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SECONDARY EYEWALL FORMATION IN TROPICAL CYCLONES

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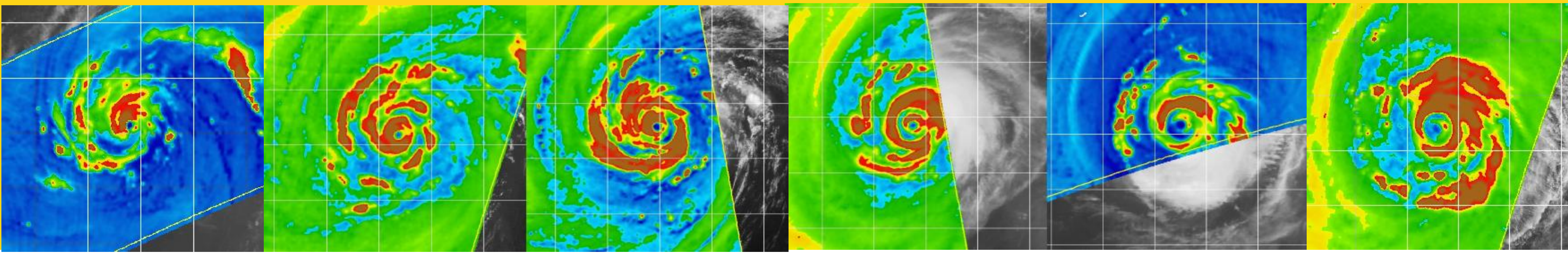

Australian Government
Department of Industry, Innovation and Science
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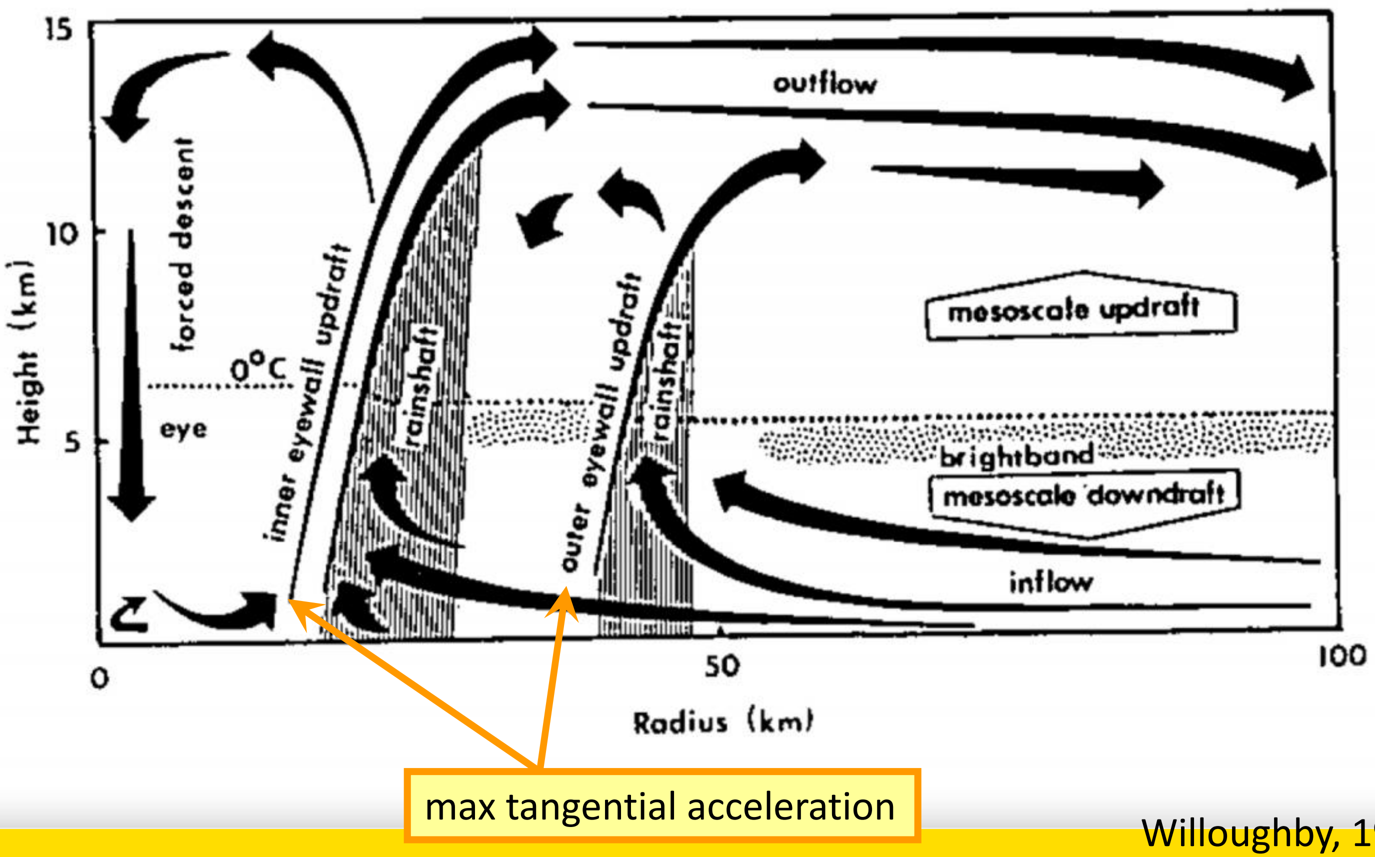
EYEWALL CONTRACTION, INTENSIFICATION AND REPLACEMENT



