Energy Conservation and Hurricane Intensity

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- ***All*** NWP models use ***approximate*** thermodynamical equations

$$c_p \, d \ln T - R_d \, d \ln p = 0$$

$$R = 287.04 \text{ J kg}^{-1} \text{ K}^{-1}$$

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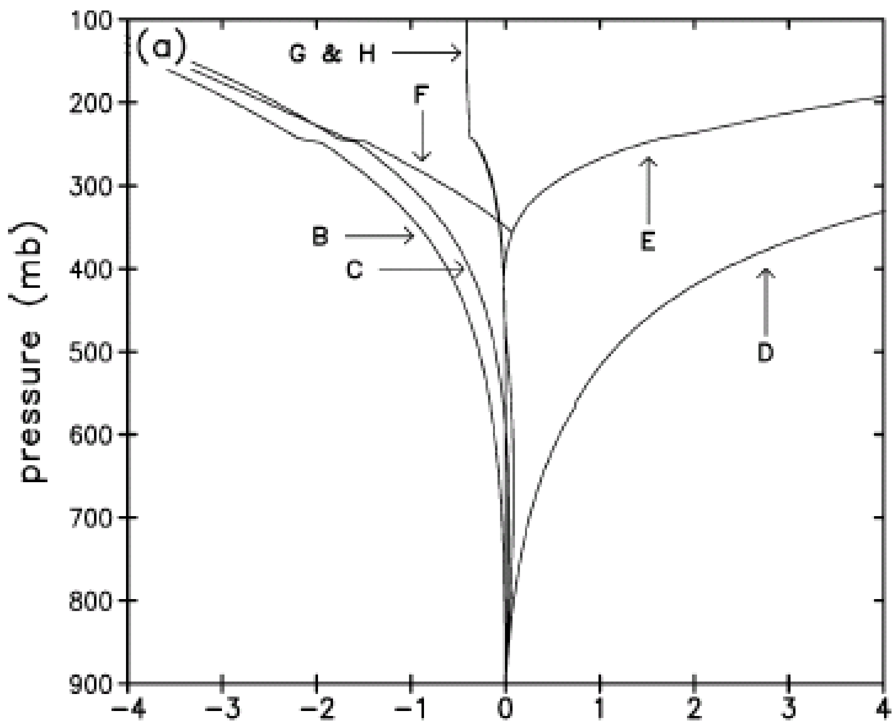
An approximation:

$$c_p = 1005.7 = \text{constant}$$

$$d \ln \left[T \left(\frac{p_0}{p} \right)^{\frac{R}{c_p}} \right] = 0$$

- In cloudy air, *more* approximations are made, and some are quite bad:

