Climate Modeling Challenges for Tropical Cyclones

Gary Lackmann, North Carolina State University

Contributors: Kevin Hill, Megan Mallard, and Chris Marciano

NCAR GEWEX Convection-Permitting Climate Modeling Workshop
8 September 2016
- Wish to know change characteristics (e.g., Knutson et al. 2010, others)

- Important role of TCs in ocean heat budget, heat uptake (e.g., Mei et al. 2013; Scoccimarro et al. 2011; Pasquero and Emanuel 2008; Hart et al. 2007; Sriver and Huber 2007; Emanuel 2001; Shay et al. 1989)

- TCs dry tropical atmosphere, transport heat vertically and meridionally (e.g., Emanuel 2008; Sobel and Camargo 2005)

- Important TC role in mid-latitude dynamics; e.g., Rossby wavetrains, jet energetics, predictability (e.g., Grams and Archambault 2016; Reynolds et al. 2014; Hart 2011; Palmen 1957)

Fig 9. Grams & Archambault, PV on 335K difference, ctrl - noTC
Challenges in TC modeling

“Dynamically, the tropical cyclone is a mesoscale power plant with a synoptic-scale supportive system.”

“The tropical cyclone is a complex system of interacting physical processes and multiscale motions. A complete description would have to cover nearly all the subjects in meteorology, from cloud physics within turbulent convection to general circulations of the tropics, and from interactions with the ocean to radiative heat transfer into outer space”

What is needed to represent TCs in a model?

- Explicit representation of convective updraft in eyewall, crucial to vortex stretching, realistic heating profile, PV tower

- Resolution of larger secondary circulation, spiral bands, outflow layer, eye

- Account of oceanic response (cold wake), requiring at least a 1-D ocean mixed-layer model

- Microphysics, with interaction/coupling to radiation scheme (ice processes, graupel, outflow layer anvil: CRF, Fovell)

- Realistic account of precursor disturbances (e.g., easterly waves, ITCZ, etc.), especially for long-duration runs
Resolution Requirements?

- Requisite grid spacing to resolve typical TC vortex?
- By mesoscale modeling standards, even coarse grids resolve TC primary circulation

Gentry and Lackmann 2010: Sensitivity of simulated tropical cyclone structure and intensity to horizontal resolution. MWR

Radius of Max Wind ~ 50 km, Diameter ~ 100 km
Eye diameter ~ 30 km

<table>
<thead>
<tr>
<th>Grid Resolution</th>
<th>Domain Width</th>
<th>Grid Resolution</th>
<th>Domain Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>4(\Delta x) partially resolved</td>
<td>(\Delta x) 25 km</td>
<td>4(\Delta x) partially resolved</td>
<td>(\Delta x) 8 km</td>
</tr>
<tr>
<td>10(\Delta x) fully resolved</td>
<td>(\Delta x) 10 km</td>
<td>10(\Delta x) fully resolved</td>
<td>(\Delta x) 3 km</td>
</tr>
</tbody>
</table>

Walters, 2000 & comments by Grasso; Skamarock and Klemp (2008): 6-8 \(\Delta x\)
Eyewall Updraft and CP

Ivan (2004) simulated at 27, 9, 8, 6, 4, 3, 2, 1 km

9–km grid, with CP:
- Weaker up/downdrafts
- Less spiral banding
- Reduced secondary circulation
- Weaker vortex stretching
- Lower TC intensity, weaker PV tower

Gentry and Lackmann 2010: Sensitivity of simulated tropical cyclone structure and intensity to horizontal resolution. MWR
Explicit Eyewall Updraft

Gentry and Lackmann 2010: Sensitivity of simulated tropical cyclone structure and intensity to horizontal resolution. MWR
Vortex Rossby Waves

850 hPa potential vorticity (PV) at different grid lengths: Wave breaking behavior, eyewall replacements only evident at higher resolution (< ~ 4km)

