The role of African easterly waves north of the African easterly jet on tropical cyclogenesis

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ATM 741 Project Presentation
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Most tropical cyclones (TCs) begin as African easterly waves (AEWs)

**Traditional thinking:** tropical cyclogenesis originates from waves south of African easterly jet (AEJ)
Two propagation paths discovered in the late 1960’s (Carlson 1969)
Background

- Two propagation paths!
Two propagation paths!

- Forms from Saharan heat low
- Maximized at low-levels (850 hPa)

Forms from moist convection and jet
- Maximized at mid-levels (700 hPa)
Background

- Two propagation paths!
  - AEW_N
    - Forms from Saharan heat low
    - Maximized at low-levels (850 hPa)
  - AEW_S
    - Forms from moist

Can AEW_Ns contribute to tropical cyclogenesis?
Can AEW\textsubscript{N}s contribute to tropical cyclogenesis?

NOT REALLY

Track density per month (Thorncroft and Hodges 2001; Hopsch et al. 2007)

Guinea highlands enhances PV generation associated with AEW\textsubscript{S} (Thorncroft and Hodges 2001; Hopsch et al. 2007)
Can AEW_Ns contribute to tropical cyclogenesis?

**YES**

Average number of TCs, AEWs, AEW_N, and AEW_S per season (Chen et al. 2008)
Can $\text{AEW}_N$s contribute to tropical cyclogenesis?

**YES**

Wet and Dry vortices merge and form TS Debby in 2006 *(Chen and Liu 2014)*
1. Can an AEW\textsubscript{N} contribute to tropical cyclogenesis?
   - Lots of low-level cyclonic relative vorticity
   - Very dry...
Questions

1. Can an AEW\textsubscript{N} contribute to tropical cyclogenesis?
   - Lots of low-level cyclonic relative vorticity
   - Very dry...

2. What is the relative or collective importance of AEW\textsubscript{N}s and AEW\textsubscript{S}s on tropical cyclogenesis?
   - AEW\textsubscript{S}s can develop ample low-level relative vorticity on its own through topographically-enhanced convection
   - Relative vorticity associated with the AEW\textsubscript{N} may be important
   - Merging can increase the low-level vorticity
Outline

1. Can an AEW_N contribute to tropical cyclogenesis?
   - Observational data lacks high spatial and temporal resolution
   - Move to modeling framework

2. What is the relative or collective importance of AEW_Ns and AEW_Ss on tropical cyclogenesis?
   - Vorticity budget (described later)
   - Quantify the importance of merging process
Case Study

- Investigate the evolution of Hurricane Danielle (2004)
- Associated with an $AEW_N$ and $AEW_S$ that merged within the main development region (MDR)
Methodology

Version 3.7.1 of the Advanced Research WRF (ARW)

- Single stagnant domain
- 27 km horizontal resolution
- 61 vertical levels
- ERA-Interim Reanalysis and NCEP Real-Time SST analysis initialization
- Output every 30 minutes

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameterization</th>
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<tbody>
<tr>
<td>microphysics</td>
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</tr>
</tbody>
</table>
Methodology

Version 3.7.1 of the Advanced Research WRF (ARW)

Two model simulations:

**Control:** ERA-Interim reanalysis inputted

**No Vortex:** $\text{AEW}_N$ removed in the model

- 61 vertical levels
- ERA-Interim
  - Reanalysis and NCEP
  - Real-Time SST
  - analysis initialization
- Output every 30 minutes

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Observed Evolution

1800 UTC 10

- start time
- merging begins
- merging ends

TS

Relative Vorticity (850 hPa)

1800 UTC 10 Aug 2004

Brightness Temperature

1800 UTC 10 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10

$10^{-5}$ s$^{-1}$

-72 -60 -48 -36 -24 -12 0 12 24 36 48

°C
Observed Evolution

1800 UTC 10
start time

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 14
TS

0000 UTC 11 Aug 2004

Relative Vorticity (850 hPa)

Brightness Temperature

-10 -8 -6 -4 -2 0 2 4 6 8 10

10^{-5} \text{s}^{-1}

-72 -60 -48 -36 -24 -12

°C
Observed Evolution

1800 UTC 10: Start time
1200 UTC 11: Merging begins
1200 UTC 12: Merging ends
1200 UTC 14: TS

Relative Vorticity (850 hPa)

Brightness Temperature
Observed Evolution

1800 UTC 10

1200 UTC 11

merging begins

1200 UTC 12

merging ends

1200 UTC 14

TS

Observed vorticity (850 hPa)

Relative Vorticity (850 hPa) 1200 UTC 11 Aug 2004

25°N

20°N

15°N

10°N

5°N

30°W 20°W 10°W 0°

Brightness Temperature 1200 UTC 11 Aug 2004

30°W 20°W 10°W 0°

°C

-10 -8 -6 -4 -2 0 2 4 6 8 10

10^-5 s^-1

-72 -60 -48 -36 -24 -12 0 12 24 36 48

°C
Observed Evolution

1800 UTC 10

start time

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 14
TS

Relative Vorticity (850 hPa)

Brightness Temperature

-10 -8 -6 -4 -2 0 2 4 6 8 10
10^{-5} \text{s}^{-1}

-72 -60 -48 -36 -24 -12 0 12 24 36 48 °C
Observed Evolution

1800 UTC 10
start time

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 14
TS

Relative Vorticity (850 hPa)

0000 UTC 12 Aug 2004

Brightness Temperature

0000 UTC 12 Aug 2004

Reference Vector

10^-5 s^-1

°C
Observed Evolution

1800 UTC 10

start time

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 14
TS

Relative Vorticity (850 hPa)