errors (^oC) from different approximate equation sets



"C" is used in most NWP models

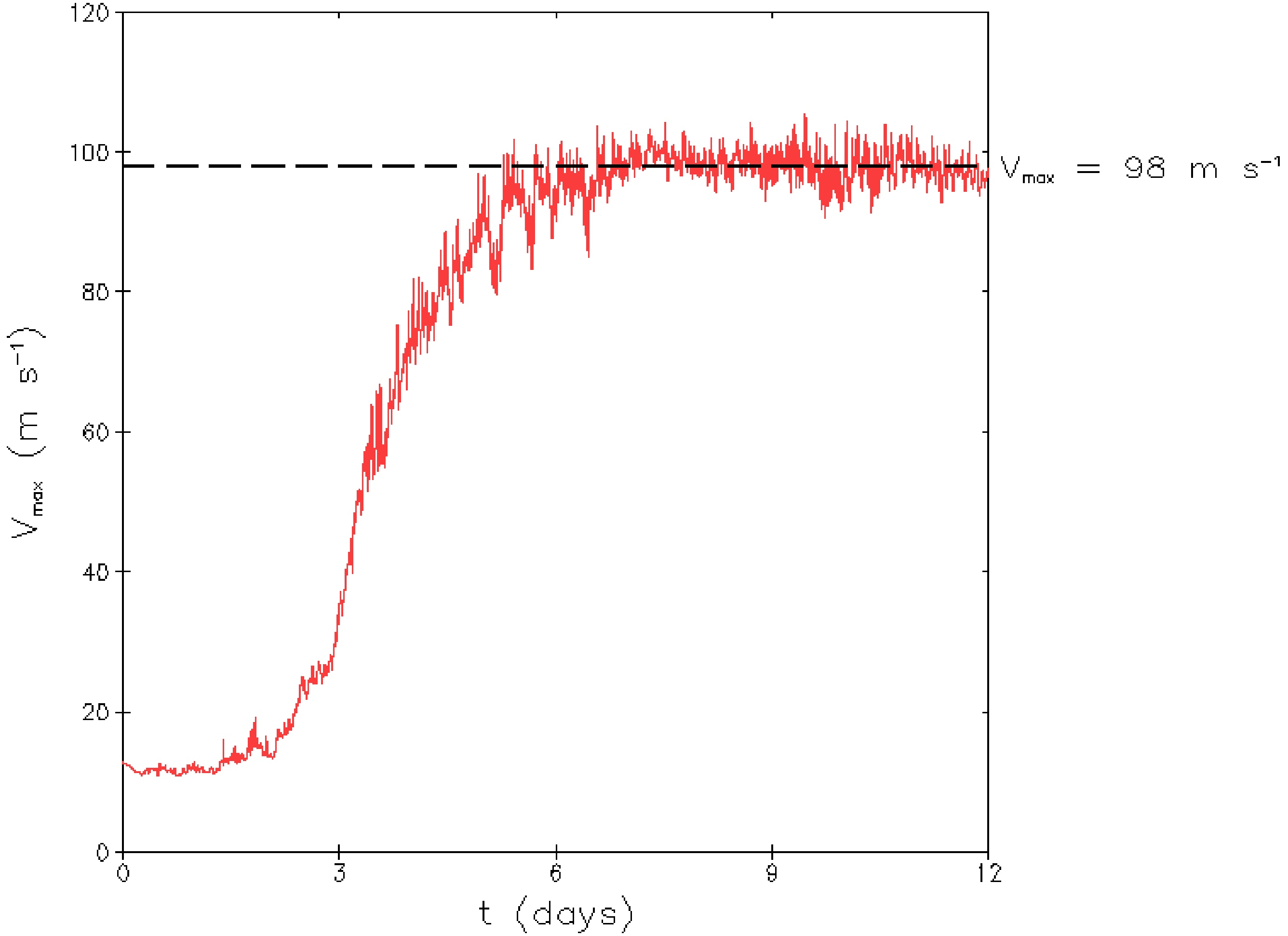
"D" is used in many LES models

Bryan and Fritsch (2004, MWR)

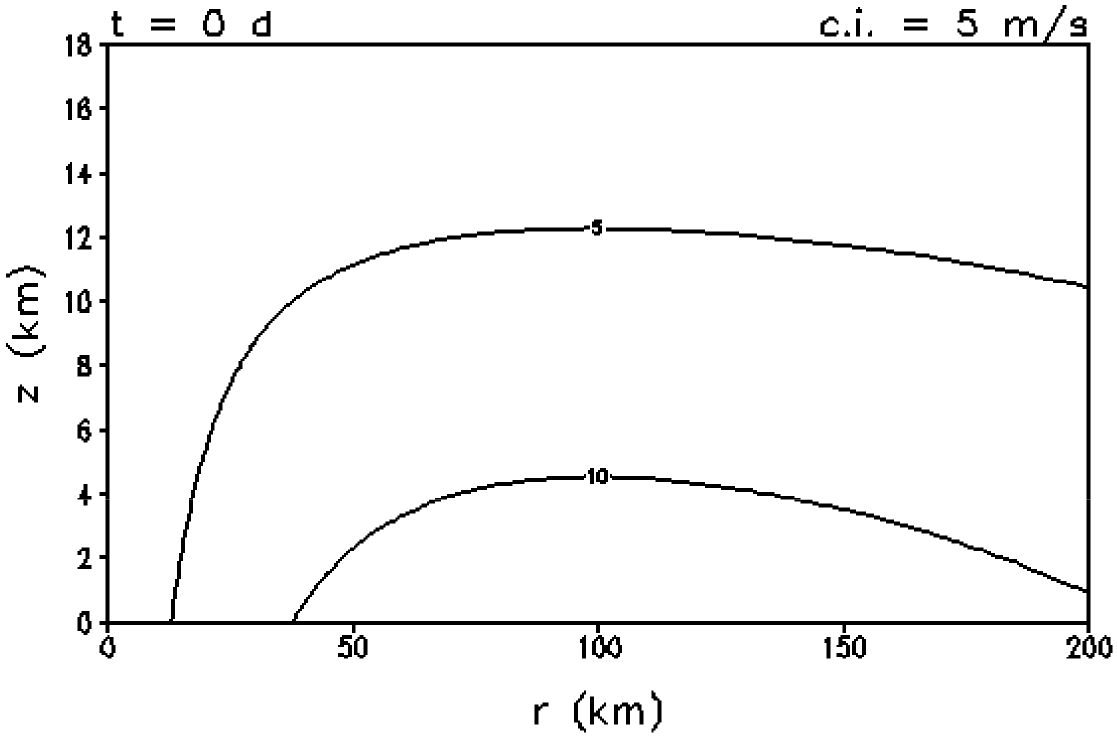
See also: Wilhelmson (1977), Tripoli and Cotton (1981), Pointin (1984)

- Numerical model: CM1
  - nonhydrostatic model developed at NCAR
  - http://www.mmm.ucar.edu/people/bryan/cm1/
- Idealized axisymmetric simulations: 2d (r,z)
  - Constant SST. Run to steady state.

Time series of max. azimuthal velocity (m s^{-1}):



Initial conditions:

