HURRICANE SPAWNED TORNADOES UNDER ANTHROPOGENIC CLIMATE CHANGE

BLUE WATERS SYMPOSIUM

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OUTLINE

- What's The Problem?
- Why it Matters
- Why Blue Waters?
- Methodology
- Preliminary Results
- Acknowledgements

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

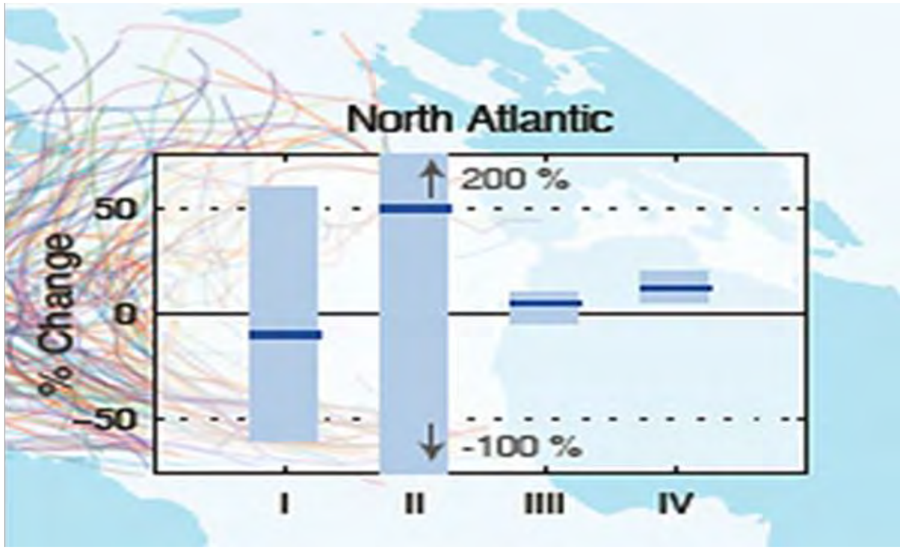
Low confidence for region specific projections

- 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

DISTRIBUTION OF TROPICAL CYCLONE TORNADOES (Edwards 2012)

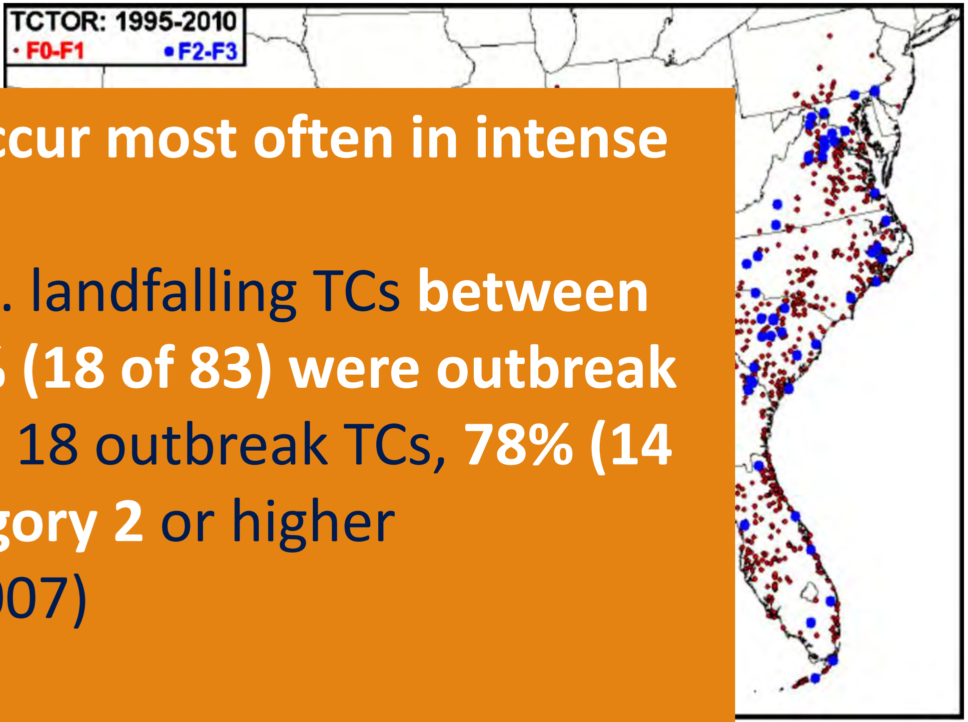
Large number of strong TCT events
occurred withi

TROPICAL CYCLONE	YEAR		
H Ivan	2004		
H Beulah	1967		
H Frances	2004		
H Rita	2005		
H Katrina	2005		
H Andrew	1992		
TS Fay	2008		
H Gustav	2008		
H Cindy	2005	48	1
H Georges	1998	48	2

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

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)



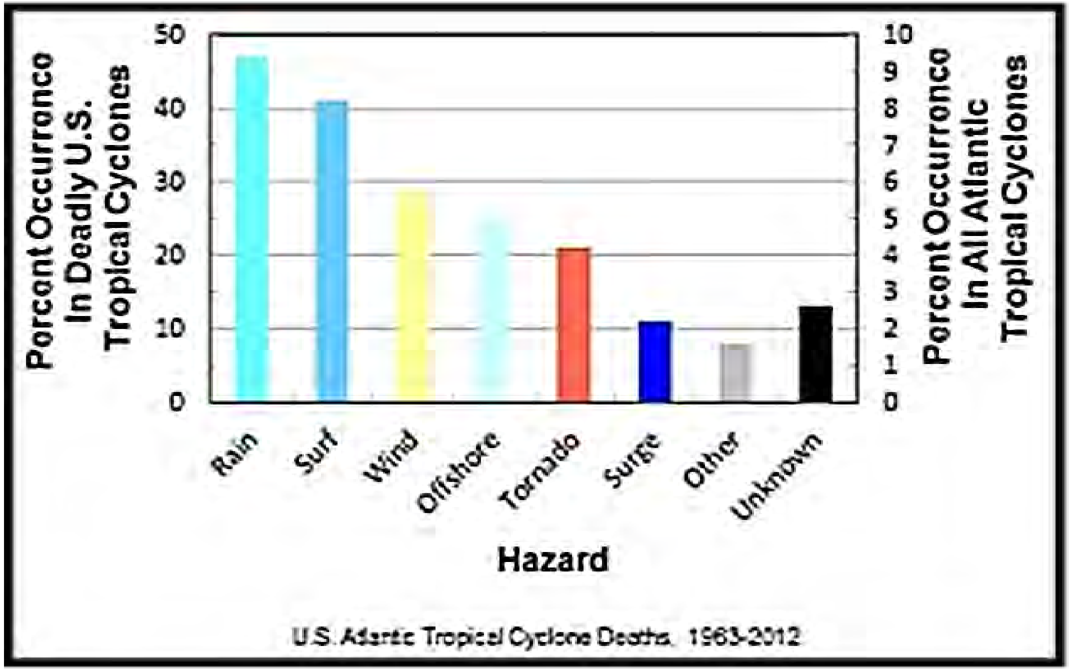
50% of the most notable TCT outbreaks (20 or more TCTs as defined by Curtis 2004) occurred in 2004-2005 seasons

Why It Matters

63% OF TC RELATED FATALITIES OCCUR INLAND.