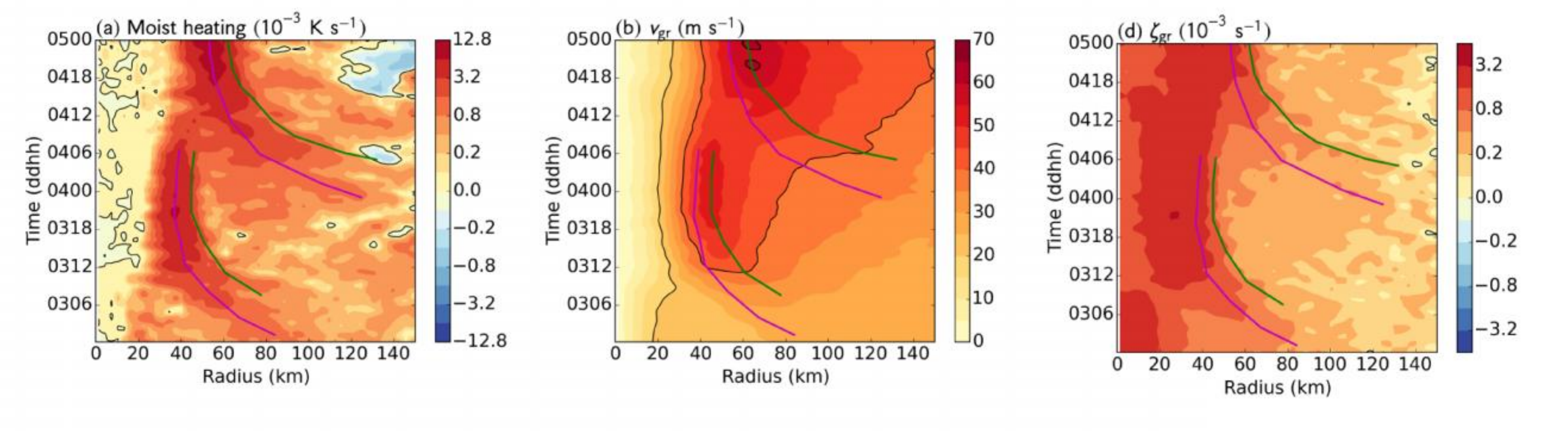
Willoughby, 1988, AMM

HOW DO SECONDARY EYEWALLS FORM?

1) Nobody really knows … not for sure, anyway
    a) i.e. there is no consensus

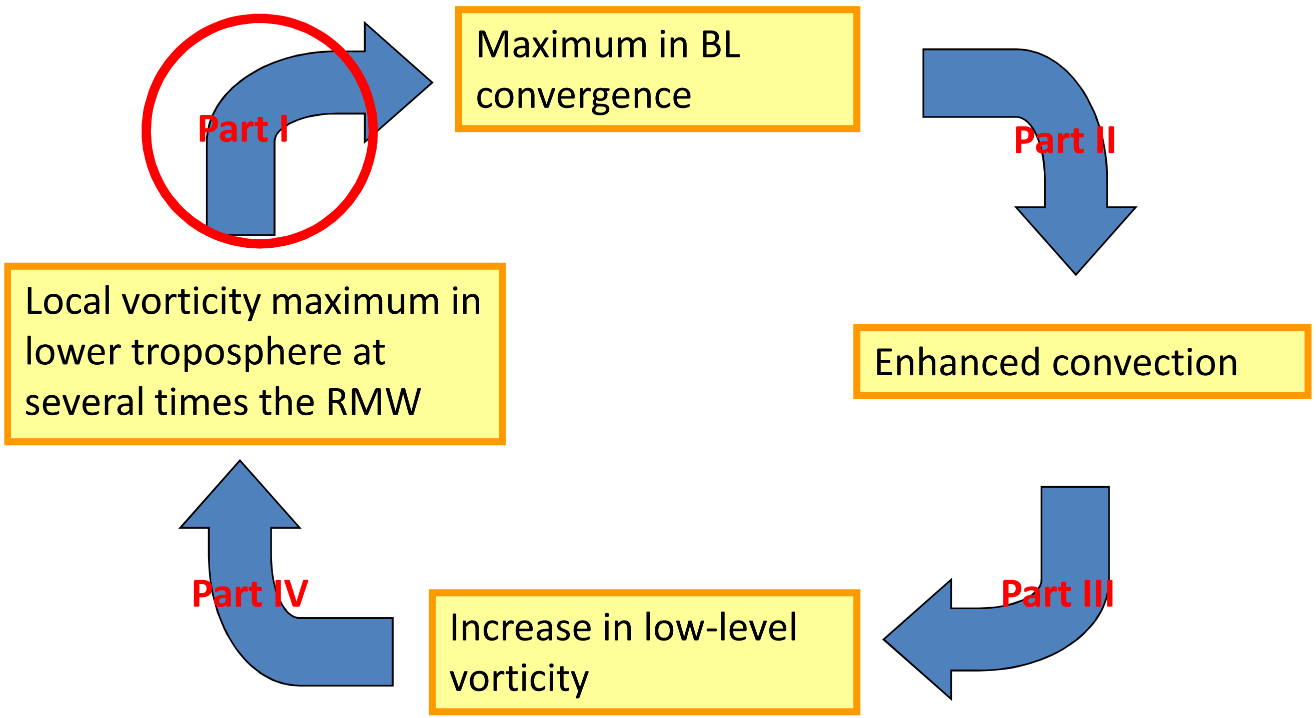
2) Numerous explanations, some have gone, others remain
    a) Vortex Rossby Waves
    b) Beta-skirt axisymmetrisation
    c) WISHE
    d) Environmental influences
    e) Boundary-layer supergradient flow
    f) and more …

THE SIMULATION



- SEF/ERC occurred in WRF simulation intended for DA research ("nature run").
- Nested in global nature run, 4 nests, 27, 9, 3 and 1 km grid.
- Magenta curve = axis of moist heating

