Climate Modeling Challenges for Tropical Cyclones

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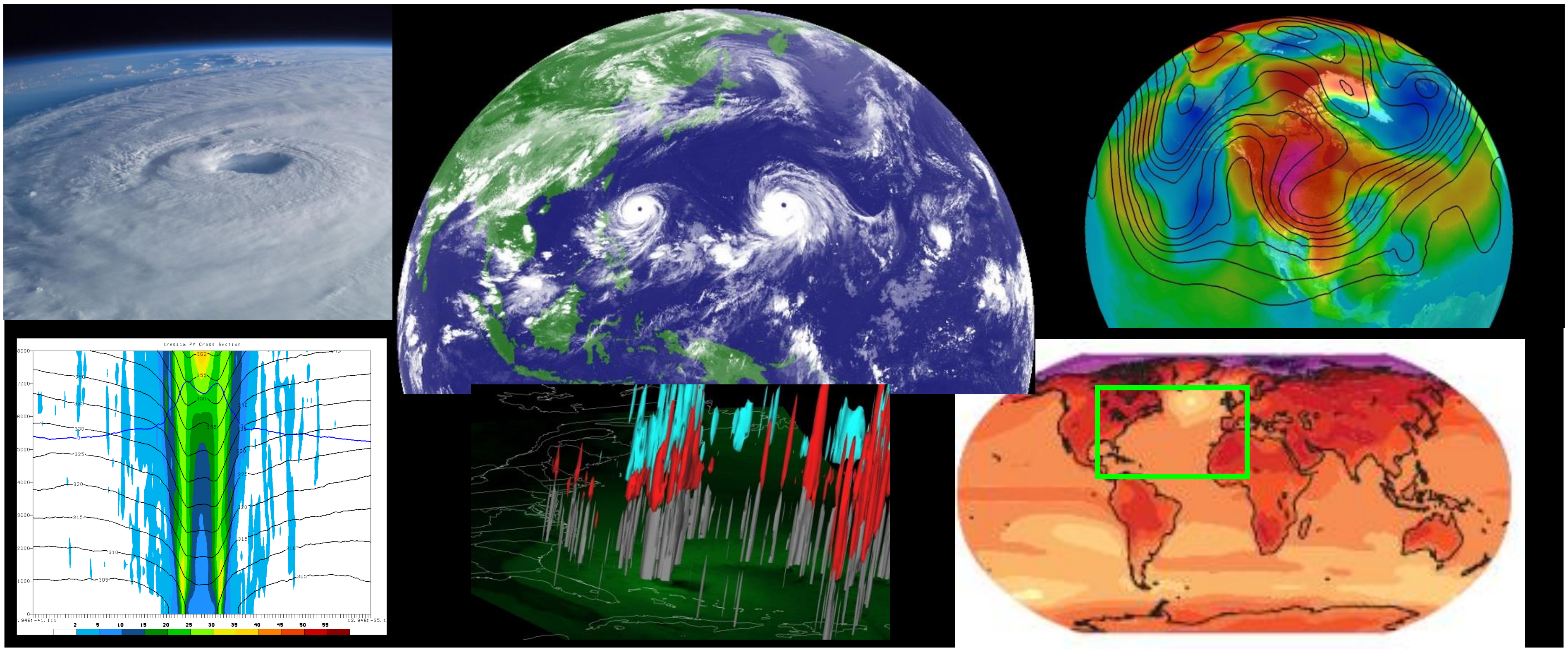


TCs in Climate Models: Why they Matter

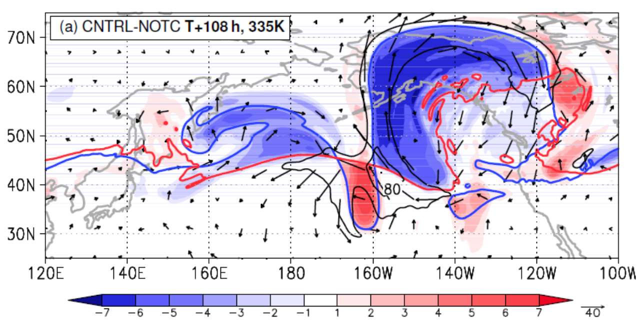
- Wish to know change characteristics (e.g., Knutson et al. 2010, others)

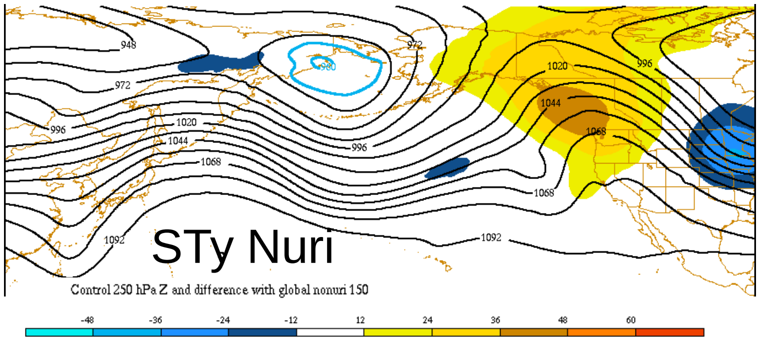
- Important role of TCs in ocean heat budget, heat uptake (e.g., Mei et al. 2013; Scoccimarro et al. 2011; Pasquero and Emanuel 2008; Hart et al. 2007; Sriver and Huber 2007; Emanuel 2001; Shay et al. 1989)

- 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”

- K. V. Ooyama 1982: Conceptual evolution of the theory and modeling of the tropical cyclone. *J. Met. Soc. Japan*

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

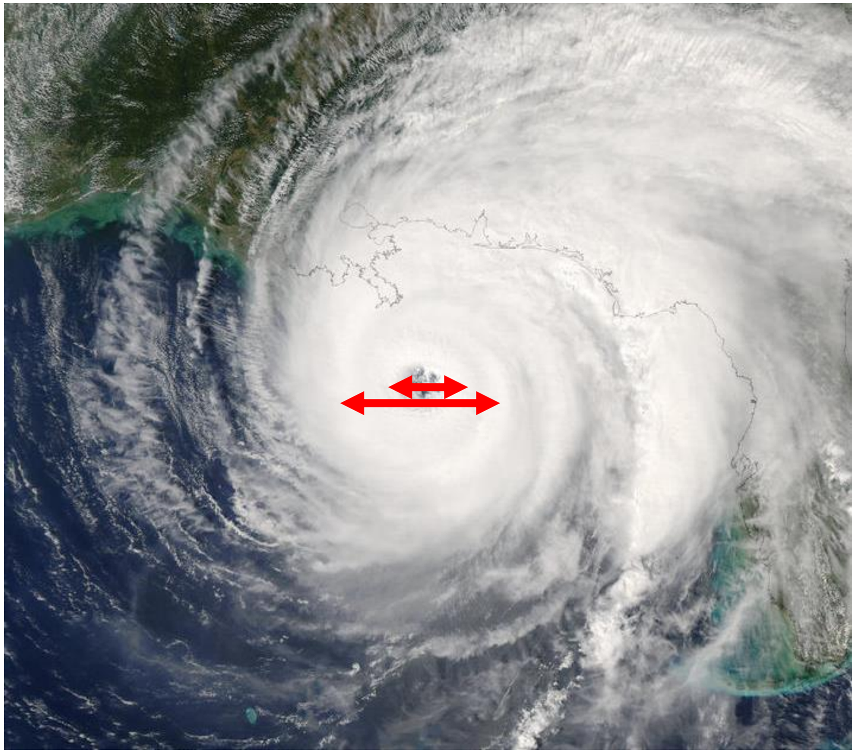
- Microphysics, with interaction/coupling to radiation scheme (ice processes, graupel, outflow layer anvil: CRF, Fovell)

- 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

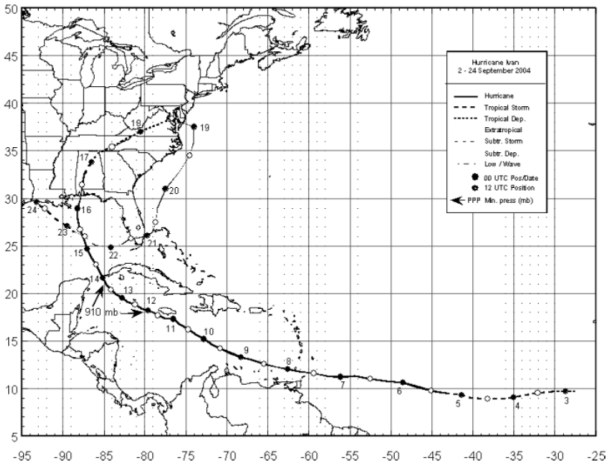
Eye diameter ~ 30 km

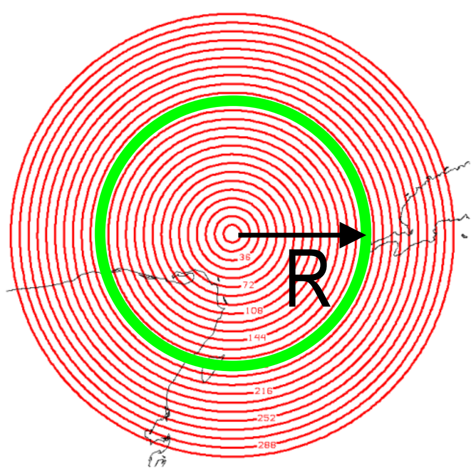
4Δx partially resolved	**Δx 25 km**	**4Δx partially resolved**	**Δx 8 km**
10Δx fully resolved	**Δx 10 km**	**10Δx fully resolved**	**Δx 3 km**