(RAPPAPORT 2000)

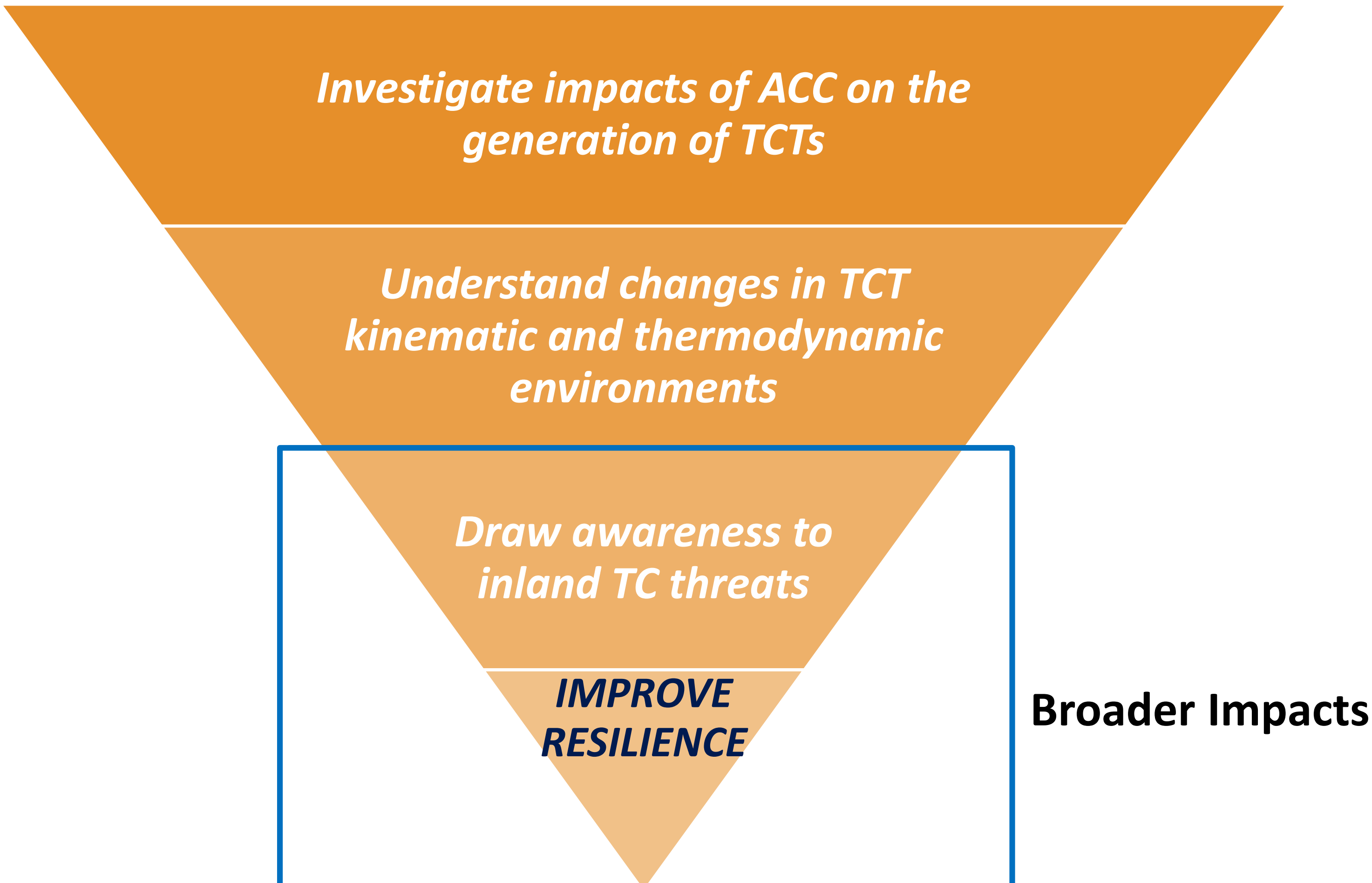
TROPICAL CYCLONE FATALITIES



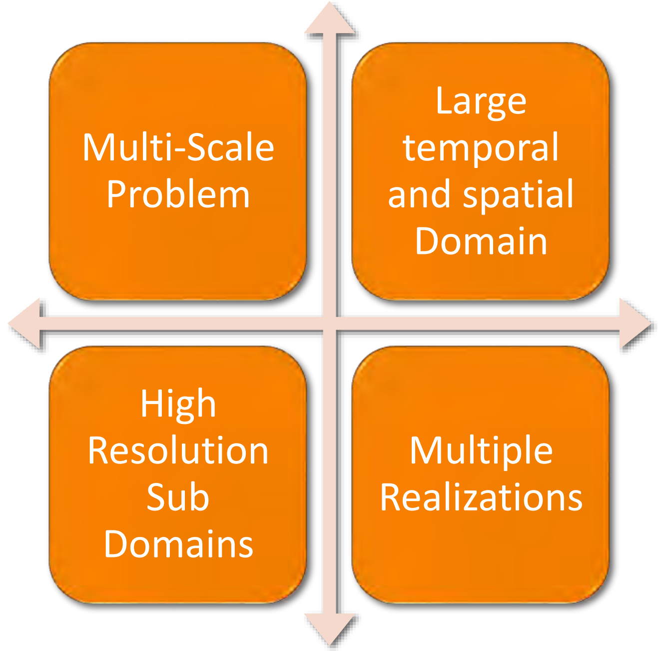
Percent occurrences of fatalities from 1963 to 2012 due to Atlantic tropical cyclones.

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.

PURPOSE



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



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

Example of Domain for 15 Sept 2004 period

*Resolution chosen in inner 2 nests is sufficient to resolve TC rainbands and considered to be convection allowing

