Idealized Tropical Cyclone Structure
What we will cover

• Introduction
• Basic dynamics
• TC Climate
• 2005 Season
• Genesis (IWTC Report)
• Internal structure (IWTC Report)
Tropical Cyclone

- Extension of the Warm Core middle–level vortex to the surface.
- Inducement of Ekman pumping
- Non-linear growth due to increased heating efficiency as vortex strengthens
- Creation of new instability by increased energy through lowering of pressure
- Carnot Cycle of heating
Hurricane Andrew

NOAA-11 Visible
August 23, 1992
12:21 UTC
Figure 10.4  Radar echo pattern seen in Hurricane Alicia (1983) labeled according to the scheme of Fig. 10.3. Contours are for 25 and 40 dBZ. (From Marks and Houze, 1987. Reproduced with permission from the American Meteorological Society.)
Theta_e Structure

Figure 10.10  Equivalent potential temperature $\bar{\theta}_e$ in Hurricane Inez (1966). (From Hawkins and Mbo, 1976. Reprinted with permission from the American Meteorological Society.)
Fig. 13. The tropical cyclone as a Carnot heat engine. See text for explanation.
Carnot Cycle Theory For Tropical Cyclones

- 4 Cycles
  1. Isothermal (diabatic) expansion of inflow along ocean surface
     a) Isothermal heat transfer from ocean surface (ocean surface temperature varies little, pressure lowers and so heat must be absorbed to keep from cooling)
     b) Moisture transfer from ocean surface
     c) Loss of Energy due to friction to surface
  2. Moist Adiabatic Ascent in Eye-Wall
     a) Moist neutral ascent (short time scale so neglect diabatic radiative transfer)
     b) Neglect diabatic gain of entropy by precipitation falling
  3. Isothermal (diabatic) compression in outflow
     a) Gradual sinking balanced by radiational cooling to maintain constant temperature
     b) Work preformed against inertial stability of the environment
  4. Moist Adiabatic Descent within outer convective downdrafts back to surface
     a) Outer convective bands tap into theta_e minimum formed after radiation induced ascent and bring air back to surface moist adiabatically over short time scale so can neglect diabatic radiation
Summary of Carnot Cycle

• Sources of Thermal Energy
  1. Thermal transfer from ocean surface
  2. Latent heat transfer from Ocean surface

• Sinks of Energy
  1. Friction at surface
  2. Work against Inertial Stability in Outflow

• Thermodynamic Efficiency of Cycle
  – A function of temperature difference between hot plate and cold plate divided by mean:
    \[ \frac{T_{sst} - T_{tropopause}}{T_{average}} \]
  – Lowest Pressure attained is a function of:
    • Sinks of Energy
    • Sources (SST)
    • Efficiency (SST and Tropopause)
Maximum Gradient Wind As a function of SST

Fig. 6. Maximum gradient wind (m s⁻¹) as a function of surface air temperature ($T_\text{s}$, °C) and outflow temperature ($T_\text{o}$, °C) computed from (43) for the same conditions as used to construct Fig. 2 and $C_s = C_p$. 
Fig. 4. Minimum attainable surface central pressure (mb) in September (a) for Atlantic and Indian Oceans and (b) for Pacific Ocean. See text for explanation.
Where Do TCs form?

**Figure 10.1** Locations of tropical cyclone formation over a 20-year period. (From Gray, 1979. Reprinted with permission from the Royal Meteorological Society.)
Webster et al. (2005)
In Atlantic, the frequency of storms is well correlated with tropical Atlantic SSTs (Emanuel (2006); Mann and Emanuel (2006)).

![Graph showing the correlation between August-October HADISST 6-18N, 20-60W and annual Atlantic storm count. The graph shows a significant increase in storms from 1970 onward, with an $r^2 = 0.74$ since that year.](image)

Emanuel (2006); Mann and Emanuel (2006)
Excellent agreement in the Atlantic and East Pacific!

Kossin et al. (in review)
Terrible agreement everywhere else!

