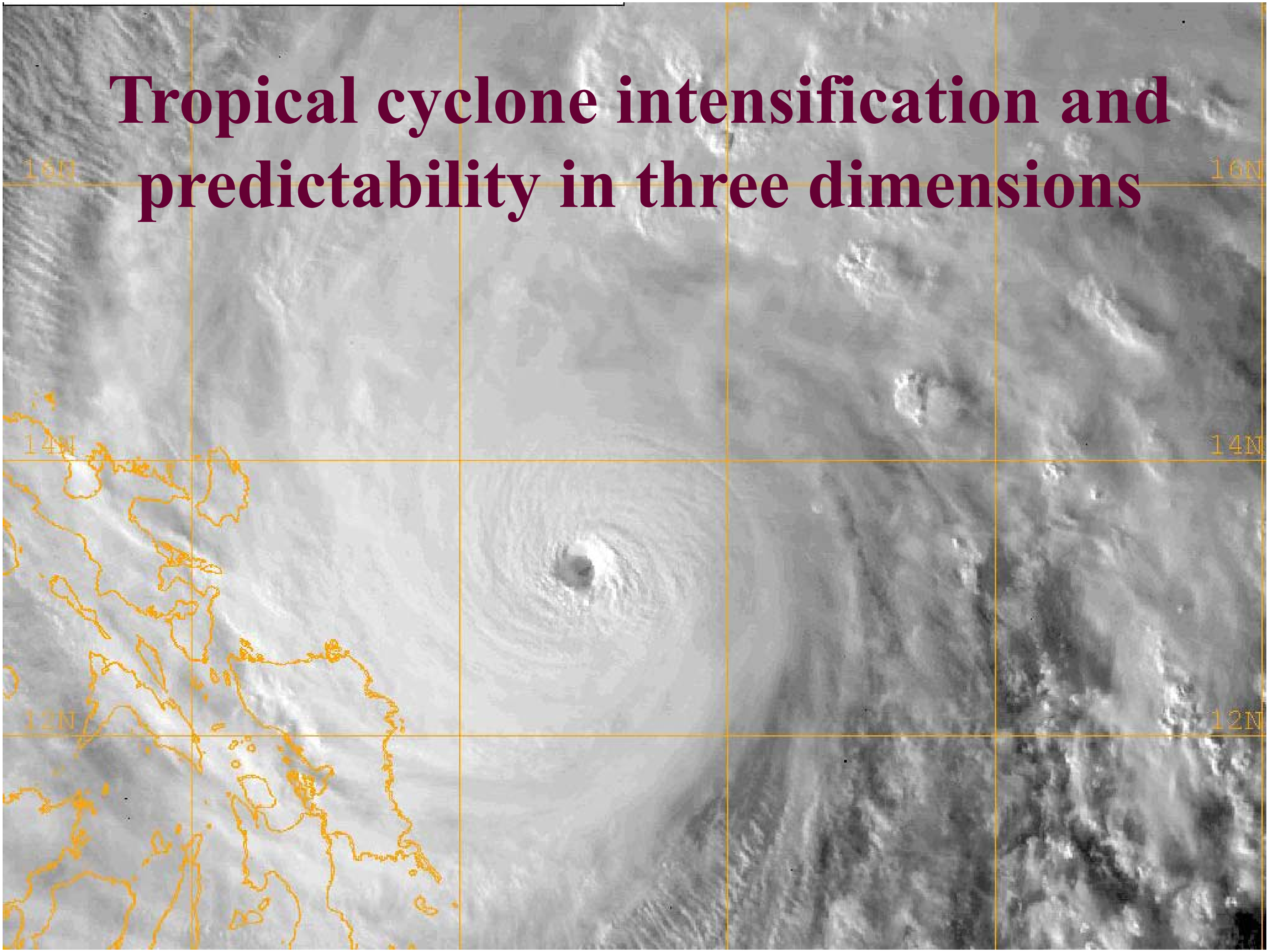
Tropical cyclone intensification and predictability in three dimensions



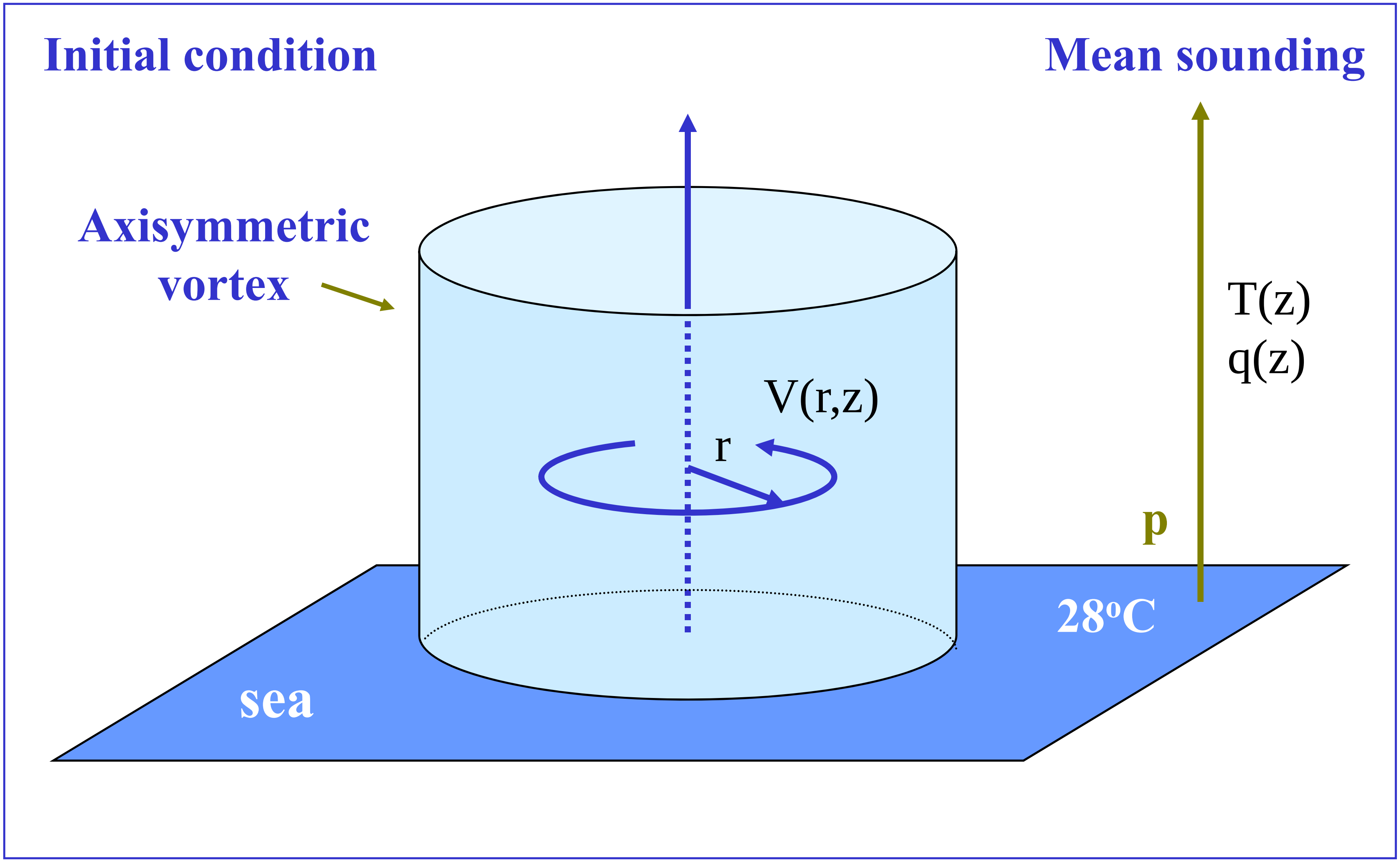
Topics

1. Introduction
   - Motivation, relevance
   - The basic thought experiment for intensification
   - Minimal hurricane models
   - Flow asymmetries
2. Idealized MM5 simulations with simple physics
   - Flow asymmetries
   - Predictability experiments
3. Conclusions

Motivation and relevance

- **At present, there is little skill in forecasting hurricane intensity change.**
- **We need to understand the processes that are contained in forecast models in order to improve the models.**
- **We need to identify and understand the processes that lead to the rapid intensification of hurricanes.**
- **We need to establish error bounds on the predictability of intensity change.**

The basic thought experiment for intensification



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 required of a minimal model for a hurricane?
- What is the analogue of the Eady Problem for hurricanes?

A minimal, three-layer hurricane model: references

Zhu, H., R. K. Smith, and W. Ulrich, 2001
A minimal three-dimensional tropical cyclone model.
***J. Atmos. Sci*., 58, 1924-1944.**

Zhu, H., and R. K. Smith, 2002
The importance of three physical processes in a minimal three-dimensional tropical cyclone model.
***J. Atmos. Sci*., 59, 1825-1840.**

Nguyen, C. M., R. K. Smith, H. Zhu, and W. Ulrich, 2002
A minimal axisymmetric tropical cyclone model.
***Quart. J. Roy. Meteor. Soc*., 128, 2641-2661.**

Zhu, H., and R. K. Smith, 2003
The importance of three physical processes in a minimal three-dimensional tropical cyclone model.
***Quart. J. Roy. Meteor. Soc*., 129, 1051-1069.**

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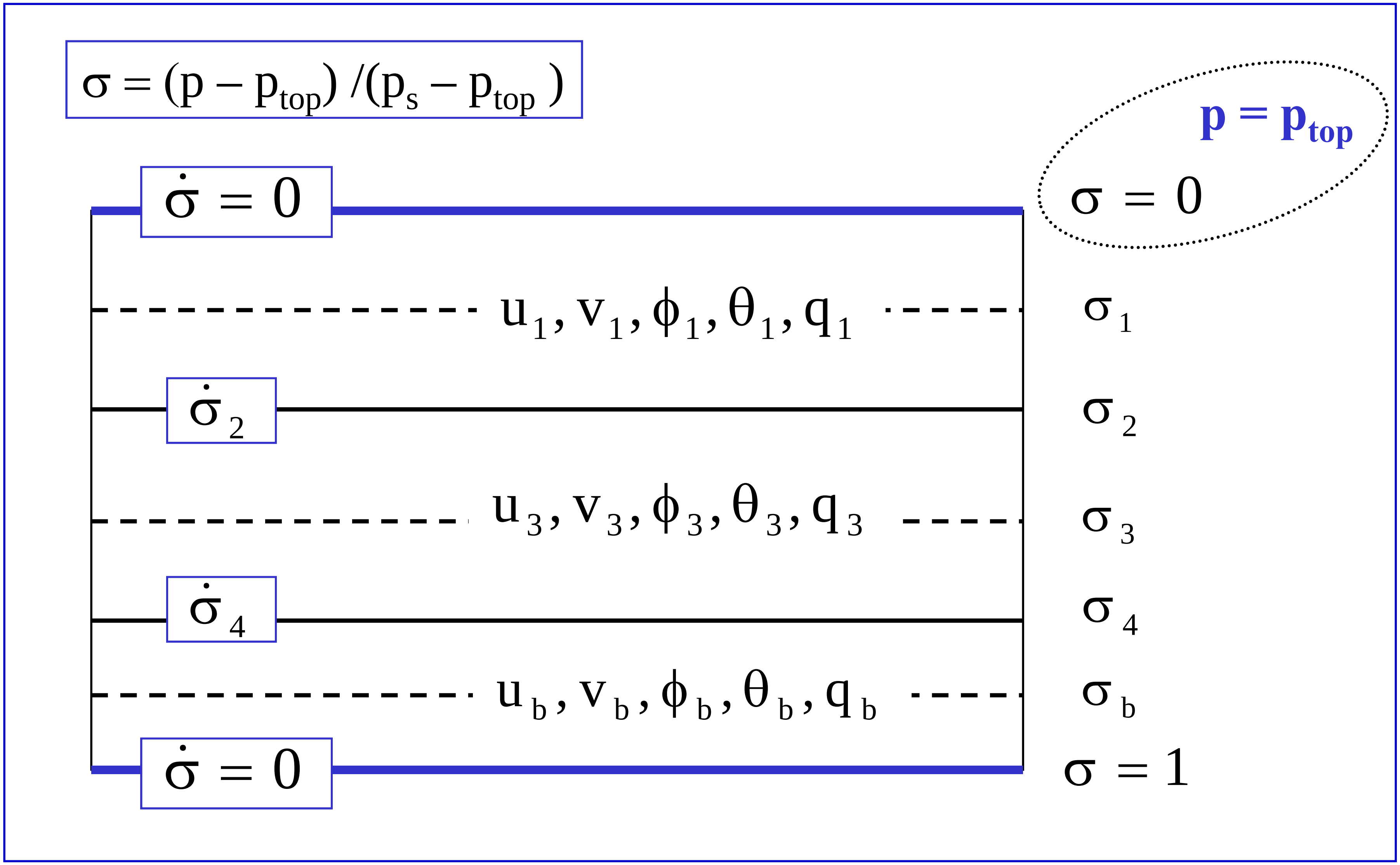
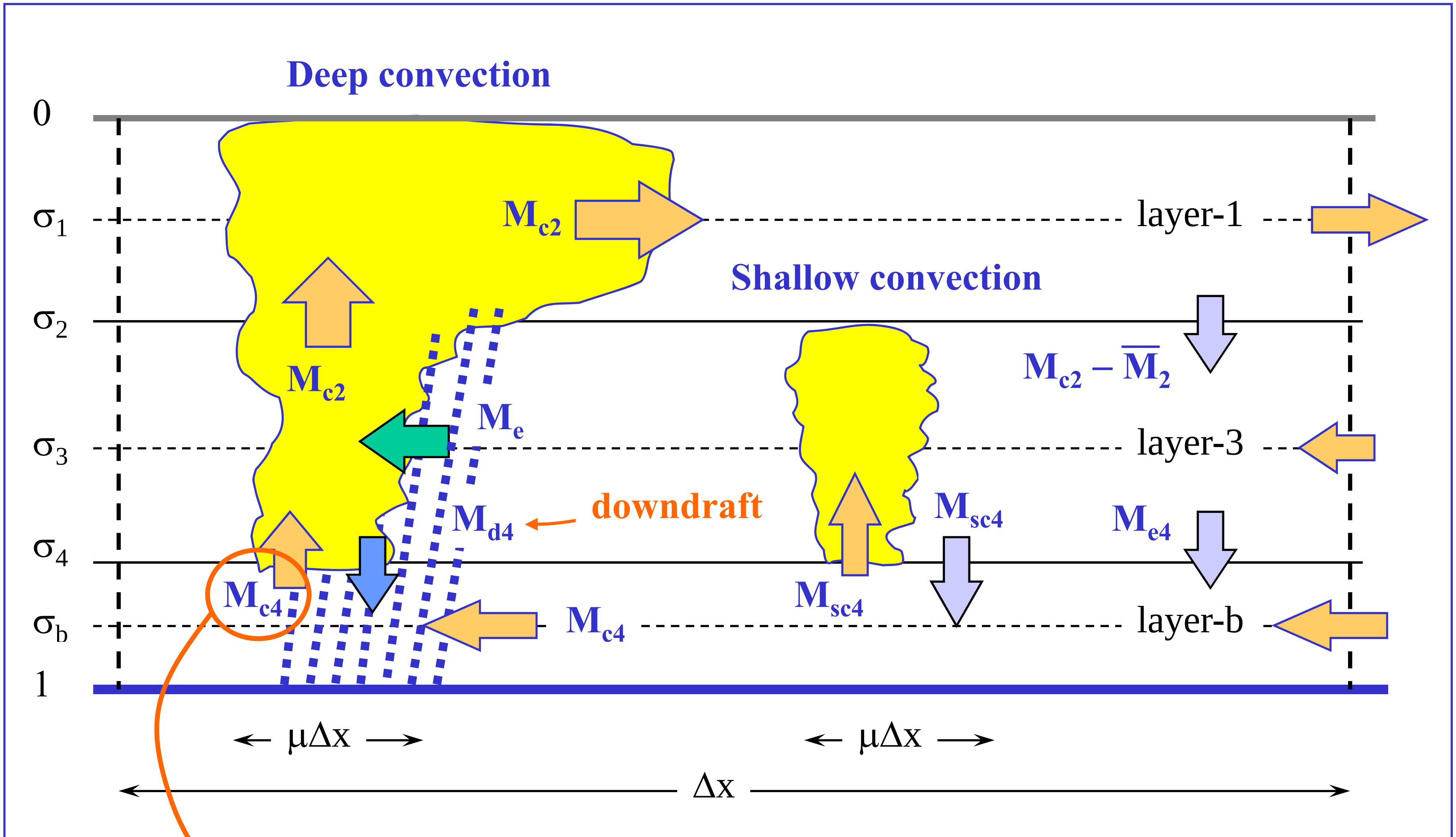
A three-dimensional tropical cyclone model in σ-coordinates with integrated thermodynamics



The representation of convection



Convection scheme closure to determine M_{c4}

Four model calculations:

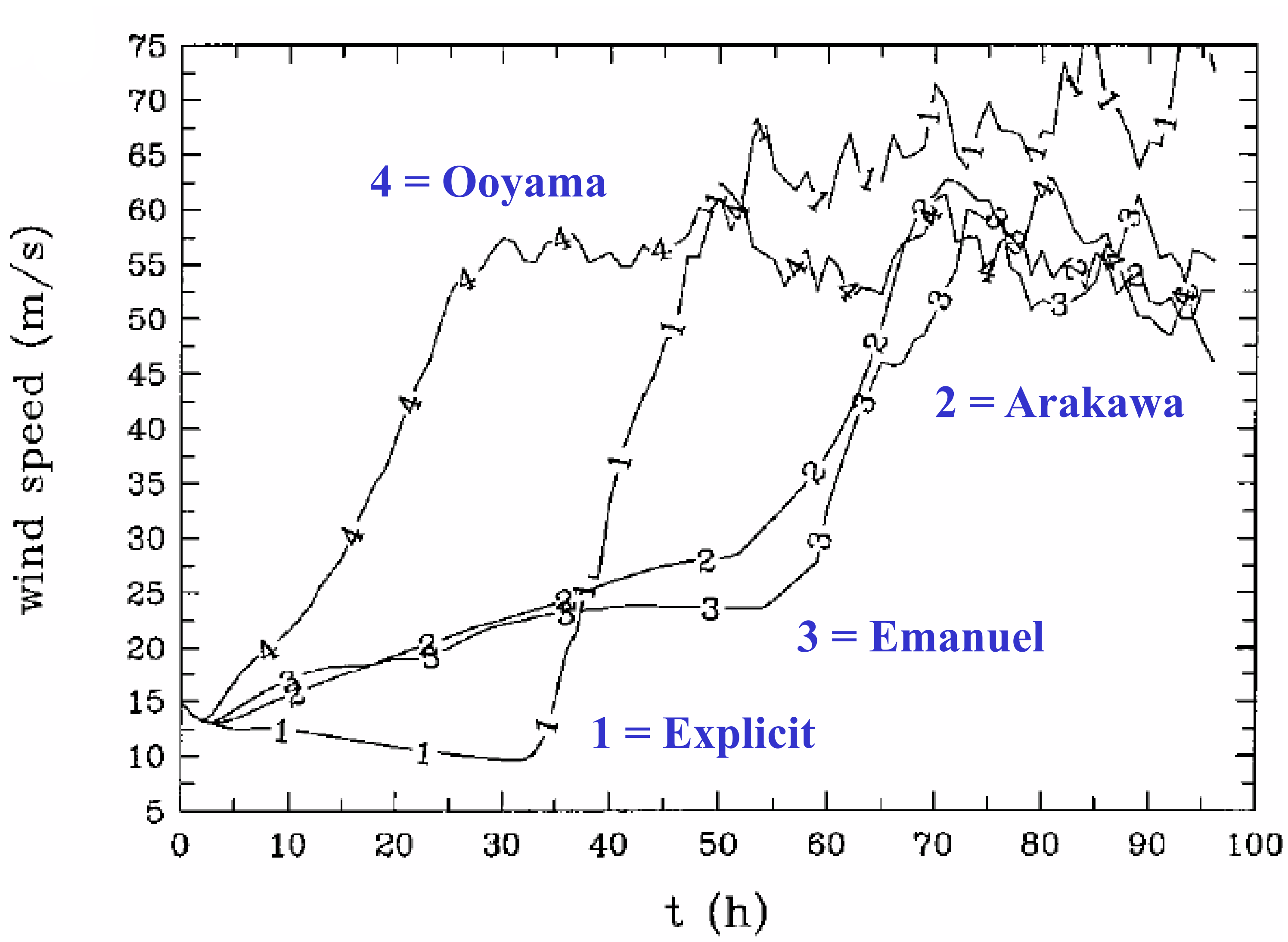
- **Initialize with an axi-symmetric vortex in gradient wind balance** (v_{max} = 15 m/sec **at** r = 120 km).