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

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

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

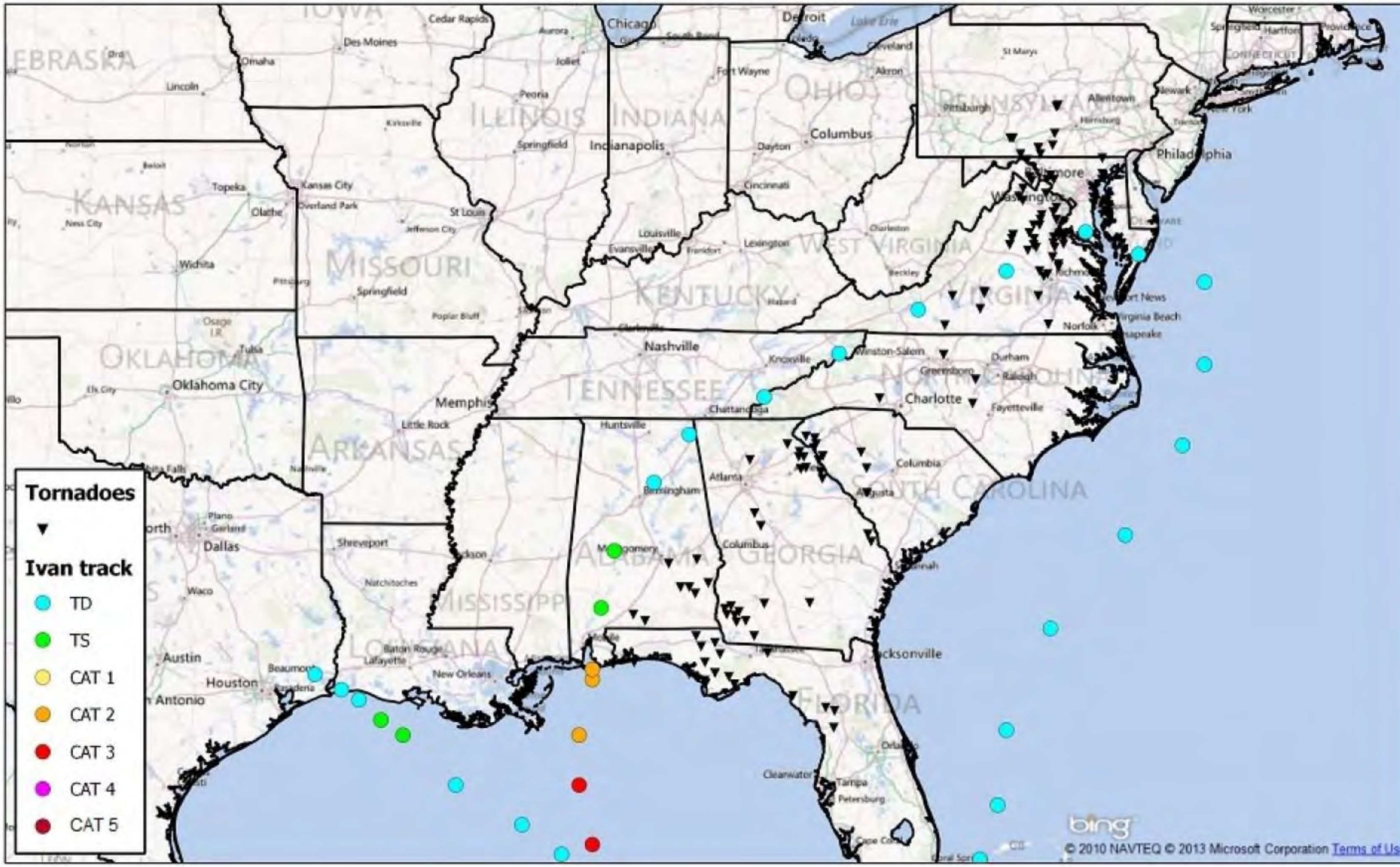
92 total deaths

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

Produced record 118 tornadoes

- Majority occurred inland

Hurricane Ivan
September 2004
Track and Reports



Results

- D1 & D2 INITIALIZED 14 SEPT 00Z TO 19 SEPT 00Z
- D3 INITIALIZED 15 SEPT 2004 18Z- 16 SEPT 2004 03Z
  - Initialized near the time of the first tornado report

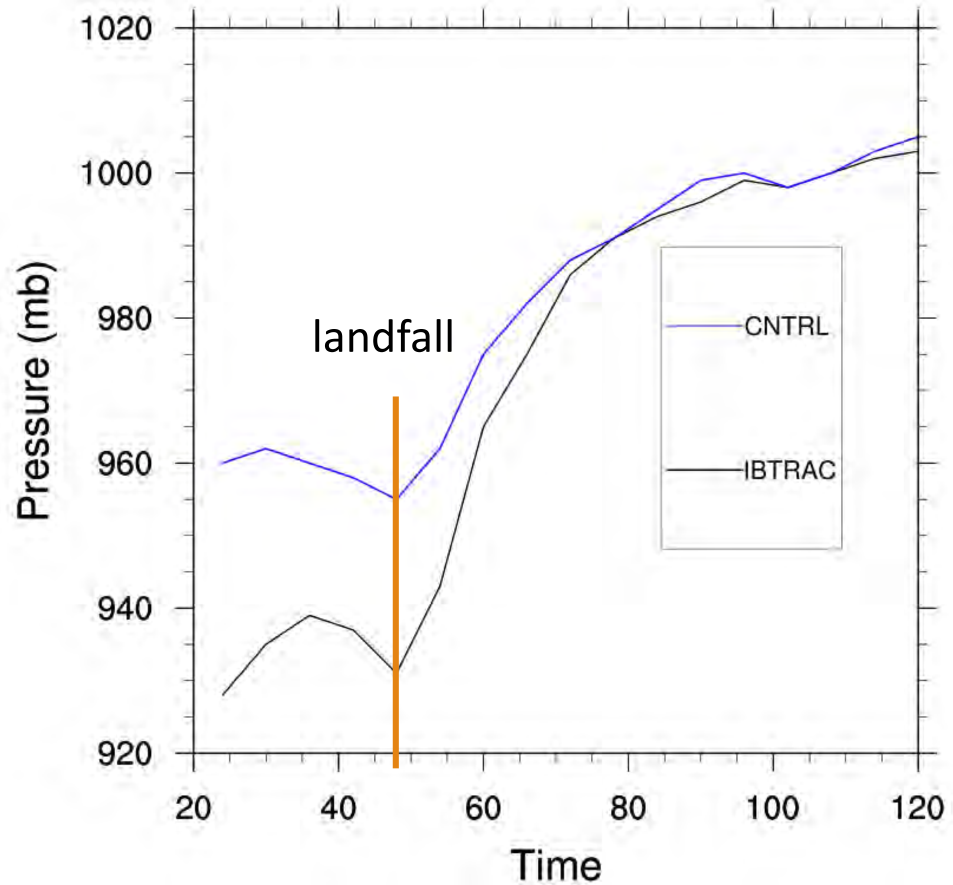
CONTROL (CNTRL) VS OBSERVED (OBS) INTENSITY (MEAN SLP)

Observed Track

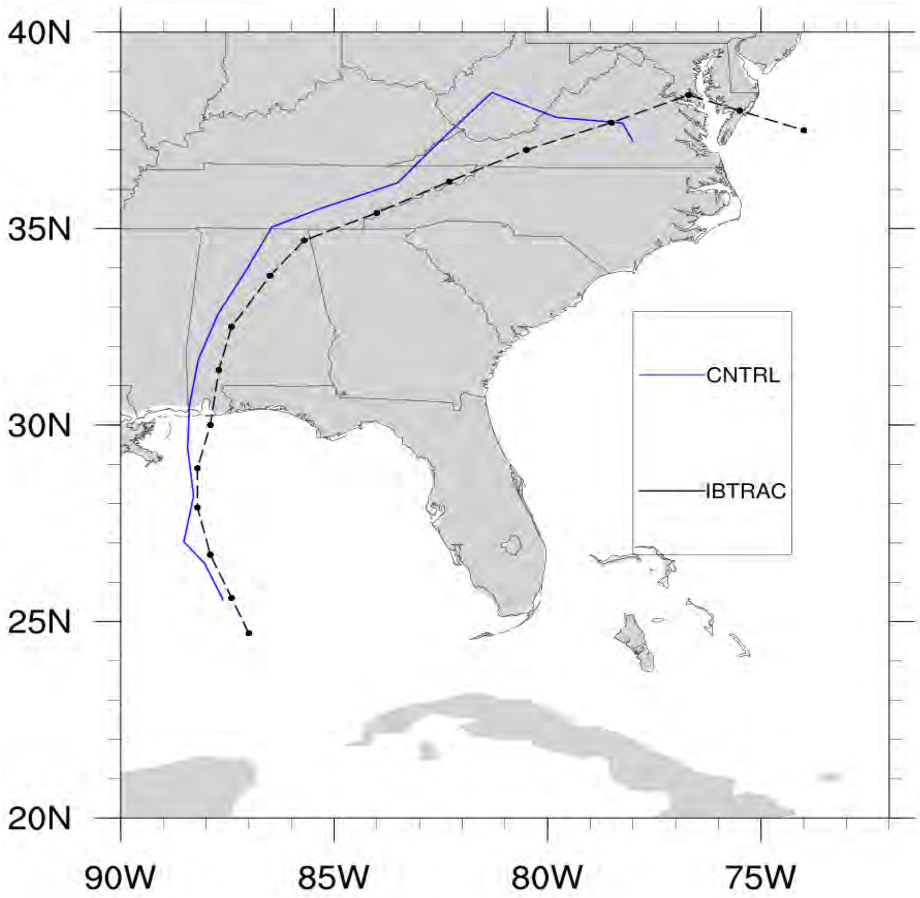
- IBTRACS -6hrly Mean Sea Level Pressure
- ~Landfall
  - ~930 mb

