Tropical Cyclone Intensification in Sheared Environments: Katia (2011) and Ophelia (2011)

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Special thanks to:
Thomas Auligne and Thomas Galarneau

NSF Graduate Research Fellowship Grant No. DGE 1060277
Motivation

- Vertical wind shear is generally detrimental for tropical cyclones (TCs)
  - Vortex tilt
  - Asymmetric convection
  - Dry air entrainment
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  - Vortex tilt
  - Asymmetric convection
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- Often TCs form and intensify in spite of moderate shear ($\geq 5 \text{ m s}^{-1}$)
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Ophelia (2011), images source: NASA
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28 Sept 2011

Shear $> 10 \text{ m s}^{-1}$

01 Oct 2011

Ophelia (2011), images source: NASA
Motivation

- TC intensity forecasts in situations of moderate shear are characterized by large uncertainty (Zhang and Tao 2013)
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**Purposes of this project:**

- Understand how weak, sheared tropical storms intensify
- Identify alternatives to improve forecasts of sheared storms
Tool: ensemble forecasts

Advanced Hurricane Weather Research and Forecasting (AHW) model
(Davis et al. 2000, Davis et al. 2008)
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- WRF-ARW core and physics
- Ensemble Kalman filter (EnKF) data assimilation
  - 6-hourly cycling
  - 96 members
Tool: ensemble forecasts

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- Multiple domains (36/12/4 km)
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- WRF-ARW core and physics
- Ensemble Kalman filter (EnKF) data assimilation
  - 6-hourly cycling
  - 96 members
- Multiple domains (36/12/4 km)
- No cumulus parameterization on 4-km domain

AHW model domains
Focus: weak tropical storms

Katia

30 Aug 2011
AHW forecasts for Katia (0000 UTC 30 August 2011)

• Good agreement in track forecasts, but high variability in MSLP forecasts
• How did Katia intensify in some members despite the initial shear of 12 m s\(^{-1}\)?
• Compare 12 strong and 12 weak members
AHW forecasts for Katia (0000 UTC 30 August 2011)

- Good agreement in track forecasts, but high variability in MSLP forecasts.
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Compare 12 strong and 12 weak members.
Motivation

Methods

Results: Katia

Results: Ophelia

Conclusions

Extra

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  - Compare 12 strong and 12 weak members
Comparison of the inner-core (100-km radius)

**Area-averaged vorticity**

• Circulation of strong members strengthens and deepens
• Circulation of weak members gradually weakens

**Comparison**

<table>
<thead>
<tr>
<th>Height (km)</th>
<th>Forecast Time (hr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

[10^5 s⁻¹]
Comparison of the inner-core (100-km radius)

- Circulation of strong members strengthens and deepens.
Comparison of the inner-core (100-km radius)

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Area-averaged vorticity

Circulation of strong members strengthens and deepens.

Circulation of weak members gradually weakens.
Vorticity budget

Following Davis and Galarneau (2009):

\[ \frac{\partial C}{\partial t} = - \bar{\eta} \tilde{\delta} A - \int \eta' V_h' \cdot \hat{n} dl + \int \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} dl + Fr \]

\( C \): circulation (area-averaged vorticity)
\( \bar{\eta} \): mean absolute vorticity along the box
\( \tilde{\delta} \): mean divergence over area \( A \)
\( \eta' \): eddy vorticity
\( V_h' \): eddy horizontal wind
\( V_h \): full horizontal wind
\( \omega \): vertical velocity
Vorticity budget

Following Davis and Galarneau (2009):

$$\frac{\partial C}{\partial t} = - \overline{\eta \tilde{\delta} A} - \iint \eta' V'_h \cdot \hat{n} dl + \iint \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} dl + Fr$$

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Contributions to the vorticity budget

\[
\frac{\partial C}{\partial t} = - \langle \eta \tilde{\delta} A \rangle - \int \eta' \mathbf{V}_h' \cdot \hat{n} dl + \int \omega \left( \hat{k} \times \frac{\partial \mathbf{V}_h}{\partial p} \right) \cdot \hat{n} dl + Fr
\]

- stretching
- eddy vorticity flux
- tilting
- friction
Contributions to the vorticity budget

**Integrated tendencies**

\[
\frac{\partial C}{\partial t} = - \tilde{\eta} \delta A \tag{stretching} - \int \nabla' \mathbf{V}_h \cdot \hat{n} d\ell + \int \omega \left( \mathbf{k} \times \frac{\partial \mathbf{V}_h}{\partial p} \right) \cdot \hat{n} d\ell + \text{Fr} \tag{friction} \]

**Area-averaged vorticity**

- **Strong**
  - Pressure levels: 400, 500, 600, 700, 800, 900 hPa
  - Forecast time: 0, 6, 12, 18, 24, 30, 36, 42, 48 hr.
  - Color scale: [0, 30] \(10^5 \text{s}^{-1}\)

- **Weak**
  - Pressure levels: 400, 500, 600, 700, 800, 900 hPa
  - Forecast time: 0, 6, 12, 18, 24, 30, 36, 42, 48 hr.
  - Color scale: [0, 30] \(10^5 \text{s}^{-1}\)
Contributions to the vorticity budget

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\frac{\partial C}{\partial t} = - \tilde{\eta} \delta A + \int \eta' \mathbf{V}_h' \cdot \mathbf{n} dl + \int \omega \left( \mathbf{k} \times \frac{\partial \mathbf{V}_h}{\partial p} \right) \cdot \mathbf{n} dl
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- stretching
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- friction

Area-averaged vorticity

Area-averaged vorticity change (10^{-5} \text{s}^{-1})

Motivation Methods Results: Katia Results: Ophelia Conclusions Extra
Contributions to the vorticity budget

\[
\frac{\partial C}{\partial t} = - \bar{\eta} \delta A - \oint \eta' \mathbf{V}_h' \cdot \mathbf{n} dl + \oint \omega \left( \mathbf{\hat{k}} \times \frac{\partial \mathbf{V}_h}{\partial p} \right) \cdot \mathbf{n} dl + Fr
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- \text{stretching}
- \text{eddy vorticity flux}
- \text{tilting}
- \text{friction}
Why stretching+tilting?
Why stretching+tilting?