BOUNDARY LAYER CONTRIBUTION TO EYEWALL REPLACEMENT CYCLES: A POSITIVE FEEDBACK

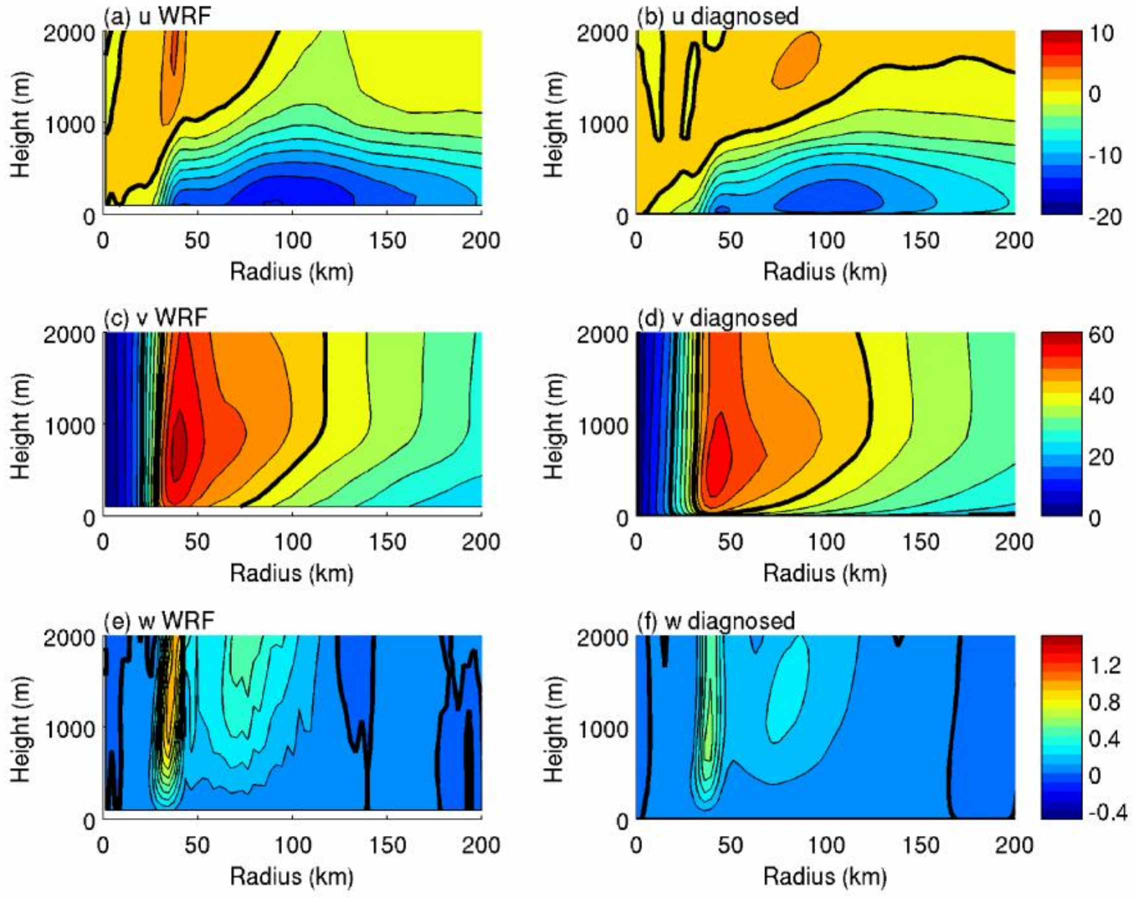


DIAGNOSTIC BOUNDARY LAYER MODEL

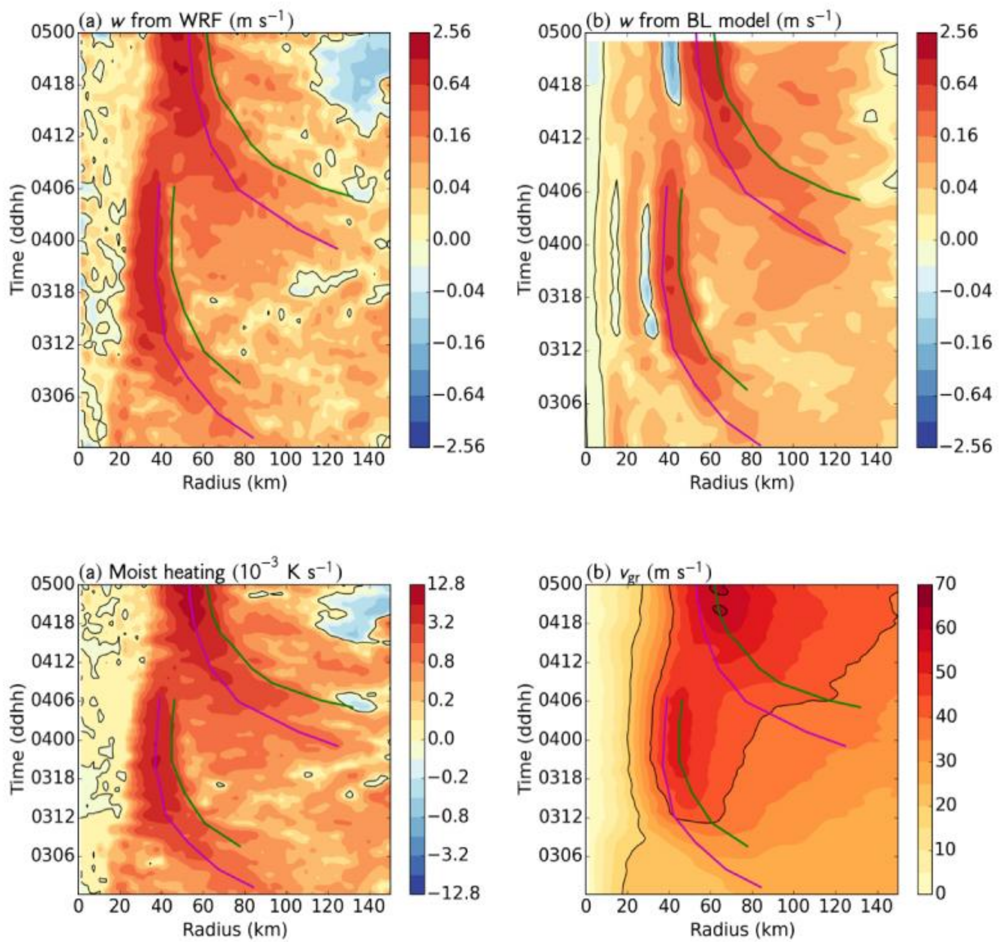
- Aim: controlled experiments on boundary-layer flow
  - Control => hold rest of the cyclone fixed
- Prescribe *p* at top of model, solve equations within.
  - Ignore feedback from BL to rest of storm
  - Diagnose one side of two-way interaction
- Prescribed *p* can be a TC-like analytical form, or taken directly from observations or a NWP model simulation

HOW WELL DOES THE DIAGNOSTIC MODEL REPRODUCE THE SIMULATION?