0600 UTC 12 Aug 2004

Brightness Temperature

0600 UTC 12 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10

10^{-5} \text{ s}^{-1}

-72 -60 -48 -36 -24 -12 0 12 24 36 48

°C
Observed Evolution

1800 UTC 10

-start time-

1200 UTC 11

merging begins

1200 UTC 12

merging ends

1200 UTC 14

TS

10^-5 \text{ s}^{-1}

Relative Vorticity (850 hPa)

1200 UTC 12 Aug 2004

Brightness Temperature

1200 UTC 12 Aug 2004

-72 -60 -48 -36 -24 -12 0 12 24 36 48

°C
Observed Evolution

1800 UTC 10
start time

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 14
TS

Relative Vorticity (850 hPa)

1800 UTC 12 Aug 2004

Brightness Temperature

1800 UTC 12 Aug 2004
Observed Evolution

1800 UTC 10

start time

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 14
TS

Relative Vorticity (850 hPa)

0000 UTC 13 Aug 2004

Brightness Temperature

0000 UTC 13 Aug 2004

10^{-5} \text{s}^{-1}

°C
Observed Evolution

- **Start time**: 1800 UTC 10
- **Merging begins**: 1200 UTC 11
- **Merging ends**: 1200 UTC 12
- **TS**: 1200 UTC 14

**Relative Vorticity (850 hPa)**

- Legend: -10, -8, -6, -4, -2, 0, 2, 4, 6, 8, 10
  - Reference Vector: $10^{-5}$ s$^{-1}$

**Brightness Temperature**

- Legend: -72, -60, -48, -36, -24, -12, 0, 12, 24, 36, 48
- 0600 UTC 13 Aug 2004
Observed Evolution

- Start time: 1800 UTC 10
- Merging begins: 1200 UTC 11
- Merging ends: 1200 UTC 12
- TS: 1200 UTC 14

Relative Vorticity (850 hPa)

Brightness Temperature
Observed Evolution

- Start time: 1800 UTC 10
- Merging begins: 1200 UTC 11
- Merging ends: 1200 UTC 12
- TS: 1200 UTC 14

Relative Vorticity (850 hPa) 1800 UTC 13 Aug 2004

Brightness Temperature 1800 UTC 13 Aug 2004
Observed Evolution

1800 UTC 10
start time

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 14
TS

Relative Vorticity (850 hPa)

0000 UTC 14 Aug 2004

Brightness Temperature

0000 UTC 14 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10
10^{-5} \text{ s}^{-1}

-72 -60 -48 -36 -24 -12 0 12 24 36 48
°C
Observed Evolution

1800 UTC 10
start time

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 14
TS

Relative Vorticity (850 hPa)
0600 UTC 14 Aug 2004

Brightness Temperature
0600 UTC 14 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10
10^{-5} \text{s}^{-1}

-72 -60 -48 -36 -24 -12 0 12 24 36 48
°C
Observed Evolution

1800 UTC 10
start time

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 14
TS

Relative Vorticity (850 hPa)

1200 UTC 14 Aug 2004

Brightness Temperature

1200 UTC 14 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10
10^{-5} \text{s}^{-1}

-72 -60 -48 -36 -24 -12 0 12 24 36 48
°C
Observed Evolution

1800 UTC 10
start time

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 14
TS

1800 UTC 14 Aug 2004
Relative Vorticity (850 hPa)

-10 -8 -6 -4 -2 0 2 4 6 8 10
10⁻⁵ s⁻¹

-72 -60 -48 -36 -24 -12 0 12 24 36 48
°C
Observed Evolution

1800 UTC 10
- start time

1200 UTC 11
- merging begins

1200 UTC 12
- merging ends

1200 UTC 14
- TS

Relative Vorticity (850 hPa) 0000 UTC 15 Aug 2004

Brightness Temperature 0000 UTC 15 Aug 2004
Observed Evolution

Hypothesis 1:
Merging between the coherent AEW_N and AEW_S is linked to the intensification of Hurricane Danielle

Hypothesis 2:
Although TC development would initially be frustrated after merging due to dry air associated with the AEW_N, moistening may have occurred in Hurricane Danielle from continued convection
Control Simulation

- 1800 UTC 10: Initialization
- 1200 UTC 11: Merging begins
- 1200 UTC 12: Merging ends
- 1200 UTC 15: TC

Relative Vorticity (850 hPa) 1800 UTC 10 Aug 2004

- Color scale: 10^-5 s^-1

- Vectors indicate direction and magnitude of vorticity.
Control Simulation
Control Simulation

The diagram shows the initialization, merging begins, merging ends, and TC events at specific UTC times. The relative vorticity map at 850 hPa for 0000 UTC 11 Aug 2004 is displayed, with contour lines indicating the vorticity values ranging from $-10$ to $10 \times 10^{-5}$ s$^{-1}$. The map includes arrows indicating the direction of the relative vorticity.
Control Simulation

Relative Vorticity (850 hPa) 0300 UTC 11 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5} s^{-1}

-10°C, -5°C, 5°C, 10°C, 15°C, 20°C, 25°C
Control Simulation

Initialization begins at 1800 UTC 10 and merging begins at 1200 UTC 11. Merging ends at 1200 UTC 12, and TC begins at 1200 UTC 15.