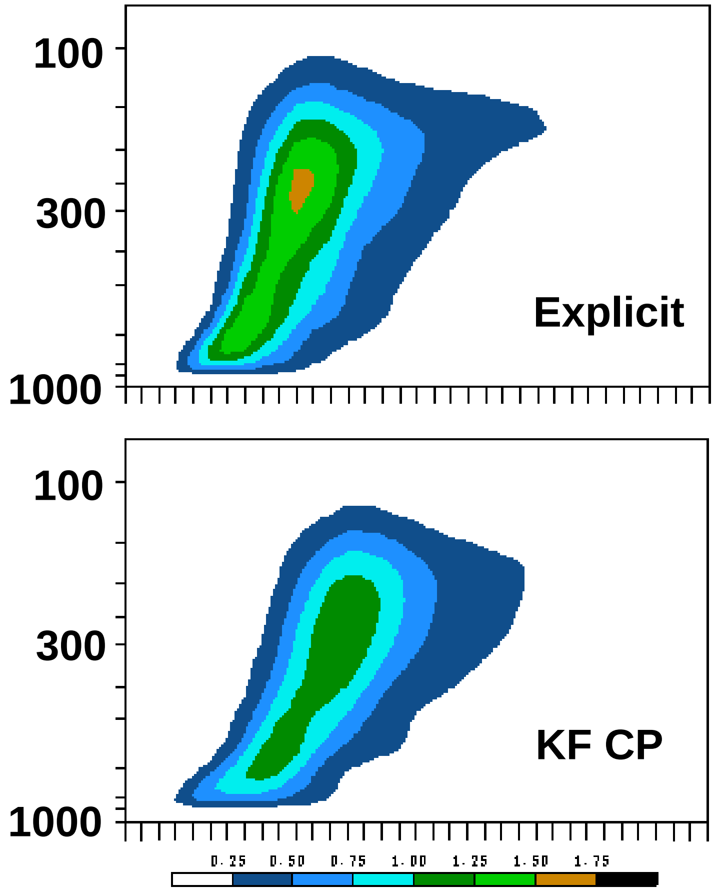
Walters, 2000 & comments by Grasso; Skamarock and Klemp (2008): 6-8 Δx

Eyewall Updraft and CP

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







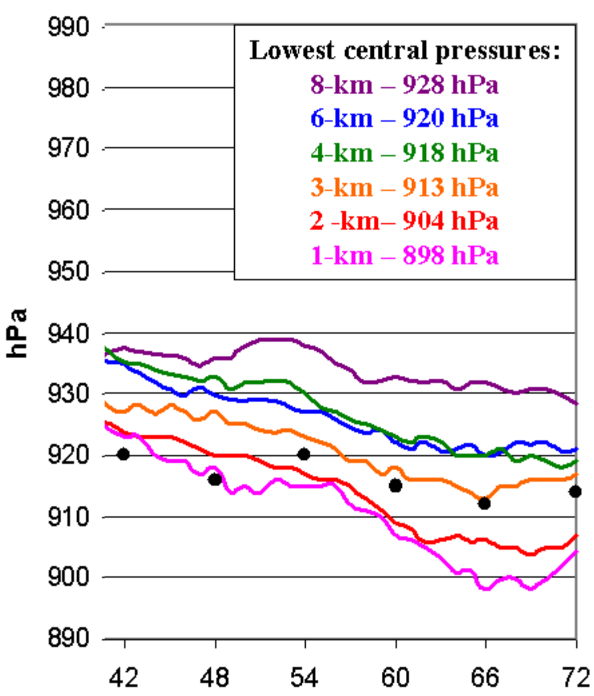
Azimuthal average, w

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



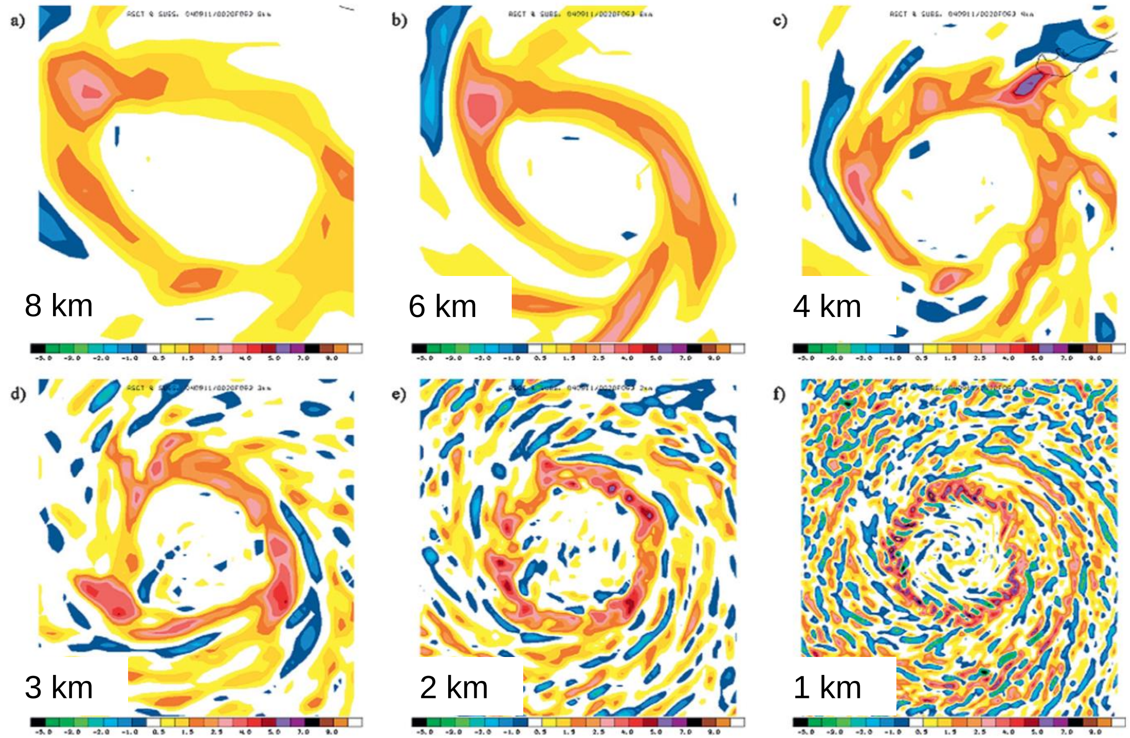
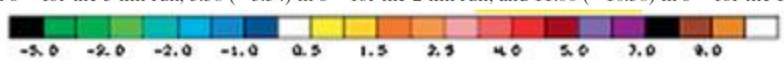


FIG. 4. 850-hPa vertical wind component at simulation time 63 h 20 min contoured 0.5 m s^{-1} up to 5 m s^{-1} and every 1 m s^{-1} thereafter for the (a) 8-, (b) 6-, (c) 4-, (d) 3-, (e) 2-, and (f) 1-km runs, with positive vertical motion in warmer colors and negative vertical motion in cooler colors. Purple coloring indicates updraft speed in excess of 5 m s^{-1}. The point maxima (minima) of vertical velocity at this time are 4.66 (−2.54) m s^{-1} for the 3-km run, 5.58 (−3.34) m s^{-1} for the 2-km run, and 11.06 (−10.58) m s^{-1} for the 1-km run.