Kossin et al. (in review)
"Complete" Atlantic Named Storms
1900 to 2006 (with 2.4 open ocean per year 1900-1964)
2005 Hurricane Season
2005 Atlantic Hurricane Season

<table>
<thead>
<tr>
<th>Storm Type</th>
<th>Name</th>
<th>Dates</th>
</tr>
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<tbody>
<tr>
<td>Tropical Storm Arlene</td>
<td></td>
<td></td>
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<tr>
<td>Tropical Storm Bret</td>
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<tr>
<td>Tropical Storm Cindy</td>
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<tr>
<td>4</td>
<td>Hurricane Dennis</td>
<td>7/5-7/11</td>
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<tr>
<td>4(3)</td>
<td>Hurricane Emily</td>
<td>7/11-7/20</td>
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<tr>
<td>Tropical Storm Franklin</td>
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<td>Tropical Storm Gert</td>
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<td>Tropical Storm Harvey</td>
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<td>8/4-8/16</td>
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<td>Tropical Storm Jose</td>
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<td>5</td>
<td>Hurricane Katrina</td>
<td>8/23-8/30</td>
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<td>2</td>
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<td>9/1-9/10</td>
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<td>Tropical Storm Nate</td>
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<tr>
<td>1</td>
<td>Hurricane Ophelia</td>
<td>9/6-9/18</td>
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<td>1</td>
<td>Hurricane Philippe</td>
<td>9/18-9/21</td>
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<td>5</td>
<td>Hurricane Rita</td>
<td>9/18-9/25</td>
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<td>1</td>
<td>Hurricane Stan</td>
<td>9/1-9/5</td>
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<tr>
<td>Tropical Storm Tammy</td>
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<tr>
<td>Tropical Storm Vince</td>
<td></td>
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<tr>
<td>5 (3)</td>
<td>Hurricane Wilma</td>
<td>10/17-10/25</td>
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<td>Tropical Storm Alpha</td>
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<td>2</td>
<td>Hurricane Beta</td>
<td>10/26-10/30</td>
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<tr>
<td>Tropical Storm Gamma</td>
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<td>11/14-11/21</td>
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<td>11/23-11/28</td>
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<td>12/01-12/08</td>
</tr>
<tr>
<td>Tropical Storm Zeta</td>
<td></td>
<td>12/31-1/06</td>
</tr>
</tbody>
</table>

27 Named Storms
7 Named Storms before 8/1
11 Hurricanes
5 Major Hurricane
3 Cat 5 Hurricanes

Lowest MSLP ever for Atlantic Hurricane

12 Named Gulf Storms
7 Gulf Hurricanes
5 Major Gulf Hurricanes
2 Cat 5 Gulf Hurricanes

Lowest MSLP ever for Gulf Hurricane

1 Storm Hits Portugal
Last storm extends into January 2006
2006 Atlantic Hurricane Season

<table>
<thead>
<tr>
<th>Storm Type</th>
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<tbody>
<tr>
<td>Tropical Storm Alberto</td>
<td>6/10-6/14</td>
</tr>
<tr>
<td>Tropical Storm Beryl</td>
<td>7/18-7/21</td>
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<tr>
<td>Tropical Storm Chris</td>
<td>8/1-8/5</td>
</tr>
<tr>
<td>Tropical Storm Debby</td>
<td>8/21-8/27</td>
</tr>
<tr>
<td>Hurricane Ernesto</td>
<td>8/24-9/1</td>
</tr>
<tr>
<td>Hurricane Florence</td>
<td>9/3-9/12</td>
</tr>
<tr>
<td>Hurricane Gordon</td>
<td>9/11-9/20</td>
</tr>
<tr>
<td>Hurricane Helen</td>
<td>9/12-9/24</td>
</tr>
<tr>
<td>Hurricane Isaac</td>
<td>9/27-10/2</td>
</tr>
<tr>
<td>Hurricane Maria</td>
<td>9/1-9/10</td>
</tr>
<tr>
<td>Hurricane Ophelia</td>
<td>9/6-9/18</td>
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- 9 Named Storms
- 2 Named Storms before 8/1
- 5 Hurricanes
- 1 Major Hurricane (questionable)
- 0 Cat 5 Hurricanes
- 1 Named Gulf Storms
- 0 Gulf Hurricanes
- 0 Major Gulf Hurricanes
- 0 Cat 5 Gulf Hurricanes

Most storms seemed to be semitropical
What Happened?
Ocean Heat Content
Effect of Loop Current on OHC