Simulated Track

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



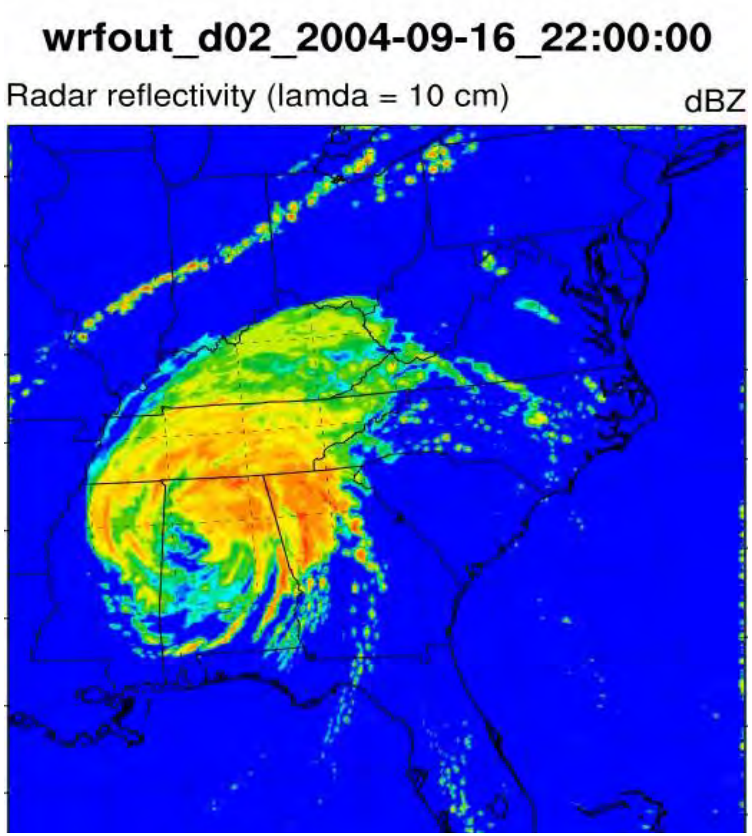
CONTROL VS OBSERVED TRACK



CNTRL Ivan tracks slightly West of the OBS track and curves into Virginia, instead of tracking upward towards Southern Maryland.

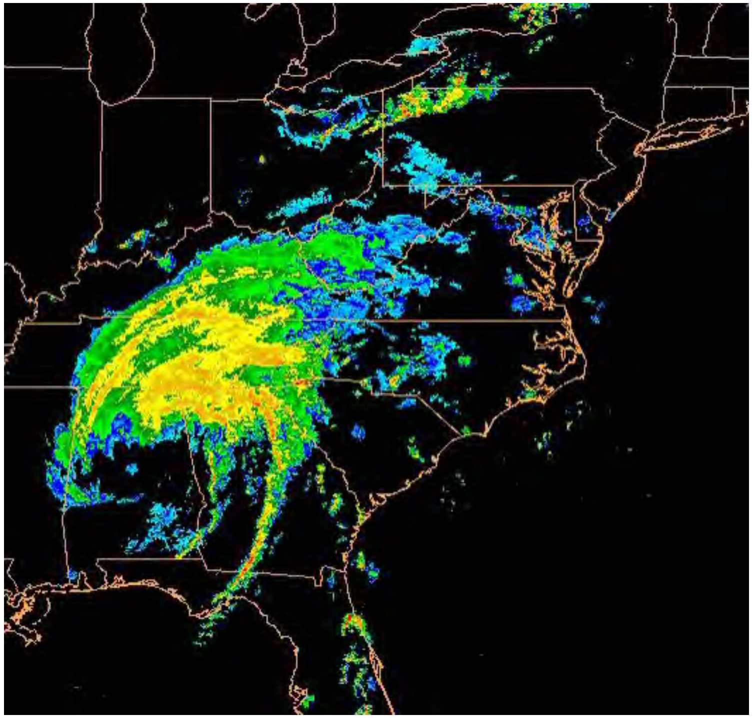
CONTROL VS OBSERVED 3KM REFLECTIVITY

CONTROL



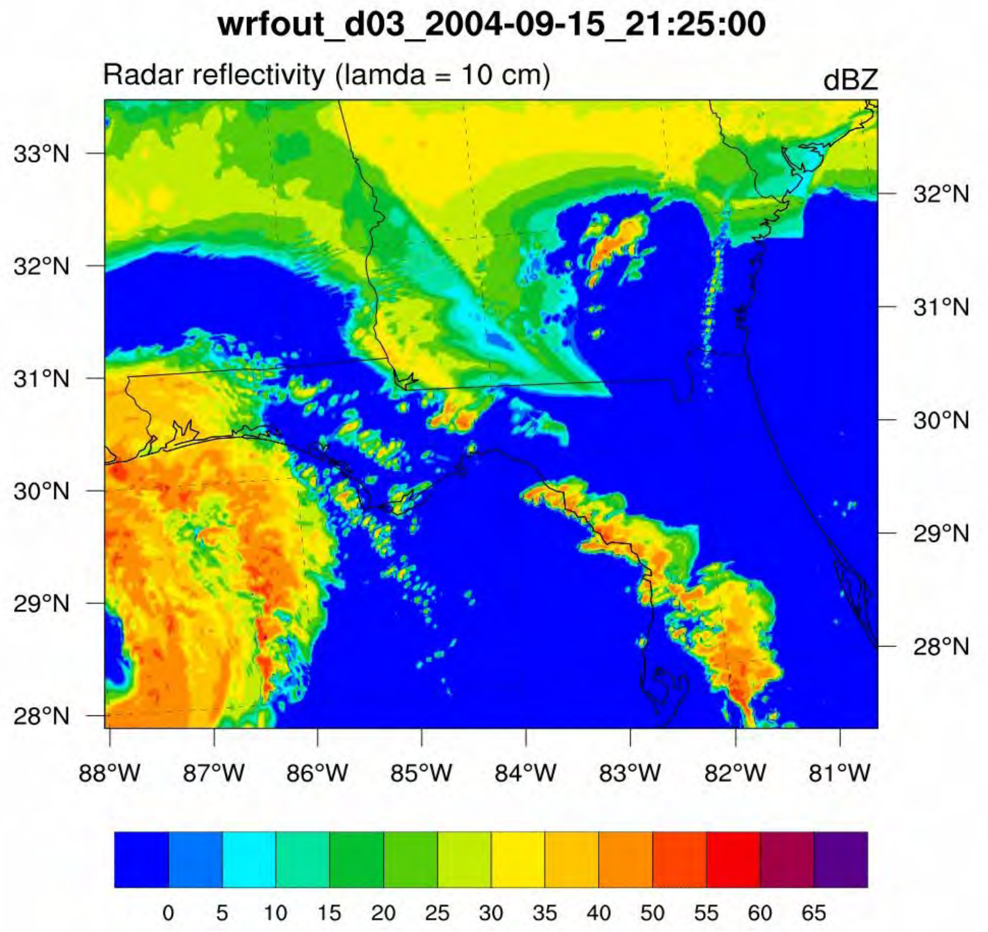
OBSERVED

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

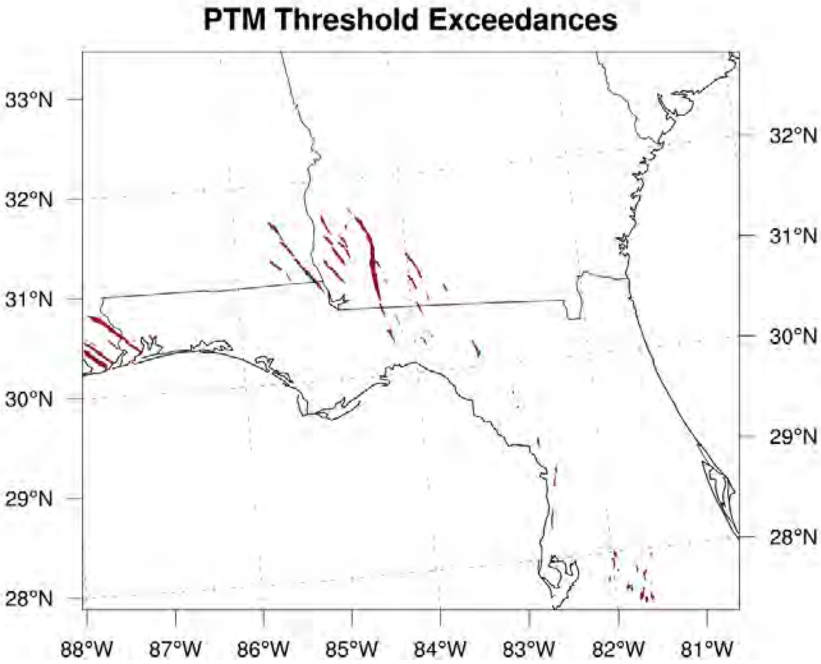
$$\mathrm{UH} = \int_{z_0}^{z_t} w\zeta \, dz,$$

Where w is vertical velocity and ζ is vertical vorticity. Let let z_0=2 km, and z_1=5 km

99.9% UH max Value = PTM threshold

TCT REPORTS VS. CONTROL

99.9% UH-CNTRL: 349.32 m^2/s^2



- 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.

