HURRICANE SPAWNED TORNADOES UNDER ANTHROPOGENIC CLIMATE CHANGE

BLUE WATERS SYMPOSIUM
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
PI: JEFF TRAPP- MODELING OF STORMS UNDER CLIMATE CHANGE
PRESENTED BY DEREKA CARROLL-SMITH
WHAT’S THE PROBLEM?

GIVEN TC CLIMATE PROJECTIONS, HOW WILL ANTHROPOGENIC CLIMATE CHANGE (ACC) IMPACT TCT GENERATION IN A MID AND LATE CENTURY CLIMATE?
TROPICAL CYCLONES AND CLIMATE CHANGE (IPCC, CH14 WG1AR5)

GLOBAL

Likely decrease or no change in global frequency of TCs
- Mean intensity is expected to increase
- Rainfall rates expected to increase

Low confidence for region specific projections
- NAT increase in intense storms is more likely than not
  - Consistent with Elsner et al. (2008)

Changes in TC activity correlated with spatial changes in SST (Sugi et al. 2009; Chauvin and Royer 2010; Murakami et al 2011; Zhao and Held 2012)
- Understanding this spatial correlation is key

REGIONAL (NAT)

Percent change in the average over period 2018-2100 relative to 2000-2019. (I) total annual frequency of tropical storms. (II) annual frequency of Cat 4 or 5 storms (III) mean Lifetime Maximum Intensity (LMI) (IV) precipitation rate within 200 km of storm center at the time of LMI. Solid Blue line is best guess of expected percent change, colored bar is the 67% likely confidence interval for this value

5/16/2017
DISTRIBUTION OF TROPICAL CYCLONE TORNADOES (Edwards 2012)

TCT outbreaks occur most often in intense landfalling TCs
Out of the 83 U.S. landfalling TCs between 1954-2004, ~22% (18 of 83) were outbreak TCs, and of those 18 outbreak TCs, 78% (14 of 18) were category 2 or higher (Verbout et al. 2007)

50% of the most notable TCT outbreaks (20 or more TCTs as defined by Curtis 2004) occurred in 2004-2005 seasons

<table>
<thead>
<tr>
<th>TROPICAL CYCLONE</th>
<th>YEAR</th>
<th>TCTS</th>
<th>REPORTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>H Ivan</td>
<td>2004</td>
<td>118</td>
<td>3</td>
</tr>
<tr>
<td>H Beulah</td>
<td>1967</td>
<td>115</td>
<td>4</td>
</tr>
<tr>
<td>H Frances</td>
<td>2004</td>
<td>103</td>
<td>2</td>
</tr>
<tr>
<td>H Rita</td>
<td>2005</td>
<td>98</td>
<td>3</td>
</tr>
<tr>
<td>H Katrina</td>
<td>2005</td>
<td>59</td>
<td>3</td>
</tr>
<tr>
<td>H Andrew</td>
<td>1992</td>
<td>56</td>
<td>3</td>
</tr>
<tr>
<td>TS Fay</td>
<td>2008</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>H Gustav</td>
<td>2008</td>
<td>49</td>
<td>2</td>
</tr>
<tr>
<td>H Cindy</td>
<td>2005</td>
<td>48</td>
<td>1</td>
</tr>
<tr>
<td>H Georges</td>
<td>1998</td>
<td>48</td>
<td>2</td>
</tr>
</tbody>
</table>

Top ten US. TC tornado producers adapted from (Edwards 2012) 80% Cat 2 or higher

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Why It Matters

63% of TC related fatalities occur inland.

(RAPPAPORT 2000)
TROPICAL CYCLONE FATALITIES

More recent Rappaport study (2013) using longer dataset shows rain and tornado related fatalities are more likely to occur despite surge making up the majority of TC related deaths.
Investigate impacts of ACC on the generation of TCTs

Understand changes in TCT kinematic and thermodynamic environments

Draw awareness to inland TC threats

IMPROVE RESILIENCE

Broader Impacts

PURPOSE
Why Blue Waters?

- Multi-scale problem, requiring a relatively long time integration, over a relatively large domain
  - High resolution sub domains that are not known a priori.
- The spatial and temporal domains are required for multiple realizations to quantify uncertainty
**WRF SETUP ON BLUE WATERS**

- WRF v3.7
- *ic/bc from NCEP FNL
- 50 Vertical levels
- Thompson microphysical scheme
- SST updates

<table>
<thead>
<tr>
<th>Domain/Grid Spacing</th>
<th>Size (dx,dy,dz)</th>
<th>Simulation Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>D01 9km</td>
<td>580 x 385 x 50 (11,165,000 pts)</td>
<td>120 hrs (5 days)</td>
</tr>
<tr>
<td>D02 3km</td>
<td>571 x 730 x 50 (20,841,500 pts)</td>
<td>120 hrs (5 days)</td>
</tr>
<tr>
<td>D03 1km</td>
<td>736 x 625 x 50 (23,000,000 pts)</td>
<td>10 hrs</td>
</tr>
</tbody>
</table>

*Resolution chosen in inner 2 nests is sufficient to resolve TC rainbands and considered to be convection allowing*
HURRICANE IVAN (2004)

Made first landfall as a Cat. 3 hurricane on 16 September 2004, in Orange Beach, Alabama
- Second landfall as a tropical depression 24 Sept.