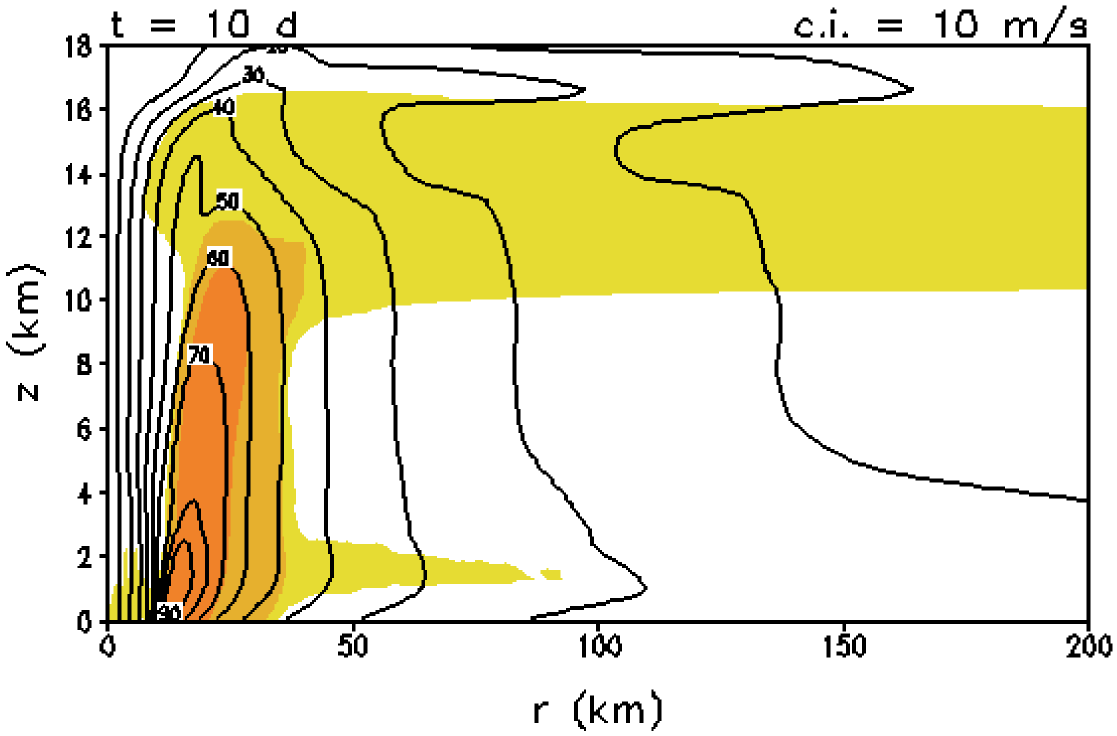


contours = v (m s^{-1})

yellow = cloud

orange = rain

t = 10 days:

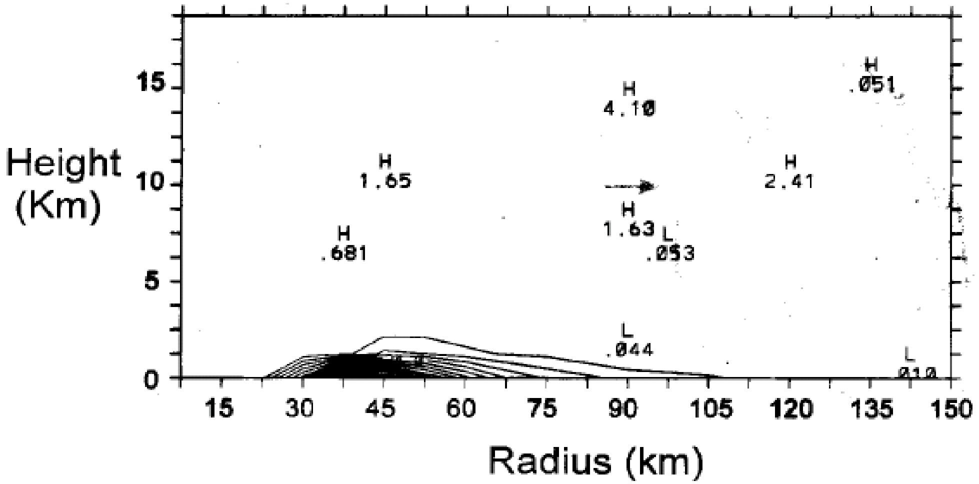


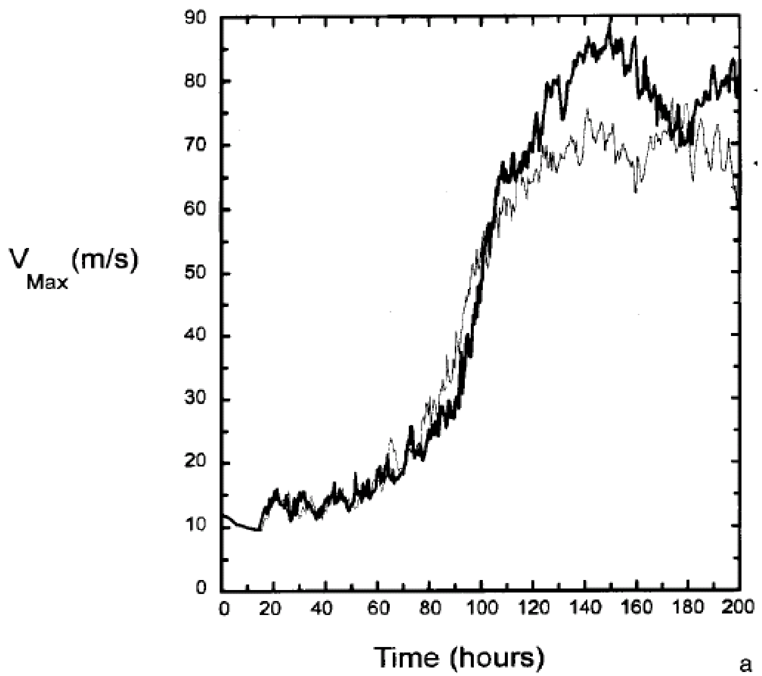
Effect #1: Dissipative heating

- The increase in internal energy (warming) that occurs when kinetic energy is dissipated (by friction)
- Important at high winds speeds
- Important for climate simulations
- $dT \sim V^3$

