2014-08

Tropical cyclones in vertical shear: dynamic, kinematic, and the thermodynamic aspects of intensity modification

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Tropical cyclones in vertical shear: dynamic, kinematic, and thermodynamic aspects of intensity modification

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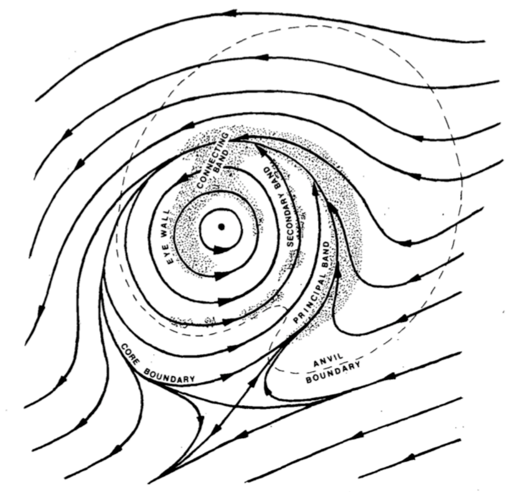
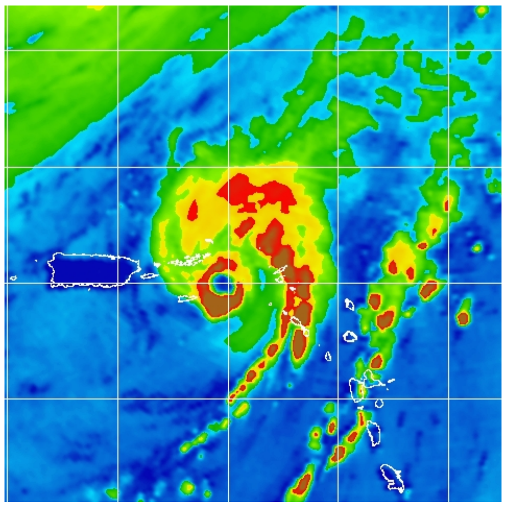
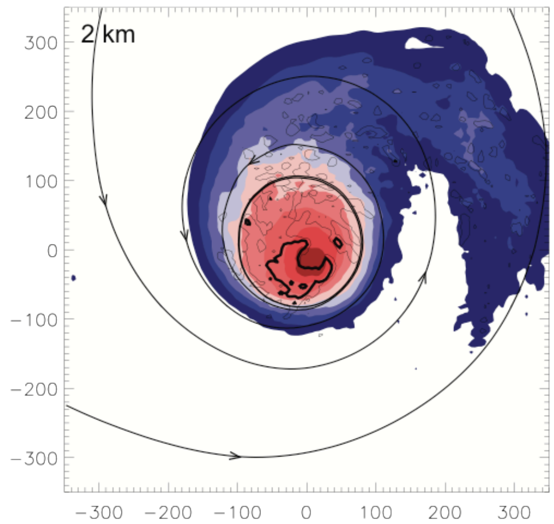






Vertical shear is a main contributor to intensity change

predictors for SHIPS
(statistical TC intensity forecast model)

Variable	Forecast interval (h) 12	24	36	48	60	72
POT	+0.62	+0.69	+0.73	+0.79	+0.84	+0.96
SHR	−0.35	−0.43	−0.43	−0.43	−0.44	−0.42
DVMX	+0.40	+0.30	+0.23	+0.18	+0.13	+0.08

TABLE 1. Predictors used in the DK94 (first 11) and later versions of SHIPS.

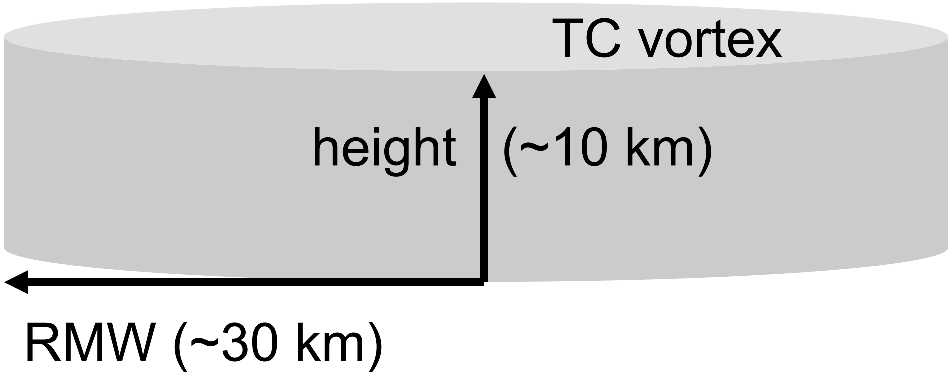
1) POT	Maximum possible intensity-initial intensity
2) SHR	Magnitude of 850–200-mb vertical shear
3) DVMX	Intensity change during previous 12 h

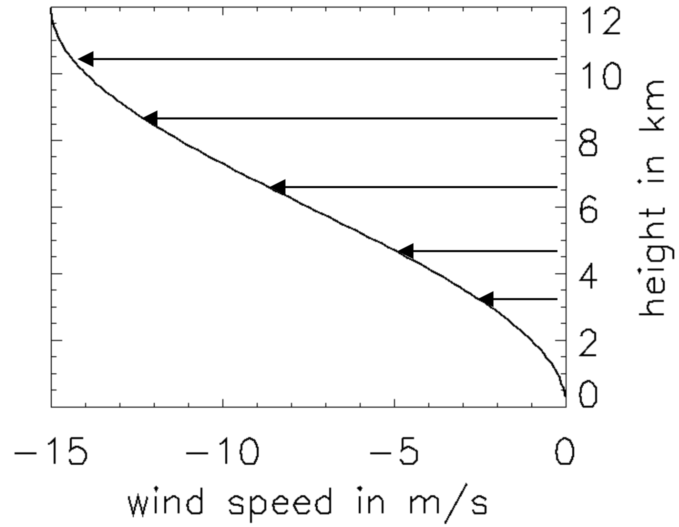
Understanding of governing processes is still incomplete.

Our goal: Improve understanding by analyzing idealized numerical experiments.

Numerical experiment: spin up TC and hit it with shear

as pioneered by e.g. Bender 1997, and Frank & Ritchie 1999, 2001





experiment	u_{max}
no shear	0 m/s
5mps	5 m/s
10mps	10 m/s
15mps	15 m/s
20mps	20 m/s

≈ 850 - 200 hPa "shear"

shear profile

$u(z) = 0.5\, u_{max}\, (\cos(\pi\, z/\, 12) - 1)$,
z = height in km

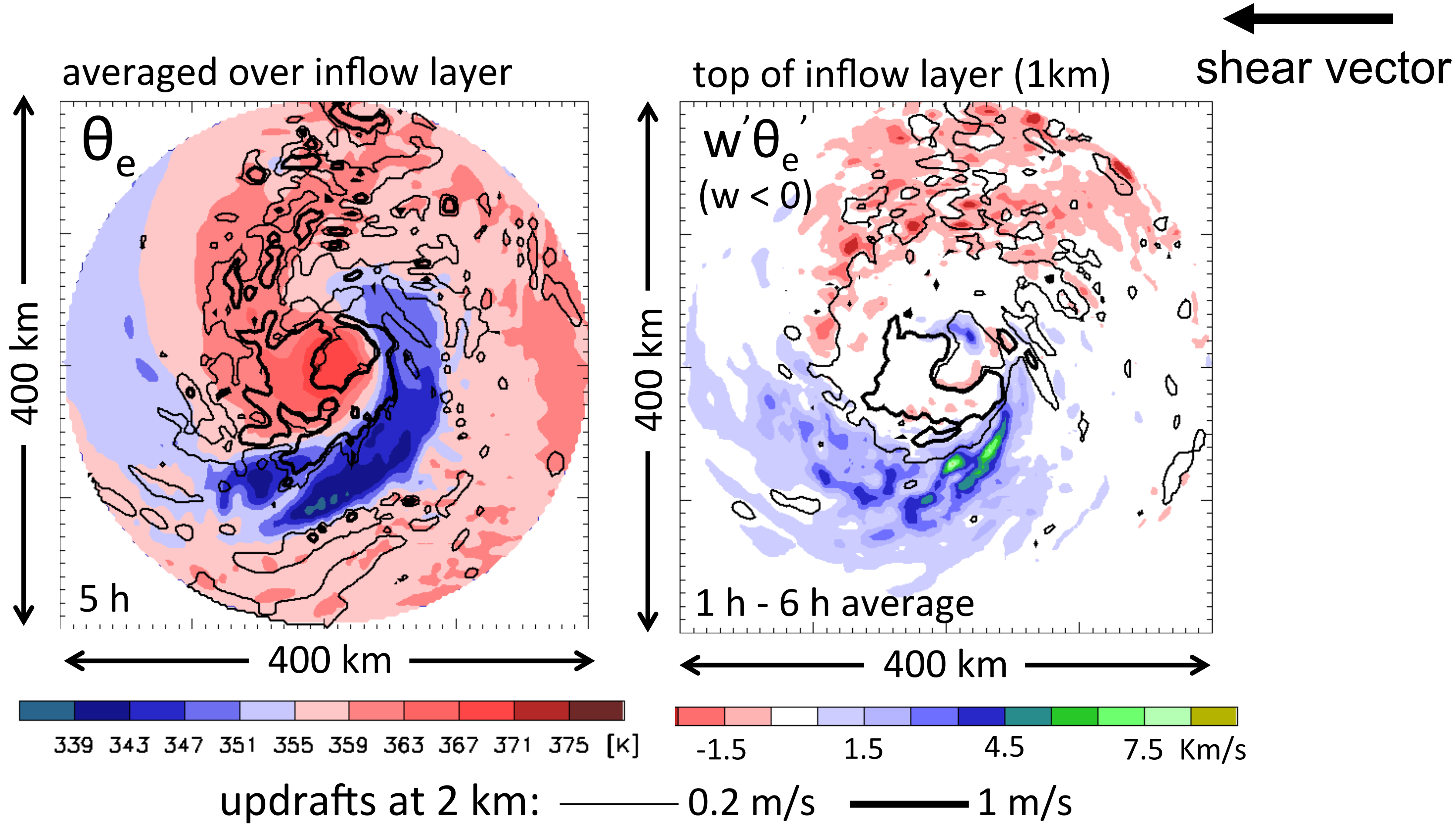
- in thermal wind balance
- virtually steady in a no-vortex experiment