$26 billion (2016 USD) in damages

92 total deaths
- 25 U.S. deaths
  - 7 out of 25 due to Inland TCTs

Produced record 118 tornadoes
- Majority occurred inland
Results

• D1 & D2 INITIALIZED 14 SEPTEMBER 00Z TO 19 SEPTEMBER 00Z

• D3 INITIALIZED 15 SEPTEMBER 2004 18Z - 16 SEPTEMBER 2004 03Z
  • Initialized near the time of the first tornado report
CONTROL (CNTRL) VS OBSERVED (OBS) INTENSITY (MEAN SLP)

**Observed Track**
- IBTRACS - 6hrly Mean Sea Level Pressure
- ~Landfall
  - ~930 mb

**Simulated Track**
- Tracking Algorithm
- 6hrly Mean Sea Level Pressure
- ~Landfall
  - 955 mb

**Graph:**
- **Pressure (mb)**: 920, 940, 960, 980, 1000, 1020
- **Time (Hours)**: 20, 40, 60, 80, 100, 120
- **Landfall** indicated on graph

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CNTRL Ivan tracks slightly West of the OBS track and curves into Virginia, instead of tracking upward towards Southern Maryland.
CONTROL VS OBSERVED 3KM REFLECTIVITY

CONTROL

wrfout_d02_2004-09-16_22:00:00
Radar reflectivity (lambda = 10 cm) dBZ

OBSERVED

Composite Radar Reflectivity Loop
Courtesy: http://www.meteo.psu.edu
1KM REFLECTIVITY FOR CNTRL

- More detailed structure in TC rainbands.
- Can identify specific potentially tornadic cells using an algorithm based on Updraft Helicity.
Potential Tornadic Mesocyclone (PTM):

- PTM
  - Need to quantify a way to compare tornado reports to the simulations since tornadoes are not explicitly resolved
  - This threshold is used to filter potential TCT mesocyclones.
    - Since tornadoes are extreme events, the 99.9% UH value is used
    - Only one hit at each point is counted

\[ UH = \int_{z_0}^{z_1} w \zeta \, dz, \]

Where \( w \) is vertical velocity and \( \zeta \) is vertical vorticity. Let \( z_0=2 \) km, and \( z_1=5 \) km
TCT REPORTS VS. CONTROL

- Comparing known event to potential for event
- “I didn’t see it” ≠ “it didn’t happen”
- Rotation tracks can feel in missing information, undocumented by reports.

99.9% UH-CNTRL: 349.32 m²/s²
SUMMARY OF CONTROL VS. OBSERVATIONS

➢ The CNTRL simulation is weaker than OBS Ivan over water, but the simulated track agrees well with OBS

➢ OBS and CNTRL show similarities in Ivan’s general structure, as shown by reflectivity

➢ Inner 1km nest resolves cells that appear capable of producing a tornado

➢ PTM hits were generally co-located with the observed tornado reports

Given the results from the control simulation, we can now assess how this will change under an anthropogenically forced climate
“PSEUDO-GLOBAL WARMING” (PGW) APPROACH

Basic approach: following Schär et al. (1996), and Frei et al. (1998) [also Lackmann (2013,2015), Trapp and Hoogewind (2016)] we conduct a control simulation of a historical event, and then re-simulate the event with 3D meteorological forcing that has been modified by a climate-change $\Delta$, e.g.

$$T(x,y,z,t) = T(x,y,z,t) + D$$

where

$$T = \overline{T(x,y,z)}_{future} - \overline{T(x,y,z)}_{past}$$

- Here, the $\Delta$’s are 2080-2089 minus 1980-1989 for the month of September
- MIROC5 climate model with Research Concentration Pathway 8.5 is the 1st of 6 experiments.