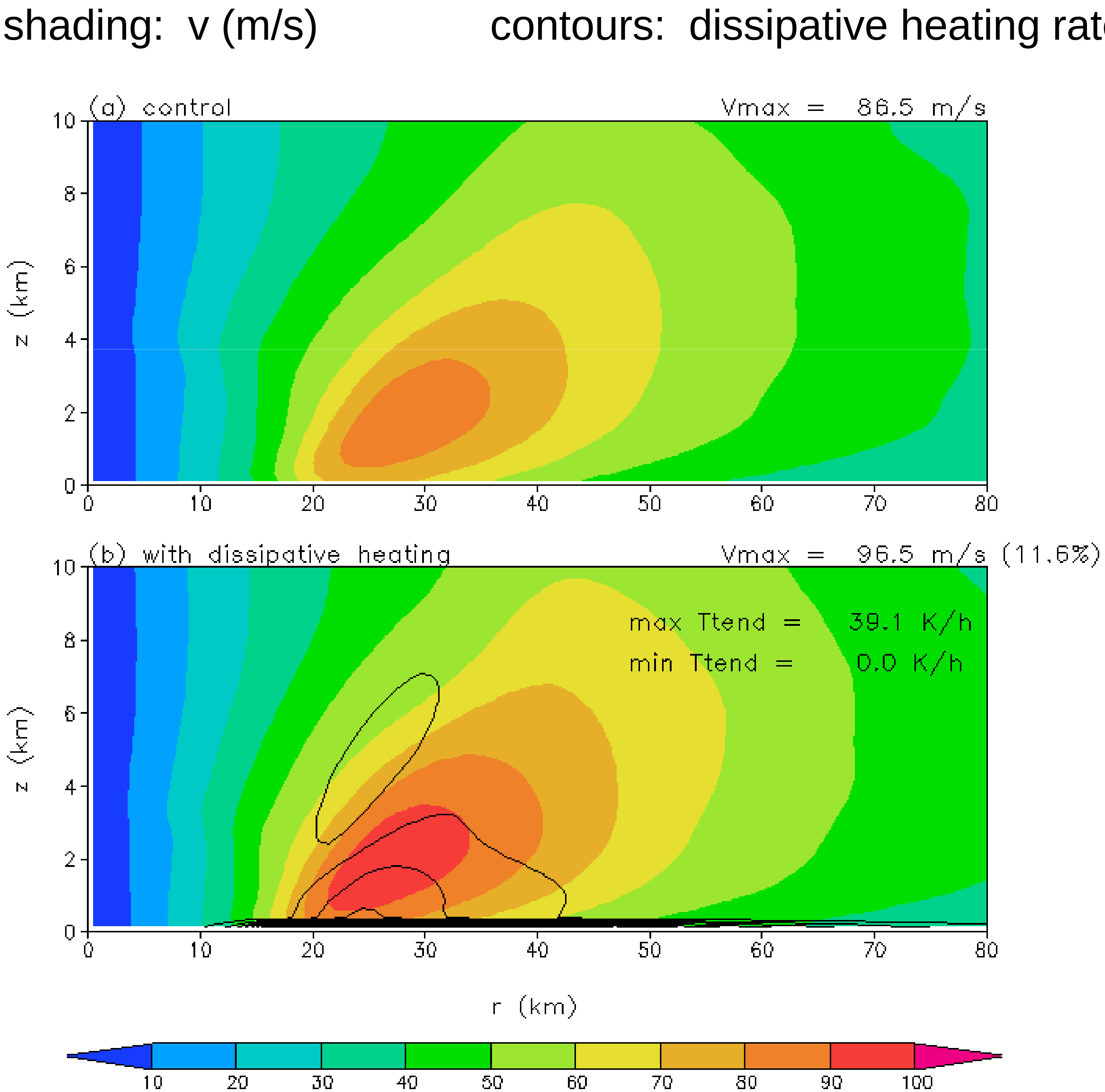
V from simulations with/without d.h.

Heating rate:

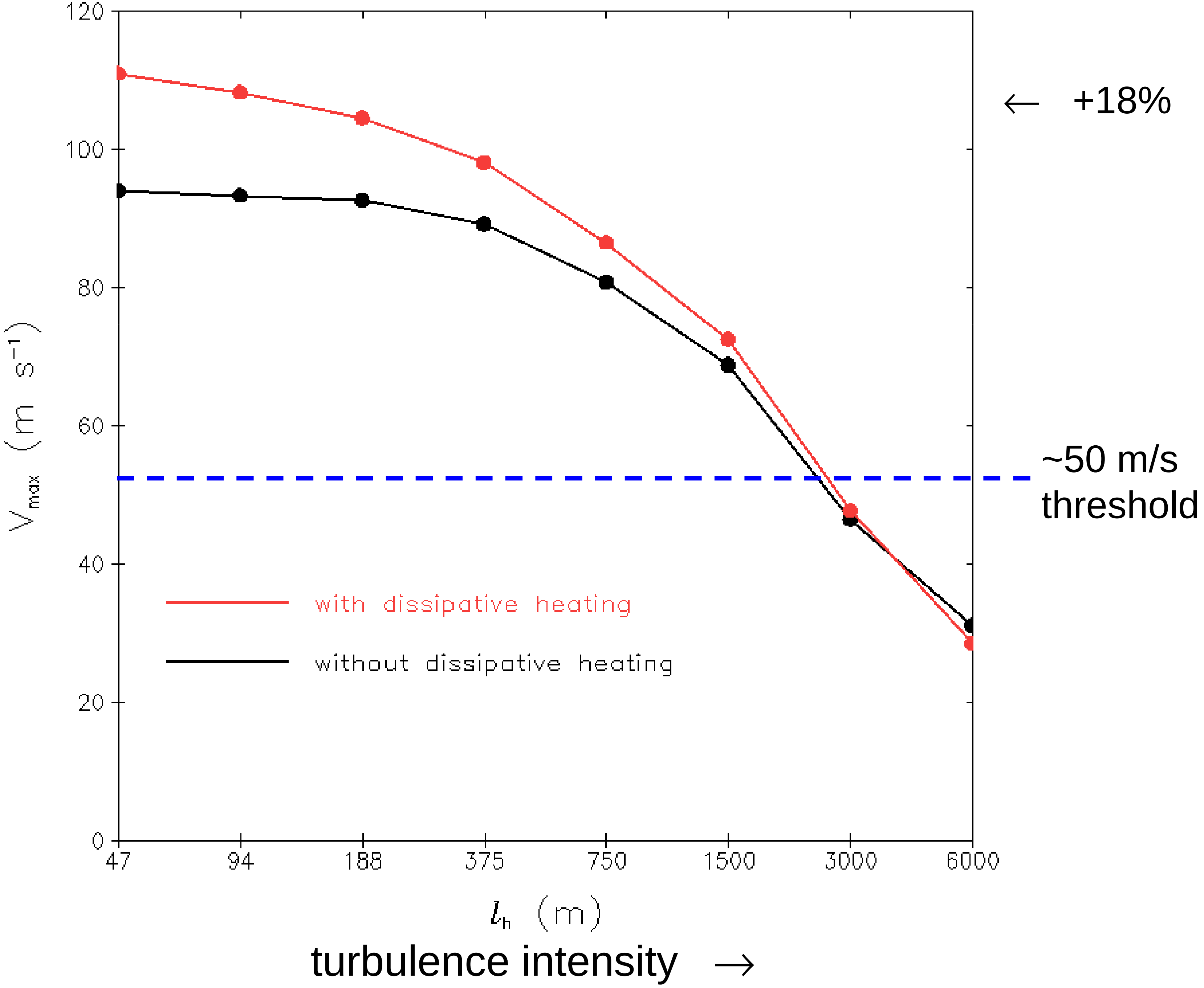




Bister and Emanuel (1998)