Numerical model: the virtue of simplicity

- RAMS (non-hydrostatic)
- surface fluxes:
  - bulk aerodynamic formula, $C_k/C_D = 1$
  - Deacon's formula for drag coefficients
- parameterizations:
  - warm rain microphysics
  - no cumulus convection scheme
  - no radiative processes
  - turbulence (based on Smagorinsky)
- SST = 28.5°C, f-plane
- double, two-way nested domain, 5 km
- intense and resilient TCs

Focus on structural changes (meso-β scale)
and conceptual understanding

An unsung pathway to shear-induced weakening



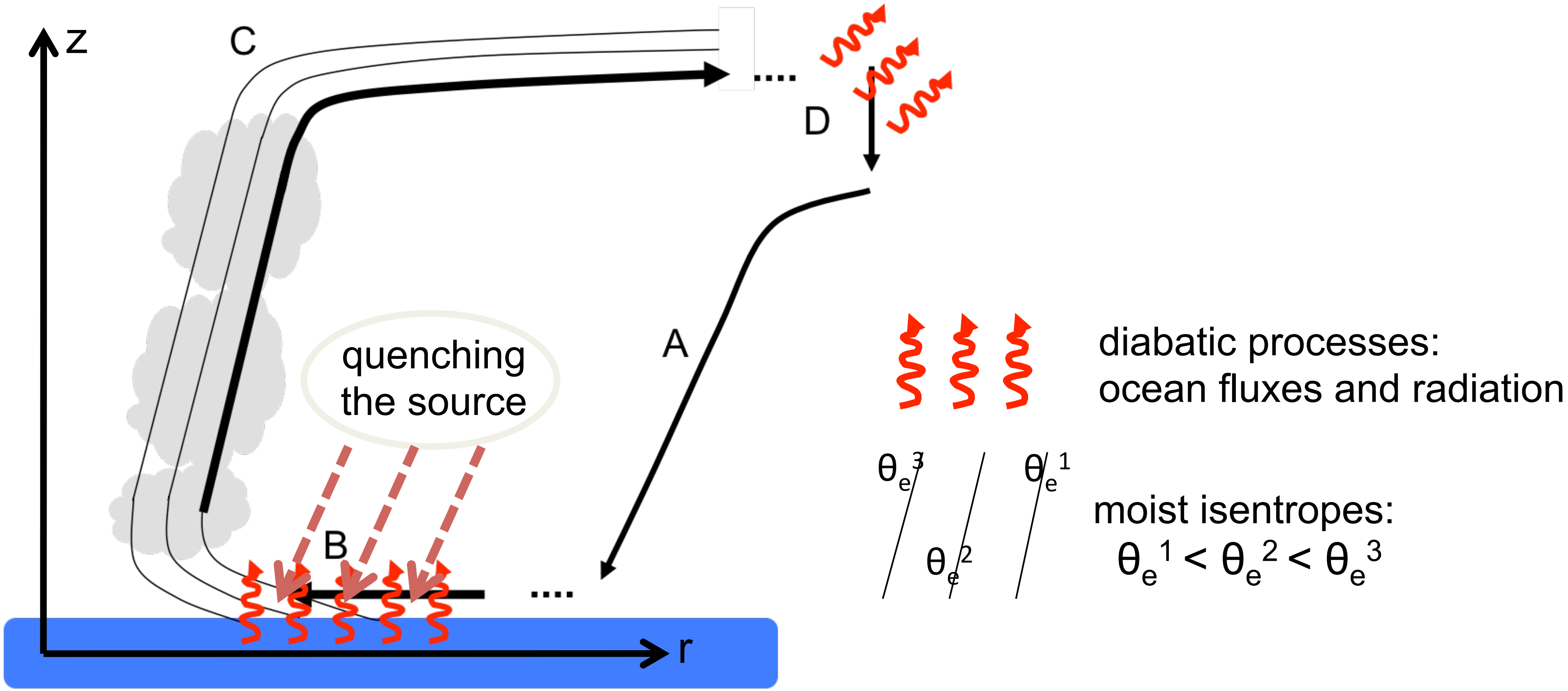
Thermodynamic impact on inflow layer:

significant θ_e depression: O(15 K)