The diagram shows the relative vorticity at 850 hPa on 0600 UTC 11 Aug 2004. The color bar indicates vorticity values ranging from $-10$ to $10 \times 10^{-5}$ s$^{-1}$, with a reference vector at the bottom.
Control Simulation

Relative Vorticity (850 hPa) 0900 UTC 11 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5} \text{s}^{-1}

-10 \rightarrow -8 \rightarrow -6 \rightarrow -4 \rightarrow -2 \rightarrow 0 \rightarrow 2 \rightarrow 4 \rightarrow 6 \rightarrow 8 \rightarrow 10 \rightarrow 0^\circ \rightarrow 10^\circ \rightarrow 20^\circ \rightarrow 30^\circ \rightarrow 25^\circ \rightarrow 20^\circ \rightarrow 15^\circ \rightarrow 10^\circ \rightarrow 5^\circ \rightarrow 0^\circ
Control Simulation

Initialization
Merging begins
Merging ends
TC

Relative Vorticity (850 hPa) 1500 UTC 11 Aug 2004

Reference Vector

10 s$^{-1}$
Control Simulation

1800 UTC 10  1200 UTC 11  1200 UTC 12
initialization  merging begins  merging ends

1200 UTC 15
TC

Relative Vorticity (850 hPa)  1800 UTC 11 Aug 2004

25°N  20°N  15°N  10°N  5°N
30°W  20°W  10°W  0°

10^{-5} \text{s}^{-1}

-10 -8 -6 -4 -2 0 2 4 6 8 10
Control Simulation

Relative Vorticity (850 hPa) 2100 UTC 11 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10

10^-5 s^-1

Initialisation begins 1200 UTC 11
Merging begins 1200 UTC 12
Merging ends 1200 UTC 15
TC
Control Simulation

1800 UTC 10  1200 UTC 11  1200 UTC 12  1200 UTC 15

initialization  merging begins  merging ends  TC

Relative Vorticity (850 hPa)  0000 UTC 12 Aug 2004

-10  -8  -6  -4  -2  0  2  4  6  8  10

10^{-5} s^{-1}
Control Simulation

- Initialization
- Merging begins
- Merging ends
- TC

Relative Vorticity (850 hPa)

0300 UTC 12 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10

10^{-5} \, s^{-1}
Control Simulation

Initialization begins at 1800 UTC 10
Merging begins at 1200 UTC 11
Merging ends at 1200 UTC 12
TC at 1200 UTC 15

Relative Vorticity (850 hPa) 0600 UTC 12 Aug 2004

Relative Vorticity

-10 -8 -6 -4 -2 0 2 4 6 8 10

10^{-5} \text{ s}^{-1}

Reference Vector

30^\circ \text{W} 20^\circ \text{W} 10^\circ \text{W} 0^\circ
Control Simulation

1800 UTC 10
1200 UTC 11
1200 UTC 12
1200 UTC 15

initialization
merging begins
merging ends
TC

Relative Vorticity (850 hPa) 0900 UTC 12 Aug 2004

10^{-5} \text{ s}^{-1}
Control Simulation

- Initialization
- Merging begins
- Merging ends
- TC

Relative Vorticity (850 hPa) 1200 UTC 12 Aug 2004

- Reference Vector
- Color scale: 10⁻⁵ s⁻¹

- 30°W 20°W 10°W 0°
- 5°N 10°N 15°N 20°N 25°N
Control Simulation

1800 UTC 10
1200 UTC 11
1200 UTC 12
1200 UTC 15

 initialization
merging begins
merging ends
TC

Relative Vorticity (850 hPa) 1500 UTC 12 Aug 2004

25°N 20°N 15°N 10°N 5°N
30°W 20°W 10°W 0°

-10 -8 -6 -4 -2 0 2 4 6 8 10 10⁻⁵ s⁻¹

Reference Vector
Control Simulation

1800 UTC 10

1200 UTC 11
initialization

merging begins

1200 UTC 12
merging ends

1200 UTC 15
TC

Relative Vorticity (850 hPa) 2100 UTC 12 Aug 2004

25°N
20°N
15°N
10°N
5°N

30°W 20°W 10°W 0°

-10 -8 -6 -4 -2 0 2 4 6 8 10 10⁻⁵ s⁻¹
Control Simulation

1800 UTC 10

1200 UTC 11

1200 UTC 12

1200 UTC 15

initialization
merging begins
merging ends
TC

Relative Vorticity (850 hPa) 0000 UTC 13 Aug 2004

25°N
20°N
15°N
10°N
5°N

30°W 20°W 10°W 0°

-10 -8 -6 -4 -2 0 2 4 6 8 10
10^{-5} s^{-1}
Control Simulation

Relative Vorticity (850 hPa) 0300 UTC 13 Aug 2004

-10  -8  -6  -4  -2  0  2  4  6  8  10  $10^{-5}$ s$^{-1}$

30°W  20°W  10°W  0°

5°N  10°N  15°N  20°N  25°N

-10°C -6°C -2°C 0°C 2°C 4°C 6°C 8°C 10°C

1800 UTC 10 1200 UTC 11 1200 UTC 12 1200 UTC 15

initialization  merging begins  merging ends  TC

ini4aliza4on  merging  TC
Control Simulation

- **Initialization**
- **Merging begins**
- **Merging ends**
- **TC**

Relative Vorticity (850 hPa)

0600 UTC 13 Aug 2004

0 2 4 6 8 10 10^-5 s^-1
Control Simulation
Control Simulation

Initialization begins at 1800 UTC 10 and merging begins at 1200 UTC 11. Merging ends at 1200 UTC 12 and TC begins at 1200 UTC 15.

Relative Vorticity (850 hPa) for 1200 UTC 13 Aug 2004 is shown in the image.

Legend:
- Black: Reference Vector
- Color bar: $10^{-5} \text{s}^{-1}$

Map areas:
- 25°N
- 20°N
- 15°N
- 10°N
- 5°N
- 30°W
- 20°W
- 10°W
- 0°
Control Simulation

Initialization begins at 1800 UTC 10, merging begins at 1200 UTC 11, merging ends at 1200 UTC 12, and TC at 1200 UTC 15.