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 <u>historical event</u>, and then re-simulate the event with 3D meteorological forcing that has been **modified by a climate-change Δ**, e.g.

$$T(x,y,z,t) = T(x,y,z,t) + \mathrm{D}T$$

where

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

- Here, the Δ's are 2080-2089 minus 1980-1989 for the month of September
- MIROC5 climate model with Research Concentration Pathway 8.5 is the 1^{st} of 6 experiments.

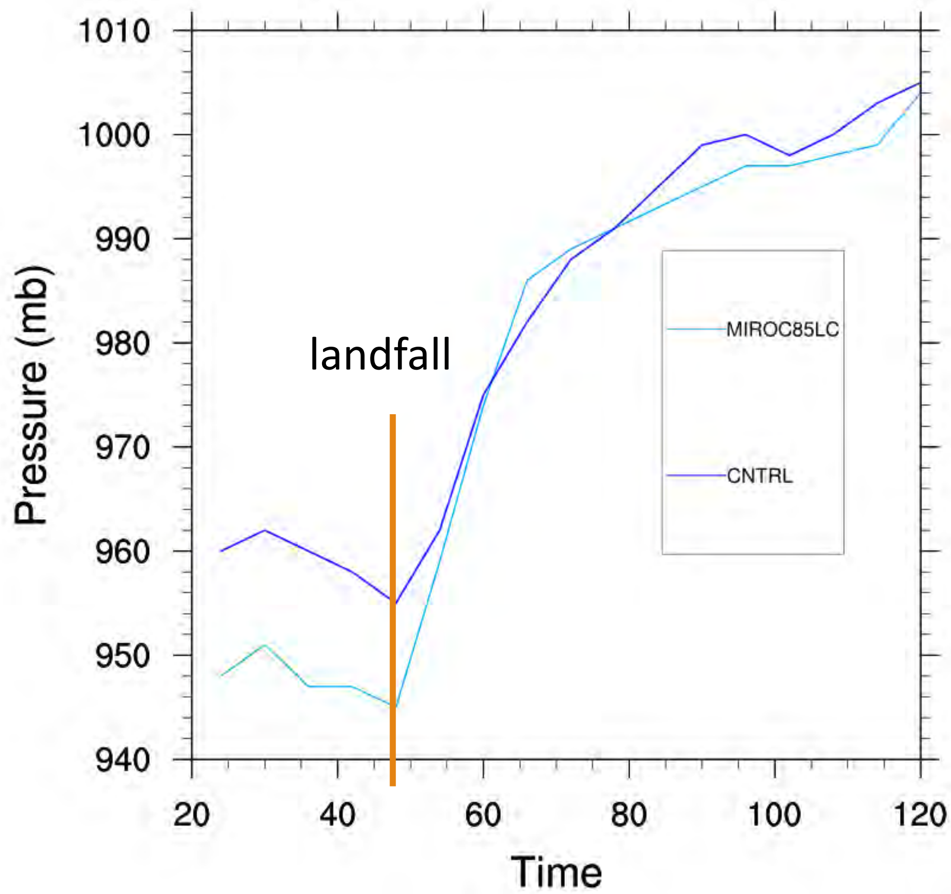
INTENSITY (MEAN SLP): CONTROL VS. PGW-MIROC-8.5-LC

Control

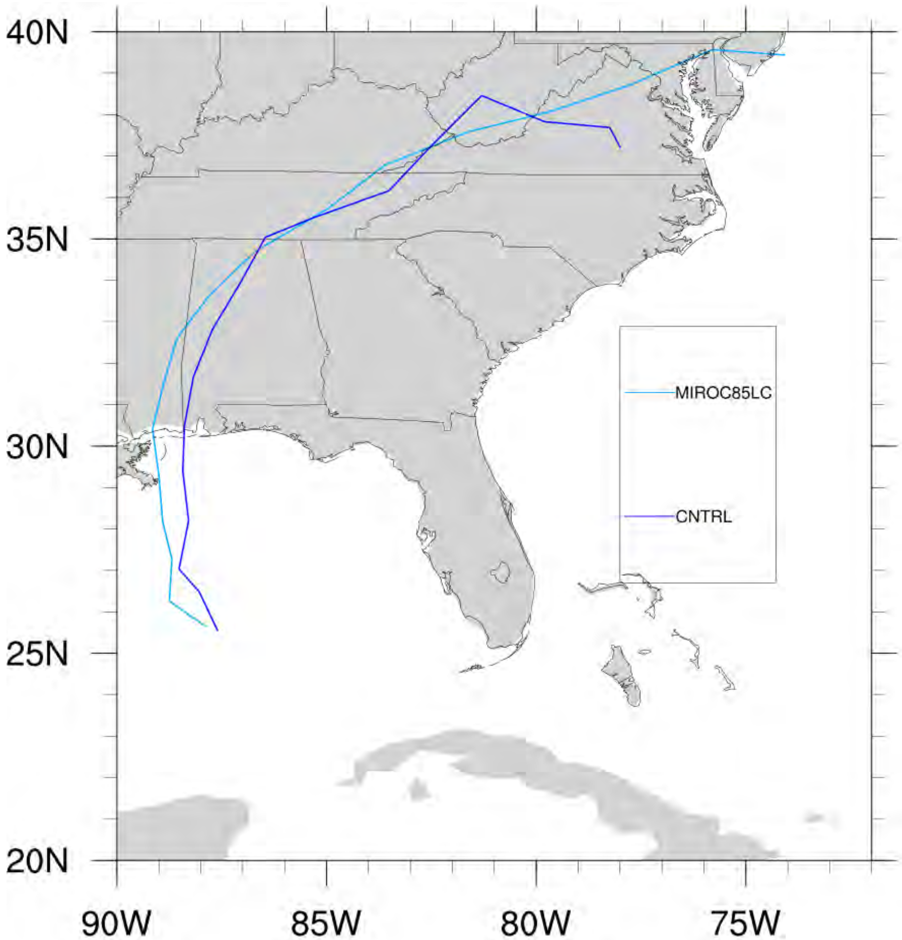
- ~Landfall
  - ~955 mb
- End of run rime
  - 1005 mb