1) Low-pass filtered, azimuthal-mean WRF (left)
2) Extract p at 2.2 km height (top of BL model)
3) Insert p in BL model and calculate equilibrium wind field (right)
4) Structure very similar
5) Diagnosed fields tend to underestimate strength of secondary circulation
   a) No buoyancy!



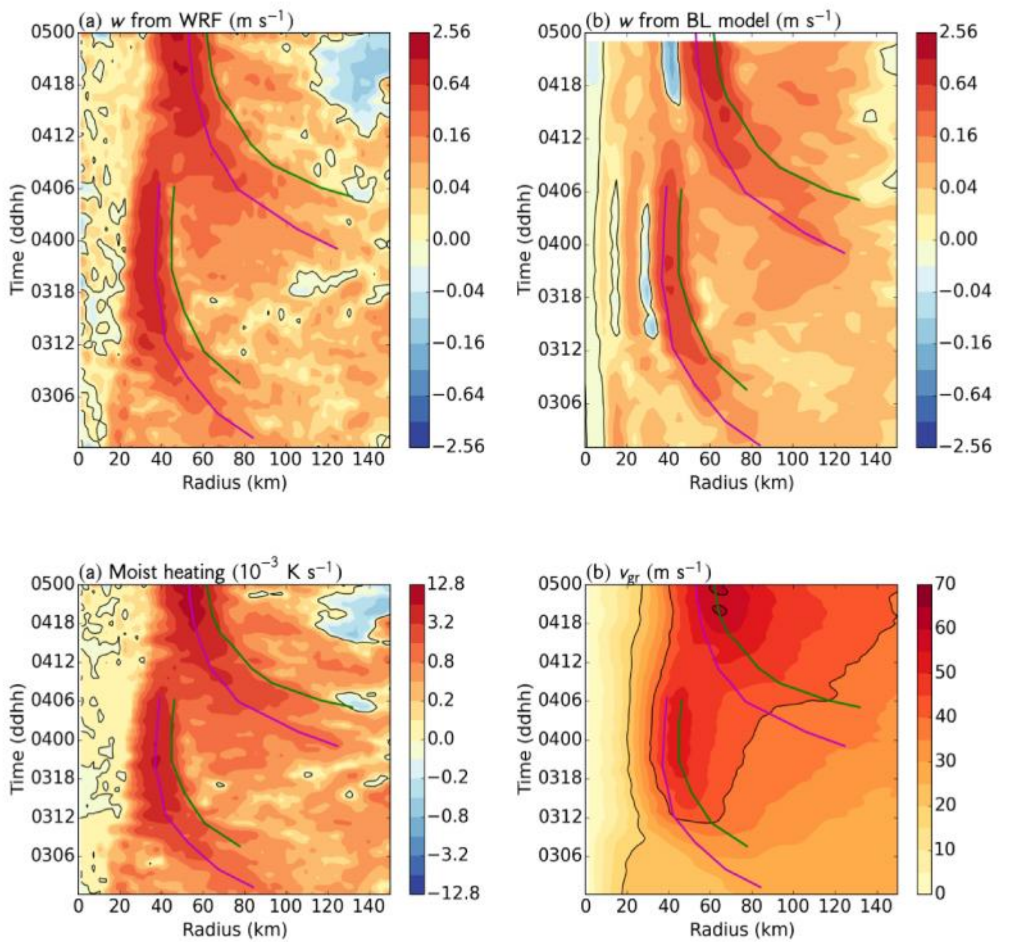
DIAGNOSED VERTICAL VELOCITY



- WRF updraft is partly explained by frictional convergence (about half)
- Also appears to be partly heating
- Why did the BL model generate convergence there?

- Must be something to do with the gradient wind (pressure) field, but what?

FRICTIONAL CONVERGENCE IN TROPICAL CYCLONES



- TCBL theory (Kepert 2013 JAS) connects frictional convergence to vorticity structure
- Outer vorticity “bumps” in the gradient wind are very efficient in producing a frictional updraft
- Updraft approx. proportional to