1) **Explicit moist processes only**

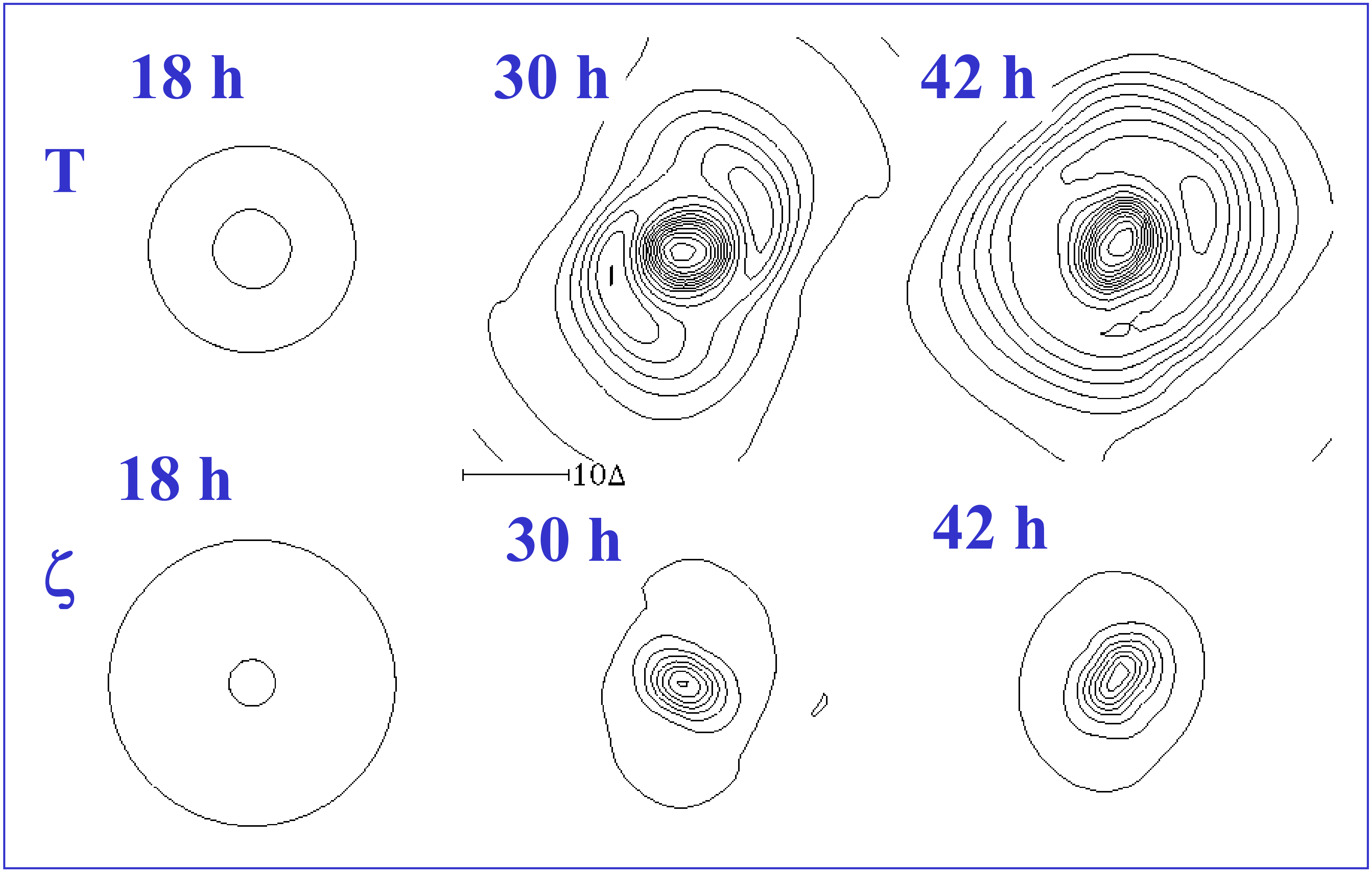
Include sub-grid-scale deep convection schemes:

2) **Arakawa closure (modified)**
3) **Emanuel closure (modified)**
4) **Ooyama closure (modified)**

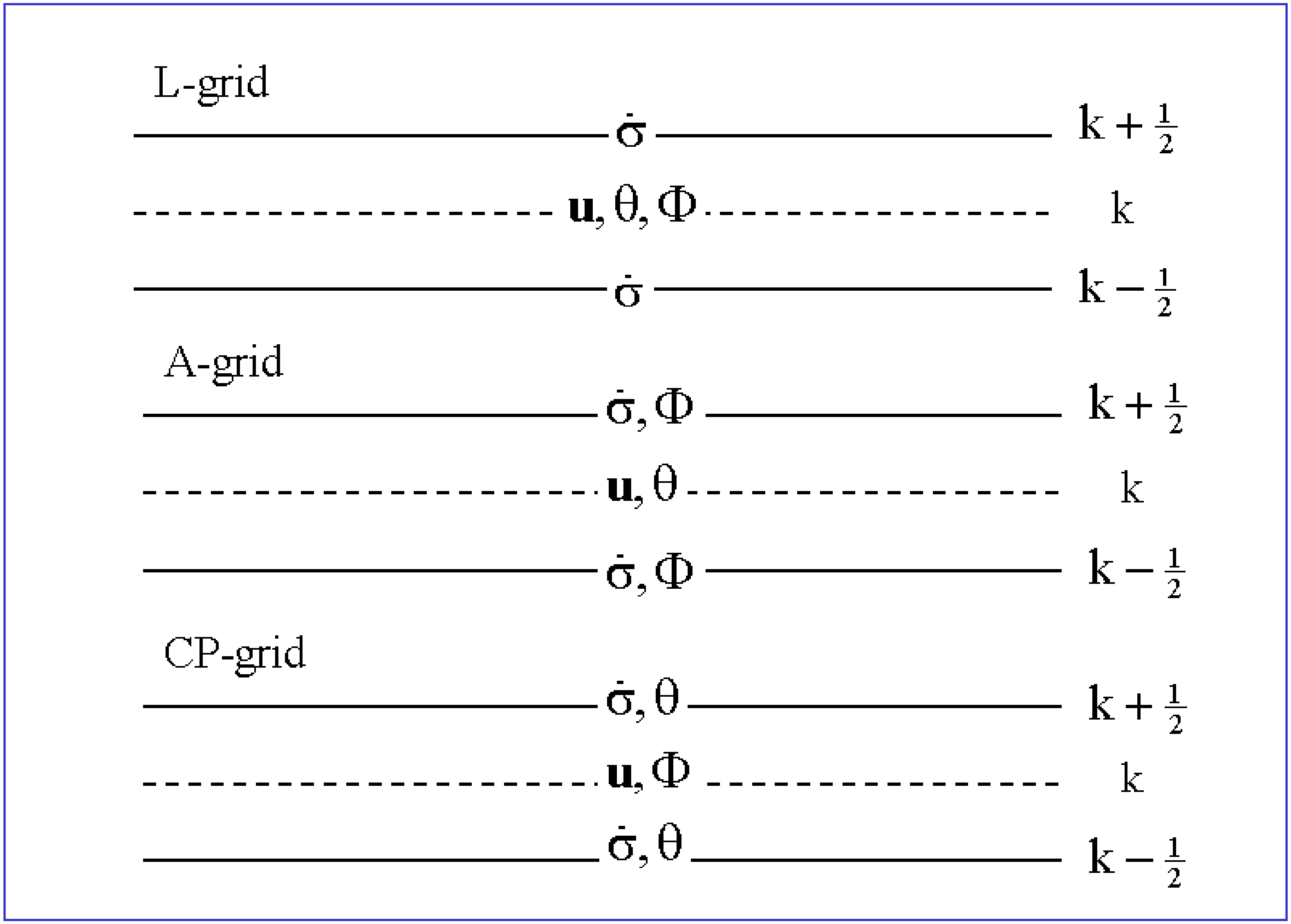
Deep convection only



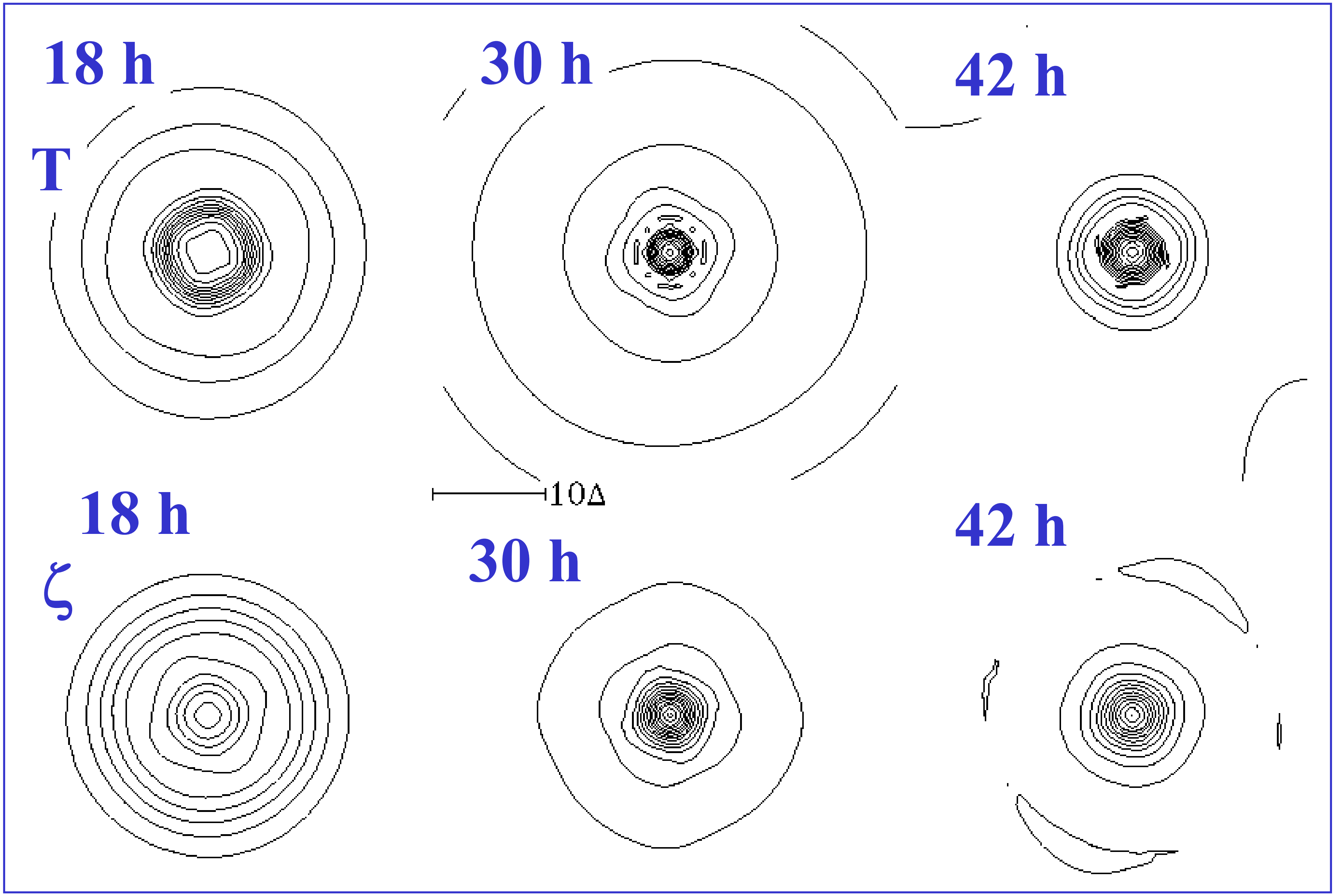
Asymmetries: L-grid



Different vertical grids



Asymmetries: CP-grid



The Eady model for TC intensification

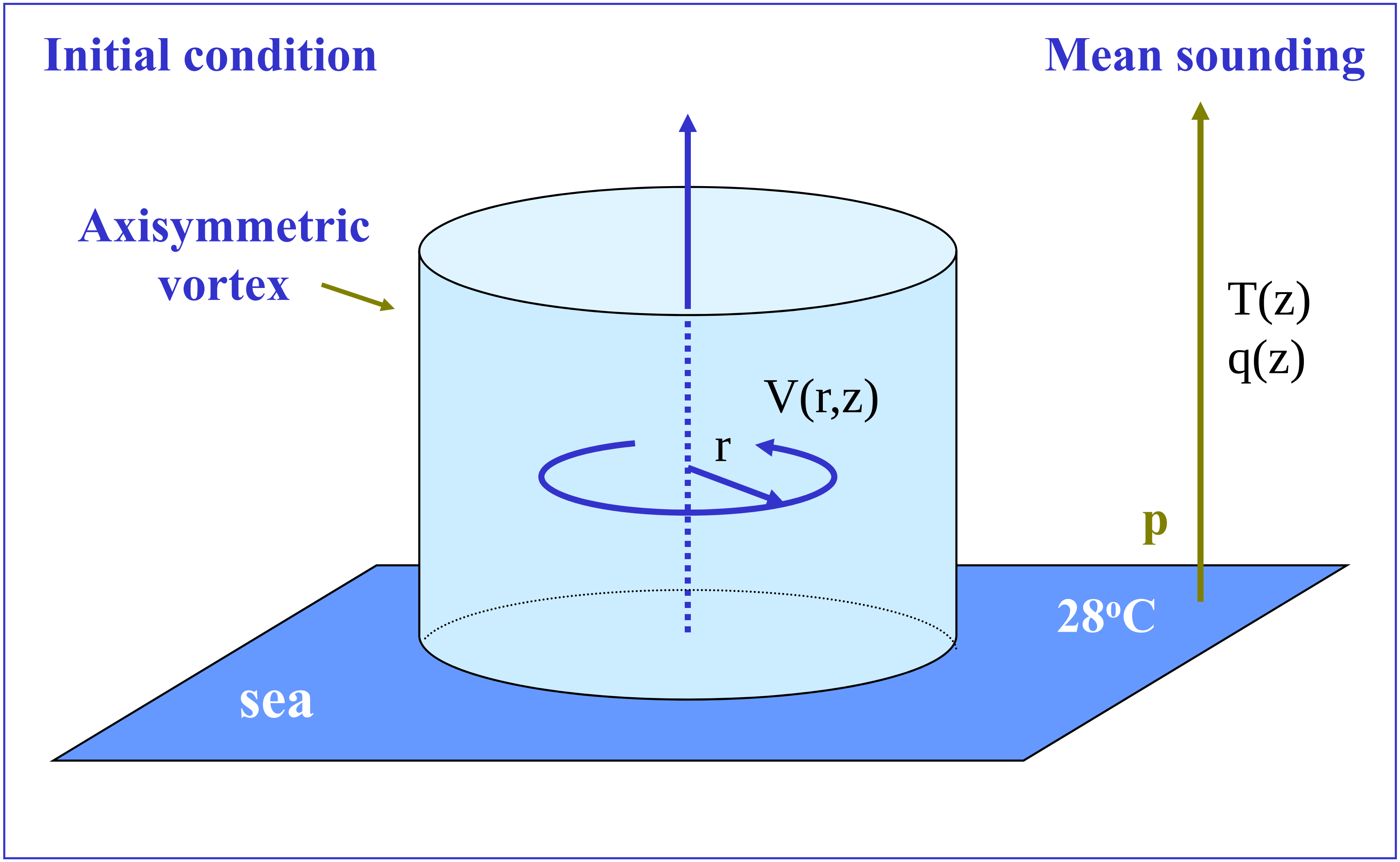
A conclusion of Zhu and Smith 2003

- **The minimal hurricane model with the CP-grid appears to provide a useful model to study hurricane intensification.**

Questions: - Do higher resolution, multi-level models give similar results?

- Do they produce asymmetries on the f-plane with no basic flow?

The basic thought experiment for intensification



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ROYAL METEOROLOGICAL SOCIETY

Tropical-cyclone intensification and predictability in three dimensions

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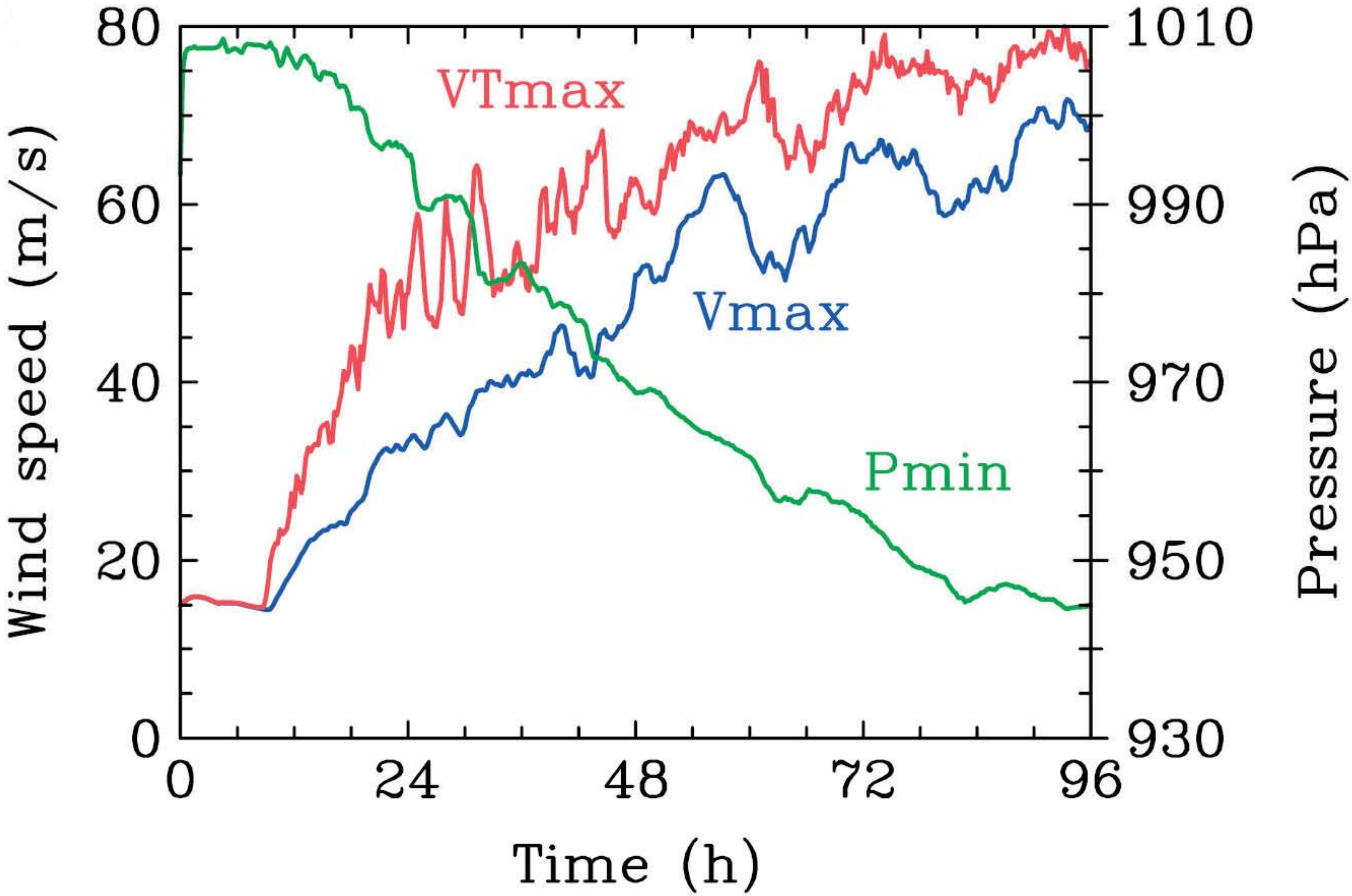
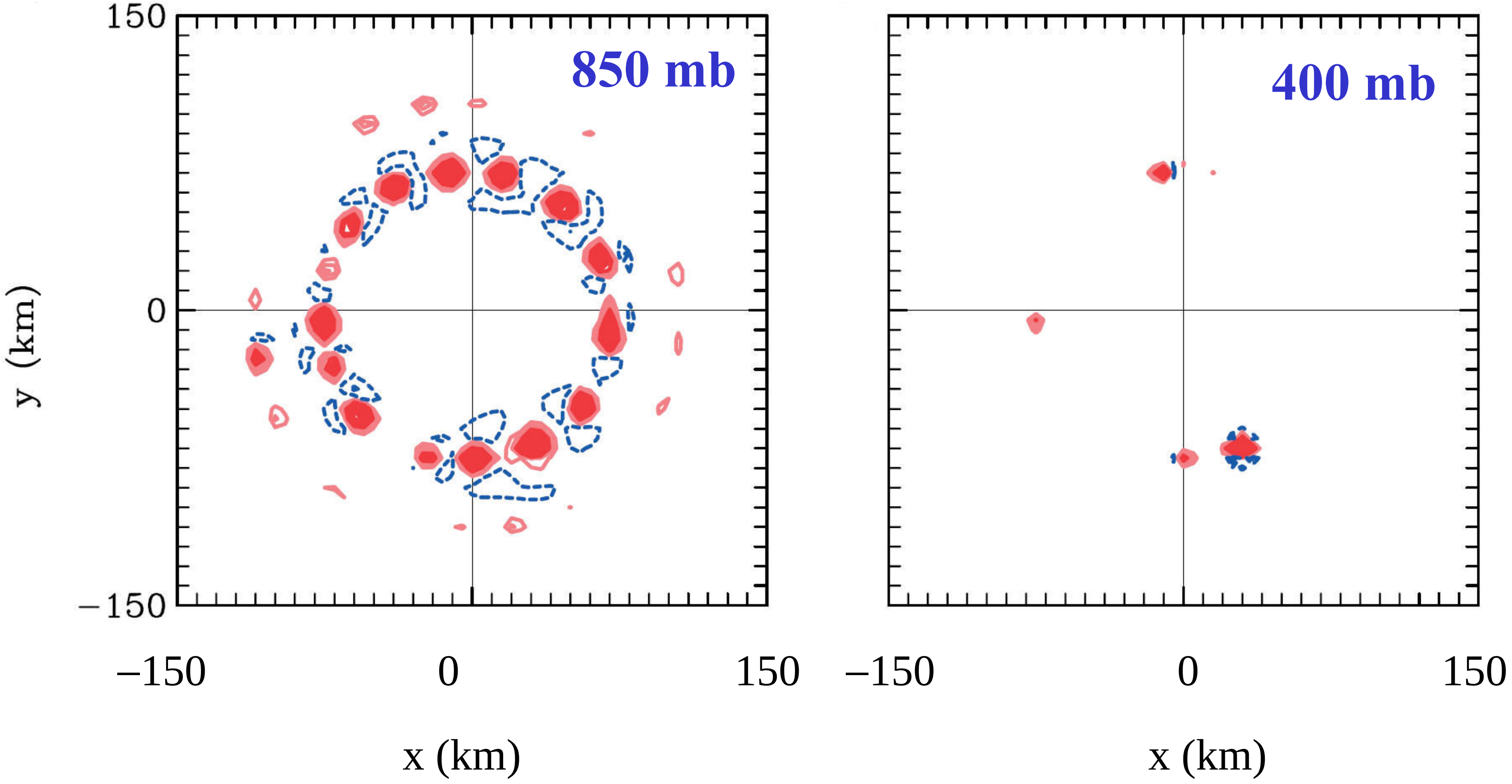
Available: http://www.meteo.physik.uni-muenchen.de/~roger

