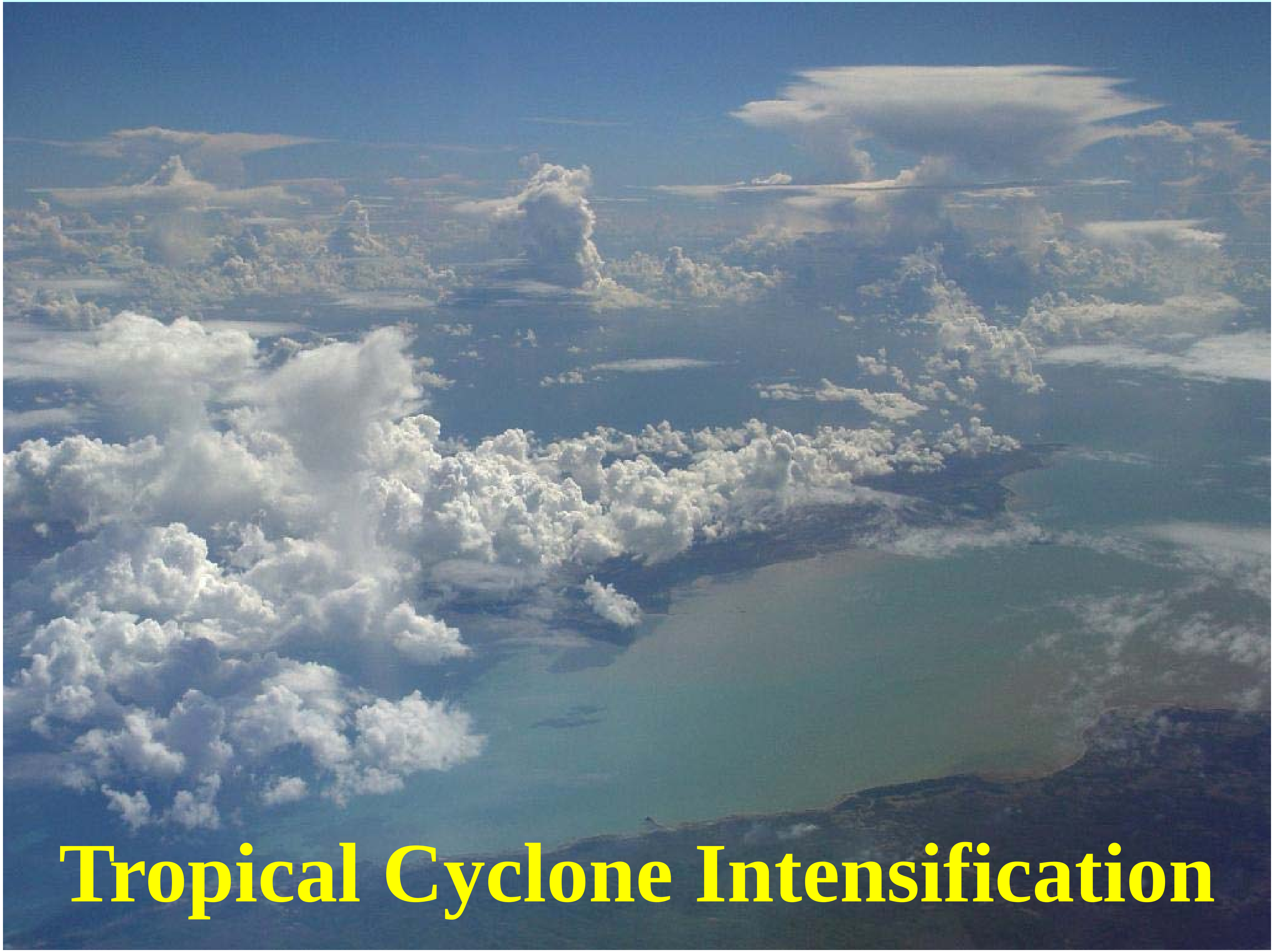


Tropical Cyclone Intensification

Theories for tropical cyclone intensification and structure

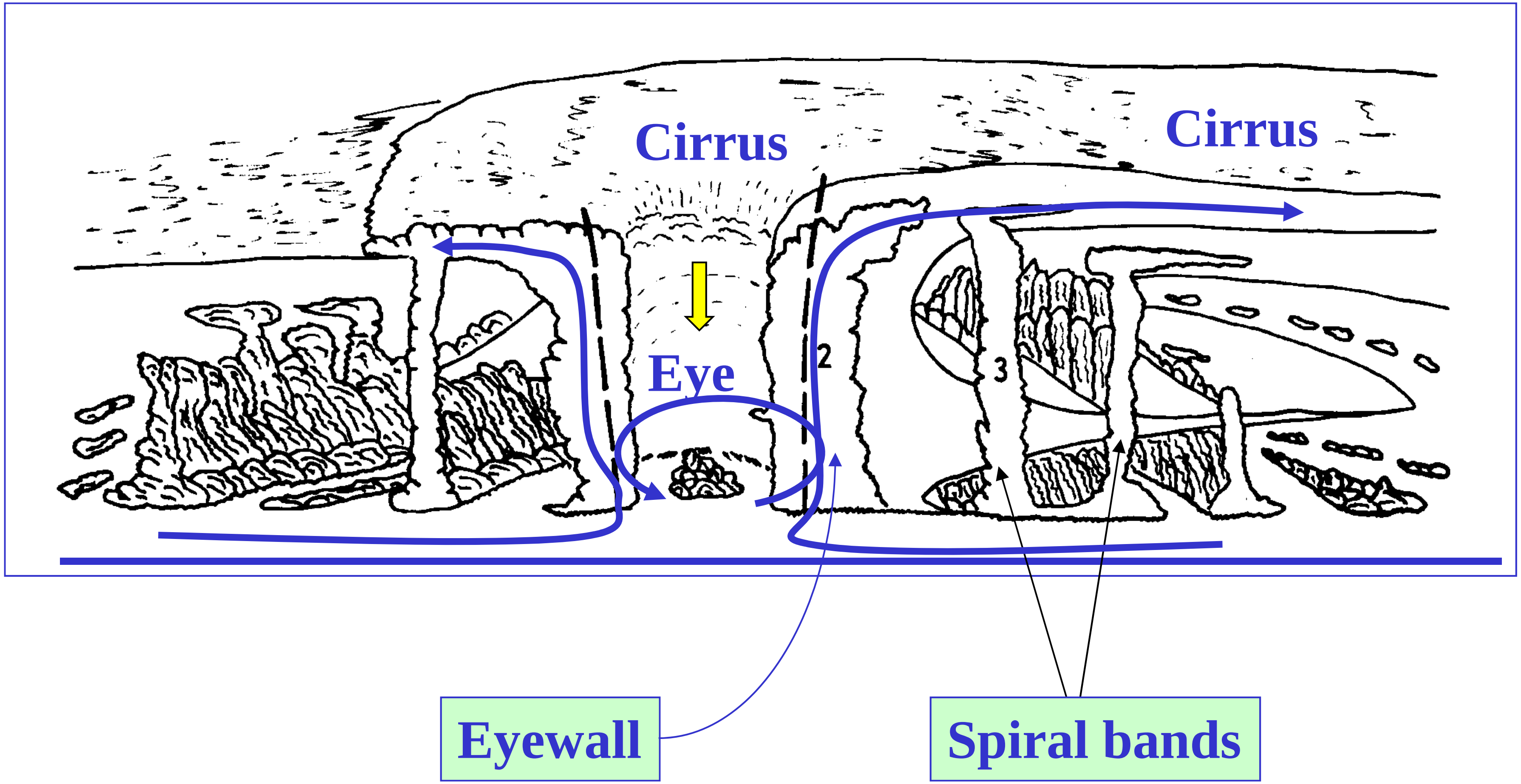
- CISK (Charney and Eliassen 1964)
- Cooperative Intensification Theory (Ooyama 1969).
- WISHE (Emanuel 1986 … , Holton and Hakim, 2012)
- Vortical deep convection paradigm whose mean field view provides an extended Cooperative Intensification Theory

Paradigms for tropical cyclone intensification

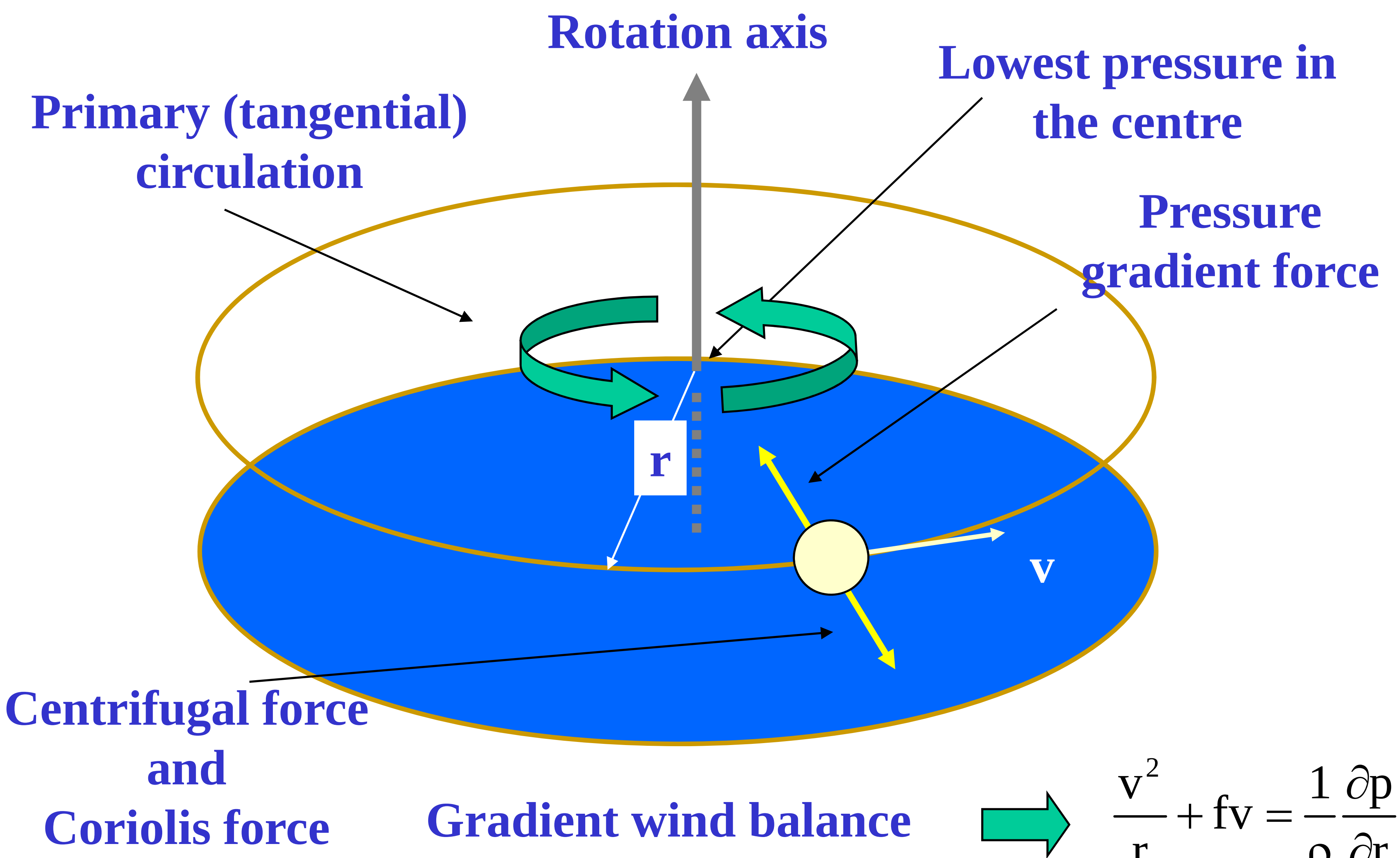
Michael T. Montgomery[a] [1]and Roger K. Smith[b]
[a] *Dept. of Meteorology, Naval Postgraduate School, Monterey, CA*
[b] *Meteorological Institute, University of Munich, Munich, Germany.*

To appear in The Bruce Morton Memorial Volume of the Australian Meteorological and Oceanographical Society Journal
http://www.meteo.physik.uni-muenchen.de/~roger/Publications/M8.pdf

Schematic cross-section through a hurricane

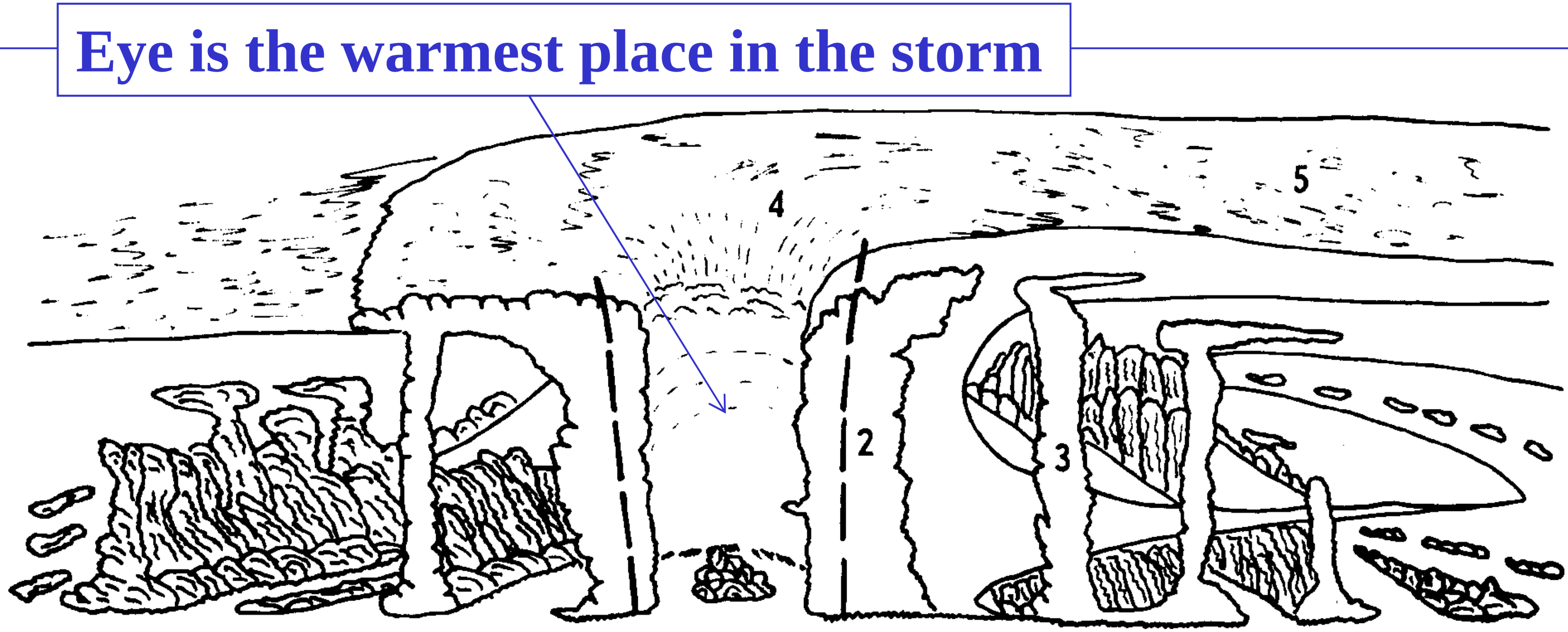


Force balance in a vortex



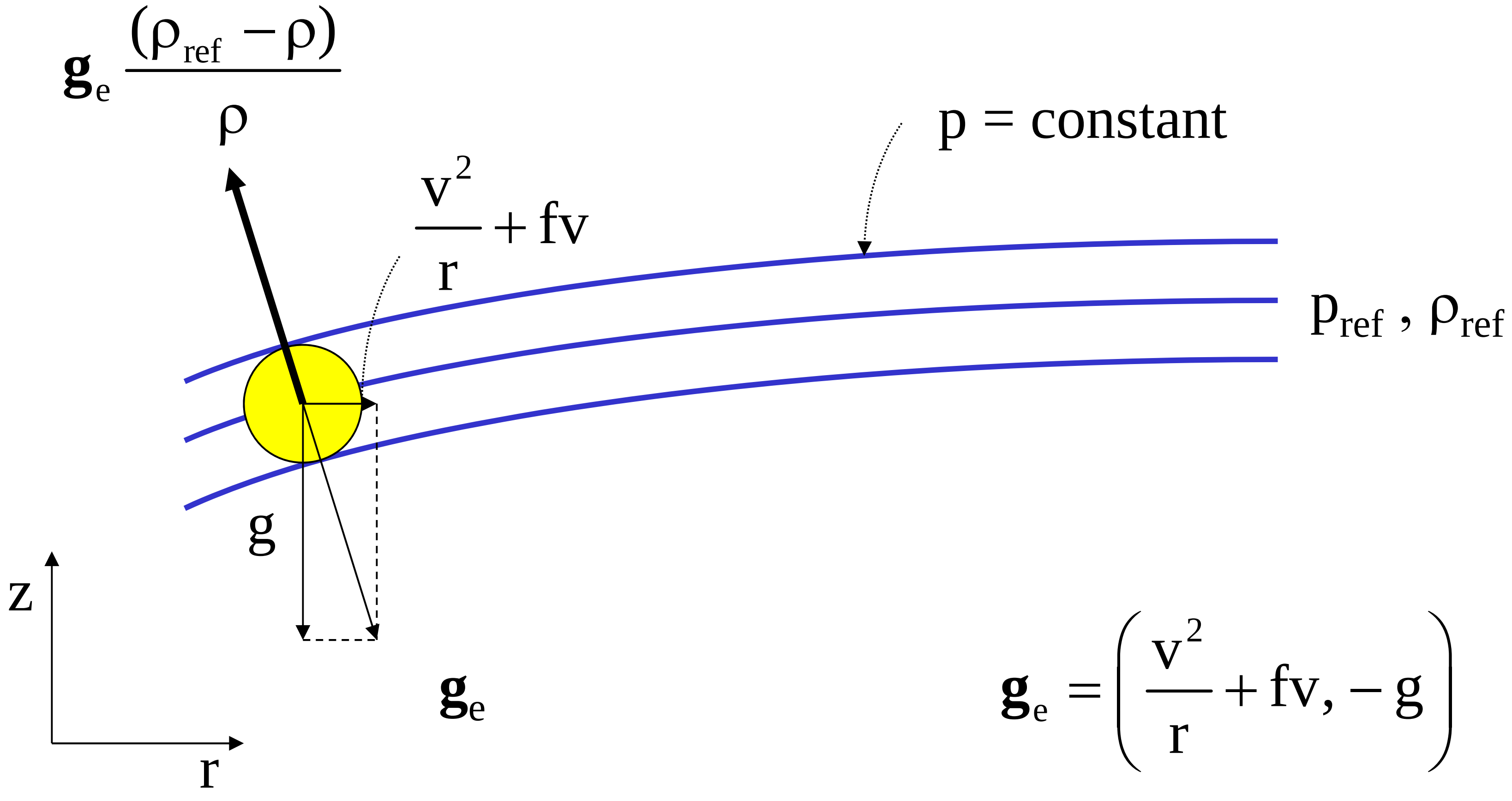
$$\frac{v^2}{r} + fv = \frac{1}{\rho}\frac{\partial p}{\partial r}$$

Are the eyewall clouds buoyant?