Gentry and Lackmann 2010: Sensitivity of simulated tropical cyclone structure and intensity to horizontal resolution. MWR
Precipitation Physics

Hour 72, Sandy explicit simulation, WSM6 microphysics

rain, snow, graupel

Convective updrafts sufficient to loft snow, microphysics scheme needs graupel
Climate change approaches for high-resolution downscaling (known to this audience):

“Surrogate Global Warming”: Apply uniform warming to analyzed initial conditions (IC), lateral boundary conditions (LBC) (Schär et al. 1996; Frei et al. 1998)

“Pseudo Global Warming (PGW)”: Apply GCM-derived (non-uniform) change to IC, LBC (e.g., Hara et al. 2007; Kimura and Kitoh 2007; also “Method R”, Sato et al. 2007; Kawase et al. 2009)
PGW Method

- Apply GCM-derived thermodynamic change to current analyses; uniform (tropics) or spatially varying (higher latitude) – PGW approach

- Replicate current events or seasons with “future or past thermodynamics”; for TC case, preserves shear, palette of incipient disturbances

Analyses: Initial, lateral BC to simulate recent season or event

Simulated future season/event, current synoptic pattern, future thermo

“Pseudo Global Warming” approach

IPCC Ensemble changes (A2, RCP4.5, etc.)
Varieties of PGW

1.) “Regional case study mode” – short integration < 1 week with regional configuration, adjusted IC, LBC, model trace gas changes not needed. Selection bias?

2.) “Regional seasonal/annual” – adjusted IC, LBC but domain of sufficient size to allow independent evolution in interior; modify trace gases, deep soil temperature.

Lateral boundary conditions (LBC) are major consideration
- Is variability in LBC better in analysis or GCM? Depends
- Driving RCM with GCM: Sufficient temporal, spatial resolution?

3.) “Global PGW” – short or longer duration, but no LBC issues. Trace gas modification needed for more than a few weeks, also deep soil T, sea ice. Maintain consistent “delta”? 
Climate Warming and TCs

**Favorable**

- Increased SST, MPI
- Increased vapor content, precipitation, latent heating
- Increased convective available potential energy (CAPE)

**Unfavorable**

- Lapse rate stabilization, reduced thermodynamic efficiency
- Increased convective inhibition
- Weakening of tropical circulation
- Increased vertical wind shear (basin dependent)
- Larger mid-level saturation deficit

A1B Atlantic MPI Difference: 5 to 20 hPa increase in potential intensity
Results: TC Intensity Change

TC intensity sensitive to T change profile

- SST increase of 1.5°C completely is offset by increase in upper tropospheric temperatures of 3 – 4°C (e.g., Shen et al. 2000; Knutson and Tuleya 2004)

Shape of GCM change profile quite variable

- GCMs with ozone recovery closer to observations; tropospheric influence (Cordero and Forster 2006)

  • GCM CP may mix heat too high into troposphere: Forster et al. (2007)

Idealized, ocean-only, f-plane, single-sounding

Ensemble of idealized 2-km WRF runs (mini ensemble – GCM, physics)

Results: Precipitation and Intensity Change

<table>
<thead>
<tr>
<th>Simulation name</th>
<th>Min SLP (hPa)</th>
<th>Increase in SLP deficit (%)</th>
<th>Precipitation (R &lt; 250 km)</th>
<th>MPI change (% relative to control)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current 2km</td>
<td>919</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1 2km</td>
<td>909</td>
<td>11%</td>
<td>+8 %</td>
<td>6.5%</td>
</tr>
<tr>
<td>A1B 2km</td>
<td>908</td>
<td>12%</td>
<td>+20 %</td>
<td>9.0%</td>
</tr>
<tr>
<td>A2 2km</td>
<td>902</td>
<td>19%</td>
<td>+27 %</td>
<td>10.7%</td>
</tr>
</tbody>
</table>

MPI increase: 6–11%

Intensity increase: 11–19%

Rainfall increase: Tied to vapor more than updraft, in eyewall

Mechanism for strengthening?