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INTENSITY (MEAN SLP): CONTROL VS. PGW-MIROC-8.5-LC

Control
- ~Landfall
- ~955 mb
- End of run
- rime
- 1005 mb

PGW
- ~Landfall
- ~945 mb
- End of run
- rime
- 1004 mb
PGW tracks West of the CNTRL track, making landfall in Louisiana instead of Alabama. PGW tracked Northeast into Northern Maryland.
3KM REFLECTIVITY: CONTROL VS PGW-MIROC-8.5-LC

CONTROL

PGW
1KM REFLECTIVITY 15 SEPT.: CONTROL VS PGW-MIROC-8.5-LC

CONTROL

PGW

Radar reflectivity (\(\lambda = 10\) cm)

```wrfout_d03_2004-09-15_21:20:00```

Radar reflectivity (\(\lambda = 10\) cm)

```wrfout_d03_2004-09-15_21:20:00```
POTENTIAL TORNADIC MESOCYCLONE (PTM): CONTROL VS. PGW

CONTROL-2402 PTM

PGW-4371 PTM

99.9% UH-CNTRL: 349.32 m²/s²

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PDF OF UH VALUES (1KM NEST): PGW VS CONTROL
SUMMARY OF FINDINGS

❖ Simulated a viable CNTRL

❖ PGW is more intense than the CNTRL prior and up to landfall, tracking West of the CNTRL.

❖ PGW produced 1969 more PTM than the CNTRL, which is suggestive of more and/or possibly larger PTMs.

❖ Larger spread of UH values in PGW vs CNTRL.
  ❖ Increase in the range of UH max values under PGW, especially towards the higher end extreme values.
FUTURE/ONGOING WORK

- 2 additional GCMs and mid century (2040-2050)
- Assess range of uncertainty
- Assess changes in kinematics and thermodynamics

Repeat Process

Apply 4\textsuperscript{th} nest (333m)

Document changes in TCT supercell structure, including depth and size

Rotation Tracks

Use as verification

- Compare to PTM instead of tornado reports

Pair with demographic data

Sample disaster risk plot for counties impacted by TCTs in future climate.
CHALLENGES

Control case working ≠ PGW case will work

◦ My radiation scheme did not work in the PGW simulation and was forced to start from scratch with a new control case last week.

There seems to be a limit in how large my d3 1km domain can be

◦ After running the 9km and 3km successfully, I had to reduce the 3km domain slightly in order to get the 1km domain running

Still working on getting the 4th 333m domain running (hopefully this doesn’t force me to change any of the other domains)
ACKNOWLEDGEMENTS

❖ Blue Water Super Computing Facilities & Symposium Committee

❖ Dr. Jeff Trapp (Adviser; PI & Blue Waters Professor)

❖ Dissertation Committee at UIUC:
  Dr. Deanna Hence
  Dr. Ryan Sriver
  Dr. Zhuo Wang

❖ NSF GRFP

❖ Questions???
  ❖ Crrllsm2@Illinois.edu
  ❖ Dereka.carroll@gmail.com
Model Set up

• IC/BC model driver
  • NCEP FNL

Physical Parameterizations:

• Thompson Scheme
  • 6-class microphysics with graupel
  • Ice and rain number concentrations also predicted (double-moment ice)
  • Time-split fall terms

• Radiation- RRTMB Shortwave and Longwave

• PBL- Mellor Yamada-Janjic

• SF_Clay-Eta Similarity Scheme

• Cu_Physics, D1 only- Kain-Fritsch Scheme

• Time Step : 27 Secs

• Run Time
  • 14 Sept 00Z to 19 Sept 00Z D1-D2
  • 15 Sept 18Z to 16 Sept 03Z D3
  • 16 Sept 18Z to 17 Sept 00Z D3
  • 17 Sept 18Z to 18 Sept 00Z D3

• Used 30 nodes per run, ~18 wall clock hours

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FAVORABLE CONDITIONS FOR TROPICAL CYCLONE TORNADOES

- Typically occur in the late morning through afternoon
  - Period of maximized buoyancy and diabatic heating from solar radiation
- 12 hours prior to, to 24 hours post landfall
  - Cases in largest outbreaks to persist >24hrs
- Commonly located on outer rain bands 200-400km from storm center (McCaul 1991)
- Favored in Right Front Quadrant (Edwards 2010)
- Most likely to develop with tropical cyclones that re-curve (Verbout et al 2007)
  - Typically associated with 500mb trough contributing to deep layer shear, favorable for mesocyclogenesis and increasing low level shear which is favorable for tornadogenesis

Cartesian plot of U.S. tornado reports from a) all TCs 1995-2009; b) hurricanes; c) tropical storms; and d) tropical depressions and post classification categories (Edwards 2010)
FAVORABLE CONDITIONS FOR TROPICAL CYCLONE TORNADOES

- 85% form out of “miniature” supercells (Edwards 2012)
  - Weak rotation makes algorithmic radar detection difficult
  - Warm core TC environment have weak thermal lapse rates, so this leaves a concentration of buoyancy in lower levels, essentially limiting supercell growth.
  - The above ground level is where max vertical wind shear is concentrated
  - Impacts convective morphology

Schematic comparing mid-latitude supercell tornadoes to miniature TC supercells (Eastin et al. 2012).