- Storm motion
- Low OHC
- High OHC
- Spent OHC
- Wake Mixing
- Deep thermocline of open Gulf
- Deep thermocline of loop current
- Shallow thermocline of open Gulf
- 10 m
- 75 m
- 150 m
IR (Saturday (9/17) – Sunday (9/25))
Rita
Wilma
Hurricanes Dennis/Cindy/Emily 1999
GOES SAL Tracking Imagery
Hurricanes Erin & Felix 2001
GOES SAL Tracking Imagery
Hurricane Danielle 29 August 1998 00 UTC
GPS dropsondes launched from the NOAA G-IV Jet
Mean Tropical Soundings (Jordan vs 2002)
10-yr climatology (1948-1957)

KEY

- HURRICANE
- TROPICAL STORM

MILES

0 200 400 600

Jordan
2002

Miami

Swan Island

San Juan

Guadeloupe

Grand Cayman
NOSAL vs. SAL Condensate 

NOSAL (left)   SAL (Right)
NOSALZS vs. SALS Condensate
NOSAL (left) SAL (Right)
Minimum MSLP over 72 Hours
2.2 Internal influences on tropical cyclone formation

IWTC-VI
Kevin Tory
Michael Montgomery
23 November 2006
Conclusions

- Saharan Air Layer is a hostile environment for tropical cyclone genesis but has less effect on potential tropical cyclone intensity.
- Hostile effects include
  - Middle level dry layer
  - Middle level jet and associated wind shear (most important)
- Role of aerosols is still to be investigated but we have no reason to believe that cumulus efficiency in forming precipitation or its ability to reach to freezing level is an issue
Introduction

• Genesis requirements
• Vorticity tendency fundamentals
• MCS role in genesis
• Genesis theories of the last decade
• Modeling studies
• Observations
• Recommendations
Genesis Requirements

- Necessary environment for genesis:
  1. Low- to mid-tropospheric cyclonic absolute vorticity
  2. Weak vertical wind shear
  3. Warm ocean
  4. Moist unstable air mass

- Genesis is the transformation from this environment to a TC scale warm-cored self-sustaining vortex

- Convection drives the transformation

- Proposed 2-step genesis definition.
  1. Pre-conditioning: the establishment of the necessary environment.
Vorticity Tendency Fundamentals

Haynes and McIntyre (1987) showed that:

(i) There can be no net transport of PV (\( \mathcal{A} \)) across any isentropic (isobaric) surface;

(ii) PV (\( \mathcal{A} \)) can neither be created nor destroyed, within a layer bounded by two isentropic (isobaric) surfaces.

Thus, TC genesis involves a near-horizontal redistribution of PV (\( \mathcal{A} \)).
Vorticity Tendency Fundamentals

What dynamical processes can lead to the development of cyclonic vortex core that spans the troposphere?

Vortex cores of tropospheric depth can develop in deep convective regions.

*Modeling results show convergence into deep convective regions (6-8 km deep) can lead to vortex enhancement.*
Vorticity Tendency Fundamentals

Low- to mid-level vorticity convergence,
balanced by divergence at larger radii.
How does the vortex intensify above ~7 km where the flow is divergent?

A vertical advection-like effect is responsible for the upward growth in intense updrafts. HM87 is not violated because local increases are balanced by nearby weakening from tilting-like effects.
Vorticity Tendency Fundamentals

Low- to mid-level vorticity convergence,
balanced by divergence at larger radii.

Vertical advection-like effect
balanced by tilting-like effect at updraft edge.
How do we get from this, …to this?

Somewhere on the web.

MCS role in genesis

Fig. 14 from Houze (2004) *Rev. of Geo.*
MCS role in genesis

Fig. 14 from Houze (2004) Rev. of Geo.
MCS role in genesis

Fig. 14 from Houze (2004) Rev. of Geo.
MCS role in genesis

It is useful to consider genesis (step 2) to involve an atmospheric transition from a mean SDP to a mean CDP (e.g., Mapes and Houze 1995; Raymond et al. 1998).
Genesis Theories
Ritchie, Holland, Simpson: Top-down merger theory.
Genesis Theories
Ritchie, Holland, Simpson: Top-down merger theory.

Outstanding Issues:
1. What does the corresponding divergence profile look like?
2. How do we get from this, ...to this?
Genesis Theories

Bister and Emanuel (1997):
Top-down showerhead theory.

a. Mid-level vortex advected down towards the surface, while evaporation of rain moistens the air progressively downward.

b. Moistened cyclonic layer reaches the surface. Surface fluxes increase low-level theta_e.

c. Near downdraft-free convection develops in the moist environment and converges cyclonic vorticity.

