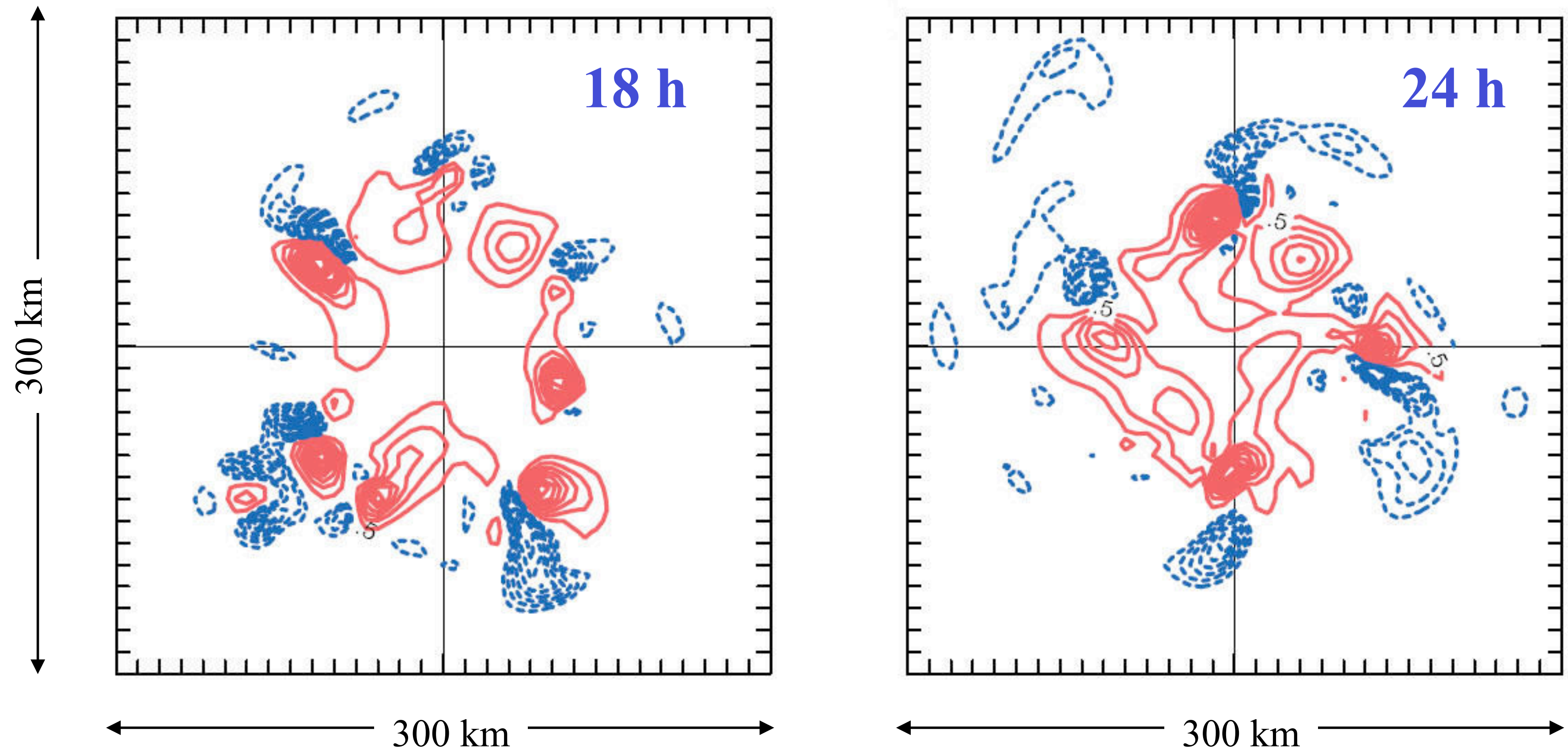


Vertical velocity **Relative vorticity**

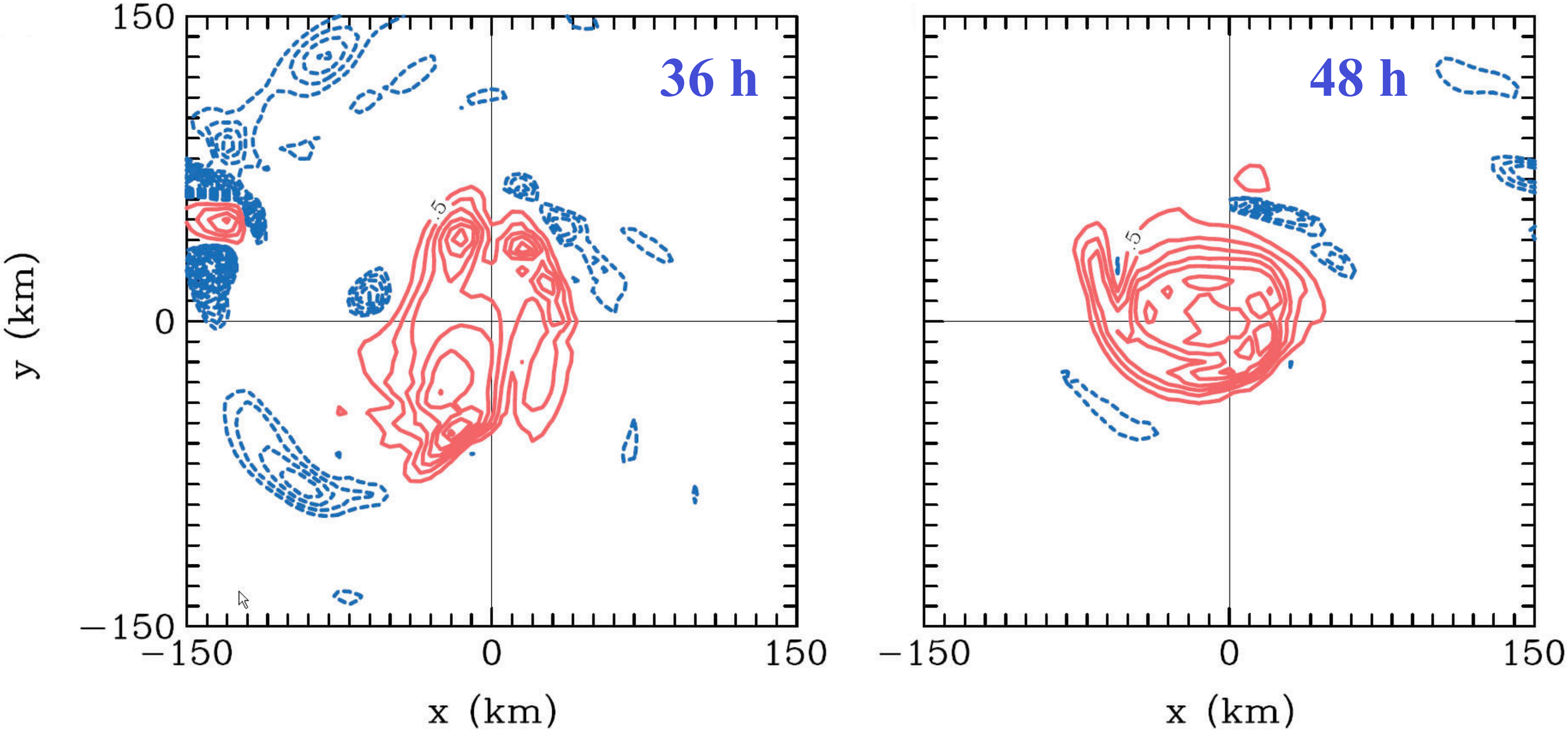
Vertical vorticity evolution at 850 mb



Vertical vorticity pattern at 850 mb



Vertical vorticity pattern at 850 mb

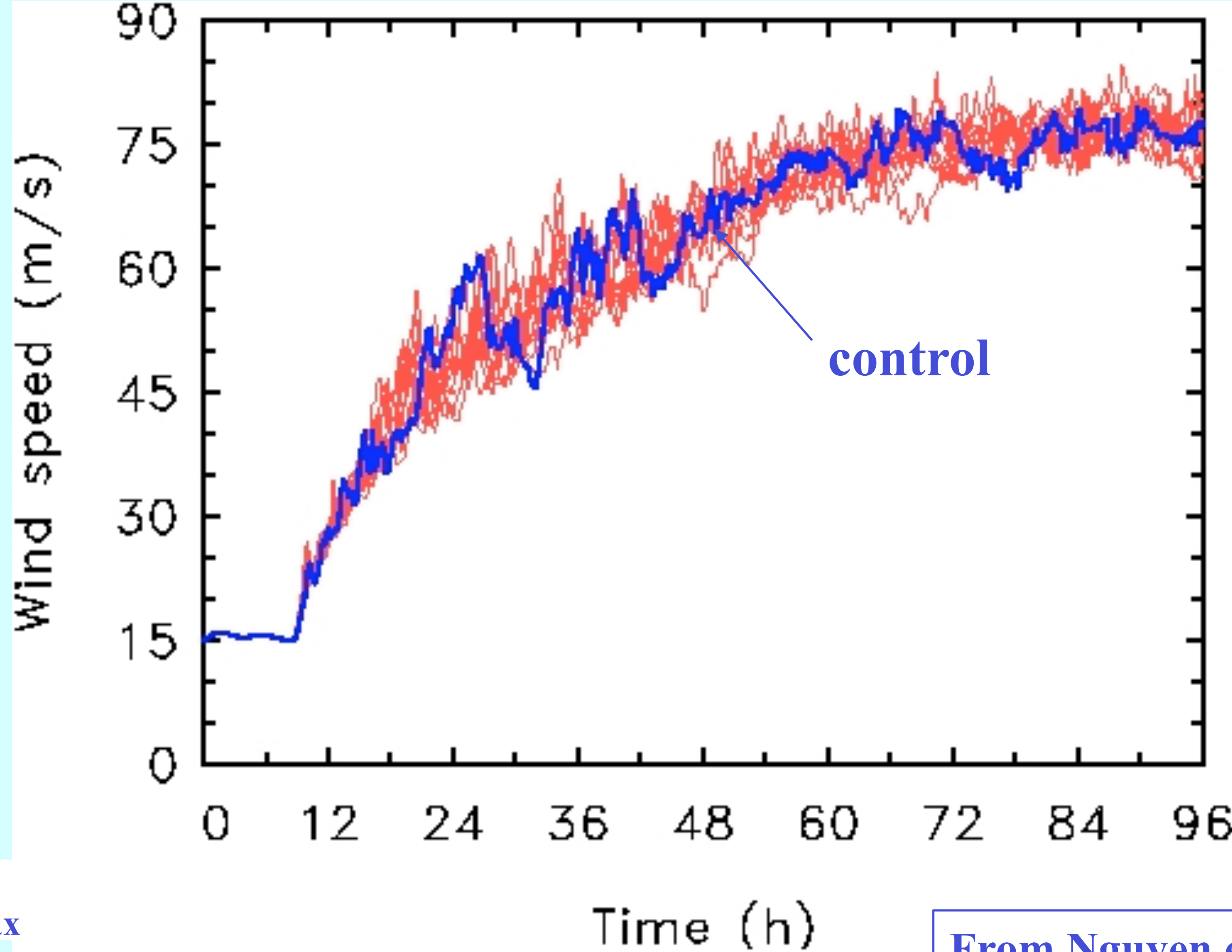


Movie 1

Interim conclusions

- **The flow evolution is intrinsically asymmetric.**
- **The asymmetries are associated with rotating convective structures that are essentially stochastic in nature.**
- **We call these structures vortical hot towers (VHTs).**
- **Their convective nature suggests that the structures may be sensitive to the low-level moisture distribution, which is known to possess significant variability on small space scales.**
- **Suggests a need for ensemble experiments with random moisture perturbations.**