850 hPa vertical velocity: Inner core/eyewall region at different grid lengths

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

Vortex Rossby Waves

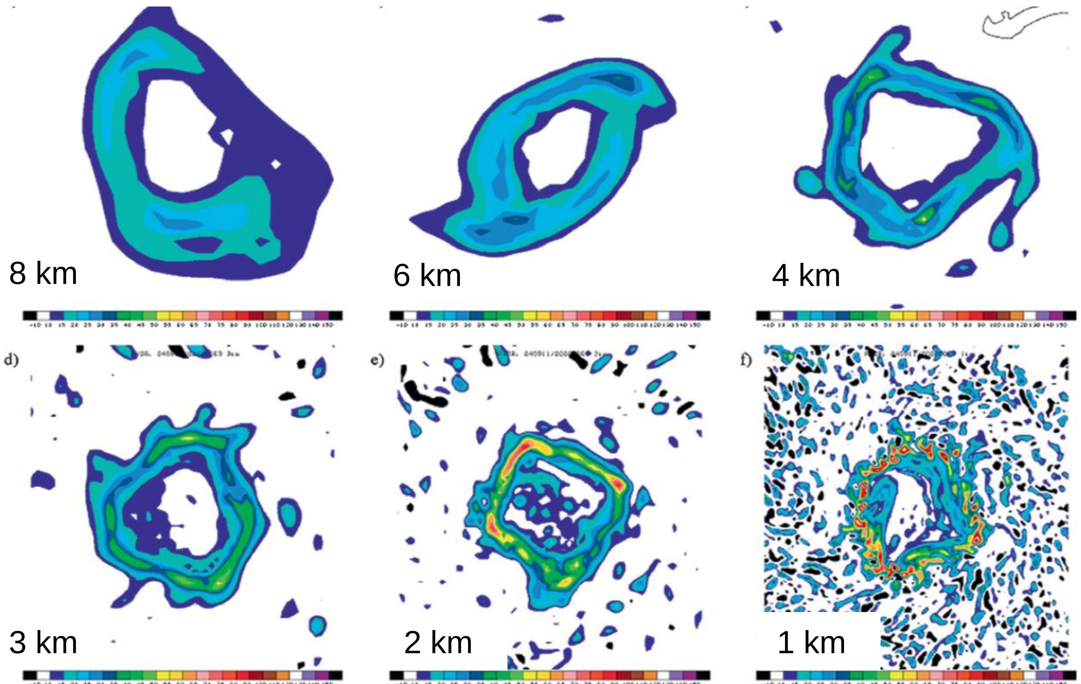
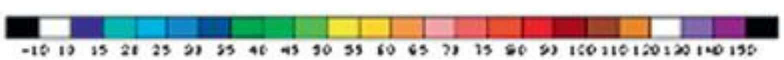
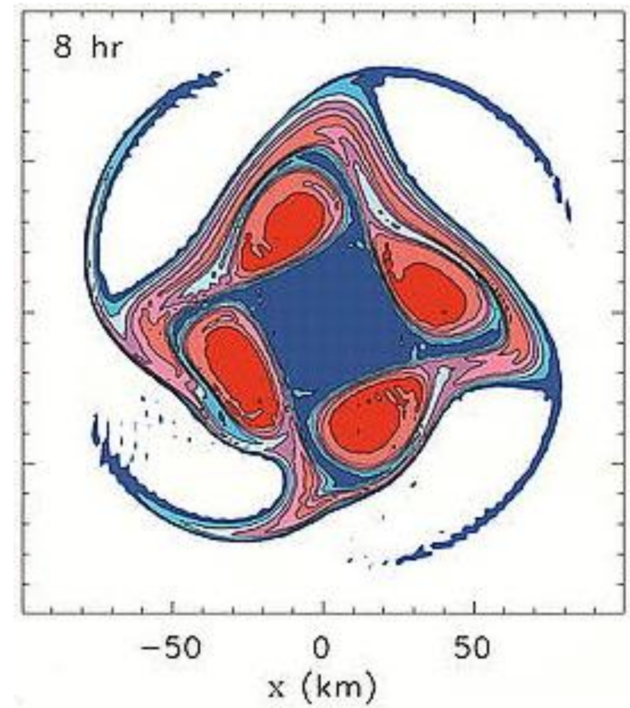


FIG. 6. 850-hPa PV at 63 h into the simulation scaled by 10^{-6} and contoured every 5 PVU from 10 PVU, shown for the (a) 8-, (b) 6-, (c) 4-, (d) 3-, (e) 2-, and (f) 1-km runs. Note that both this figure and the next one are representative of the appearance of the PV field at different times throughout the run.





Schubert et al. 1999

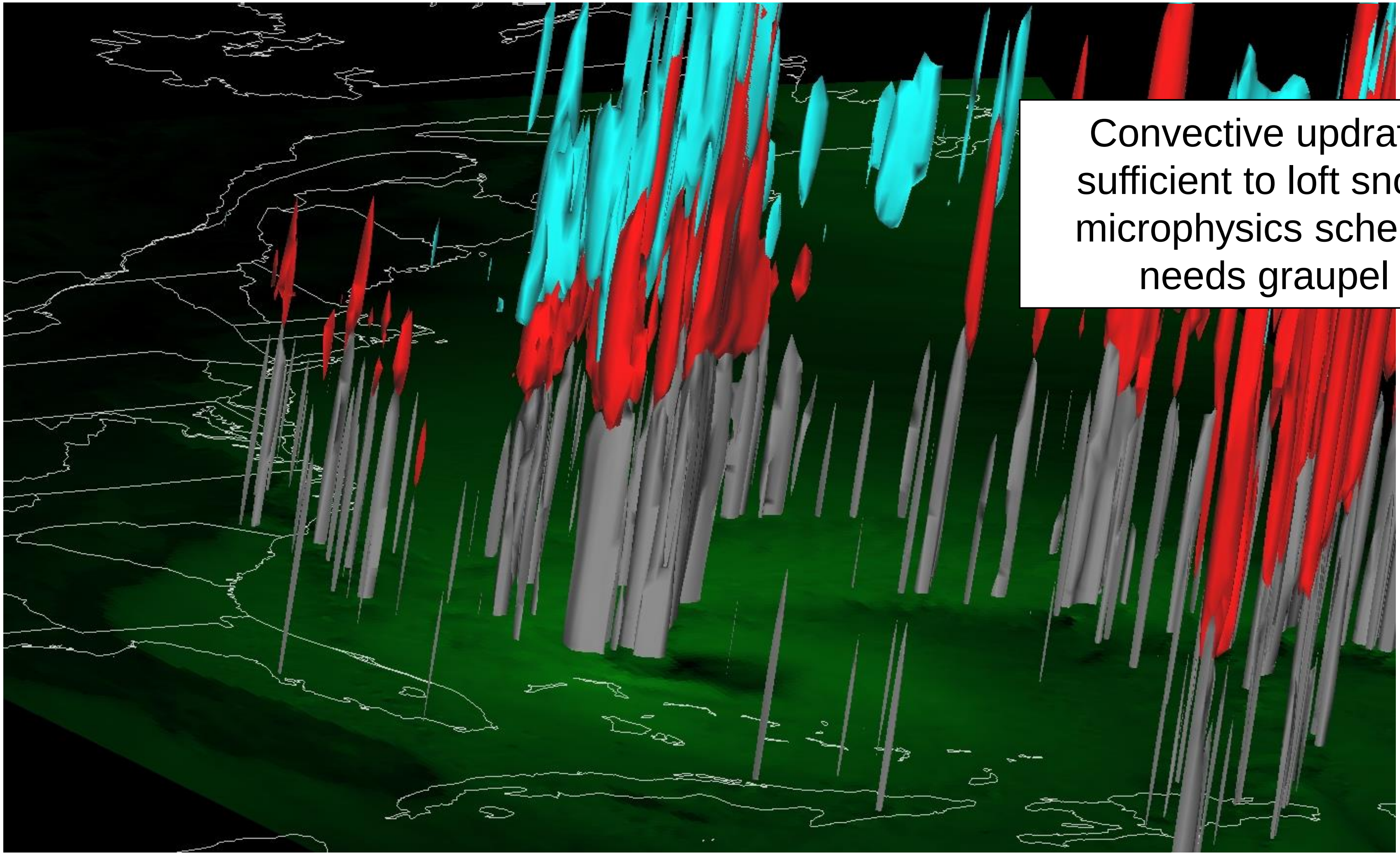
850 hPa potential vorticity (PV) at different grid lengths: Wave breaking behavior, eyewall replacements only evident at higher resolution (< ~ 4km)

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):

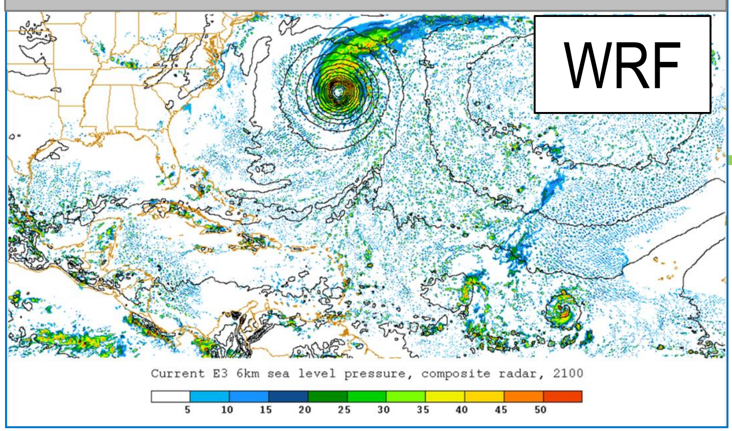
"*Surrogate Global Warming*": Apply uniform warming to analyzed initial conditions (IC), lateral boundary conditions (LBC) (Schär et al. 1996; Frei et al. 1998)

"*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)

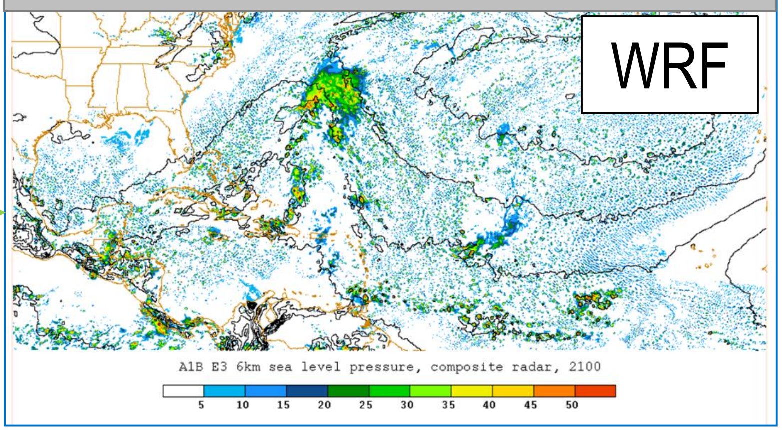
PGW Method

- 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

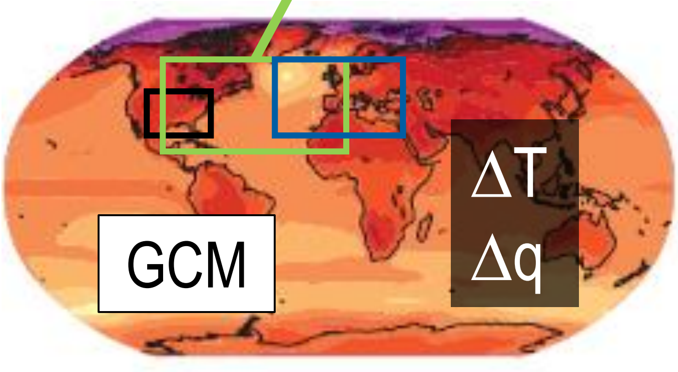
Analyses: Initial, lateral BC to simulate recent season or event