- **Idealized MM5 simulations with simple physics**
- 5 **km (**1.67 **km) resolution in the finest nest,** 24 **σ-levels**
- **The simplest explicit scheme for moist processes**
- **A simple bulk formulation for the boundary layer**

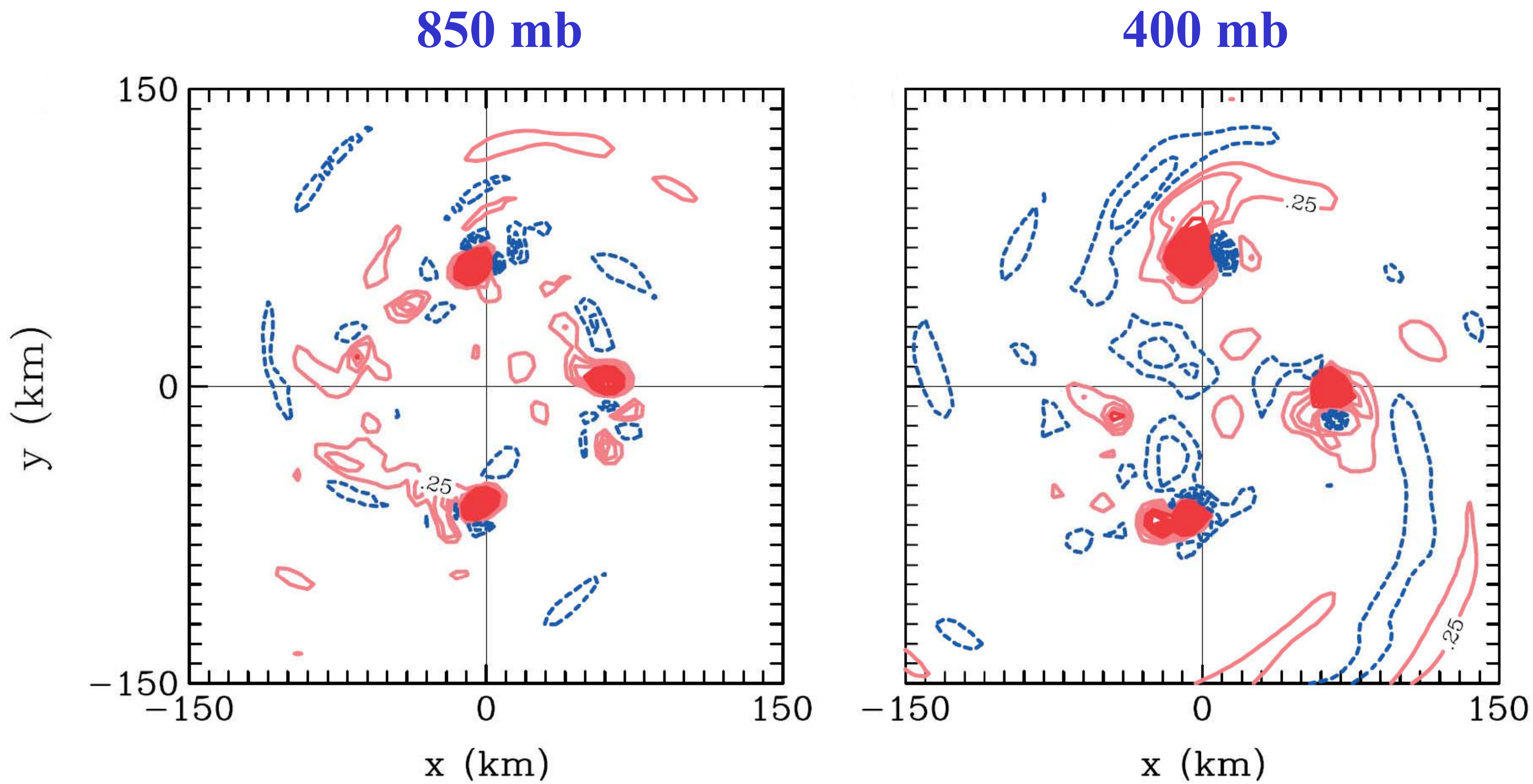
Evolution of Intensity



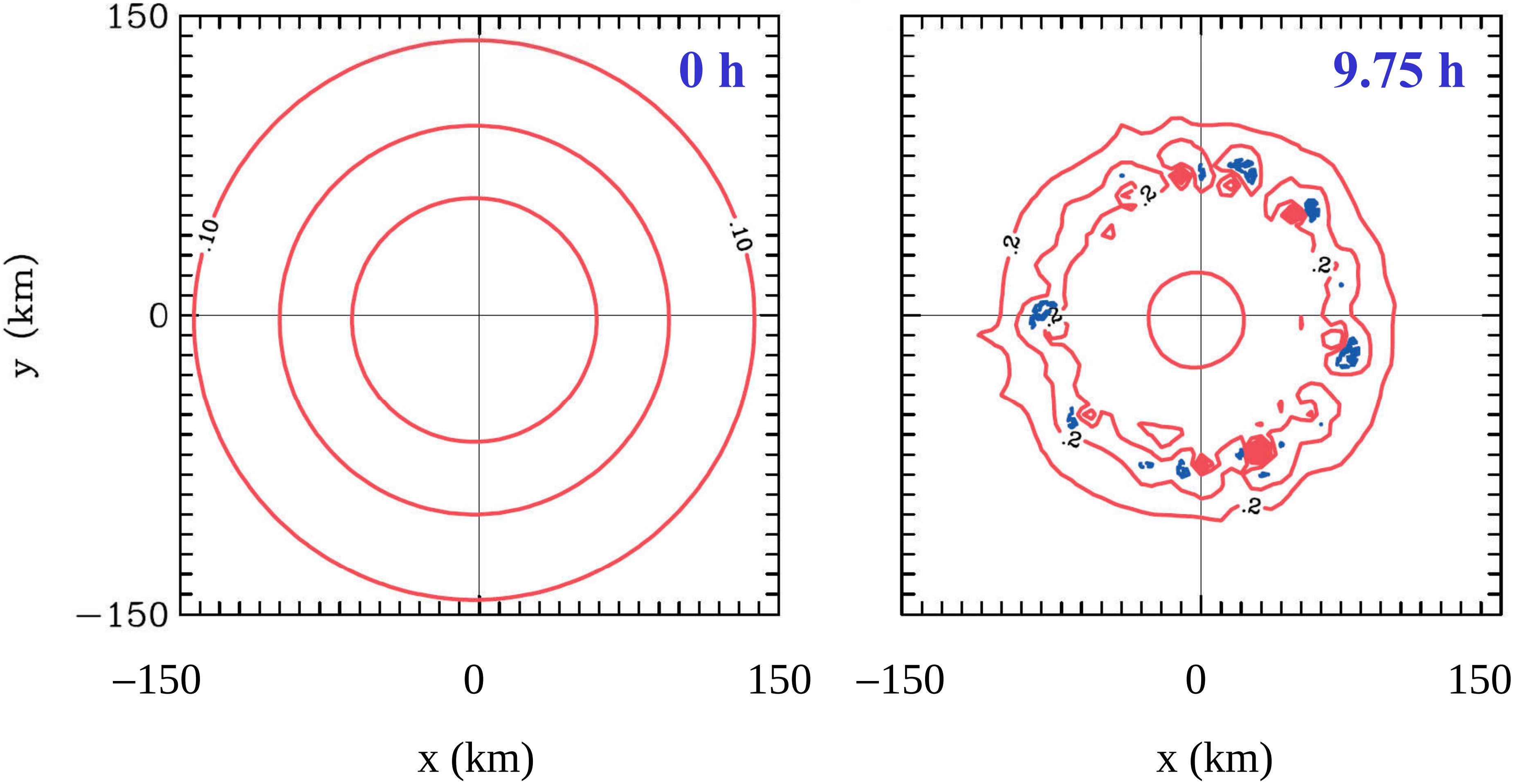
Vertical velocity pattern at 9.75 h



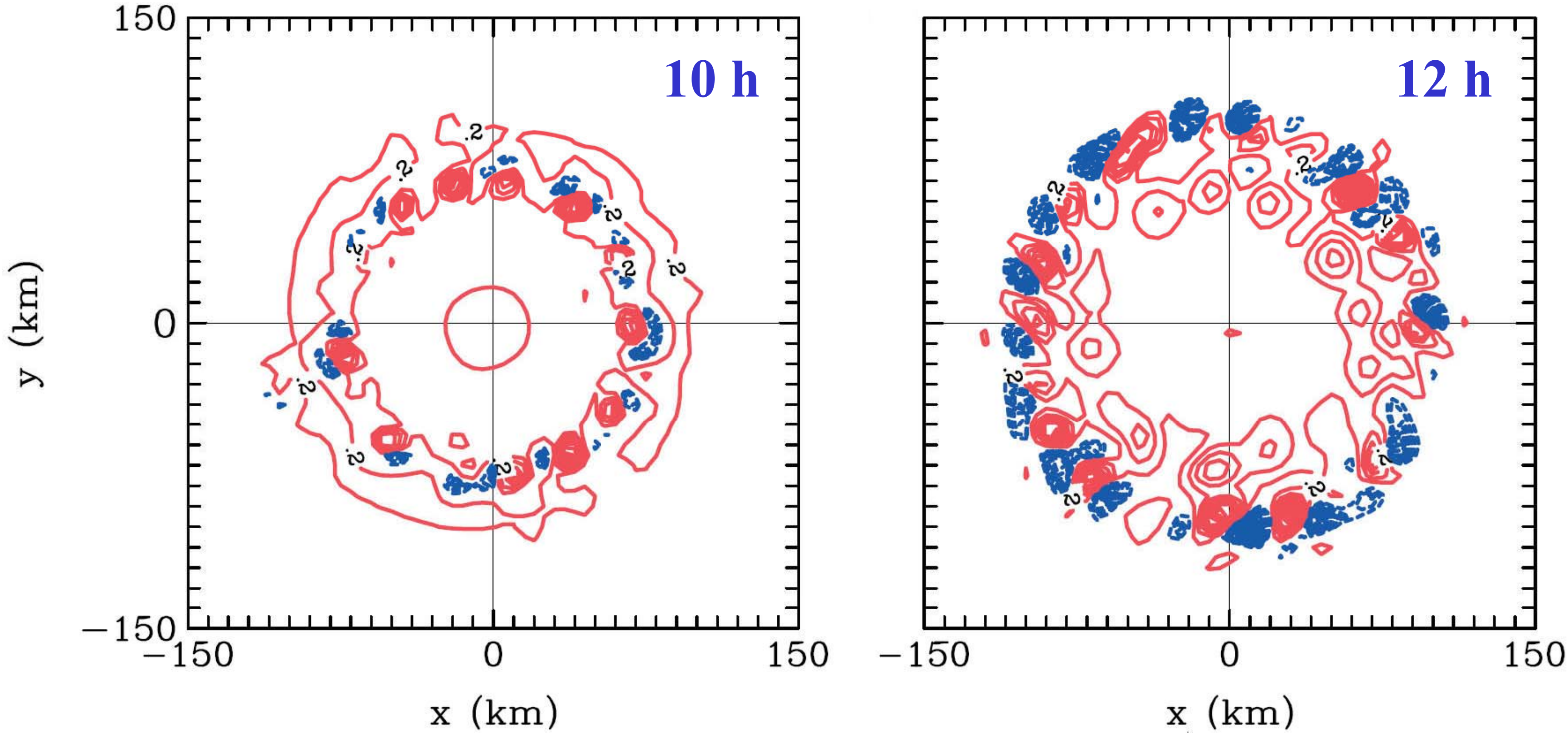
Vertical velocity pattern at 24 h



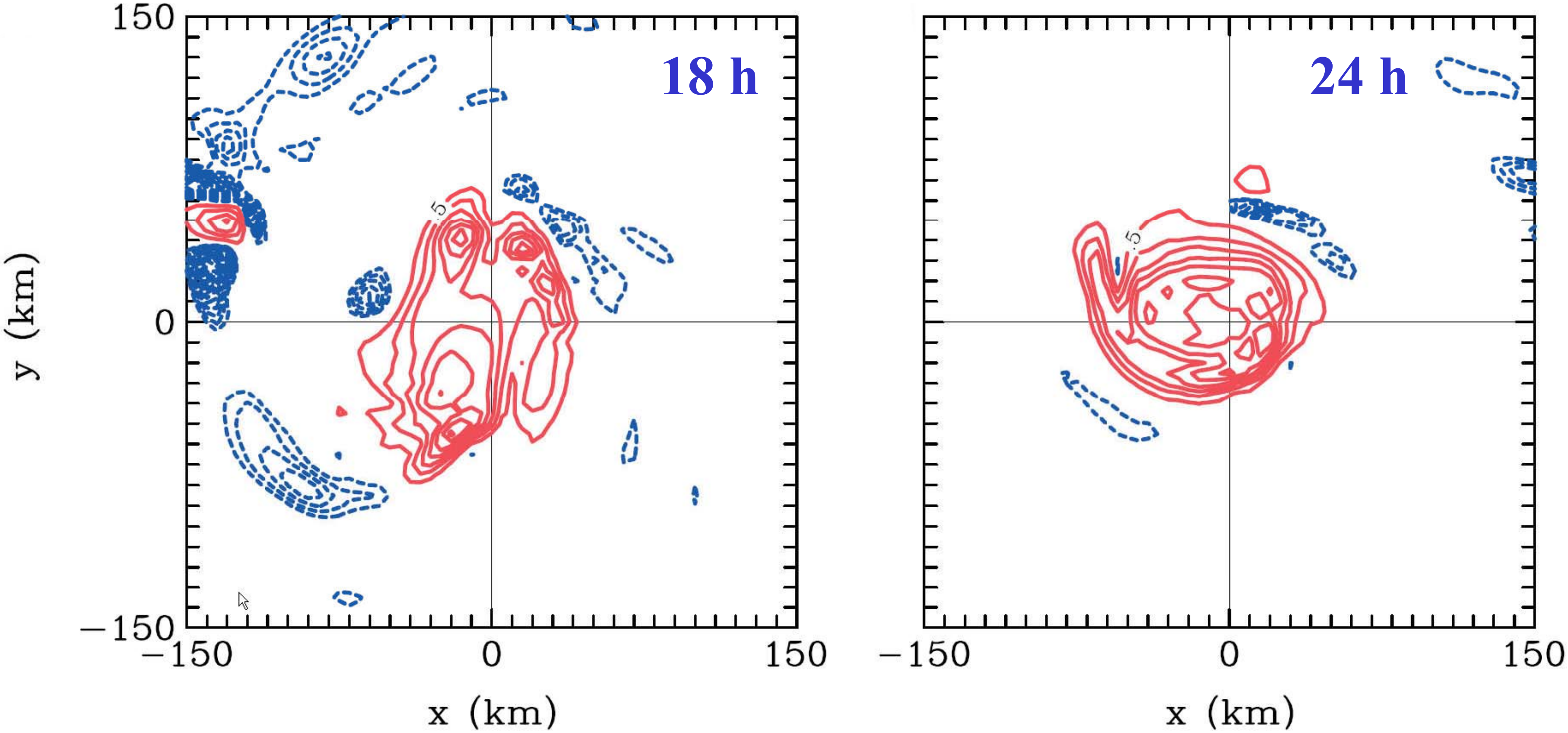
Vertical vorticity pattern at 850 mb



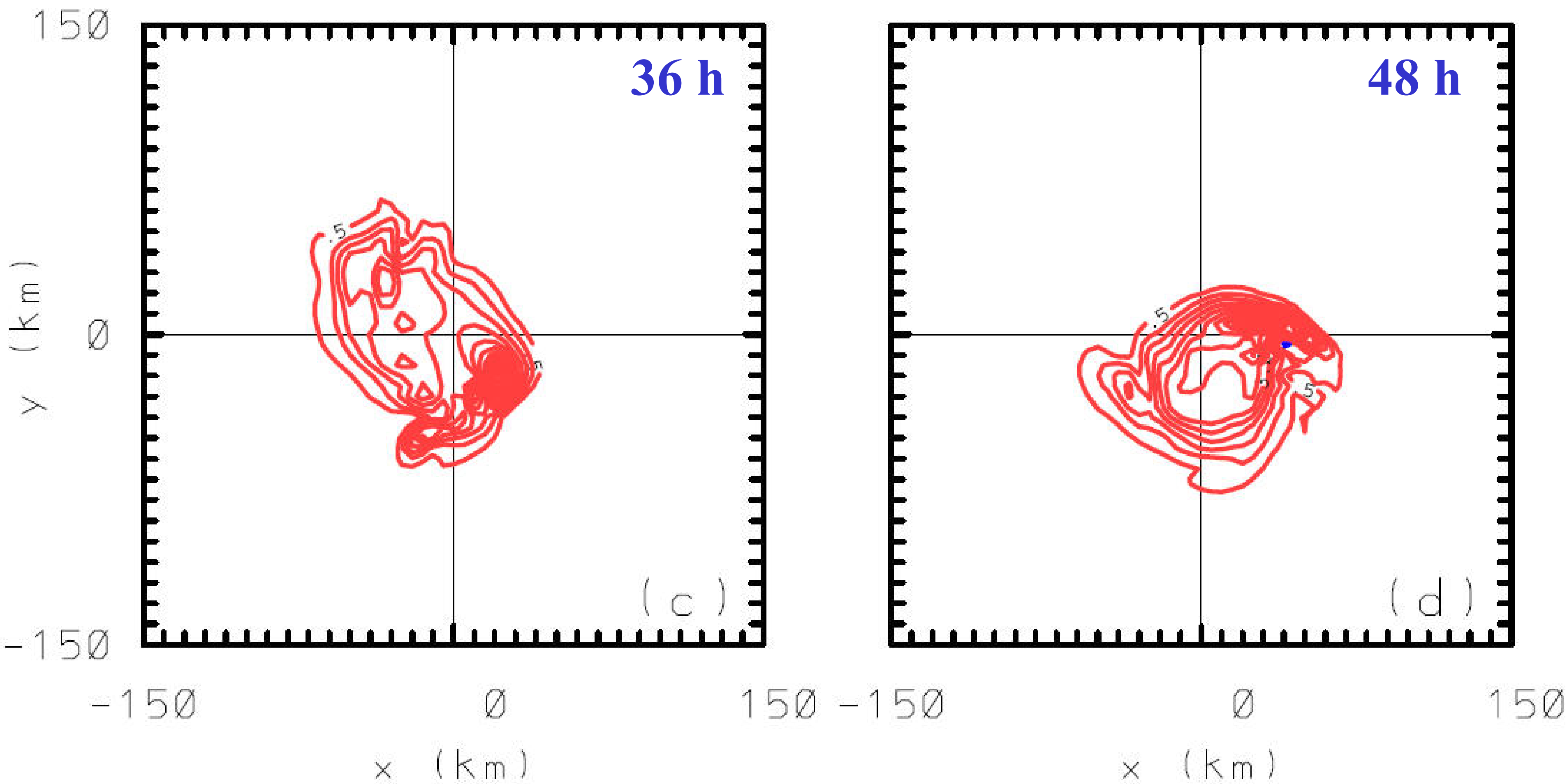
Vertical vorticity pattern at 850 mb



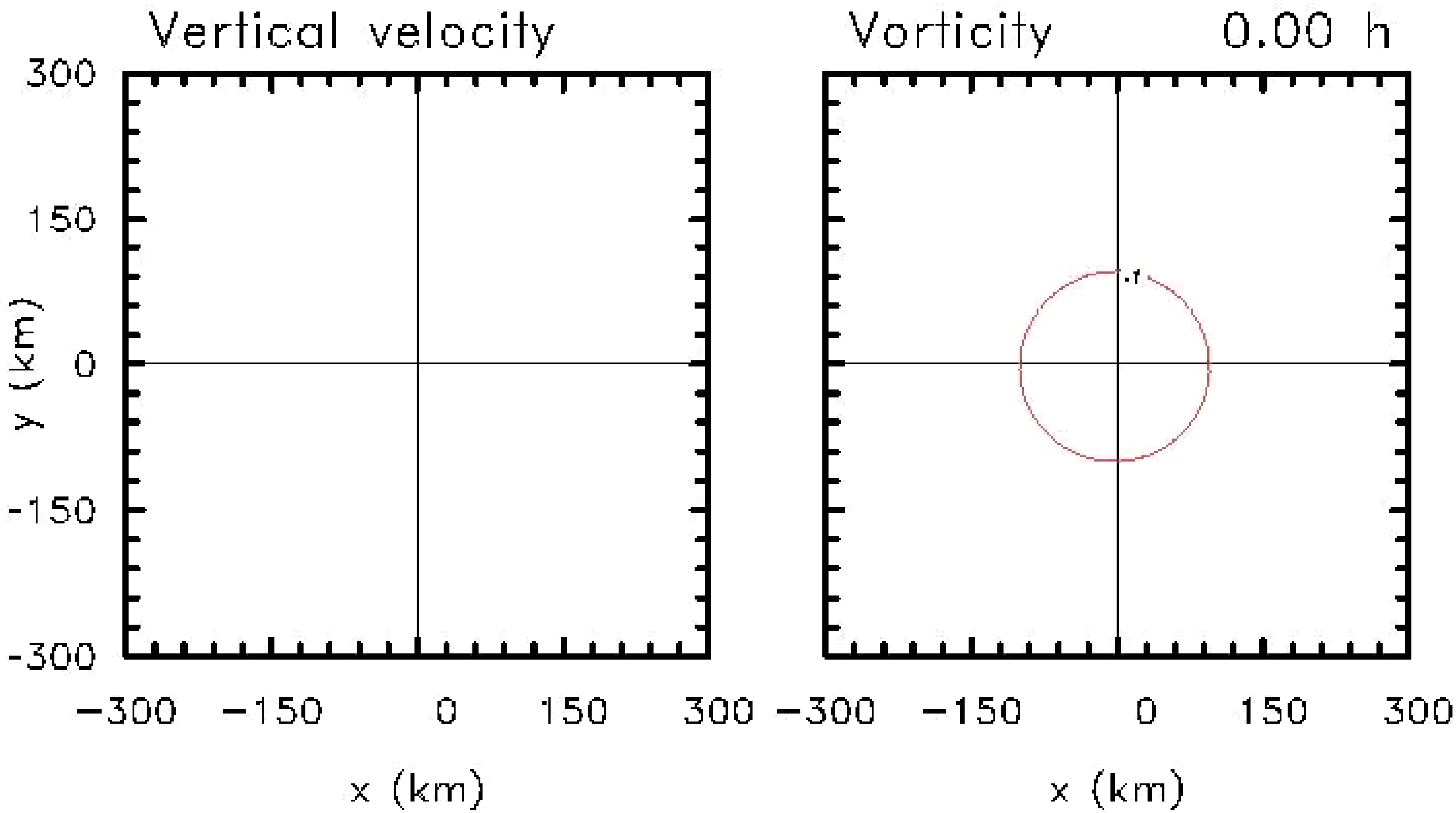
Vertical vorticity pattern at 850 mb



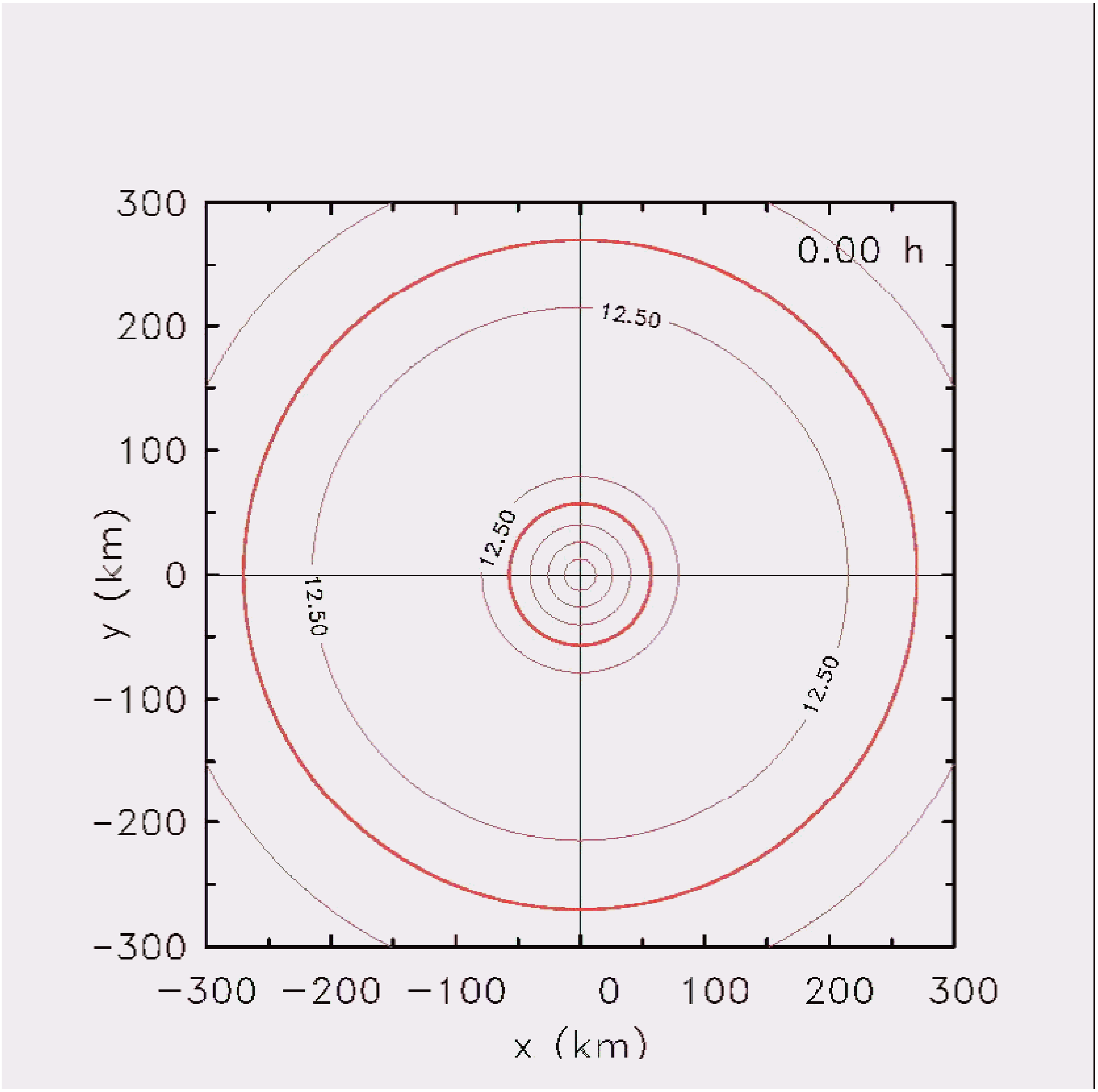
Vertical vorticity pattern at 850 mb



Movie: 850 mb vertical velocity and vorticity



VT
850 mb

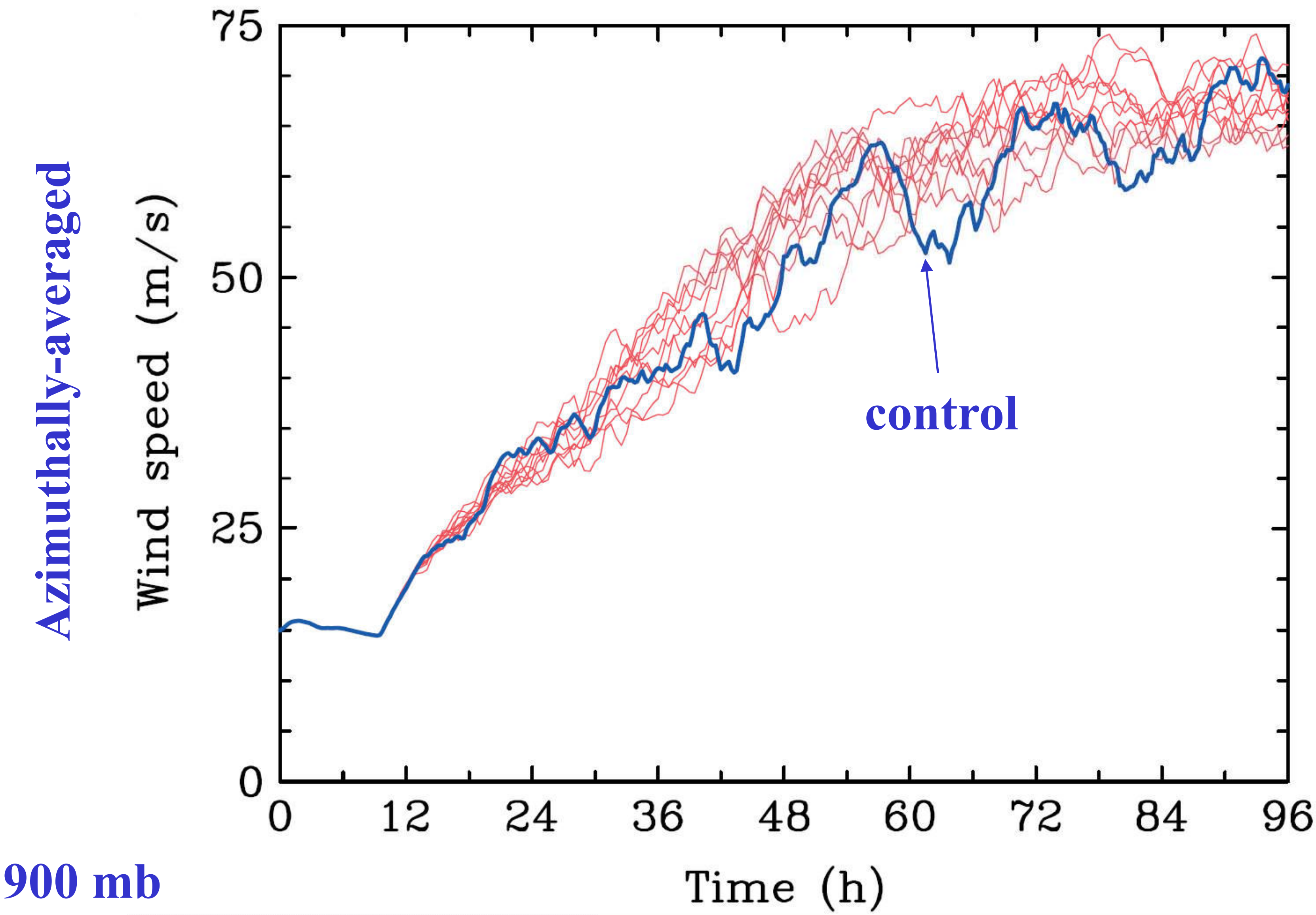


0.00 h
12.50
12.50
12.50
12.50
300
200
100
0
−100
−200
−300
y (km)
−300
−200
−100
0
100
200
300
x (km)

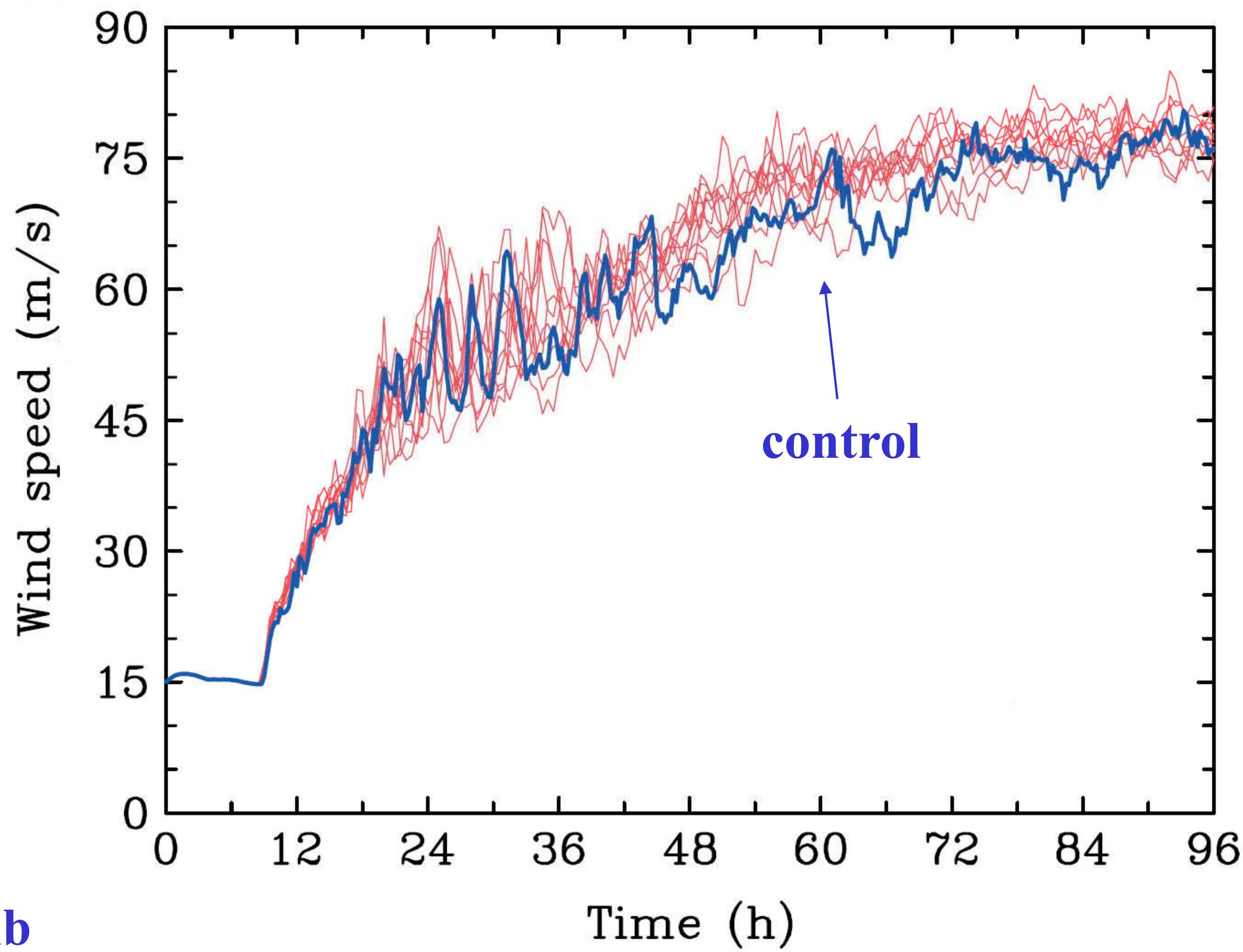
Interim conclusions

- **The flow evolution is intrinsically asymmetric.**
- **The asymmetries are associated with rotating convective structures that are essentially stochastic in nature.**
- **These structures are similar to those of Hendricks et al. (2004), who called them vortical hot towers.**
- **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 intensity: 10 ensembles



