Cumulus air parcels and their vertical momentum budgets

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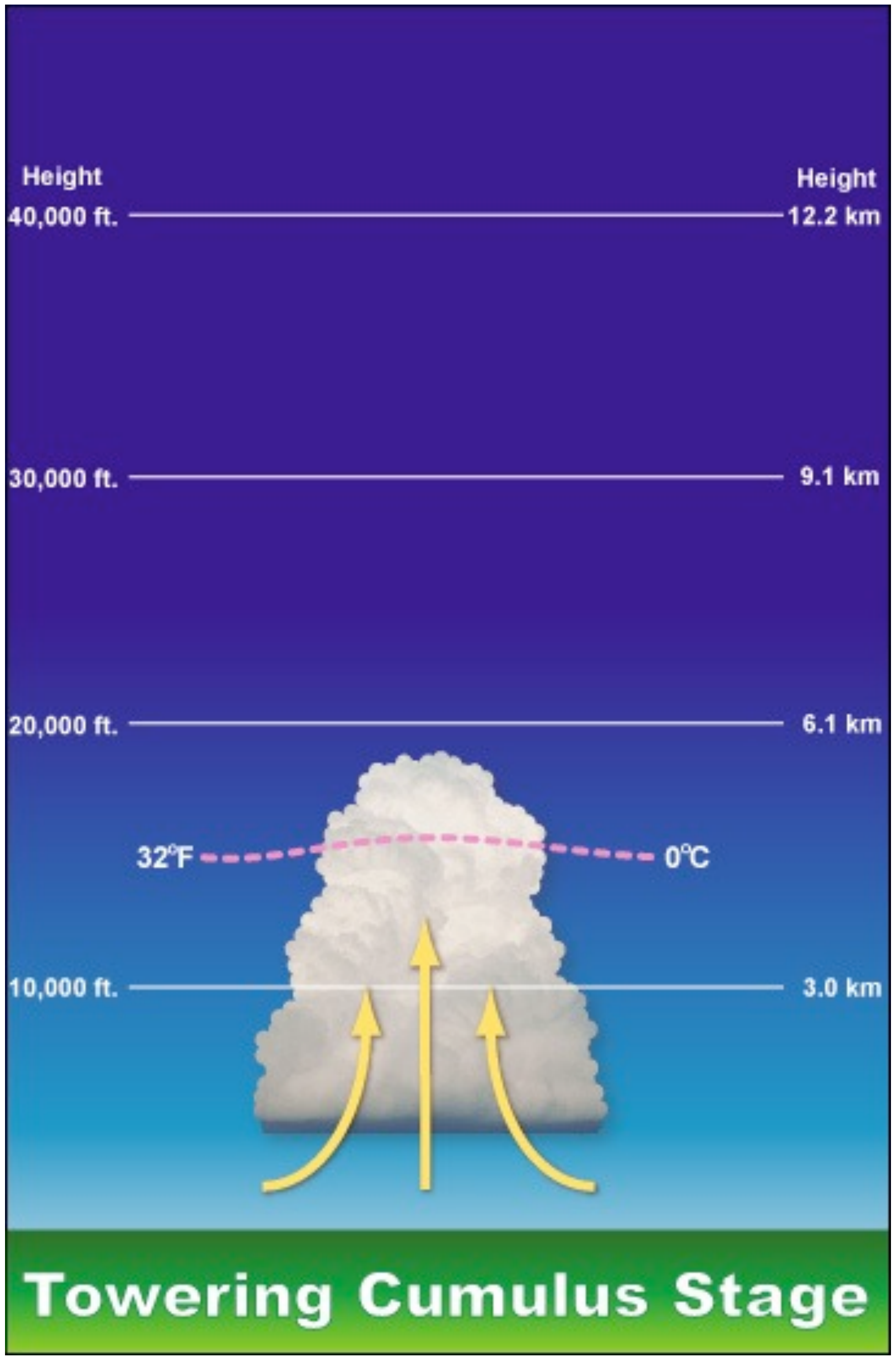
Conceptual model of cumulus

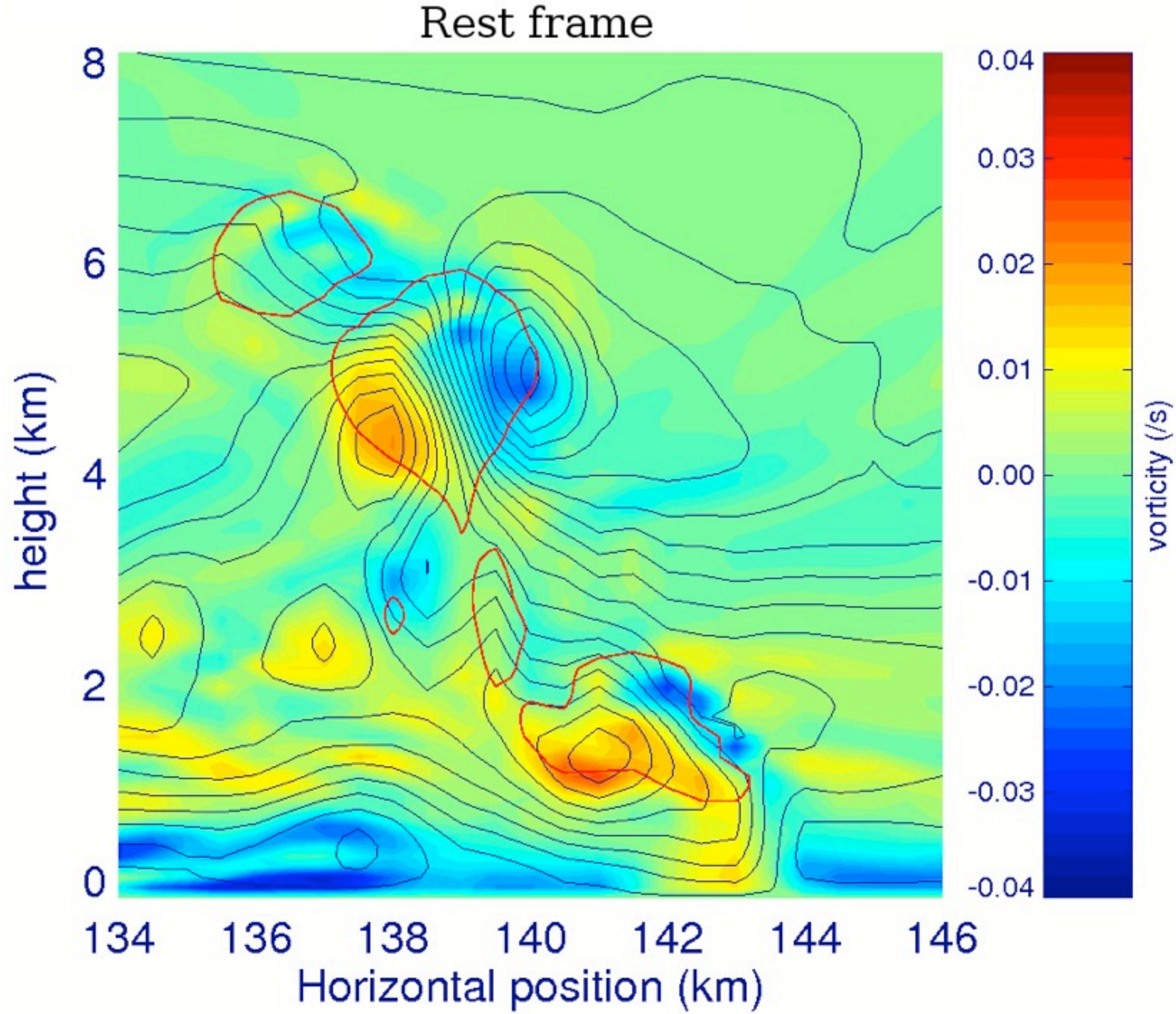


Assumptions

- Cloud properties horizontally uniform
- high shear at cloud edges
- net entrainment → $dM/dz > 0$.
- Cumulus = rising cloud (wherever $w >> 0$, $q_c >> 0$)
- Parcel = cumulus

problem

- w, q_c are not conserved tracers, not good for tracking a rising parcel, especially w/entrainment.