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

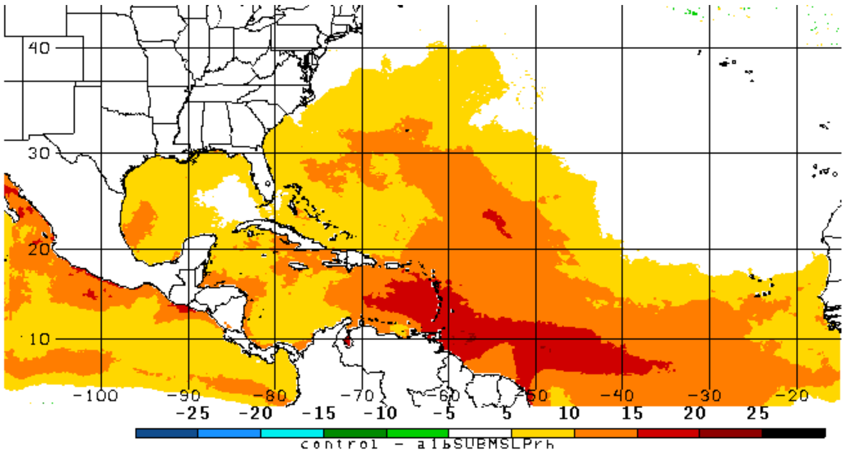
- **Is variability in LBC better in *analysis* or *GCM*? Depends**
- **Driving RCM with GCM: Sufficient temporal, spatial resolution?**

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

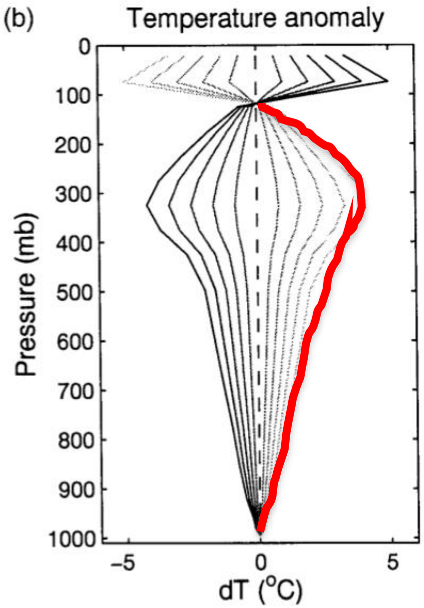
- SST increase of 1.5°C completely is offset by increase in upper tropospheric temperatures of 3 – 4°C (e.g., Shen et al. 2000; Knutson and Tuleya 2004)

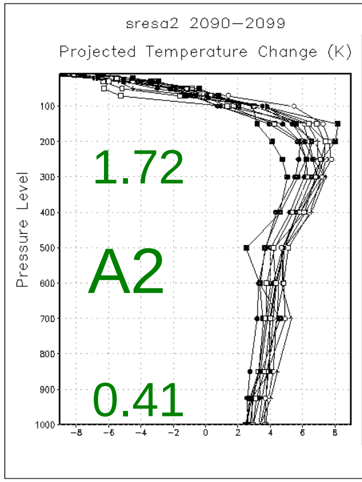
Shape of GCM change profile quite variable

- 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)





	Mean	Min	Max	STDEV
10	−7.95	−11.10	−6.02	1.37
20	−5.88	−6.95	−4.51	0.88
30	−4.43	−6.34	−2.92	1.07
50	−2.48	−6.29	−0.39	1.72
70	−0.51	−5.24	1.40	1.58
100	2.74	0.72	5.46	1.32
150	5.66	3.19	8.15	1.34
200	6.53	4.10	8.00	1.00
250	6.64	4.77	7.78	0.77
300	6.54	5.07	7.40	0.72
400	5.55	4.34	6.53	0.68
500	4.32	2.51	5.11	0.69
600	4.14	3.27	4.83	0.53
700	4.13	3.17	5.27	0.55
850	3.61	2.74	4.42	0.43
925	3.21	2.57	3.99	0.47
1000	2.99	2.45	3.71	0.41

Hill and Lackmann 2011: The impact of future climate change on TC intensity and structure: A downscaling approach. J. Climate

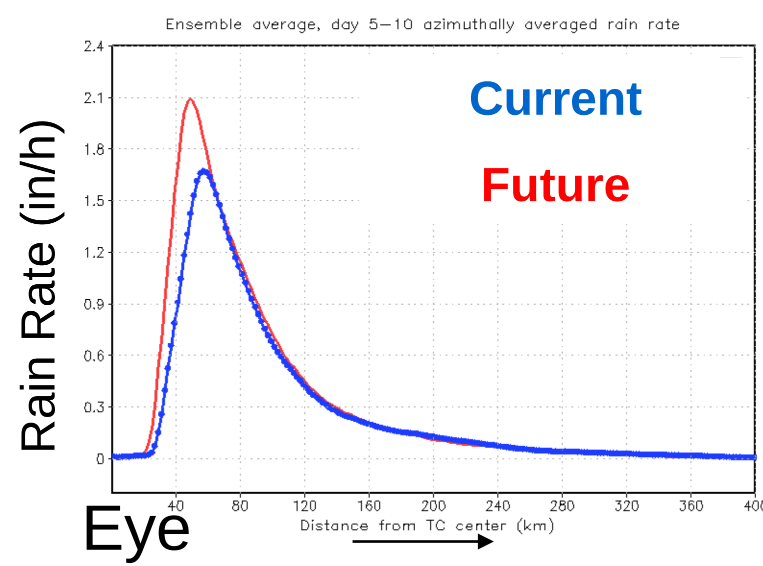
Results: Precipitation and Intensity Change

Simulation name	Min SLP (hPa)	Increase in SLP deficit (%)	Precipitation (R < 250 km)		MPI change (% relative to control)
Current 2km	919				
B1 2km	909	**11%**	**+8 %**		**6.5%**
A1B 2km	908	**12%**	**+20 %**		**9.0%**
A2 2km	902	**19%**	**+27 %**		**10.7%**

MPI increase: **6–11%**

Intensity increase: **11–19%**

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



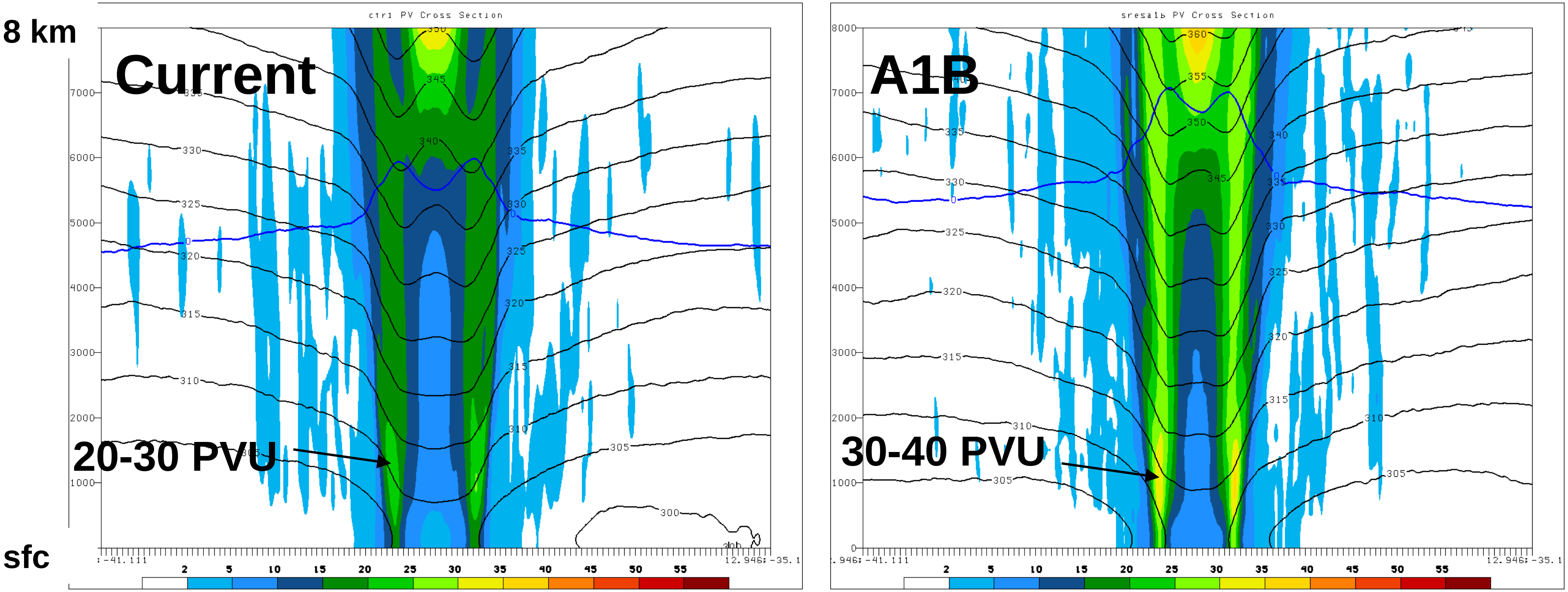
Hill and Lackmann 2011: The impact of future climate change on TC intensity and structure: A downscaling approach. J. Climate