See Smith, Montgomery and Zhu (2005) ***Dyn. Atmos & Oceans***

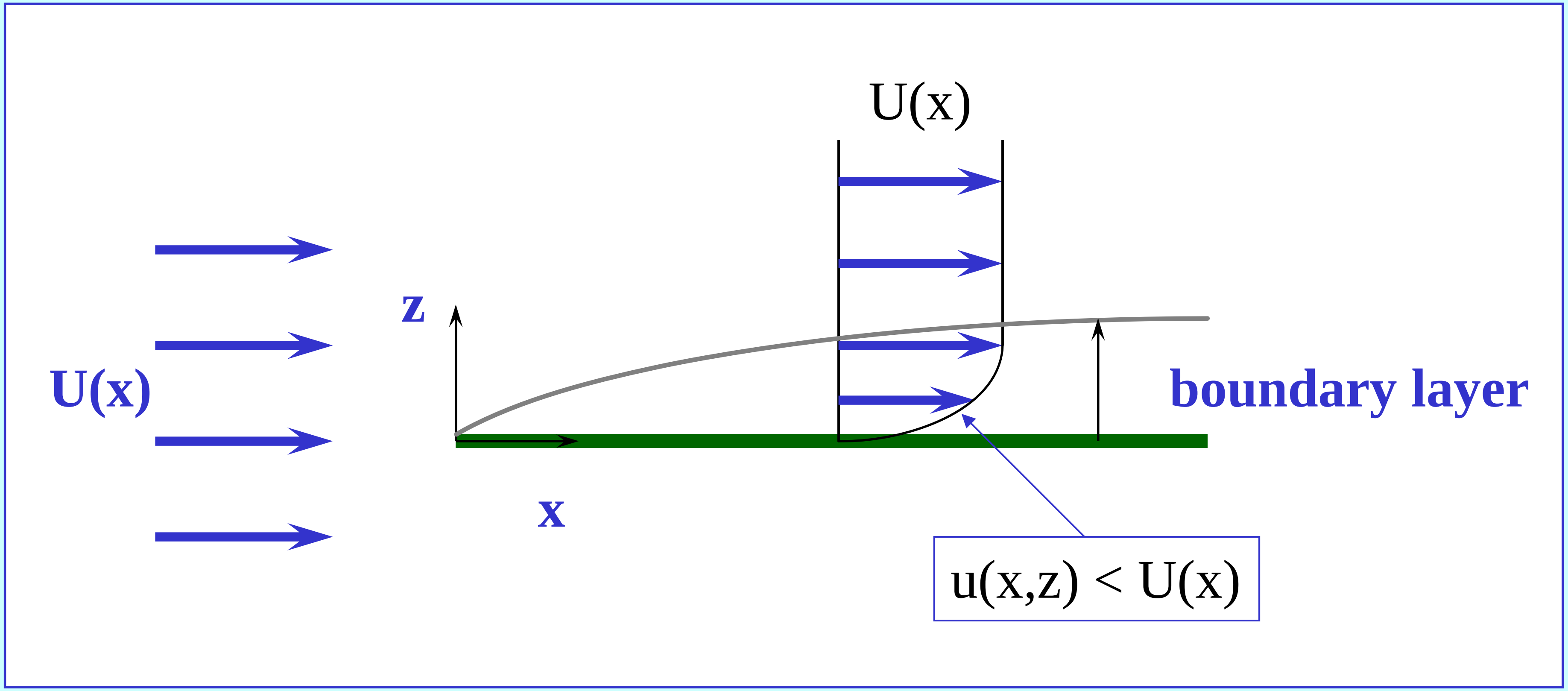
Have to consider generalized buoyancy!



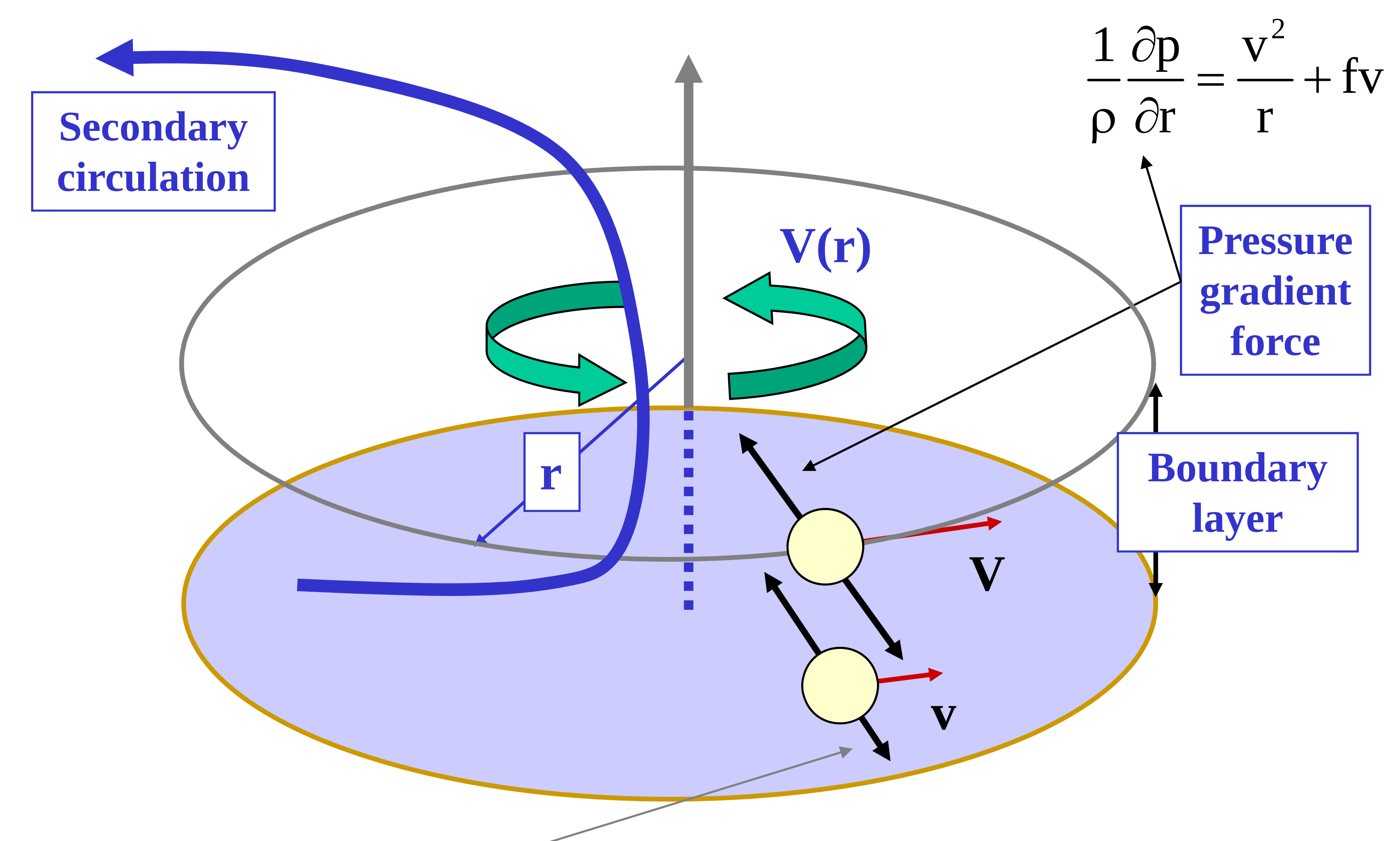
$$\mathbf{g}_e = \left(\frac{v^2}{r} + fv, -g \right)$$

Boundary layers in nonrotating fluids

A simple example: steady two-dimensional boundary layer on a flat plate at normal incidence to an almost parallel stream U(x)**.**



Frictionally-induced secondary circulation

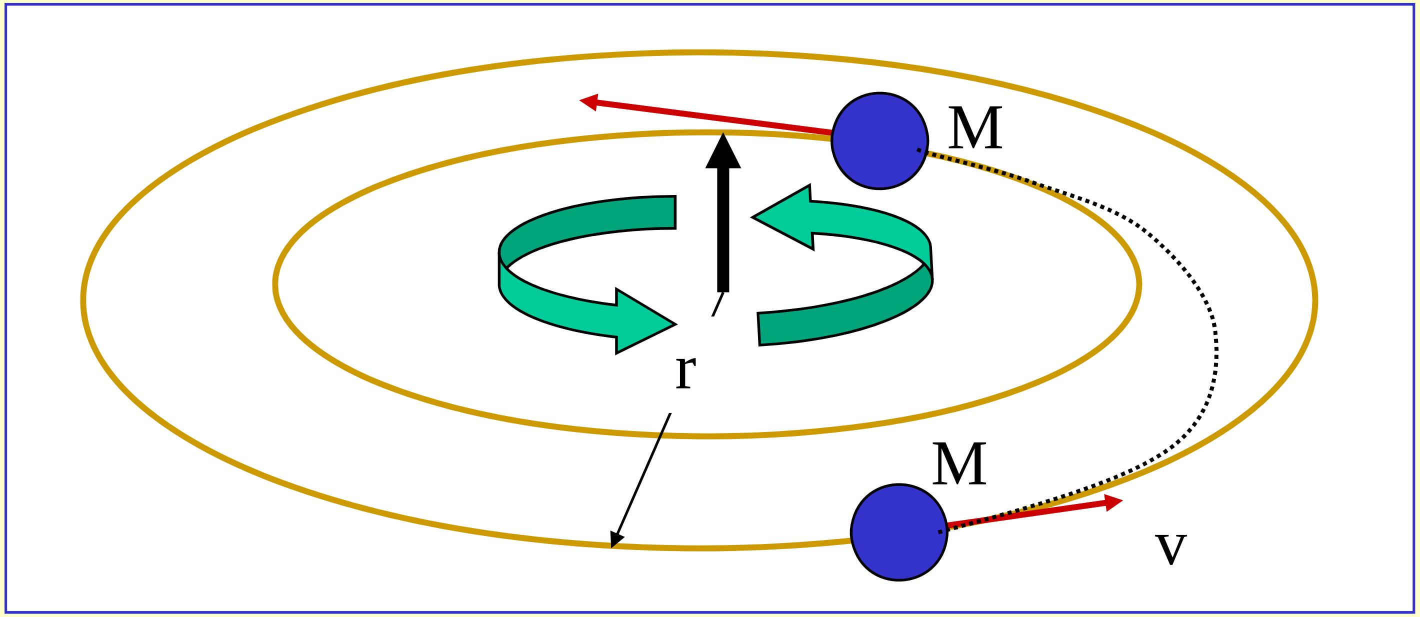


Centrifugal force and Coriolis force reduced by friction

Tropical cyclone intensification

Basic principle: conservation of absolute angular momentum:

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

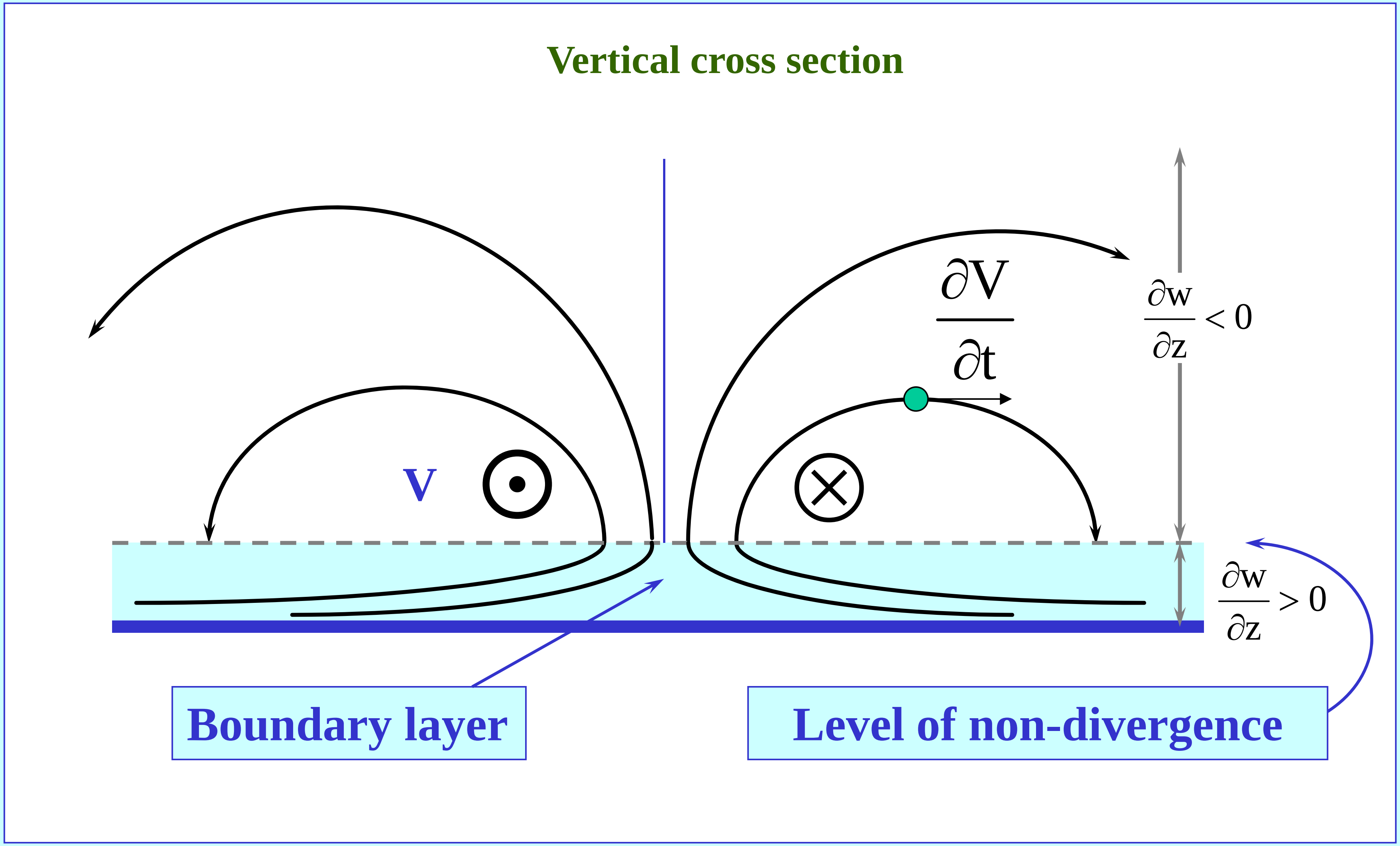


$$v = \frac{M}{r} - \tfrac{1}{2} f r$$

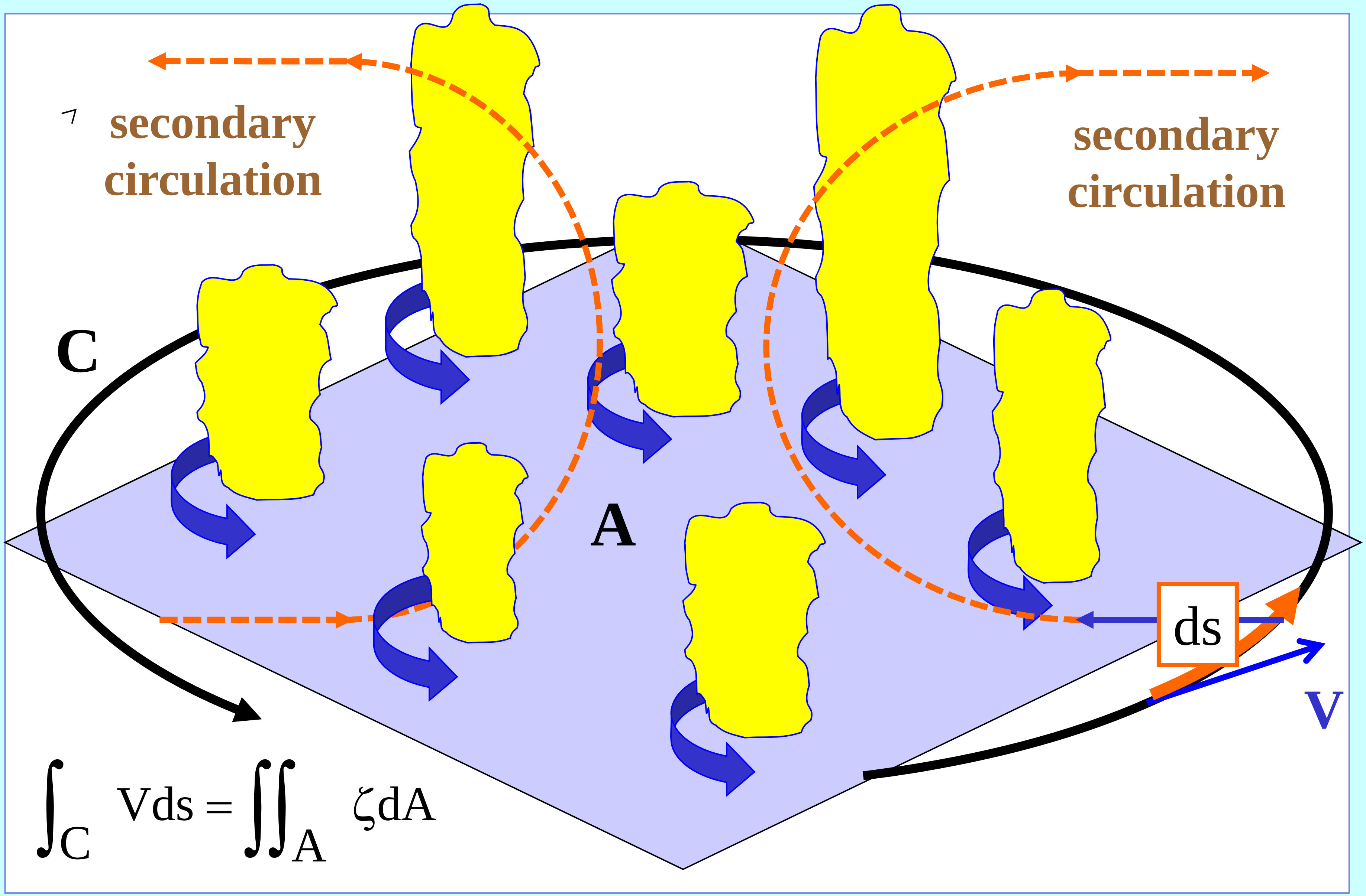
⇒ **If r decreases, v increases!**

⇒ **Spin up requires radial convergence**

Dynamics of vortex spin down



The secondary, or in-up-out, circulation



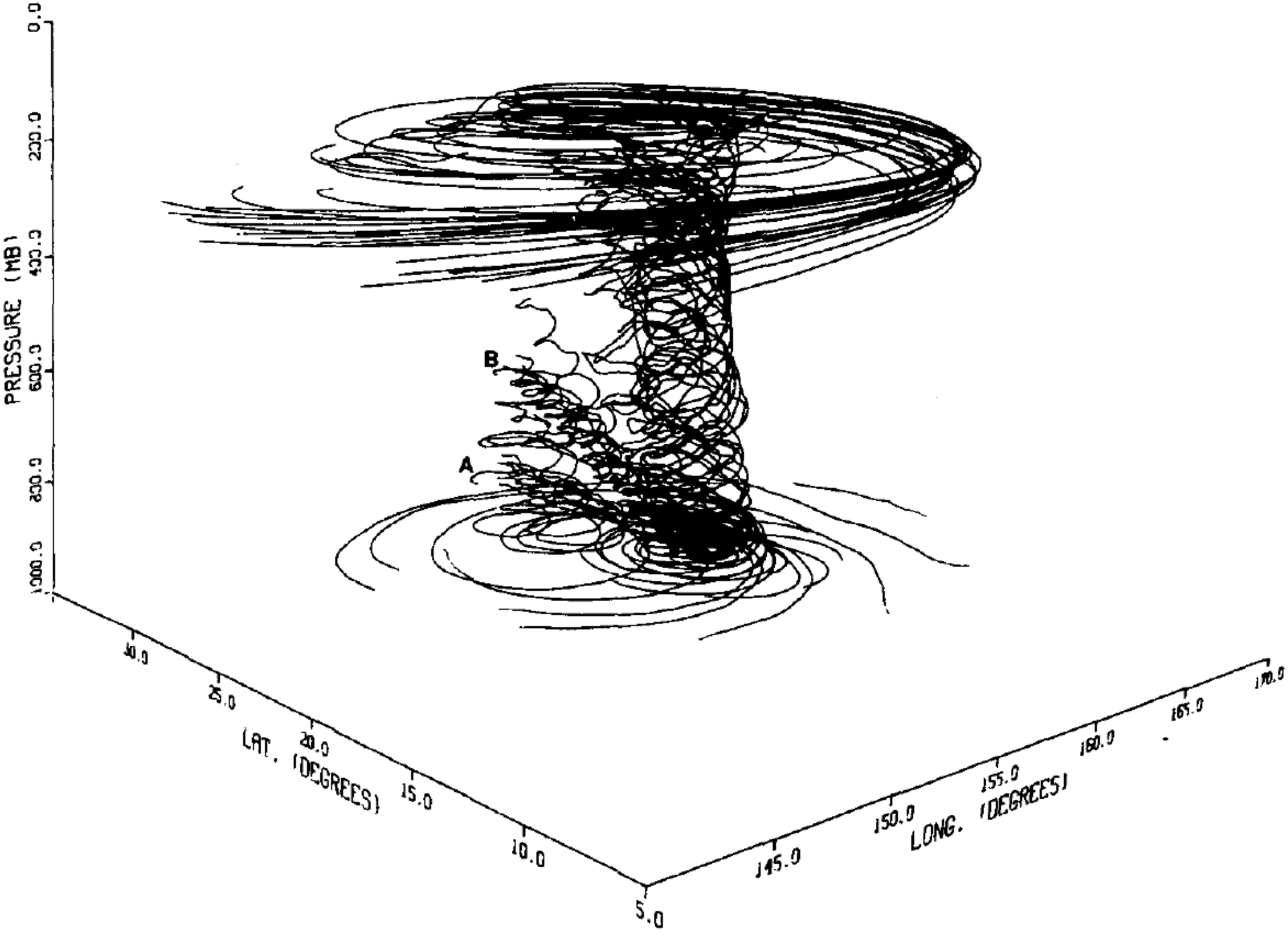
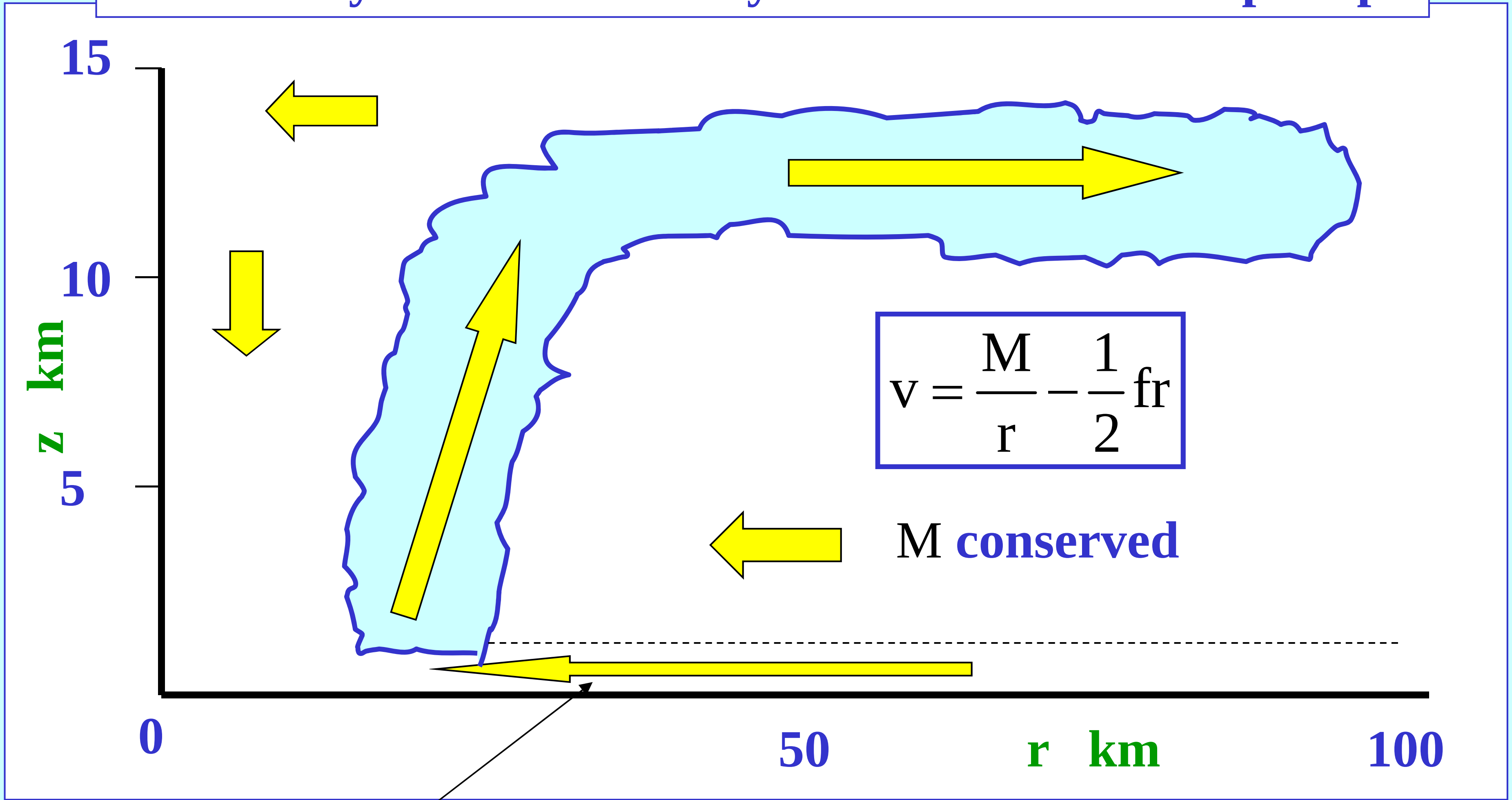


FIG. 9. Trajectories formed by particles released at various radii and pressure levels at $t = 0$. Most particles that reach the outflow level are transported outward by the outflow jet. Most particles released at radii of 20 km (A) and 100 km (B) are "trapped" inside the radius of the maximum wind and only rise slowly and drift toward the NW.

Conventional view of intensification: axisymmetric

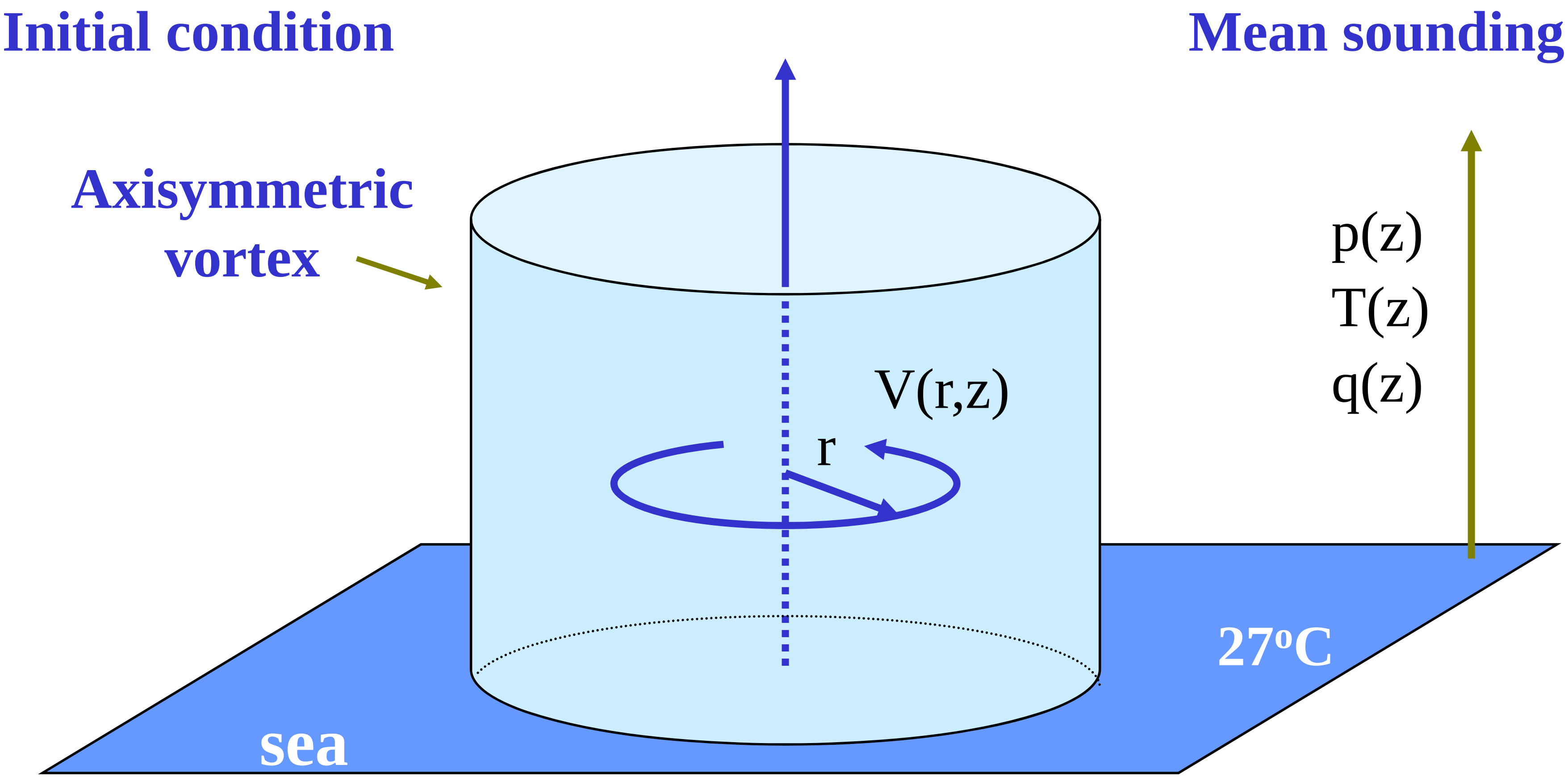
Thermally-forced secondary circulation leads to spin up



M **not conserved, inflow feeds the clouds with moisture**

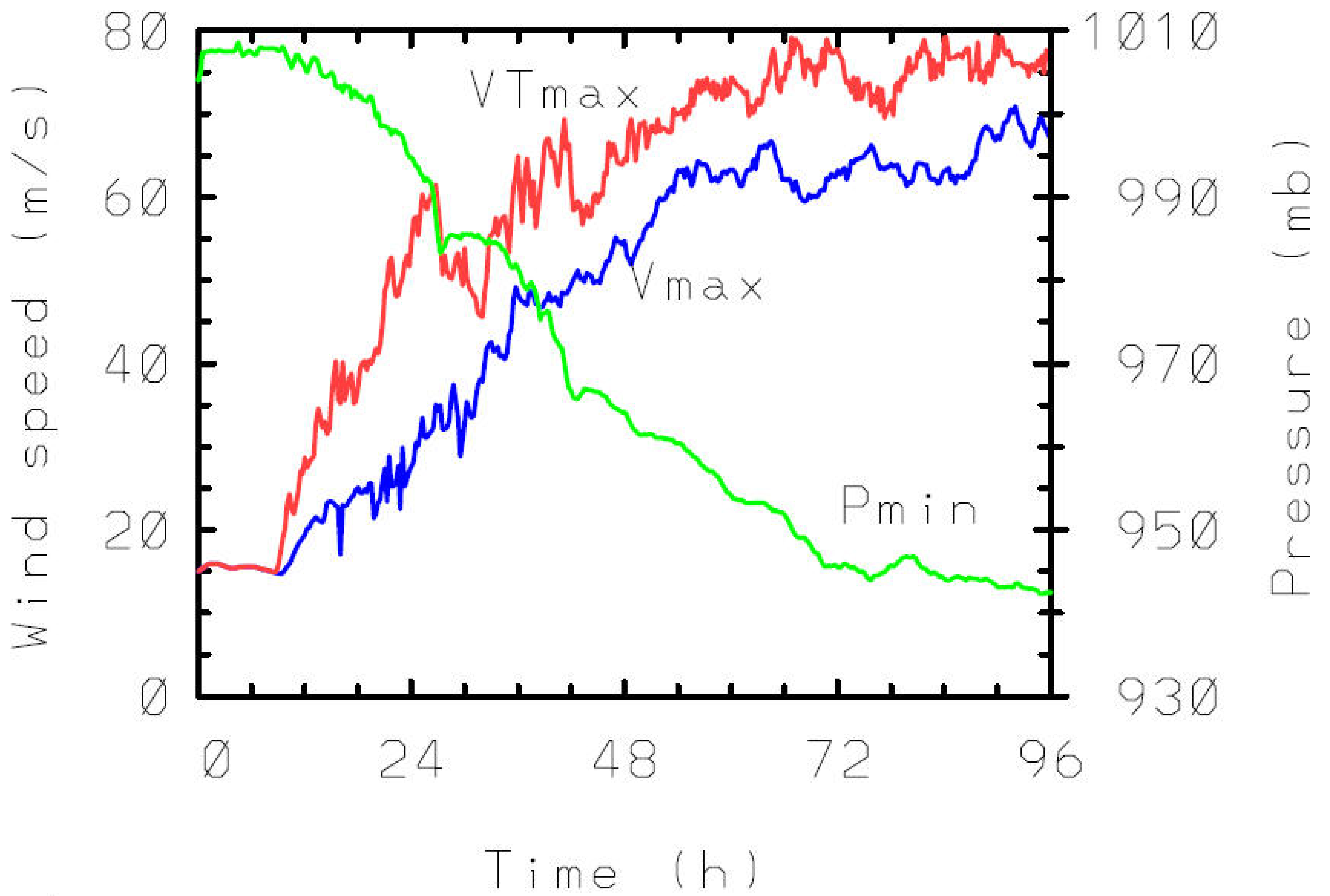
Is that it?

The basic thought experiment for TC intensification



Nguyen, Smith and Montgomery calculation, QJRMS, 2008:

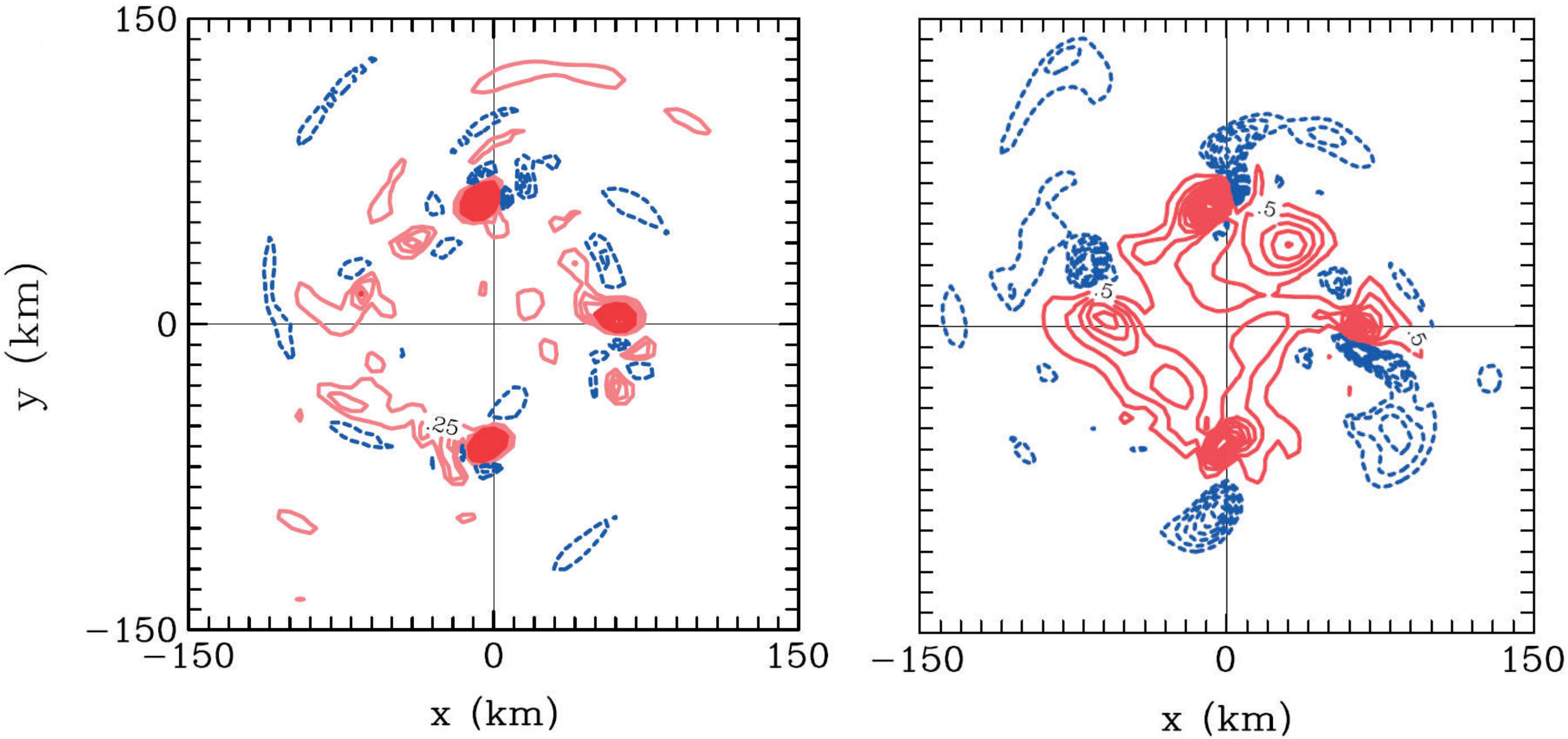
- **Idealized numerical model simulations, simple physics, MM5**
- 5 **km (**1.67 **km) resolution in the finest nest,** 24 **σ-levels**



VTmax
Vmax
Pmin
Wind speed (m/s)
Pressure (mb)
Time (h)
0
20
40
60
80
930
950
970
990
1010
0
24
48
72
96