Fig. 13 from Bister and Emanuel (1997) *Mon. Wea. Rev.*
Bister, and Emanuel (1997): Top-down showerhead theory.

Outstanding Issues:

1. Downward advection of cyclonic vorticity leads to nearby changes in the opposite sense through tilting.

2. Divergence weakens vorticity magnitude near the surface.

3. Dry air inflow would inhibit the moistening process.

4. A moist neutral atmosphere is required for downdraft-free convection. (Zipser, per. com.)

5. But is downdraft-free convection or near downdraft-free convection necessary?

Fig. 13 from Bister and Emanuel (1997) *Mon. Wea. Rev.*
Genesis Theories
Montgomery, Enagonio: Bottom-up theory.

Consider the interaction of the stratiform and convective vortices.
Genesis Theories

Montgomery, Enagonio: Bottom-up theory.
Genesis Theories
Montgomery, Enagonio: Bottom-up theory.

Assumptions:
1. Convective regions must develop in low-level cyclonic environment.
2. Sufficient number and/or size of convective regions are necessary for such an interaction to take place.
Modeling Studies
Chen and Frank (1993), modeling study:
Modeling Studies
Chen and Frank (1993), modeling study:

Convective region “takes over”.

[Diagram showing atmospheric circulation and convective regions]
Convective region “takes over”.
Grid resolution 25 km, hence minimum resolved updraft Scale is about 100 km.
Modeling Studies
Chen and Frank (1993), modeling study:

Issues:
1. The convective region quickly dwarfs the stratiform region. What happened?
2. Could this adequately represent the transformation from an SDP dominant MCS to a CDP dominant MCS in the real world?
3. Or is it just a product of an overly active convective paramaterization scheme, which forces updrafts on the minimum resolvable scale (~100 km)?
Modeling Studies
Montgomery et al. (2006) modeling study:

*Illustrates a possible path from this,*

...to *this*?
Montgomery et al. (2006) idealised modeling study:

- RAMS, near cloud resolving, non-hydrostatic, 2 and 3 km grid spacing.

- Intense cyclonic vortices develop on the convective scale (vortical hot towers, VHTs).

- VHTs interact to form larger more intense vortices (upscale vortex cascade).

- Net heating in the VHTs generates inflow above the boundary layer and system-scale convergence of angular momentum (System Scale Intensification, SSI).
Modeling Studies
Montgomery et al. (2006) idealised modeling study:

Vortex Upscale Cascade
Modeling Studies

Montgomery et al. (2006) modeling study:

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Modeling Studies

Montgomery et al. (2006) modeling study:

Vortex Upscale Cascade
Montgomery et al. (2006) modeling study:

System-Scale Intensification
Modeling Studies
Hendricks et al. (2004) modeling study:

Vortex upscale cascade example

- Low- and mid-level vorticity distribution
- Low-level merger
- Mid-level anticyclonic absolute vorticity anomalies consistent with HM87
- Ejection of anticyclonic absolute vorticity anomalies
Modeling Studies

Hendricks et al. (2004) modeling study:
Modeling Studies

Davis and Bosart (2006) coming soon to QJRMS:

15 hours

Bore front

Squall line

Deep convection, reduced downdrafts

10 m winds, Cloud top temperatures.
Modeling Studies

Davis and Bosart (2006) coming soon to QJRMS:

36 hours

Relatively large cyclonic vortex results.

10 m winds, Cloud top temperatures.
Modeling Studies

Davis and Bosart (2006) coming soon to QJRMS:

Deep convection preferred to the east of the circulation centre.

“The small-scale vorticity anomalies were the result of relatively intense convection and heating on the scale of individual cumulonimbi or convective systems less than ~50 km in length.”

10 m winds, Cloud top temperatures.
Deep convection preferred to the east of the circulation centre.

“The small-scale vorticity anomalies were the result of relatively intense convection and heating on the scale of individual cumulonimbi or convective systems less than ~50 km in length.”

10 m winds, Cloud top temperatures.
Deep convection preferred to the east of the circulation centre.

“The small-scale vorticity anomalies were the result of relatively intense convection and heating on the scale of individual cumulonimbi or convective systems less than ~50 km in length.”
Modeling Studies

Davis and Bosart (2006) coming soon to QJRMS:

84 hours

Deep convection preferred to the east of the circulation centre.