→ reduction of eyewall θ_e by a few Kelvin

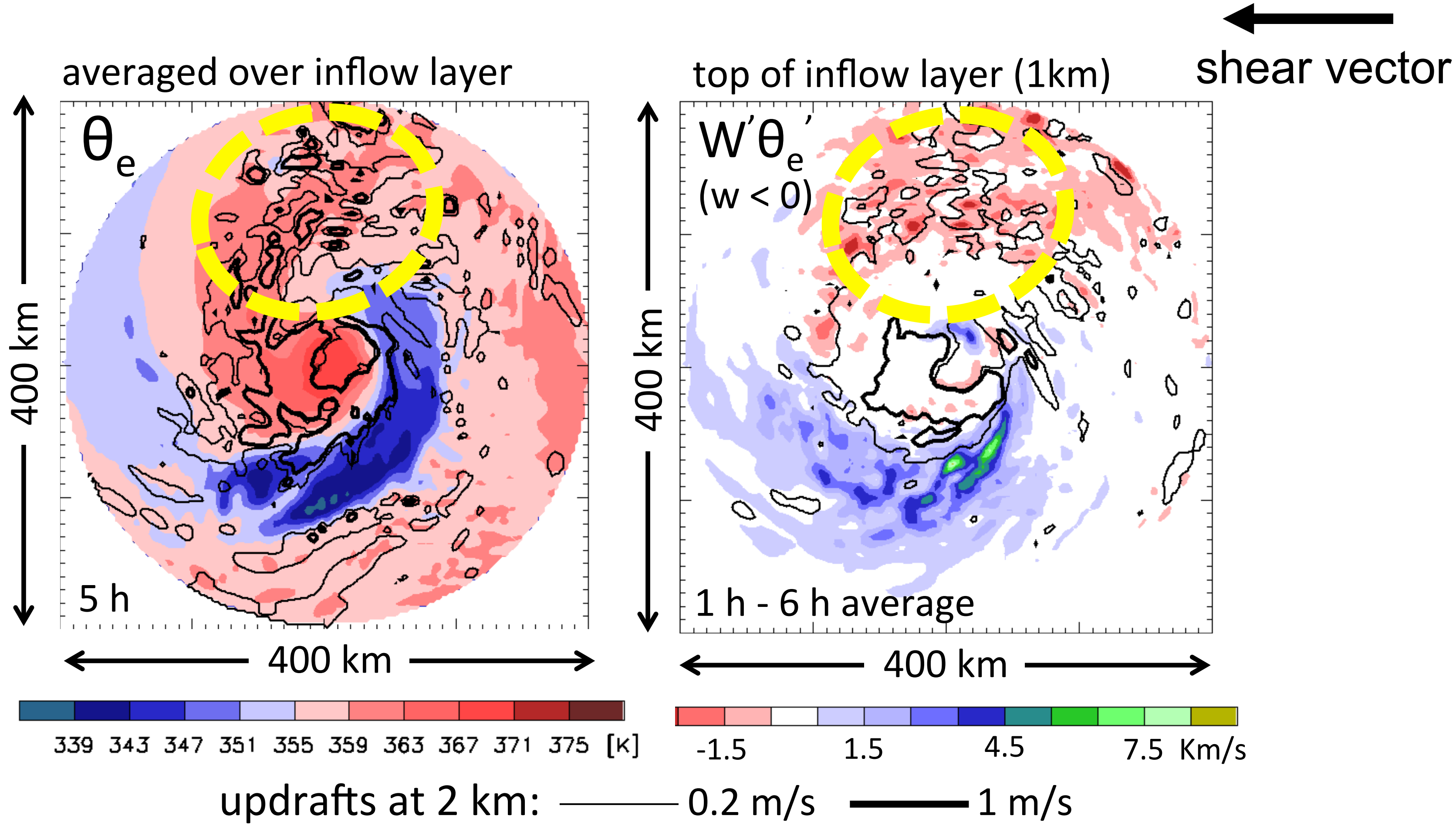
→ (relative) weakening of some 10 m/s

Weakening of TC's thermodynamic (Carnot) cycle



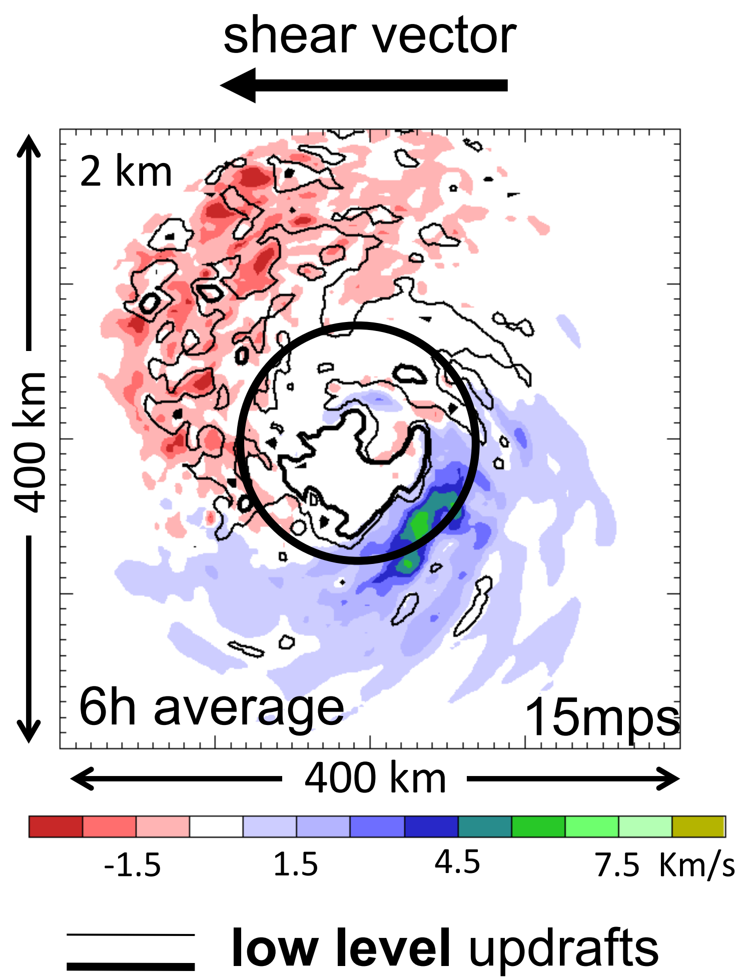
distinct, shear-induced thermodynamic impact on inflow layer

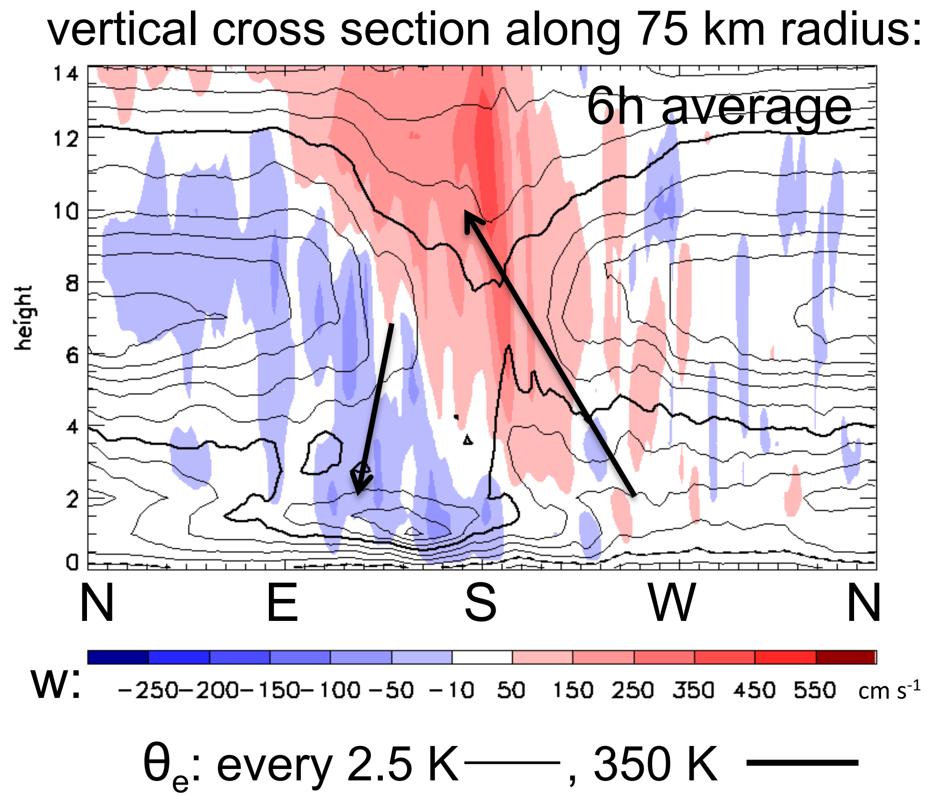
A distinct structural change



Formation of convective asymmetry
outside of the eyewall
"stationary band complex" (SBC)

Downdraft formation and the "stationary band complex"



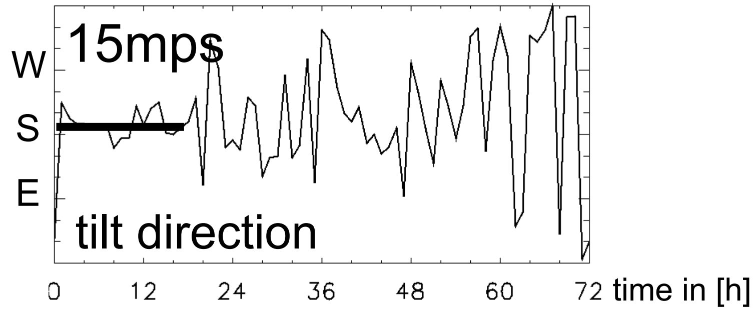


downdrafts form underneath the **helical** updrafts of the SBC
precipitation evaporating in unsaturated air below

Dynamic contribution to "stationary band complex" formation

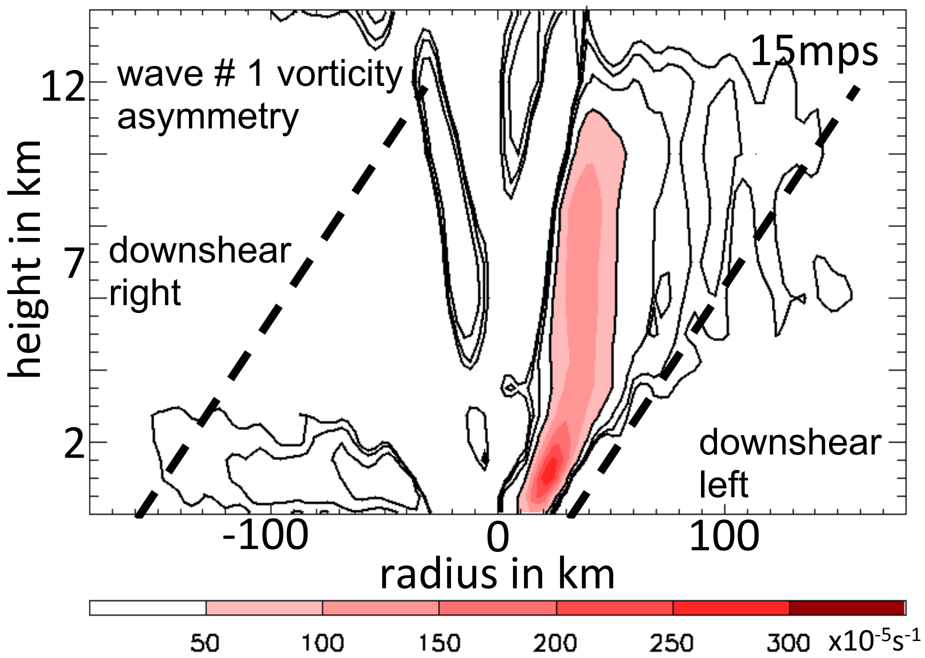
Tilt evolves consistent with balanced dynamics (not shown here)

vortex settles into left-of-shear tilt equilibrium
(e.g. Reasor, Montgomery and Grasso 2004)