Vertical velocity\vorticity pattern at 24 h

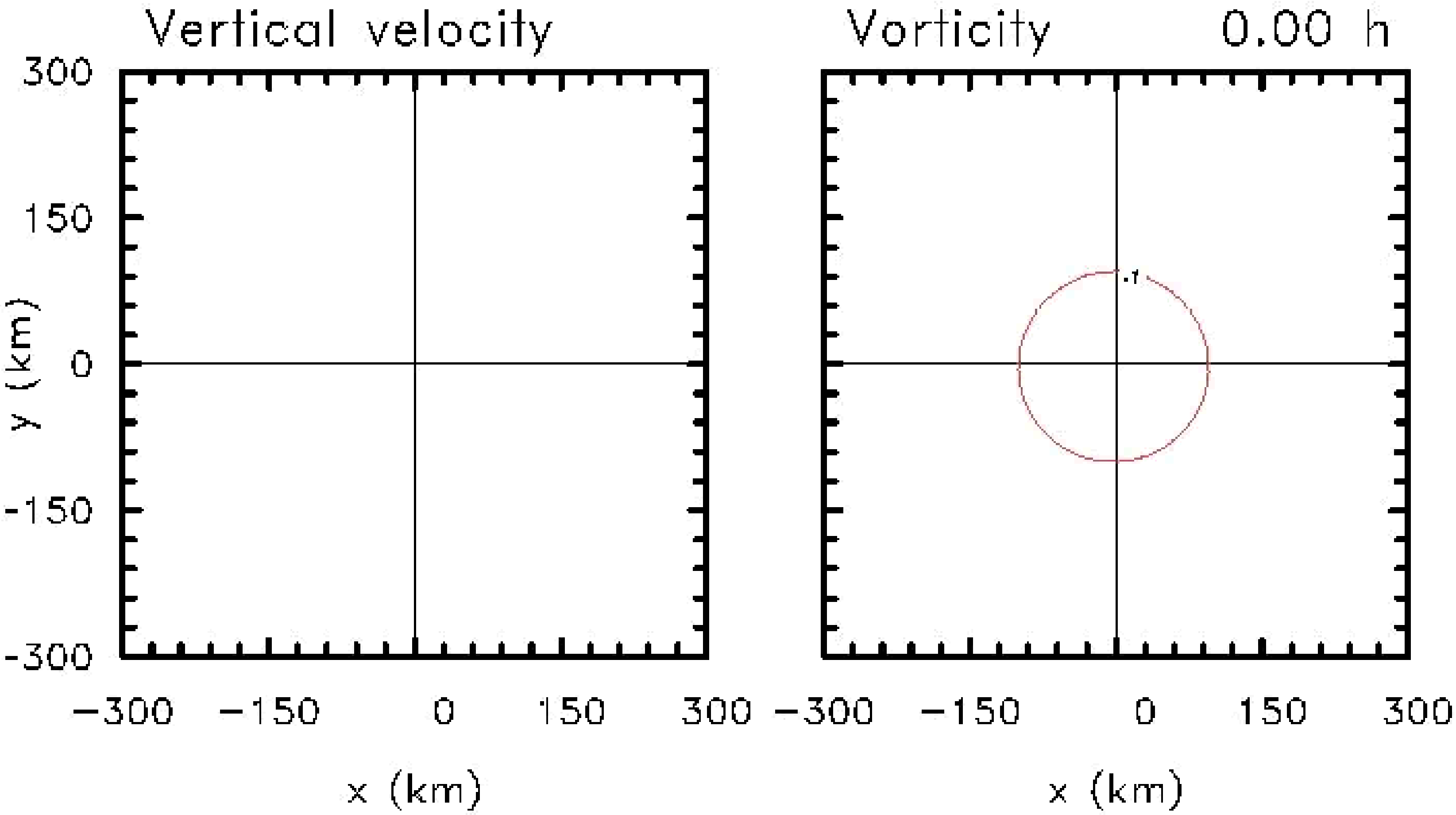
850 mb ~ 1.5 **km** **850 mb**



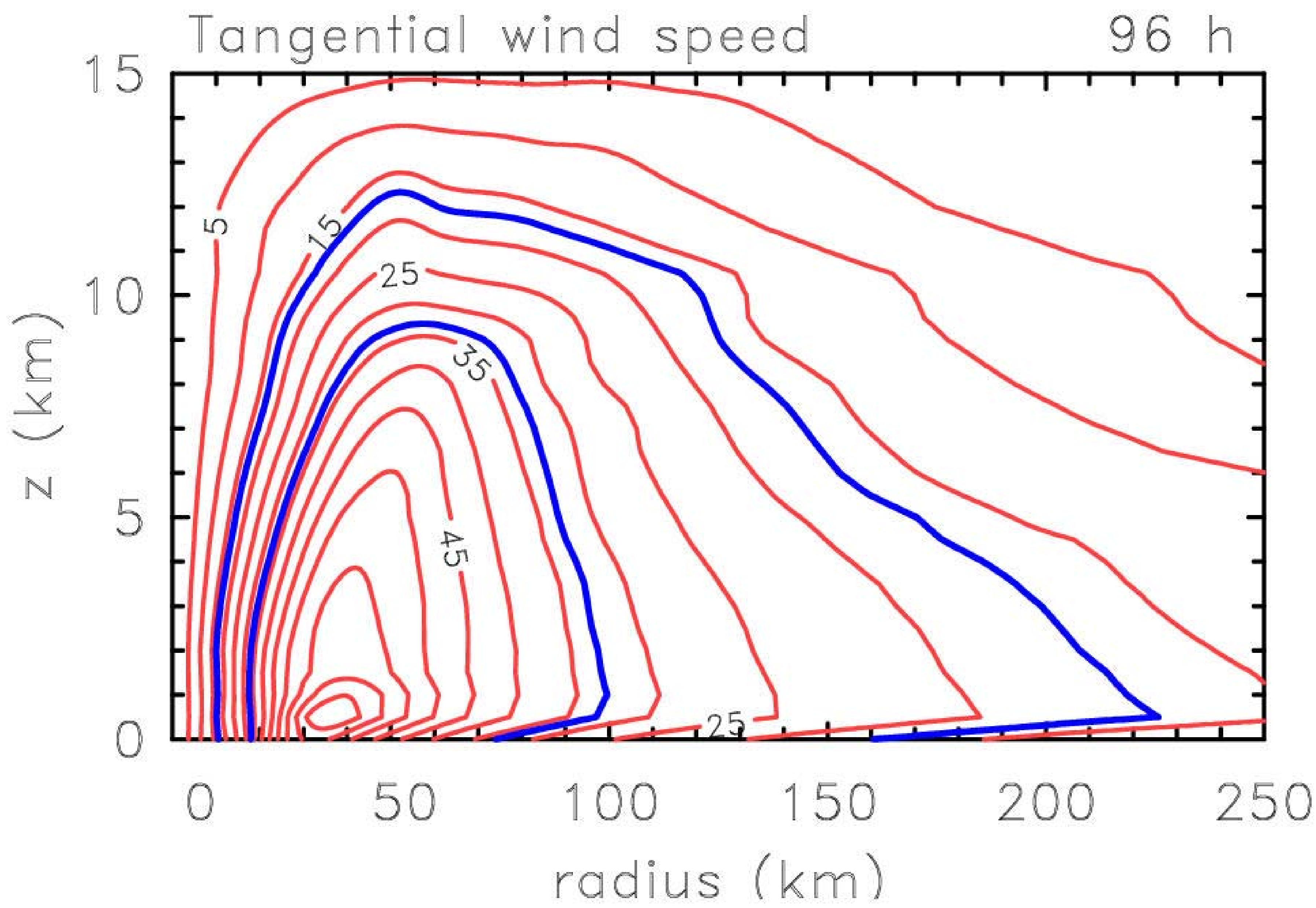
Vertical velocity **Relative vorticity**

From Nguyen, Smith and Montgomery, QJ, 2008

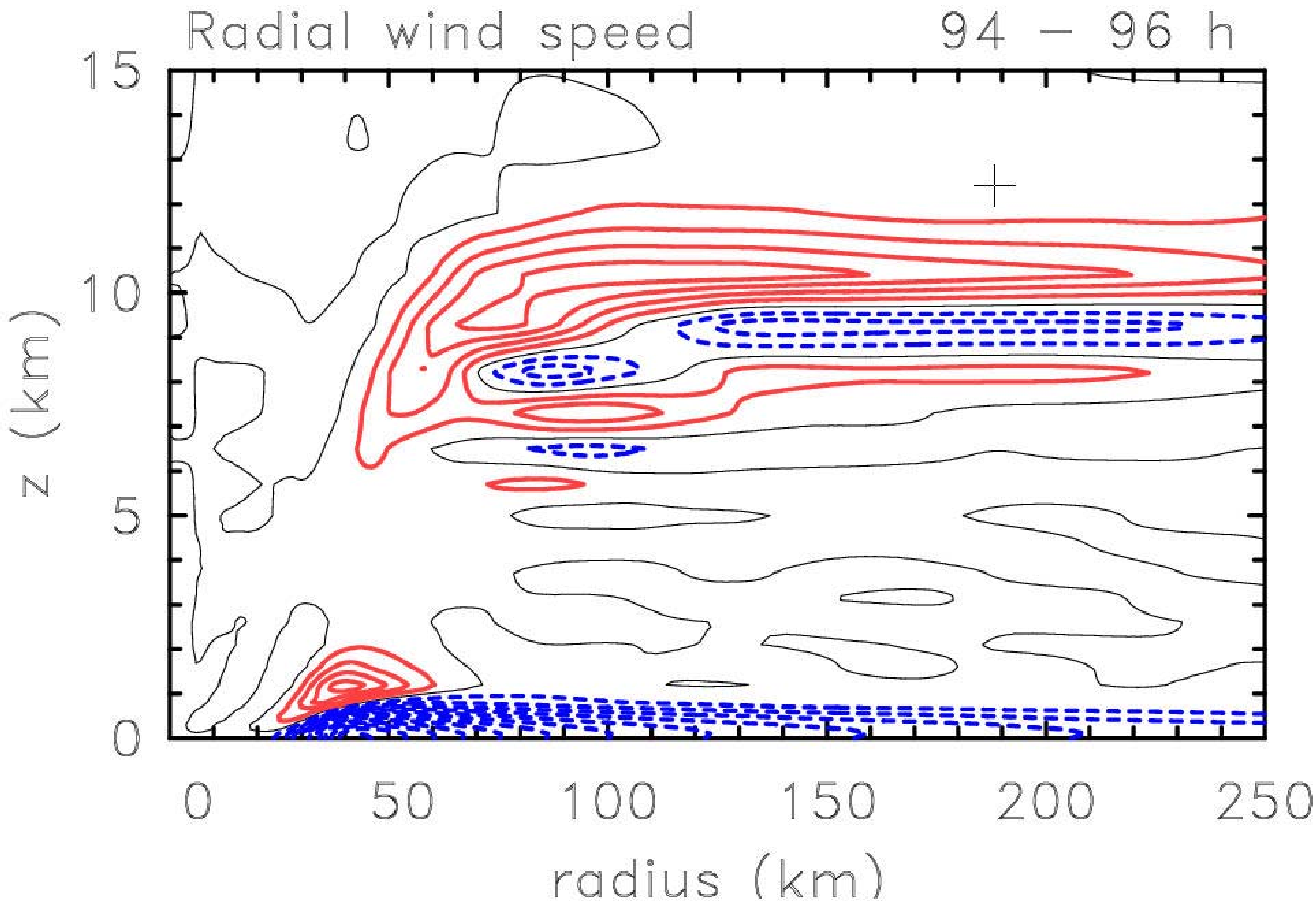
Movie



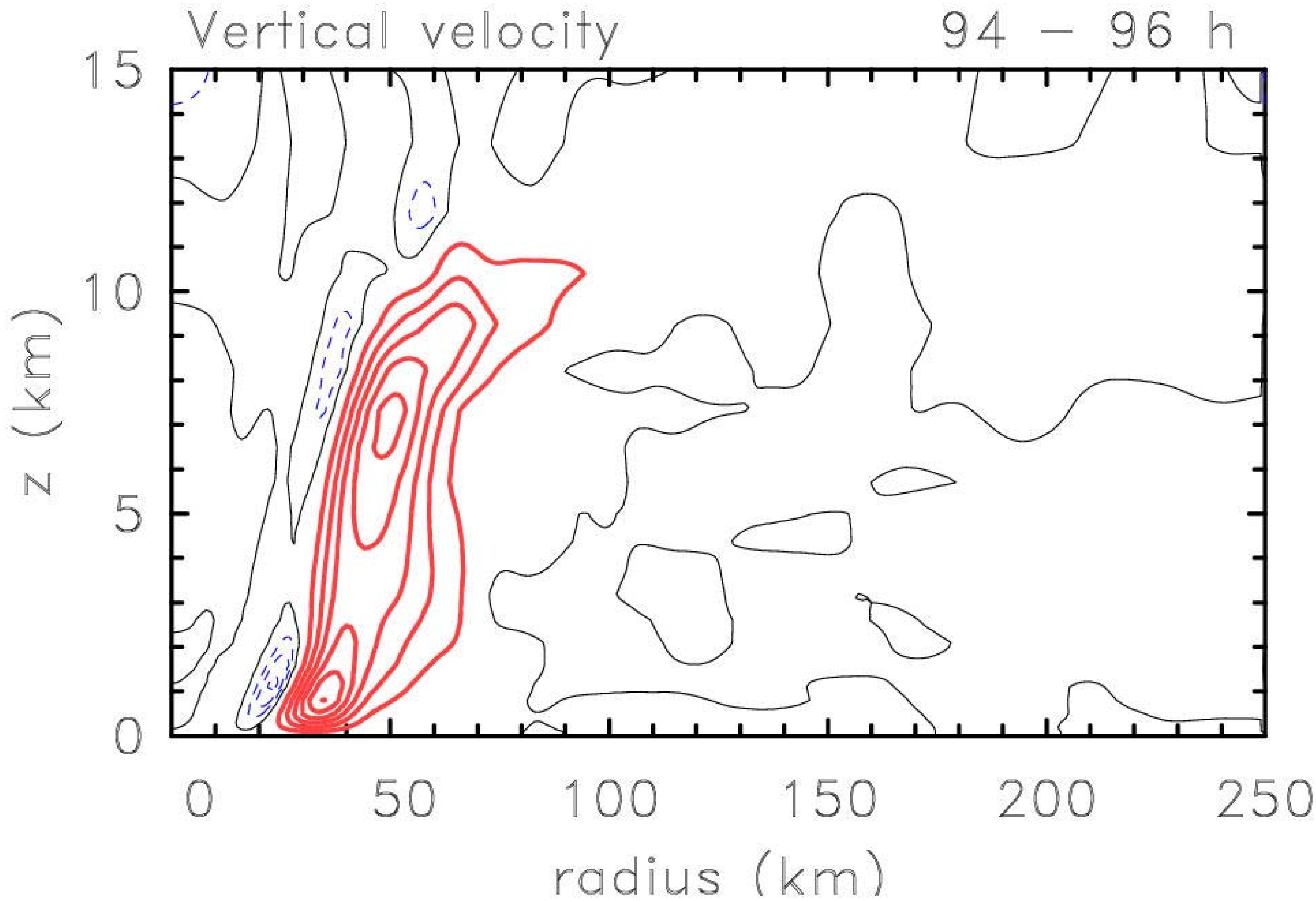
Vertical velocity
Vorticity
0.00 h
300
150
0
-150
-300
y (km)
−300
−150
0
150
300
x (km)



From Montgomery, Nguyen & Smith (2009): QJRMS



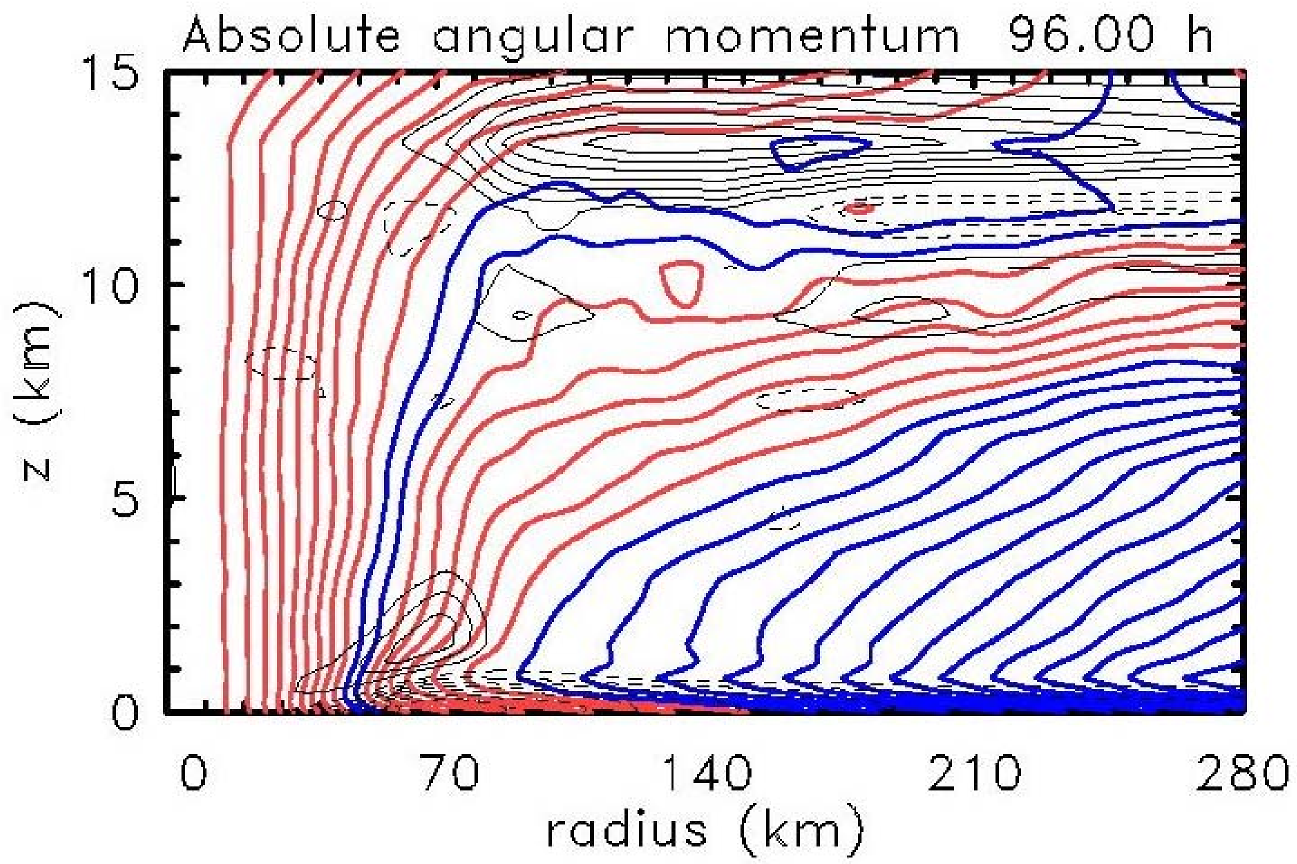
From Montgomery, Nguyen & Smith (2009): QJRMS



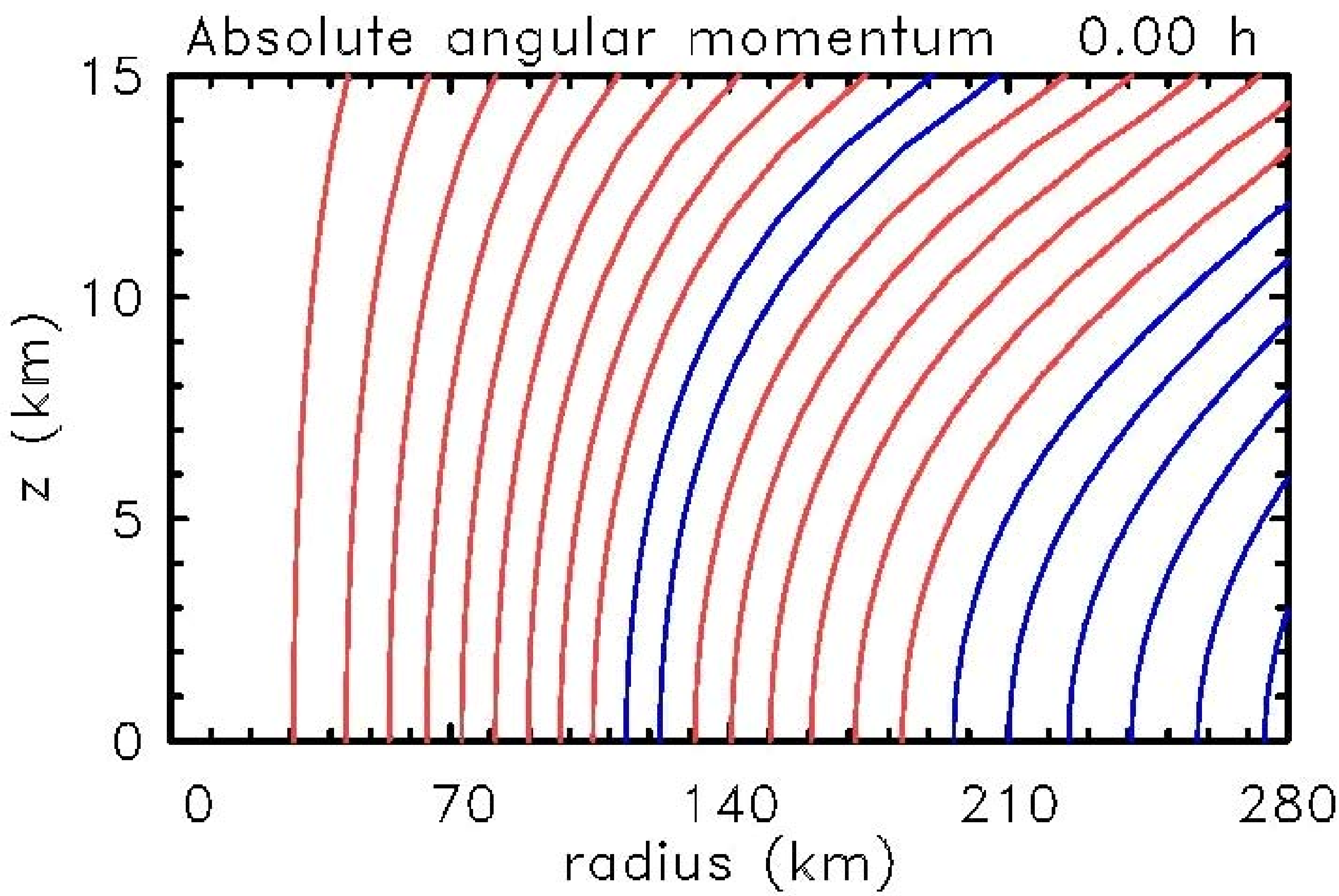
From Montgomery, Nguyen & Smith (2009): QJRMS

