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)

Understanding of governing processes is still incomplete.

Our goal: Improve understanding by analyzing idealized numerical experiments.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Forecast interval (h)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>12</td>
</tr>
<tr>
<td>POT</td>
<td>+0.62</td>
</tr>
<tr>
<td>SHR</td>
<td>-0.35</td>
</tr>
<tr>
<td>DVMX</td>
<td>+0.40</td>
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</tbody>
</table>

**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
Numerical experiment: spin up TC and hit it with shear

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

shear profile

\[ u(z) = 0.5 u_{\text{max}} \left( \cos \left( \frac{\pi z}{12} \right) - 1 \right), \]
\[ z = \text{height in km} \]

\[ \approx 850 - 200 \text{ hPa} \]

• 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 $\theta_e$ depression: $O(15 \text{ K})$
- reduction of eyewall $\theta_e$ 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

Figure 6a from Jones 1995 (dry PE experiment, note the different aspect ratio)
Forcing of vertical motion by low-level vorticity anomaly

vertical motion:

\[ w_{\text{Ekman}} \sim \frac{1}{2} H_{BL} \zeta^1 \]

wave #1 asymmetry

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

balanced TC vortex \textit{dynamics} \rightarrow \textit{thermodynamic impact}
Kinematic contribution to “stationary band complex” formation

“moist envelope” = local (meso-β scale) region of high-θₑ air

Streamline in co-moving frame → flow quasi-steady

- θₑ ≈ “tracer” of full 3-D flow
- θₑ 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-θₑ 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”

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

Streamline in co-moving frame
→ flow quasi-steady

storm-relative environmental flow

formation of downdrafts outside of moist envelope
Robustness of results in our suite of experiments

same general pattern:
- a) SBC and
- b) $\theta_e$-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

2013: Further examination of the thermodynamic modification of the inflow layer of tropical cyclones by vertical wind shear
M. Riemer, M. T. Montgomery, and M. E. Nicholls

2011: Simple kinematic models for the environmental interaction of tropical cyclones in vertical wind shear
M. Riemer and M. T. Montgomery

2010: A new paradigm for intensity modification of tropical cyclones: thermodynamic impact of vertical wind shear on the inflow layer
M. Riemer, M. T. Montgomery, and M. E. Nicholls
Flow boundaries in idealized numerical experiment

\[ \theta_e \approx \text{“tracer” of full 3-D flow} \]

1) \( \theta_e \) distribution \( \approx \) limit cycle \( \rightarrow \)
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 $\theta_e$.

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