Rest frame
height (km)
8
6
4
2
0
134
136
138
140
142
144
146
Horizontal position (km)
vorticity (/s)
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04

J. O. Dabiri and M. Gharib

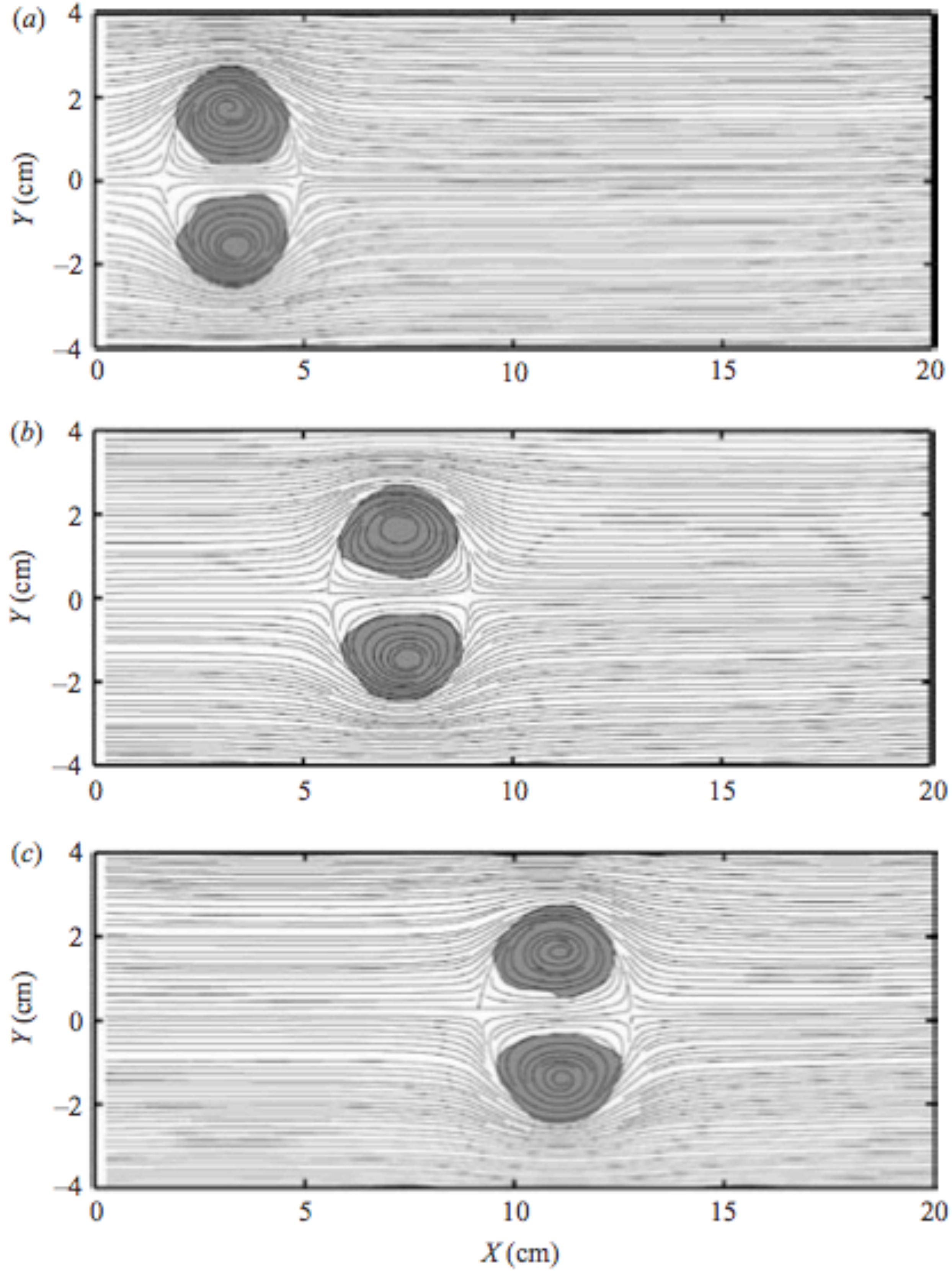


FIGURE 5. Instantaneous streamlines and vorticity patches for protocol *LD2-CF0*. (*a*) $T = 1.67$ s; (*b*) $T = 3.54$ s; (*c*) $T = 5.34$ s. Minimum vorticity level is $1 s^{-1}$.

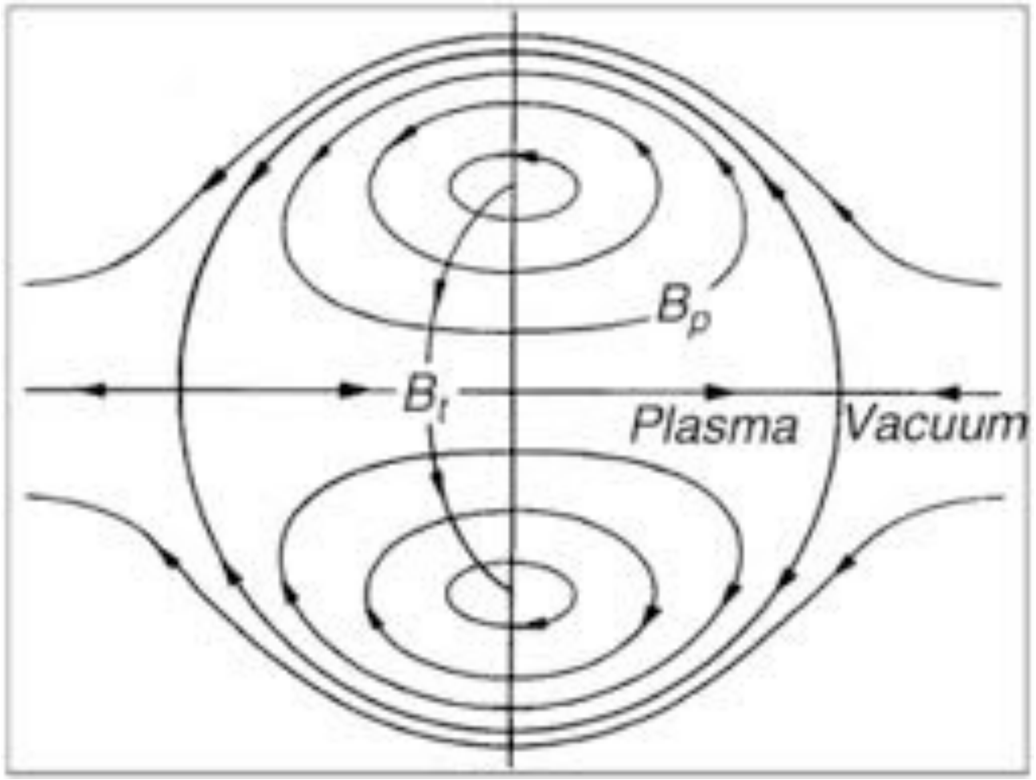
Lab studies

Vortex rings propagate easily with less than 10% velocity loss after traveling 6 diameters (Dabiri and Gharib 2004)

highly robust (and virtually no drag)

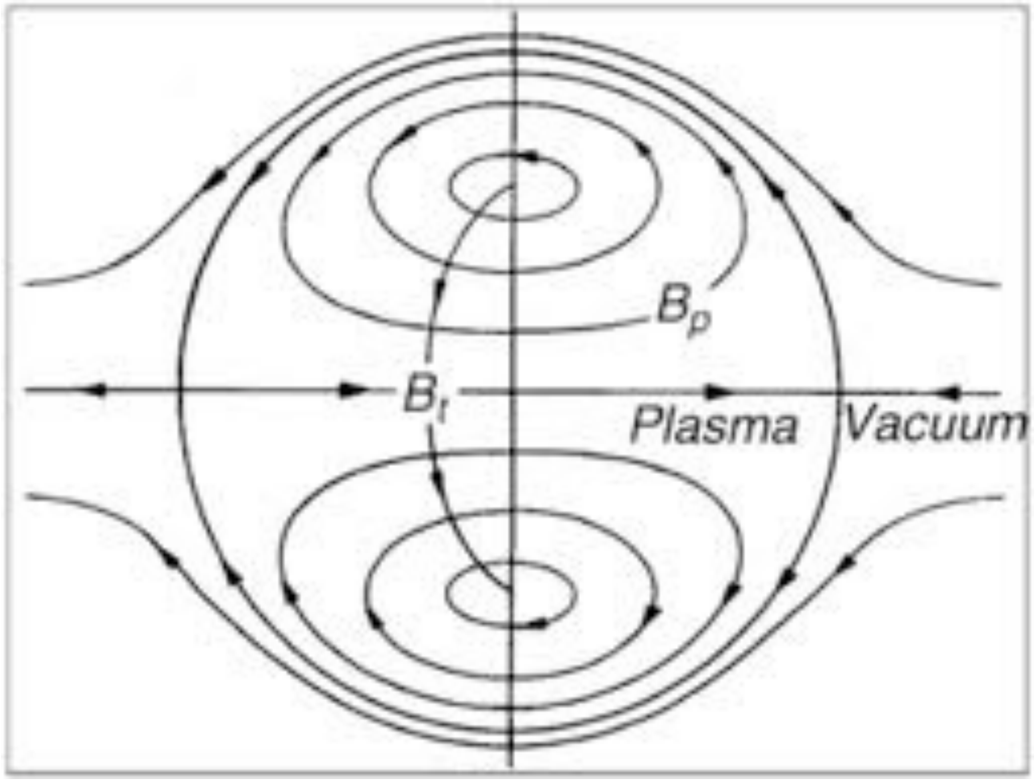
--> "real" parcels!!