Heavier precipitation for future TCs:
- Strength of steady-state PV tower related to precipitation rate
- Very high correlation in ensemble between Rain and PV, PV and SLP

Time, azimuthal-average PV cross sections, 2-km runs

Hill and Lackmann 2011: J. Climate
Compensation? Inflow, Outflow Temperature

Time averaged: hour 216 – 240, 2-km

Shading: T increase (relative to current)

Black contours: future radial flow
Red contours: current radial flow

• Stronger warming of mass-weighted outflow in future

• Inflow warming ~SSTΔ

• Result: Reduced heat engine efficiency in future

• Less intensification relative to what SST change would imply

• Omission of CP enabled this analysis

Hill and Lackmann 2011: J. Climate
TC Frequency Change: Basin-Scale PGW

- KF convective scheme (CP)
  - On 54- & 18-km grids

- Initial & boundary conditions:
  - 1° GFS FNL analyses
  - 0.5° RTG SST (24 h)

- Mini-physics ensemble (PBL, microphysics)

Ocean mixed layer model (OML) for TC cold wakes

Modified to combine SST update with OML (relaxation time)
18 vs. 6 km: Storm Count

18-km runs overestimate TC frequency

Cause?
- Sensitivity to TC detection algorithm
- KF CP here doesn’t modify momentum (e.g., Moorthi et al.; ’01; Han & Pan ’05)

Improvement at 6 km grid length

Ensemble-mean storm count: Sept 2005

18 km Current 2005
6 km Current 2005

Mallard et al. 2013: Atlantic hurricanes and climate change: Part II: Role of thermodynamic changes in decreased hurricane frequency. J. Climate
High-Resolution (6 km grid) Simulations Side-by-Side Ensemble Member E3

Recent September

Future: Reduced TC activity with same pattern
Mallard et al. 2013 a,b, *J. Climate* for details
High-Resolution Simulations
Side-by-Side Ensemble Member E3

Recent September

A1B Modified

Future: Reduced TC activity with same pattern
Mallard et al. 2013 a,b, J. Climate for details
Future TC Activity Change

Accumulated Cyclone Energy (ACE) reduced in future (both resolutions, 2005 + 2009)

Storm count decreases at both 18 and 6 km grid length

Fewer storms, longer time to genesis, shorter duration
TC Genesis-Relevant Changes

- Knutson et al. 2010 review: Overall TC frequency decrease with warming. Causes?
  - Increased stability, decreased TC efficiency (e.g., Sugi et al. 2002; Yoshimura et al. 2006; Oouchi et al. 2006; Bengtsson et al. 2007; Gualdi et al. 2008; Hill & Lackmann 2011)
  - Weakening vertical motion in tropics (e.g., Sugi et al. 2002; Bengtsson et al. 2007; Murakami and Wang 2010; Lavender and Walsh 2011)
  - Increased vertical wind shear (e.g., Gualdi et al. 2008; Garner et al. 2009)
  - Increased TC sensitivity to shear with warming SST (Nolan and Rappin 2008)
  - Increased mid-level saturation deficit (Emanuel 2008; Rappin et al. 2010)
Emanuel et al. 2008; Rappin et al. 2010:

$$\chi_m = \frac{S_b - S_{mid}}{S_0 - S_b} \propto \frac{\chi_{mid}}{\chi_{flux}}$$

Proportional to time until TC genesis

Larger $\chi_{mid}$ & TC frequency:
- Larger midlevel saturation deficit: more subsaturated downdrafts
- Near saturation necessary condition for TC genesis
- Delayed TC genesis, reduced TC frequency

$$s = c_p \ln T - R_d \ln p + \frac{L_v q}{T} - R_v q \ln RH$$
PGW allows comparison of “same” events, current + future