“The small-scale vorticity anomalies were the result of relatively intense convection and heating on the scale of individual cumulonimbi or convective systems less than ~50 km in length.”

10 m winds, Cloud top temperatures.
Modeling Studies

Tory et al. (2006): *Elcho Island storm*

TC develops on the poleward side (cyclonic shear) of the monsoon westerly surge.

A number of low and mid-level PV anomalies merge/ are axisymmetrized into a central PV monolith.

Shear tilts developing PV cores, whereas convection on the down-tilt side serves to realign them.

- 850 PV anomaly at the initial circulation centre is axisymmetrized into the PV monolith by 14 hours.

- Significant tilt on the developing PV monolith at 8,10 hours with strongest convection on the downtilt side.

- Continued convection on the downtilt side aligns the developing PV monolith.
Elcho Island Storm

850 hPa PV, wind
500 hPa PV, wind

Reference Vectors

250 hPa up motion
- 1—3 Pa/s
- 3—5 Pa/s
Elcho Island Storm

850 hPa PV, wind
500 hPa PV, wind

250 hPa up motion
- 1—3 Pa/s
- 3—5 Pa/s

Reference Vectors

0 25
Elcho Island Storm

850 hPa PV, wind
500 hPa PV, wind

250 hPa up motion
- 1—3 Pa/s
- 3—5 Pa/s

Reference Vectors

04
Elcho Island Storm

850 hPa PV, wind
500 hPa PV, wind
250 hPa up motion

Reference Vectors

06
Elcho Island Storm

850 hPa PV, wind
500 hPa PV, wind
250 hPa up motion

Reference Vectors

0
25

1—3 Pa/s
3—5 Pa/s
850 hPa PV, wind
500 hPa PV, wind
250 hPa up motion

Reference Vectors

1—3 Pa/s
3—5 Pa/s
Elcho Island Storm

850 hPa PV, wind
500 hPa PV, wind
250 hPa up motion

Reference Vectors

0 25

1—3 Pa/s
3—5 Pa/s

20
Elcho Island Storm

850 hPa PV, wind
500 hPa PV, wind
250 hPa up motion

Reference Vectors

0  25

250 hPa up motion
- 3 Pa/s
- 5 Pa/s

24
Modeling Studies

Davis and Bosart (2006): Similar development to Montgomery, Hendricks. VHTs play an important role.

Tory et al. (2006): Again similar development, except coarser resolution (~15 km grid spacing) leads to larger-scale features.

Note: while genesis was underway downdrafts were present in all three higher resolution studies.
Modeling Studies

- Modeling studies show a transition from mean SDP to mean CDP without the need for downdraft free convection.

- Downdraft free convection (or near downdraft free convection) may result in time.

- Good results using 0.15° grid spacing in TC-LAPS suggests genesis may be driven largely by scales resolvable by this model.
Modeling Studies

• Hypothesis:

1. The development of multiple convective hot towers within an MCS drives the transition from mean SDP to mean CDP.

2. With sufficient cyclonic vorticity, continued convective activity, and mean CDP, a positive feedback will result, which will lead to even stronger CDP and weaker downdrafts (to satisfy continuity).
Observations

• Until recently observations have been too sparse to assess the behavior predicted in the higher resolution modeling studies.

• Instead only profiles of MCS divergence, vorticity and vertical velocity have been determined from most field experiments.
Observations

- Kingsmill and Houze (1999)
Observations

- Kingsmill and Houze (1999)

Deep layer inflow
Observations

• Kingsmill and Houze (1999)

Saturated $\theta_e$ decreasing with height in updraft inflow.
Observations

- Kingsmill and Houze (1999)

The higher the BL theta_e is the longer lived and larger the MCSs tend to be.
Observations

- Kingsmill and Houze (1999)

Very low theta_e mid-level inflow. Uncertain connection to the convective scale downdrafts.
Observations

- Kingsmill and Houze (1999)

*Uncertain connection to the convective scale downdrafts.*

*Shallow patches of low theta_e air in the precipitating regions of the BL.*

VHTs?
• VHT’s? Montgomery et al. (2006) show low-level theta_e distribution consistent with Kingsmill and Houze.

Shallow patches of low theta_e air in the precipitating regions of the BL.
Observations

• Reasor et al. (2005) and Sippel et al. (2006) used ground based and airborne Doppler radar respectively to investigate some of the vorticity structures present during the formation of Hurricane Dolly and TS Allison.