Relative Vorticity (850 hPa) 1500 UTC 13 Aug 2004

- Reference Vector
- 10^-5 s^-1

Color scale:
- Dark blue for -10
- Light blue for -8
- Light blue for -6
- Light blue for -4
- Light blue for -2
- Light blue for 0
- Yellow for 2
- Orange for 4
- Light red for 6
- Red for 8
- Dark red for 10

- 30°W 20°W 10°W 0°
- 25°N 20°N 15°N 10°N 5°N
Control Simulation

1800 UTC 10 initialization
1200 UTC 11 merging begins
1200 UTC 12 merging ends
1200 UTC 15 TC

Relative Vorticity (850 hPa) 1800 UTC 13 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5}$ s$^{-1}$

$\text{Reference Vector}$
Control Simulation

- Initialization begins at 1800 UTC 10
- Merging begins at 1200 UTC 11
- Merging ends at 1200 UTC 12
- TC formation at 1200 UTC 15

Relative Vorticity (850 hPa)

- 2100 UTC 13 Aug 2004
- Color scale: 10^{-5} \text{s}^{-1}
- Reference vector
Control Simulation

- Initialization
- Merger begins
- Merger ends
- TC

Relative Vorticity (850 hPa) 0000 UTC 14 Aug 2004

- 1800 UTC 10
- 1200 UTC 11
- 1200 UTC 12
- 1200 UTC 15

legend: 10^-5 s^-1

- 30°W
- 20°W
- 10°W
- 0°

- 25°N
- 20°N
- 15°N
- 10°N
- 5°N

- -10 -8 -6 -4 -2 0 2 4 6 8 10
Control Simulation

1800 UTC 10 1200 UTC 11 1200 UTC 12 1200 UTC 15
initialization merging begins merging ends TC

Relative Vorticity (850 hPa) 0300 UTC 14 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5} \text{s}^{-1}
Control Simulation

1800 UTC 10

1200 UTC 11

1200 UTC 12

1200 UTC 15

initialization

merging begins

merging ends

TC

Relative Vorticity (850 hPa) 0600 UTC 14 Aug 2004

30°W 20°W 10°W 0°

-10 -8 -6 -4 -2 0 2 4 6 8 10

10^{-5} s^{-1}
Control Simulation

1800 UTC 10 1200 UTC 11 1200 UTC 12 1200 UTC 15

initialization merging begins merging ends TC

Relative Vorticity (850 hPa) 0900 UTC 14 Aug 2004

25°N 20°N 15°N 10°N 5°N

30°W 20°W 10°W 0°

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5} \text{s}^{-1}

Reference Vector
Control Simulation

Relative Vorticity (850 hPa) 1200 UTC 14 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10
10^{-5} \text{s}^{-1}

-30^\circ \text{W} -20^\circ \text{W} -10^\circ \text{W} 0^\circ

initialization merging begins merging ends TC
Control Simulation

1800 UTC 10

1200 UTC 11
initialization
merging begins

1200 UTC 12
merging ends

1200 UTC 15
TC

Relative Vorticity (850 hPa) 1500 UTC 14 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10
10^{-5} s^{-1}

30°W 20°W 10°W 0°
Control Simulation

![Diagram showing initialization, merging begins, merging ends, and TC with relative vorticity at 850 hPa on 14 Aug 2004.](image)
Control Simulation
Control Simulation
Control Simulation

- Initialization: 1800 UTC 10
- Merging begins: 1200 UTC 11
- Merging ends: 1200 UTC 12
- TC: 1200 UTC 15

Relative Vorticity (850 hPa) 0300 UTC 15 Aug 2004

Legend:
- 10⁻⁵ s⁻¹

Map shows a region of high vorticity indicating the formation of a tropical cyclone (TC).
Control Simulation

Initialization begins at 1800 UTC 10 and merging begins at 1200 UTC 11. Merging ends at 1200 UTC 12 and TC formation occurs at 1200 UTC 15.

The relative vorticity map at 0600 UTC 15 Aug 2004 shows a region of high vorticity in the Southern Hemisphere, indicating potential tropical cyclone development. The color bar represents the relative vorticity in units of $10^{-5}$ s$^{-1}$.
Control Simulation

- Initialization
- Merging begins
- Merging ends
- TC

Relative Vorticity (850 hPa) 0900 UTC 15 Aug 2004

- 1800 UTC 10
- 1200 UTC 11
- 1200 UTC 12
- 1200 UTC 15
Control Simulation

1800 UTC 10

1200 UTC 11

1200 UTC 12

1200 UTC 15

initialization

merging begins

merging ends

TC

Relative Vorticity (850 hPa) 1200 UTC 15 Aug 2004

25°N

20°N

15°N

10°N

5°N

30°W 20°W 10°W 0°

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5} \text{s}^{-1}

Reference Vector

ini4aliza4on
merging
begins
merging
ends
TC

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5} \text{s}^{-1}
• The development of a TC circulation occurs at a different location and time than observations.

• However, the timing, placement, and shape of the merging process in the model appears to realistically capture the evolution in the ERA-Interim.