shading: v (m/s)
contours: dissipative heating rate (K/h)
(a) control
Vmax = 86.5 m/s
(b) with dissipative heating
Vmax = 96.5 m/s (11.6%)
max Ttend = 39.1 K/h
min Ttend = 0.0 K/h
z (km)
r (km)
0
2
4
6
8
10
0
10
20
30
40
50
60
70
80
10
20
30
40
50
60
70
80
90
100



See Bryan and Rotunno (2009, MWR)

Effect #2: hydrometeor heat content: updrafts

- Usually neglected in nonhydrostatic model's thermodynamic equations
- Complicated!

$$\frac{D\ln\theta}{Dt} = -\left(\frac{R_m}{c_{\mathrm{vml}}} - \frac{Rc_{\mathrm{pml}}}{c_p c_{\mathrm{vml}}}\right)\frac{\partial u_j}{\partial x_j} - \left[\frac{c_v L_v}{c_{\mathrm{vml}} c_p T} - \frac{R_v}{c_{\mathrm{vml}}}\left(1 - \frac{R}{c_p}\frac{c_{\mathrm{pml}}}{R_m}\right)\right]\frac{Dr_v}{Dt}$$

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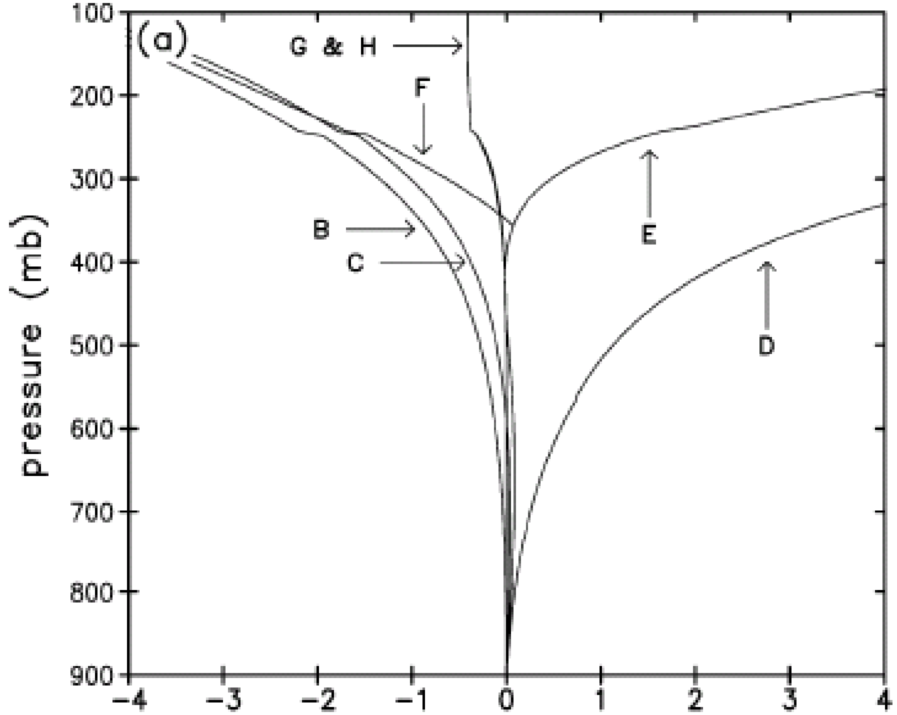
$$\frac{D\ln\theta}{Dt} = -\frac{L_v}{c_p T}\frac{Dr_v}{Dt}$$

parcel model tests:

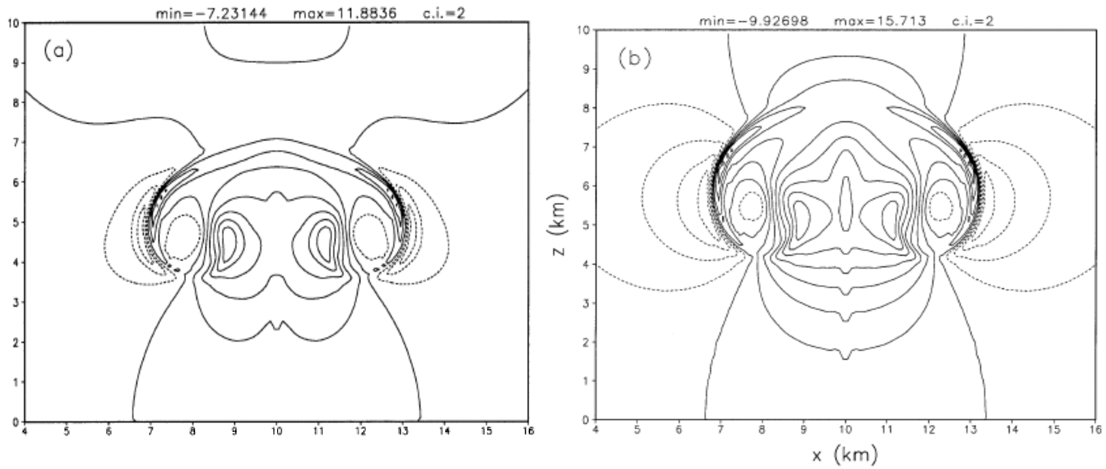


Bryan and Fritsch (2004, MWR)