outer-vortex tilt = standing VRW wave #1 pattern = low-level vorticity anomaly

vertical cross sections along tilt axis



contours = [5,10,20,50] $x10^{-5}s^{-1}$

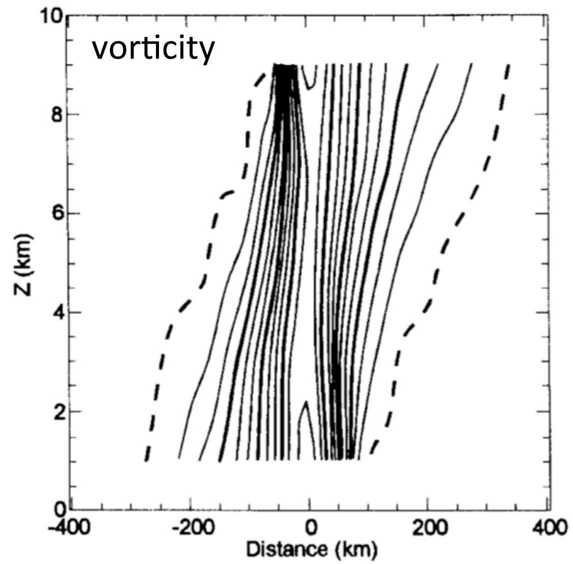


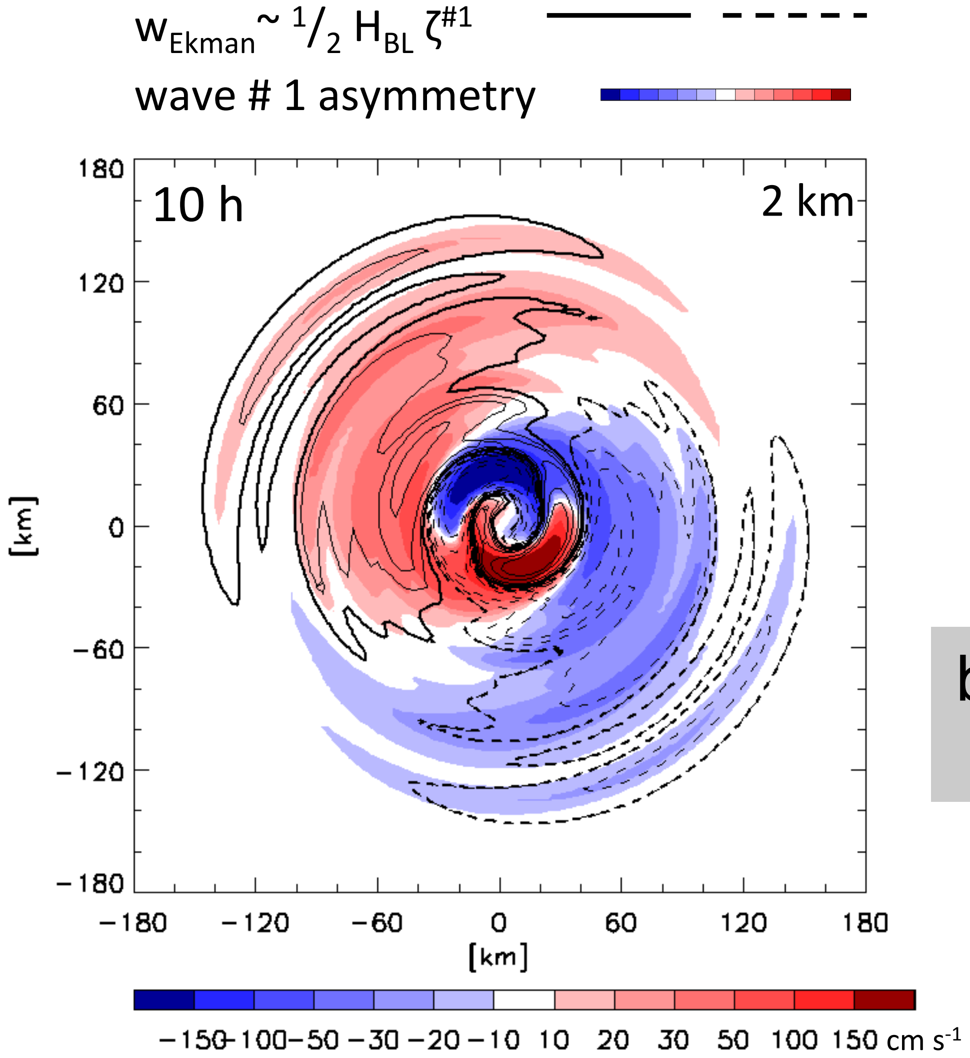
Figure 6a from Jones 1995 (dry PE experiment, note the different aspect ratio)

Forcing of vertical motion by low-level vorticity anomaly

vertical motion:

$w_{Ekman} \sim {}^{1}/_{2}\, H_{BL}\, \zeta^{\#1}$

wave # 1 asymmetry



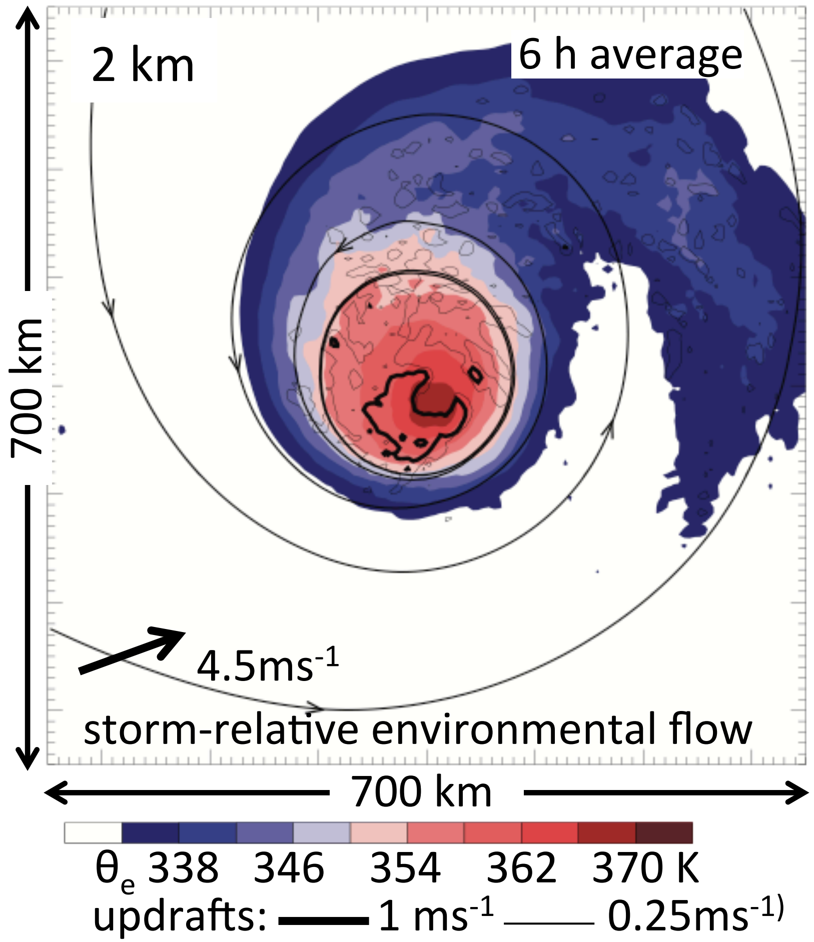
frictional convergence provided by vortex tilt: favorable meso-β scale environment for SBC formation

balanced TC vortex **dynamics**
→ thermodynamic impact

Kinematic contribution to "stationary band complex" formation

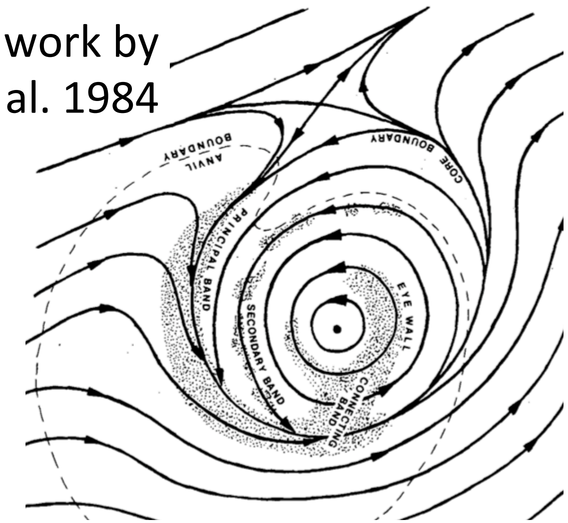
"moist envelope" = local (meso-β scale) region of high-θ_e air

Streamline in co-moving frame
→ flow quasi-steady



- θ_e ≈ "tracer" of full 3-D flow
- θ_e distribution governed by advection and steering of the quasi-steady flow
- moist envelope confined to TC