• What about moisture field?
Control Simulation

 Initialization

 merging begins

 merging ends

 TC

 Relative Vorticity (850 hPa) 1800 UTC 10 Aug 2004

 Relative Humidity (850 hPa) 1800 UTC 10 Aug 2004

 \(10^{-5} \text{ s}^{-1}\)
Control Simulation

1800 UTC 10

1200 UTC 11

1200 UTC 12

1200 UTC 15

ini4aliza4on

merging
begins

merging
ends

TC

Relative Vorticity (850 hPa) 0000 UTC 11 Aug 2004

Relative Humidity (850 hPa) 0000 UTC 11 Aug 2004
Control Simulation

- Initialization
- Merging begins
- Merging ends
- TC

Relative Vorticity (850 hPa) 0600 UTC 11 Aug 2004

Relative Humidity (850 hPa) 0600 UTC 11 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5} \text{s}^{-1}

0 10 20 30 40 50 60 70 80 90 100 %
Control Simulation

1800 UTC 10

1200 UTC 11

initialization

merging begins

1200 UTC 12

merging ends

1200 UTC 15

TC

Control Simulation
Control Simulation

- Initialization
- Merging begins
- Merging ends
- TC

Relative Vorticity (850 hPa) 1800 UTC 11 Aug 2004

Relative Humidity (850 hPa) 1800 UTC 11 Aug 2004
Control Simulation

Initialization

Merging begins

Merging ends

Control Simulation
Control Simulation

![Diagram showing time lines with initialization, merging begins, merging ends, and TC marks. There are two plots: one for Relative Vorticity (850 hPa) and another for Relative Humidity (850 hPa). The plots are labeled with 0600 UTC 12 Aug 2004.]
Control Simulation

1800 UTC 10

1200 UTC 11

initialization

merging begins

1200 UTC 12

merging ends

1200 UTC 15

TC

Relative Vorticity (850 hPa) 1200 UTC 12 Aug 2004

Relative Humidity (850 hPa) 1200 UTC 12 Aug 2004

10^{-5} \text{s}^{-1}
**Control Simulation**

- **1800 UTC 10**: Initialization
- **1200 UTC 11**: Merging begins
- **1200 UTC 12**: Merging ends
- **1200 UTC 15**: TC

**Relative Vorticity (850 hPa) 1800 UTC 12 Aug 2004**

- **Relative Humidity (850 hPa) 1800 UTC 12 Aug 2004**

**Legend**

- **Reference Vector**: 10
- **Color Bar**: 10^-5 s^-1
- **Color Bar**: %
Control Simulation

Relative Vorticity (850 hPa) 0000 UTC 13 Aug 2004

Relative Humidity (850 hPa) 0000 UTC 13 Aug 2004
Control Simulation

1800 UTC 10

1200 UTC 11
initialization

1200 UTC 12
merging begins

1200 UTC 15
merging ends

1200 UTC 15
TC

Relative Vorticity (850 hPa) 0600 UTC 13 Aug 2004

Relative Humidity (850 hPa) 0600 UTC 13 Aug 2004
Control Simulation

1800 UTC 10  1200 UTC 11  1200 UTC 12  1200 UTC 15

initialization  merging begins  merging ends  TC

Relative Vorticity (850 hPa)  1200 UTC 13 Aug 2004

Relative Humidity (850 hPa)  1200 UTC 13 Aug 2004

Control Simulation
Control Simulation

1800 UTC 10 1200 UTC 11 1200 UTC 12

initialization merging begins merging ends

1200 UTC 15
TC

Relative Vorticity (850 hPa) 1800 UTC 13 Aug 2004

Relative Humidity (850 hPa) 1800 UTC 13 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5} \text{s}^{-1}

0 10 20 30 40 50 60 70 80 90 100 \%
Control Simulation

1800 UTC 10

1200 UTC 11
 initialization

1200 UTC 11
 merging begins

1200 UTC 12
 merging ends

1200 UTC 15
 TC

Relative Vorticity (850 hPa) 0000 UTC 14 Aug 2004

Relative Humidity (850 hPa) 0000 UTC 14 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10

10^{-5} \text{s}^{-1}

0 10 20 30 40 50 60 70 80 90 100

%
Control Simulation

1800 UTC 10

1200 UTC 11

1200 UTC 12

1200 UTC 15

TC

ini4aliza4on
merging
begins
merging
ends

Relative Vorticity (850 hPa)
0600 UTC 14 Aug 2004

Relative Humidity (850 hPa)
0600 UTC 14 Aug 2004
Control Simulation

1800 UTC 10 1200 UTC 11 1200 UTC 12 1200 UTC 15

initialization merging begins merging ends TC

Relative Vorticity (850 hPa) 1200 UTC 14 Aug 2004

Relative Humidity (850 hPa) 1200 UTC 14 Aug 2004
Control Simulation

1800 UTC 10 initialization
1200 UTC 11 merging begins
1200 UTC 12 merging ends
1200 UTC 15 TC

Relative Vorticity (850 hPa) 1800 UTC 14 Aug 2004

Relative Humidity (850 hPa) 1800 UTC 14 Aug 2004
Control Simulation

1800 UTC 10

1200 UTC 11

1200 UTC 12

1200 UTC 15

ini4aliza4on

merging

begins

merging

ends

TC

Control

Simula4on

Relative Vorticity (850 hPa) 0000 UTC 15 Aug 2004

Relative Humidity (850 hPa) 0000 UTC 15 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10

10^-5 s^-1

0 10 20 30 40 50 60 70 80 90 100

%
Control Simulation

- Initialization
- Merging begins
- Merging ends
- TC

Relative Vorticity (850 hPa)

Relative Humidity (850 hPa)
Control Simulation

- Initialization
- Merging begins
- Merging ends

Relative Vorticity (850 hPa) - 1200 UTC 15 Aug 2004

Relative Humidity (850 hPa) - 1200 UTC 15 Aug 2004
Control Simulation

1800 UTC 10

1200 UTC 11

merging begins

1200 UTC 12

merging ends

1200 UTC 15

TC

ini4aliza4on
merging

begins

ends

Relative Vorticity (850 hPa) 1200 UTC 15 Aug 2004

Relative Humidity (850 hPa) 1200 UTC 15 Aug 2004
Moistening occurs both before and after merging.
North-South Cross Section