• The development process was consistent with the modeling study of Hendricks et al. (2004).

• At some point in the development all three showed an area of enhanced low-level cyclonic vorticity, with a feeder band of discrete vortices spiralling toward the enhanced area.
Observations

Enhanced vorticity
Feeder band
Observations

Hendricks et al. (2004).

Sippel et al. (2006)

Enhanced vorticity

Feeder band
Tropical Cyclone
Inner Core Dynamics

Jeff Kepert
Bureau of Meteorology Research Centre

Team: Michael Foley, Jeff Hawkins, Jim Kossin, David Nolan, Melinda Peng, Roger Smith, Yuqing Wang and Samuel Westrelin

Sixth International Workshop on Tropical Cyclones,
Costa Rica, 2006

Hurricane Isabel, 12 Sep 2005. UW-CIMSS Image
Fig. 2.9 Vertical-zonal cross-section of: (a) azimuthal winds (kt); and (b) temperature anomaly (K) in Hurricane Hilda (1964) (Hawkins and Rubsam, 1968).
Fig. 2.8 Schematic of the secondary circulation and precipitation distribution for a tropical cyclone similar to Hurricane Gilbert at the time in Fig. 2.4 (Willoughby 1988).
Regimes for Eye Structure

Hurricane Diana (1984)

Kossin and Eastin (2001) JAS
Eyewall Meso-vortices

- Ring of vorticity (U-shaped wind profile) is barotropically unstable and can break down into small vortices.
- These may merge into a “vortex monopole”.
  - V-shaped wind profile

Kossin and Eastin (2001) JAS
Where does the instability come from?

- Latent heat release generates vorticity in eyewall.

- Subsidence suppresses vorticity in eye (squashing).

- Haynes and MacIntyre (JAS, 1987)
  - wrote vorticity equation in flux form
  - showed that total vorticity in a layer is constant.
  - vorticity changes by horizontal rearrangement.

- Therefore
  - Vorticity increase in eyewall must be balanced by reduction in eye and adjacent areas.
  - So intense storms tend to be more peaked ($V \sim r^{-0.7}$) than weak ones ($V \sim r^{-0.3}$). (Mallen et al. JAS 2005; Willoughby et al. MWR 2006)
Vortex Crystals / Polygonal Eyewalls

- Some unstable eyewall configurations can break down into a quasi-steady configuration of several vortices that resist further merger.

Kossin and Schubert (2005) BAMS
Potential Intensity (PI)

- PI theories attempt to predict maximum intensity for given thermodynamics.
- e.g. Emanuel (Carnot cycle heat engine, WISHE), Holland (CAPE-based).
- Both sensitive to $\theta_e$ of boundary layer beneath eyewall.

Fig. 3. Hypothetical air trajectory in a modified Carnot cycle. Air does not flow into the center but instead turns and flows up through the eyewall. The budget calculations discussed in text are performed inside the dashed box.
Fig. 1. Dependence of minimum sea level pressure (MSLP) on eyewall surface relative humidity (see text for details) predicted by Holland’s (1997) (solid) and Emanuel’s (1997) (dashed) MPI theories. Initial conditions: $T_s = 300$ K and $p_{env} = 1015$ mb.
EMV’s and Superintensity

- Surface fluxes and low pressure can cause very high values of \( \theta_e \) in eye.
- EMV’s, other instabilities, BL circulation can mix this into the eyewall updraft.
- Storm can exceed PI from theory.
- Isabel (13 Sept) exceeded PI by approx 20 m/s.

(Montgomery et al., 2006, BAMS)
EMV Forecast Implications

- Pressure perturbation – minimum pressure is not necessarily the central pressure.
- Wind perturbation – part of the storm, but variable on short time-scales.
- Superintensity.
- How often are they detectable? Predictable?
- Should warnings of intensity or best-track analyses include their effect?
EMV’s in a Sheared TC

FIG. 17. (a) Absolute vorticity (shading) and divergence (contours) at 25.8 h averaged over the 1–4-km layer. Contour intervals for vorticity and divergence are $1 \times 10^{-3}$ s$^{-1}$ with vorticity starting at $2 \times 10^{-3}$ s$^{-1}$. (b) Absolute vorticity (shading) and pressure perturbation (contours) for the same time and layer. Pressure perturbation is obtained by subtracting the azimuthal mean pressure. The contour interval is 0.5 hPa. In (a) and (b), positive (negative) values are indicated by solid (dashed) lines and the zero contour is omitted.