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

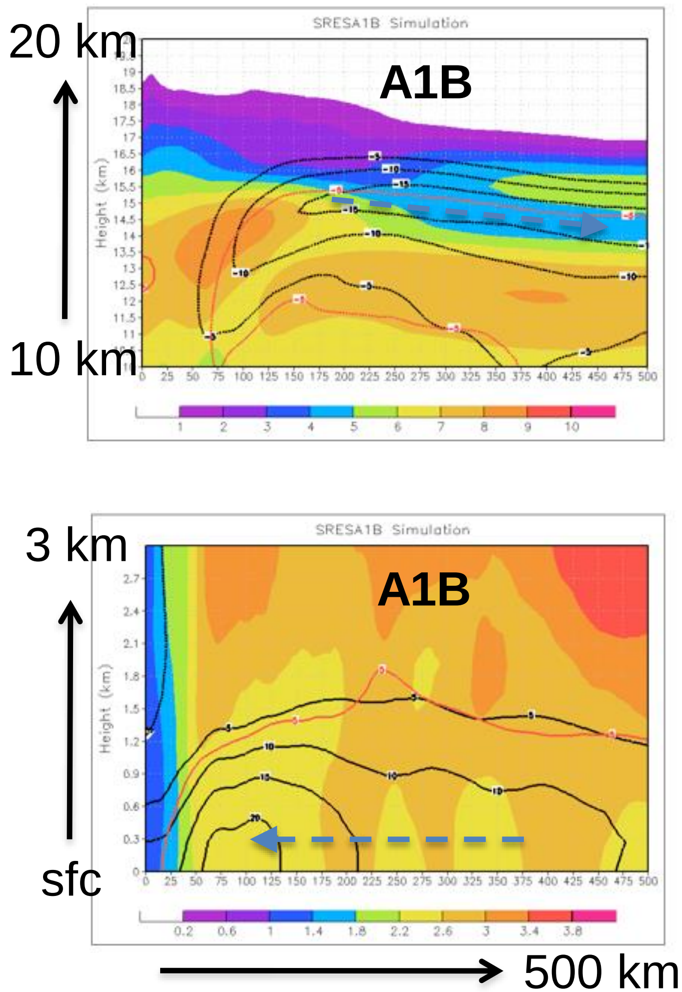
Time averaged: hour 216 – 240, 2-km

Shading: T increase (relative to current)

Black contours: future radial flow

Red contours: current radial flow

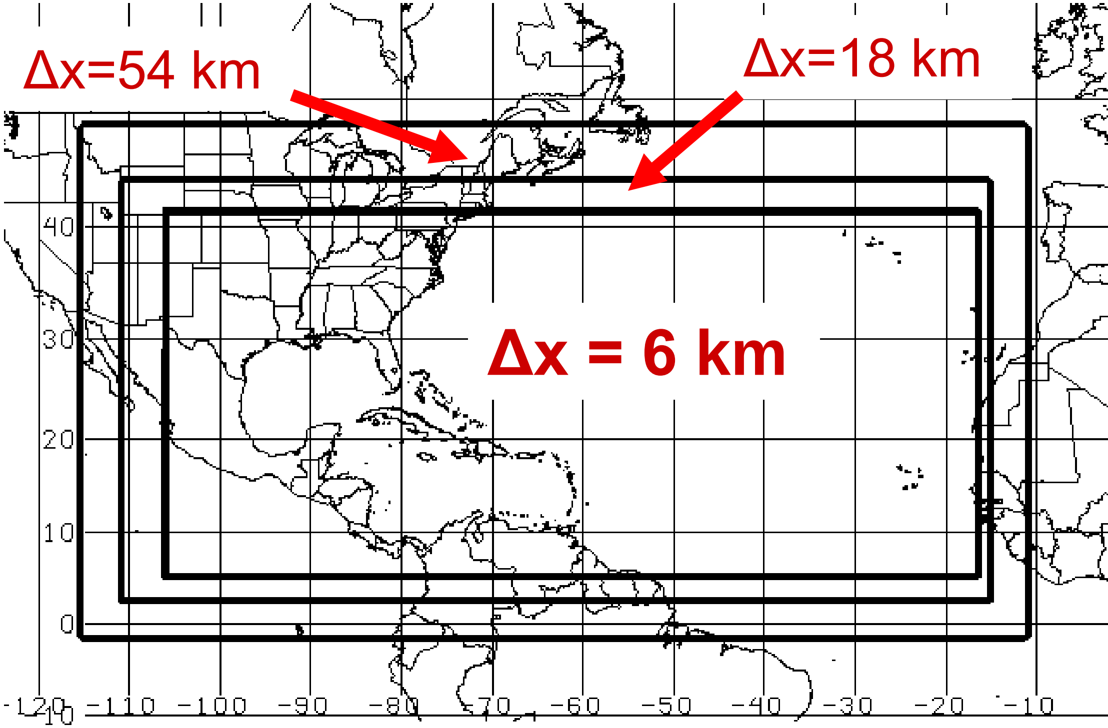
- Stronger warming of mass-weighted outflow in future
- Inflow warming ~SSTΔ
- Result: Reduced heat engine efficiency in future
- Less intensification relative to what SST change would imply
- Omission of CP enabled this analysis