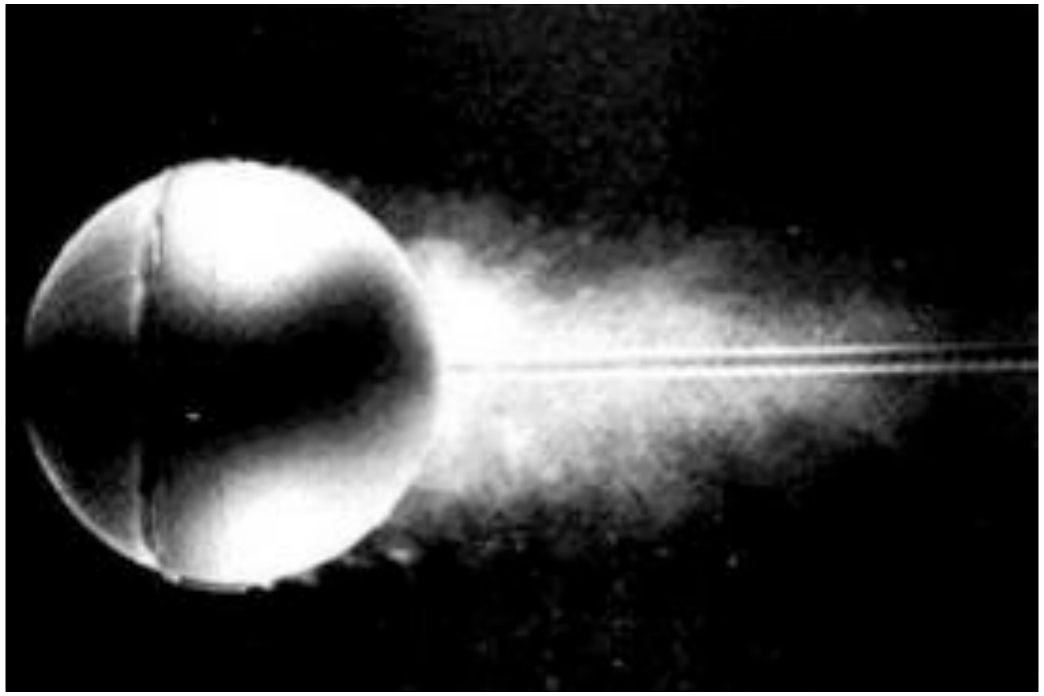
Hill's spherical vortex



An exact solution to the Navier-Stokes equations.
Shear vanishes to first order on vortex boundary surface

Hill's spherical vortex





An exact solution to the Navier-Stokes equations.
Shear vanishes to first order on vortex boundary surface

Problems:

- Outside of vortex not conventionally counted as part of "cloud," since $w \sim 0$
- Dry air entrained into vortex not counted (for a while) since $q_c = 0$.
- We propose that vortices be considered and tracked as the the fundamental entities. The vortex-parcels will have fractional cloud amount.

- We find radius r such that $\int_r w\, dV = dz_{therm}/dt$
- Entrainment distance calculated as:

$$D_{entrain} = \frac{\int_V \rho\omega dV}{\oint \vec{u}' \cdot \hat{n} H(\vec{u}' \cdot \hat{n}) \rho dS}$$

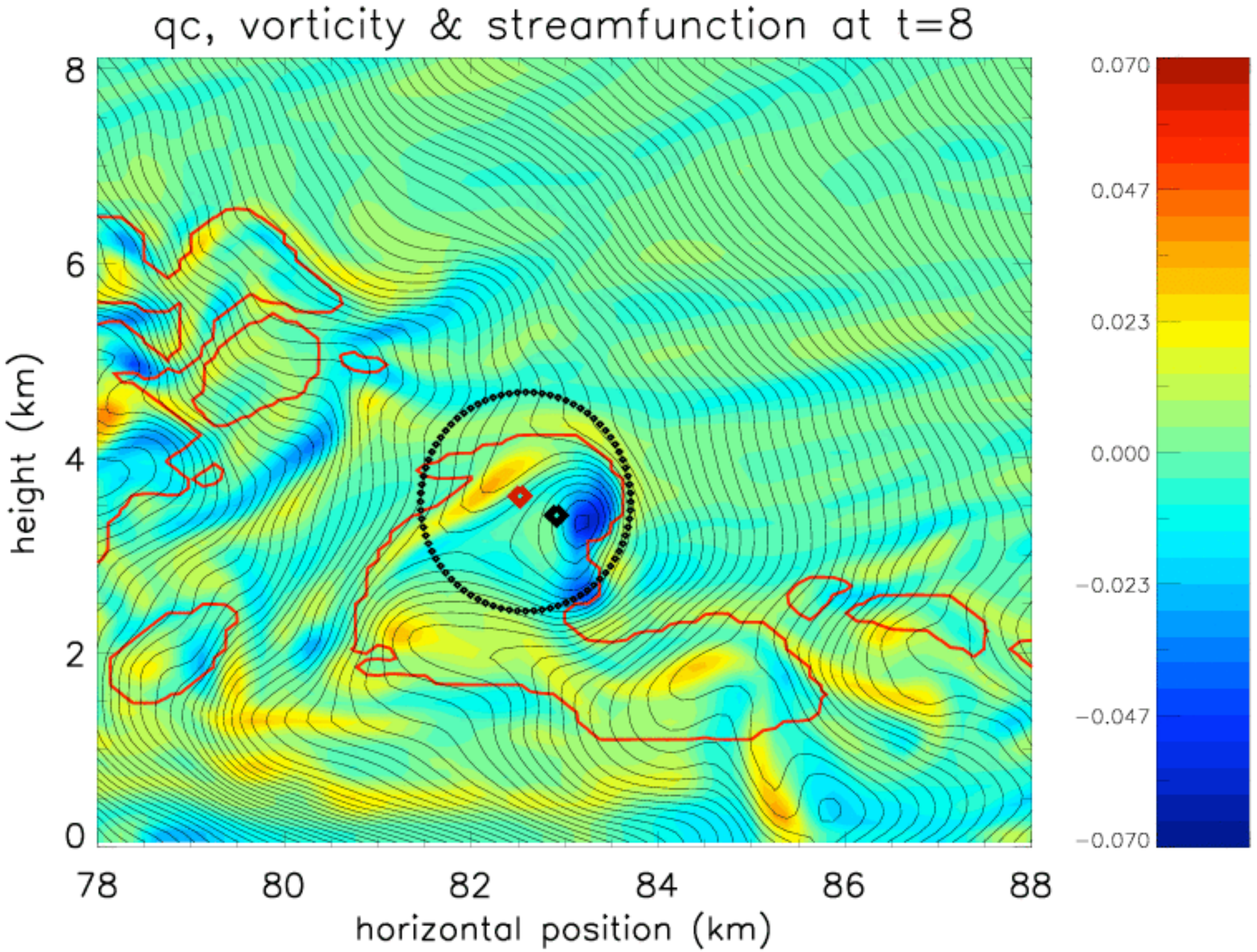
- Momentum flux *M* into thermal calculated as:

$$M = \frac{\oint \vec{u}' \cdot \hat{n} \rho \omega' dS}{\int_V \rho dV}$$

- Momentum budget of thermal is

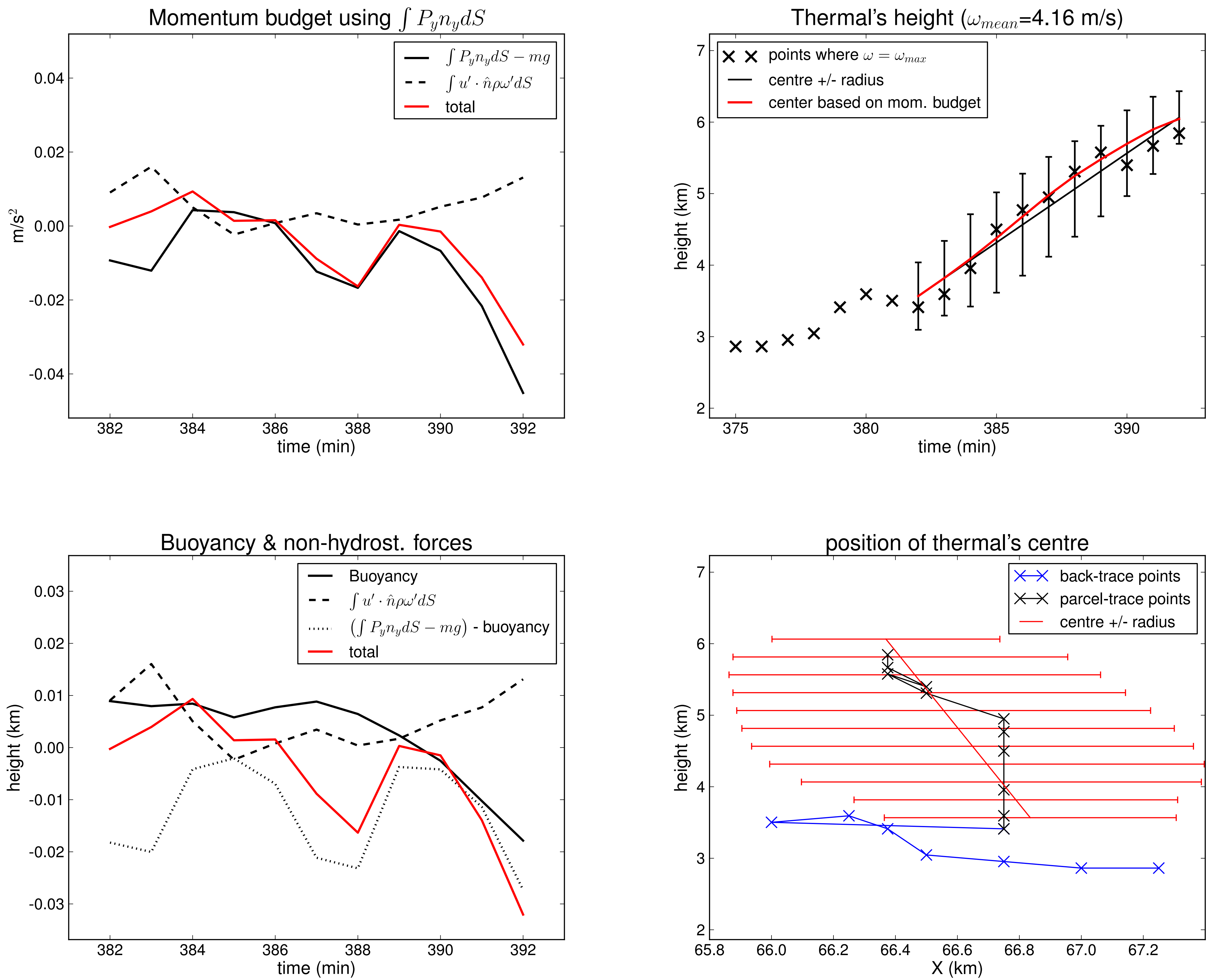
$$\rho dw/dt = \int pk \cdot n dS - mg + M$$

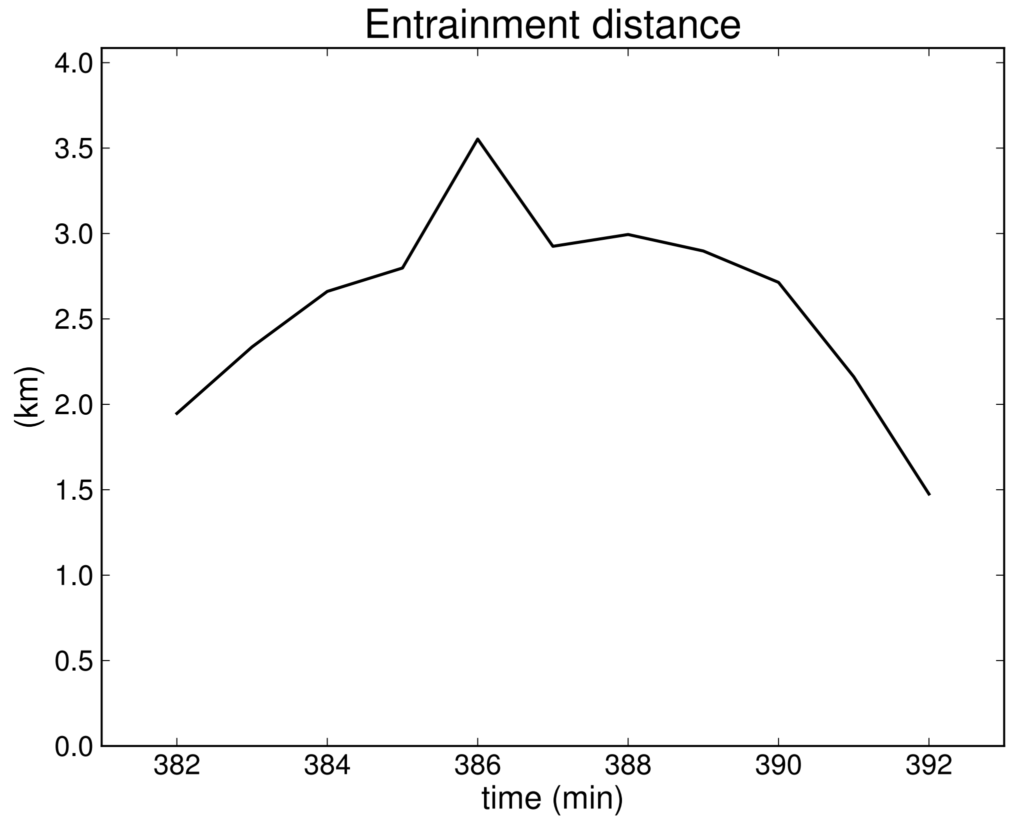
(buoyancy + wave drag + form drag + other nonhyd.)