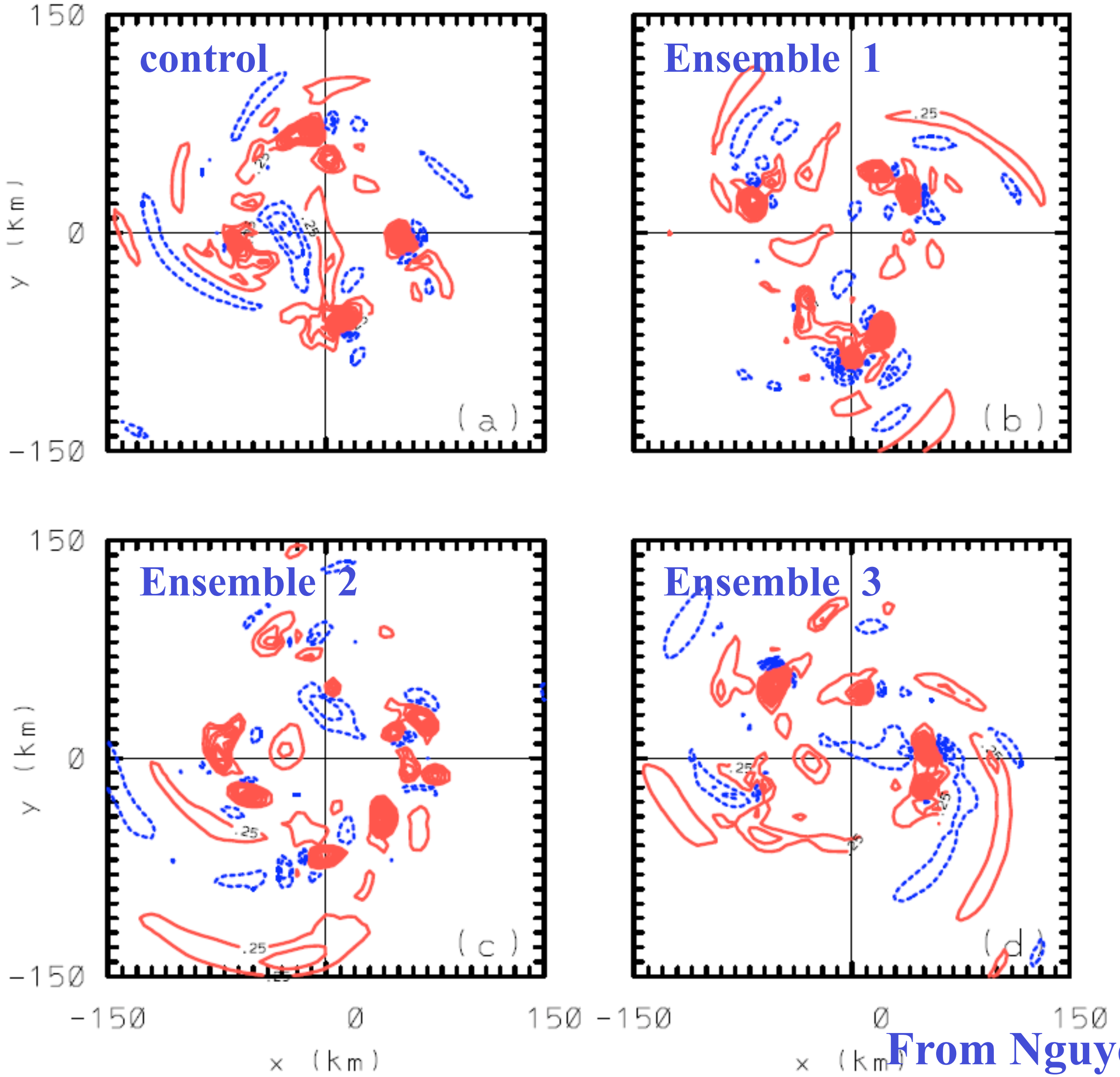
Evolution of local intensity: 10 ensembles



VT_{max}

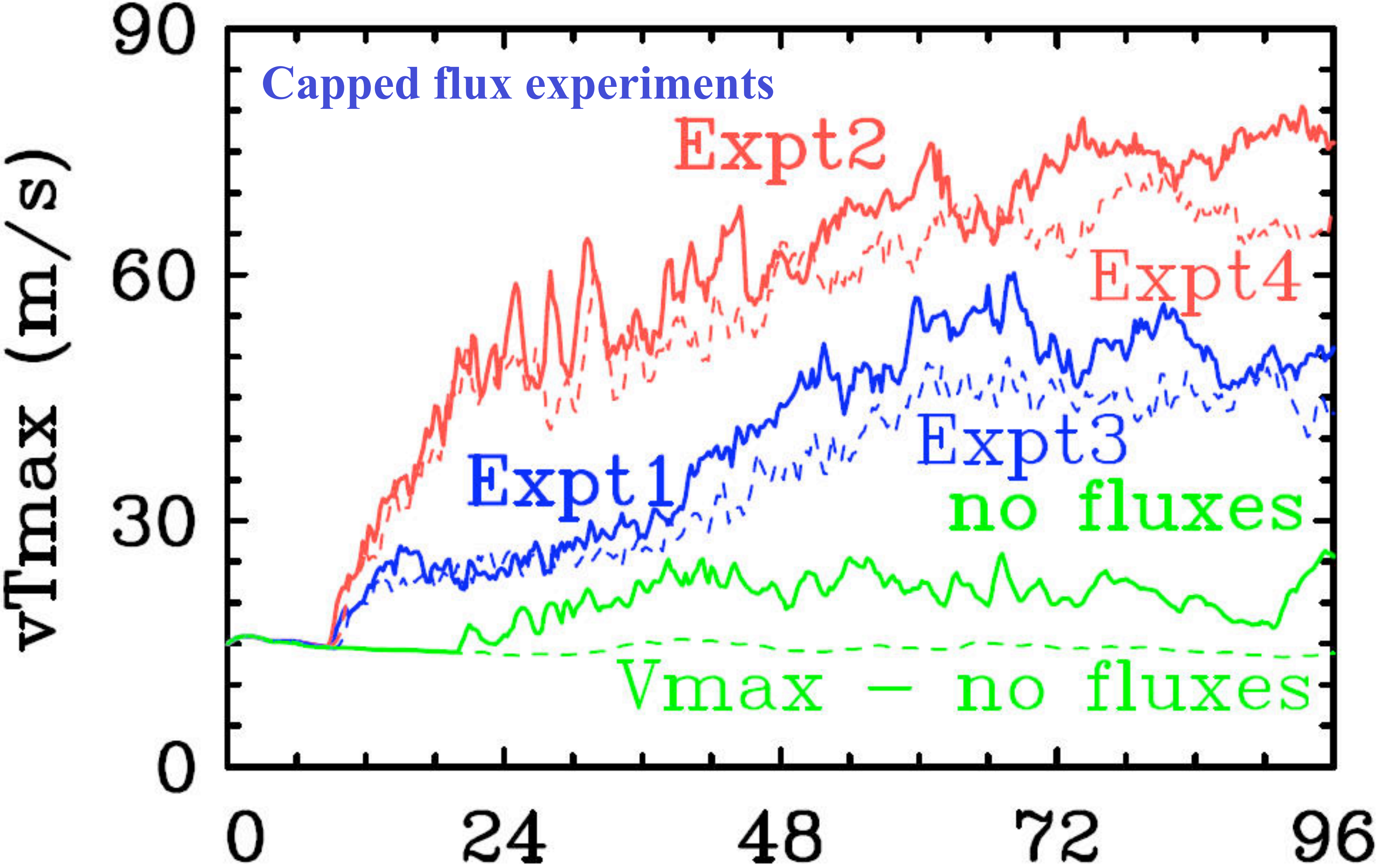
From Nguyen et al. 2008

Vertical velocity pattern at 850 mb at 24 h



From Nguyen et al. 2008

Is WISHE relevant?