Movie

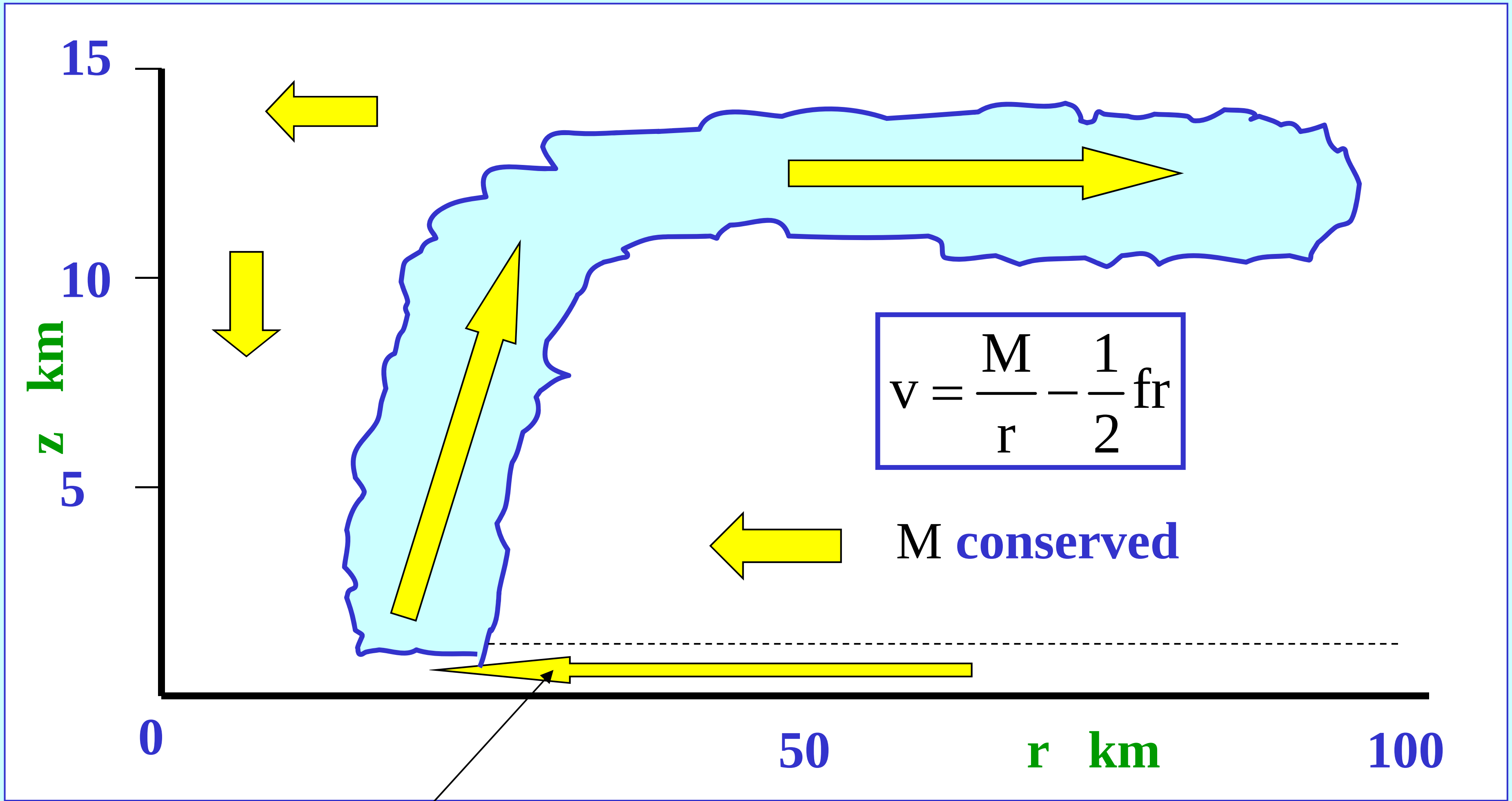
Time-height sequence of Absolute Angular Momentum



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


Absolute angular momentum 0.00 h
15
10
5
0
z (km)
0
70
140
210
280
radius (km)

Revised view : two spin-up mechanisms



M reduced by friction, but
strong convergence ➔ small r ➔ large v

A surprise

- **The maximum wind speed in the boundary layer can exceed that above the boundary layer.**
  - **An unusual in feature boundary layers in general.**
  - **A special feature of the termination boundary layer of intense vortices.**
- **Anthes (1972):**
  - **Inward increase of** V **due to large radial displacements in the boundary layer with partial conservation of AAM opposes the fictional loss of AAM to the surface.**

Some steady theories/models

- ➢ Emanuel (JAS 1986) : An air-sea interaction theory for tropical cyclones. Part I: Steady state maintenance.
- ➢ Wirth & Dunkerton (JAS 2006): A unified perspective on the dynamics of axisymmetric hurricanes and monsoons.
- ➢ Hakim (JAS 2011): The mean state of axisymmetric hurricanes in statistical equilibrium.

Questions

- ➢ What would be the requirements for a (globally) steady-state hurricane to exist?
- ➢ Do the foregoing theories/formulations satisfy such conditions?

Angular momentum considerations

- **Anthes (*Rev. Geophys*. 1974): The dynamics and energetics of mature tropical cyclones.**

  For a tropical cyclone to achieve a steady state, there would have to be an input of cyclonic relative angular momentum to replenish that lost by friction to the sea surface.

- **Carrier *et al*. (JFM 1971): A model of the mature hurricane.**

  A hurricane could last about 30 days before it used up its angular momentum.

Absolute angular momentum

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

M **satisfies**

$$\frac{\partial M}{\partial t} + u \frac{\partial M}{\partial r} + w \frac{\partial M}{\partial z} = E_1 + D$$

$$E_1 = - < u' \frac{\partial M'}{\partial r} > - < w' \frac{\partial M'}{\partial z} >$$

$$D = \frac{1}{r} \frac{\partial}{\partial r} \left[r^3 K_r \frac{\partial}{\partial r} \left(\frac{v}{r} \right) \right] + \frac{1}{\rho} \frac{\partial}{\partial z} \left[\rho K_z \frac{\partial M}{\partial z} \right]$$

Steady flow, no diffusion or eddies: $(u, w) \cdot \left(\frac{\partial M}{\partial r}, \frac{\partial M}{\partial z} \right) = 0$

Continuity

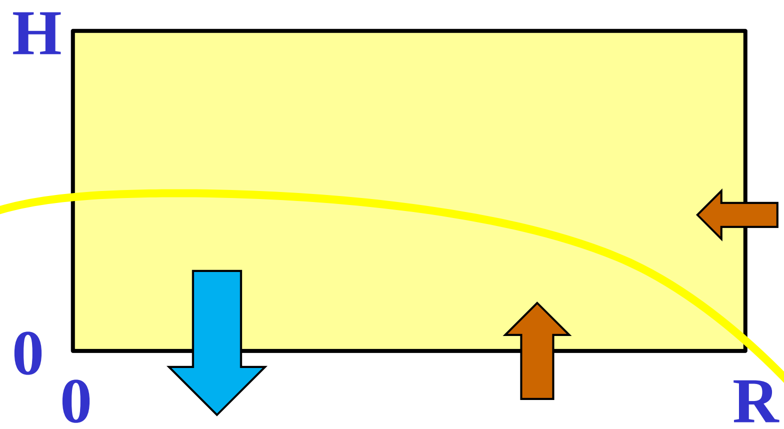
$$\frac{1}{r}\frac{\partial \rho r u}{\partial r} + \frac{\partial \rho w}{\partial z} = 0$$

Flux form

$$\rho\frac{\partial M}{\partial t} + \frac{1}{r}\frac{\partial r\,\rho u M}{\partial r} + \frac{\partial \rho u M}{\partial z} = E_2 + \rho D$$

$$E_2 = -\frac{1}{r} < \frac{\partial \rho r u' M'}{\partial r} > - < \frac{\partial \rho w' M'}{\partial z} >$$

Integrate the flux form for the steady state:



$$\int_0^H (\rho u M)_{r=R} dz = -\int_0^R \left[\rho K_z \frac{\partial M}{\partial z}\right]_{z=0} r\,dr$$

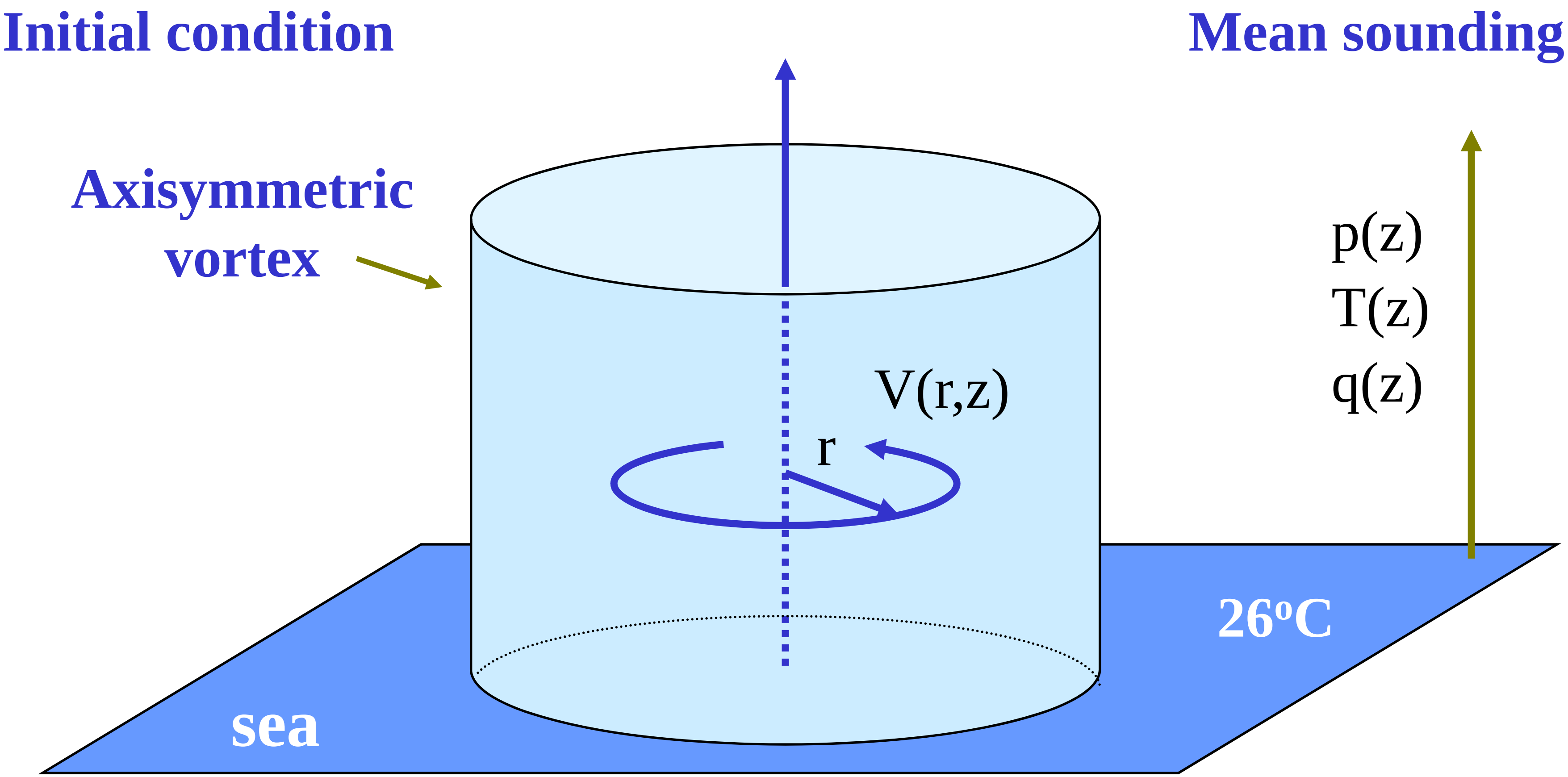
Advective flux through r = R

Diffusion at z = 0

$$+\int_0^H \left[\rho K_r r^3 \frac{\partial}{\partial r}\left(\frac{v}{r}\right) - <\rho r u' M'>\right]_{r=R} dz$$

Eddy and diffusive flux flux through r = R

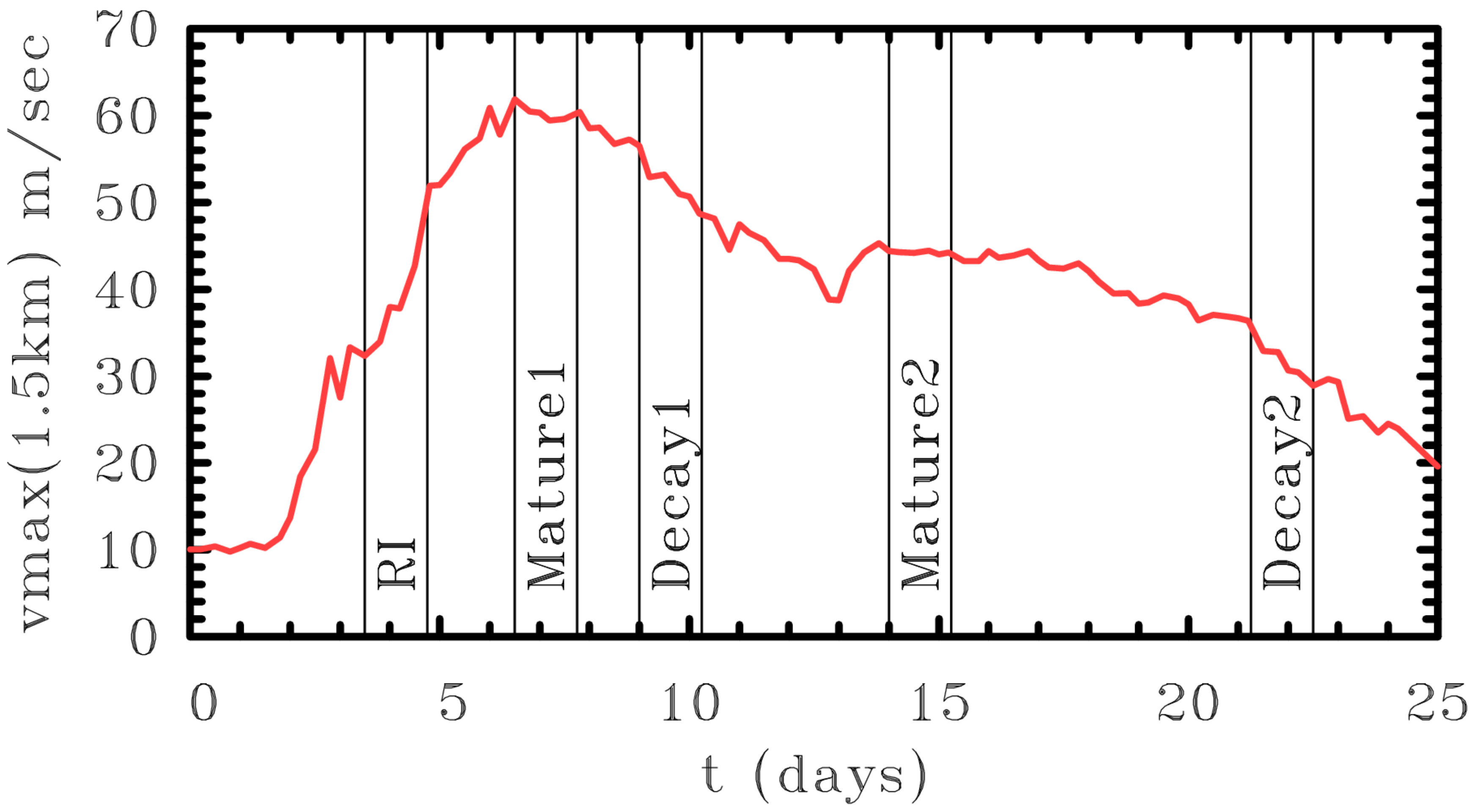
The basic thought experiment for intensification



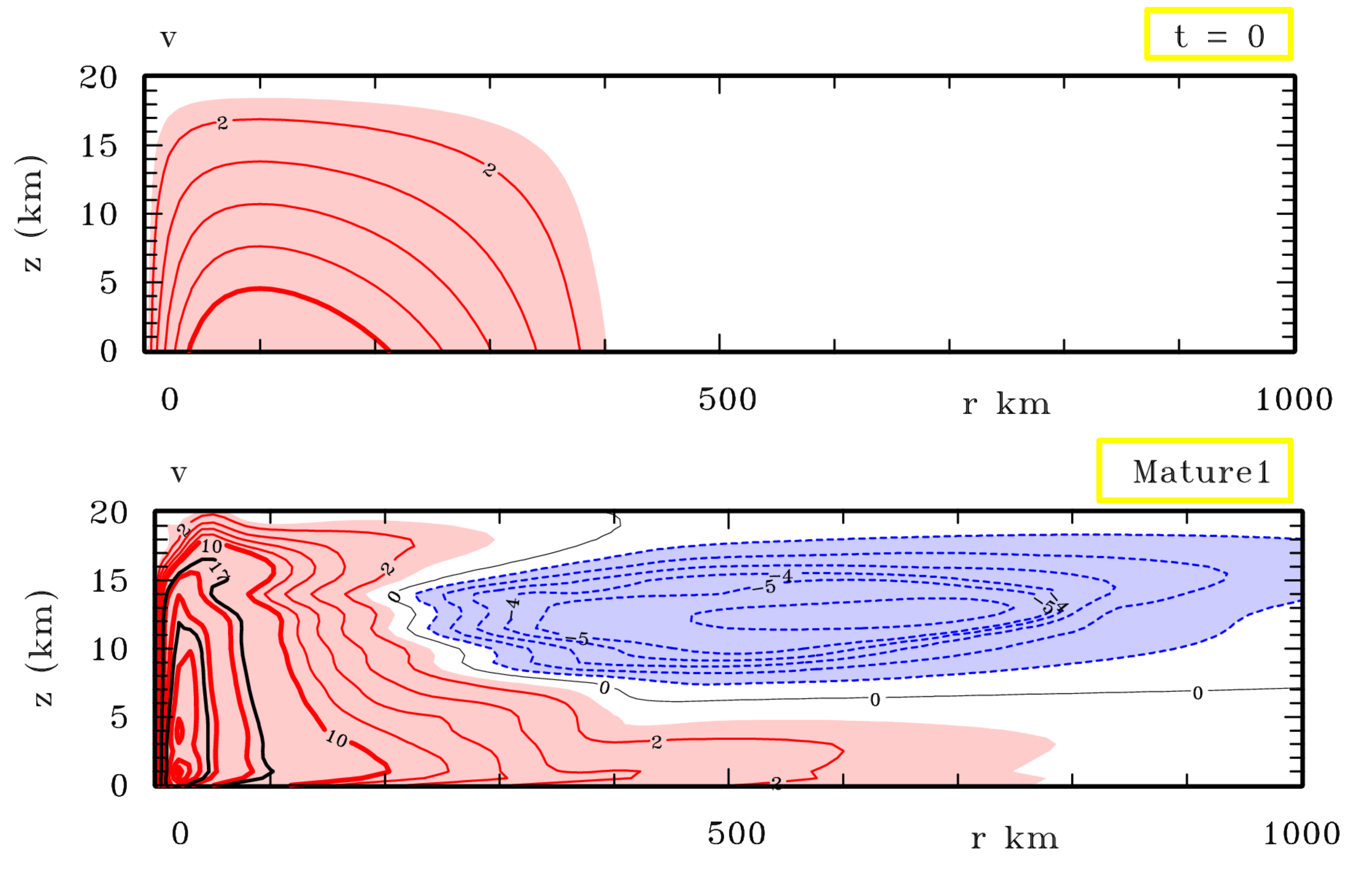
Persing, Montgomery, McWilliams, Smith, *Atm. Chem. Phys*. 2013:

- **Idealized numerical model simulations, simple physics, CM1**
- 3 **km horizontal grid spacing,** 24 **σ-levels**

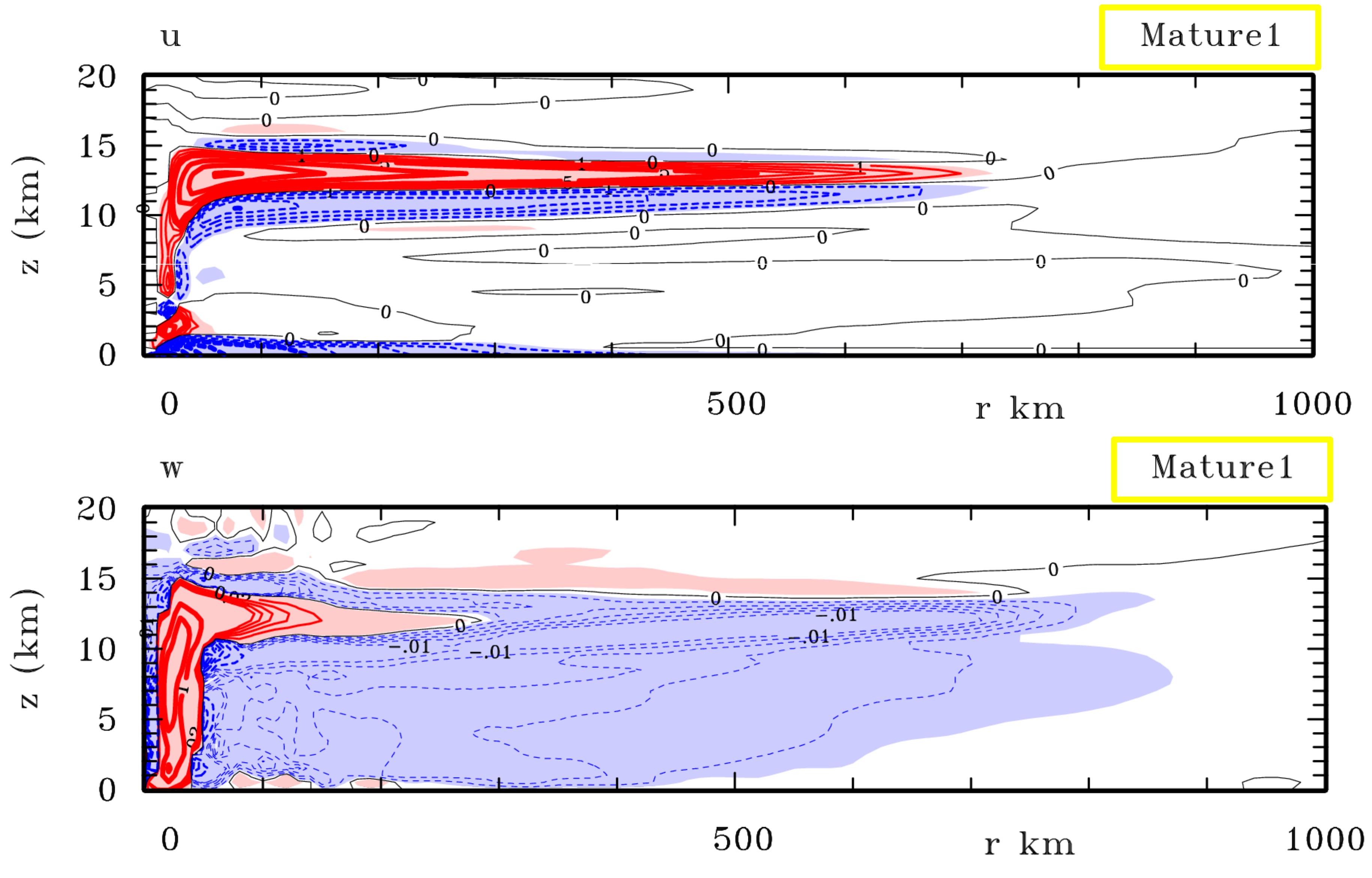
Evolution in intensity



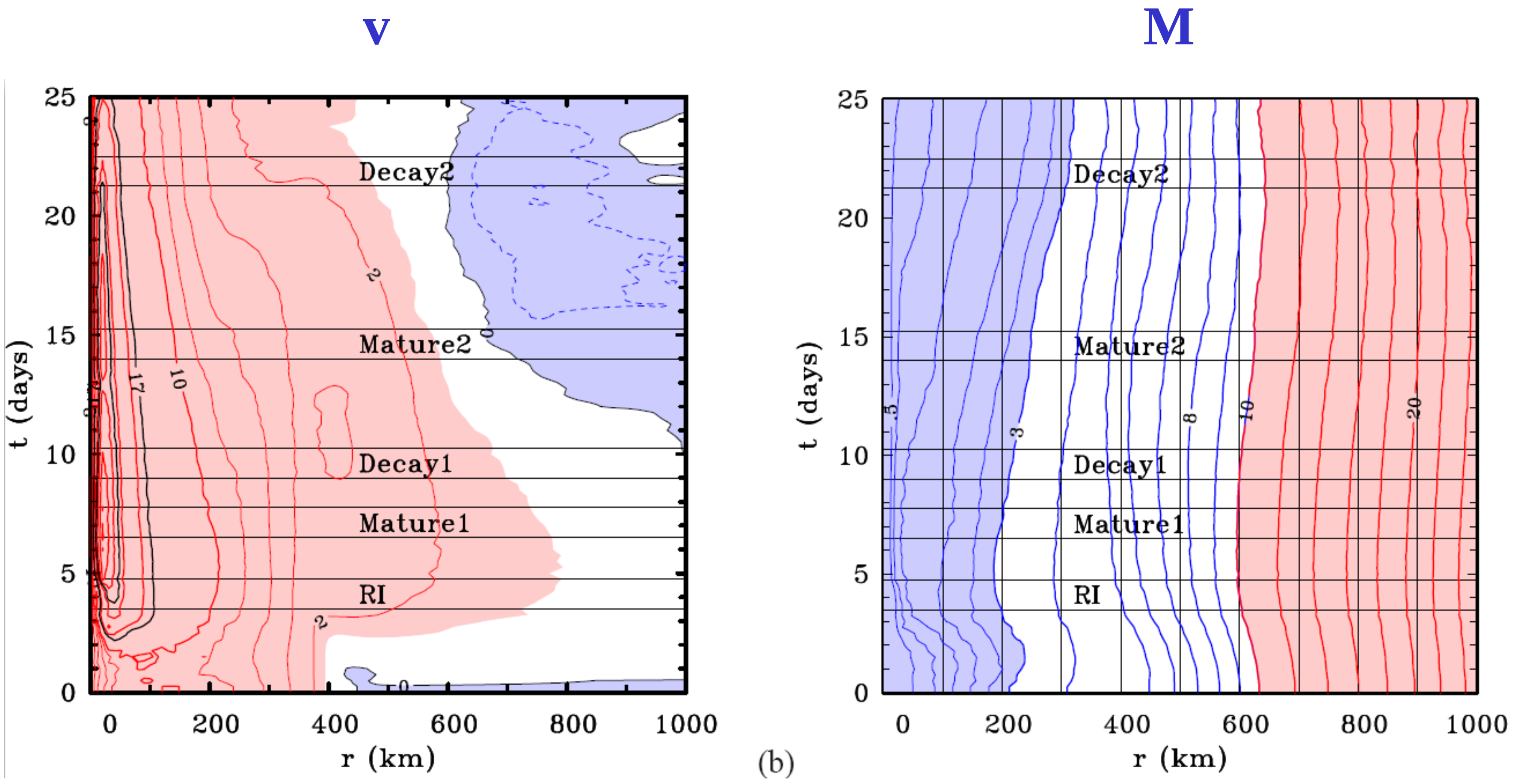
Azimuthal mean tangential wind component