• Cases # 1 to 4 (Current Genesis/Future fail)
  – Genesis in current simulation, corresponding disturbance non-developing in future simulation

• Cases # 5 & 6 (Current Genesis/Future Genesis)
  – Genesis occurs in similar timeframe for both current/future

• Here, focus on representative Genesis/Fail events, use “matching” ensemble members (same physics)
Case 1: Current Genesis, Future Fail

- Initial disturbance appears as closed low, convection to east, south

- **Current**: convection persists, TC genesis

- **Future**: convection dissipates

Model simulated radar & sea-level pressure (every 2 hPa) 7 Sept. 12 UTC to 11 Sept. 12 UTC 2005, 1st ensemble member
Case 1: Current Genesis, Future Fail

- Initial disturbances enter marginal humidity environment
- **Current:** Convection moistens environment, reduces saturation deficit
- **Future:** large deficits persist, convection eventually dissipates
- Same RH in each
In favorable moisture environment, genesis in both simulations.
TC Frequency Results

- As in many previous studies, reduced future TC frequency, **even with “same” synoptic pattern, same shear** environment

- Comparison: **several incipient TCs in marginal humidity environments fail to develop in future**, while able to develop in current

- Why don’t future TCs develop?
  - Increased mid-level saturation deficit ($\chi_{\text{mid}}$),
  - Increase in incubation parameter: Longer time to genesis

- **Results: thermodnamic effect alone explains TC frequency decrease in these simulations**

- Results consistent with Emanuel et al. (2008, 2010), Rappin et al. (2010); contrast with Garner et al. (2009), Lavender & Walsh (2011)

- Basin dependence? Is Atlantic basin more “moisture limited”? Larger decrease there relative to other basins?
Global Experiments

• Atlantic storm track studies: Results dependent on regional versus global configuration due to LBCs (Willison et al. 2015; Willison 2015)

• Example here: Super typhoon Nuri (2014)
  – Major extratropical transition event in Western Pacific
  – Associated with large downstream blocking event over western North America
  – In turn, associated with massive cold-air outbreak in eastern US

The November 2014 North American cold wave was an extreme weather event that occurred across most of Canada and the contiguous United States, including parts of the Western United States up to western California. One of the first events of the winter, the cold wave was caused by the northward movement of an extremely powerful bomb cyclone's associated with Typhoon Nuri's remnant, which shifted the jet stream far northward, creating an omega block pattern. This allowed a piece of the polar vortex to advance southward into the Central and Eastern United States, bringing record cold temperatures to much of the region. In contrast, Alaska experienced above-average temperatures.

This was the worst cold wave that the North American region had experienced since an earlier cold wave in early 2014. The cold wave was expected to last for a few weeks, extending at least until American Thanksgiving. Although the Omega Block broke down on November 20, due to a powerful storm moving into the Gulf of Alaska, frigid conditions continued to persist across much of the United States. There was also concern among some meteorologists that another cold wave or abnormally cold trend might persist throughout the winter of 2014–15, the chances of which were "above average." On November 23, a warming trend primarily in the Eastern United States brought an end to the cold wave, however, below-average temperatures were forecast to return to the Midwest by November 24. Despite the development of a second cold wave, it ended on December 6, when a ridge of high pressure brought above-average temperatures to the region, especially in the Central United States.
Nuri, extratropical transition, blocking ridge

GFS analysis, 250-hPa geopotential height (black) and sea level pressure (shaded), 18 UTC 11 Nov 2014
Buffalo, NY lake-effect snow event, 18 Nov 2014

Conduct experiment with Nuri removed to isolate influence

Hypothesis: Without Nuri, reduced cold-air outbreak

http://fox41blogs.typepad.com/a/6a0148c78b79ee970c01b8d0939a20970c-pi
STY Nuri, Best Track and WRF Control

Grid length ~ 39 km
Control (left) and Nuri removed (right)

500-hPa Z, vorticity

500 mb height, vorticity for control, hour 00
500 mb height, vorticity No Nuri, hour 00

SLP, T anomaly

SLP and 2 meter T anomaly, control
SLP and 2 meter T anomaly, No Nuri
Control 250 hPa height and difference (shaded), SLP < 984 (red) control minus no Nuri (regional)
What about the Cold-Air Outbreak?
Hour 348 (during Buffalo LES event)
Amazingly similar!
Preliminary Conclusion

Perhaps Nuri played smaller role in block and subsequent cold-air outbreak than hypothesized.