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Tropical cyclone spin up revisited

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[b] *Dept. of Meteorology, Naval Postgraduate School, Monterey, CA & NOAA's Hurricane Research Division*

Abstract:
We present numerical experiments to investigate axisymmetric interpretations of tropical-cyclone spin up in a three-dimensional model. Two mechanisms are identified for the spin up of the mean tangential circulation. The first involves the convergence of absolute angular momentum above the boundary layer and is a mechanism to spin up the outer circulation, i.e. to increase the vortex size. The second involves the convergence of absolute angular momentum within the boundary layer and is a mechanism to spin up the inner core. It is associated with the development of supergradient wind speeds in the boundary layer. The existence of these two mechanisms provides a plausible physical explanation for certain long-standing observations of typhoons by Weatherford and Gray, which indicate that inner-core changes in the azimuthal-mean tangential wind speed often occur independently from those in the outer-core. The unbalanced dynamics in the inner core region are important in determining the maximum radial and tangential flow speeds that can be attained, and therefore important in determining the azimuthal-mean intensity of the vortex. We illustrate the importance of unbalanced flow in the boundary layer with a simple thought experiment. The analyses and interpretations presented are novel and support a recent hypothesis of the boundary layer in the inner core region.
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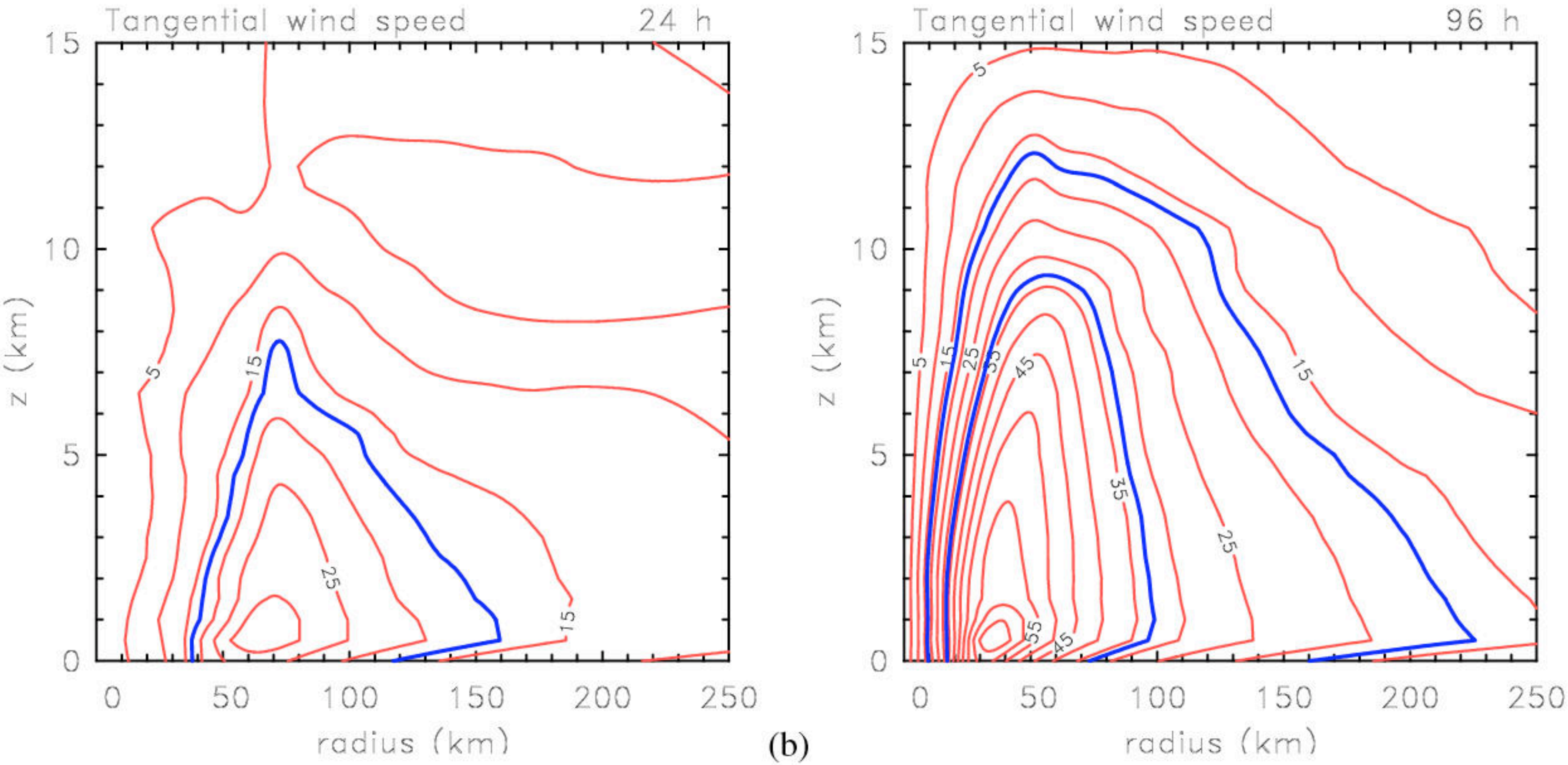
In press