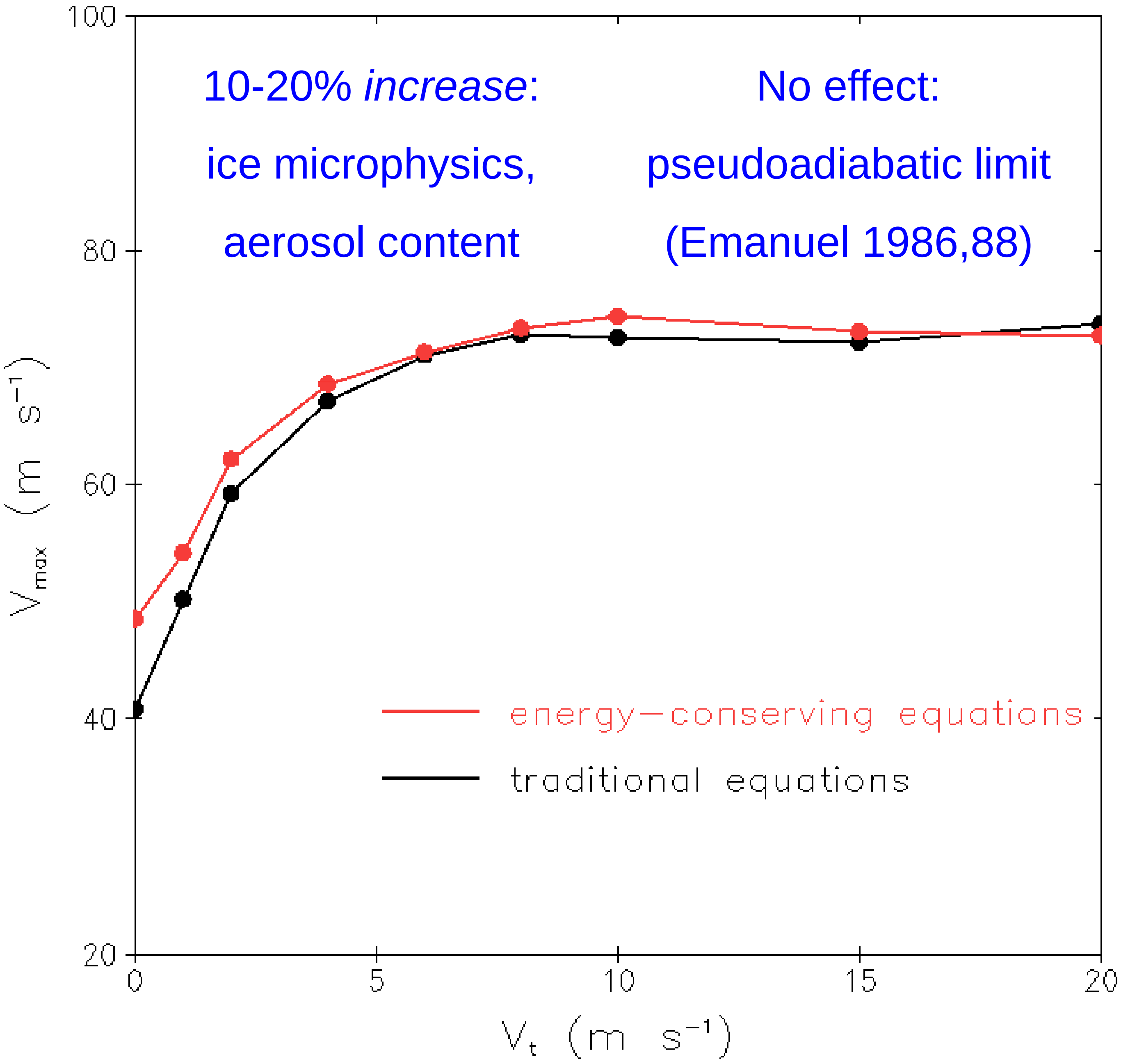
Simple 2D warm bubble:

without terms:

with terms:



Bryan and Fritsch (2002)

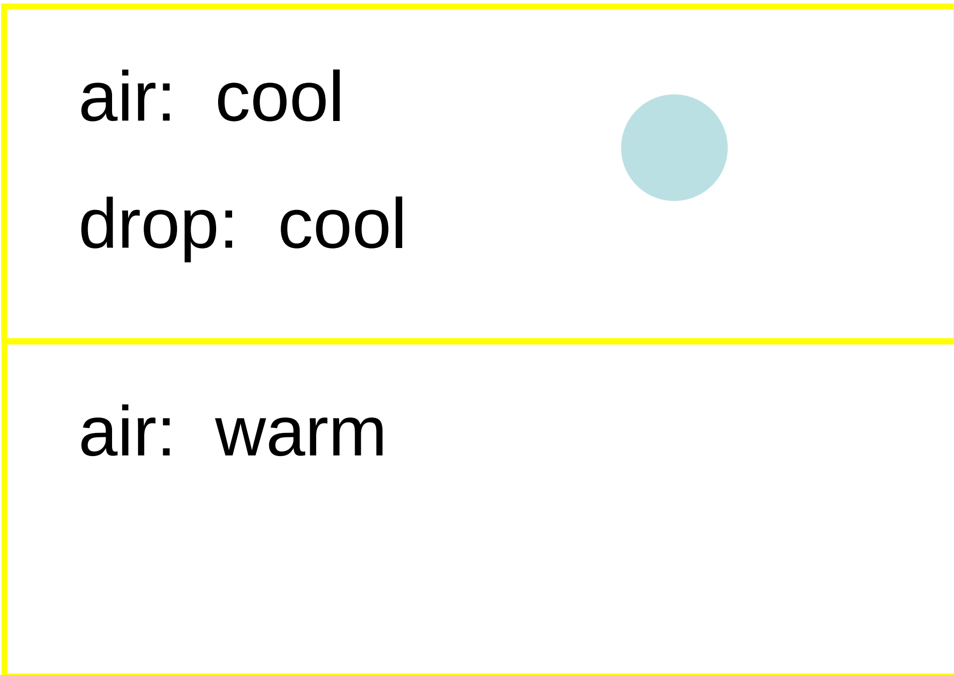


fall velocity of condensate →

See: Bryan and Rotunno (2009, MWR), Bryan and Rotunno (2009, JAS)