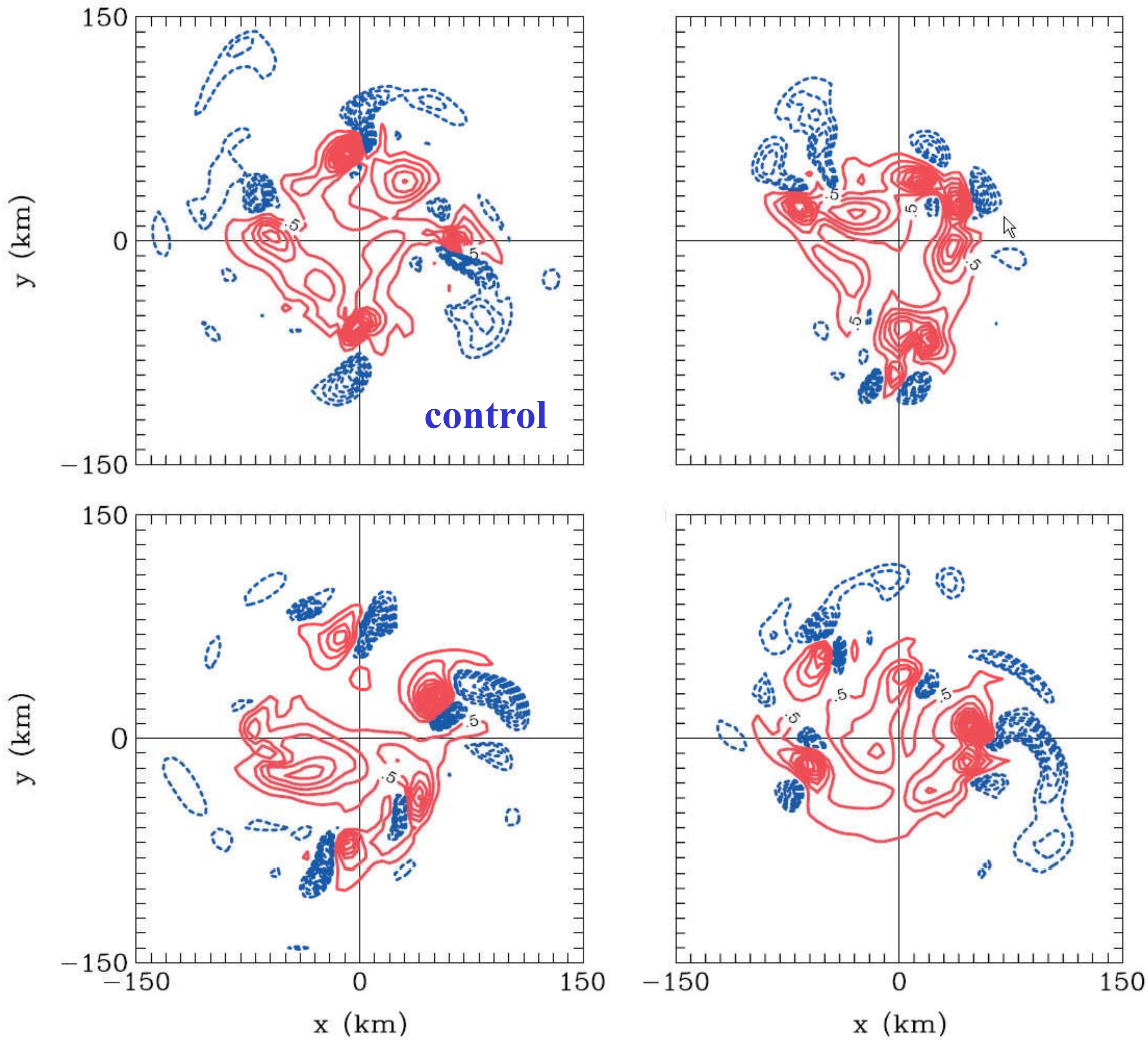
Evolution of intensity: 10 ensembles



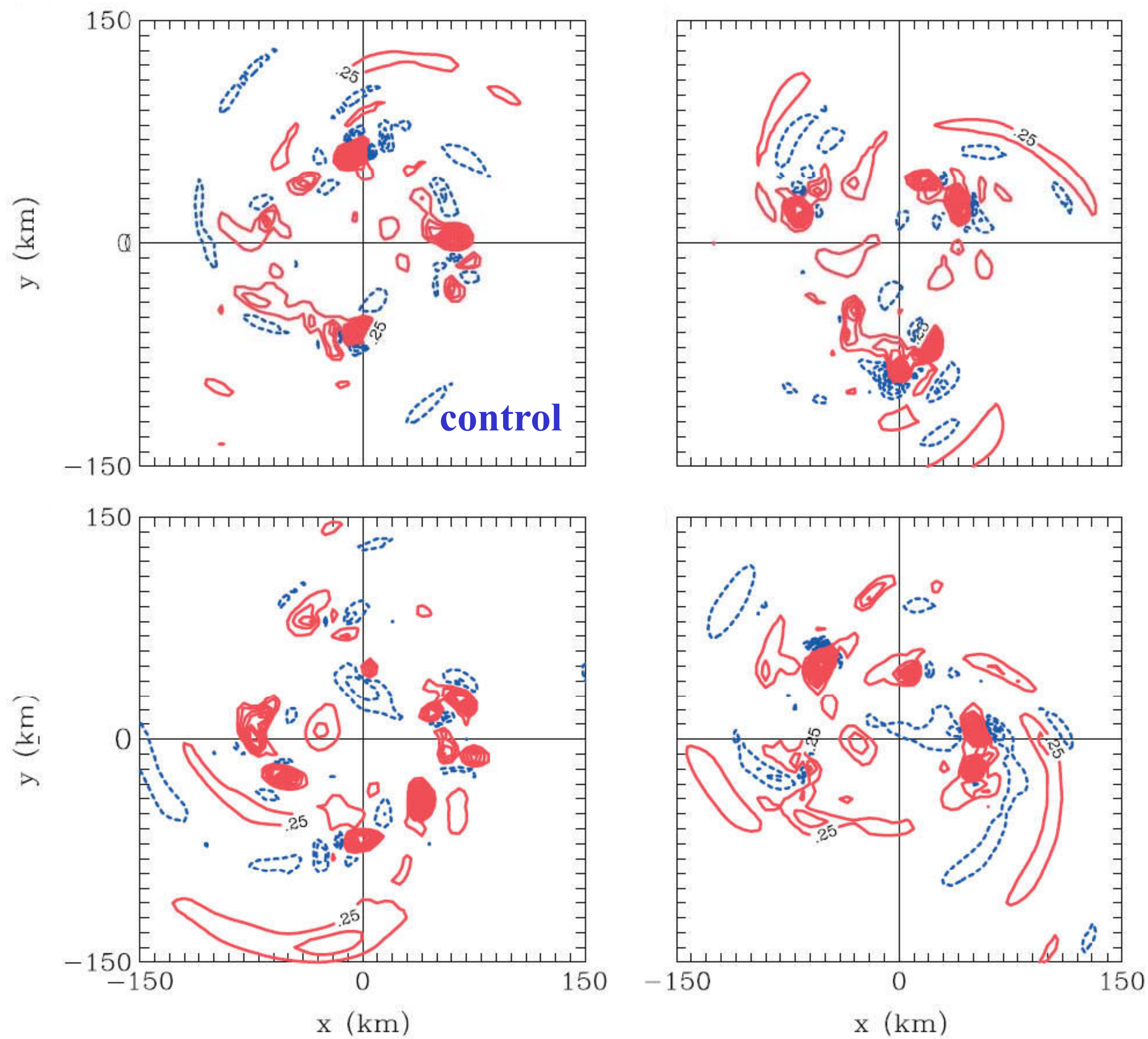
Total

900 mb

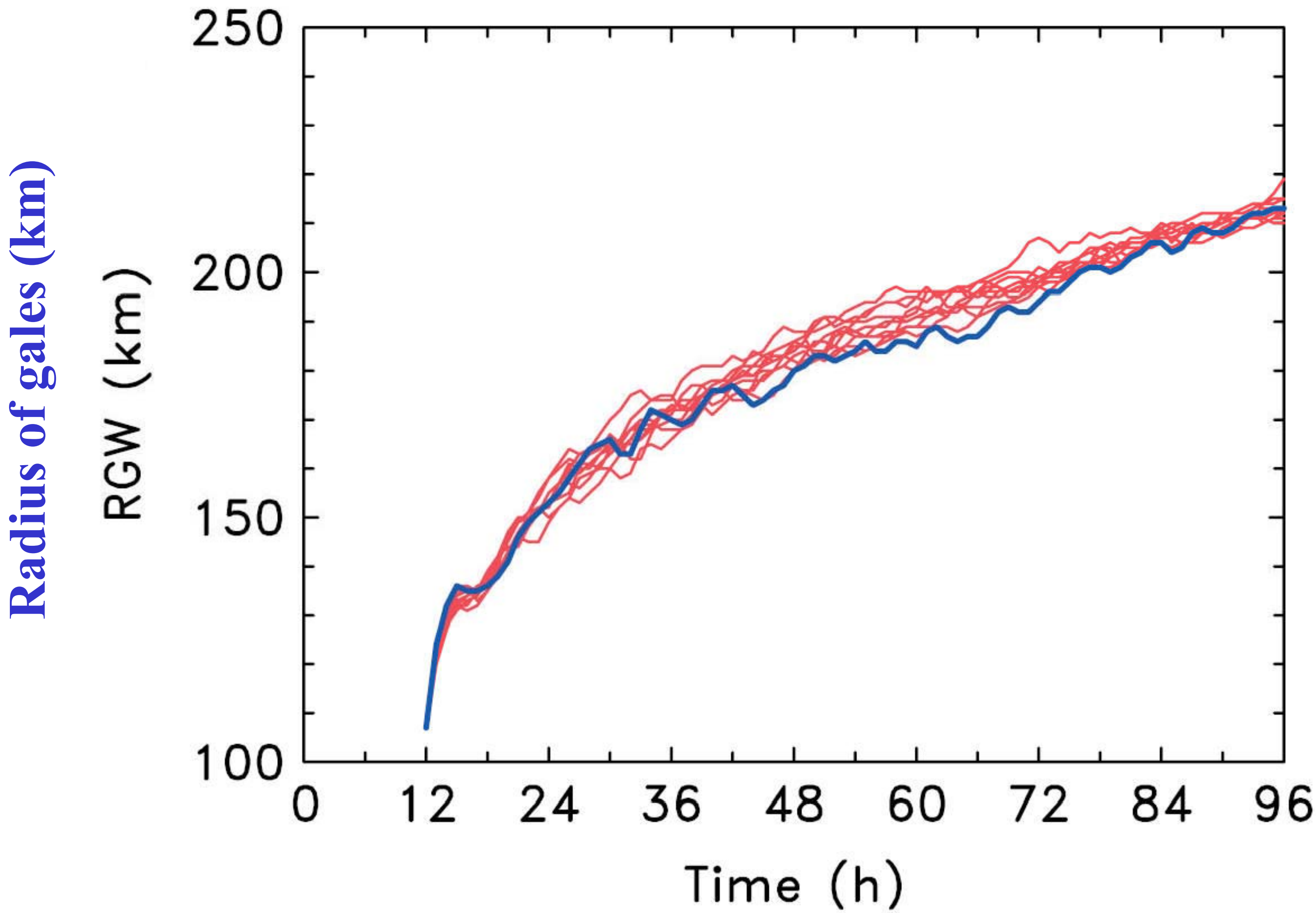
Vertical vorticity pattern at 850 mb at 24 h



Vertical velocity pattern at 850 mb at 24 h



Radius of gale-force wind speed



Conclusions

- The inner-core flow asymmetries in a tropical cyclone are intrinsically unpredictable and chaotic.
- The lack of predictability is a reflection of the convective nature of the inner-core region and extends to the prediction of intensity itself.
- Deep convective towers growing in the rotation-rich environment of the incipient core amplify the local vertical rotation we call them "vortical hot towers" .
- These are the basic coherent structures of the intensification process, which itself is intrinsically asymmetric and chaotic in nature.

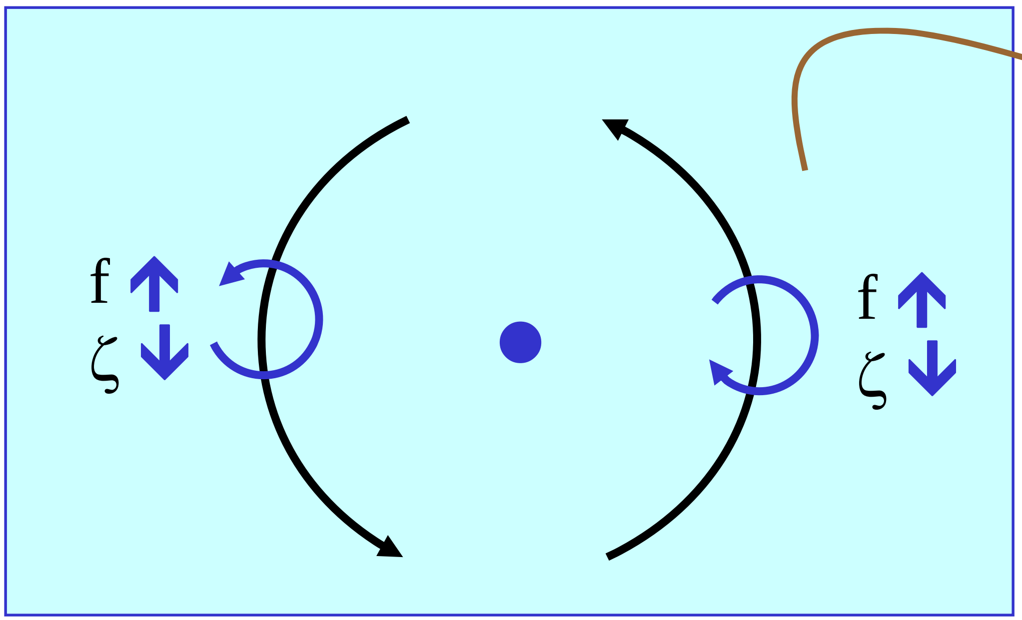
Conclusions

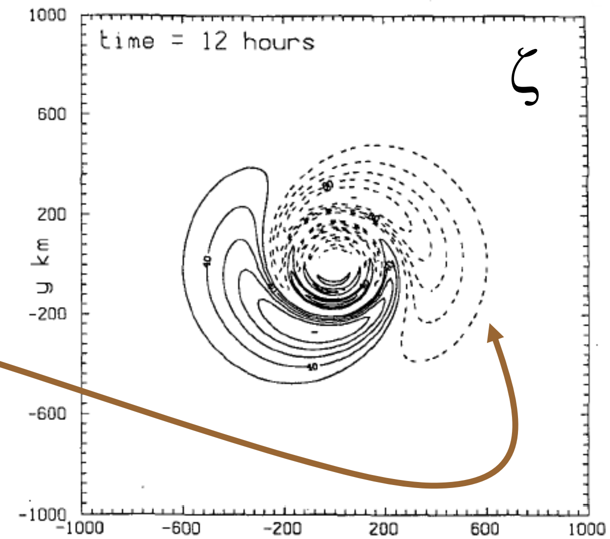
- In the foregoing thought experiments it is the progressive segregation, merger and axisymmetrization of the VHTs that is fundamental to the intensification process.
- Axisymmetrization is never complete. There is always a prominent low azimuthal wavenumber asymmetry (often wavenumber one or two) of the inner-core relative vorticity.

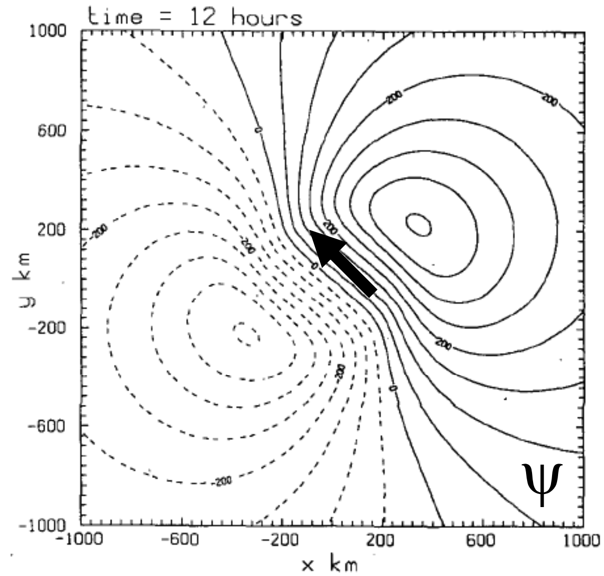
Calculations on a β-plane ($f = f_o + \beta(y - y_o)$)

If $f + \zeta$ were conserved following air parcels:

↓ Asymmetric vorticity ➔

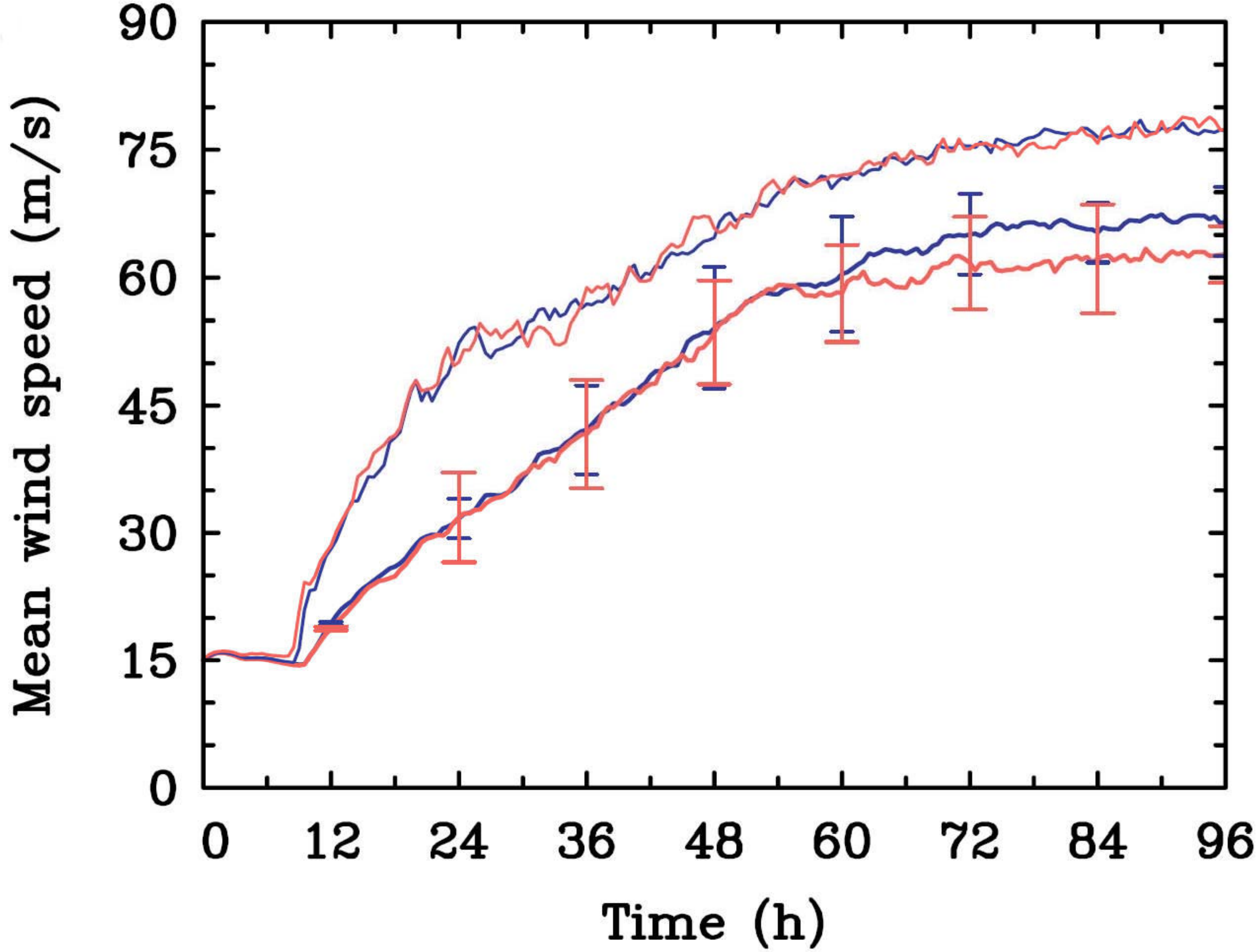




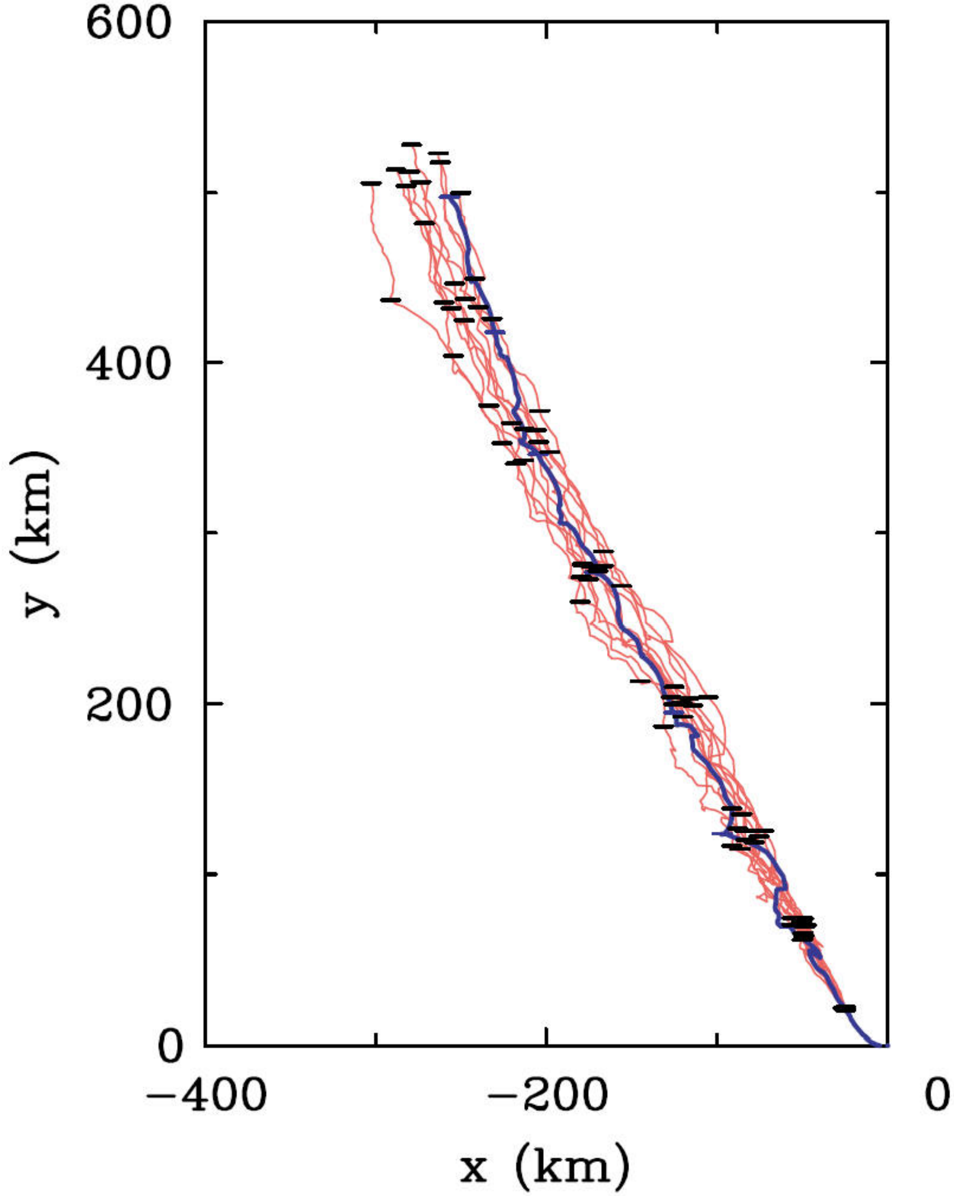


Asymmetric streamfunction ➔

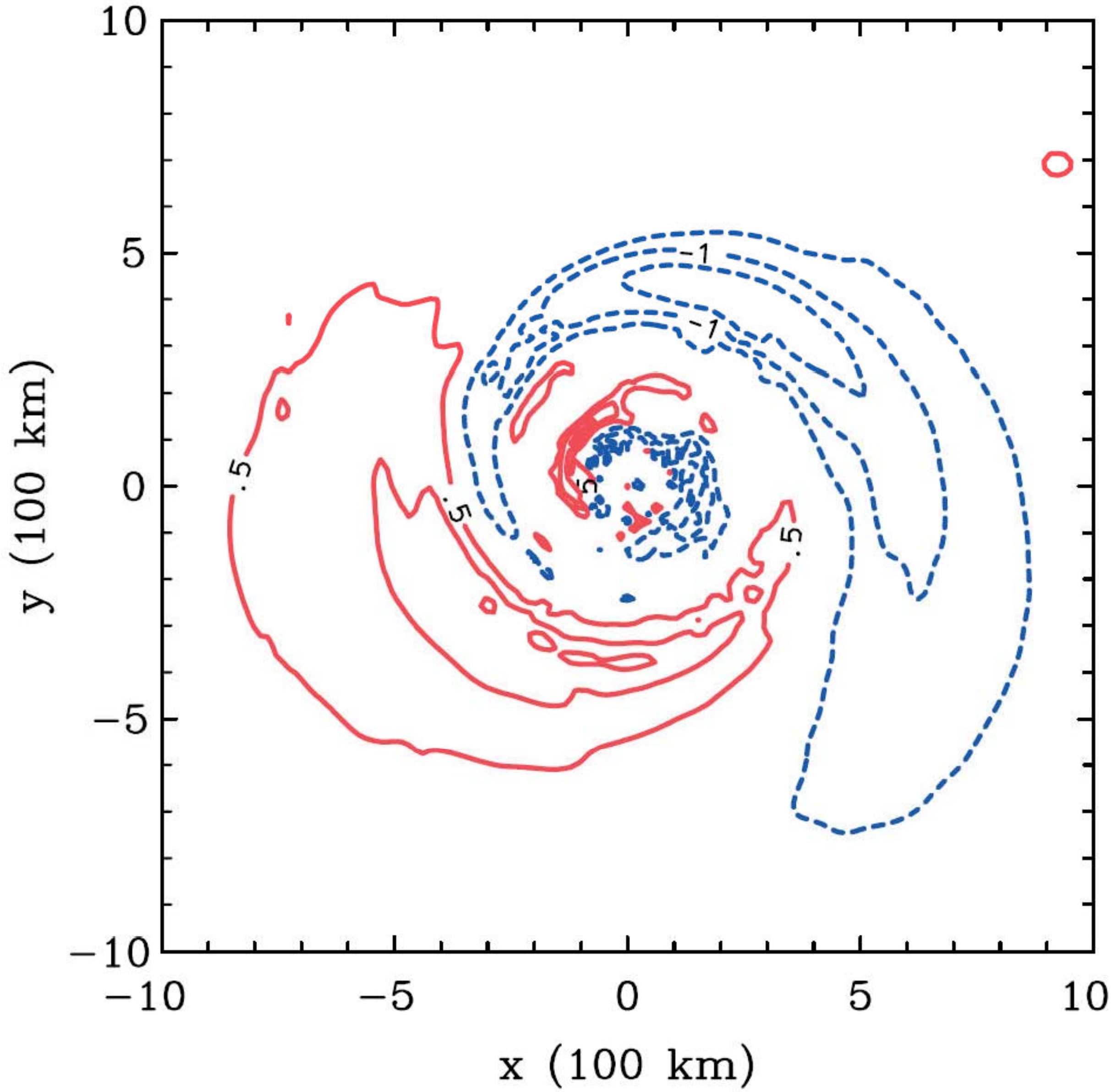
Ensemble-average, v_{max}, on f-plane and β-plane