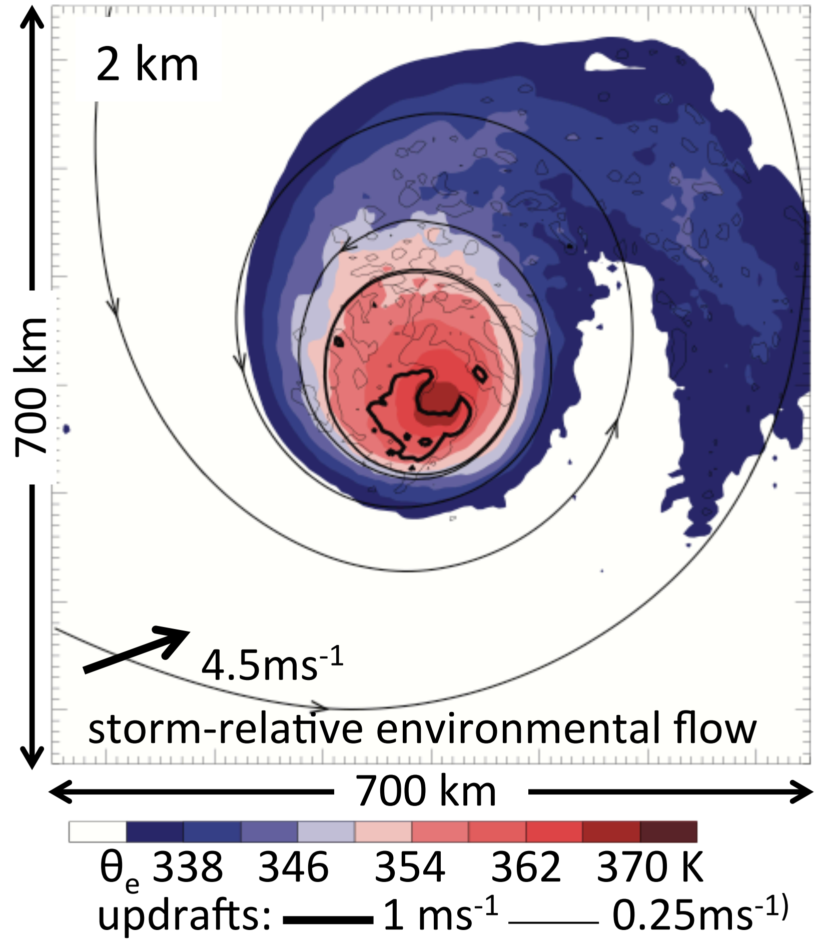
seminal work by
Willoughby et al. 1984

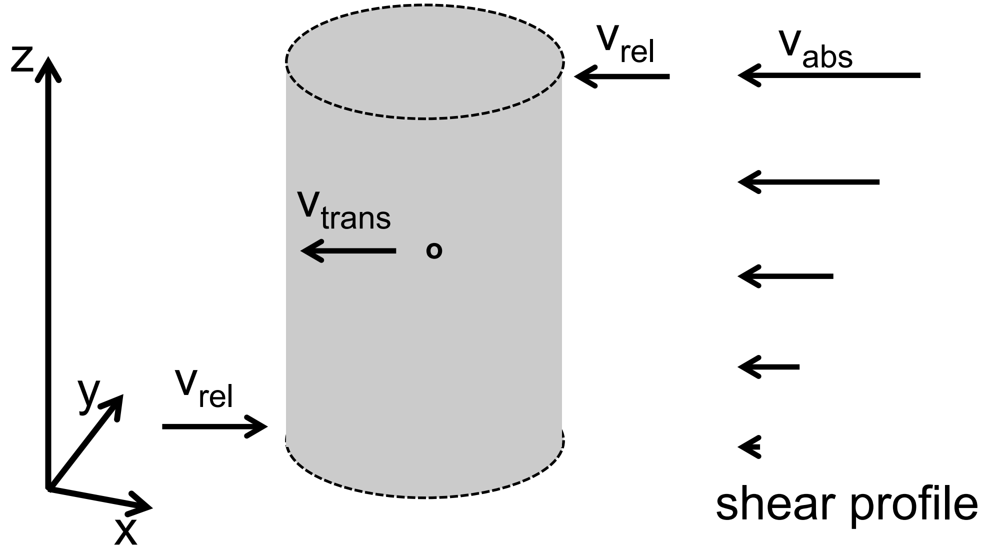


distortion of moist envelope:
favorable meso-β scale, high-θ_e
environment for SBC formation

Shear-induced environmental storm-relative flow

Streamline in co-moving frame
→ flow quasi-steady

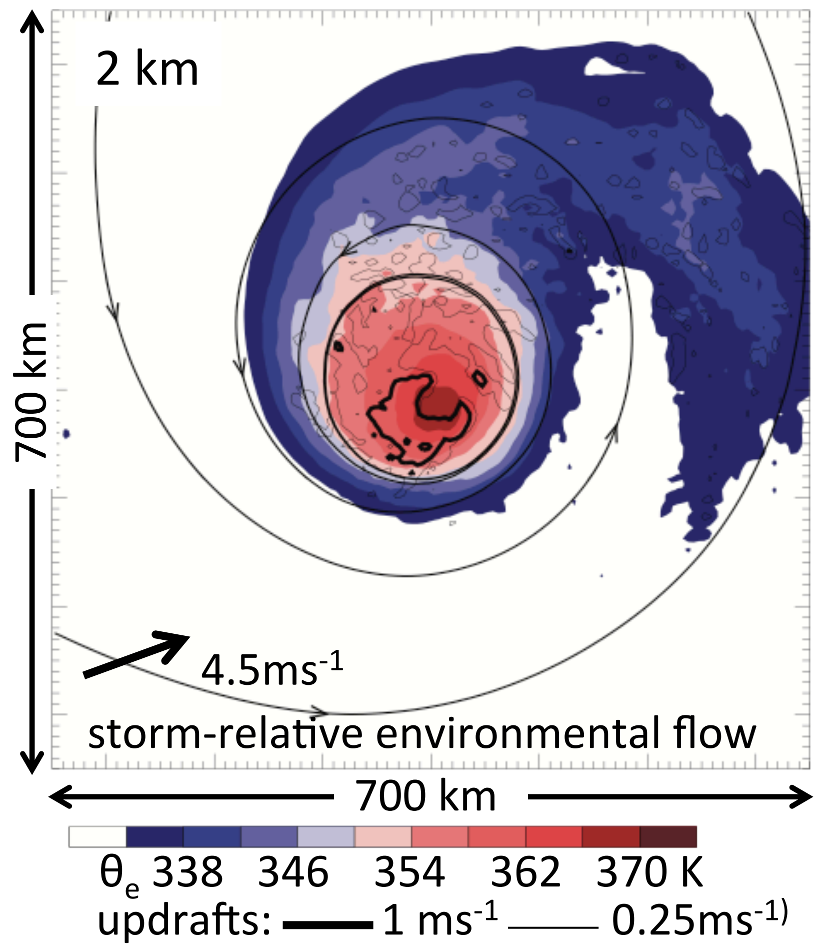


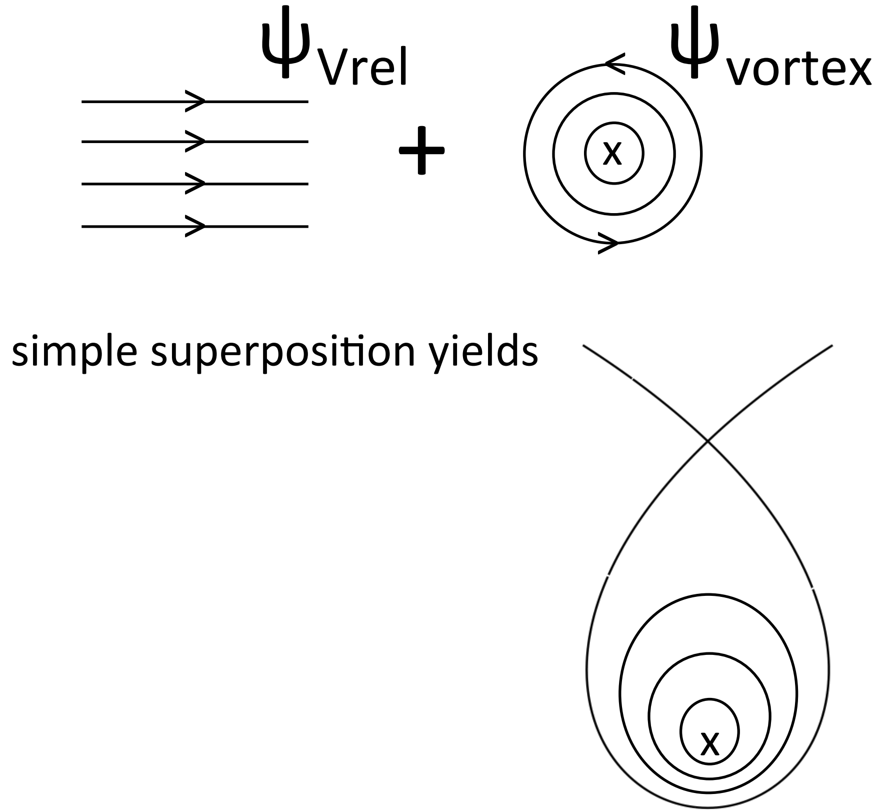


Vertical wind shear →
environmental storm-relative flow

Shear-induced deformation of the "moist envelope"

