WMO Training Course on Tropical Cyclones
La Réunion (September 2015)

1. **Internal structure & variability**
2. **External influences**
3. **Inter-annual & intra-seasonal variability**
4. **Climatic changes**
1. Internal structure & variability
   • Primary & secondary circulations
   • Thermal engine
   • Eyewall replacement cycle
   • External bands
   • Circulation in the eye
Which factors control the intensity of tropical cyclones?

- **Internal**: thermodynamics and dynamics of the eyewall and of the external rainbands, …

- **External**: SST, wind shear, dry zones, upper-level features, …
Primary circulation: tangential (few 10 m/s)
Secondary circulation: radial and vertical (few m/s)
THE PRIMARY CIRCULATION

The centrifugal acceleration of the wind (\(\Rightarrow\)) balances the centripetal force toward the central pressure low (D);

The central pressure low (D) results from the presence of warm air aloft;

\[ \text{THERMAL WIND BALANCE : } \frac{\partial V_T}{\partial z} \propto \frac{\partial \theta}{\partial r} \]
TROPICAL CYCLONE AS A HEAT ENGINE:

- « Cold Source » at $T = T_{\text{TROPO}}$
  - Radiative cooling $\Rightarrow \theta_E \downarrow$
  - Large-scale circulation $\Rightarrow M \uparrow$

- « Warm Source » at $T = T_{\text{OCEAN}}$
  - Moisture flux $\Rightarrow \theta_E \uparrow$
  - Surface friction $\Rightarrow M \downarrow$

In the Eyewall:
\[ \theta_{E1} > \theta_{E0} \text{ et } M_1 < M_0 \]
- Condensation $\rightarrow$ Heat + Precipitation
- $D < 100 \text{ km} : 10 \text{ cm/jour} \Leftrightarrow 3000 \text{ W/m}^2$
  - [1 storm $\approx 2500$ nuclear power plants]

\[ P_{\text{min}}, V_{\text{max}} = f(T_{\text{ocean}}, T_{\text{tropo}}, \text{Latitude}) \]

Thermal energy: $\theta_{E0}$
Angular momentum: $M_0$
\[ (M = r V + f r^2/2) \]

Distance to storm center
TROPICAL CYCLONE AS A HEAT ENGINE:
Air-sea interactions (1)

CBLAST (Coupled Boundary Layers Air-Sea Transfer, 2003-04):
processes controlling the ocean-atmosphere flux in cyclonic conditions with strong winds, waves, sea spray, induced circulations in the oceanic mixed layer
TROPICAL CYCLONE AS A HEAT ENGINE :  
Air-sea interactions (2)

Heat and moisture fluxes at the ocean surface are the main sources of energy for cyclonic circulation. Reciprocally, friction of the wind at surface transfers energy to the ocean through the generation of waves et currents at various depths.

The « bulk » formulation expresses these fluxes as functions of the mean flow and of transfer coefficients:

**Sensible heat flux de chaleur :**  
\[ Q_S = \rho \ C_S \ |V_{air}| \ C_P (\theta_{surf} - \theta_{air}) \]

**Latent heat flux :**  
\[ Q_L = \rho \ C_L \ |V_{air}| \ L (q_{surf} - q_{air}) \]

[ Enthalpy flux :  
\[ Q_E = Q_S + Q_L \]

**Momentum flux (i) :**  
\[ Q_{Vi} = \rho \ C_D \ |V_{air}| (V_{i_{air}}) \]

( \( \rho \) = air density,  \( |V_{air}| \) = wind module, \( \theta \) = potential temperature, \( q \) = mixing ration,  
\( C_P \) = specific heat at cst P, \( L \) = latent heat of vaporization  
\( C_S \) = Stanton number, \( C_L \) = Dalton number, \( C_D \) = surface drag coefficient)
TROPICAL CYCLONE AS A HEAT ENGINE: Air-sea interactions (3)

CBLAST Hurricane Component (2003 + 2004): airborne in situ and remote sensing measurements + surface and sub-surface observations with dropped buoys and profilers, and platforms

Figure 1. CBLAST survey pattern showing planned expendable probe deployments along a figure 4 pattern relative to the storm’s eyewall and rainband features. Location of planned stepped-descent patterns to measure boundary layer fluxes is shown schematically.