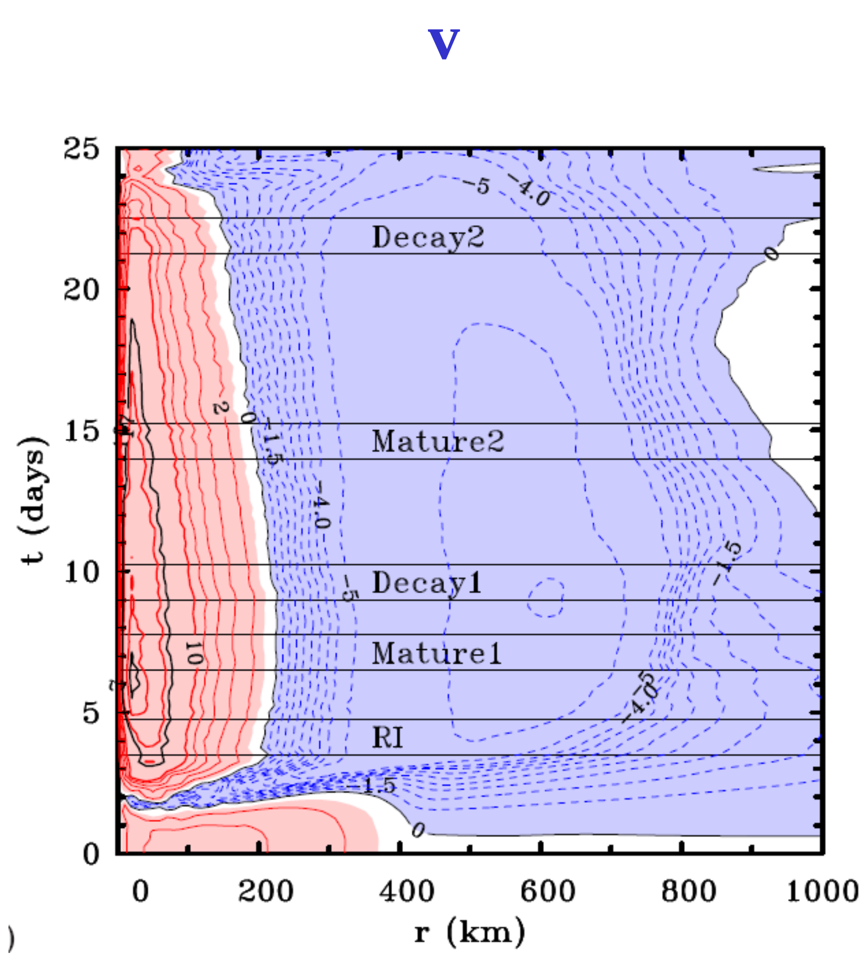
The overturning circulation

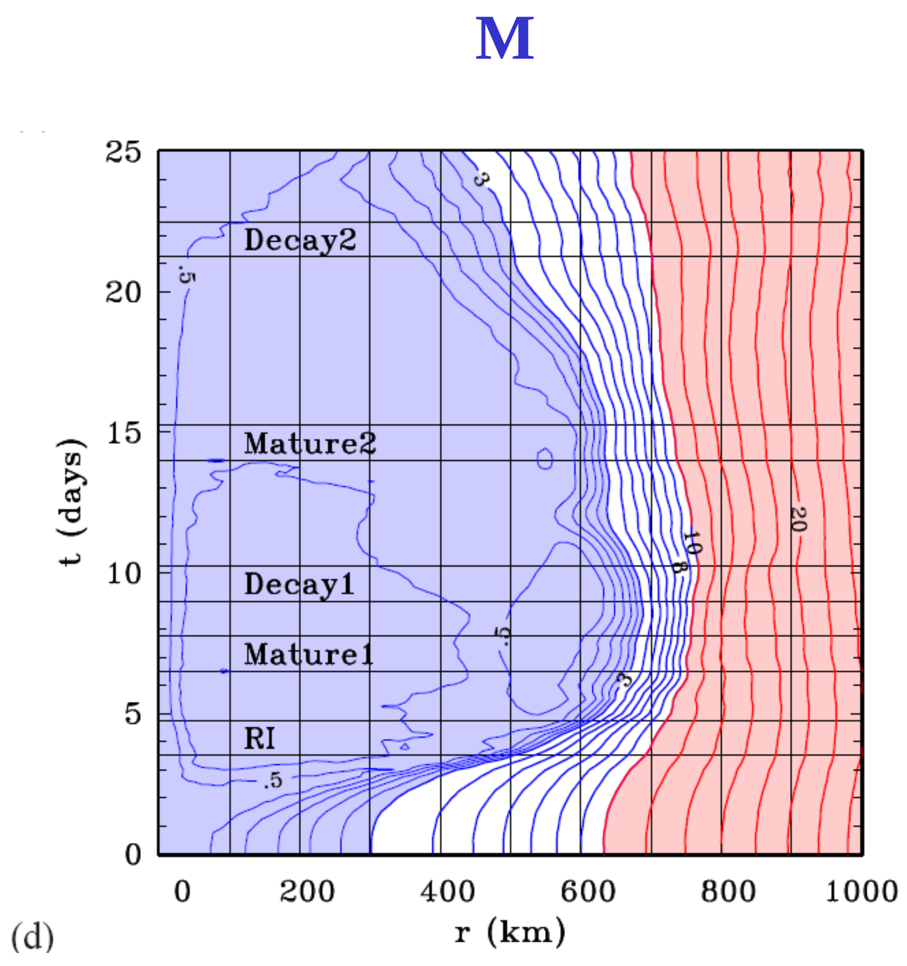


Radius-time plots of v and M at 1.5 km

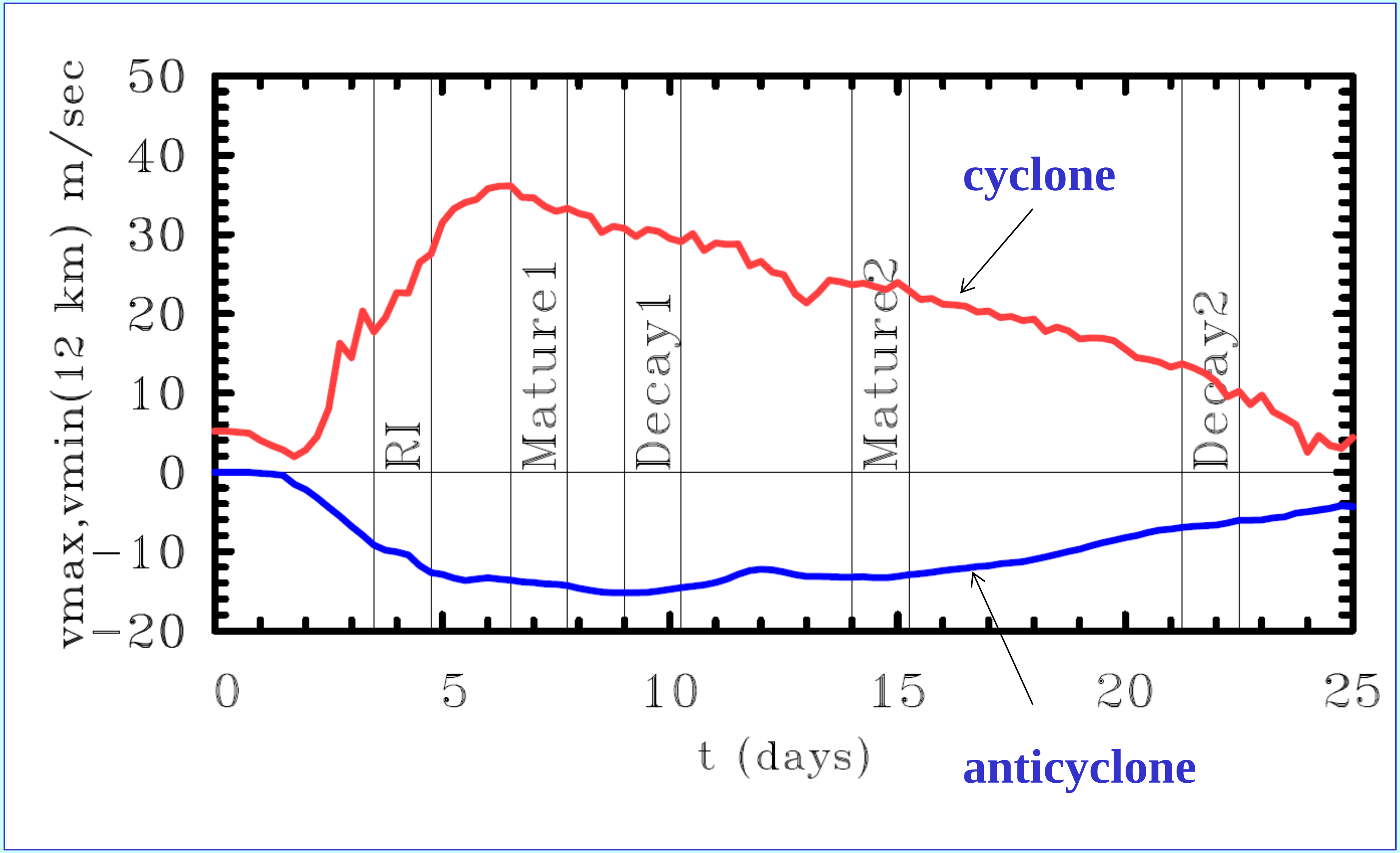


Radius-time plots of v and M at 12 km

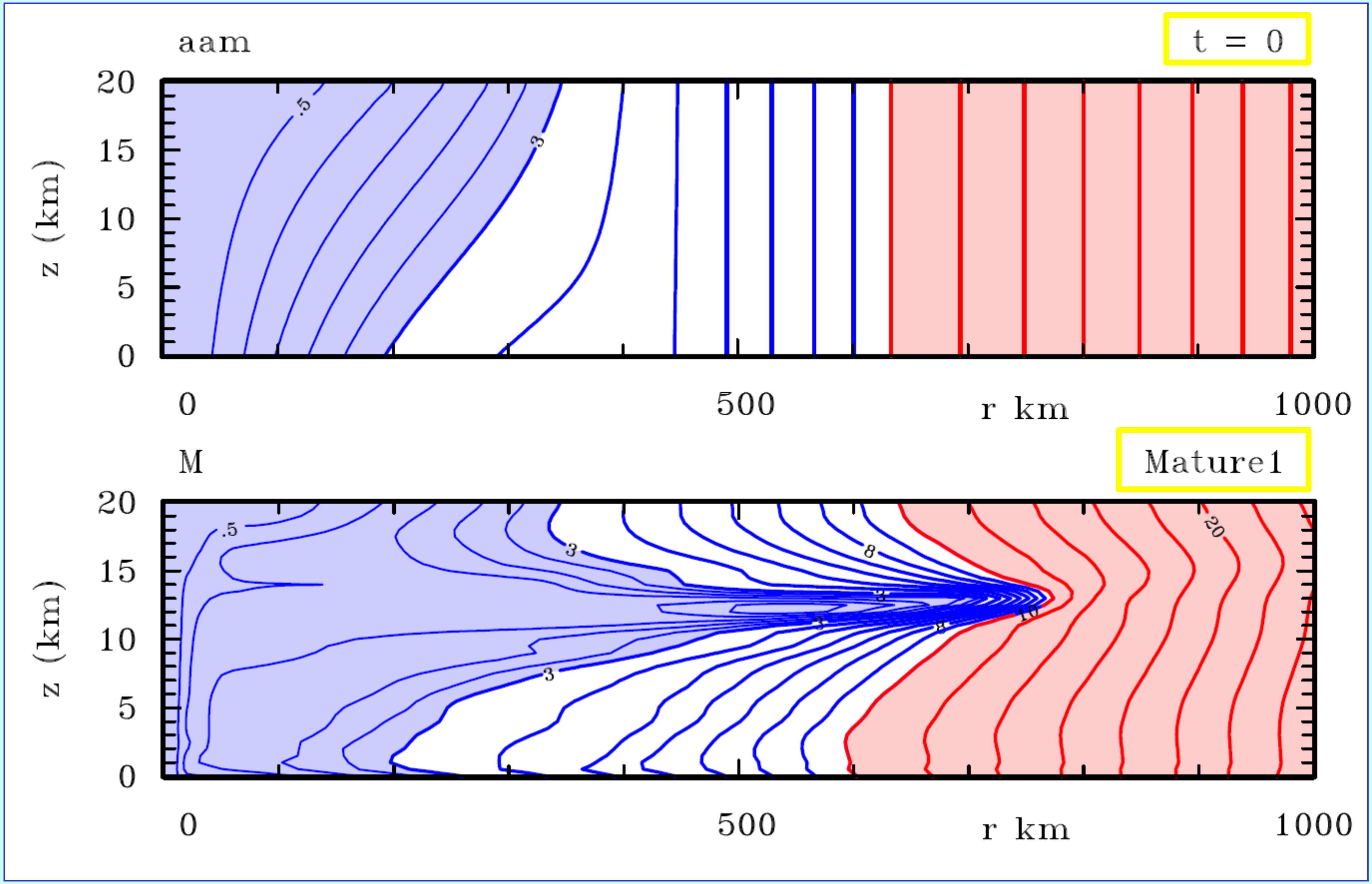




Evolution in intensity at 12 km

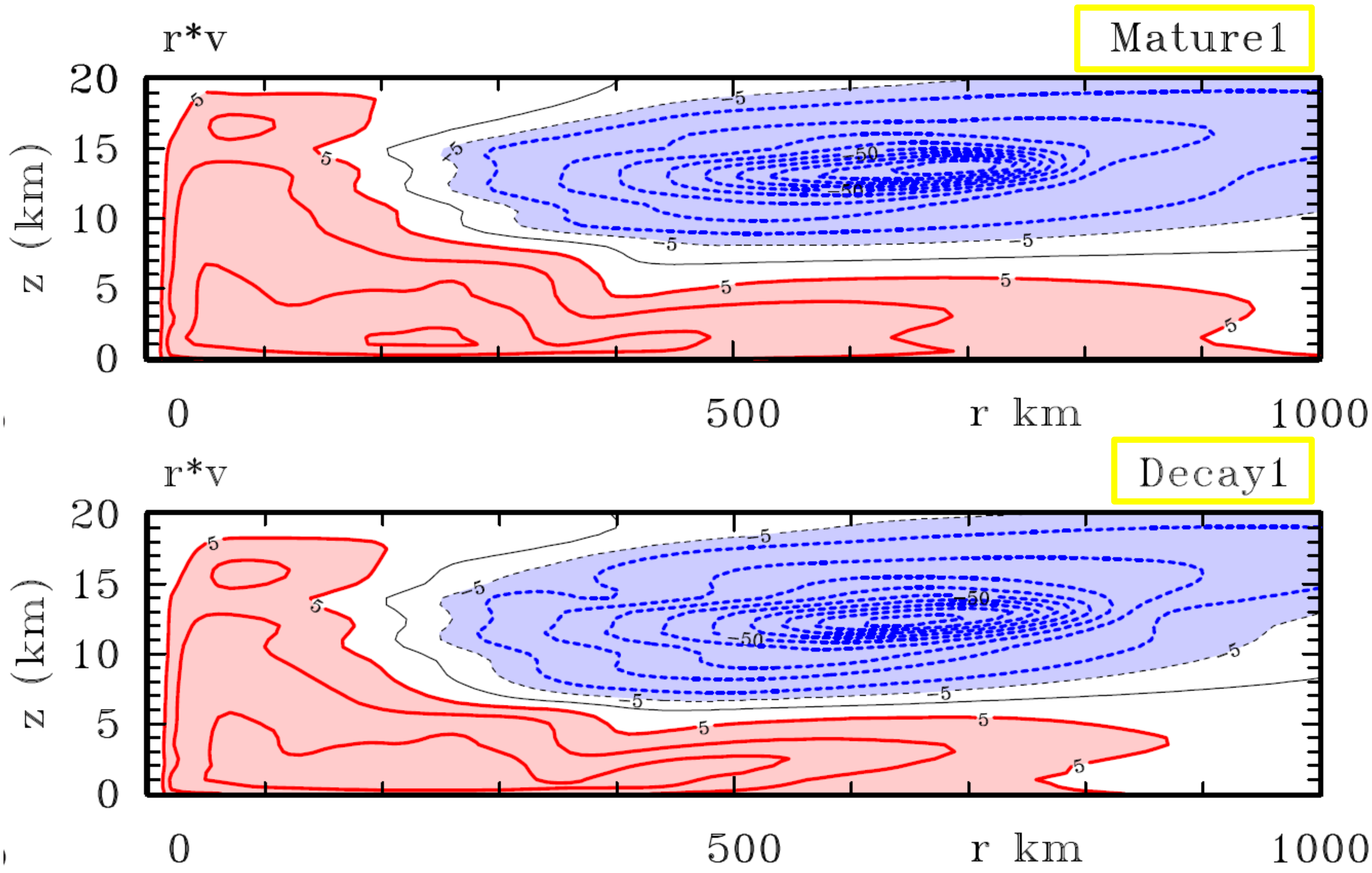


M surfaces

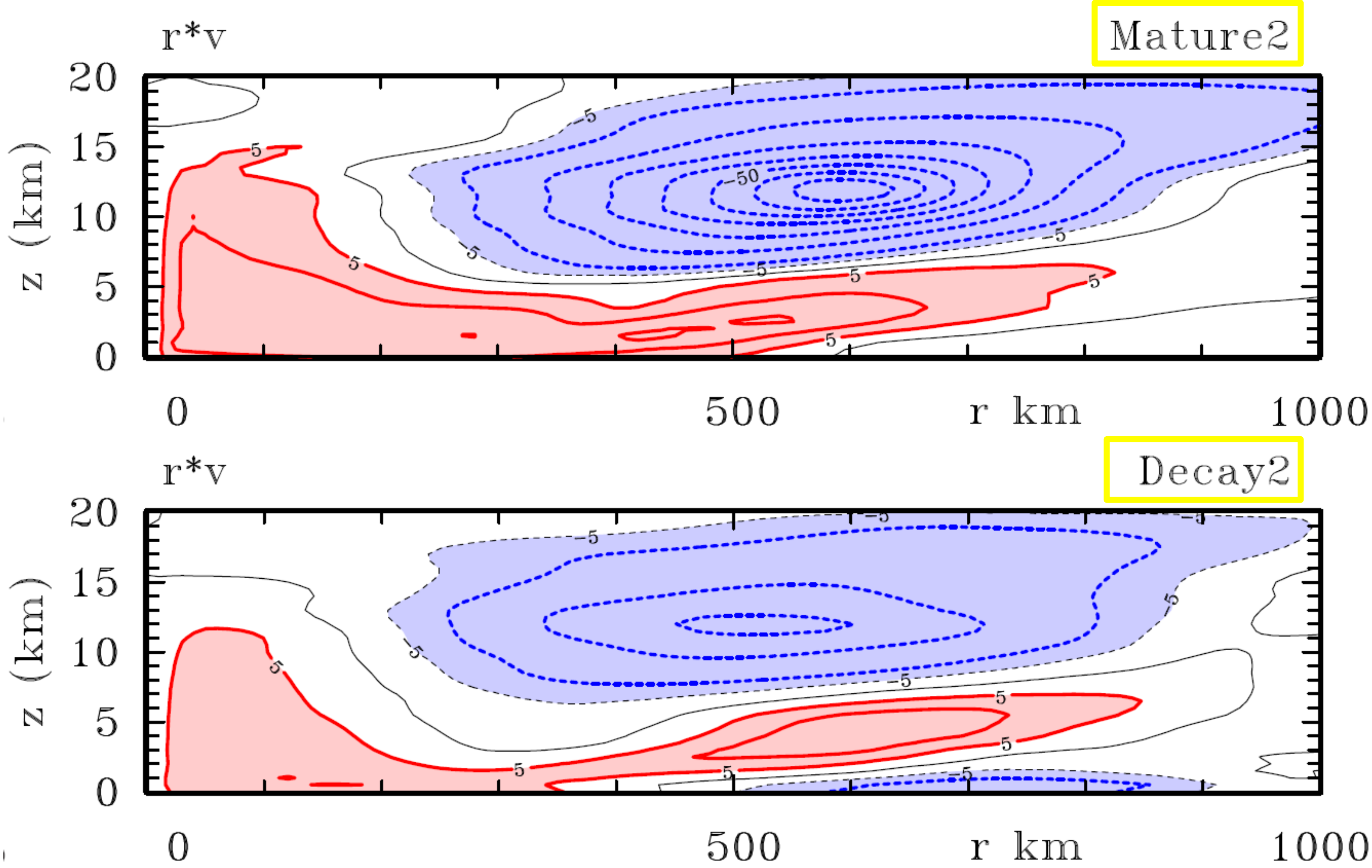


aam
t = 0
20
15
10
5
0
z (km)
.5
3
0
500
r km
1000
M
Mature1
20
15
10
5
0
z (km)
.5
3
8
20
10
0
500
r km
1000