Streamline in co-moving frame
→ flow quasi-steady

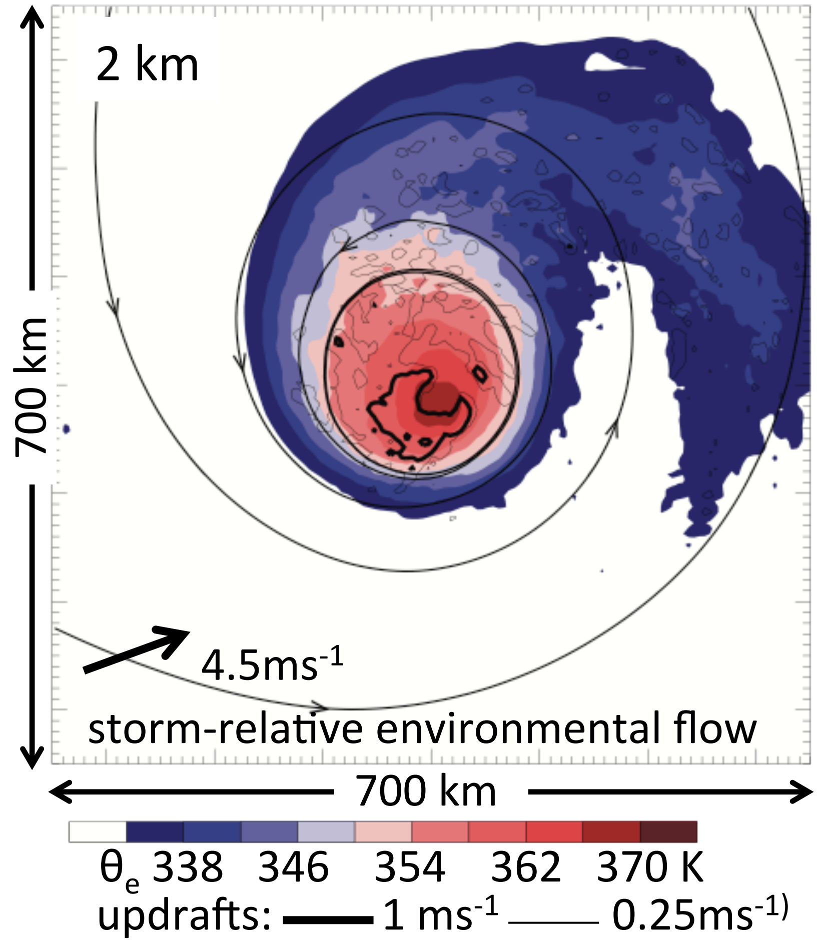


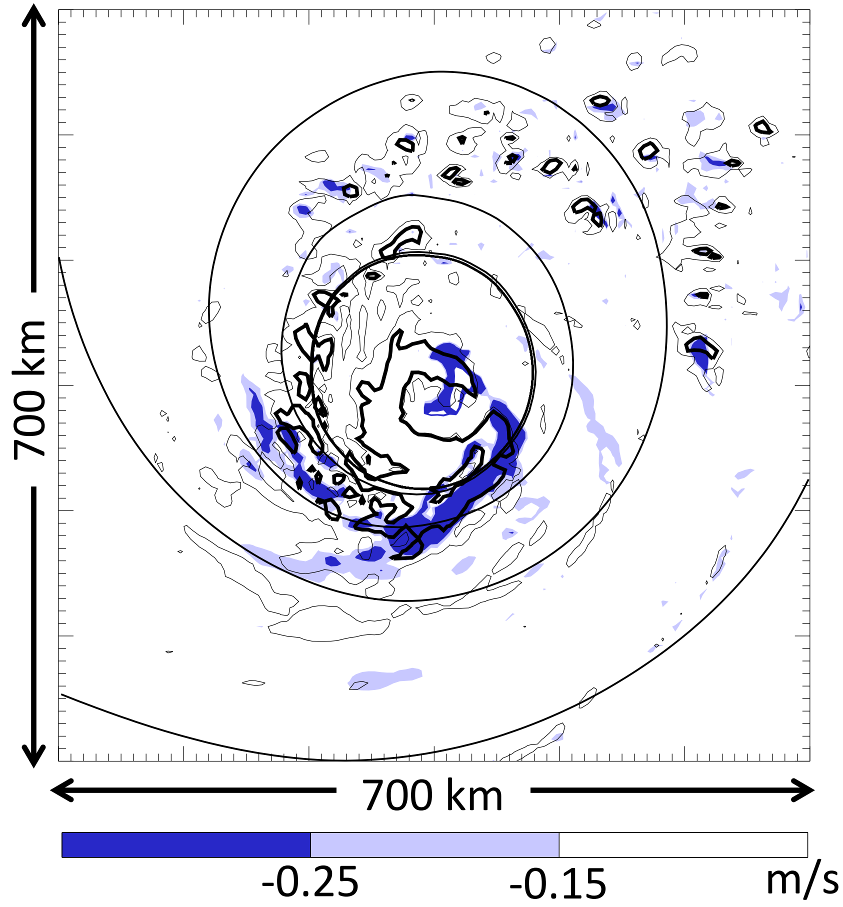


Deformation of moist envelope is simple kinematic consequence of vertical shear

Downdrafts outside of the moist envelope

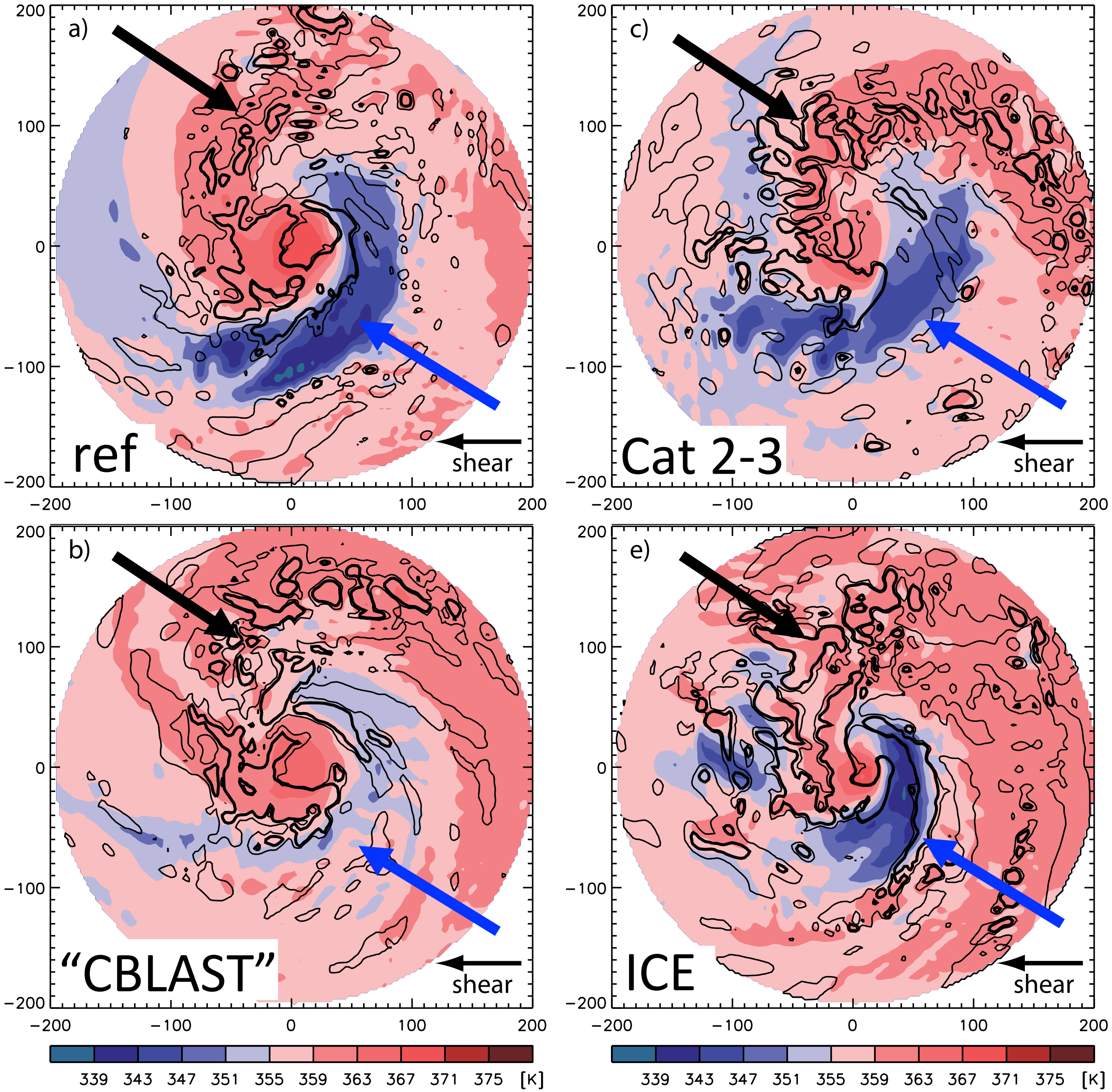
Streamline in co-moving frame
→ flow quasi-steady