Azimuthal average of the Nguyen *et al*. control calculation

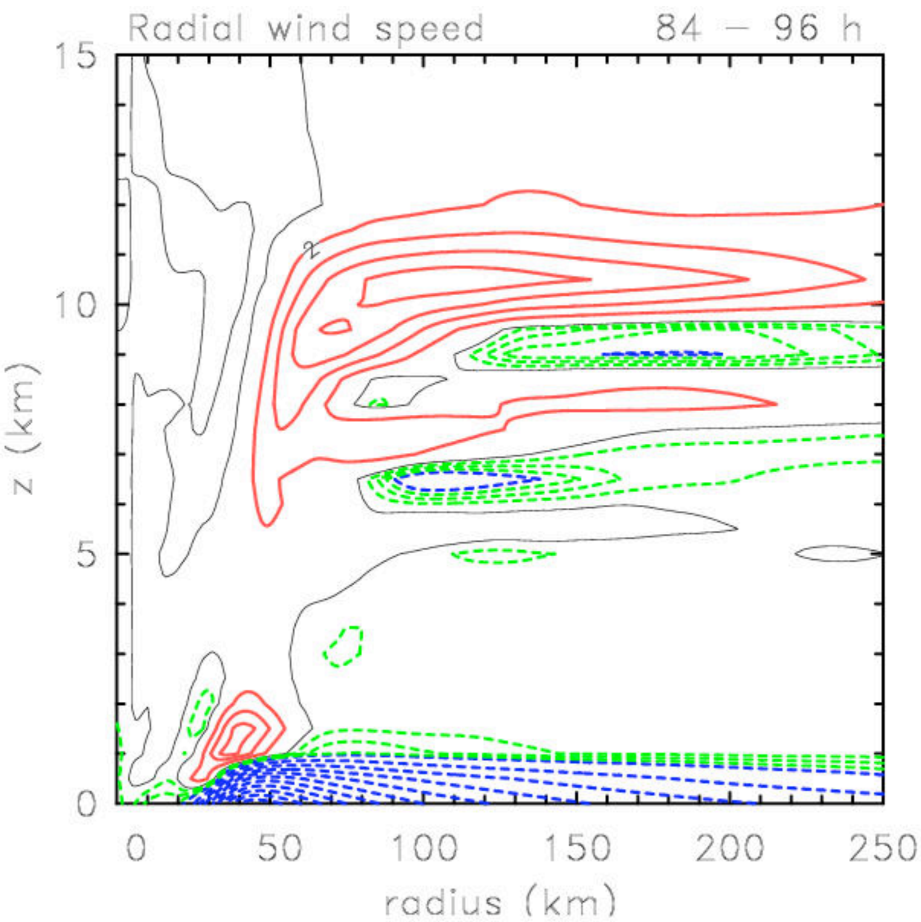
Tangential wind speed



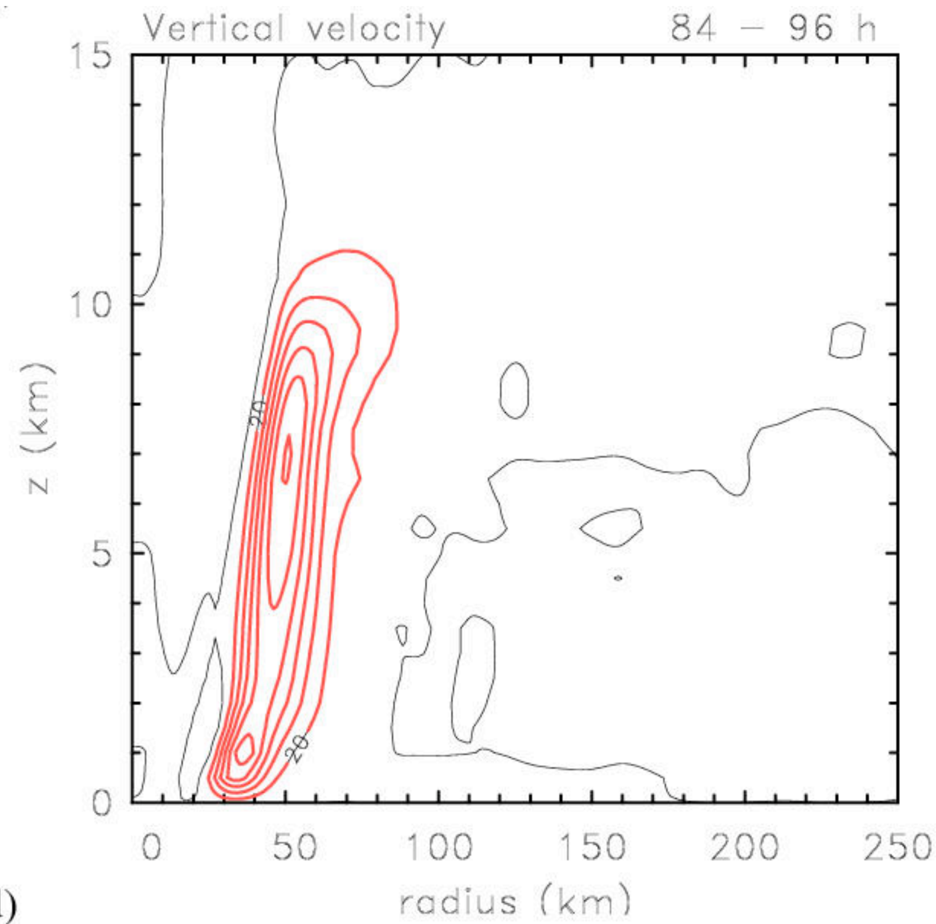
(b)