Braun et al. (2006) JAS
Annular Hurricanes

Hurricane Luis

Knaff et al (2003) MWR
Eyewall Replacement Cycle

Hurricane Wilma
Rotating WN 2 in eye of Elena

- Fourier analysis shows radar asymmetry consists of stationary WN 1 and rotating WN 2.
- WN 2 associated with generation of bands on NW eyewall.
Outward and retrograde propagation of vortex Rossby waves
Vortex Rossby Waves

- Propagate slower than azimuthal wind (about half speed).
- Propagate outwards.
- Good match between theory and observations for wavenumber 1 and 2.
  - phase speed and group velocity
- Impact on intensity
  - consume low-level moist inflow
  - transport angular momentum inwards
  - help to resist shear
  - still subject of much debate!
In BL, flow is across angular momentum surfaces due to friction.

Above BL, secondary flow conserves angular momentum.

Angular momentum

Top of BL

Azimuthal wind

Kepert and Wang (2001) JAS
Large Variation in Nearby Wind Profiles

Idealised Model

Observed, Hurricane Mitch

Thick: Inside RMW
Thin: Outside RMW

Kepert (2006b) JAS
Supergradient Flow

Supergradient flow from 300 m – 2 km.

- Max imbalance ~10 m/s (15%) at 700 m.

- In contrast, H Georges (1998), similar intensity but not supergradient.
  - Due to relatively “flat” wind profile outside of RMW.

Kepert (2006b) JAS

Hurricane Mitch (1998)
Between Storms

- Mean observed eyewall normalised wind speed profile in 7 storms.
- Significant variation
  - Incl in surface wind.
- Similar variation present in idealised simulations (Kepert and Wang 2001).
  - Due to differences in storm structure.
BL Variability Within the Storm

Kepert (2006a) JAS

Hurricane Georges (1998)
BL Variability Within the Storm

Hurricane Georges (1998)

$v_{rad}$

Kepert (2006a) JAS
Hurricane Bonnie (1998) Schematic

either entrainment or
1/2 viscous dissipation
balances budget

$\bar{\theta}_e \sim 357$

$\frac{1}{2} \varepsilon \sim 110 \text{ Wm}^{-2}$

$830 \text{ Wm}^{-2}$

$10 \text{ ms}^{-1}$

inflow lcp 1600 m

$\bar{\theta}_e \sim 353$

$\frac{1}{2} \varepsilon \sim 10 \text{ Wm}^{-2}$

$520 \text{ Wm}^{-2}$

$530 \text{ Wm}^{-2}$

Radial distance to circulation center (km)

Wroe and Barnes (2003) MWR
- Reflectivity bands:
  - outwards moving
  - 10 – 15 km scale
  - ~5 km deep.

Gall et al (1998) MWR
- High-res model simulations generate similar features.

Coherent in all Variables

Romine and Wilhelmson (2006) MWR
Shear instability of radial flow

Nolan (2005) DAO
Boundary layer rolls

- Instability of Ekman-like flow.
  - Shear instability of radial flow.
- Counter-rotating rolls aligned almost with mean flow.
- Downdrafts associated with strong surface winds.
- TC’s are ideal for BL rolls.

Foster (2005) MWR
Fine-scale band dynamics

• Good evidence for shear instability of radial flow.
  – Similar to Kelvin-Helmholtz instability.
  – Similar to boundary-layer rolls.
  – Modified by moist processes.
  – Likely at multiple scales.
  – Favoured ahead of storm and near landfall = high shear situations.
Summary

• Near-surface winds
  – Spatial variation in surface wind factor
  – Streaks / boundary-layer rolls / fine-scale spiral bands.
  – Measurement advances.

• Supergradient flow in upper boundary layer.

• Strong ability to monitor eyewall replacement cycle
  – With impact on forecasts, at times.

• Eyewall mesovortices
  – Direct hazard
  – Impact on storm structure
  – Role in “superintensity”

• Vortex Rossby Waves
  – Explain inner-core scale spiral bands (structure and motion)
  – Important in genesis, response to shear, intensification.
  – Less successful in explaining fine-scale bands.