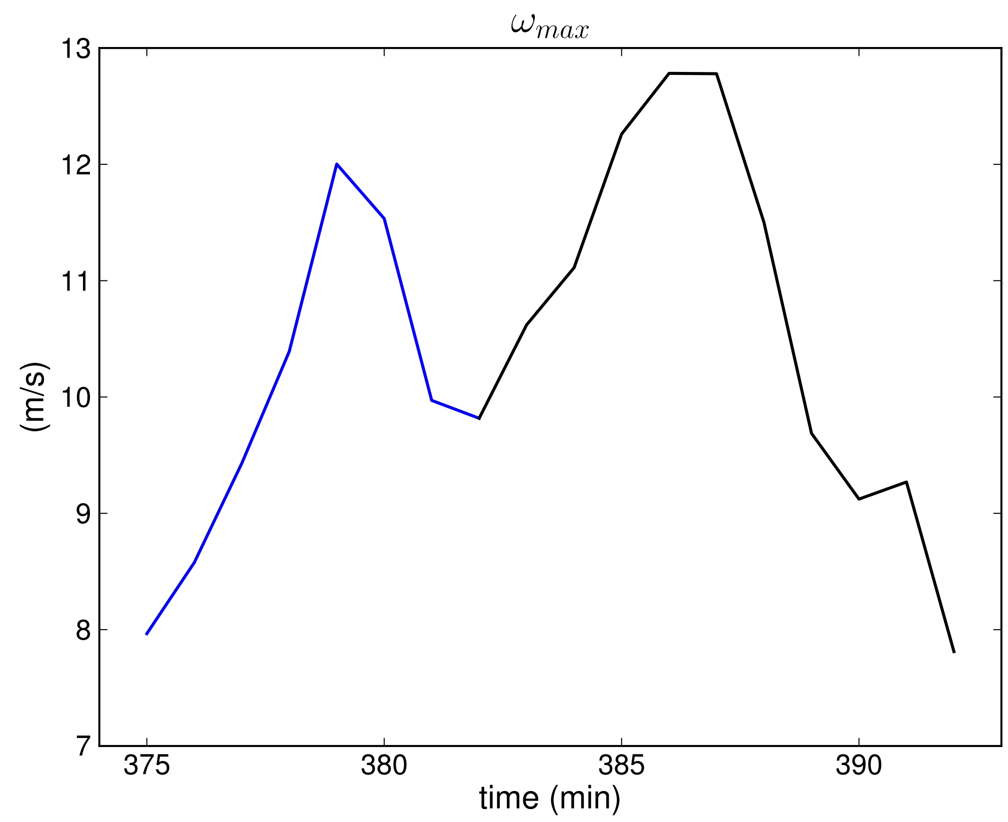


qc, vorticity & streamfunction at t=8
height (km)
horizontal position (km)
0
2
4
6
8
78
80
82
84
86
88
0.070
0.047
0.023
0.000
−0.023
−0.047
−0.070

Case 1 (t0 = 382 min)



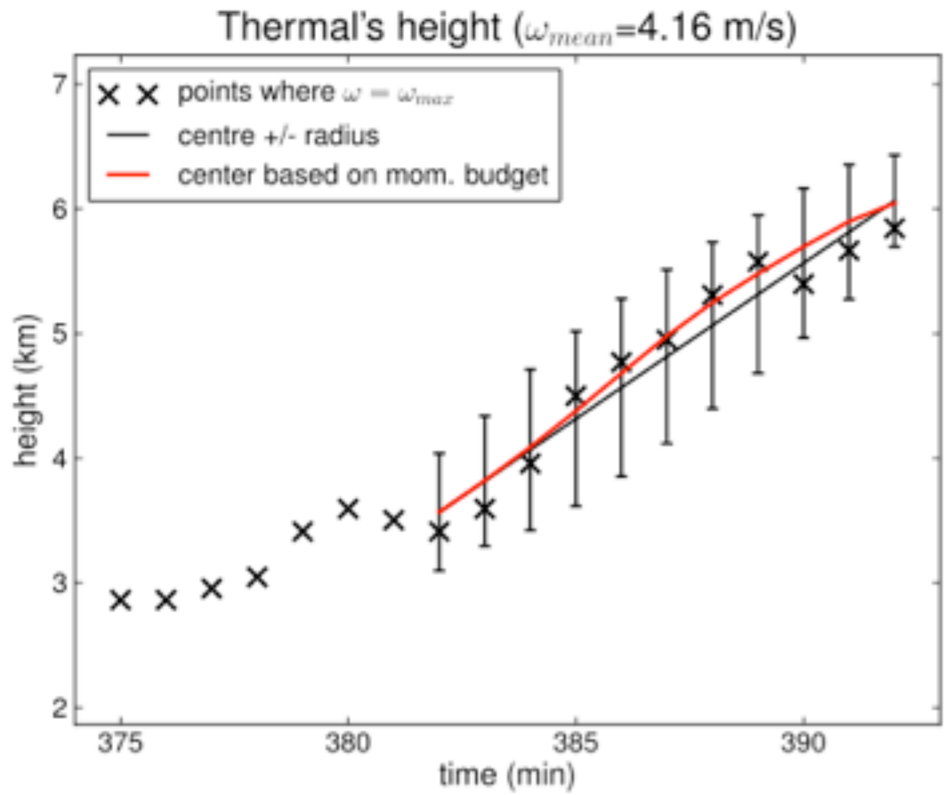




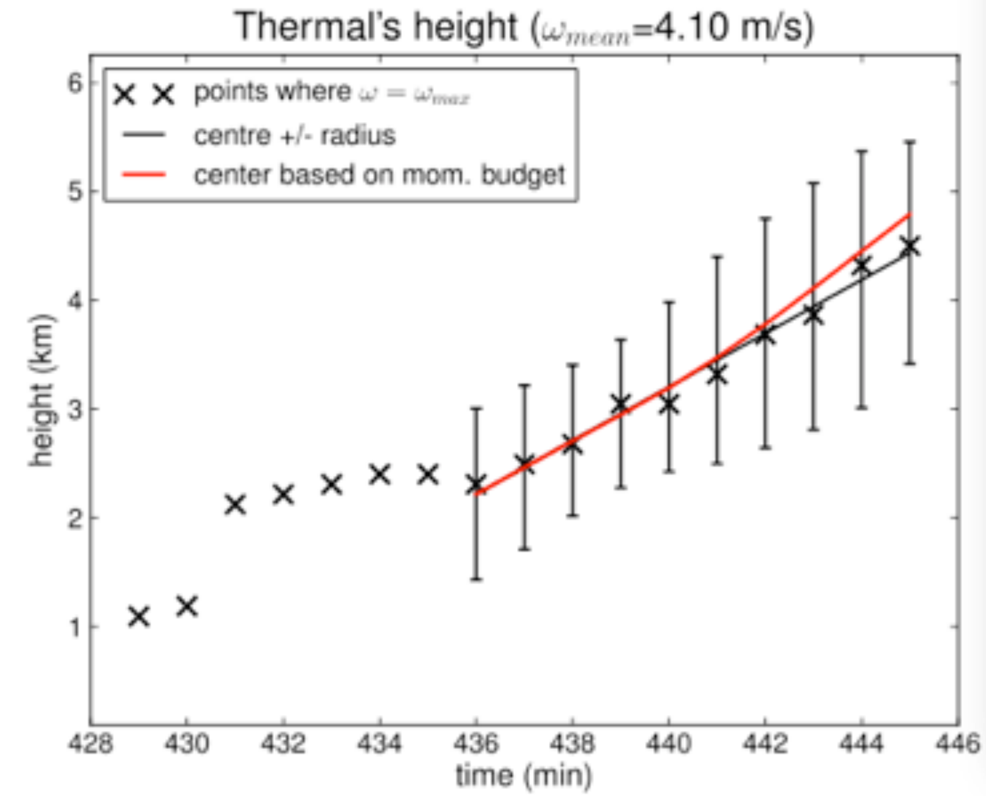
Peak w inside thermal is ~3x the rise rate of the whole thermal.