Tracks on β-plane



Ensemble-mean relative vorticity at 850 mb at 48 h



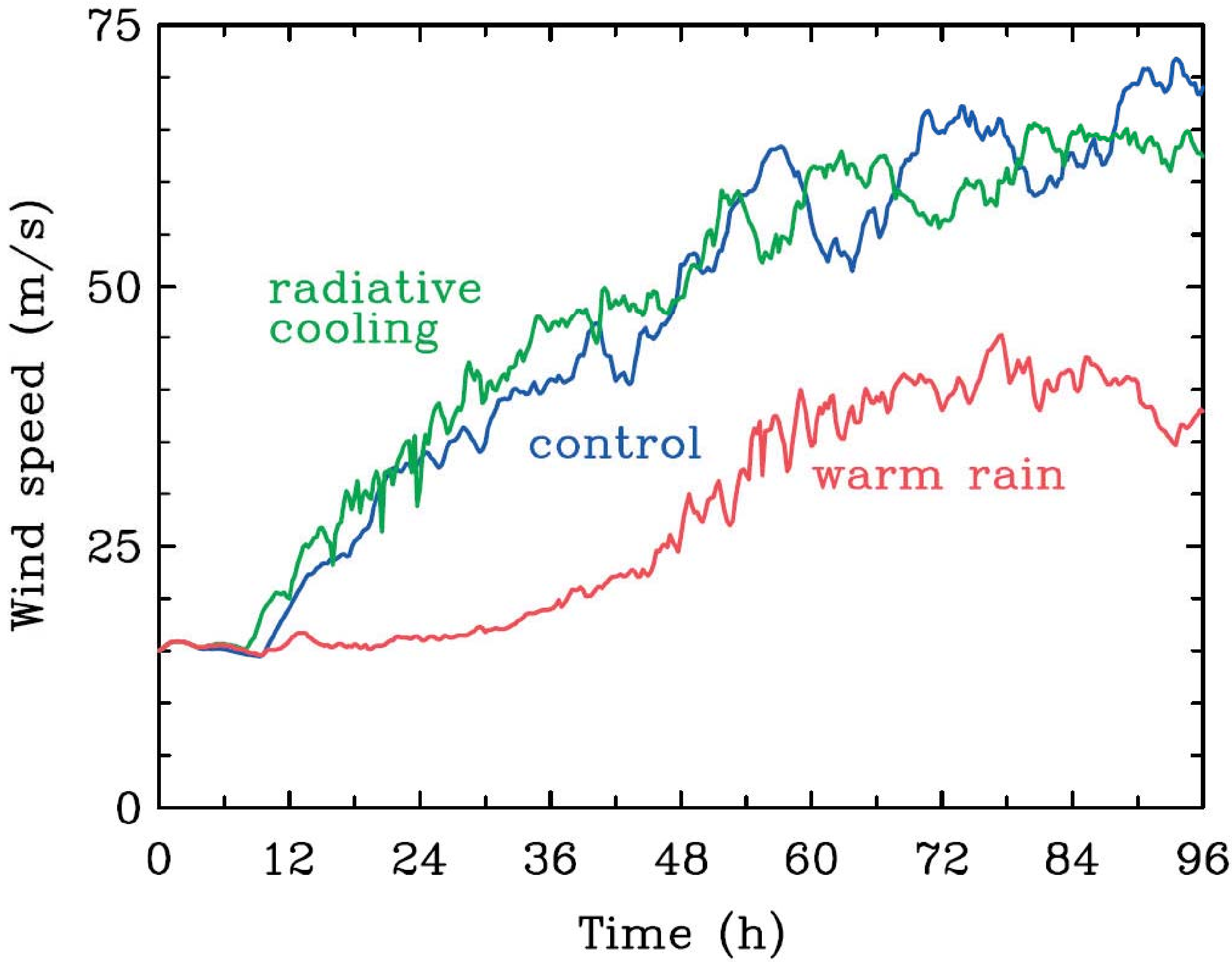
Conclusions

- **On a β-plane, the β-gyre asymmetries are robust features of the ensemble calculations, but the inner-core asymmetries are not.**

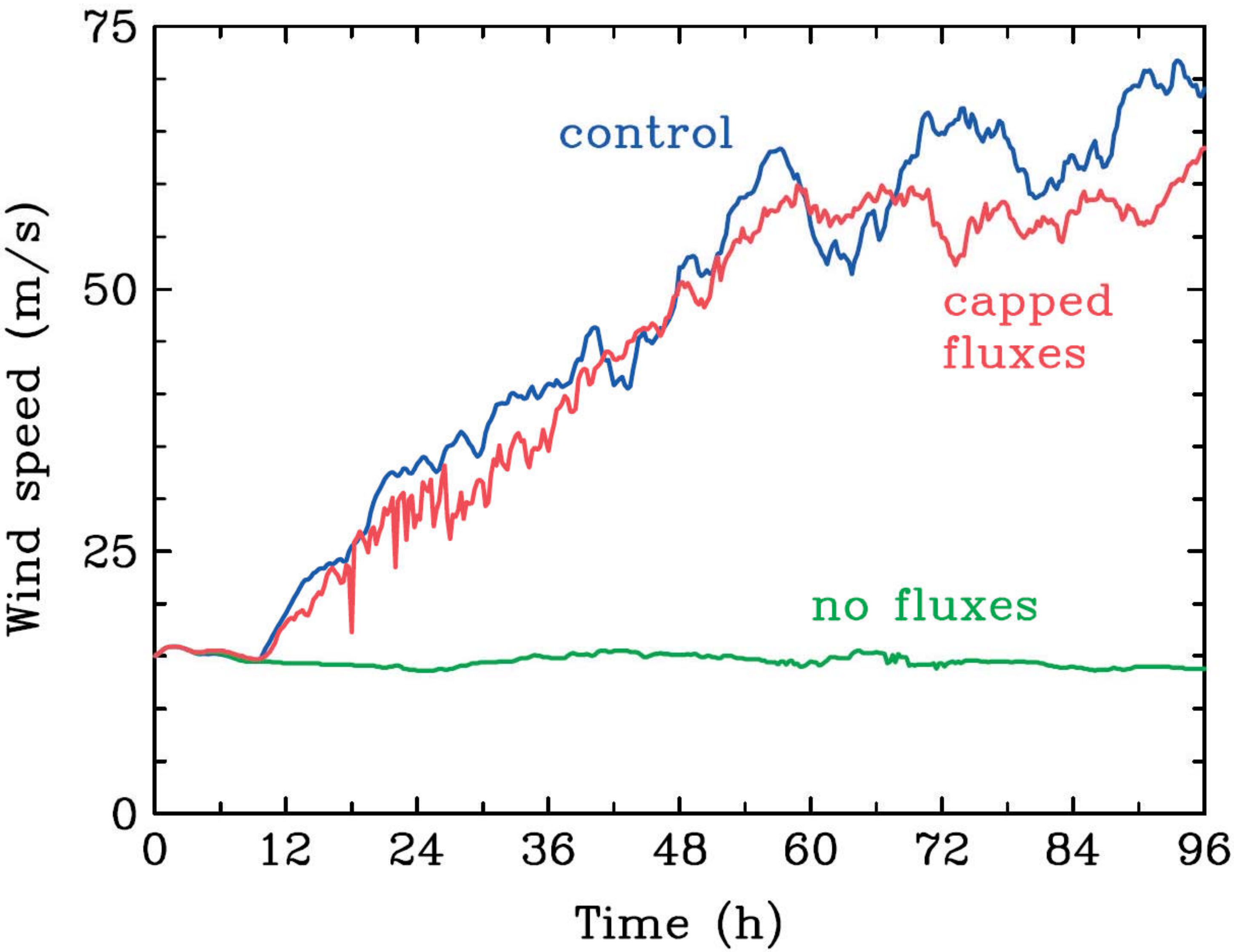
TABLE 2. Sensitivity experiments.

No.	Name	Description
S1	Radiative cooling	Same as control experiment (C0), except the simple cooling option for radiation scheme.
S2	Warm rain	Same as the control experiment, but including the warm-rain scheme
S3	No heat flux	Same as the control experiment, but the surface latent and sensible heat fluxes are set to zero.
S4	Capped heat flux	Same as the control experiment, but the wind-speed dependence of the surface latent and sensible heat fluxes is suppressed beyond a wind speed of 10 m s^{-1}
S5	High resolution	Same as the control experiment, except that a fourth domain with a horizontal grid size of 1.67 km is added.