Figure 2. Experiment setup for the ASIT during CBLAST. The photo indicates where variables where measured on the met tower, fixed array, and profiling mast. The solar and infrared radiometers where measured 22-m above mean sea level.
The surface drag coefficient $C_d$ reaches a maximum for a 40 m/s wind, and slowly decreases beyond.

The enthalpy exchange coefficient $C_e$ is roughly constant for winds $\leq 30$ m/s. It could increase beyond 50 m/s, in relation with sea spray.
TROPICAL CYCLONE AS A HEAT ENGINE:
Air-sea interactions (5)


Fig. 13. Drawings of the three varieties of floats and a surface drifter as deployed into Hurricane Frances. Schematic depicts operations in Hurricane Frances (2004).

Fig. 16. Evolution of the density structure of the upper ocean near the radius of maximum winds of Hurricane Frances. (a) Wind speed and atmospheric pressure from HRD H**WIND analysis at the two Lagrangian floats. (b) Potential density contours (kg m^{-2}; in black), trajectories of Lagrangian floats (red and blue), measured depth of the mixed layer (magenta), and estimated depth of the mixed layer from a vertical heat budget (yellow, dashed).
TROPICAL CYCLONE AS A HEAT ENGINE:
Air-sea interactions (6)

TROPICAL CYCLONE AS A HEAT ENGINE: Air-sea interactions (7)


Fig. 1. Schematics of a coupled atmosphere-wave-ocean modeling system with the component atmosphere, surface wave, and ocean circulation models, as well as the coupling parameter exchanges between each of the component models.

Hurricane Frances at 1200 UTC 31 Aug 2004

rain rate (color, mm h⁻¹)

enthalpy flux (color, W m⁻²)
surface wind speed (black contour)
surface wind (vector)
TROPICAL CYCLONE AS A HEAT ENGINE:
Air-sea interactions (8)
TROPICAL CYCLONE AS A HEAT ENGINE:
Pumping the upper-ocean heat (1)
Rita weakens before it reaches the Texas coast

Decreasing « ocean heat content »
In the Gulf of Mexico
TROPICAL CYCLONE AS A HEAT ENGINE:
Pumping the upper-ocean heat (3)
TROPICAL CYCLONE AS A HEAT ENGINE:
Climatological Maximum Potential Intensity (1)

\[ P_{\text{min}}, V_{\text{max}} = f(T_{\text{ocean}}, T_{\text{tropo}}, \text{Latitude}) \]
TROPICAL CYCLONE AS A HEAT ENGINE:
Climatological Maximum Potential Intensity (1)

Tropical cyclone as a heat engine, showing climatological maximum potential intensity (1). The diagram indicates a relationship between Tocéan (°C) and Ttropopause (°C) with speed thresholds marked in km/h. The term 'Global warming' highlights a shift in the present condition, marked by a question regarding 'Hypercanes.'
THE SECONDARY CIRCULATION
THE SECONDARY CIRCULATION
Observations (1)

Jorgensen 1984 [ J. Atmos. Sci., 41, 1287-1311 ]:
a conceptual model for the inner core of Hurricane Allen (1980)
THE SECONDARY CIRCULATION
Observations (2)

Willoughby et al. 1982 [ J. Atmos. Sci., 39, 395-411 ]: a mechanism for the formation of concentric eyewalls

An illustration of the concentric eye cycle made up from individual profiles in Hurricanes David (1979) and Allen (1980)
THE SECONDARY CIRCULATION
Numerical Models (1)

Kinematic, thermodynamic and microphysical structures in the simulated core region compare favorably to previous observations of hurricanes.
THE SECONDARY CIRCULATION
Numerical Models (2)


Axisymmetric structure of the storm (6-km horizontal grid):
• moist inflow in the boundary layer, outflow in the upper troposphere, slantwise ascent in the eyewall where the tangential wind is maximum;
• penetrative dry downdraft at the inner edge of the eyewall;
• weak subsiding motion in the eye with warming/drying above an inversion, below warm/moist air coming from the low-level inflow and downdraft.
THE SECONDARY CIRCULATION
Numerical Models (3)