Hill and Lackmann 2011: J. Climate

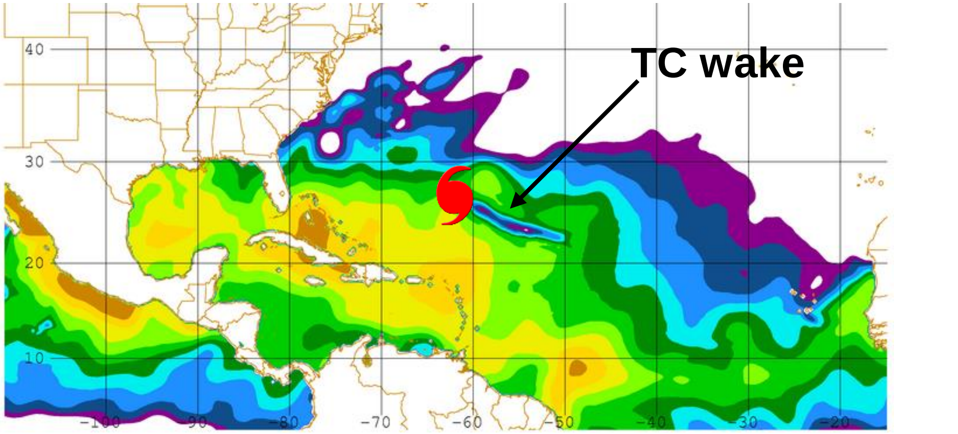
TC Frequency Change: Basin-Scale PGW

- 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

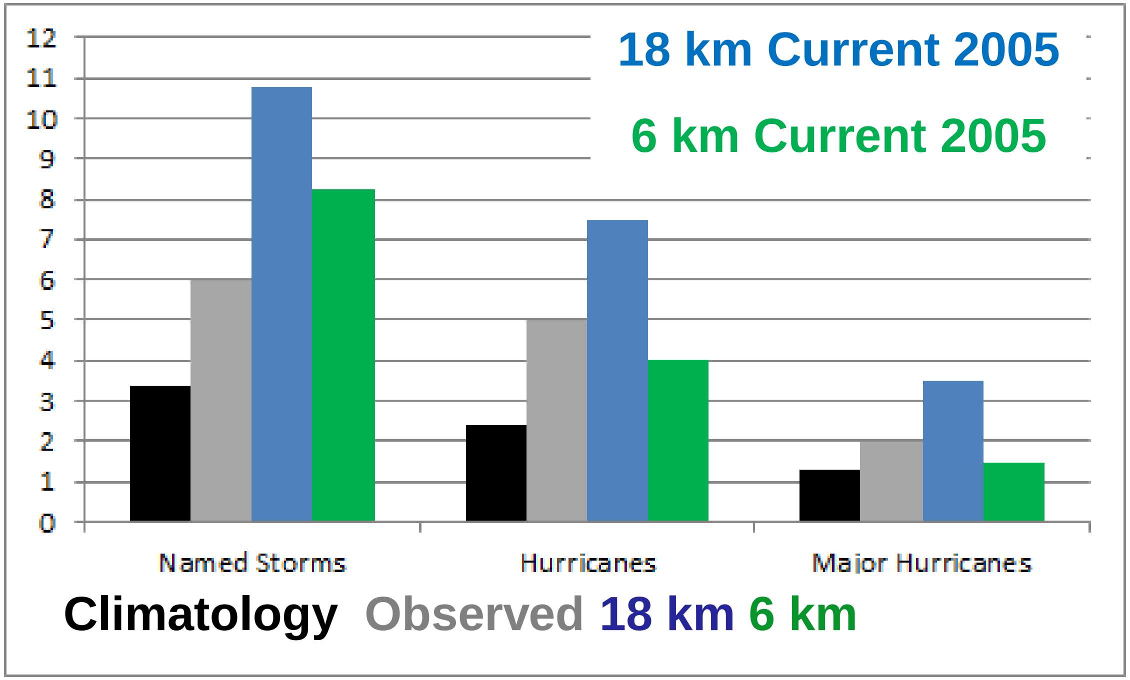
18-km runs overestimate TC frequency

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

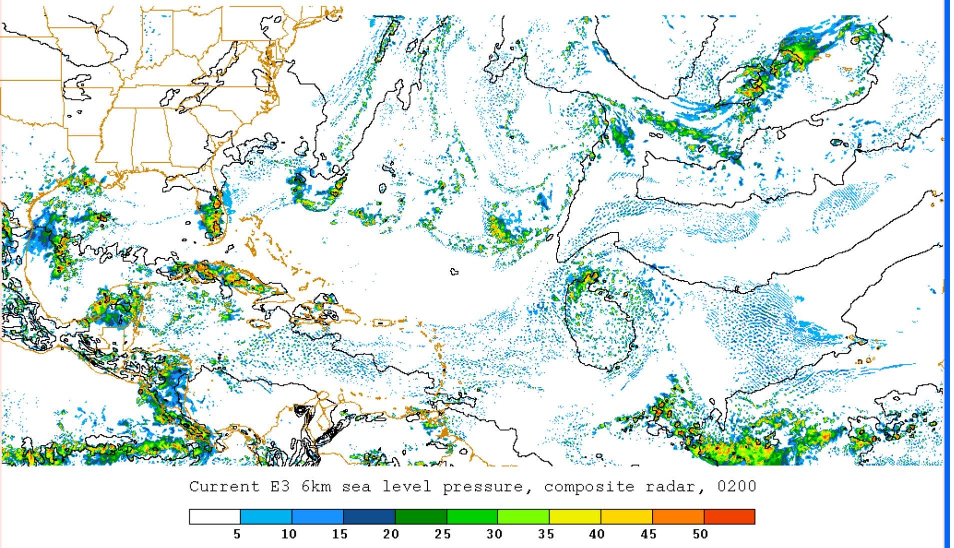
Ensemble-mean storm count: Sept 2005



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

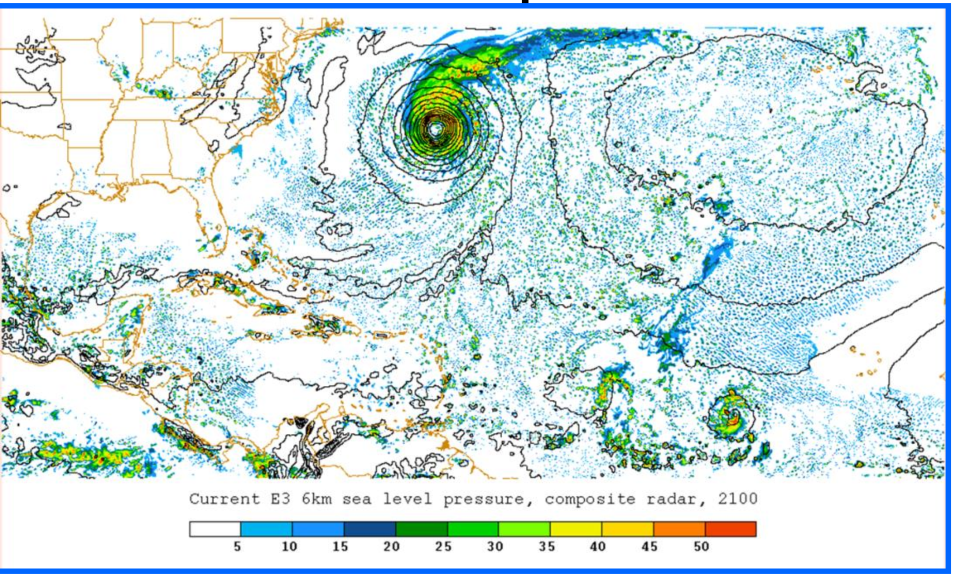


Future: Reduced TC activity with same pattern

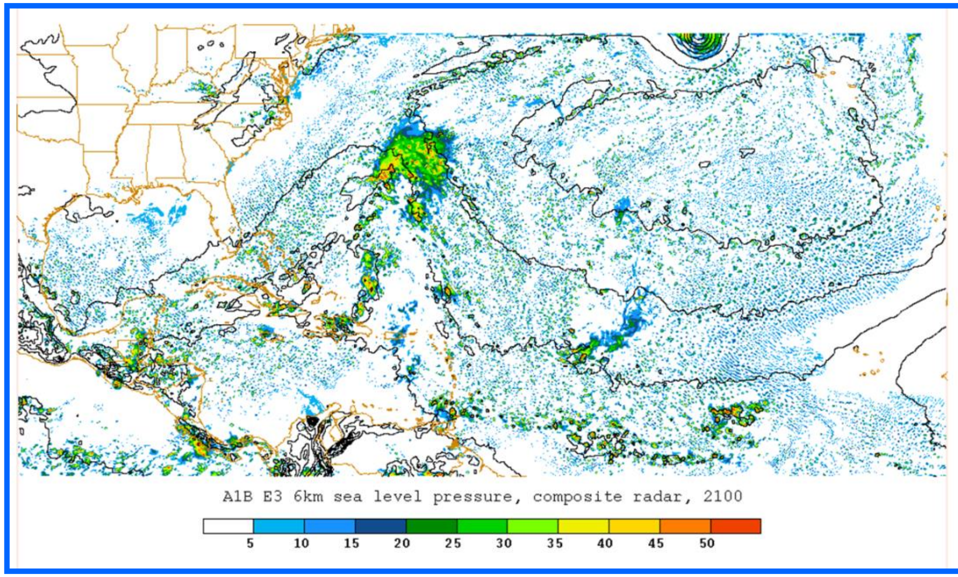
Mallard et al. 2013 a,b, *J. Climate* for details

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

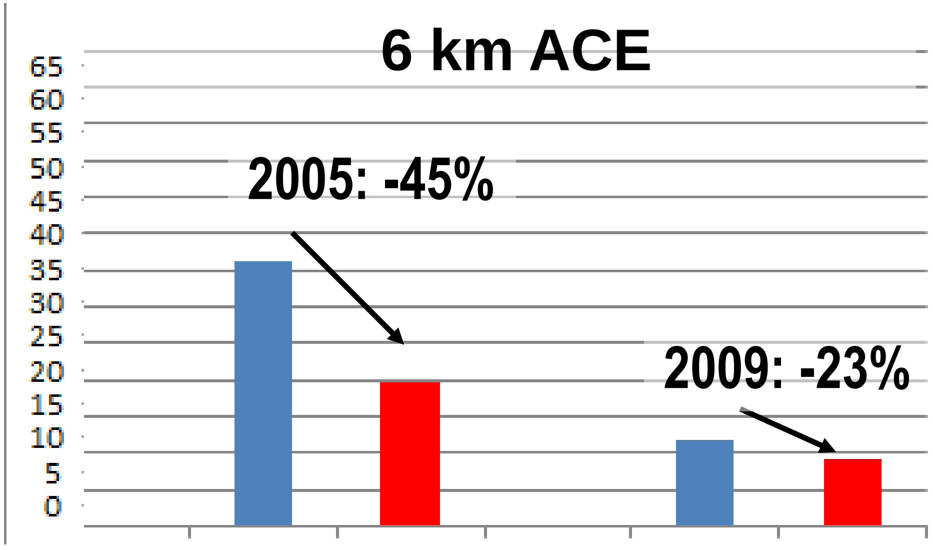
Future TC Activity Change

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

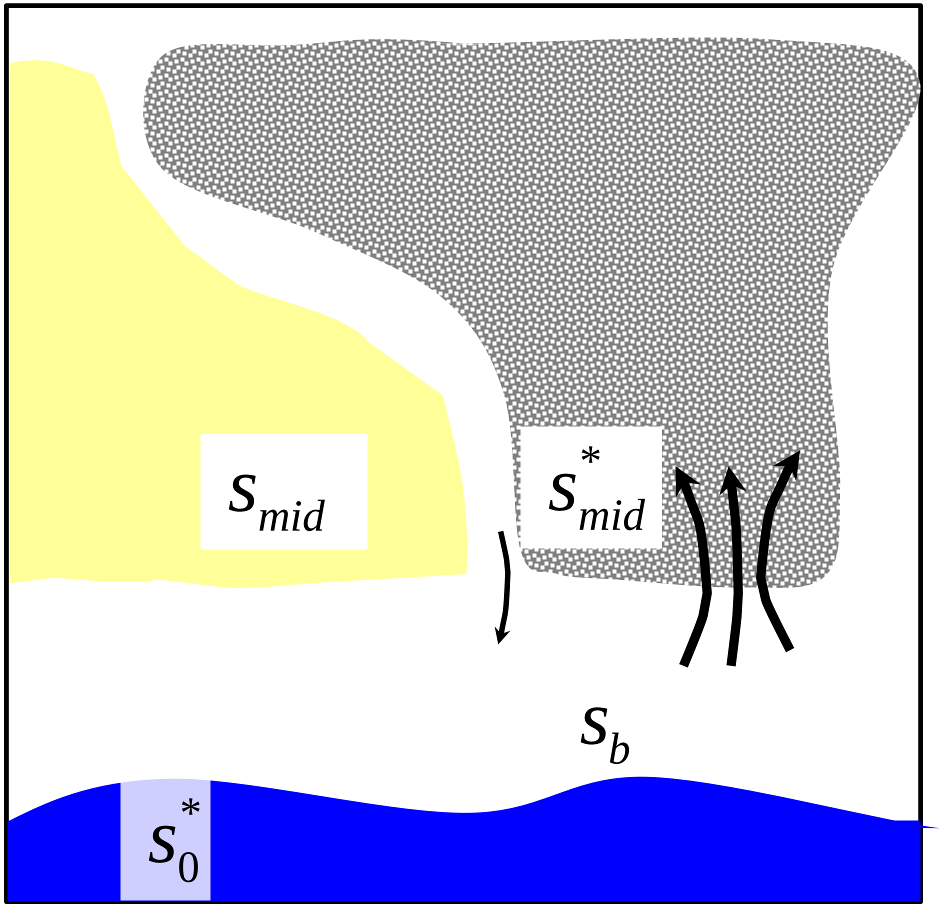
Ensemble mean activity change



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)