$$\frac{-}{(\ +\ )}\ \_\_$$

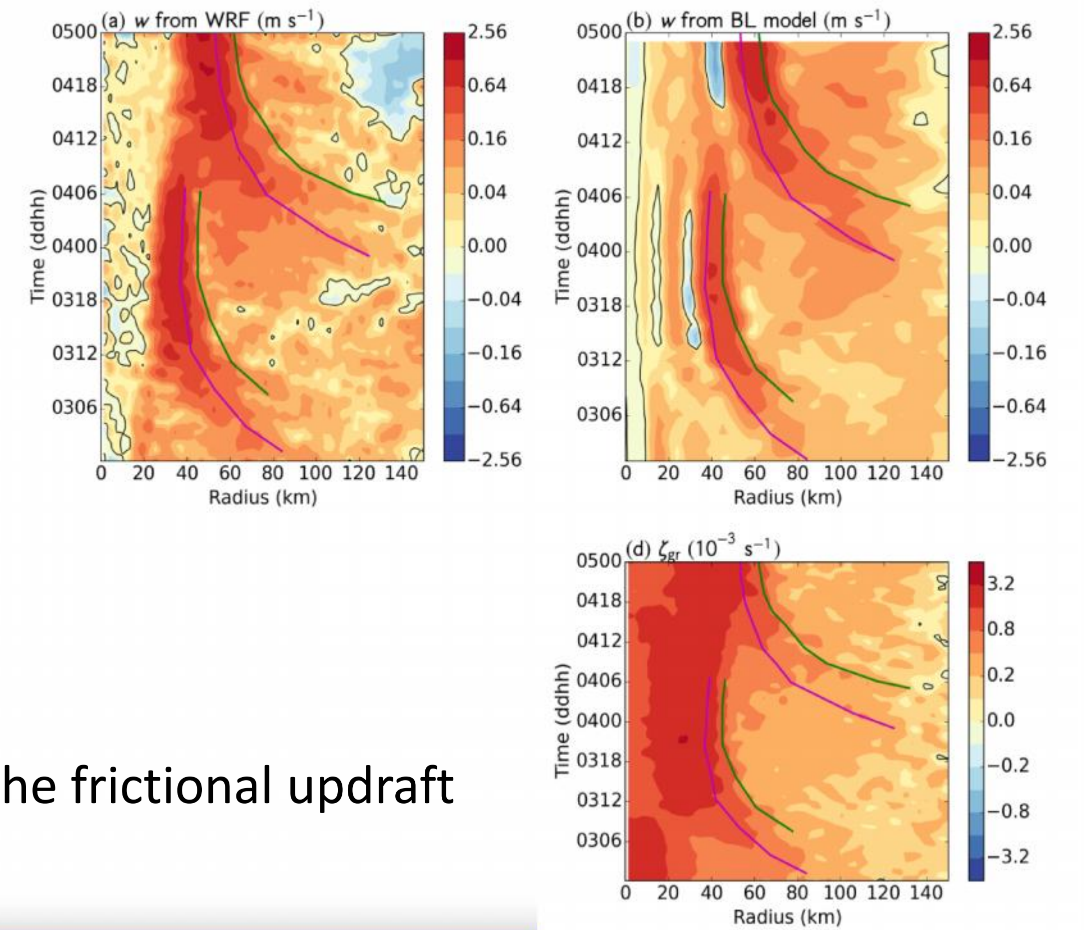
DIAGNOSED VERTICAL VELOCITY

Magenta: axis of heating

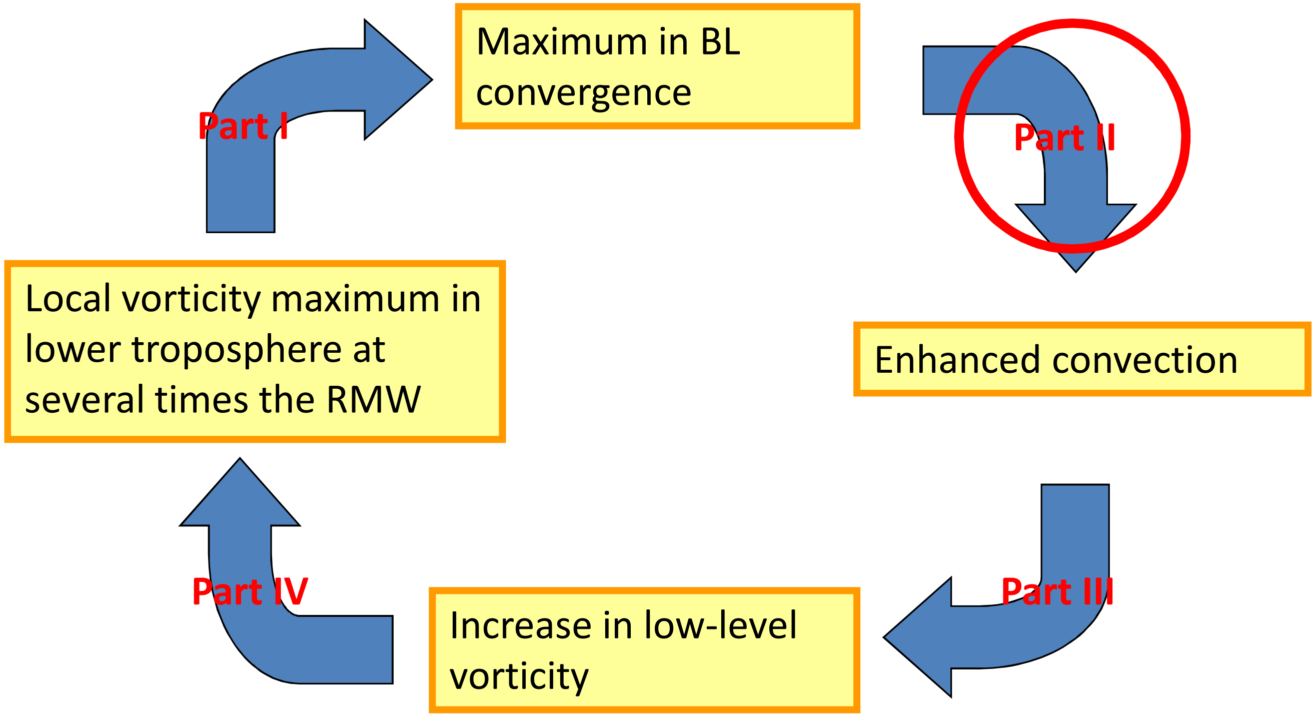
Green: radius of maximum negative vorticity gradient

Vorticity and the heating evolve together, consistent with BL updraft theory (but still need to explain radial displacement)

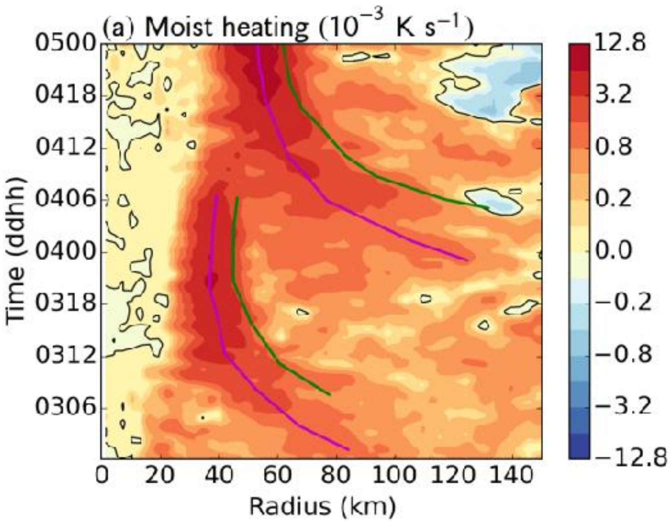
Gradient vorticity structure explains the frictional updraft