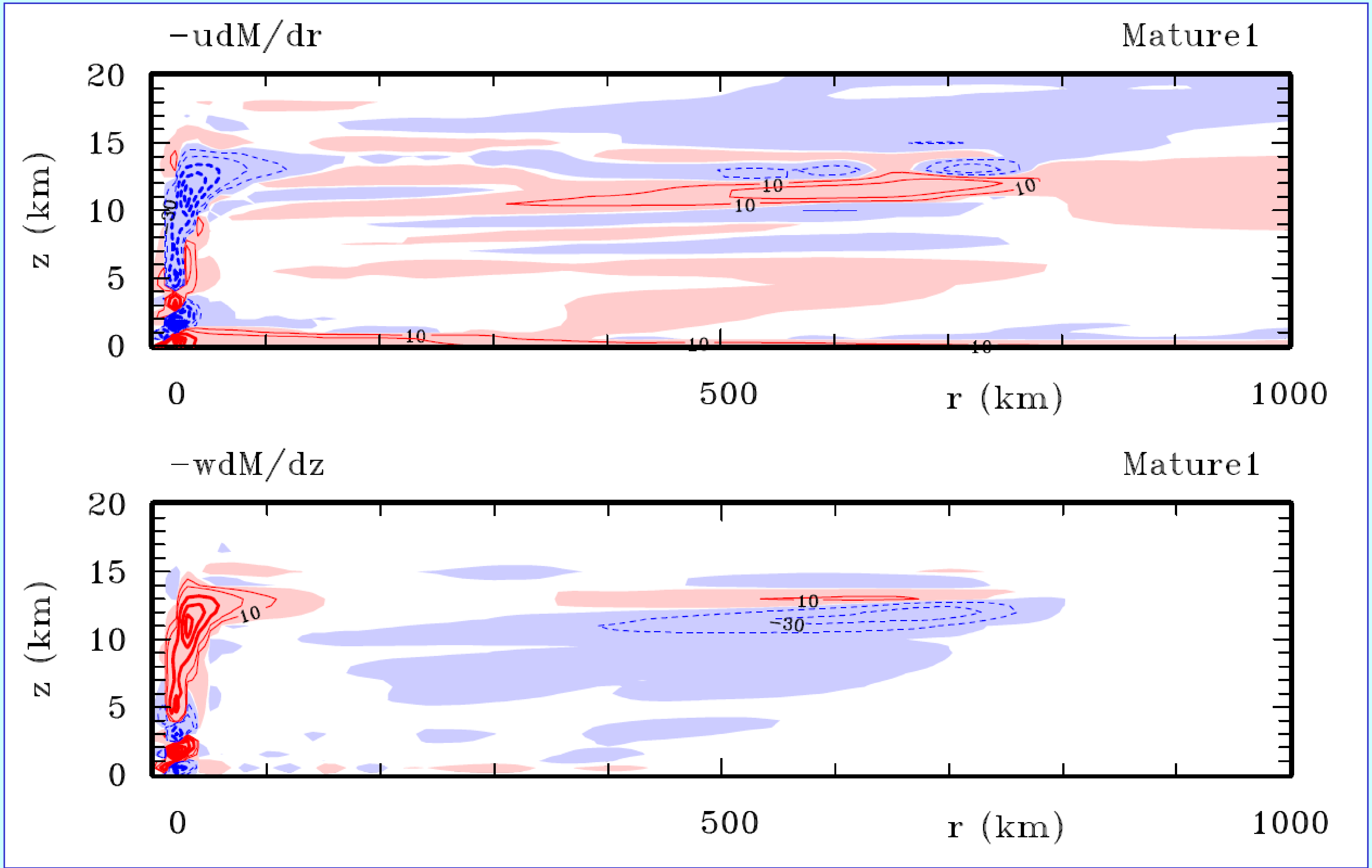
RAM surfaces



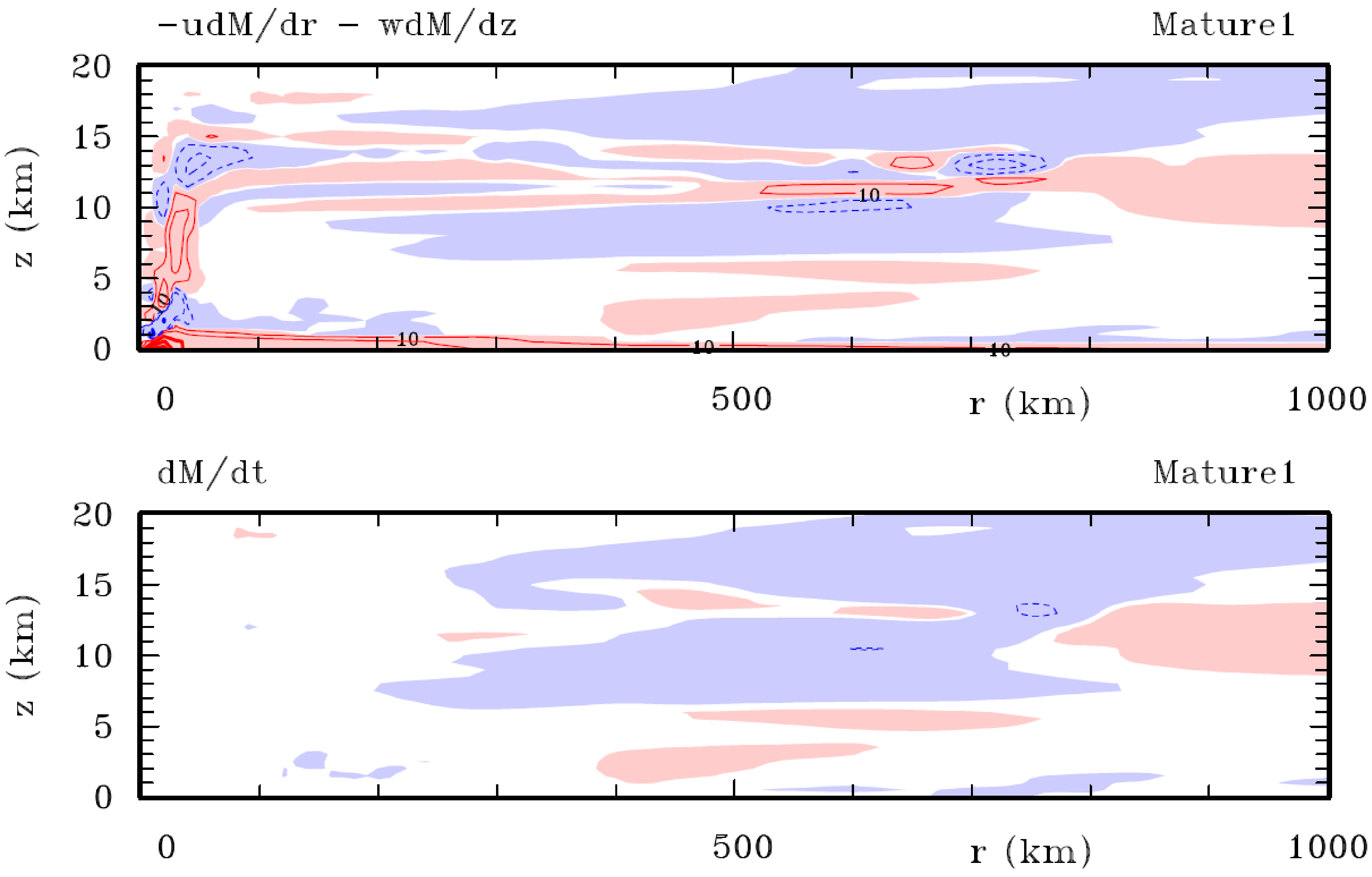
RAM surfaces



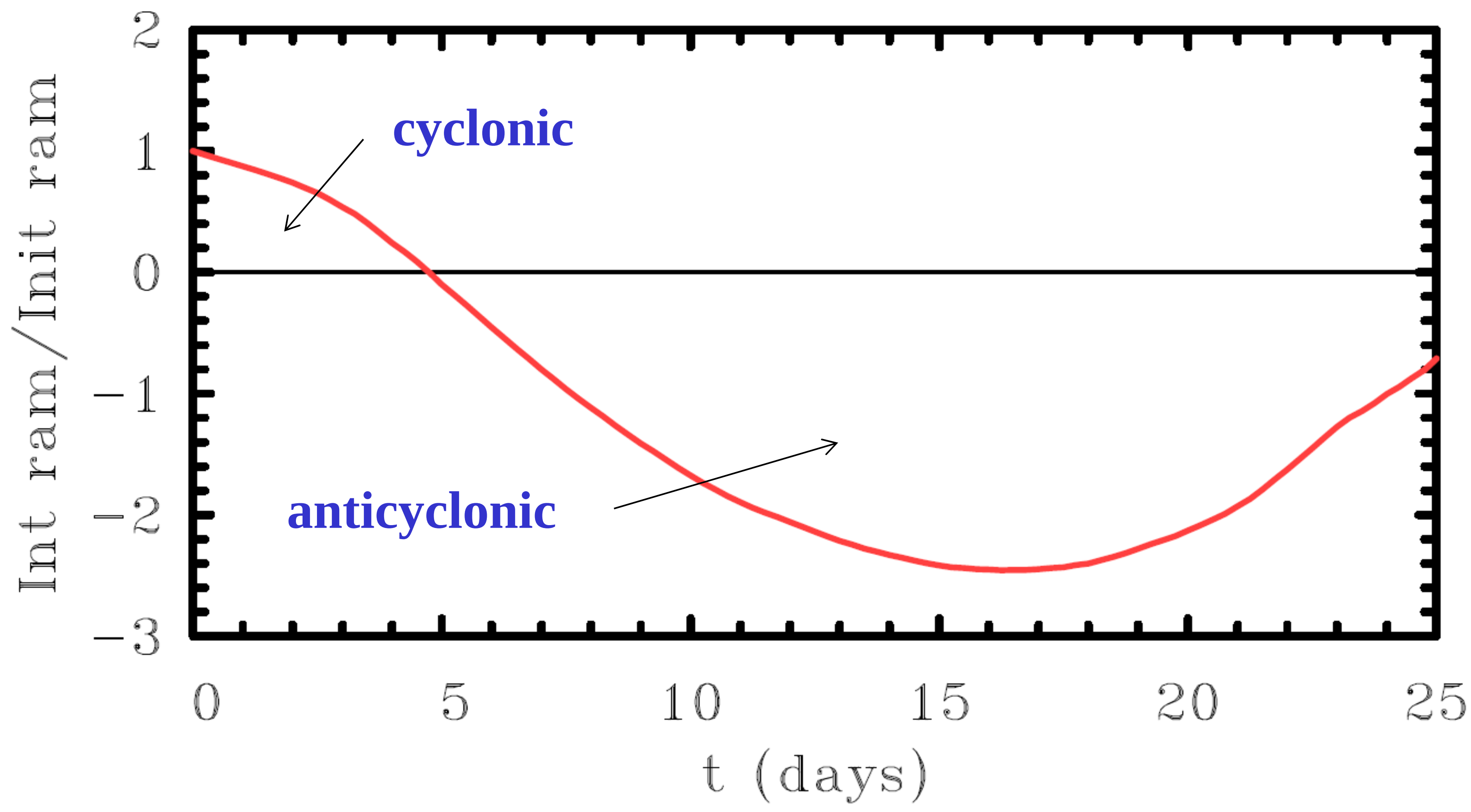
M tendencies



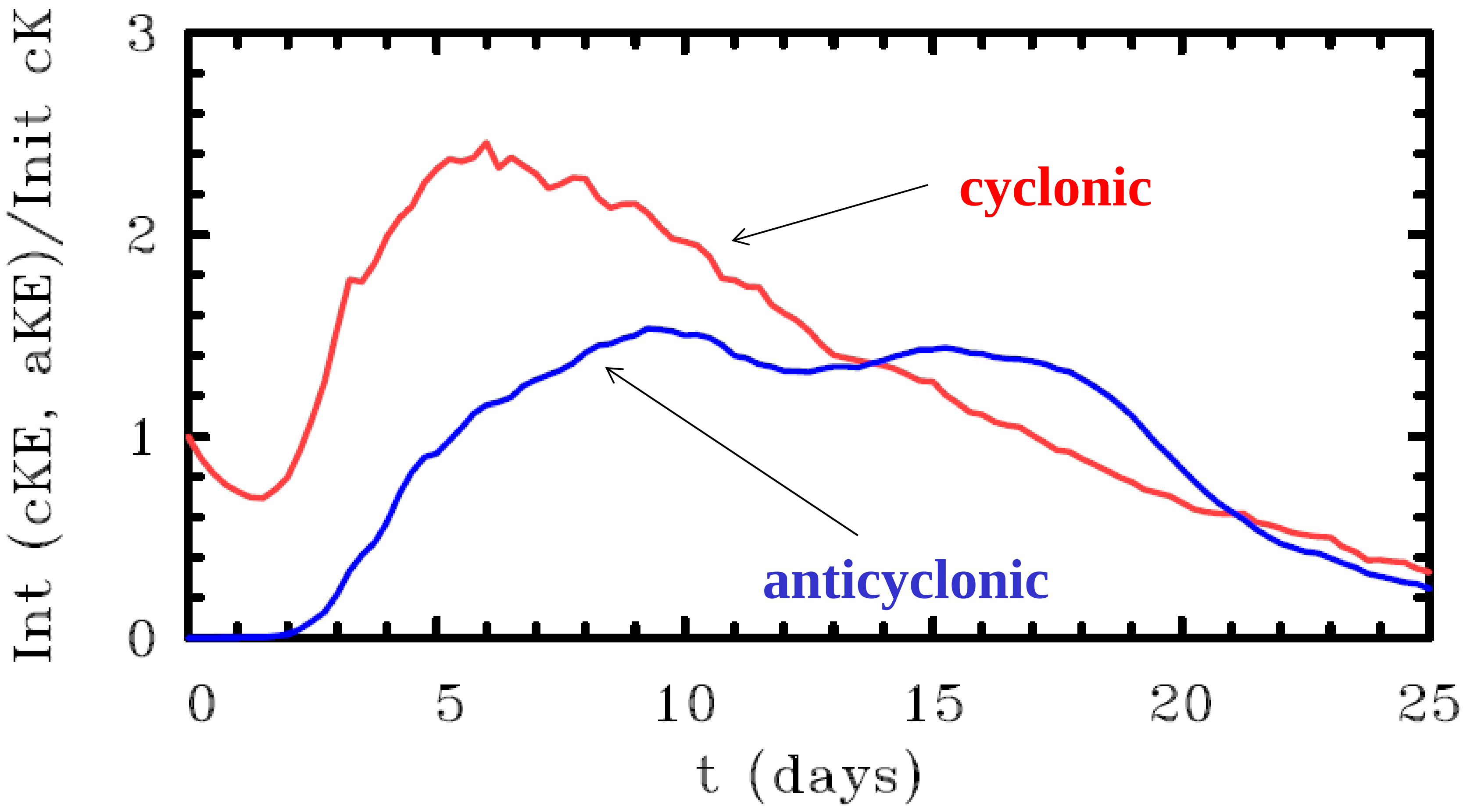
M tendencies



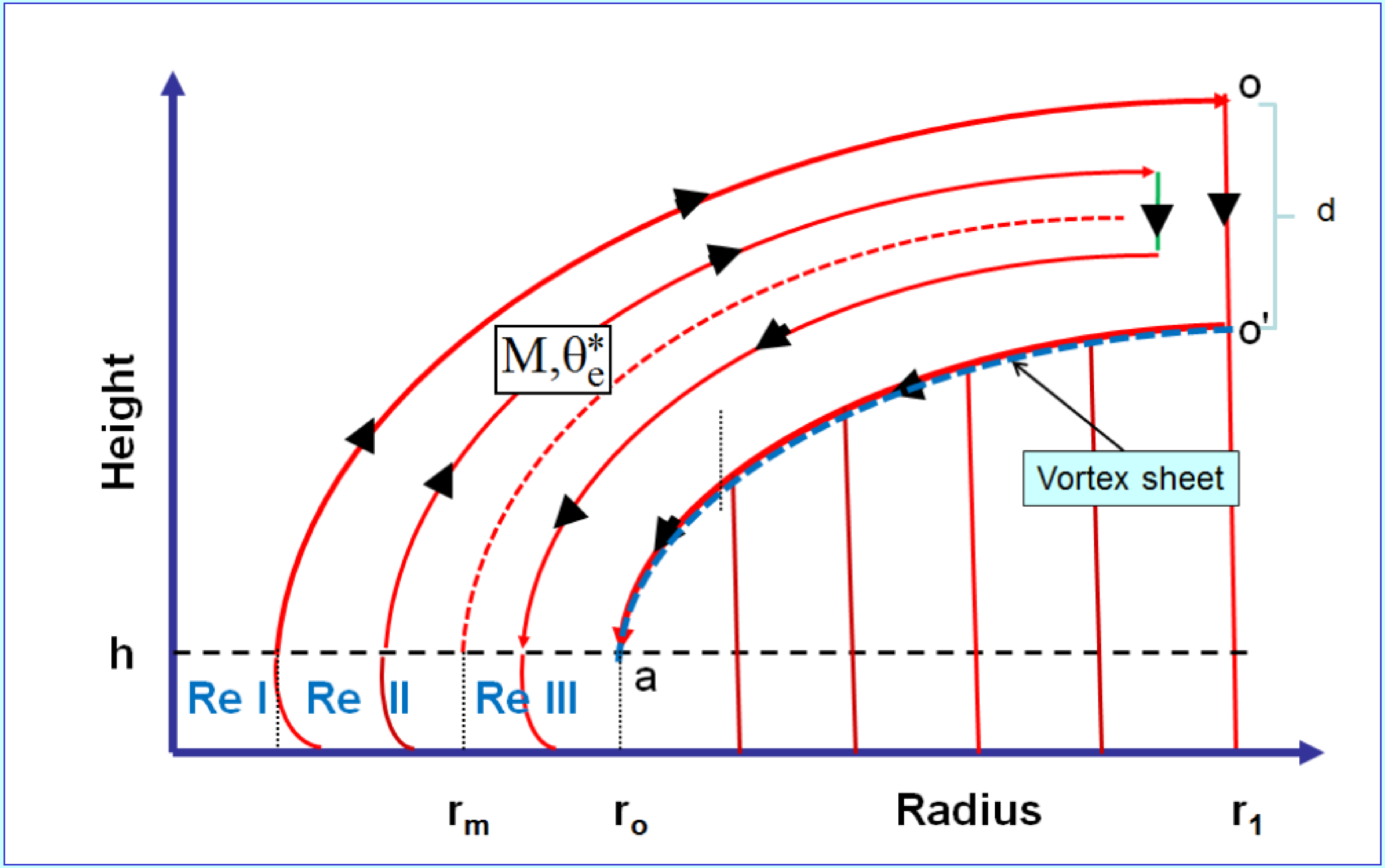
Integrated RAM / Integrated RAM(t = 0)



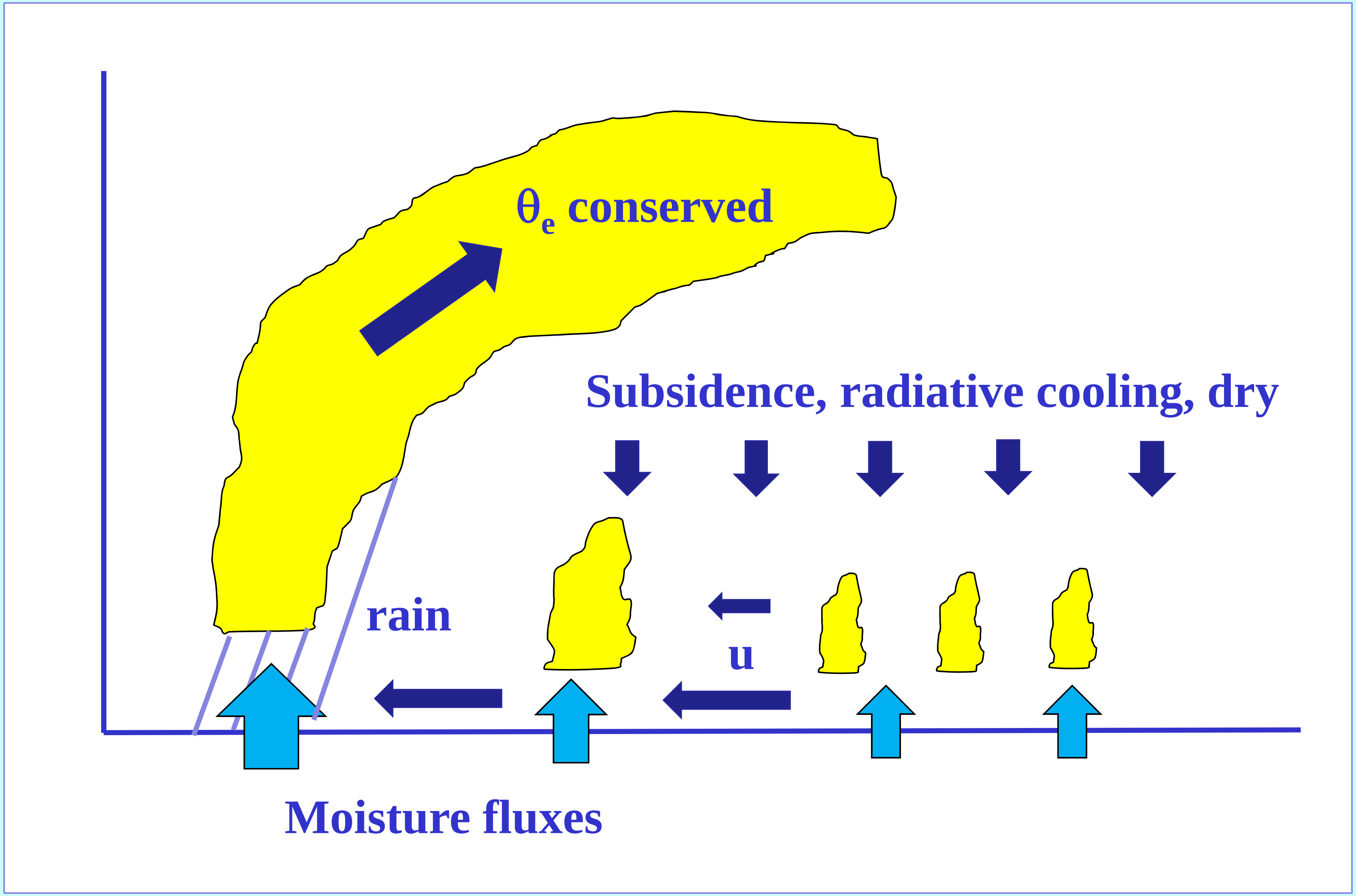
Integrated KE / **Integrated** KE(t = 0)



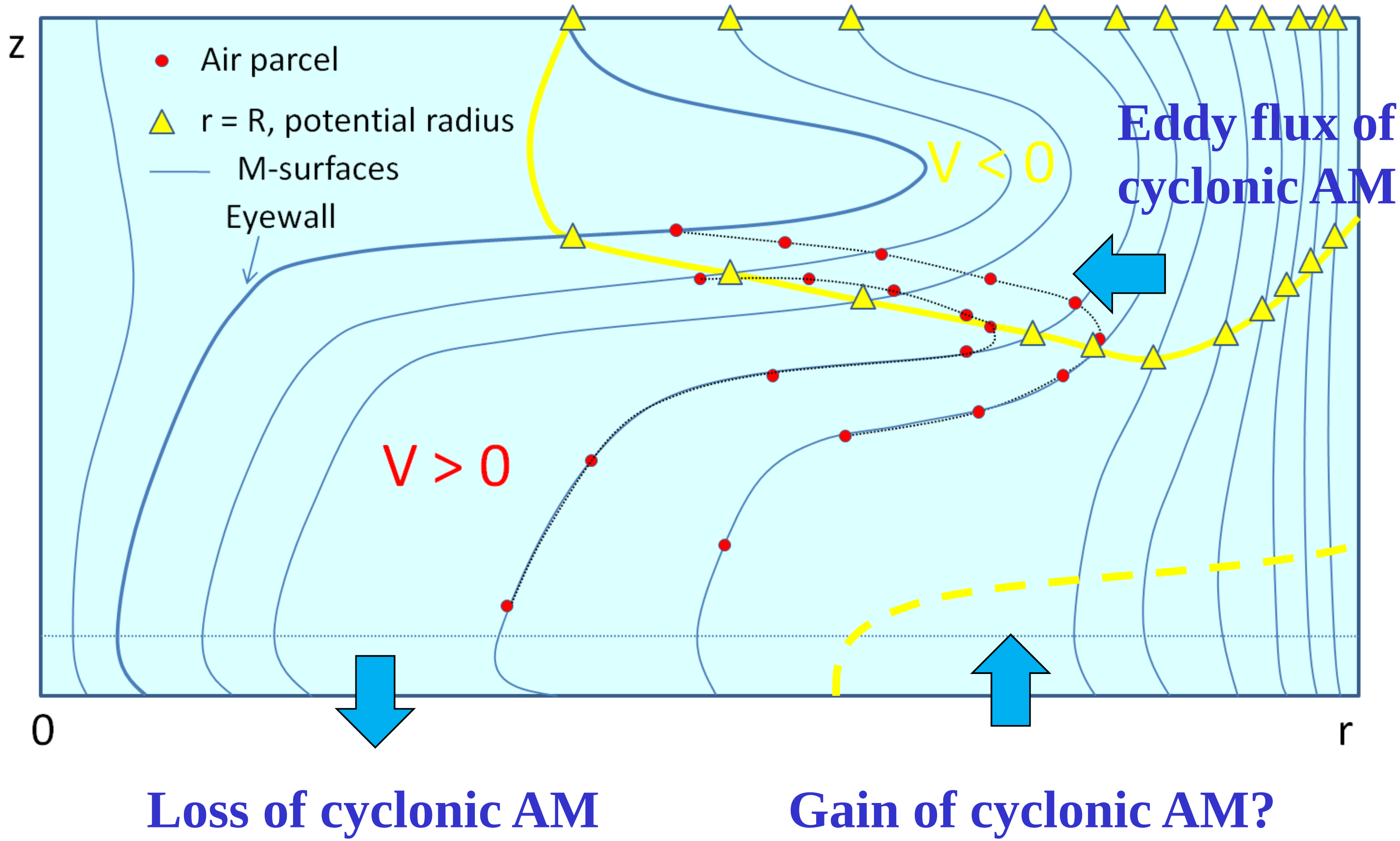
The Emanuel (1986) steady model

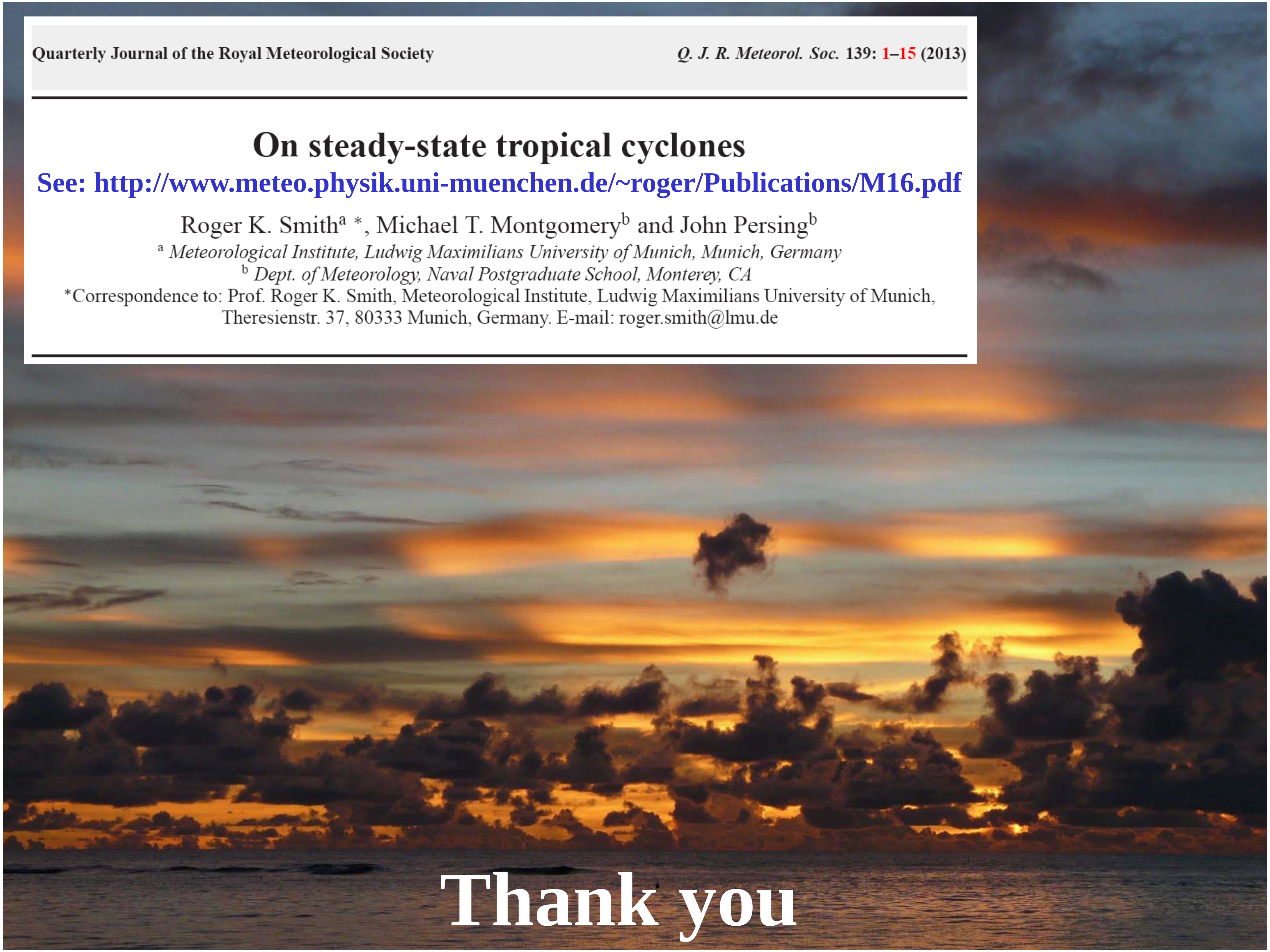


Summary 1: thermodynamic requirements for a steady state



Summary 2: dynamic requirements for a steady state





Quarterly Journal of the Royal Meteorological Society *Q. J. R. Meteorol. Soc.* 139: 1–15 (2013)

On steady-state tropical cyclones

See: http://www.meteo.physik.uni-muenchen.de/~roger/Publications/M16.pdf

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Thank you