Incubation Parameter



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 χ_{mid} & TC frequency:

- Larger midlevel saturation deficit: more subsaturated downdrafts
- Near saturation necessary condition for TC genesis
- *Delayed TC genesis, reduced TC frequency*

$$s = c_p \ln T - R_d \ln p + \frac{L_v q}{T} - R_v q \ln RH$$

See Emanuel 1989, 1995, Emanuel *et al. 2008*, Rappin *et al. 2010*

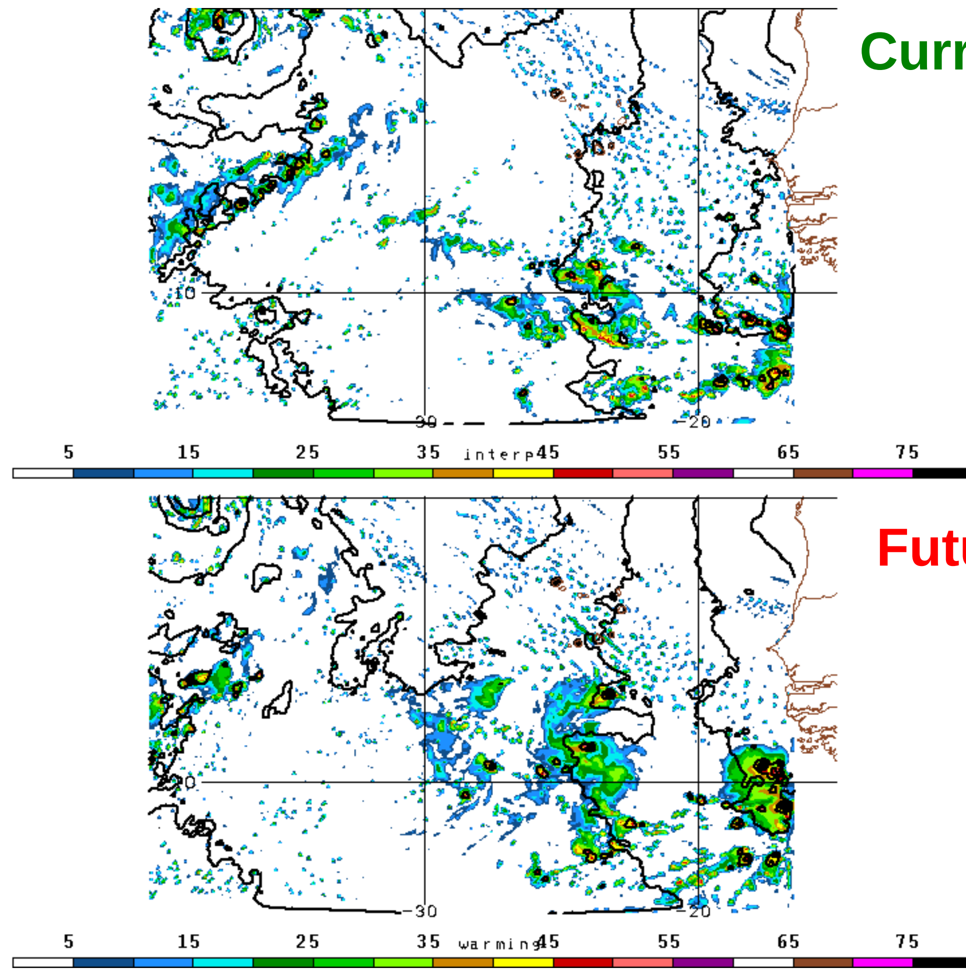
PGW allows comparison of “same” events, current + future