VERTICAL MOMENTUM BUDGET

\[ \pi = \left( \frac{P}{P_0} \right)^{C_p} \], \ \theta = \frac{T}{\pi} \quad \text{with} \quad \pi = \pi_0 + \pi_1, \ \theta = \theta_0 + \theta_1 \]

hydrostatic equilibrium: \[ C_p \theta_v \frac{\partial \pi_0}{\partial z} = -g \]

\[ \frac{Dw}{Dt} \]

\[ \frac{\partial w}{\partial t} \]

with:

- total tendency
- local tendency
- total advection
- turbulent advection
- diffusion
- vertical pressure perturbation
- gradient force
- thermal buoyancy
- liquid + ice water loading
- loading
THE SECONDARY CIRCULATION
Numerical Models (4)

vertical acceleration in the eyewall results from a small difference between vertical pressure gradient force, buoyancy and water loading.
THE SECONDARY CIRCULATION
Numerical Models (5)

RADIAL MOMENTUM BUDGET

\[
\frac{Du}{Dt} = \frac{\partial u}{\partial t} + (\nabla \cdot \nabla) u = -D(u) - C_p \theta_v v_0 \frac{\partial \pi_1}{\partial r} + \frac{v^2}{r} + f v
\]

Gradient wind balance:
\[
C_p \theta_v v_0 \frac{\partial \pi_1}{\partial r} = \frac{v^2}{r} + f v
\]

"Super - gradient" wind: "centrifugal + Coriolis" forces > "rad. press. pert. grad." force

u = radial wind component ; \ v = tangential wind component

Departure from «thermal wind balance»:
«supergradient» flow and radial acceleration near the bottom of the eyewall.

\[ \frac{V_T^2}{r} + f V_T > C_p \theta_0 \frac{\partial \pi}{\partial r} \]

because of angular momentum conservation
→ net outward radial force
THE SECONDARY CIRCULATION
Numerical Models (7)


• 72-h simulation of Hurricane Bob (1991) [16 Aug 00 UTC → 19 Aug 00 UTC] using a 36-km grid A

• at 48 h, one-way nested 12-km grid B and a two-way nested 4-km grid C are activated (hourly boundaries from the 36-km grid)

• at 62 h ($<V>_{max}=58$ ms$^{-1}$, $P_{min}=970$ hPa), a two-way nested 1.3-km grid D is initialized. Both 4-km and 1.3-km grids are moved with the storm.
THE SECONDARY CIRCULATION
Numerical Models (8)

- Time-average structure of the horizontal flow is characterized by a wavenumber-1 asymmetry (relative to the nearly aligned storm motion and wind shear vector) in the low-level vertical motions, near-surface tangential wind, inflow and outflow above the boundary layer.
THE SECONDARY CIRCULATION
Numerical Models (9)

• Some air parcels originating from outside the eyewall in the lowest part of the boundary layer penetrate furthest into the eye, then accelerate outward sharply while rising out of the boundary layer.
• Occasionally high-$\theta_e$ air from the eye is drawn into the eyewall updraft, through episodic rather than continuous venting of the eye air into the eyewall.
THE SECONDARY CIRCULATION
Numerical Models (10)

THE SECONDARY CIRCULATION
Airborne-Doppler Radar Observations

Rogers et al. 2012:
THE SECONDARY CIRCULATION: Microphysics (1)


impact of cloud microphysics on tropical cyclone structure and intensity
using a 2D axis-symmetric non-hydrostatic model with 2 km horizontal grid size

Time series of minimum surface level pressure (MSLP) and maximum tangential winds at 3.1 km in water (W) and ice (I) models.
THE SECONDARY CIRCULATION : Microphysics (2)

*Wang 2002a* [*Mon. Wea. Rev., 130, 3022-3036*]

→ sensitivity of the simulated TC structure and intensity to the details of cloud microphysics parameterization: warm-rain only (WMRN), crystal-snow-graupel (CTRL), crystal-snow-hail (HAIL), no evaporation of rain (NEVP), no melting (NMLT)

The simulated TC develops more rapidly and reaches a stronger intensity for « warm-rain only », « no evaporation » and « no melting » experiments
THE SECONDARY CIRCULATION:
Microphysics (3)
THE SECONDARY CIRCULATION: Microphysics (4)