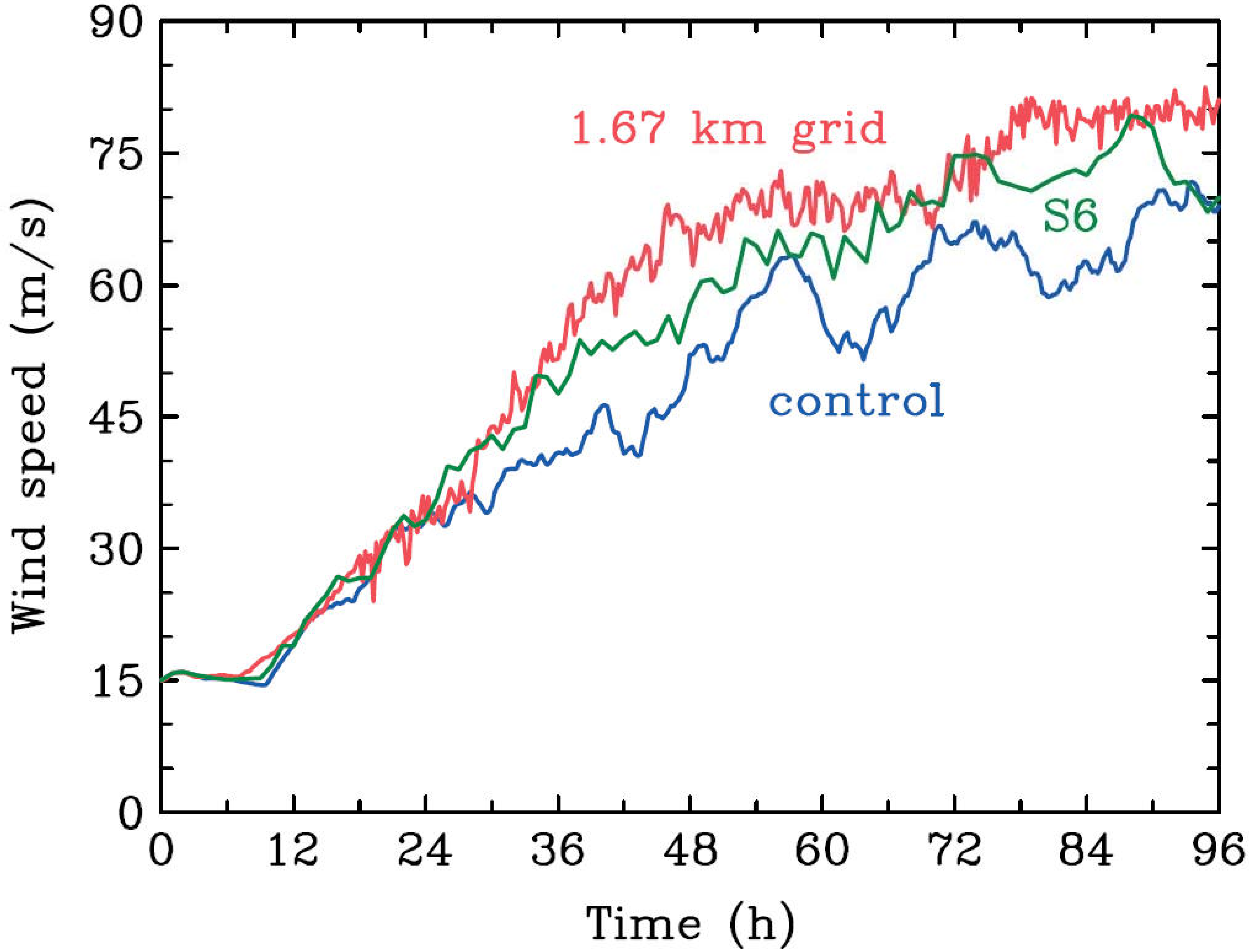
V_{max} in sensitivity experiments



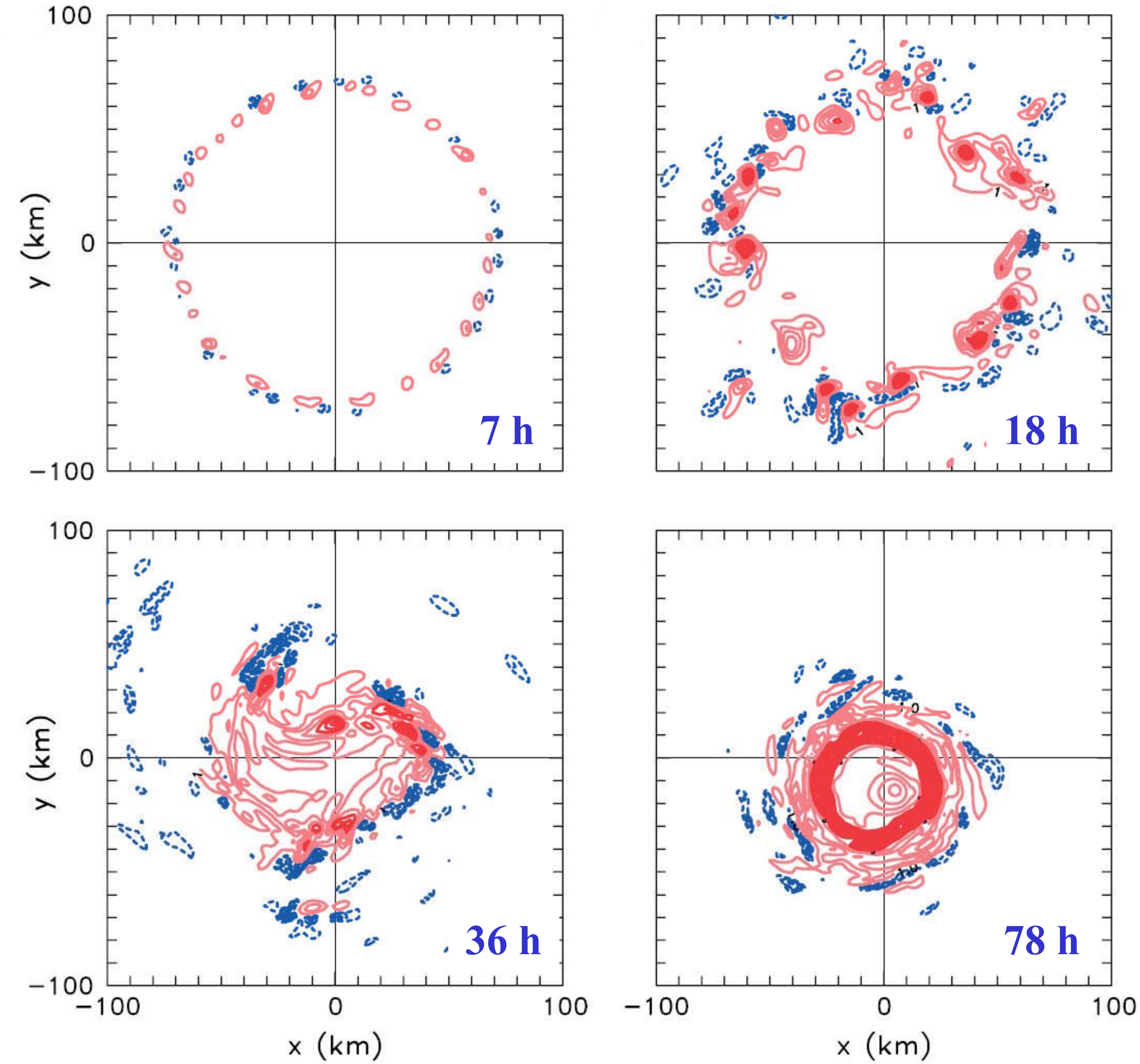
V_{max} in WISHE assessment experiments



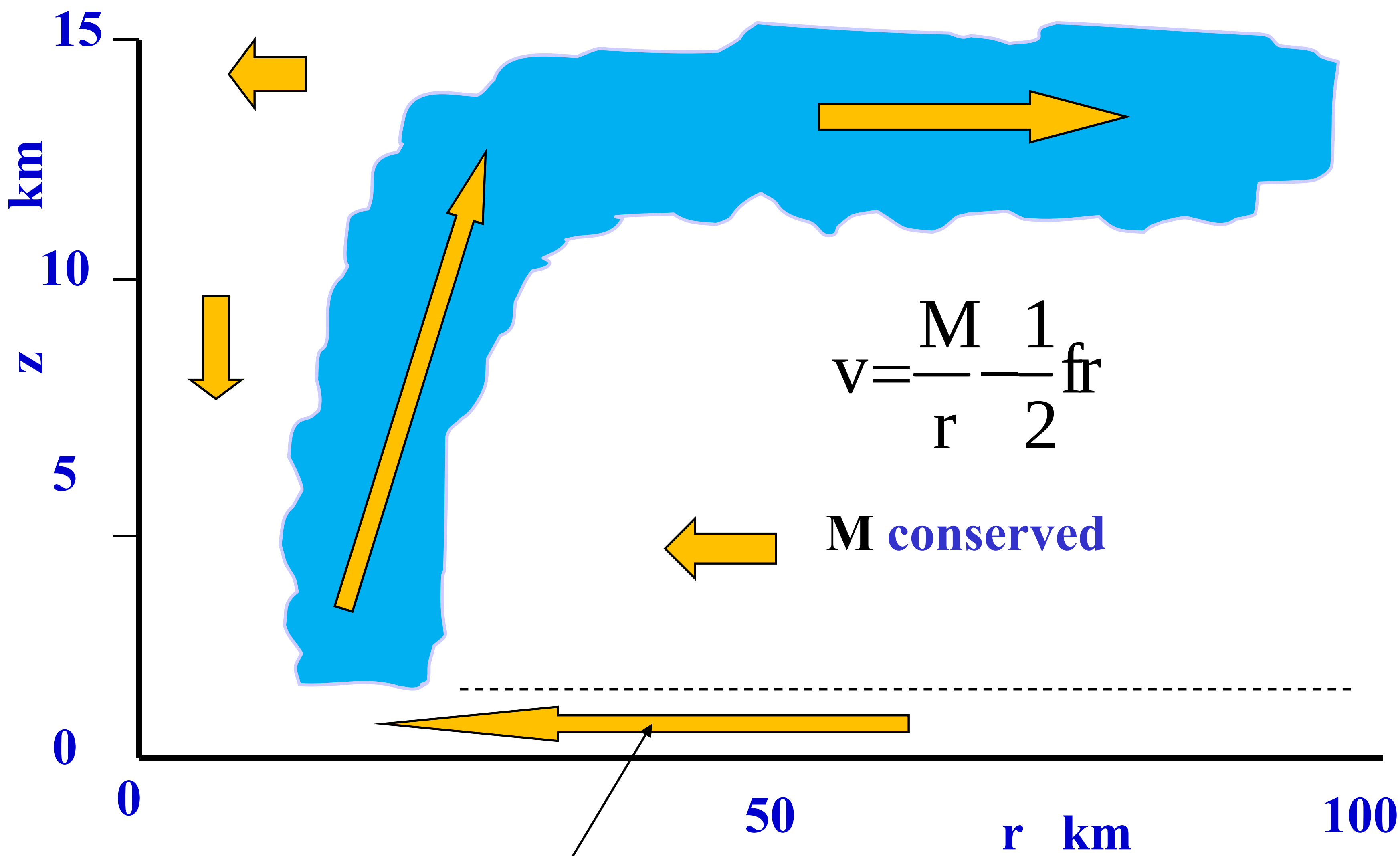
Evolution of intensity



Vertical velocity pattern at 850 mb in 1.67 km run

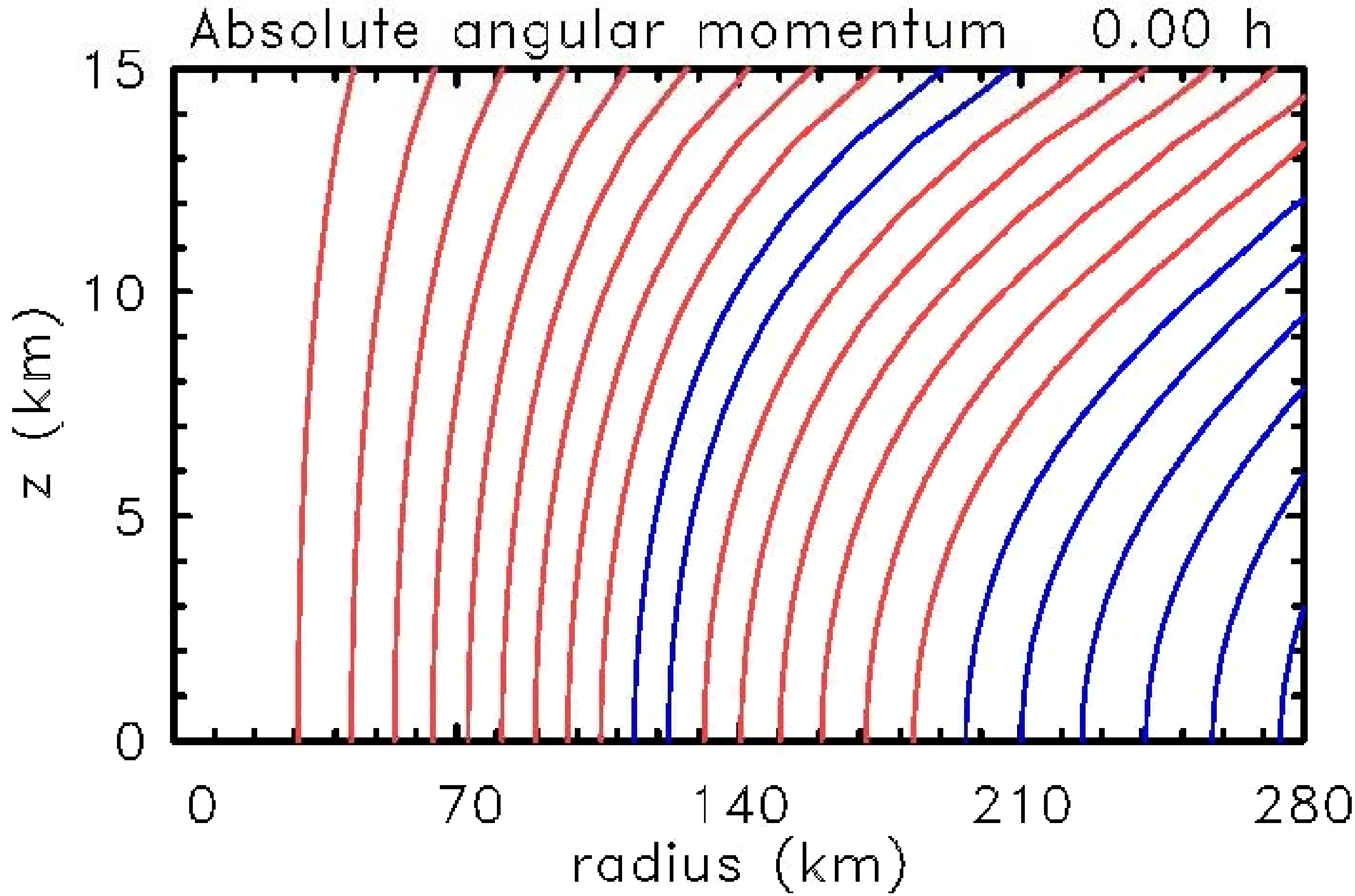


A revised view of tropical-cyclone intensification

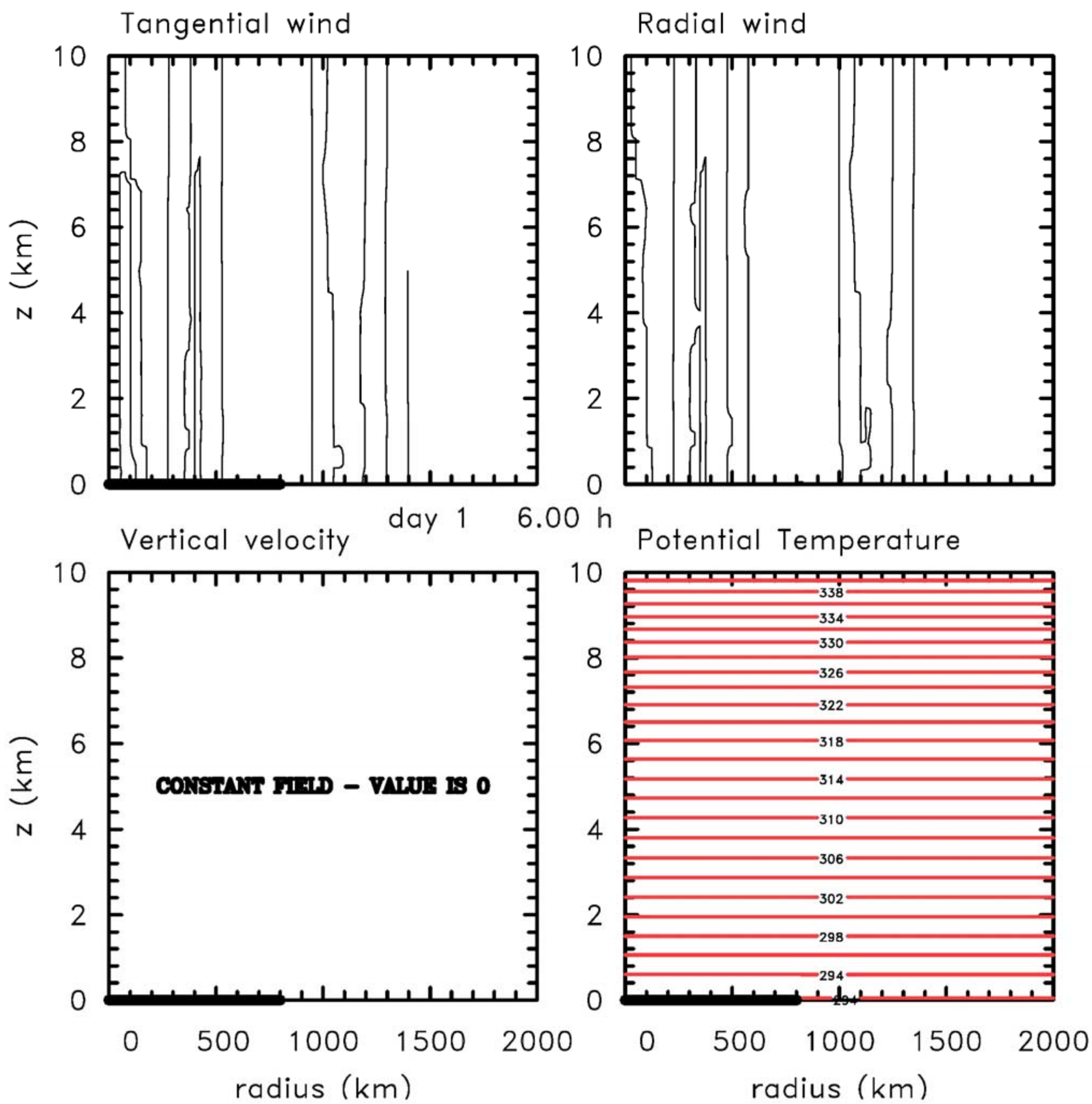


M reduced by friction, but strong convergence → small r

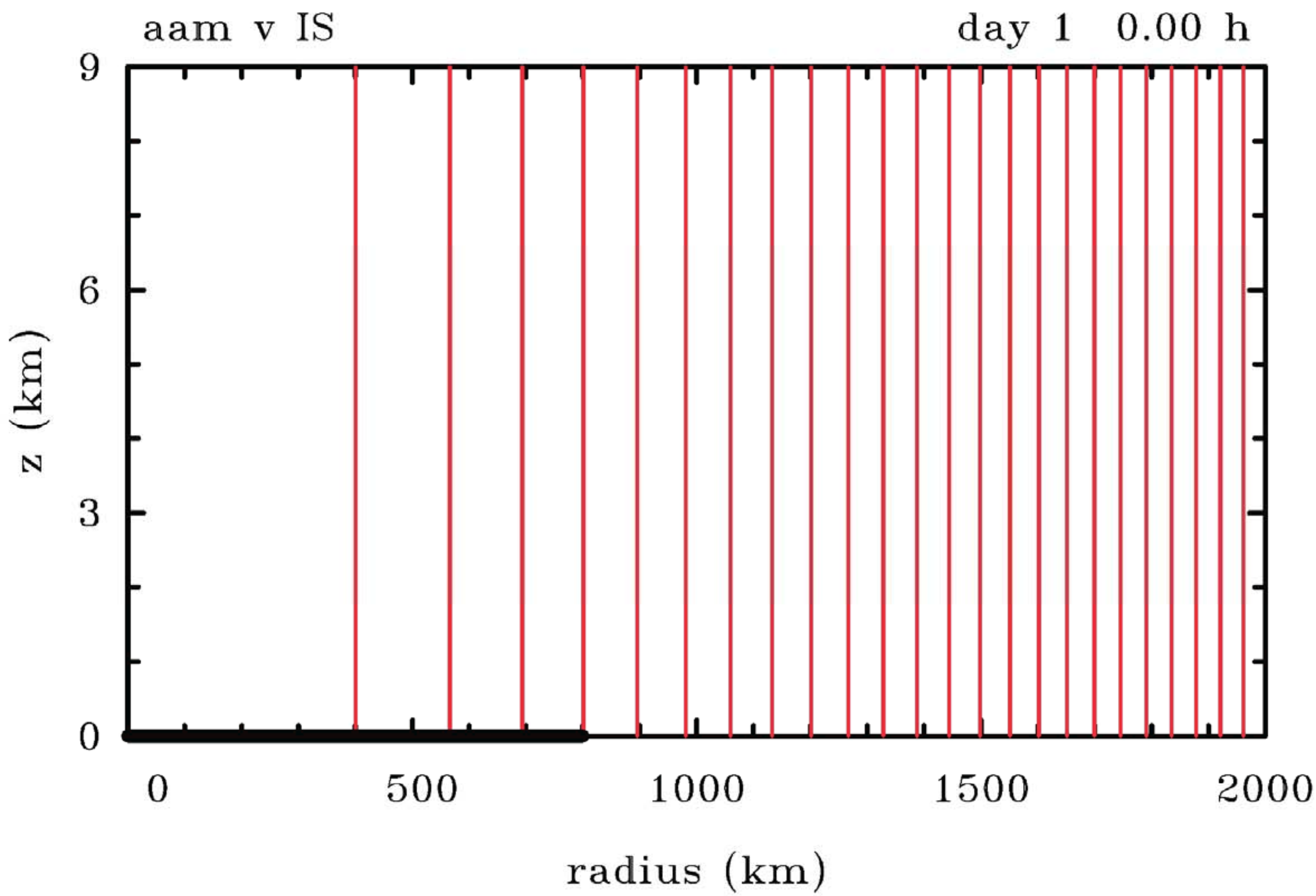
$$M = vr + \frac{1}{2}fr^2 \quad \Rightarrow \quad v = \frac{M}{r} - \frac{1}{2}fr$$



Analogy with heat lows



Analogy with heat lows: u and M



How do tropical cyclones form?

For a cyclone to form several preconditions must be met:

1. Warm ocean waters (of at least 26.5°C) throughout a sufficient depth (unk[illegible]own how deep, but at least on the order of 50 m). Warm waters are necessary to fuel [illegible] engine of the tropical cyclone.

2. An atmosphere which cools fast enough with height (is "[illegible]uch that it encourages thunderstorm activity. It is the thunderstorm [illegible]s the heat stored in the ocean waters to be liberated for the tropical c[illegible]