Radial wind speed

vertical velocity

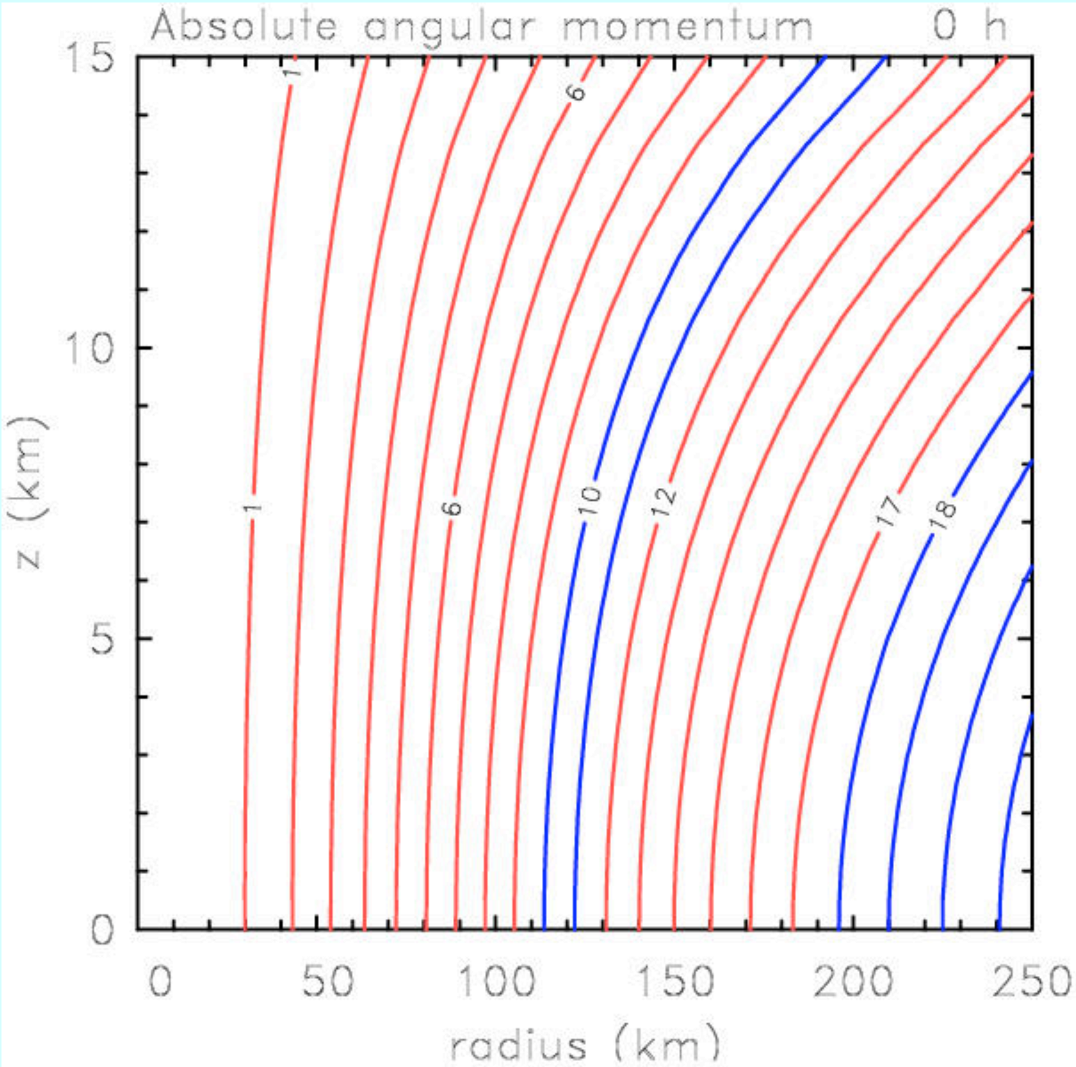


(d)



Movie 2

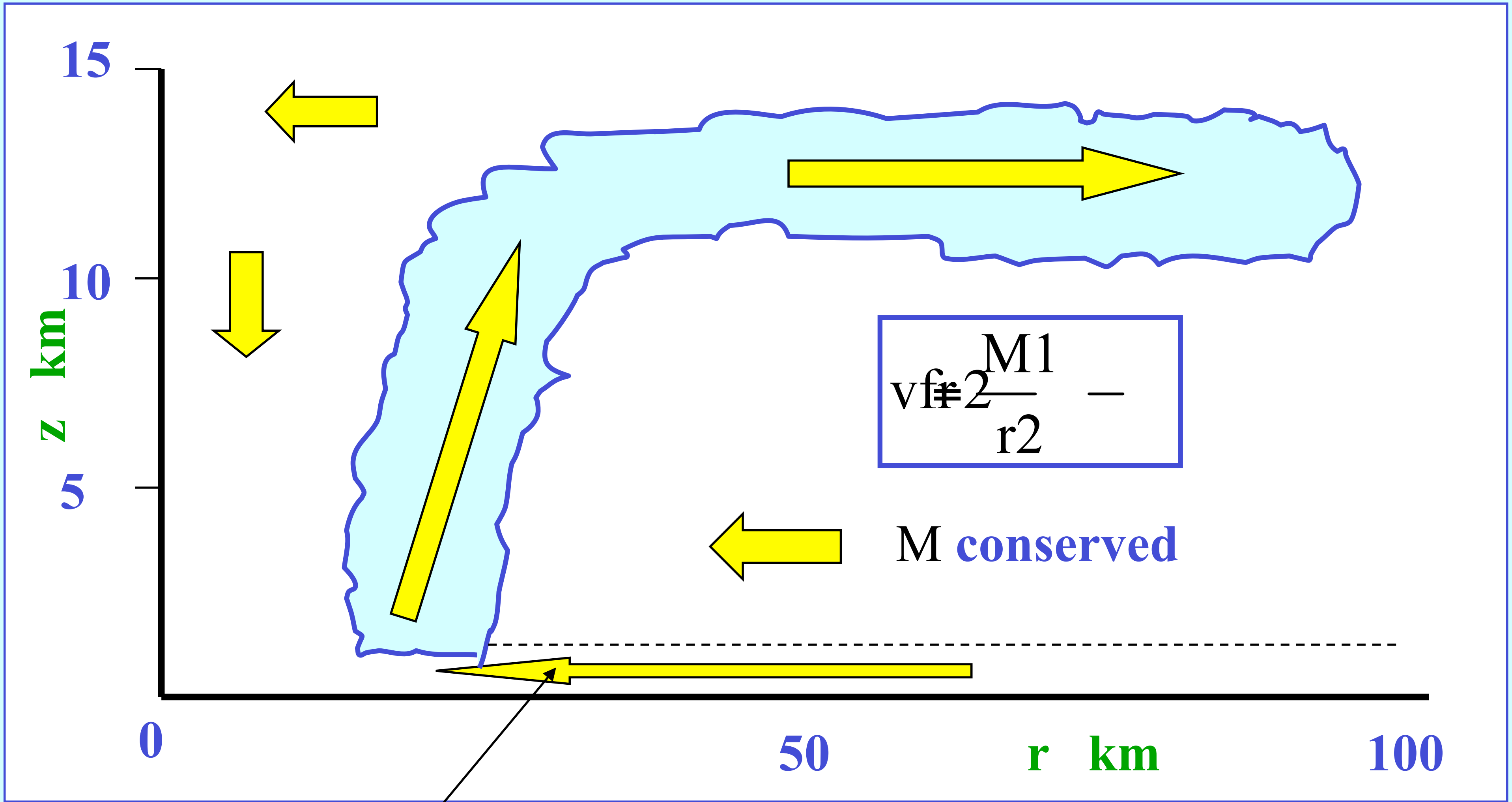
Time-height sequence of Absolute Angular Momentum