Zonal vertical cross-section of reflectivity

Surface reflectivity in 360 km x 360 km
THE SECONDARY CIRCULATION: Microphysics (5)

Simulation of Hurricane Katrina (2005) with the triple-nested (15, 5 and 1.667 km) WRF model with six different microphysical schemes (including the ice phase)

The sensitivity tests show no significant difference in track among the different microphysical schemes.
THE SECONDARY CIRCULATION : Microphysics (6)

Minimum sea level pressure (hPa) obtained from WRF forecasts of Hurricane Katrina using six different microphysical schemes

<table>
<thead>
<tr>
<th></th>
<th>3ICE-Hail</th>
<th>3ICE-Graupel</th>
<th>2ICE</th>
<th>WSM6</th>
<th>Lin</th>
<th>Thompson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid hydrometeors</td>
<td>46.6%</td>
<td>36.4%</td>
<td>24.8%</td>
<td>50.4%</td>
<td>65.3%</td>
<td>34.2%</td>
</tr>
<tr>
<td>Solid hydrometeors</td>
<td>53.4%</td>
<td>63.6%</td>
<td>75.2%</td>
<td>49.6%</td>
<td>34.7%</td>
<td>65.8%</td>
</tr>
</tbody>
</table>

Domain- and 72-h time-average accumulated liquid (warm rain) and solid (ice) water species for the Hurricane Katrina case.
Latent heating is largest in the lower and middle troposphere for the warm rain only physics, whereas it is larger aloft in both « ice » schemes.

→ modeling studies suggest that the larger the latent heating is in the lower and middle troposphere, the stronger the storm intensity and the larger the eyewall can be.
**THE SECONDARY CIRCULATION : Microphysics (8)**

*Braun 2006* [ *J. Atmos. Sci.*, *63*, 43-64 ]

Numerical simulation of Hurricane Bonnie (23 Aug 1998)
→ Water vapor, cloud condensate & precipitation budget

![Diagram showing water budget and fluxes in Hurricane Bonnie](image)

- **Eyewall** (convective)
  - In: +18
  - Out: -12
  - Precip = 12 (55 mm/h)
  - HFlux = 18
  - SFlux = 1

- **Outer Region** (stratiform)
  - In: +57+4+7=+68
  - Out: -45-18-5=-68
  - Precip = 45 (30 mm/h)
  - HFlux = 5
  - SFlux = 4

- Total water budget:
  - [100 = ΣCond = 2 \(10^9\) kg s\(^{-1}\)]
THE SECONDARY CIRCULATION: Lightning (1)


Variation of lightning in Hurricane Andrew, superimposed on infrared satellite images. The insets show a 2× view of the eye and eyewall.
THE SECONDARY CIRCULATION : Lightning (2)

Ground flash density (from NLDN) for 9 Atlantic hurricanes:
• weak maximum in the eyewall region (↑ before/during intensification)
  → ∼ weakly electrified oceanic monsoonal convection
• minimum 80-100 km outside the eyewall (positive flashes)
  → mostly stratiform precipitation
• strong maximum in outer rainbands (200-300 km radius)
  → more convective

Dots indicate liquid hydrometeors;
• Stars indicate frozen hydrometeors with increasing symbol size representing larger graupel or hail.
Hourly eyewall total lightning flash rate detected for Hurricanes Katrina and Rita of 2005 by LASA (Los Alamos National Laboratory’s Sferic Array) → The eyewall lightning outbreaks might be a useful forecast tool to predict changes in hurricane intensity and therefore to diagnose storm intensification.
The eyewall and the strongest rainbands contained the largest updrafts and mixing ratios of graupel and cloud water → they are more conducive for collisional « Non-Inductive » charging processes to operate. → they produce the largest flash rates in the TC.
THE SECONDARY CIRCULATION:
« Convective » Sources and « Thermal Wind » Balance

Willoughby et al. 1982
*J. Atmos. Sci.*, **39**, 395-411

- **Heat source**

- **Momentum source**
THE SECONDARY CIRCULATION : Evolution

Augmentation de la vitesse

Diminution de la vitesse

Tangential wind (m/s)