Relative Vorticity

12 UTC Aug 11 2004 (13.7°W)

10^{-5} \text{ s}^{-1}

1800 UTC 10
initialization

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 15
TC
North-South Cross Section

- Initialization begins at 1800 UTC 10
- Merging begins at 1200 UTC 11
- Merging ends at 1200 UTC 12
- TC formation occurs at 1200 UTC 15

Relative Vorticity

精密旋度

00 UTC Aug 12 2004 (15.5°W)

- Pressure (hPa)
- 10N, 20N

色码：
- 10^-5 s^-1
- %
North-South Cross Section

1800 UTC 10

initialization

1200 UTC 11

merging begins

1200 UTC 12

merging ends

1200 UTC 15

TC

Relative Vorticity

12 UTC Aug 12 2004 (17.8°W)

10^-5 s^-1

%
North-South Cross Section

1800 UTC 10  1200 UTC 11  1200 UTC 12  1200 UTC 15

initialization  merging begins  merging ends  TC

Relative Vorticity

12 UTC Aug 15 2004 (23.0°W)

-10  -8  -6  -4  -2  0  2  4  6  8  10

10^-5 s^-1

0  10  20  30  40  50  60  70  80  90  100

%
The AEW₇ appears to play a significant role in amplifying the low-level vorticity associated with the AEWₛ.

To isolate the importance of the AEW₇ in low-level vorticity generation, a separate model simulation is conducted with the AEW₇ removed from the initial conditions.
WRF built-in TC removal routine
- removes **symmetric** and **balanced** components of the wind, temperature, and geopotential.
No Vortex Evolution

1800 UTC 10
initialization

1200 UTC 11
merging begins

1200 UTC 12
merging ends

1200 UTC 15
TC

Relative Vorticity (850 hPa) 1800 UTC 10 Aug 2004

Relative Humidity (850 hPa) 1800 UTC 10 Aug 2004
No Vortex Evolution

1800 UTC 10

1200 UTC 11

initialization

merging begins

1200 UTC 12

merging ends

1200 UTC 15

TC

Relative Vorticity (850 hPa) 0000 UTC 11 Aug 2004

Relative Humidity (850 hPa) 0000 UTC 11 Aug 2004

10^-5 s^-1

%
No Vortex Evolution

1800 UTC 10
1200 UTC 11
1200 UTC 12
1200 UTC 15

initialization
merging begins
merging ends
TC

Relative Vorticity (850 hPa)
Relative Humidity (850 hPa)

0600 UTC 11 Aug 2004
No Vortex Evolution

1800 UTC 10

1200 UTC 11
 initialization
 merging begins

1200 UTC 12
 merging ends

1200 UTC 15
 TC

Relative Vorticity (850 hPa) 1200 UTC 11 Aug 2004

Relative Humidity (850 hPa) 1200 UTC 11 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5} \text{s}^{-1}

0 10 20 30 40 50 60 70 80 90 100 \%
No Vortex Evolution

1800 UTC 10

1200 UTC 11

1200 UTC 12

1200 UTC 15

initialization

merging begins

merging ends

TC

Relative Vorticity (850 hPa) 1800 UTC 11 Aug 2004

Relative Humidity (850 hPa) 1800 UTC 11 Aug 2004
No Vortex Evolution

1800 UTC 10

1200 UTC 11

1200 UTC 12

1200 UTC 15

initialization
merging begins
merging ends
TC

Relative Vorticity (850 hPa) 0000 UTC 12 Aug 2004

Relative Humidity (850 hPa) 0000 UTC 12 Aug 2004
No Vortex Evolution

1800 UTC 10	1200 UTC 11	1200 UTC 12	1200 UTC 15
initialization	merging begins	merging ends	TC

Relative Vorticity (850 hPa) 0600 UTC 12 Aug 2004

Relative Humidity (850 hPa) 0600 UTC 12 Aug 2004

No Vortex Evolution
No Vortex Evolution

1800 UTC 10  1200 UTC 11  1200 UTC 12

initialization  merging begins  merging ends

1200 UTC 15
TC

Relative Vorticity (850 hPa)  1200 UTC 12 Aug 2004

Relative Humidity (850 hPa)  1200 UTC 12 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5} s^{-1}

0 10 20 30 40 50 60 70 80 90 100 %
No Vortex Evolution

1800 UTC 10, 1200 UTC 11, 1200 UTC 12, 1200 UTC 15

- Initialization
- Merging begins
- Merging ends
- TC

Relative Vorticity (850 hPa) 1800 UTC 12 Aug 2004

Relative Humidity (850 hPa) 1800 UTC 12 Aug 2004

Scale: $10^{-5}$ s$^{-1}$

Scale: %
No Vortex Evolution

1800 UTC 10  1200 UTC 11  1200 UTC 12  1200 UTC 15
initialization  merging begins  merging ends  TC

Relative Vorticity (850 hPa)  0000 UTC 13 Aug 2004

Relative Humidity (850 hPa)  0000 UTC 13 Aug 2004

[Maps showing relative vorticity and humidity with color scales and reference vectors]
No Vortex Evolution