PGW

- ~Landfall
  - ~945 mb
- End of run rime
  - 1004 mb



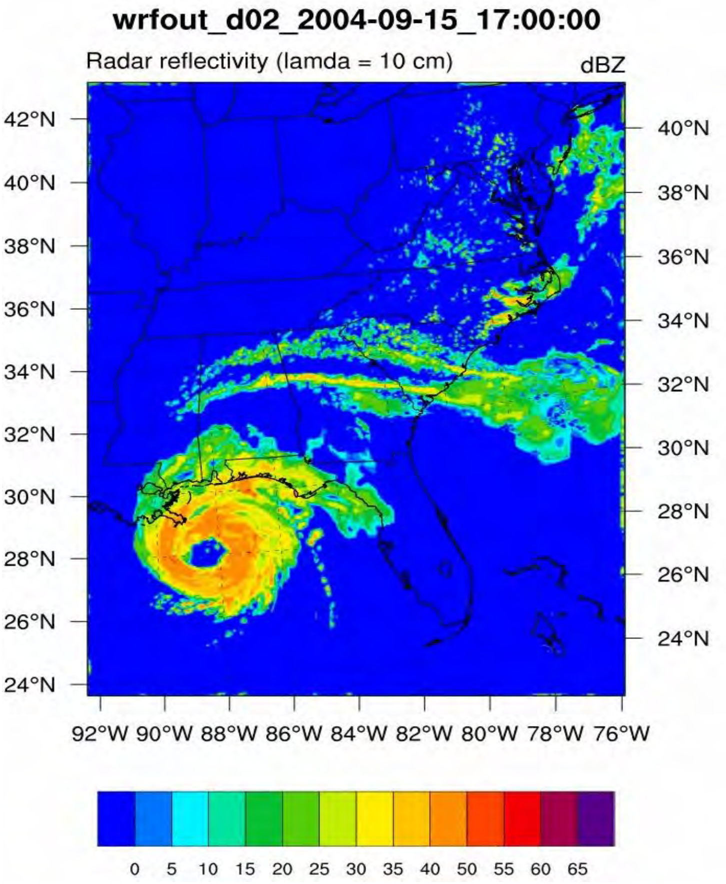
TRACK : CONTROL VS. PGW-MIROC-8.5-LC



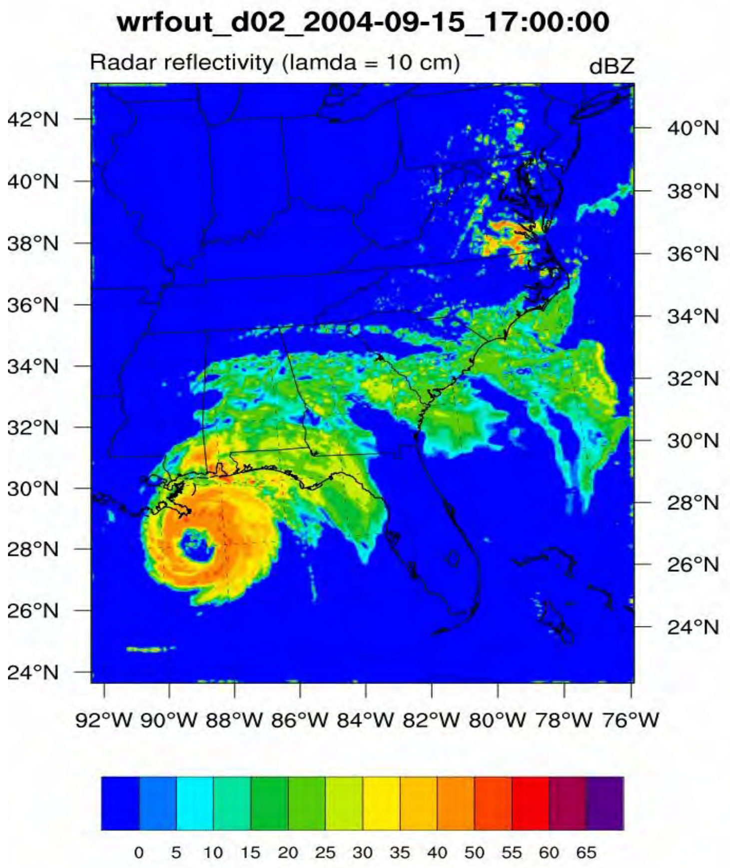
PGW tracks West of the CNTRL track, making landfall in Louisiana instead of Alabama. PGW tracked Northeast into Northern Maryland.