Altitude (km)

Radius (km)

Augmentation de la vitesse

Diminution de la vitesse
THE SECONDARY CIRCULATION:
Eyewall Replacement Cycle (1a)
THE SECONDARY CIRCULATION:
Eyewall Replacement Cycle (1b)
THE SECONDARY CIRCULATION:
Eyewall Replacement Cycle (1c)

<table>
<thead>
<tr>
<th>$T_0$</th>
<th>PRECIPITATION</th>
<th>$T_0 + 2-3 \text{ h}$</th>
<th>RADIAL PROFILE OF $V_T$</th>
<th>$T_0 + 4-6 \text{ h}$</th>
</tr>
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</table>

$\Rightarrow P \uparrow$
THE SECONDARY CIRCULATION:
Eyewall Replacement Cycle (1d)

<table>
<thead>
<tr>
<th>Time</th>
<th>Precipitation</th>
<th>Radial Profile of $V_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>$T_0 + 2-3 h$</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>$T_0 + 4-6 h$</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>$T_0 + 6-9 h$</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>
THE SECONDARY CIRCULATION:
Eyewall Replacement Cycle (2)

Hurricane Intensity and Eyewall Replacement
Robert A. Houze, Jr., et al.
Science 315, 1235 (2007);

RAINEX

Fig. 1. Forecast of surface rainfall intensity in Hurricane Rita.
(A) 0715 UTC 21 September, (B) 1115 UTC 22 September, (C) 1715 UTC 22 September. Colors show the rainfall rate (mm h\(^{-1}\)) at the sea surface generated by the University of Miami’s high-resolution, vortex-following, coupled atmosphere-wave-ocean version of the fifth-generation Pennsylvania State University NCAR nonhydrostatic mesoscale model (MM5) (34) operating at a horizontal resolution of 1.67 km. Initial fields at 0000 UTC 20 September 2005 and lateral boundary conditions are from the NOGAPS global numerical forecast model (35).

Fig. 2. Aircraft data collected in Hurricane Rita between 1800 and 1820 UTC 22 September 2005. (A) and (B) are plan views; (C) is a vertical cross section across the northwest side of the storm (along the white line in the plan views). Colored lines in (A) denote the flight tracks of the three RAINEX aircraft: yellow and red are the NOAA aircraft tracks; blue is the NRL aircraft, which was instrumented with ELDORA. The dots show aircraft locations as of 1830 UTC. The yellow track segment is for the 80 min preceding that time; the red and blue track segments are for the preceding 45 min. The yellow NOAA track was part of a wide pattern to determine the broad-scale structure of the cyclone vortex. The red NOAA track was part of an intermediate pattern, with shorter legs across the center of the storm to monitor the two eyewalls. The blue NRL track was the circumnavigation that obtained the key radar and sounding data referred to in this article. The
Two interacting eyewalls, separated by the moat, were contracting inward.

- The vertical lines below the clouds indicates precipitation;
- Thin arrows show the direction of air motion relative to the storm. Dashed segments indicate partially interrupted flow;
- Wavy arrows at the sea surface indicate upward water vapor flux;
- The broad arrows indicate the dry downward motion in the eyewall;
- The hatched zone shows the top of the near-surface moist layer, which is capped by the stabilizing and drying effect of subsiding air above.
THE SECONDARY CIRCULATION:
Eyewall Developments

ER-2 Doppler Radar (EDOP) Views Detailed Super-Anatomy of Intense Hurricane Emily During NASA’s TCSP Experiment

Vertical slice showing rain structure across the entire storm - 1:30 - 2:00 AM CST July 17, 2005

NASA Lockheed ER-2

Hurricane Georges over Hispaniola
EXTERNAL RAINBANDS (1)


EXTERNAL RAINBANDS (2)


Triply-nested, 2-way interactive, movable mesh model using hydrostatic primitive equations, with explicit "liquid+ice" microphysics, initialized with an axisymmetric vortex embedded in uniform easterly flow of 5 m/s on a "f-plane".
# EXTERNAL RAINBANDS (3)


Table 1. Summary of hypotheses that have been proposed to explain the formation of core and outer spiral rainbands within hurricanes. Small-scale bands are defined as observed bands that have ~10 km horizontal scale.