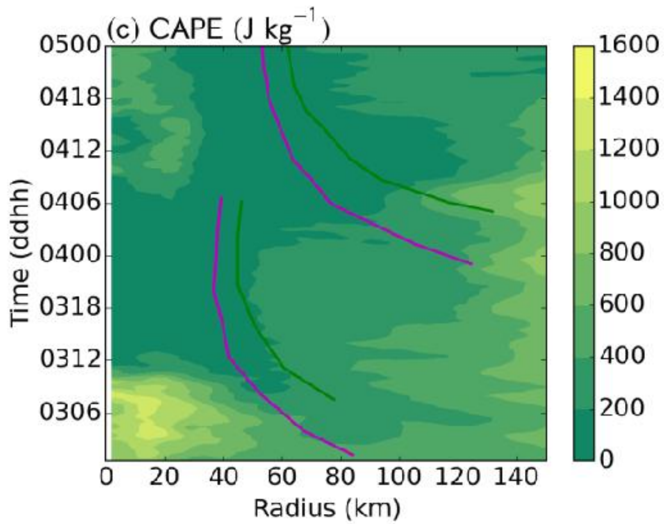


BOUNDARY LAYER CONTRIBUTION TO EYEWALL REPLACEMENT CYCLES: A POSITIVE FEEDBACK



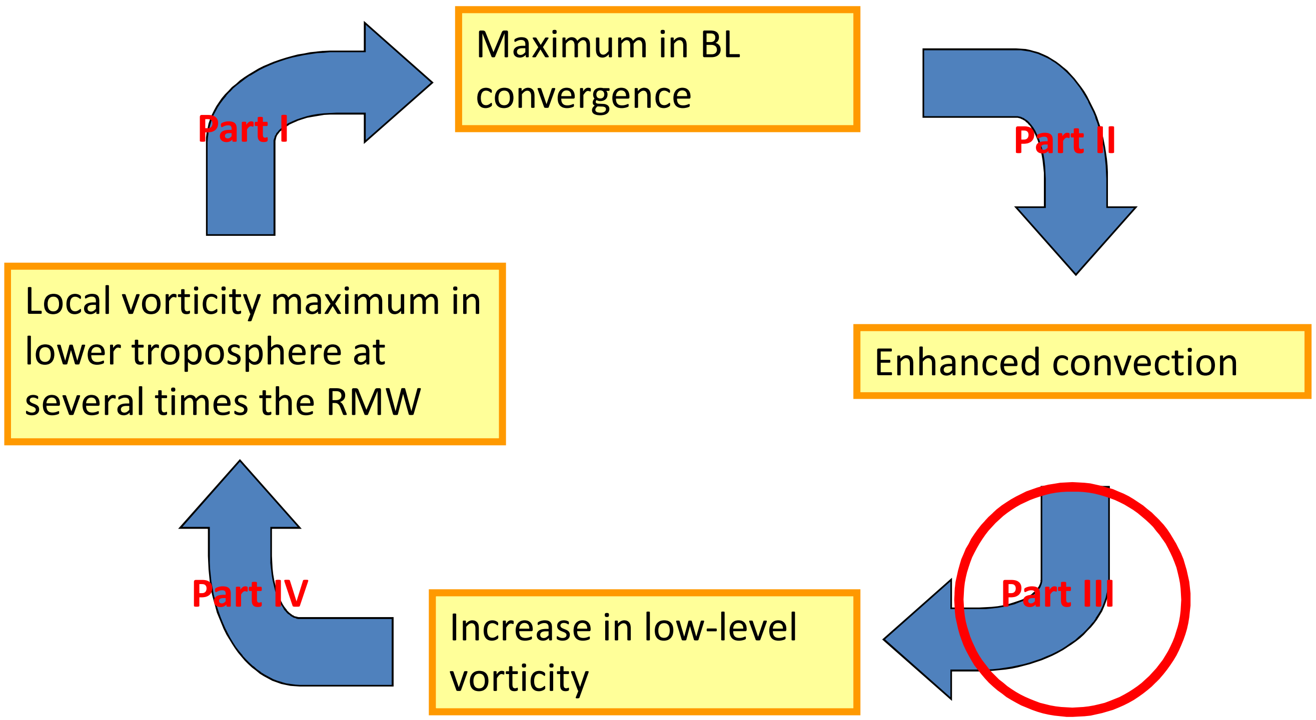
WHAT CAUSES THE OUTER CONVECTION CHANGES?