formation of downdrafts **outside** of moist envelope

Robustness of results in our suite of experiments

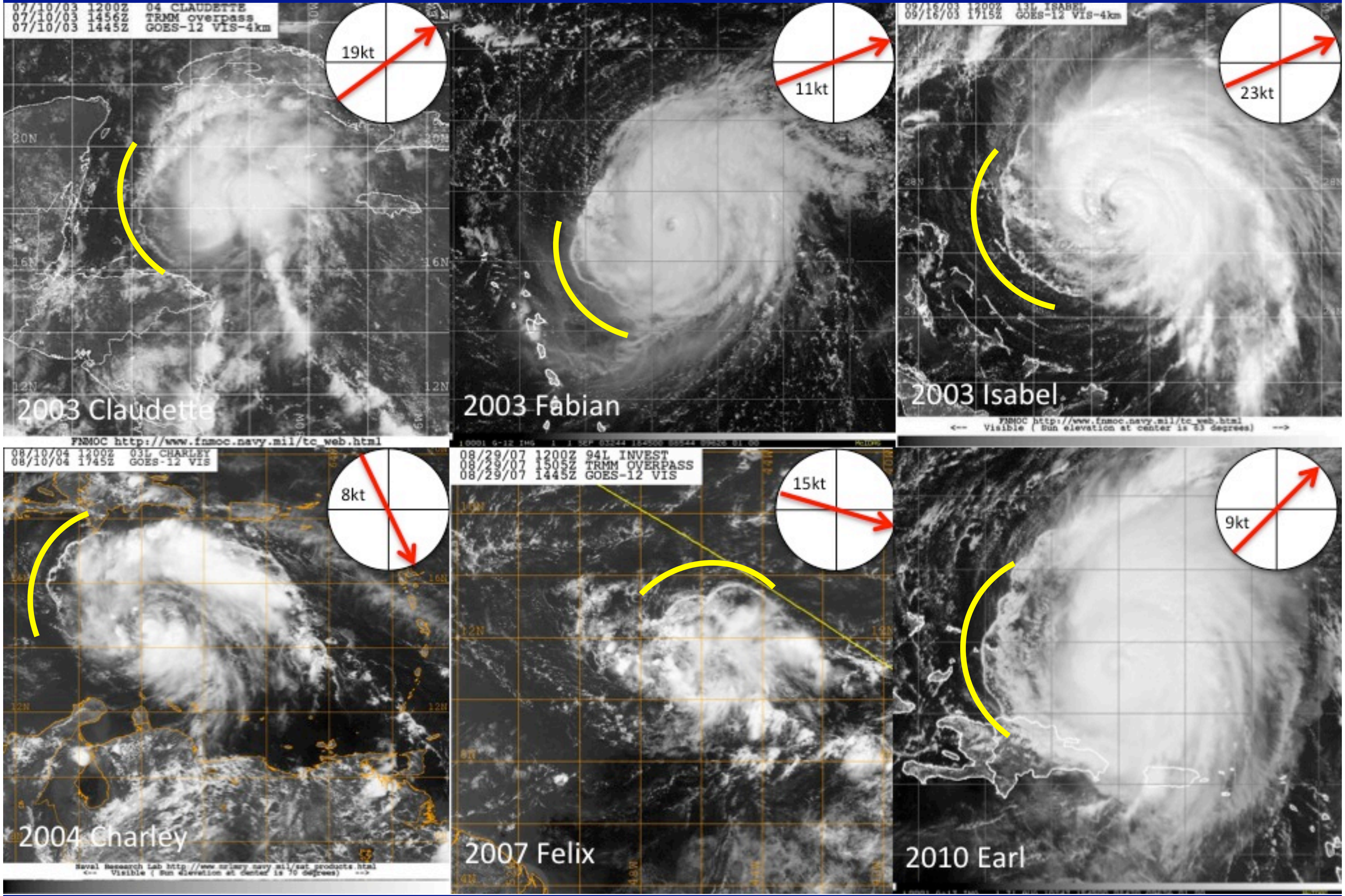


same **general** pattern:
a) SBC and
b) θ_e-depression

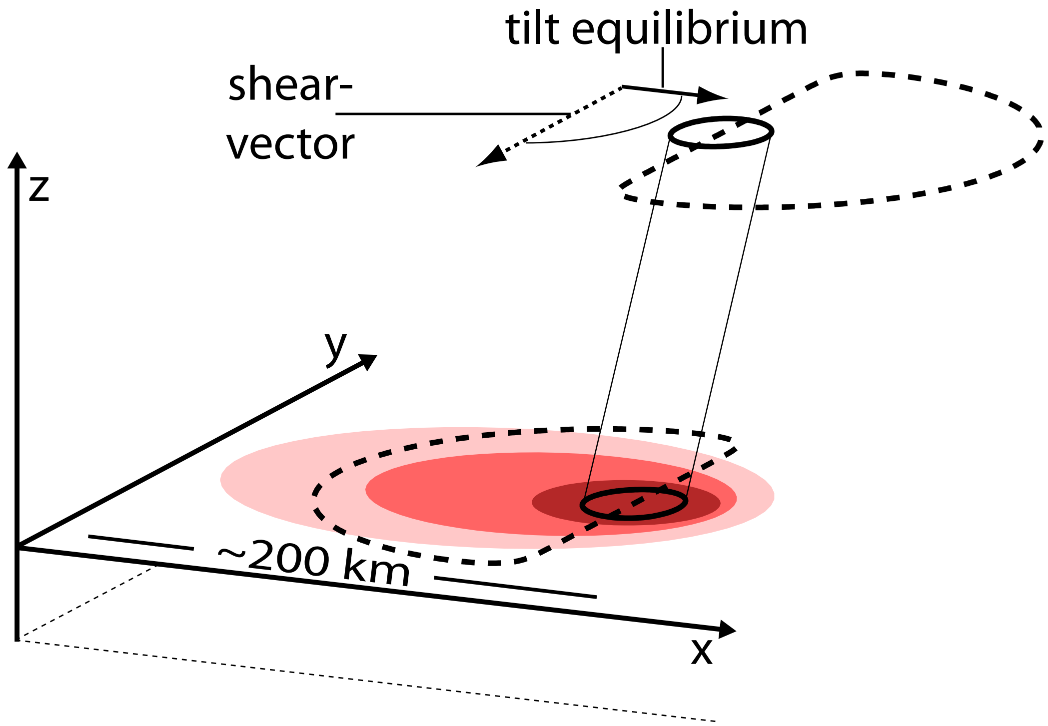
+ same **general** tilt behavior (not shown)