3KM REFLECTIVITY: CONTROL VS PGW-MIROC-8.5-LC

CONTROL

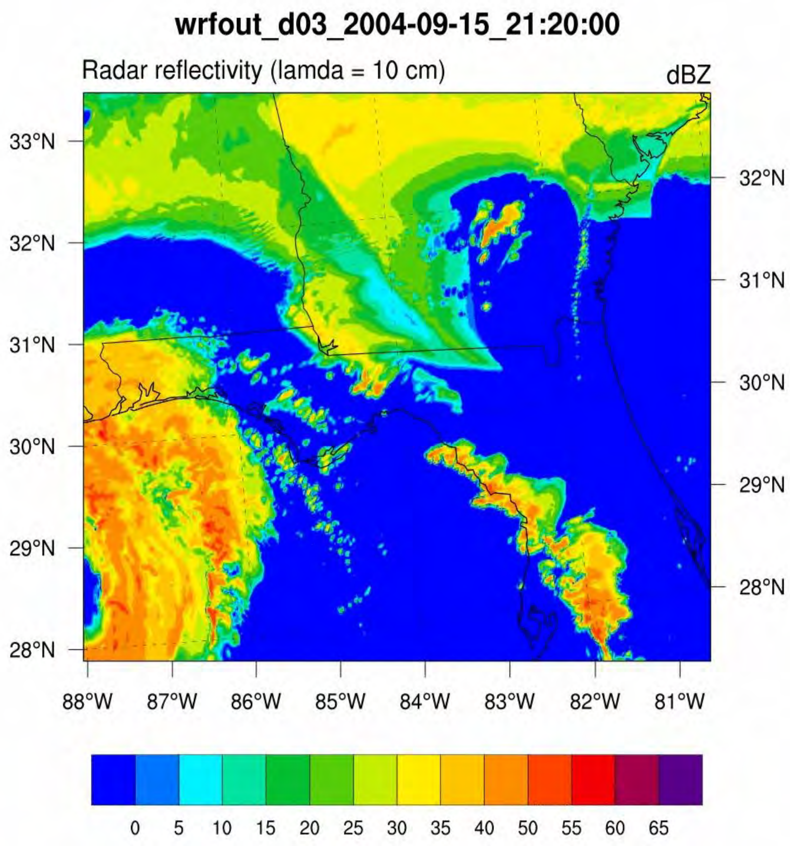


PGW

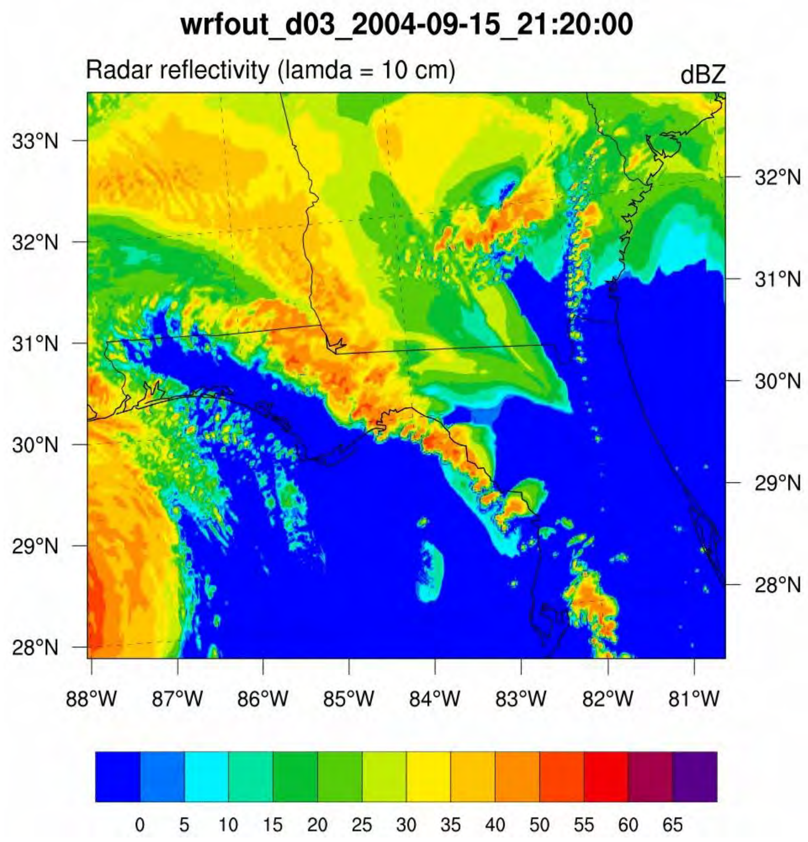


1KM REFLECTIVITY 15 SEPT.: CONTROL VS PGW-MIROC-8.5-LC

CONTROL



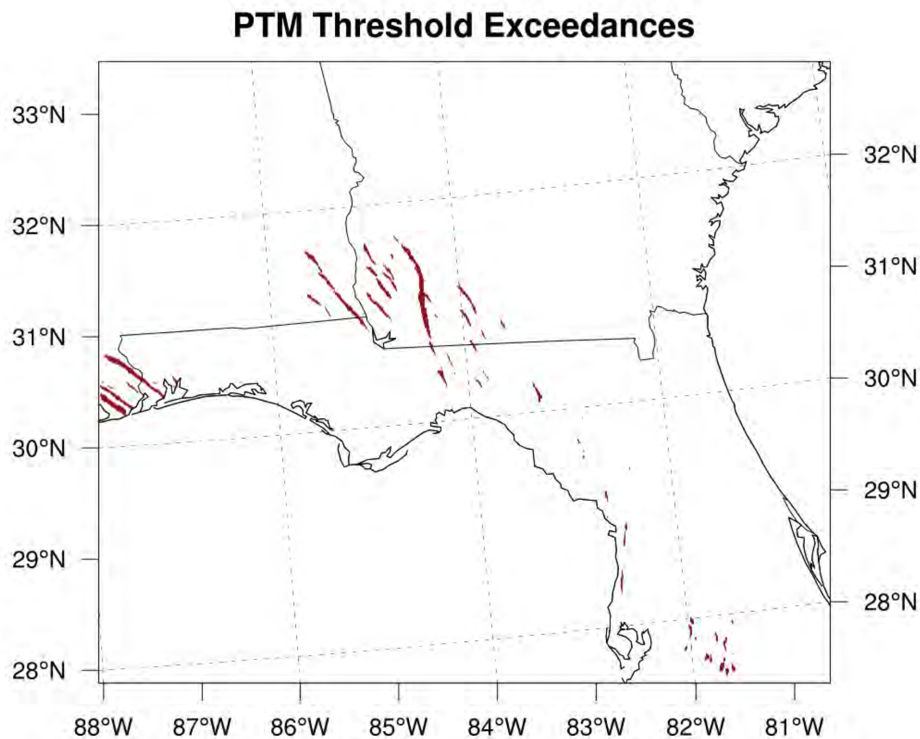
PGW



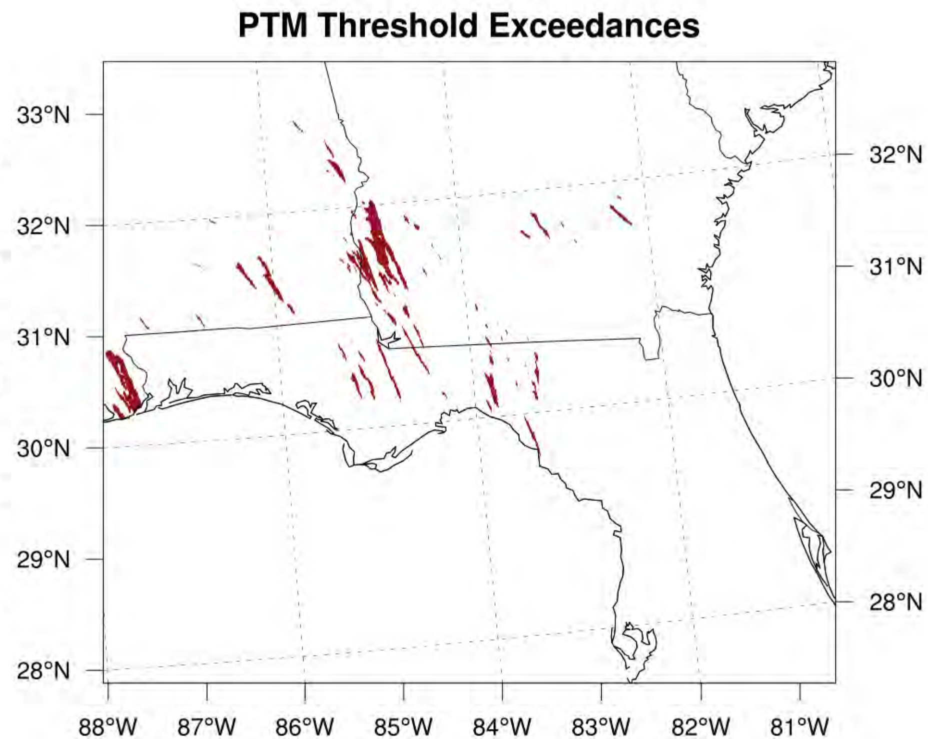
POTENTIAL TORNADIC MESOCYCLONE (PTM): CONTROL VS. PGW