1

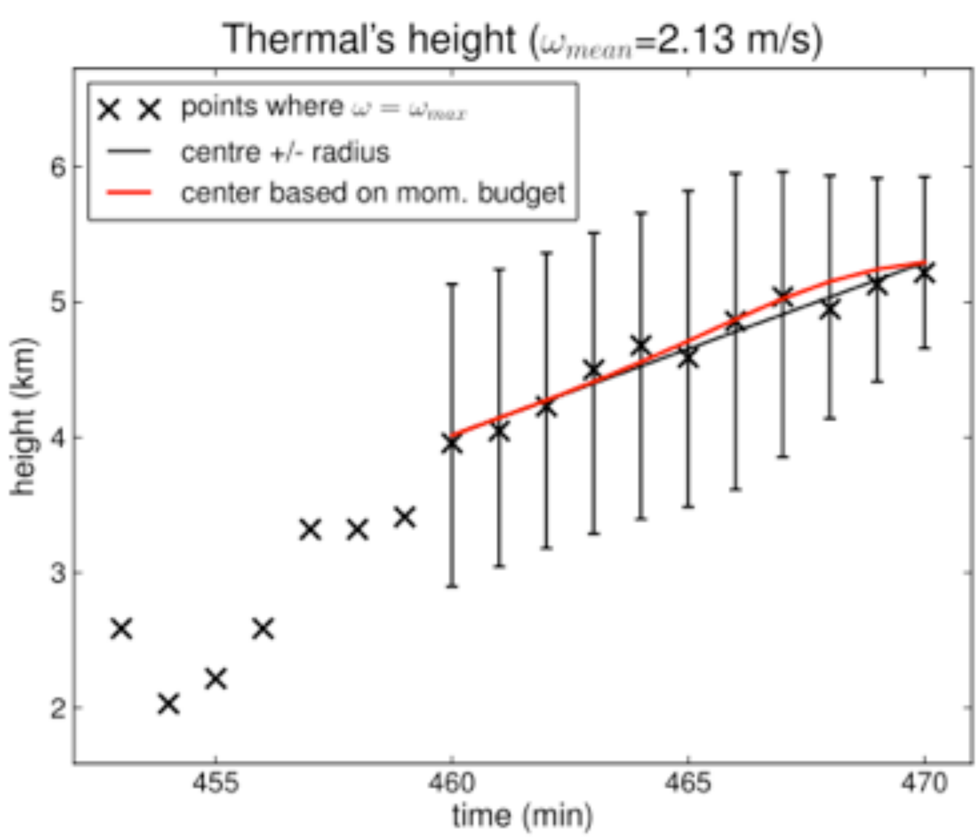
Entrainment rates ~ 0.3-0.5 km^{-1}



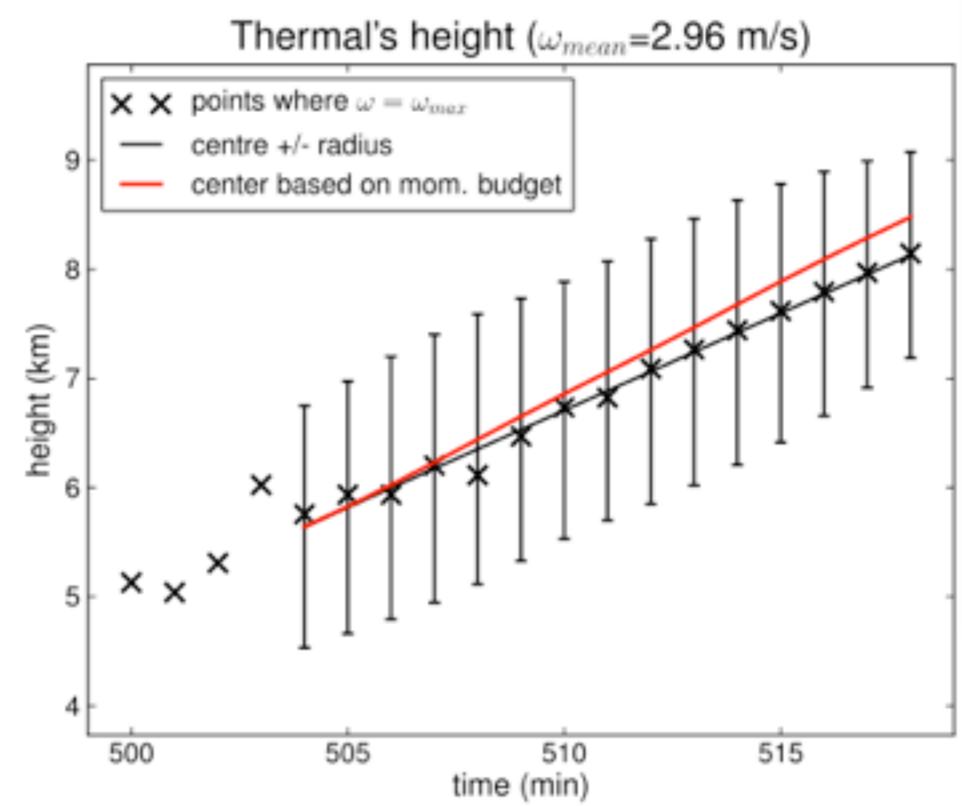
Thermal's height (ω_{mean}=4.16 m/s)
points where $\omega = \omega_{max}$
centre +/- radius
center based on mom. budget
height (km)
time (min)



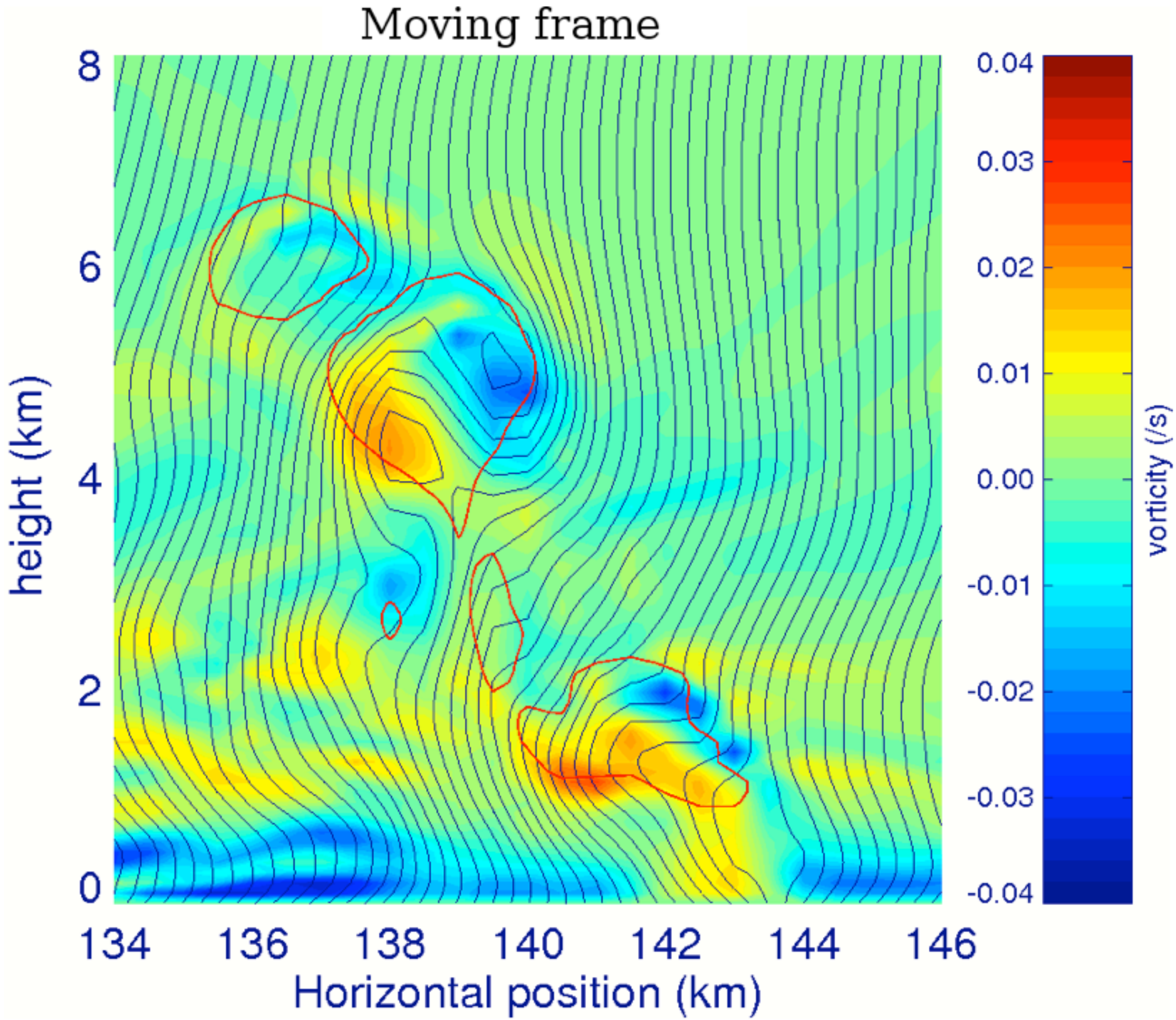
Thermal's height (ω_{mean}=4.10 m/s)
points where $\omega = \omega_{max}$
centre +/- radius
center based on mom. budget
height (km)
time (min)



Thermal's height (ω_{mean}=2.13 m/s)
points where $\omega = \omega_{max}$
centre +/- radius
center based on mom. budget
height (km)
time (min)



Thermal's height (ω_{mean}=2.96 m/s)
points where $\omega = \omega_{max}$
centre +/- radius
center based on mom. budget
height (km)
time (min)