Effect #3: hydrometeor heat content, part 2: hydrometeor sedimentation

- Falling hydrometeors are cooler than the surrounding air: can act as a heat sink



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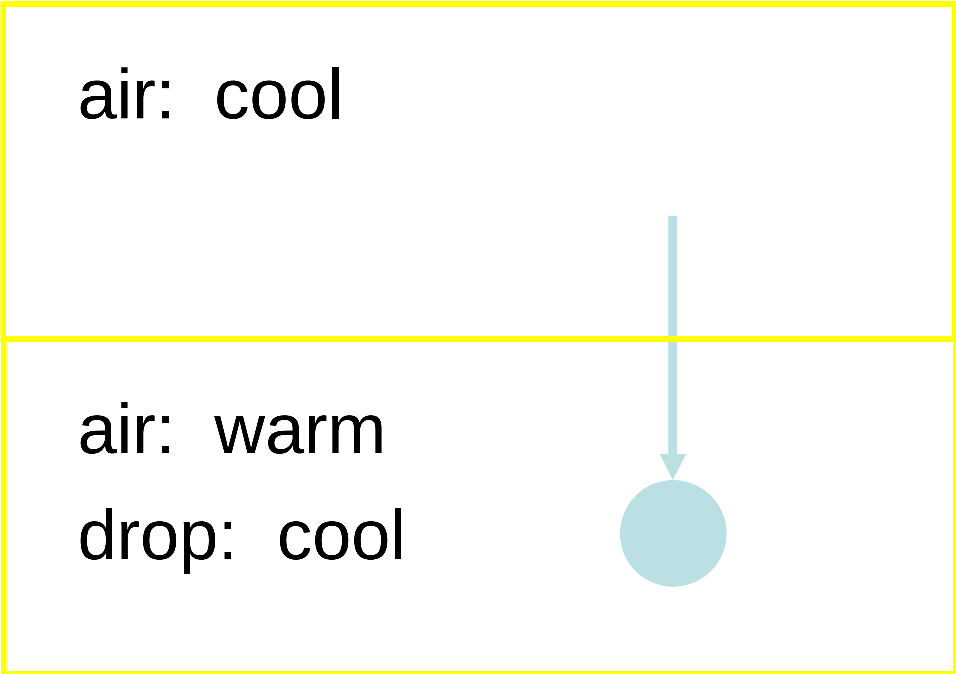
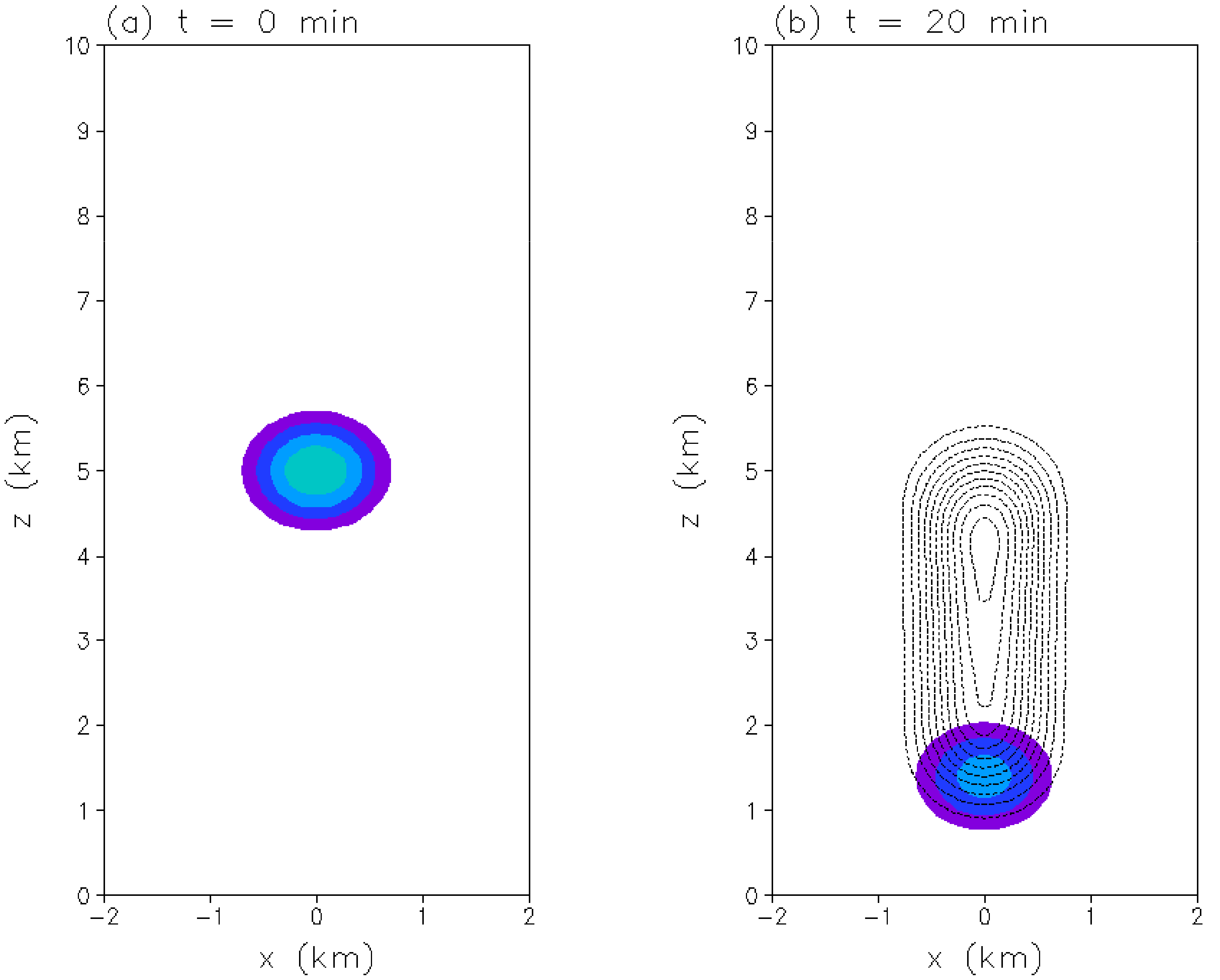