$$M = rv + \frac{1}{2} f r^2$$

$$v = \frac{M}{r} - \frac{1}{2} f r$$

Revised view of intensification: two mechanisms



M **reduced by friction, but strong convergence ➔ small** r

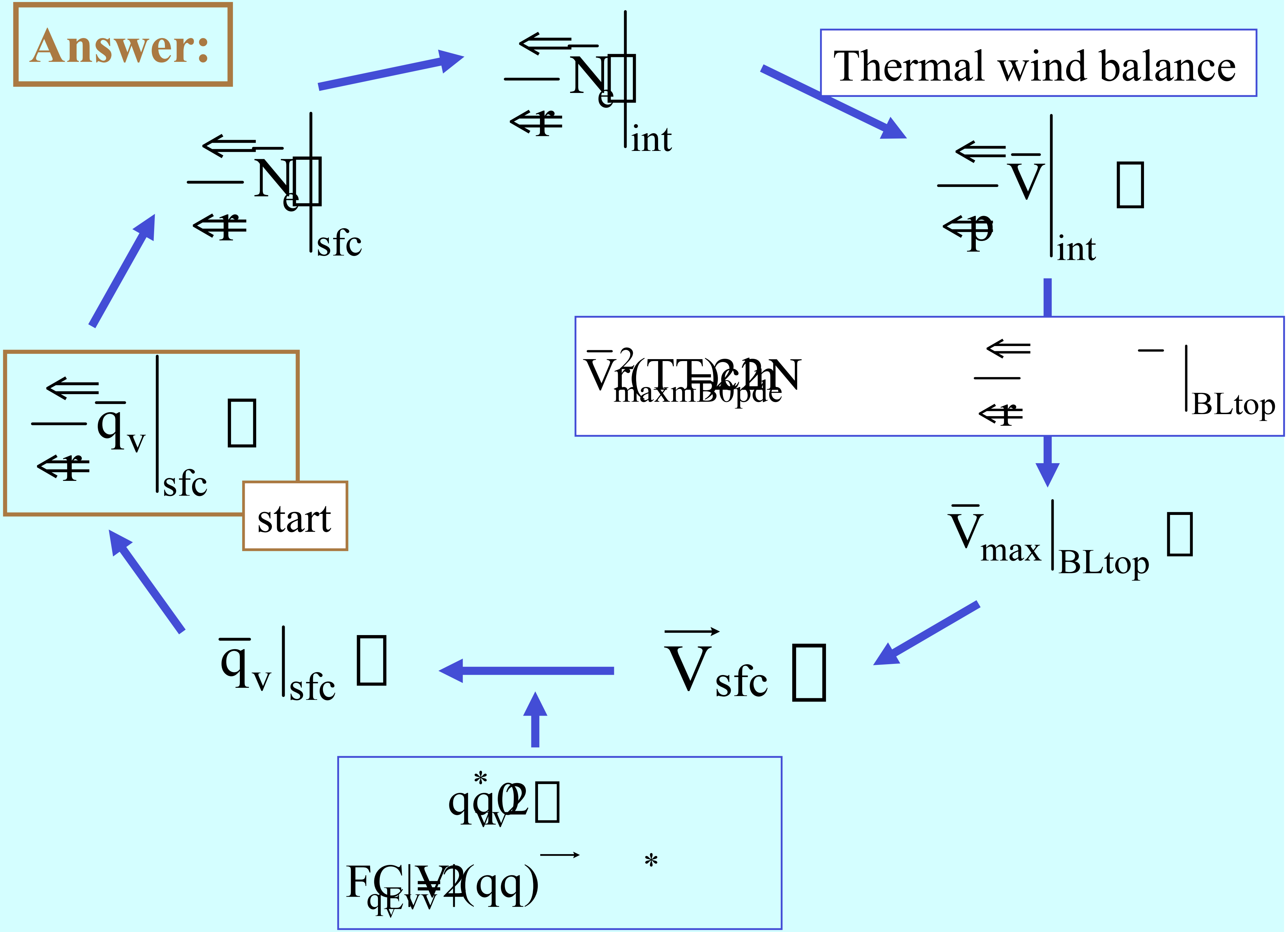
Exciting times!

- There is much work to do to pursue all the consequences of our recent findings and the new paradigm for intensification.
- We need to determine the limits of predictability for intensity and especially for rapid intensification.
- We need to much better understand the flow in the inner core, beneath and inside the eyewall, and to determine the utility of conventional (boundary layer) representations of this region in models.
- We need to develop a new theory for the potential intensity of tropical cyclones for climate assessments.