Moving frame
8
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4
2
0
height (km)
134
136
138
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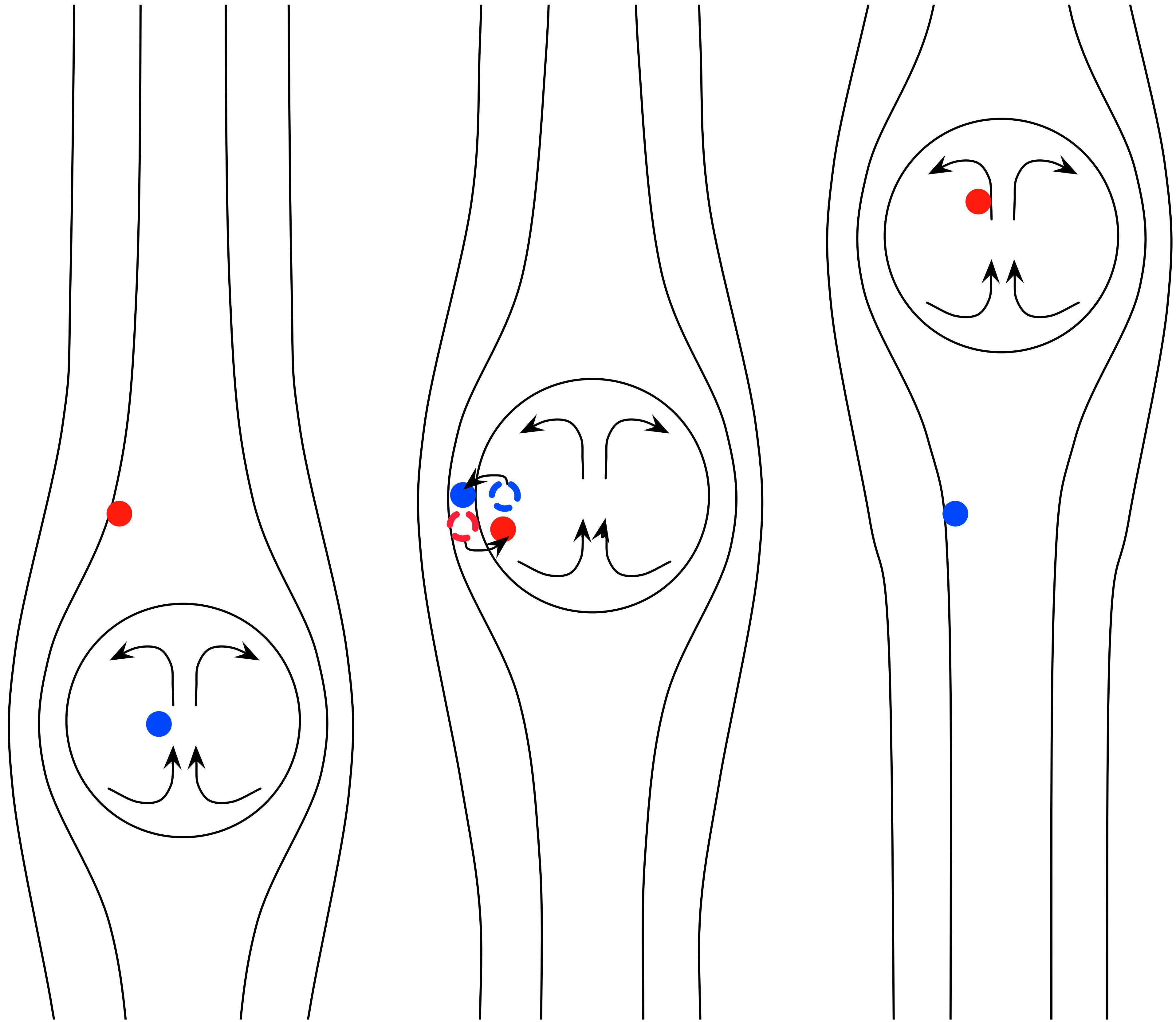
146
Horizontal position (km)
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
vorticity (/s)

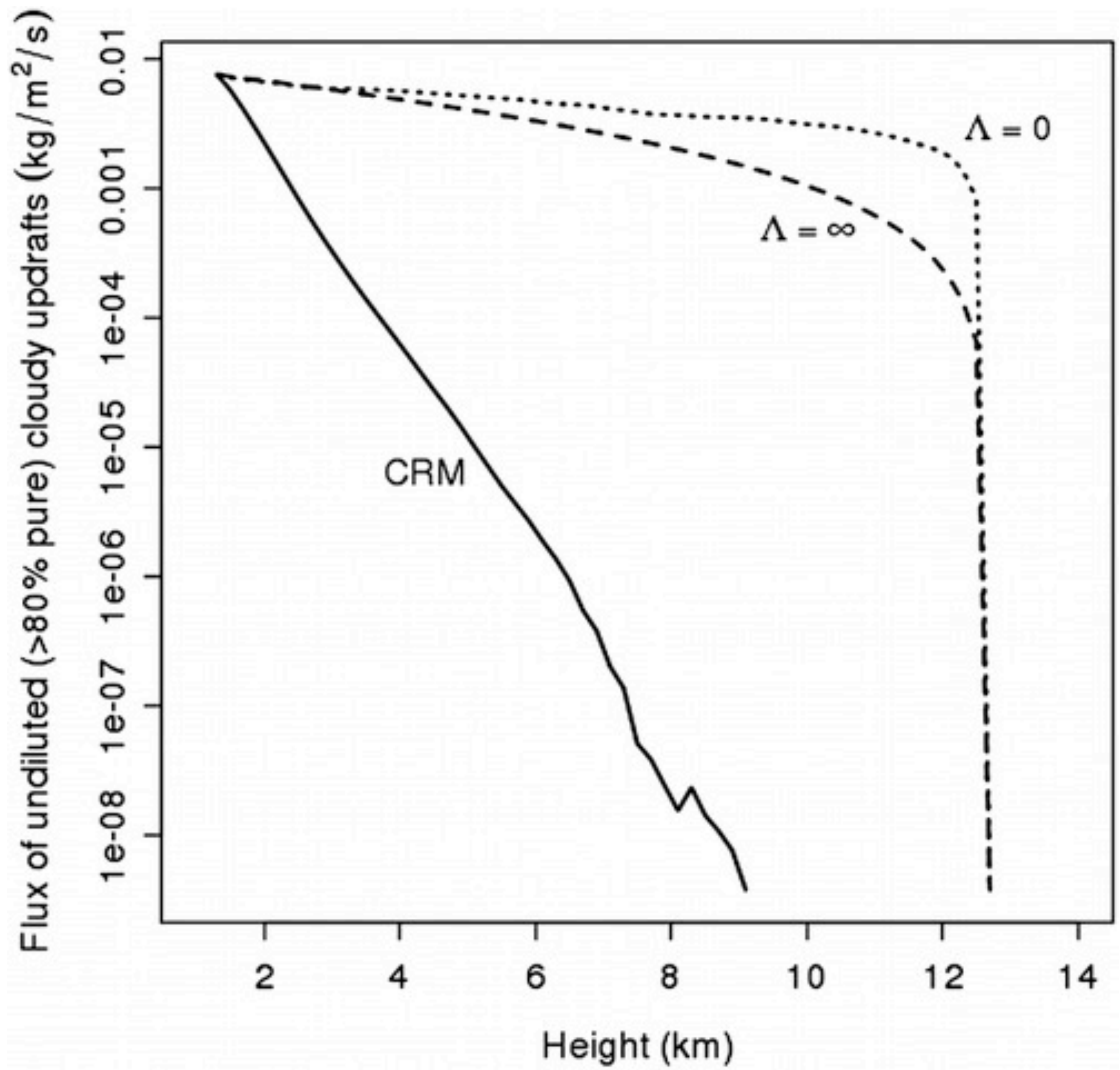
Why?