Motivation

Methods

Results: Katia

Results: Ophelia

Conclusions

Extra

Strong member (24 hr)

Weak member (24 hr)

shading: CAPE contours: 500–850 hPa vertical velocity

Rios-Berrios et al., JAS, revised.
Contrasting cases

Katia

Ophelia

30 Aug 2011

28 Sept 2011
AHW ensemble forecasts for Ophelia (1200 UTC 28 Sept 2011)
AHW ensemble forecasts for Ophelia (1200 UTC 28 Sept 2011)

Motivation

Methods

Results: Katia

Results: Ophelia

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Extra
AHW ensemble forecasts for Ophelia (1200 UTC 28 Sept 2011)

- Also large variability in intensity forecasts
AHW ensemble forecasts for Ophelia (1200 UTC 28 Sept 2011)

- Also large variability in intensity forecasts
- Repeat the same steps by comparing strong and weak members
Comparison of the inner-core (75-km radius)

Area-averaged vorticity

• Circulation of strong members strengthens and deepens right from the onset
• Circulation of weak members remains weak and shallow

Area-averaged vorticity
Comparison of the inner-core (75-km radius)

- Circulation of strong members strengthens and deepens right from the onset

**Area-averaged vorticity**

![Diagram showing area-averaged vorticity with color scales indicating vorticity values]
Comparison of the inner-core (75-km radius)

- Circulation of strong members strengthens and deepens right from the onset
- Circulation of weak members remains weak and shallow
Contributions to the vorticity budget

\[
\frac{\partial C}{\partial t} = - \overline{\eta \tilde{\delta} A} - \int \eta V'_h \cdot \hat{n} dl + \int \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} dl + Fr
\]

- **Stretching**: \( \overline{\eta \tilde{\delta} A} \)
- **Eddy Vorticity Flux**: \( \int \eta V'_h \cdot \hat{n} dl \)
- **Tilting**: \( \int \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} dl \)
- **Friction**: \( Fr \)
Contributions to the vorticity budget

Integrated tendencies

\[
\frac{\partial C}{\partial t} = - \eta \tilde{\delta} A + \iint \eta' \mathbf{v}' \cdot \hat{n} dl + \iint \omega \left( \mathbf{k} \times \frac{\partial \mathbf{v}_h}{\partial p} \right) \cdot \hat{n} dl + Fr
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Area-averaged vorticity

- Strong
- Weak
Why also stretching+tilting?
Why also stretching+tilting?

Strong members (12 hr)

Weak members (12 hr)

shading: 500-hPa vertical velocity

vectors: 500-hPa horizontal vorticity

Rios-Berrios et al., JAS, to be submitted.
Concluding remarks
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- TC intensification amid moderate shear

- Vortex stretching + tilting

- Two cases: Katia (easterly shear) and Ophelia (westerly shear)

- Amount and location of convection was key in both cases

- Need to better understand 3-D structure and evolution of convection in weak, sheared tropical storms
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  - Two cases: Katia (easterly shear) and Ophelia (westerly shear)
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Extra slides
Comparing the environment (within 500-km radius)

- Vortex removed using the method of Galarneau and Davis (2013)
- Strong members have weaker shear during 18–36 h
- Strong members have significantly more precipitable water
Comparing the environment (within 500-km radius)

- Ensemble mean
- Strong members
- Weak members

- Vortex removed using the method of Galarneau and Davis (2013)

Difference is statistically significant
Comparing the environment (within 500-km radius)

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- weak members

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Comparing the environment (within 500-km radius)

- Moderate shear, only significantly different after 24 hrs
- Strong members have lower SSTs
- Small differences in PW only significant between 0–6 hrs
- Difference is statistically significant
Comparing the environment (within 500-km radius)

- Moderate shear, only significantly different after 24 hrs

200–850 hPa Wind Shear Magnitude

- ensemble mean
- strong members
- weak members

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**200–850 hPa Wind Shear Magnitude**

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**200–850 hPa Wind Shear Magnitude**

**Sea surface temperature**

**Total precipitable water**

- difference is statistically significant
Contributions to the circulation budget

Area-averaged vorticity

- Similar to the 12–24 hr period, except for deeper stretching
Contributions to the circulation budget

Integrated tendencies

- strong
- weak

- tilting
- stretching
+ fr

eddy flux

Area-averaged vorticity

- Similar to the 12--24 hr period, except for deeper stretching
Motivation Methods Results: Katia Results: Ophelia Conclusions Extra

Distribution of 500–850 hPa vertical velocity

- Most of the convective updrafts are left-of-shear in strong members, but downshear in weak members.
Why also stretching+tilting?
Why also stretching+tilting?

Strong member (12 hr)

Weak member (12 hr)

shading: 200-hPa potential vorticity

contours: 500–850 hPa vertical velocity
Why is more left-of-shear convection important?
Why is more left-of-shear convection important?

**Strong members**

- Shading: 250-hPa potential vorticity

**Weak members**

- Barbs: 250-hPa storm-relative winds