Convection =
- ✗ instability +
- ✗ moisture +
- ✓ lifting

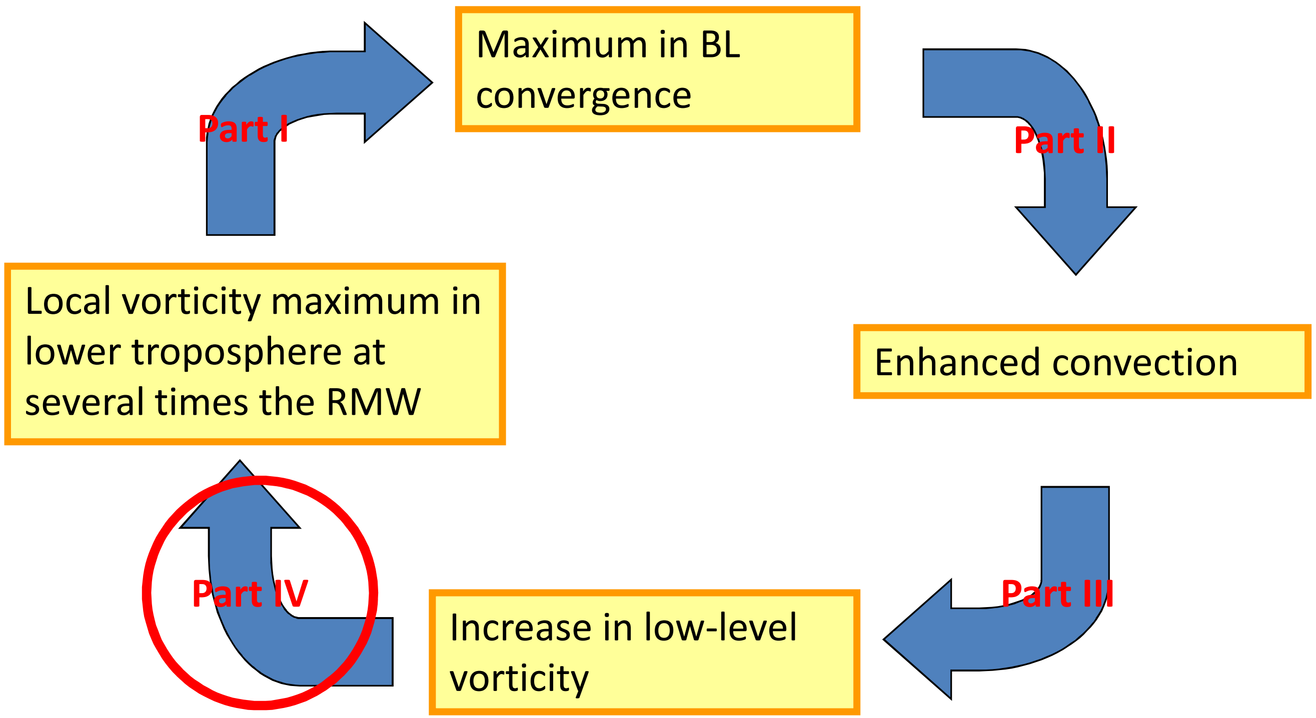
BOUNDARY LAYER CONTRIBUTION TO EYEWALL REPLACEMENT CYCLES: A POSITIVE FEEDBACK



HOW DOES CONVECTION AFFECT VORTICITY?

- Convection changes vorticity mainly via
  - stretching of ambient absolute vorticity (amplifies, doesn't change sign)
  - tilting of horizontal vorticity, especially shear vorticity in the boundary layer (generates vorticity of both signs)
- Stretching becomes more effective as ambient vorticity increases

BOUNDARY LAYER CONTRIBUTION TO EYEWALL REPLACEMENT CYCLES: A POSITIVE FEEDBACK

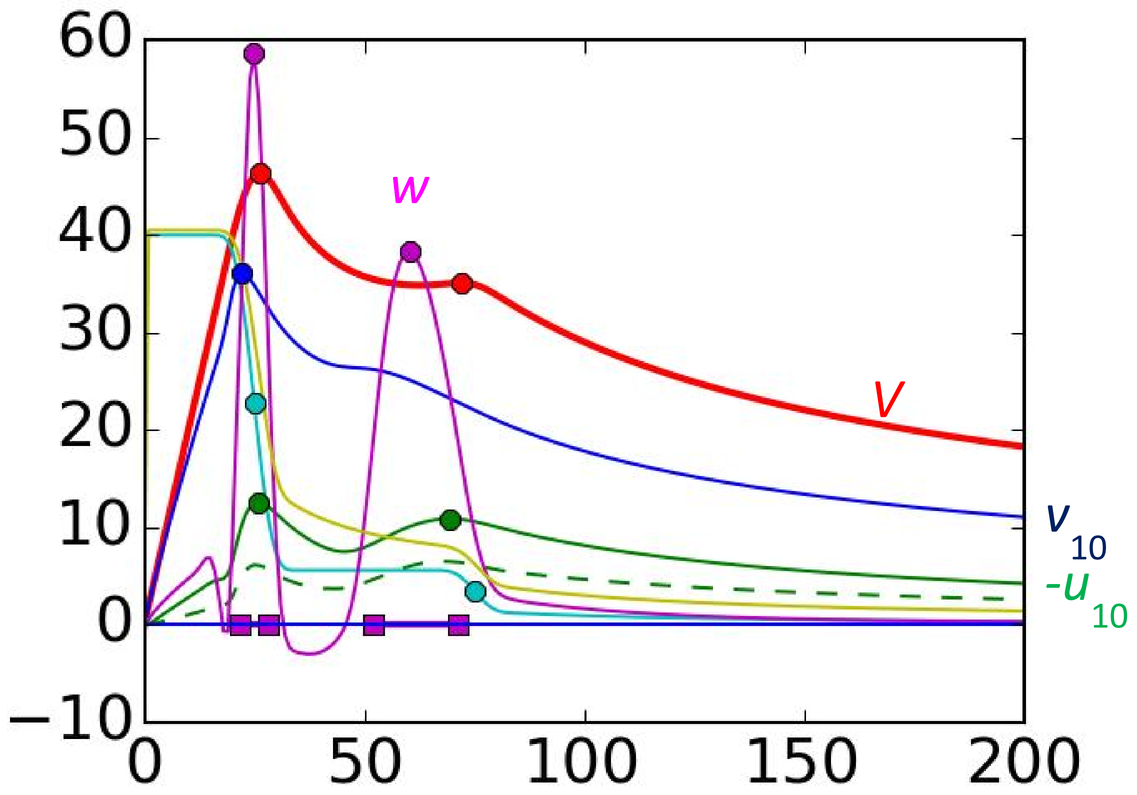


ARE THE VORTICITY CHANGES DUE TO CONVECTION IN THE RIGHT SPOT?

- Vorticity "bump" (or the increased vorticity gradient on the outer side of the bump) is related to the frictional updraft via Kepert (2001) w equation.
- Convection adds to the frictional updraft
- Vortex stretching in the convection increases the vorticity

- If the convective vorticity tendency is to reinforce the existing vorticity bump, it needs to happen in the right spot.
- Linearized w equation puts it in the **wrong** spot
- Need to more closely understand where the frictional updraft forms