3. Relatively moist layers near the mid-tro[illegible]y mid levels are not conducive for allowing the continuing de[illegible]pread thunderstorm activity.

4. A minimum distance of arou[illegible] equator. Some of the earth's spin (Coriolis force) is needed to m[illegible]ssure of the system. (Systems can form closer to the equator but it's a [illegible]

5. A pre-existi[illegible] the surface with sufficient spin (vorticity) and inflow (convergence[illegible] cannot be generated spontaneously. To develop, they require a weakly orga[illegible]th sizeable spin and low level inflow.

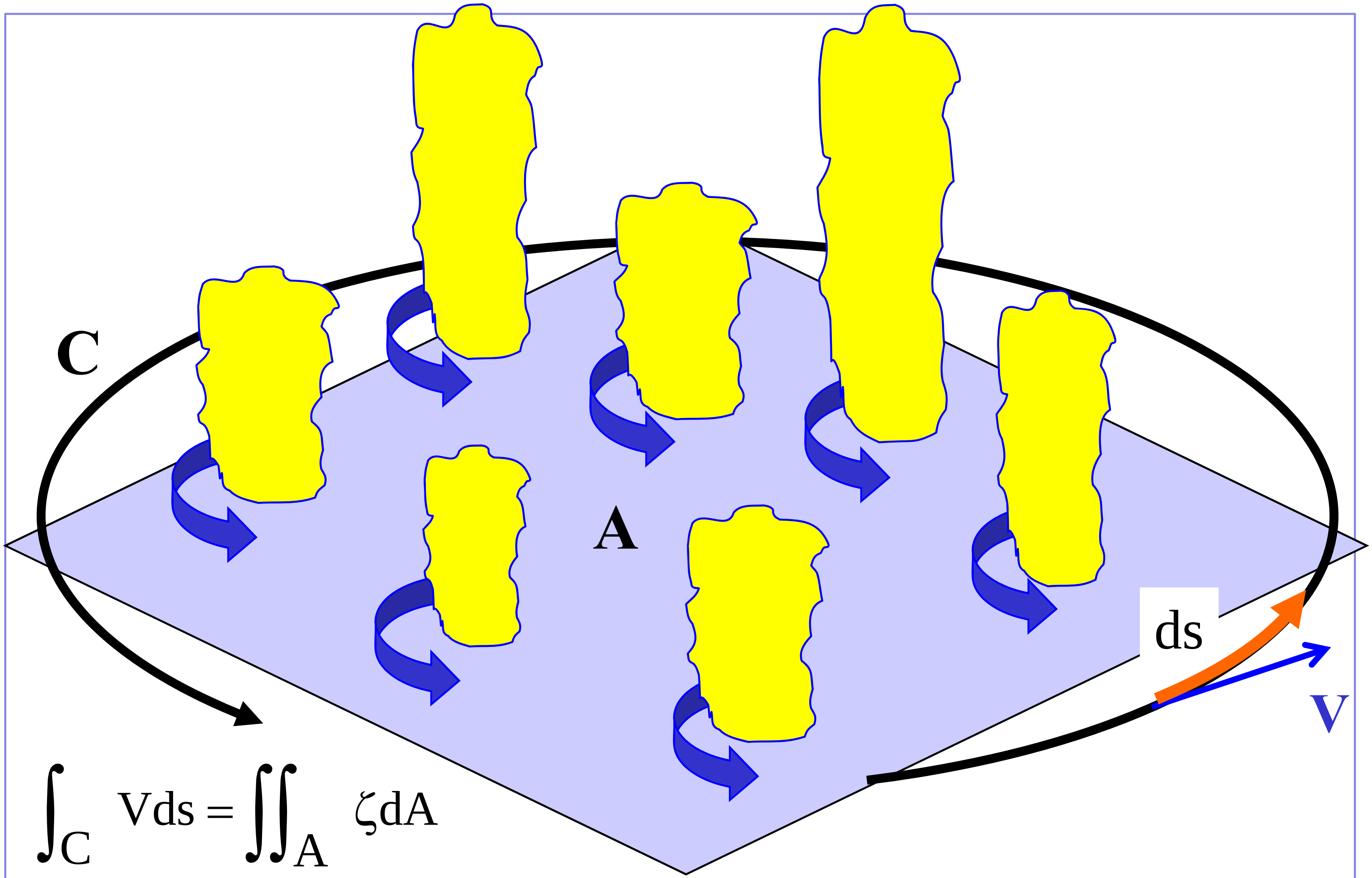
6. Little c[illegible] the wind with height (low vertical wind shear, i.e. less than 40 km/h from surface to tropopause). Large values of wind shear tend to disrupt the organisation of the thunderstorms that are important to the inner part of a cyclone.

So: how do they form? !!!

Having these conditions met is necessary, but not sufficient as many disturbances that appear to have favourable conditions do not develop.

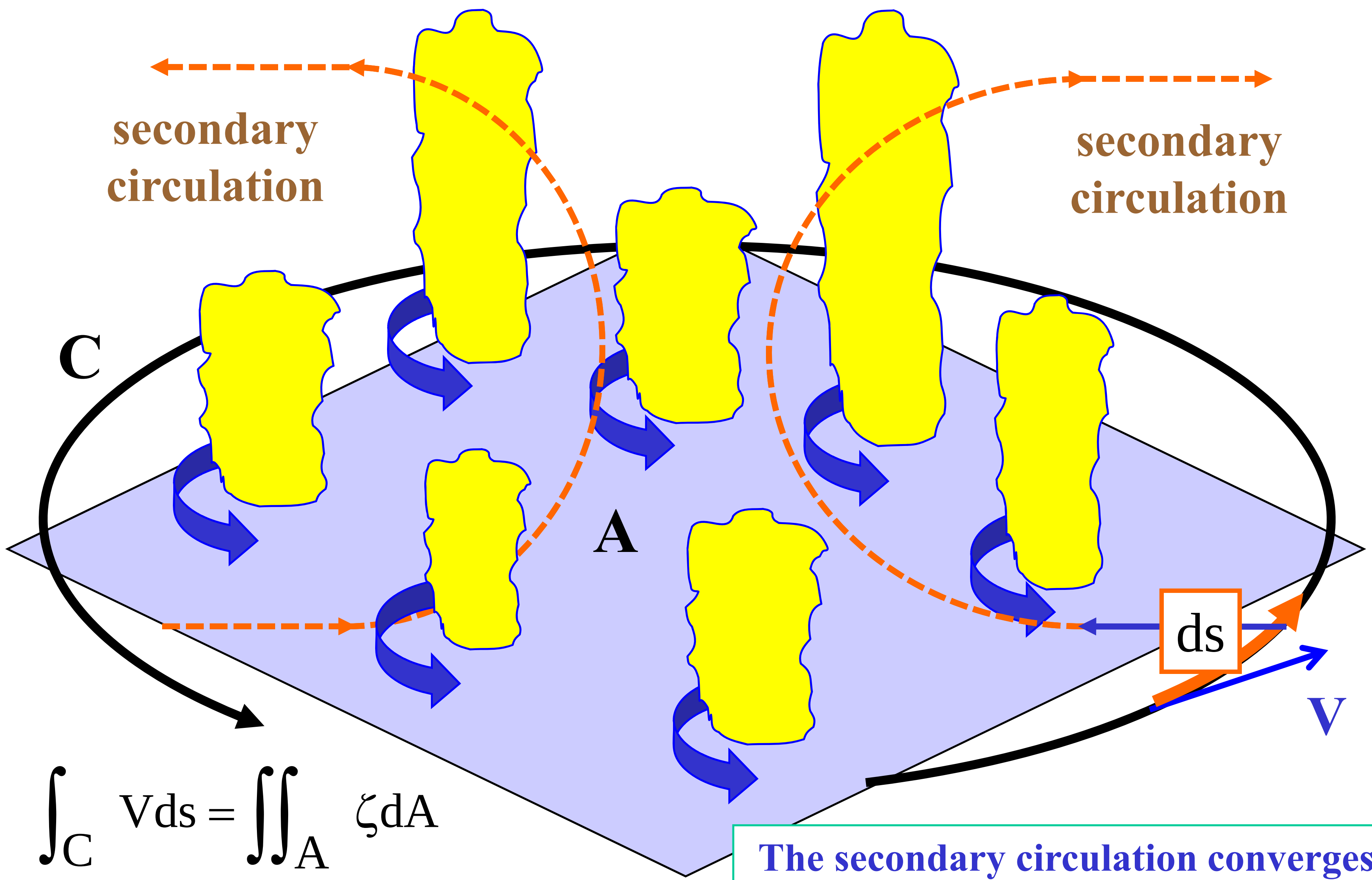
http://www.bom.gov.au

A unified view of tropical cyclogenesis and intensification



$$\int_C V ds = \iint_A \zeta dA$$

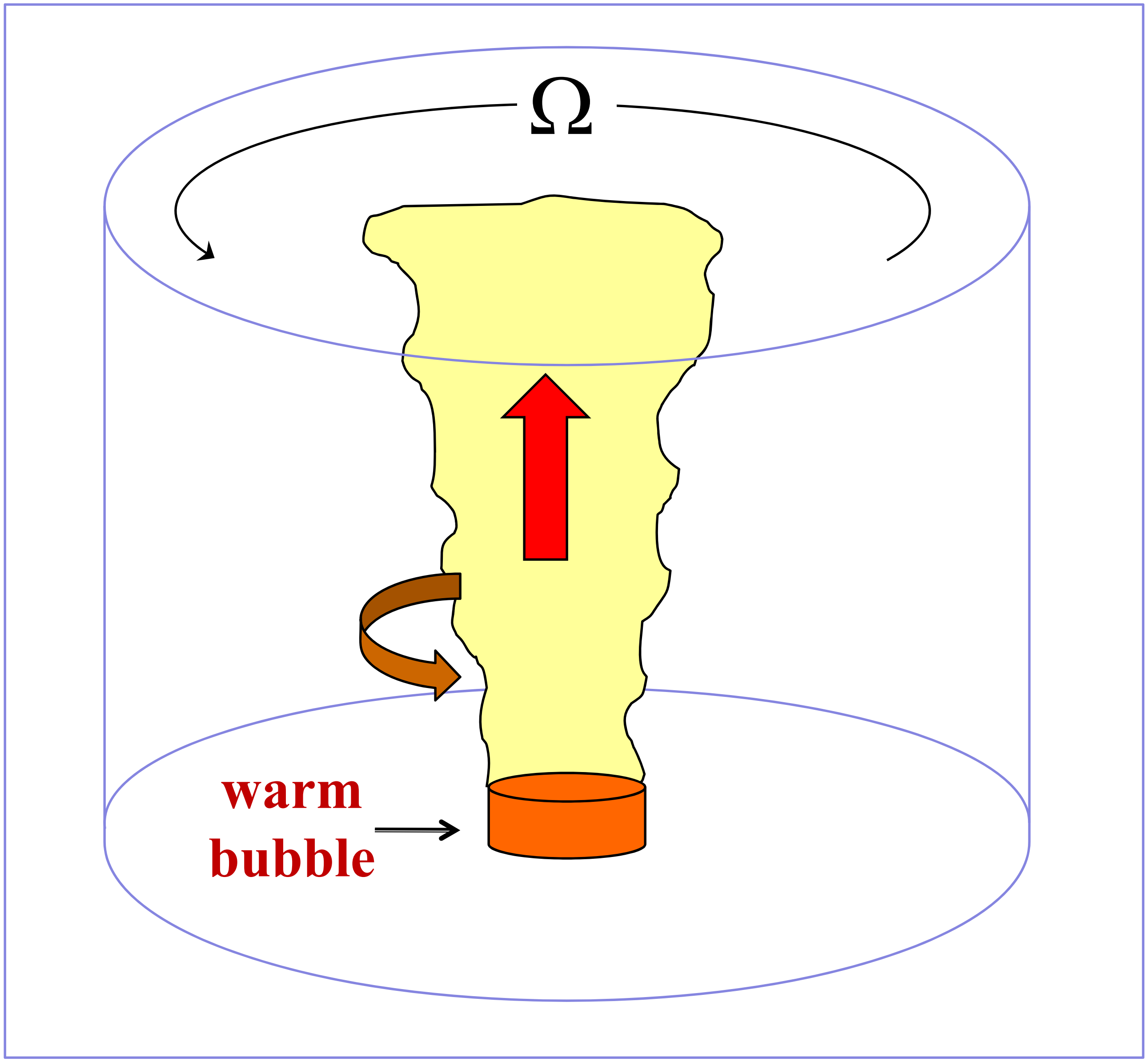
The secondary, or in-up-out, circulation