1800 UTC 10  1200 UTC 11  1200 UTC 12  1200 UTC 15

initialized  merging begins  merging ends  TC

Relative Vorticity (850 hPa)  0600 UTC 13 Aug 2004

Relative Humidity (850 hPa)  0600 UTC 13 Aug 2004

-10 -8 -6 -4 -2  0  2  4  6  8  10  10^{-5} \text{s}^{-1}

0 10 20 30 40 50 60 70 80 90 100 %
No Vortex Evolution

1800 UTC 10

1200 UTC 11
initiation

merging begins

1200 UTC 12
merging ends

1200 UTC 15
TC

Relative Vorticity (850 hPa)  1200 UTC 13 Aug 2004

Relative Humidity (850 hPa)  1200 UTC 13 Aug 2004
No Vortex Evolution

1800 UTC 10

1200 UTC 11

1200 UTC 12

1200 UTC 15

initialization

merging begins

merging ends

TC

Relative Vorticity (850 hPa) 1800 UTC 13 Aug 2004

Relative Humidity (850 hPa) 1800 UTC 13 Aug 2004
No Vortex Evolution

Relative Vorticity (850 hPa) 0000 UTC 14 Aug 2004

Relative Humidity (850 hPa) 0000 UTC 14 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10 10^{-5} \text{s}^{-1}

-10 0 10 20 30 40 50 60 70 80 90 100 \%

1800 UTC 10 1200 UTC 11 1200 UTC 12 1200 UTC 15

initialization merging begins merging ends TC

ini4aliza4on merging begins merging ends
No Vortex Evolution

1800 UTC 10  1200 UTC 11  1200 UTC 12

initialization  merging begins  merging ends

1200 UTC 15  TC

Relative Vorticity (850 hPa)  0600 UTC 14 Aug 2004

Relative Humidity (850 hPa)  0600 UTC 14 Aug 2004

No Vortex Evolution
No Vortex Evolution

1800 UTC 10  1200 UTC 11  1200 UTC 12  1200 UTC 15

initialization  merging begins  merging ends  TC

Relative Vorticity (850 hPa)  1200 UTC 14 Aug 2004

Relative Humidity (850 hPa)  1200 UTC 14 Aug 2004
No Vortex Evolution

1800 UTC 10
Initialization

1200 UTC 11
Merging begins

1200 UTC 12
Merging ends

1200 UTC 15
TC

Relative Vorticity (850 hPa) 0000 UTC 15 Aug 2004

Relative Humidity (850 hPa) 0000 UTC 15 Aug 2004

-10 -8 -6 -4 -2 0 2 4 6 8 10
10^{-5} \text{s}^{-1}

0 10 20 30 40 50 60 70 80 90 100
%
No Vortex Evolution

1800 UTC 10

1200 UTC 11

1200 UTC 12

1200 UTC 15

initialization
merging begins
merging ends
TC

Relative Vorticity (850 hPa) 0600 UTC 15 Aug 2004

Relative Humidity (850 hPa) 0600 UTC 15 Aug 2004
No Vortex Evolution

- **1800 UTC 10**: Initialization
- **1200 UTC 11**: Merging begins
- **1200 UTC 12**: Merging ends
- **1200 UTC 15**: TC

**Relative Vorticity (850 hPa)**: 
- Colors represent vorticity values, with a scale ranging from -10 to 10 $10^{-5}$ s$^{-1}$.

**Relative Humidity (850 hPa)**: 
- Colors represent humidity, with a scale ranging from 0% to 100%.
• No TC vortex develops by 1200 UTC 15 August in the No Vortex simulation

→ The AEW\_N is important in the development of a TC circulation
Vorticity Budget

Temporal rate of change in area-averaged vorticity

\[
\frac{\partial \zeta}{\partial t} = -\bar{\eta} \bar{\delta} - \frac{1}{A} \oint \eta' V'_h \cdot \hat{n} \, dl + \frac{1}{A} \oint \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \, dl + \frac{1}{A} \oint (\hat{k} \times F) \cdot \hat{n} \, dl
\]

- stretching
- eddy vorticity flux
- tilting
- friction
The vorticity budget equation is given by:

$$\frac{\partial \zeta}{\partial t} = -\tilde{\eta} \delta - \frac{1}{A} \int \eta' V' \cdot \hat{n} \, dl + \frac{1}{A} \oint \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \, dl + \frac{1}{A} \oint \left( \hat{k} \times F \right) \cdot \hat{n} \, dl$$

Where:
- $\zeta$ is the relative vorticity.
- $\eta'$ and $V'$ represent perturbations in the vorticity and velocity fields.
- $\delta$ is a correction term.
- $\omega$ is the vorticity.
- $\hat{n}$ is the normal vector.
- $A$ is the area element.
- $F$ is the forcing term.

The diagram illustrates the relative vorticity at 850 hPa for 12 UTC Aug 11 2004, with vectors depicting the wind field and contours indicating the vorticity distribution. The budget components are highlighted:
- **Stretching**
- **Eddy vorticity flux**
- **Tilting**
- **Friction**
\[
\frac{\partial \zeta}{\partial t} = \tilde{\eta} \delta - \frac{1}{A} \oint \eta' V'_h \cdot \hat{n} \, dl + \frac{1}{A} \oint \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \, dl + \frac{1}{A} \oint (\hat{k} \times F) \cdot \hat{n} \, dl
\]
Vorticity Budget

\[
\frac{\partial \zeta}{\partial t} = -\tilde{\eta} \delta - \frac{1}{A} \oint \eta' V'_h \cdot \hat{n} \, dl + \frac{1}{A} \oint \omega \left( k \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \, dl + \frac{1}{A} \oint (k \times F) \cdot \hat{n} \, dl
\]