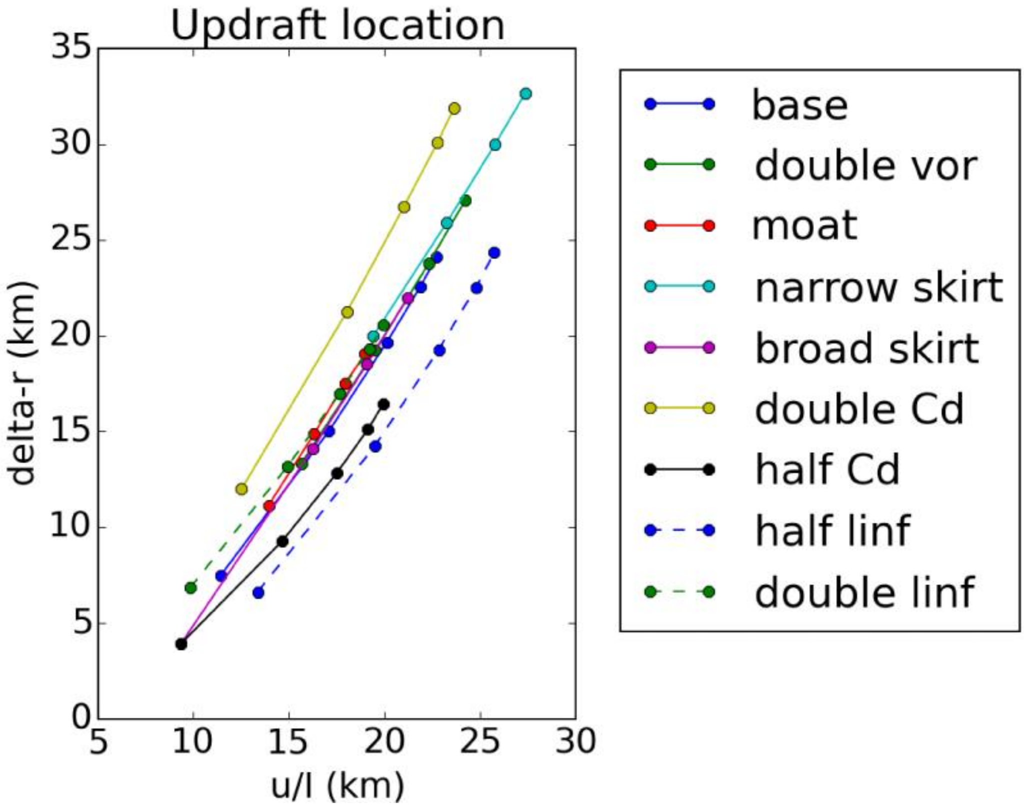
UPDRAFT LOCATION WITH SECONDARY EYEWALLS



Distance between updraft and wind max is greater for outer eyewall than inner

What determines this distance?

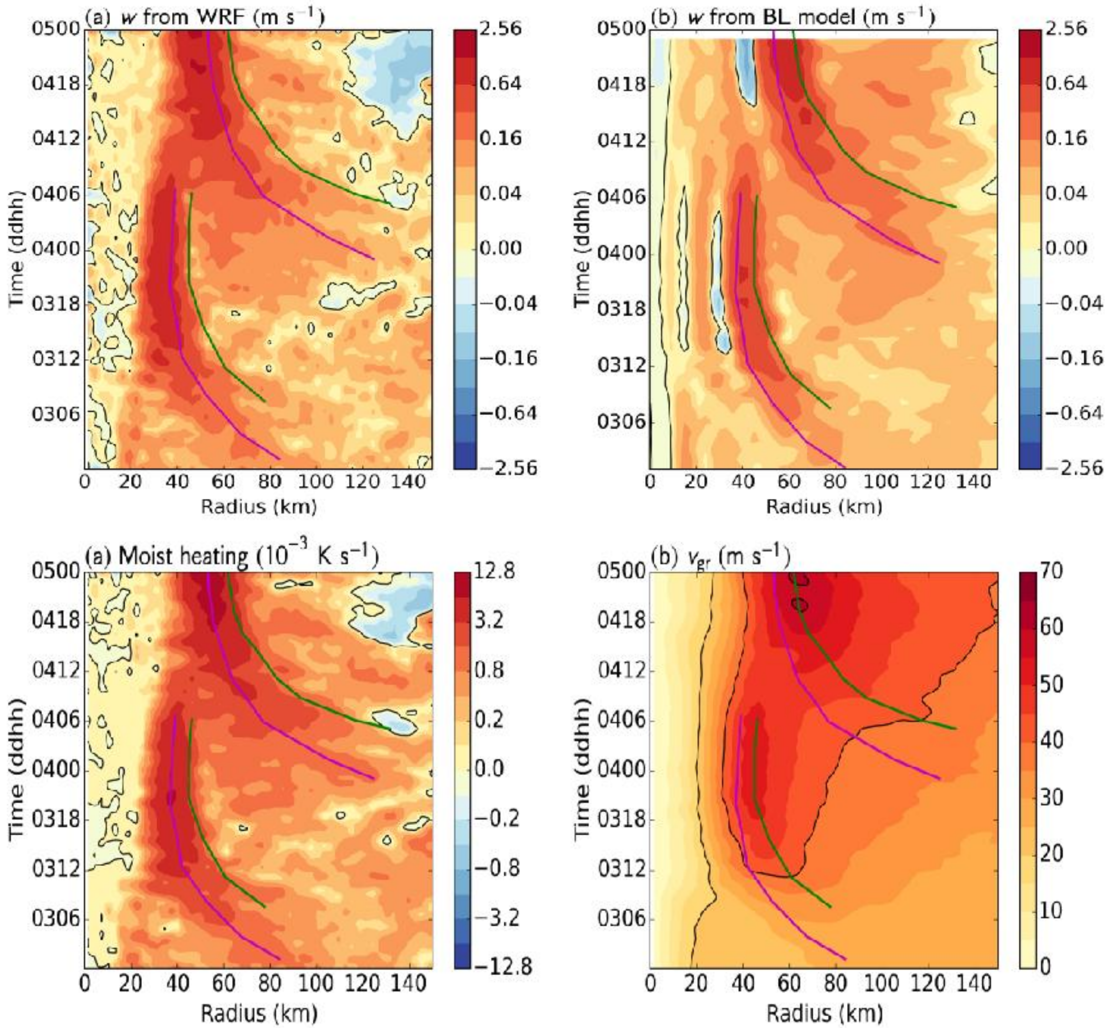
EYEWALL UPDRAFT LOCATION, SECONDARY EYEWALL



Increasing secondary RMW →

- Inwards displacement of secondary eyewall updraft at 1-km height (relative to ∂ζ/∂r extremum)
- Various secondary RMWs (50 – 150 km)
- Various strengths
- Vary outer structure
- Vary C_d and *K*

DIAGNOSED VERTICAL VELOCITY



- Nonlinear "overshoot" of inflow appears to be responsible for getting BL convergence in correct position relative to existing vorticity bump.

BOUNDARY LAYER CONTRIBUTION TO EYEWALL REPLACEMENT CYCLES: A POSITIVE FEEDBACK