<table>
<thead>
<tr>
<th>Case</th>
<th>Proposed banding mechanism</th>
<th>Brief description</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inertia-buoyancy waves</td>
<td>Outward-propagating disturbance excited by eyewall convection</td>
<td>Three gravity wave modes, all with horizontal scales much larger than small-scale bands (25-200 km)</td>
</tr>
<tr>
<td></td>
<td>(Kurihara 1976)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Inertia-buoyancy waves</td>
<td>Outward-propagating disturbance excited by eyewall convection</td>
<td>Favored horizontal scale ~20 km</td>
</tr>
<tr>
<td></td>
<td>(Willoughby 1977)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Inertia-buoyancy waves</td>
<td>Inward- and outward-propagating Eliassen-Palm waves</td>
<td>Unrealistic phase speeds relative to observations, large variation in proposed horizontal scale with radius</td>
</tr>
<tr>
<td></td>
<td>(Willoughby 1978)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Rayleigh instability</td>
<td>Ekman shearing–induced circulations in the boundary layer, outward propagating</td>
<td>20-60-km horizontal scale, increasing with radius, slow to stationary phase speed</td>
</tr>
<tr>
<td></td>
<td>(Fung 1977)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Symmetric instability</td>
<td>Primarily attributed to eyewall convection</td>
<td>May act as a trigger mechanism for gravity or potential vorticity waves of varying scale</td>
</tr>
<tr>
<td></td>
<td>(Braun 2002)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Boundary layer rolls</td>
<td>Outward propagating, driven by boundary layer shear with deep convection</td>
<td>Deep horizontal roll vortices, structure and propagation similar to small-scale bands</td>
</tr>
<tr>
<td></td>
<td>(GTH98)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Boundary layer rolls</td>
<td>Shear parallel boundary layer rolls</td>
<td>Shallow roll vortices, over one order of magnitude smaller scale than small-scale bands, not suggested to cause rainbands</td>
</tr>
<tr>
<td></td>
<td>(Wurman and Winslow 1998)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Potential vorticity waves</td>
<td>Vortex shedding (outward) and/or potential vorticity source entrainment (inward)</td>
<td>Slow outward velocity and horizontal scale increasing with radius from center of 20-50 km</td>
</tr>
<tr>
<td></td>
<td>(Montgomery and Kallenbach 1997)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Kelvin–Helmholtz instability</td>
<td>Propagating gravity wave mode generated under extreme shear conditions</td>
<td>Scale and propagation characteristics similar to small-scale bands, applied to rainbands associated with postfrontal precipitation</td>
</tr>
<tr>
<td></td>
<td>[Testud et al. (1980) based on mode III waves proposed by Lallas and Einaudi (1976)]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
EXTERNAL RAINBANDS (4)

MacDonald 1968 [Tellus, 20, 138-150]

- potential vorticity: \[ PV = \frac{1}{\rho} \left( \nabla \cdot \mathbf{v} + \theta \nabla \cdot \mathbf{v} + \mathbf{f} \cdot \nabla \right) \cdot \nabla \theta \]

- equation for PV: \[ \frac{D(PV)}{Dt} = \frac{\zeta_a}{\rho} \cdot \nabla \theta + \frac{1}{\rho} \left( \nabla \times \mathbf{F} \right) \cdot \nabla \theta \]

- Rossby PV waves: in a basic state with a horizontal gradient of PV, a perturbation of the PV contours (which are material contours in an adiabatic flow) propagates relative to the basic flow.

In a tropical cyclone, the axi-symmetric PV field, with highest values in the center, is a basic state on which such waves can propagate.\textsuperscript{59}
Linearized non-divergent barotropic model: the non-linear breaking of Rossby waves in a TC-like PV field leads to irreversible distortion of the PV contours and a horizontal spreading of PV, until an axi-symmetric distribution is reached, with highest values in the center.


EXTERNAL RAINBANDS (5)
EXTERNAL RAINBANDS (6)

Montgomery & Kallenbach 1997 [ QJRMS, 123, 435-465 ]

Two-dimensional non-divergent inviscid flow in a « f-plane »: wavenumber-N Rossby waves propagate from a basic state characterized by a stable vorticity « monopole ».