→ results robust in our suite of experiments

Some supporting evidence from the real atmosphere

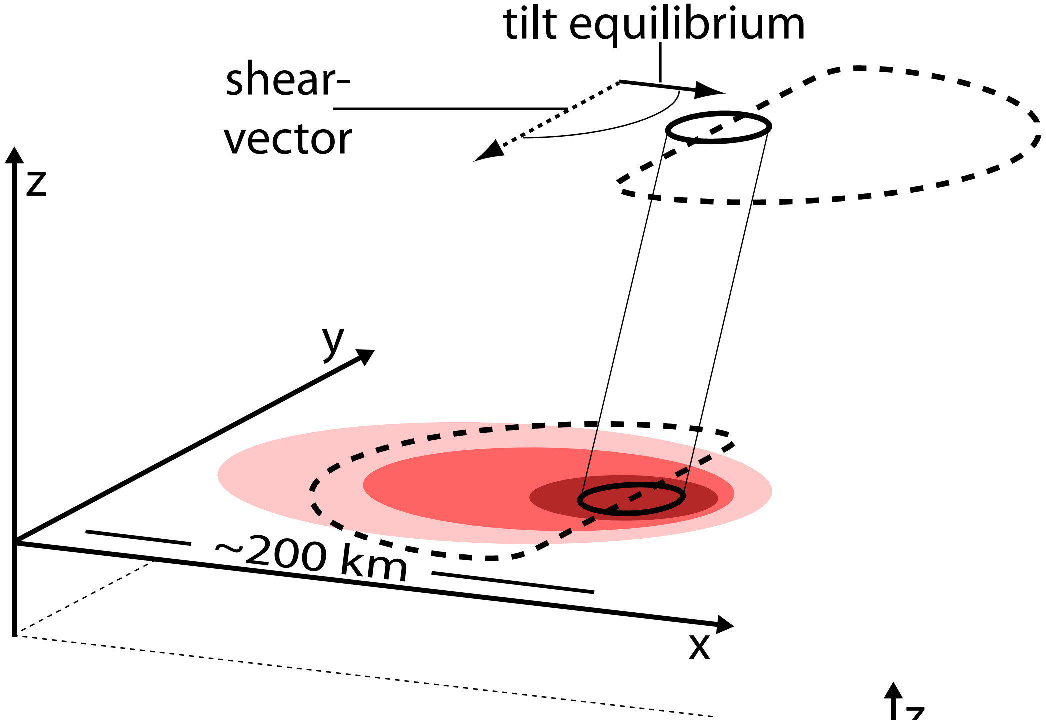


Synthesis



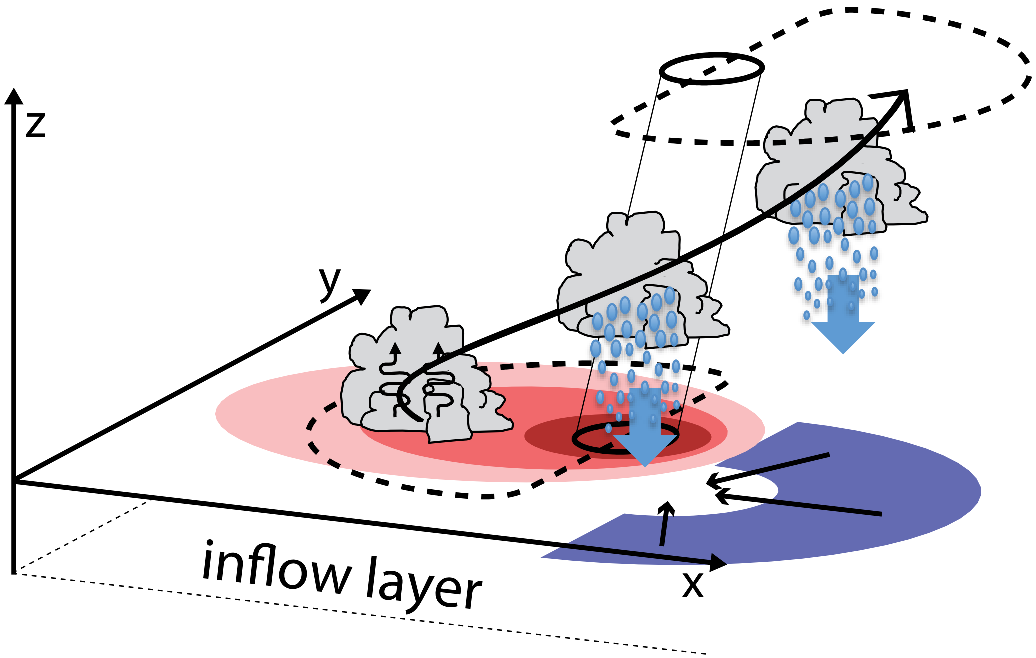
dynamic (vortex tilt) +
kinematic (moist envelope)
consequences of vertical shear
→ favorable meso-β scale
environment for SBC formation

Synthesis



dynamic (vortex tilt) +
kinematic (moist envelope)
consequences of vertical shear
→ favorable meso-β scale environment for SBC formation

swirling winds → **helical** updrafts
→ precip falls into **environmental** low-θ_e air
→ downdrafts form and flush low-θ_e into inflow layer



Conclusions

• shear-induced, thermodynamic impact on the inflow layer

• downdrafts associated with “stationary band complex”

• favorable meso-β scale environment for SCB by vortex tilt (dynamics) and distortion of moist envelope (kinematics)

• same basic structural evolution with associated weakening is found for weaker TCs, more realistic values of C_K and C_D, and ice microphysics also

Atmospheric Chemistry and Physics

2013: **Further examination of the thermodynamic modification of the inflow layer of tropical cyclones by vertical wind shear**

M. Riemer[1], M. T. Montgomery[2,3], and M. E. Nicholls[4]

2011: **Simple kinematic models for the environmental interaction of tropical cyclones in vertical wind shear**

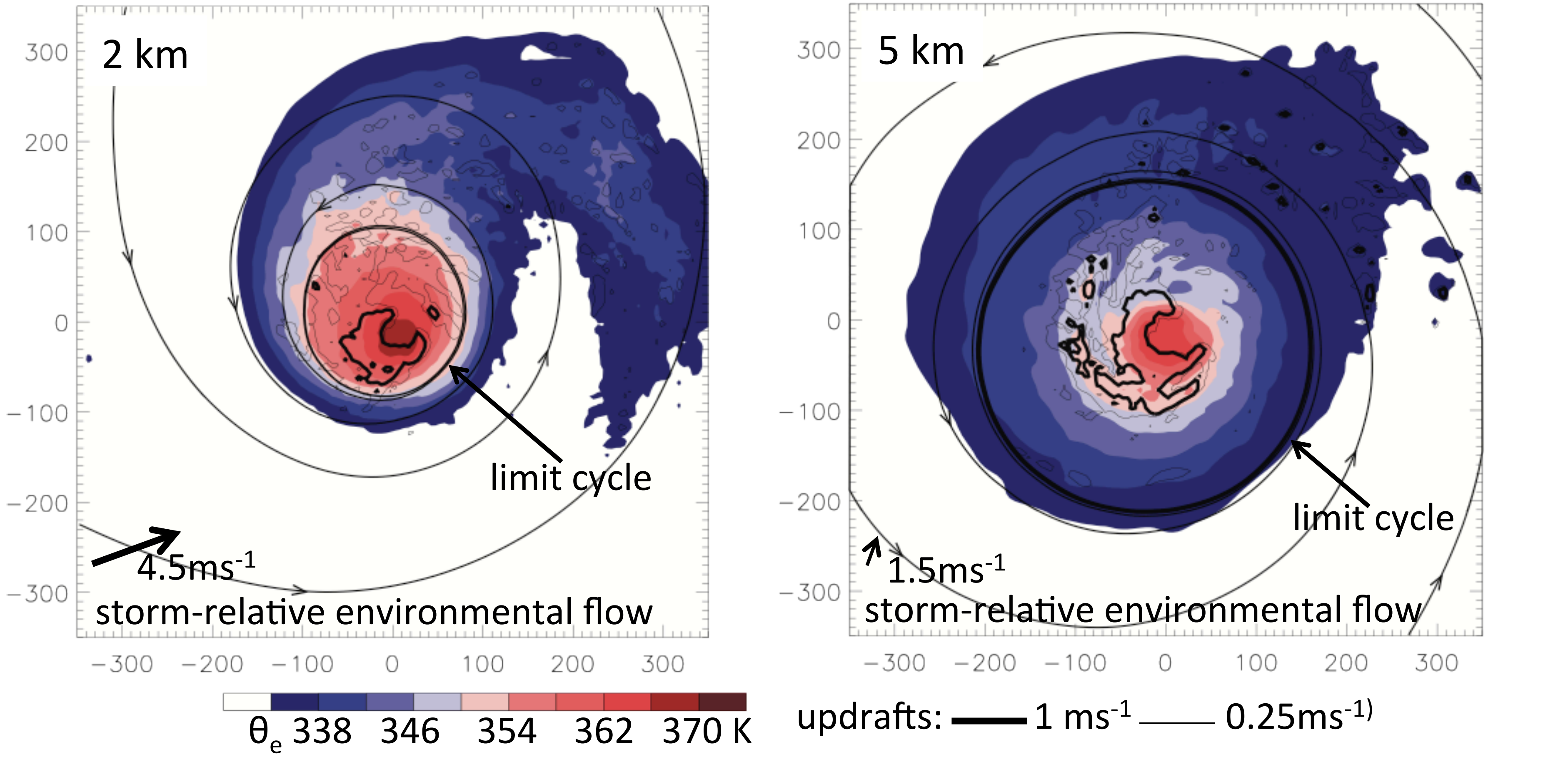
M. Riemer[1,*] and M. T. Montgomery[1,2]

2010: **A new paradigm for intensity modification of tropical cyclones: thermodynamic impact of vertical wind shear on the inflow layer**

M. Riemer[1], M. T. Montgomery[1,2], and M. E. Nicholls[3]

Flow boundaries in idealized numerical experiment

$\theta_e \approx$ "tracer" of full 3-D flow



1) θ_e distribution ≈ limit cycle →
distortion of moist envelope governed by steady, horizontal flow
2) Eyewall well protected from intrusion by steady, horizontal flow

Rapid and pronounced weakening with ice microphysics associated with by the far the most pronounced depression of inflow layer θ_e

$\Delta\theta_e$ ~ 2-3 times of "warm rain"