99.9% UH-CNTRL: 349.32 m^2/s^2

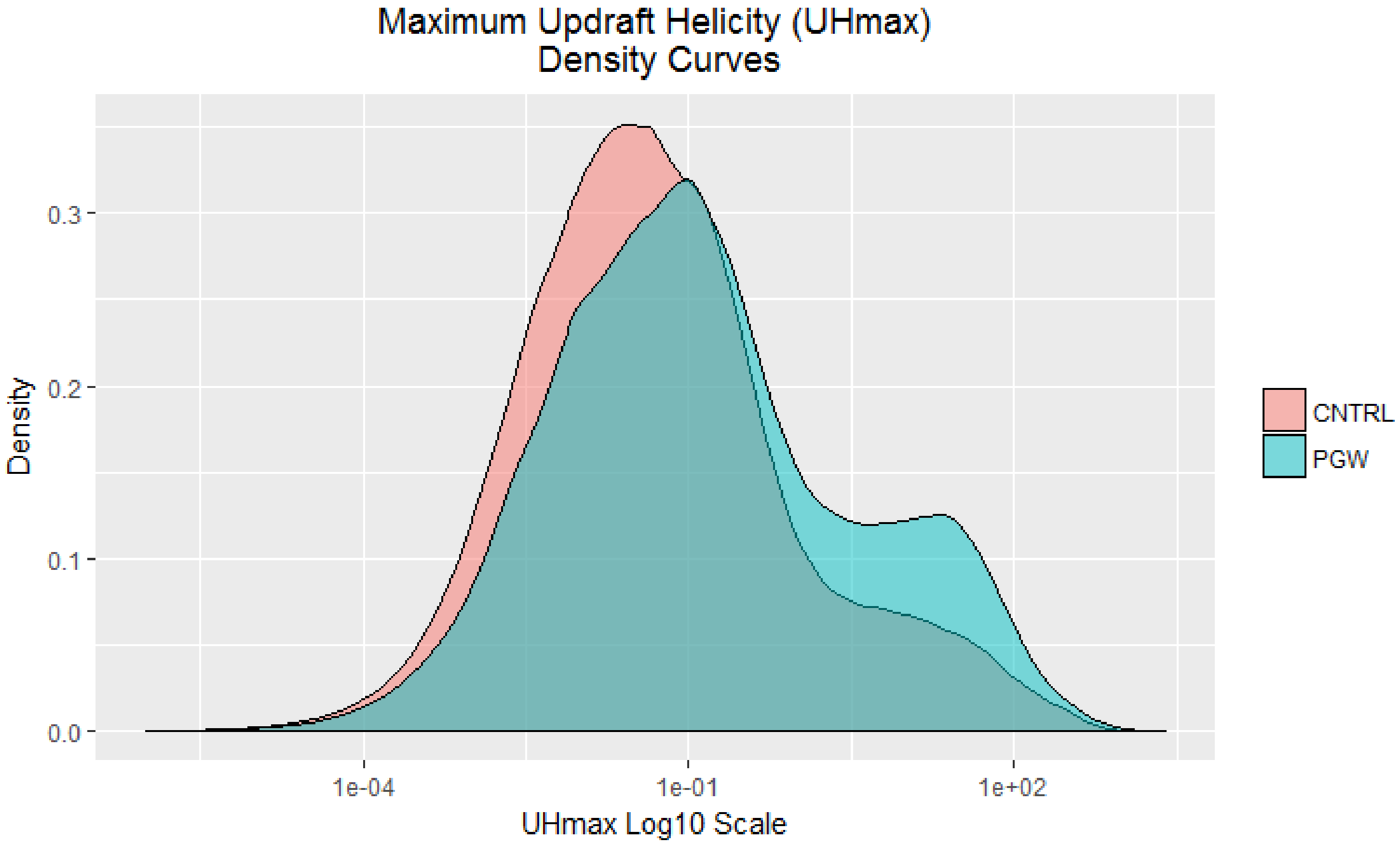
CONTROL-2402 PTM



PGW-4371 PTM



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

Repeat Process

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

Apply 4th nest(333m)

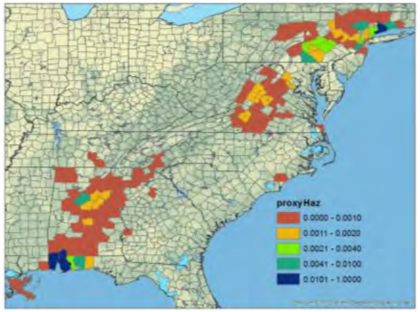
Document changes in TCT supercell structure, including depth and size

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 4^{th} 333m domain running (hopefully this doesn't force me to change any of the other domains)

ACKNOWLEDGEMENTS

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  - Dr. Ryan Sriver
  - Dr. Zhuo Wang
- NSF GRFP

- Questions???

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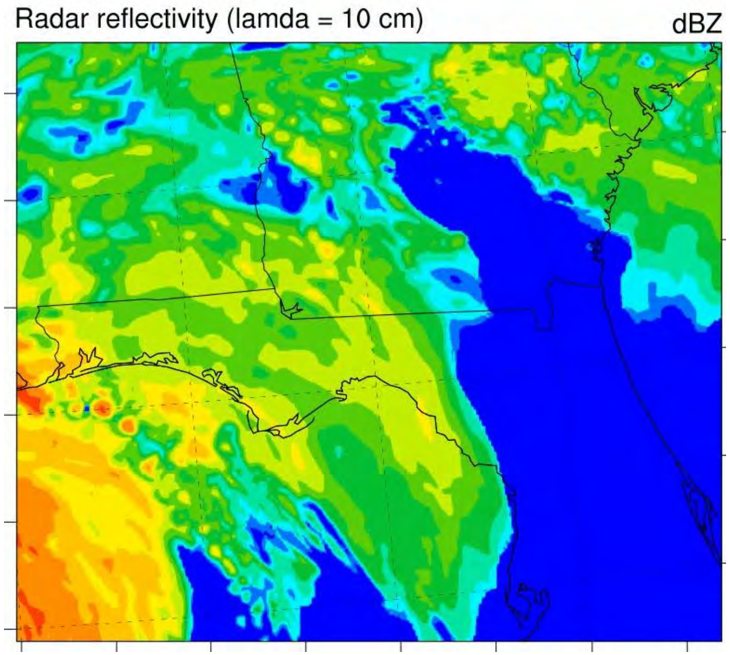


Radar Loop PGW Ivan

Model Set up

- IC/BC model driver
  - NCEP FNL

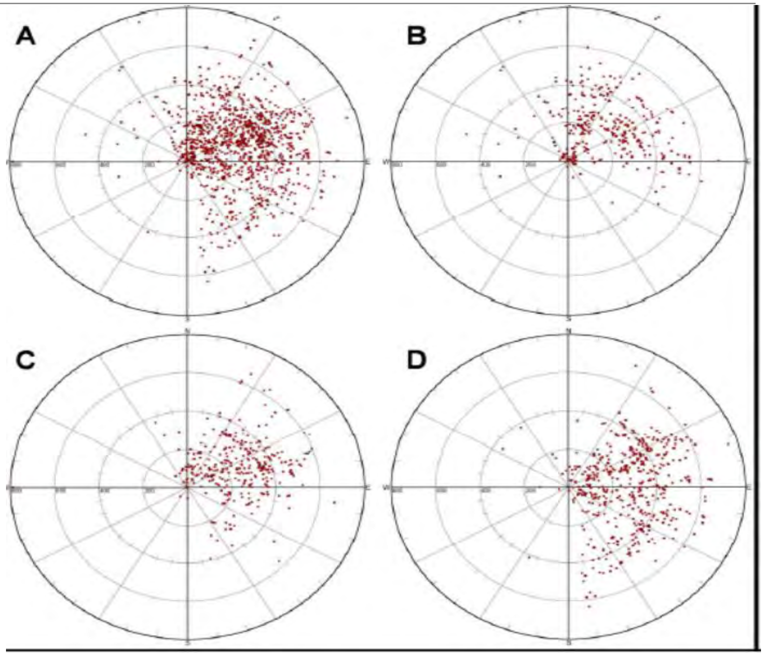
Physical Parameterizations:

- 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

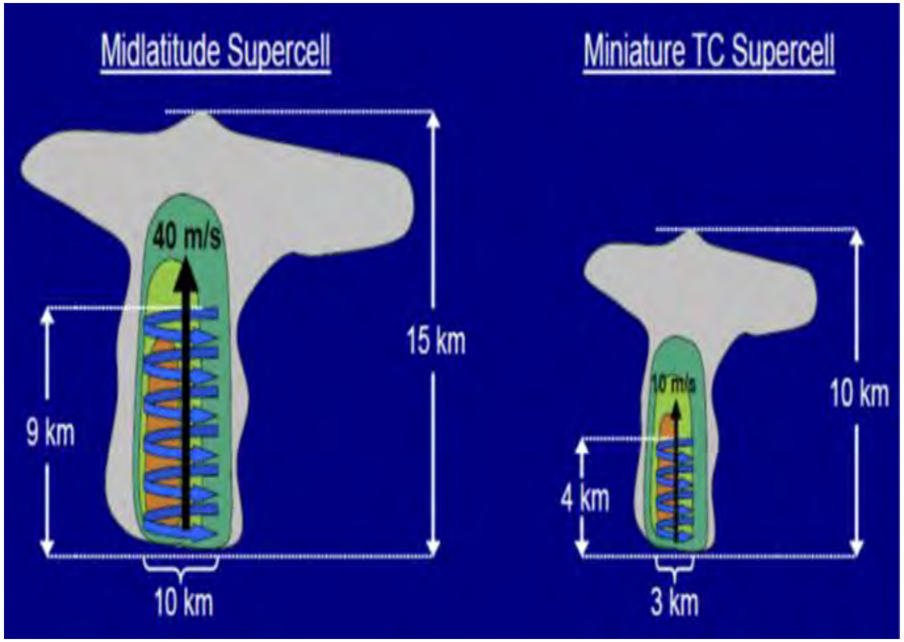
FAVORABLE CONDITIONS FOR TROPICAL CYCLONE TORNADOES

- 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



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

- 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