Wavenumber-1

Wavenumber-2
EXTERNAL RAINBANDS (7)

Interaction between the waves and the mean flow leads to an acceleration of the tangential wind inside the radius of maximum wind which increases the relative vorticity \(2 \frac{V_T}{r}\) at low radii (→ « monopole » distribution)
**EXTERNAL RAINBANDS (8)**


An azimuthal wavenumber-2 feature dominates the asymmetry in relative vorticity below 3 km height in hurricane Olivia (1994) (*from reflectivity and wind composites from airborne Doppler radar data*)

![Perturbation vorticity at 3-km height](image)
EXTERNAL RAINBANDS (9)

Chen & Yau 2001 [ J. Atmos. Sci., 58, 2128-2145 ]

An initially axisymmetric hurricane was explicitly simulated using MM5 (Liu et al. 1997) with constant SST=28°C

→ continuous generation of PV through latent heat release in the eyewall (+ spiral bands)

Horizontal distribution of PV at 6 km altitude
Radar reflectivity at 0.5° elevation:
perturbation field = actual field – (7 gates x 7 rays) average + correlation between successive scans

properties of the small-scale spiral structures.

1) They spiral out from the storm center in a clockwise fashion.
2) The scale across the structures is of the order of 10 km.
3) They appear to extend around the storm for distances, along the spiral, of up to 100 km.
4) From the animation, they appear to move with the tangential wind.
5) Individual bands can be followed for periods of at least 1 h.
6) The bands form an angle of perhaps 10° with circles about the center of the hurricane.
7) Along a fixed radius from the hurricane center they would appear to move outward.
8) The variation in reflectivity across the bands is about 10 dBZ.
SMALL-SCALE STRUCTURES (2)

Kelvin-Helmholtz instability combined with boundary-layer radial and tangential wind shear.

Quasi-streamlines rolls, with radial wavelength of 4-10 km, acquire their energy from the vertical shear.
CIRCULATION IN THE EYE (1)
CIRCULATION IN THE EYE (2)

Category 5

Category 3
POLYGONAL EYEWESTAL (1)

Schubert et al., 1999 [ J. Atmos. Sci., 56, 1197-1223 ]

Tropical cyclone eyewall occasionally show polygonal (triangular to hexagonal) shapes. Other observations reveal the existence of intense « mesovortices » within or near the eye region.
POLYGONAL EYEWALL (2)

Barotropic non-divergent model of 200 km x 200 km initialized with a ring of high PV in the eyewall, at some distance from the storm center. When the instability grows to finite amplitude, the vorticity of the eyewall region pools into discrete areas, creating the appearance of polygonal eyewalls with embedded mesovortices.
Barotropic dynamics in the presence of both a cyclonic mean flow and a high PV gradient near the edge of the eye:

– the propagation of vortex Rossby waves in the cyclonic mean flow makes the eye rotate cyclonically
– the rotation period is longer than the period of advected parcels because the vortex Rossby waves propagate upwind
POLYGONAL EYEWALL (4)

Kuo et al. 1999 [ J. Atmos. Sci., 56, 1659-1673 ]

The elliptical eye of typhoon Herb (1996) with a semi-major axis of 30 km and a semi-minor axis of 20 km rotated cyclonically with a period of ≈145 min.
Aircraft flight level data show two distinct regimes of the kinematic and thermodynamic distribution within the eye and the eyewall:

- **1st regime**: angular velocity is greatest within the eyewall and relatively depressed within the eye.
- **2nd regime**: radial profile of vorticity is nearly monotonic with maximum found at the eye center.
- Transition from 1st to 2nd regime can occur in less than 1 h, accompanied with dramatic changes in the thermodynamic structure.
This evolution can be explained through horizontal vorticity mixing (idealized 2D barotropic framework)

**Regime 1**: the eye is warm and dry, $\theta_e$ is high in the eyewall and depressed in the eye

**Regime 2**: relative humidity is close to 100% everywhere, $\theta_e$ is maximum in the eye
POLYGONAL EYEWALL (7)

Perturbations of the horizontal and vertical wind induced by (wavenumber-2) Rossby-waves triggered spiral rainbands in the inner core.