Or, is this result a figment of our methods?

- Use of analyzed lateral boundary conditions: Locked in ridge at northern edge of domain
- Use global WRF to avoid northern BC influence
Does Global WRF Provide Consistent Results?

- Relatively coarse global grid (~37 km)
- Nesting in GWRF reveals mass non-conservation, not used

Hour 102

Regional Control

Global Control
Does Global WRF Provide Consistent Results?

- By hour 144, significantly different evolution over N. America, influence of Nuri more apparent
Conclusions

Global WRF results reveal influence of lateral boundary condition on large-domain regional experiments.

For some problems, *global* modeling strategy is needed.

Inconclusive results regarding Nuri’s role in cold-air outbreak; models struggle to reproduce blocking.

In TC genesis test, use of analyzed LBC was helpful. Not so for Nuri case!

Nudging (spectral or otherwise) strengthens some limitations imposed by LBCs.

With higher resolution GCMs, driving RCM directly is becoming a better option.
Conclusions and Future Work

Representation of TCs is important to many aspects of climate

Convection-permitting resolutions beneficial for process analysis, representation of TC structure, size, and intensity

High-resolution global domains needed for upcoming ET study, MPAS seems to be best option, 3 km to 15 km to 60 km?

Also ¼ degree CESM run available (Small et al. 2015)
Global PGW Challenges

For seasonal-scale runs, extratropical transition under warming (new project), global domain beneficial

WRF is not climate a model, challenged to maintain realistic “deltas”:

- Lack of aerosol forcing
- Unsure about ozone effects (stratospheric representation)
- Limited ocean coupling, soil/land surface, sea ice issues

MPAS seems promising… we are pursuing this

- Scale-aware physics?
- Learning curve
- Stability issues in early tests
- Versatility of grid configuration?
Acknowledgements

U.S. National Science Foundation (NSF) grants AGS 1546743 & 1007606 and U.S. Department of Energy (DOE) grant ER64448 awarded to North Carolina State University; WRF model is made available through NCAR, sponsored by the NSF.

The Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the CMIP3 model output.

The WCRP’s Working Group on Coupled Modeling (WGCM) for organizing the model data analysis activity. The WCRP CMIP3 multimodel dataset is supported by the Office of Science, U.S. Department of Energy.

Megan Mallard, Kevin Hill, Chris Marciano and other former students contributed to this work.

Andreas Prein, Roy Rasmussen for this invitation, and for organizing the workshop.

Satellite images on first slide courtesy of https://www.wunderground.com/blog/JeffMasters/comment.html?entrynum=3077
Questions appropriate for PGW approach:

1.) If a specific weather event (synoptic pattern) were repeated in future, how might it differ due large-scale environmental change?

2.) If a specific weather event had happened in the past, how would it have differed from what actually happened?
PGW Advantages:
- Guarantees realistic synoptic pattern (happened before, could happen again)
- Allows clean isolation of thermodynamic effects
- Strength in its simplicity

PGW Disadvantages:
- Limited in scope, e.g., more difficult to address changes in, e.g., synoptic pattern frequency
- Conservative approach if adding averaged GCM changes (but this is not required)


Mallard, M. S., and G. M. Lackmann, 2013: Atlantic hurricanes and climate change. Part II: Role of thermodynamic changes in decreased hurricane frequency. *J. Climate, in review (minor revision).*