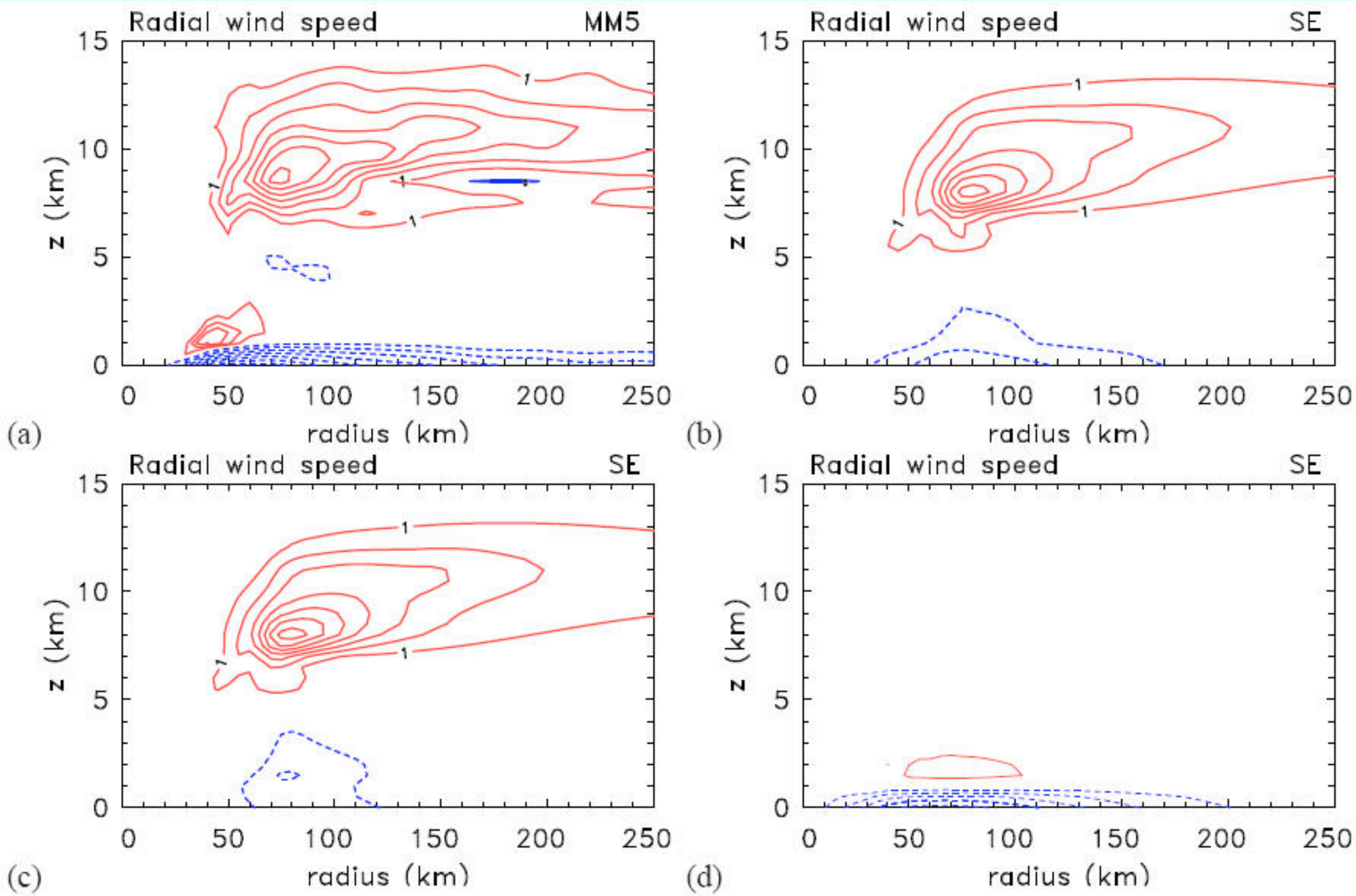

UNITED STATES DEPT. OF COMMERCE
Thank you

What is WISHE?

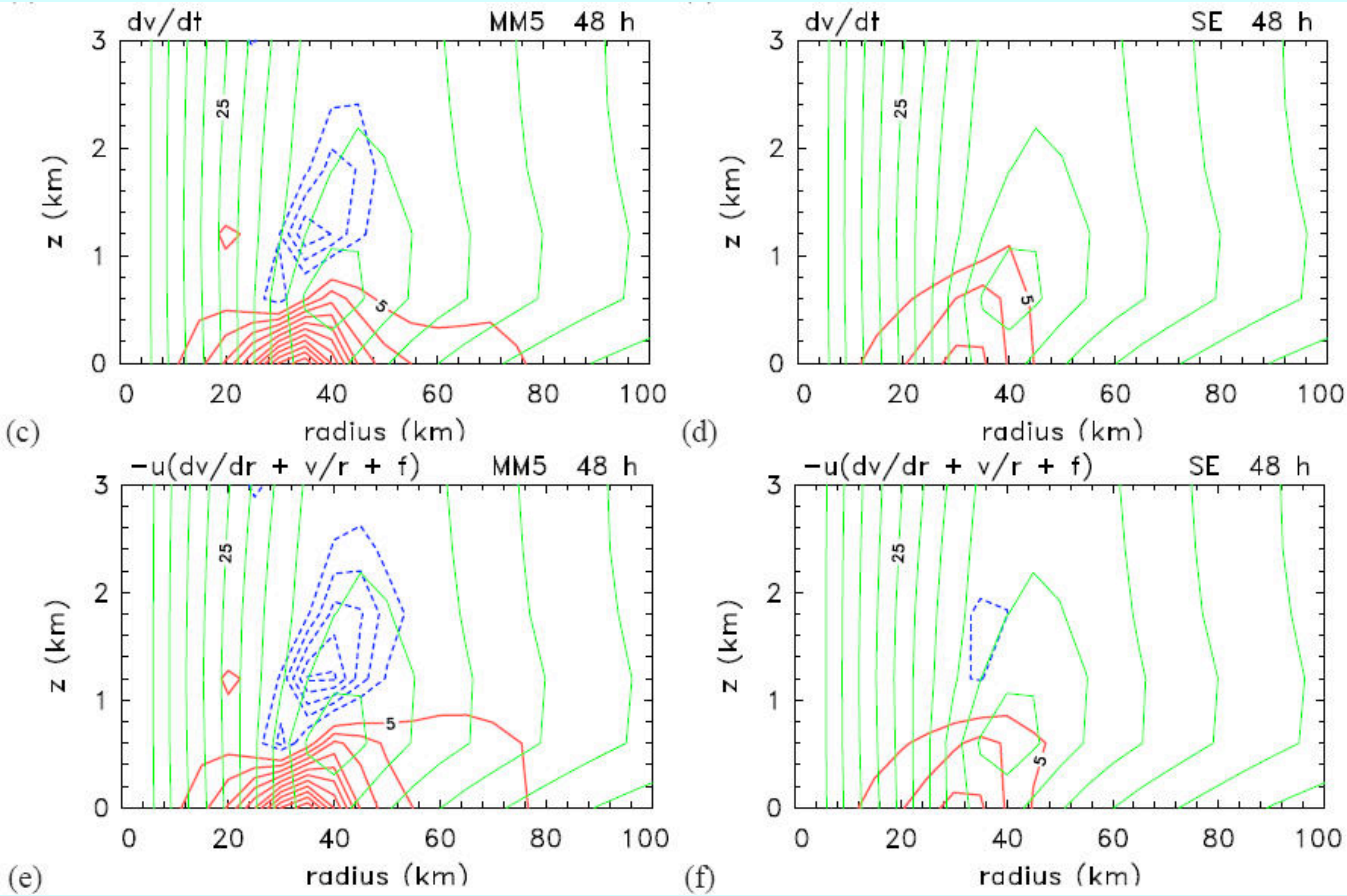
- **WISHE = Wind Induced Surface Heat Exchange**
- **Acronym used to link source of fluctuations in sub-cloud layer entropy or θ_e arising from fluctuations in wind speed (Yano & Emanuel 1991).**
- **Q: What is the WISHE mechanism of TC intensification?**
- **A: Positive feedback between near-surface mean θ_e and near-surface mean wind speed.**
- **It has become the accepted paradigm for explaining TC development in Univ. Textbooks and Review Articles (Holton 2004; Asnani 2005; Lighthill 1998)**
- **Q: But how does it work?**


Answer:
Thermal wind balance
start

Balanced versus unbalanced dynamics



Balanced versus unbalanced dynamics



Effects of different boundary layer schemes