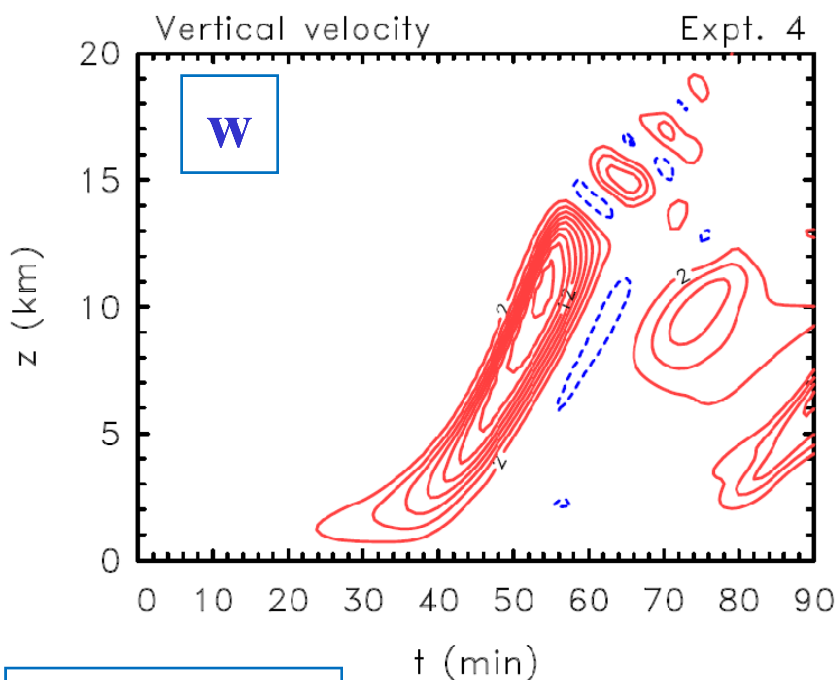
$$\int_C V ds = \iint_A \zeta dA$$

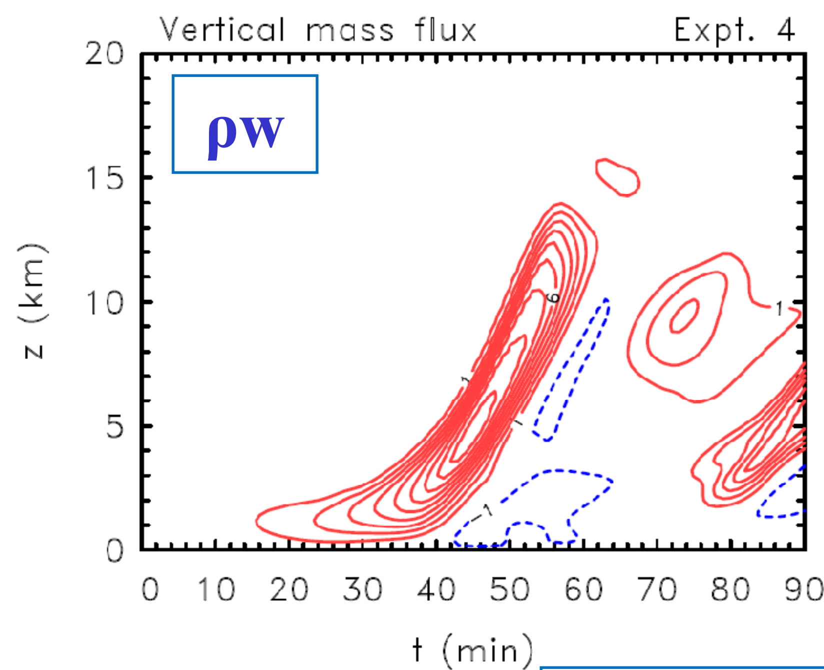
The secondary circulation converges mean absolute vorticity

Numerical simulation of rotating deep convection: idealized VHT



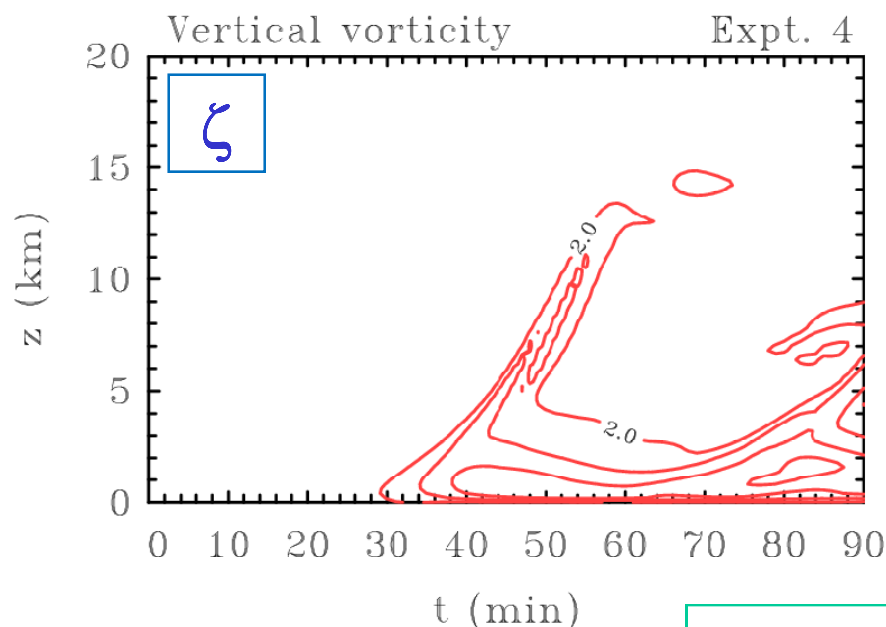
From Wissmeier and Smith QJ (2011)





contour
$2\ m\ s^{-1}$

contour
$1\ kg\ s^{-1} m^{-2}$



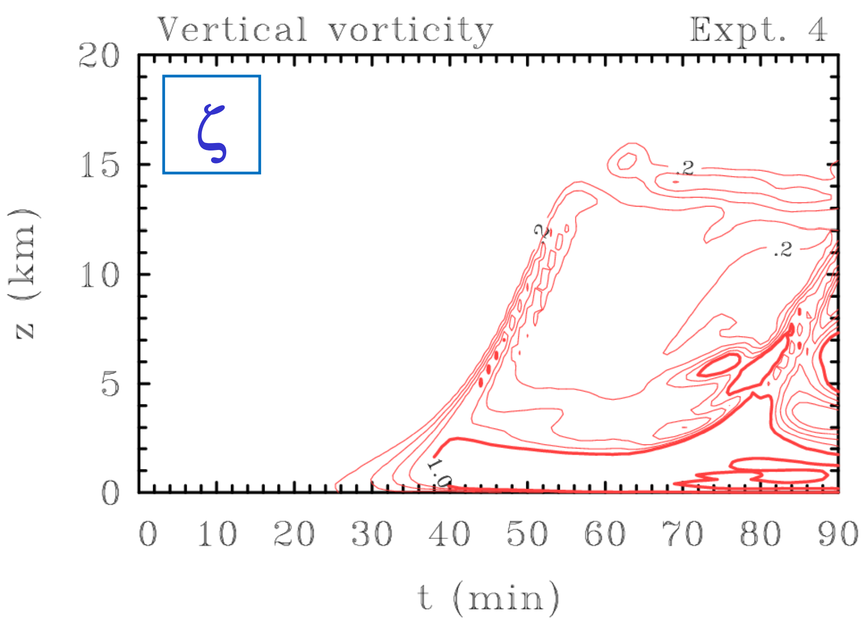
$f = 3 \times 10^{-4}\ s^{-1}$

contour
$2 \times 10^{-3}\ s^{-1}$

Wissmeier and Smith, QJ, (2011)

Background rotation: $f = 5 \times 10^{-5}\ s^{-1}$

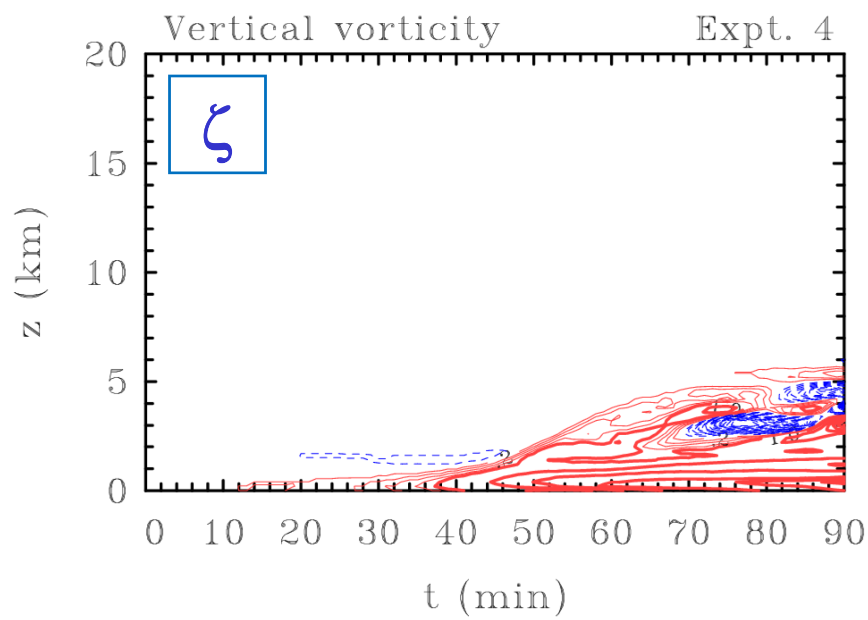
Deep convective cloud



contour
$1 \times 10^{-3}\ s^{-1}$, thin lines $2 \times 10^{-4}\ s^{-1}$

~40 × amplification

Cumulus congestus cloud

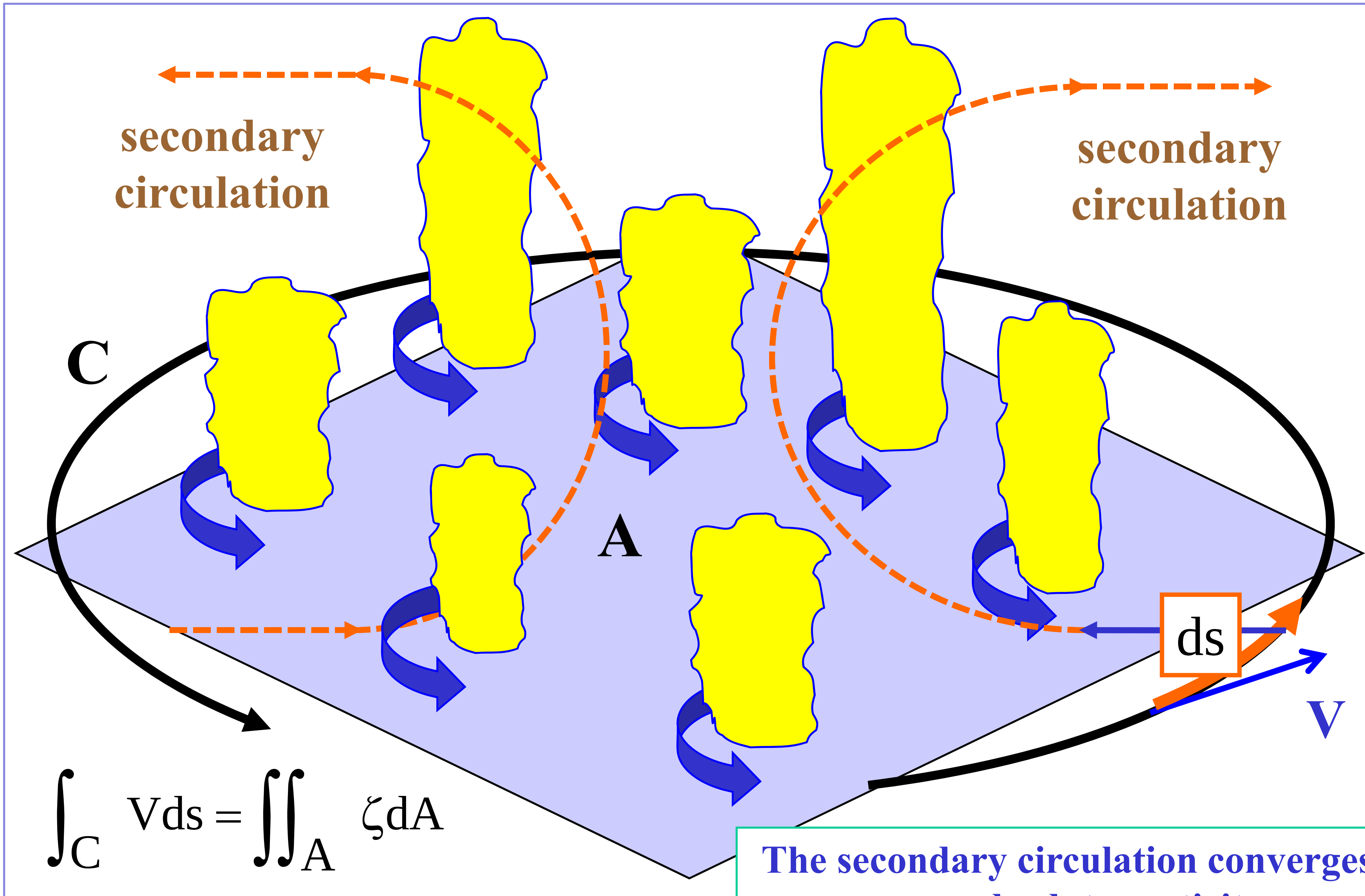


contour
$1 \times 10^{-4}\ s^{-1}$, thin lines $2 \times 10^{-5}\ s^{-1}$

~8 × amplification

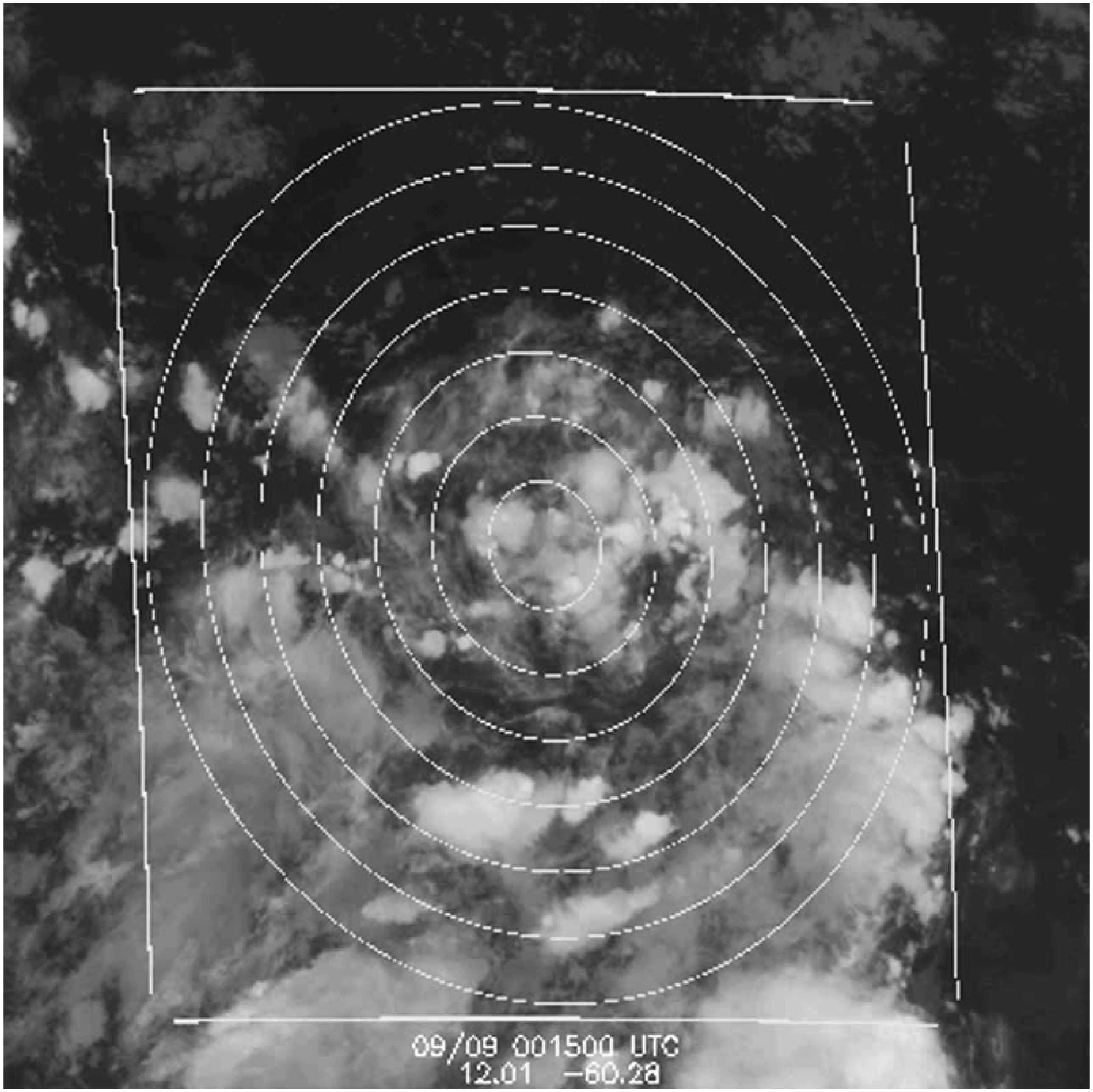
Wissmeier and Smith, QJ, (2011)

The secondary, or in-up-out, circulation



The secondary circulation converges mean absolute vorticity

Genesis of Hurricane Karl 2010



A unified view of tropical cyclogenesis and intensification

Basis for a unified view of tropical cyclogenesis and intensification:

- **Deep convection developing in the presence of vertical vorticity amplifies the vorticity locally by vortex tube stretching, irrespective of the strength of the updraught and the depth of convection,**
- **The vortical remnants outlive the convection that produced them in the first place.**
- **The vortical remnants tend to aggregate in a quasi two-dimensional manner with a corresponding upscale energy cascade and some of these remnants will be intensified further by subsequent convective episodes.**

The unified view continued

- The amplification and aggregation of vorticity represents an increase in the relative circulation within a fixed circuit encompassing the convective area.
- The collective effect of diabatic heating in the convection generates a secondary in-up-out circulation that further amplifies the formation process.
- As the circulation progressively increases in strength, there is some increase in the surface moisture fluxes.
- It is not necessary that the moisture fluxes continue to increase with surface wind speed.


The End