$$\frac{\partial T}{\partial t} = q_l \, V_{\mathrm{t}} \, \frac{c_l}{c_p} \, \frac{\partial T}{\partial z} \sim 5 \ \mathrm{K\ h^{-1}}$$

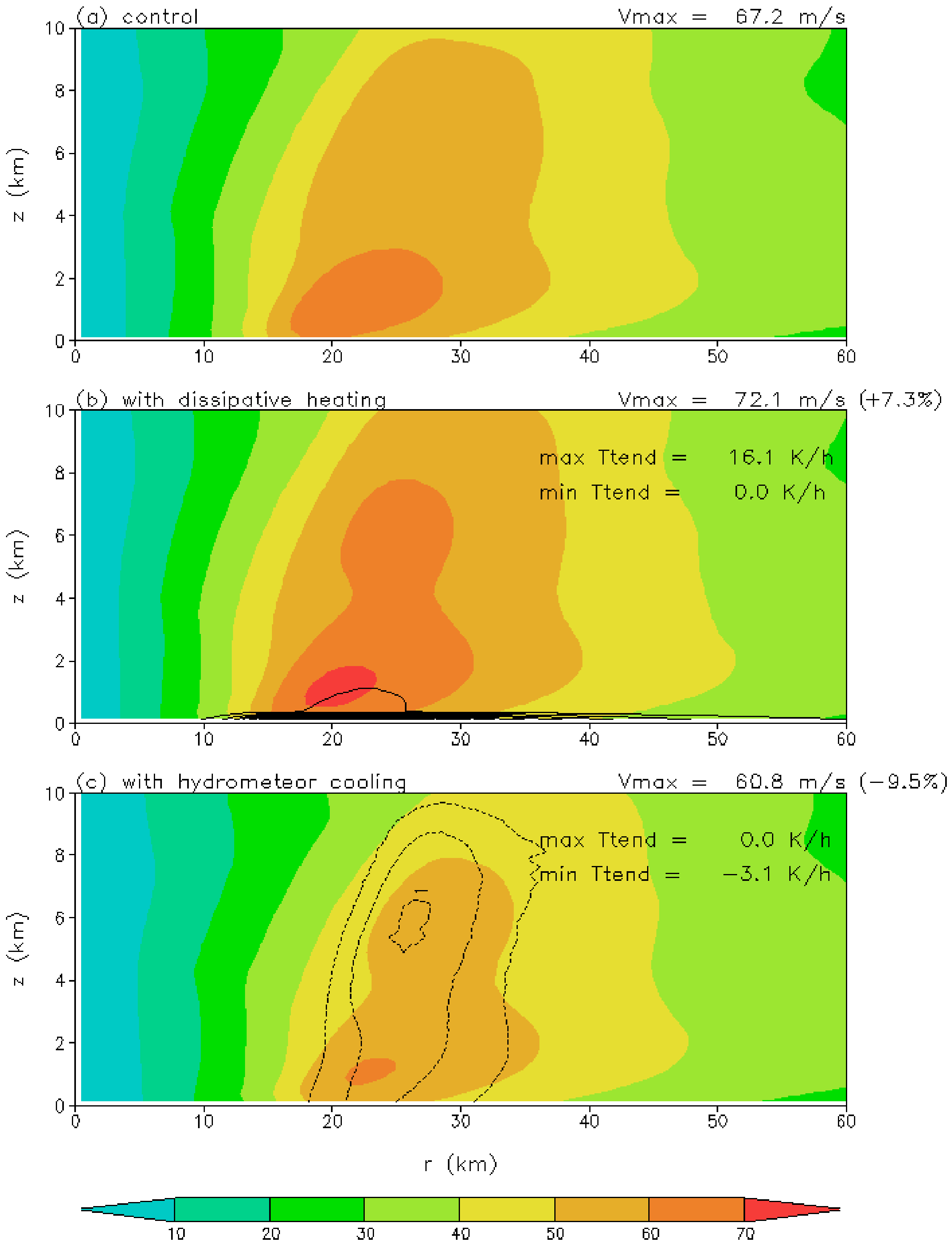
shading: q_l contours: cooling rate



shading: v (m/s)

contours:

temperature tendency (K/h)



Summary

- Energy conservations affects hurricane intensity:
  - Dissipative heating:
    - ~10% *increase*
    - (for wind speeds V > 50 m/s only)
  - Hydrometeor heat content in updrafts:
    - ~10% *increase*
    - (for fall velocities $V_t < 5$ m/s)
  - Hydrometeor heat content in fallout:
    - ~10% *decrease*
    - (for water content $q_l > 10$ g/kg)
- Note: some effects tend to counteract one another
- Could be important for long-term climate simulations