- stretching
- eddy vorticity flux
- tilting
- friction

Relative Vorticity (850 hPa) 12 UTC Aug 11 2004

Relative Vorticity (850 hPa) 12 UTC Aug 11 2004
\[
\frac{\partial \zeta}{\partial t} = -\tilde{\eta} \delta - \frac{1}{A} \int \eta' V'_h \cdot \hat{n} \, dl + \frac{1}{A} \int \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \, dl + \frac{1}{A} \int (\hat{k} \times F) \cdot \hat{n} \, dl
\]

- **Stretching**
- **Eddy Vorticity Flux**
- **Tilting**
- **Friction**
Vorticity Budget

\[ \frac{\partial \zeta}{\partial t} = -\bar{\eta} \delta - \frac{1}{A} \oint \eta' V'_h \cdot \hat{n} \, dl + \frac{1}{A} \oint \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \, dl + \frac{1}{A} \oint (\hat{k} \times F) \cdot \hat{n} \, dl \]

- stretching
- eddy vorticity flux
- tilting
- friction

Relative Vorticity (850 hPa) 12 UTC Aug 11 2004

\[ - \frac{1}{A} \oint \eta' V'_h \cdot \hat{n} \, dl \]

\[ - + + - \]
\[
\frac{\partial \zeta}{\partial t} = -\bar{\eta} \delta - \frac{1}{A} \int \eta' V'_h \cdot \hat{n} \, dl + \frac{1}{A} \int \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \, dl + \frac{1}{A} \int (\hat{k} \times F) \cdot \hat{n} \, dl
\]

- **Stretching**
- Eddy vorticity flux
- Tilting
- Friction

Absolute vorticity > 0
The Vorticity Budget is given by:

$$\frac{\partial \zeta}{\partial t} = -\bar{\eta}\delta - \frac{1}{A} \oint \eta' V' \cdot \hat{n} \, dl + \frac{1}{A} \oint \omega \left( \mathbf{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \, dl + \frac{1}{A} \oint (\mathbf{k} \times \mathbf{F}) \cdot \hat{n} \, dl$$

- **Stretching**
- Eddy vorticity flux
- Tilting
- Friction

The absolute vorticity is shown to be greater than zero.
Vorticity Budget

\[
\frac{\partial \zeta}{\partial t} = -\bar{\eta} \bar{\delta} - \frac{1}{A} \oint \eta' V' \cdot \hat{n} \ dl + \frac{1}{A} \oint \omega \left( \mathbf{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \ dl + \frac{1}{A} \oint (\mathbf{k} \times F) \cdot \hat{n} \ dl
\]

- **Stretching**
- **Eddy Vorticity Flux**
- **Tilting**
- **Friction**

\(-\bar{\eta} \bar{\delta}\)
\[ \frac{\partial \zeta}{\partial t} = -\tilde{\eta} \tilde{\delta} - \frac{1}{A} \int \eta' V'_h \cdot \hat{n} \, dl + \frac{1}{A} \int \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \, dl + \frac{1}{A} \int (\hat{k} \times F) \cdot \hat{n} \, dl \]

- **stretching**
- **eddy vorticity flux**
- **tilting**
- **friction**

absolute vorticity > 0
Vorticity Budget

\[
\frac{\partial \zeta}{\partial t} = -\tilde{\eta} \delta - \frac{1}{A} \int \eta' V'_h \cdot \hat{n} \, dl + \frac{1}{A} \int \omega \left( \hat{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \, dl + \frac{1}{A} \int (\hat{k} \times F) \cdot \hat{n} \, dl
\]

- stretching
- eddy vorticity flux
- tilting
- friction

Image from Davis and Galarneau (2009)
\[
\frac{\partial \bar{\zeta}}{\partial t} = -\bar{\eta} \delta - \frac{1}{A} \oint \eta' V'_h \cdot \hat{n} \, dl + \frac{1}{A} \oint \omega \left( \mathbf{k} \times \frac{\partial V_h}{\partial p} \right) \cdot \hat{n} \, dl + \frac{1}{A} \oint \left( \mathbf{k} \times \mathbf{F} \right) \cdot \hat{n} \, dl
\]

- stretching
- eddy vorticity flux
- tilting
- friction

Relative Vorticity (850 hPa)

12 UTC Aug 11 2004
- Stretching has vertical dipole (upward motion)
- Eddy vorticity flux has comparable magnitude as stretching
- Tilting is positive at mid-levels
1. Can an AEW$_N$ contribute to tropical cyclogenesis?
   - Control simulation developed a TC, while the No Vortex simulation did not
   - AEW$_N$s can contribute to tropical cyclogenesis
2. What is the relative or collective importance of $\text{AEW}_\text{N}$s and $\text{AEW}_\text{S}$s on tropical cyclogenesis?

- Merging at least as important as diabatic processes at increasing the low-level vorticity of the merged vortex
Conclusions

2. What is the relative or collective importance of $\text{AEW}_N$s and $\text{AEW}_S$s on tropical cyclogenesis?

- Merging at least as important as diabatic processes at increasing the low-level vorticity of the merged vortex

When forecasting tropical cyclogenesis, it may be important to consider $\text{AEW}_N$!
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Links

Simulations:

Control-tangential wind:
http://www.atmos.albany.edu/student/ymcheng/ATM741/with-vortex/vt-850.html

Interim tangential wind:

tangential wind time series (10m)
http://www.atmos.albany.edu/student/ymcheng/ATM741/with-vortex/vt-time-series-10m.png

tangential wind time series (850)

budget friction term:
http://www.atmos.albany.edu/student/ymcheng/ATM741/with-vortex/budget-12hr-fr.html

TRMM precip vs WRF:
http://www.atmos.albany.edu/student/ymcheng/ATM741/precip/precip.html