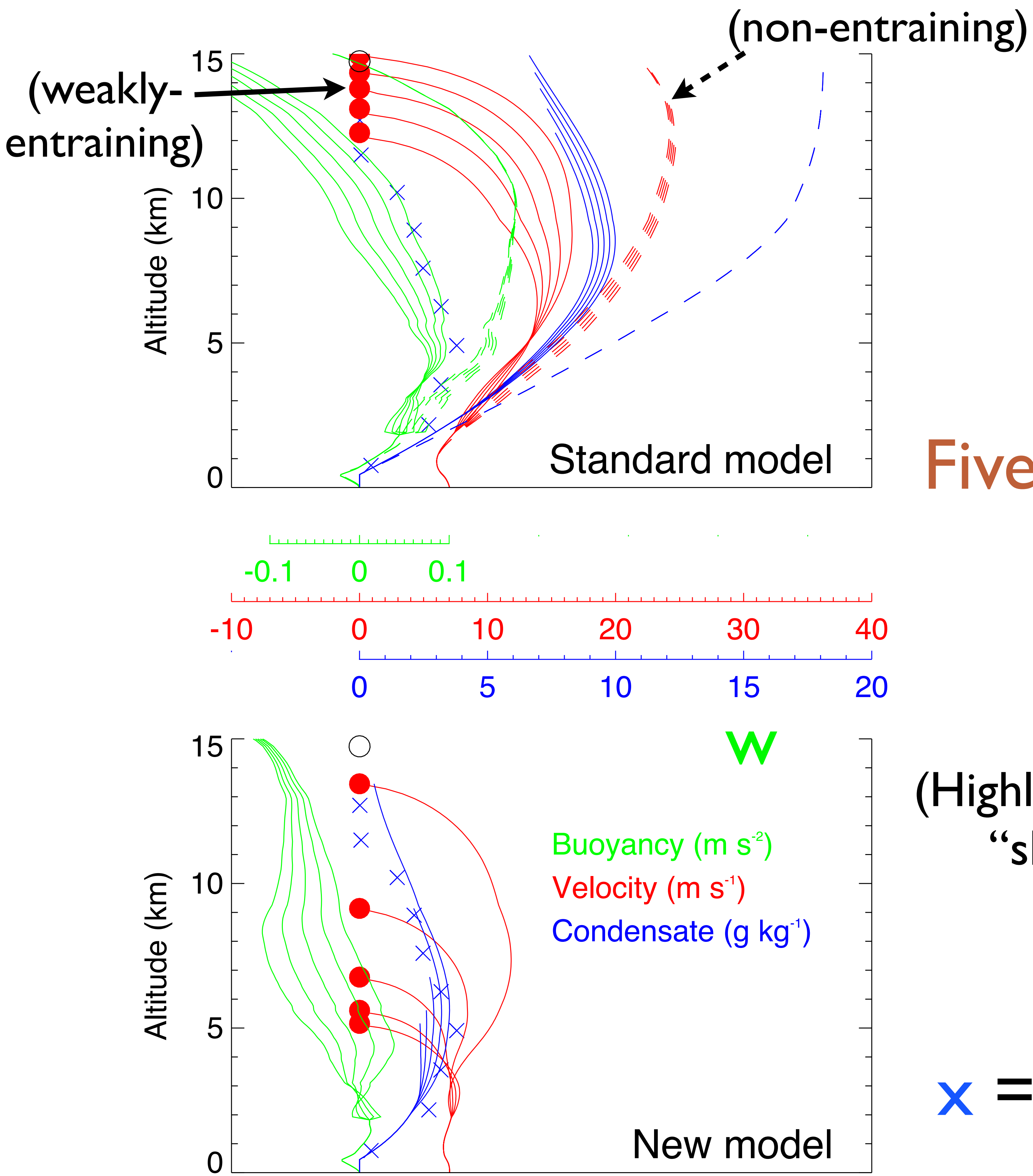
Fluid exchange at sides of thermal does not alter the momentum budget



Entrainment paradox

- CRM studies show entrainment rates ~ (2 km)$^{-1}$ (Khairoutdinov and Randall 2006, Romps and Kuang 2010)
- Highly inconsistent with cumulus parameterizations (Romps and Kuang 2010)





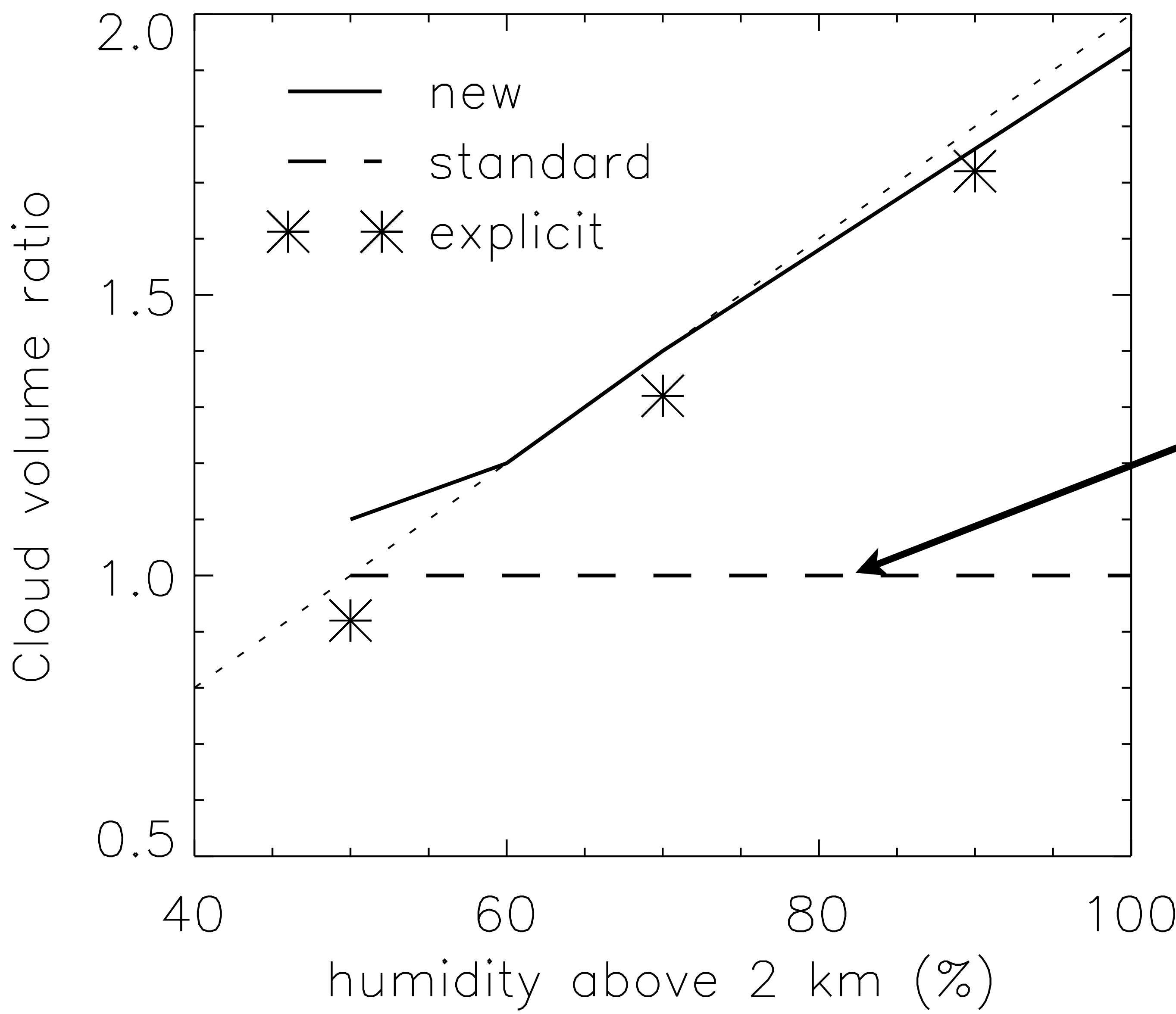
1-D parcel calculations.

Five values of RH above 2 km: 60-100%.

(Highly entraining; "slippery")

x = CRM cloud water

Predicted ratio of cloud volume to updraft volume



Traditional assumption

Conclusions

- Thermal vortex: a more consistent "parcel"
- Their motion in growing cumulus is primarily <u>inertial</u>, determined by initial kick. Friction and bouyancy relatively weak; entrainment rapid but accompanied by detrainment of zero-*w* fluid.
- This appears contradictory to common assumptions.
- Initial stages of deep cumulus may be more like shallow convection.

Slippery thermals may:

- Allow highly-entraining clouds to reach upper troposphere.
- Allow more realistic spread of cloud heights?
- Resolve problem of insensitivity to mid-level humidity (cf. *Derbyshire et al* 2004)
- Accurately predict cloud water content and trends in cloud amount
- Predict strong role for boundary layer processes, gusts, etc.--boost continental convection