- 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**

Current



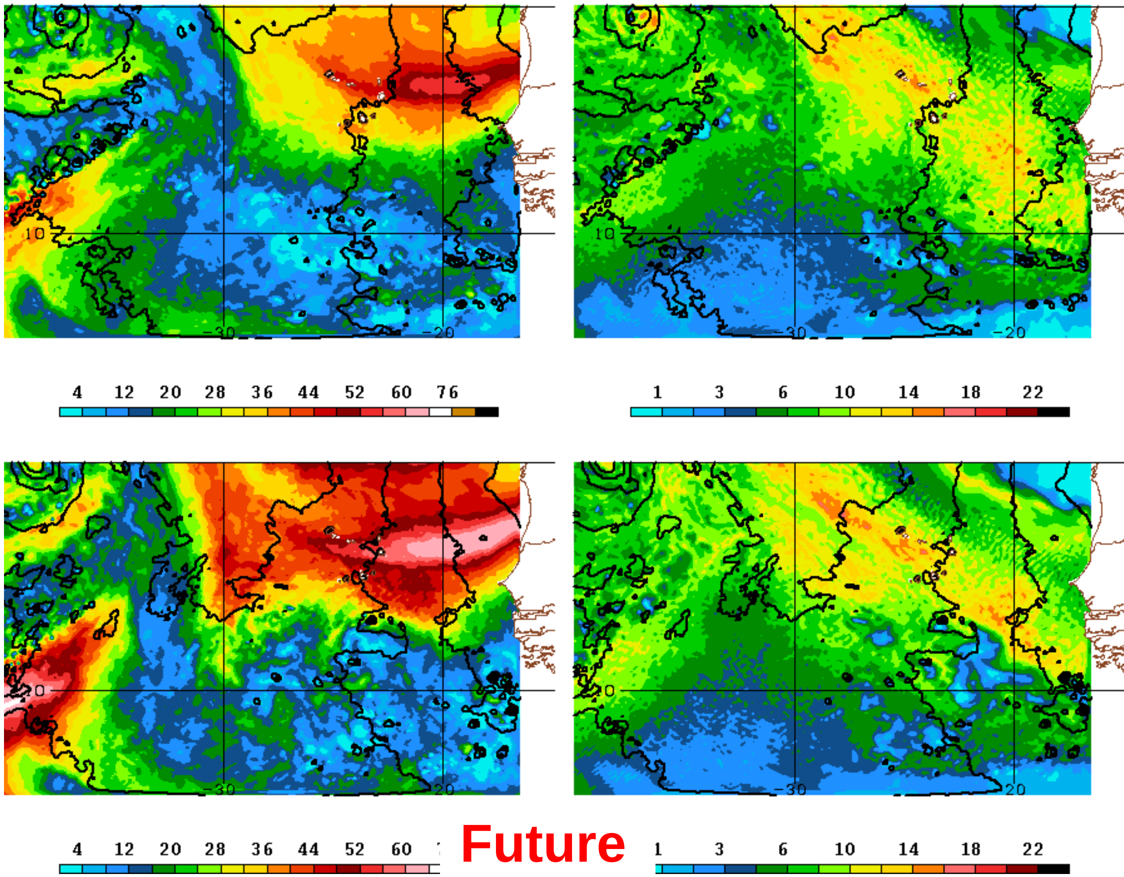
Future

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

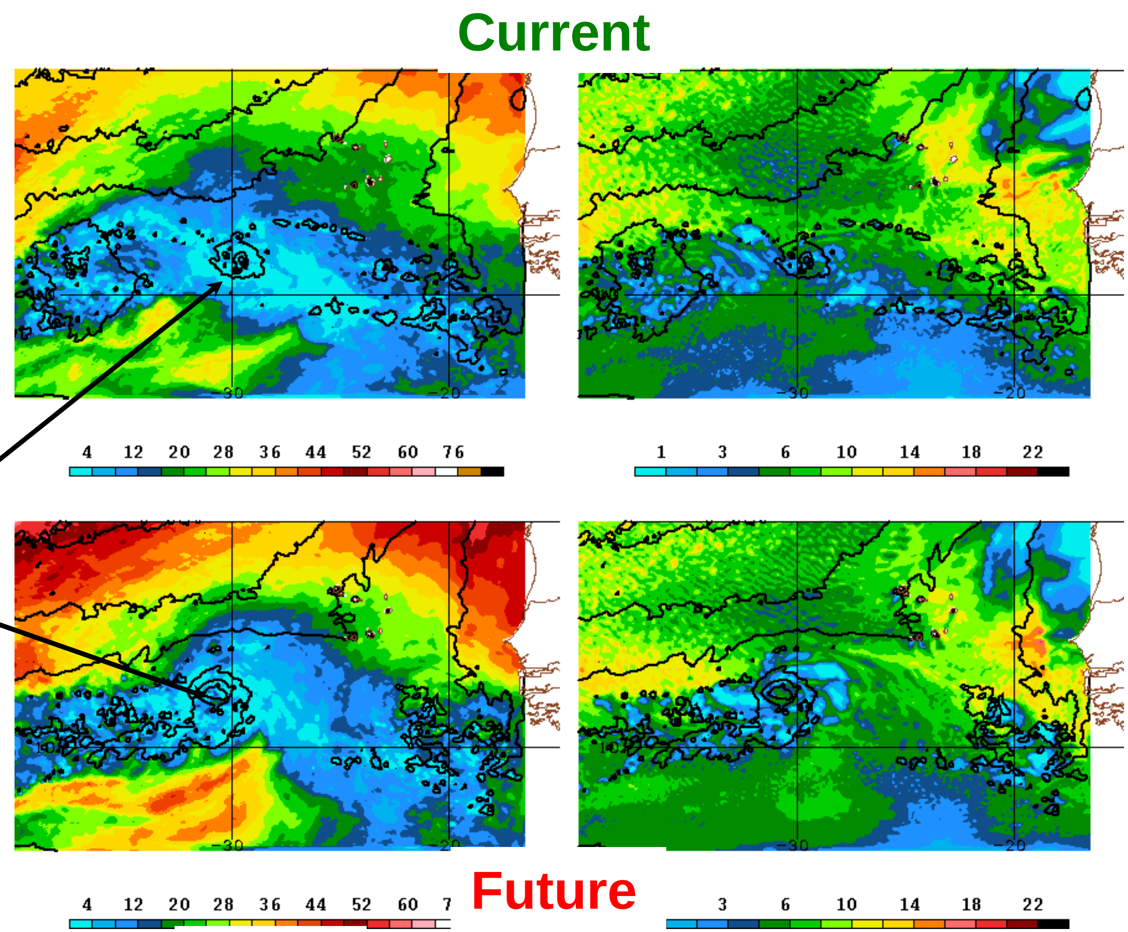
Current



χ_{mid} Incubation (χ_m)

Case 5: Current Genesis, Future Genesis

In favorable moisture environment, genesis in both simulations



χ_{mid} Incubation (χ_m)

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 (χ_{mid}),
  - Increase in incubation parameter: Longer time to genesis
- **Results: *thermodynamic* 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

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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.[6][7][8] In contrast, Alaska experienced above-average temperatures.

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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.[9] 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."[10] On November 23, a warming trend primarily in the Eastern United States brought an end to the cold wave;[1] 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.

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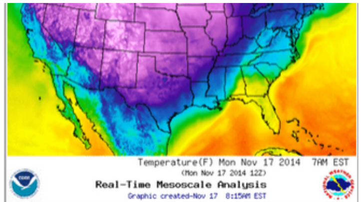
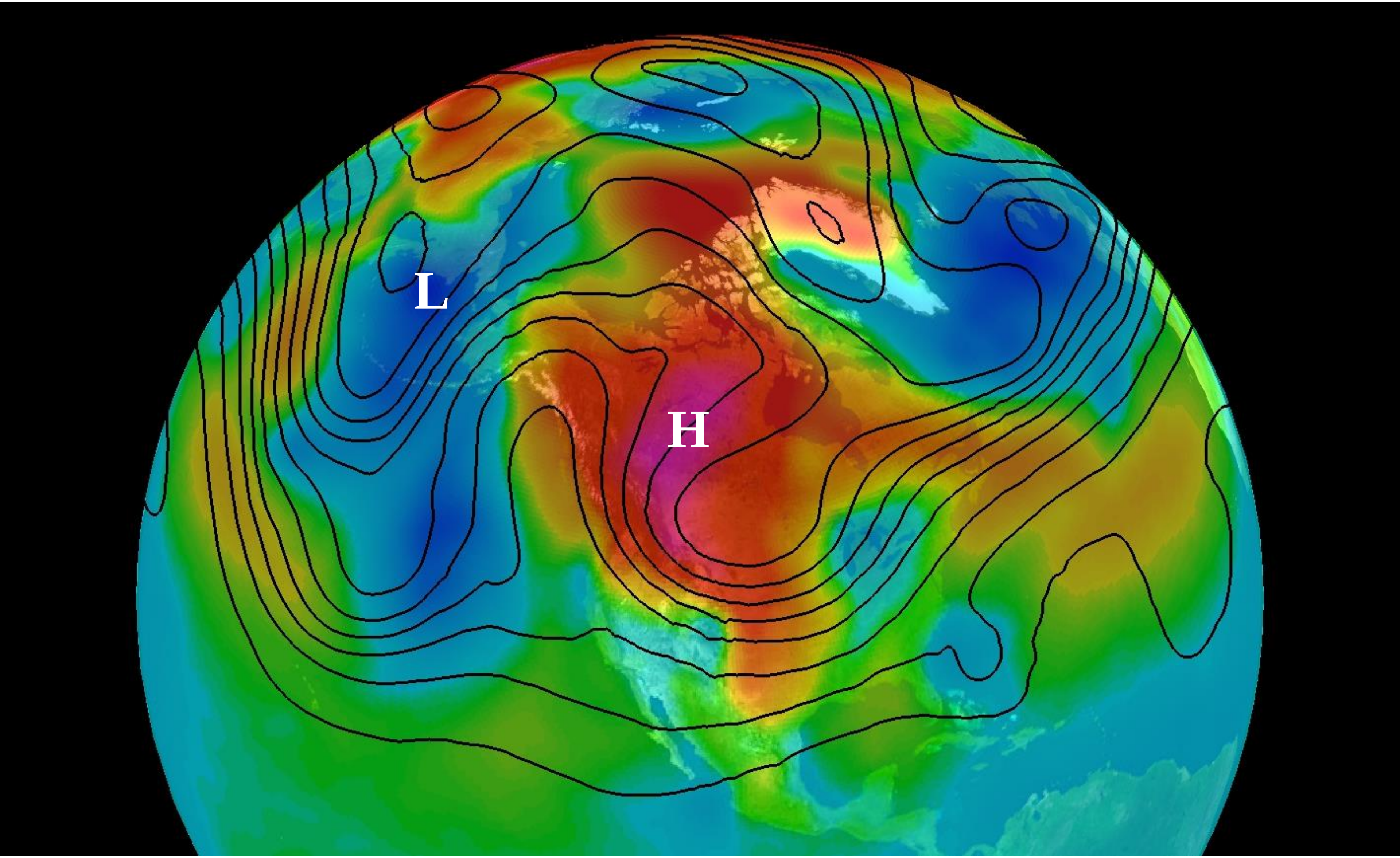


A temperature map of the frigid conditions on November 13, 2014.

Formed	November 8, 2014
Dissipated	November 23, 2014[1]

Nuri, extratropical transition, blocking ridge

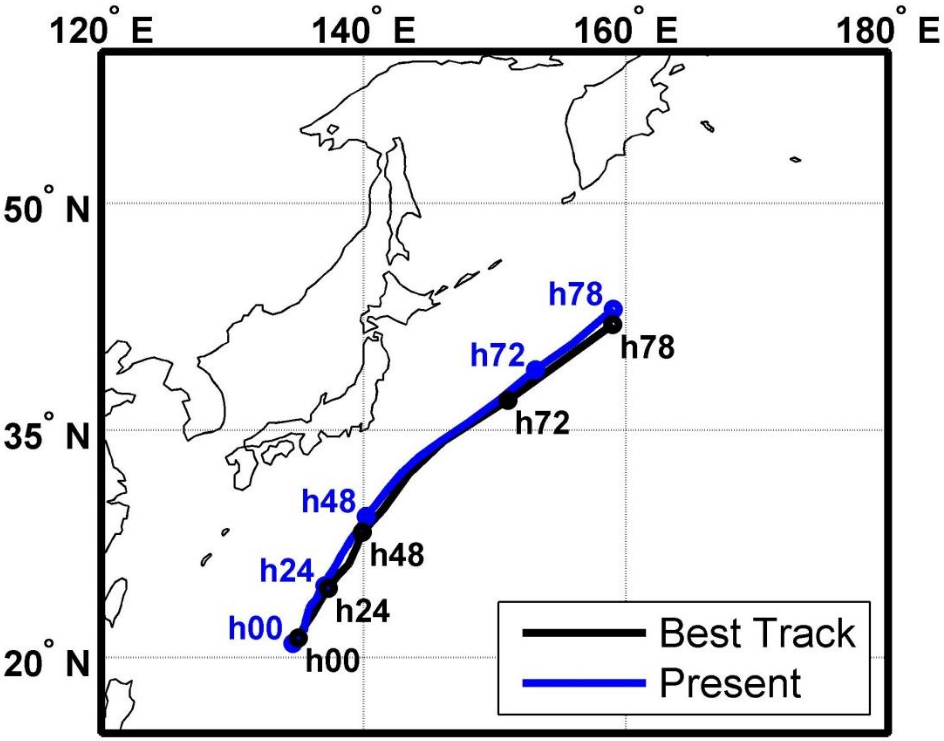


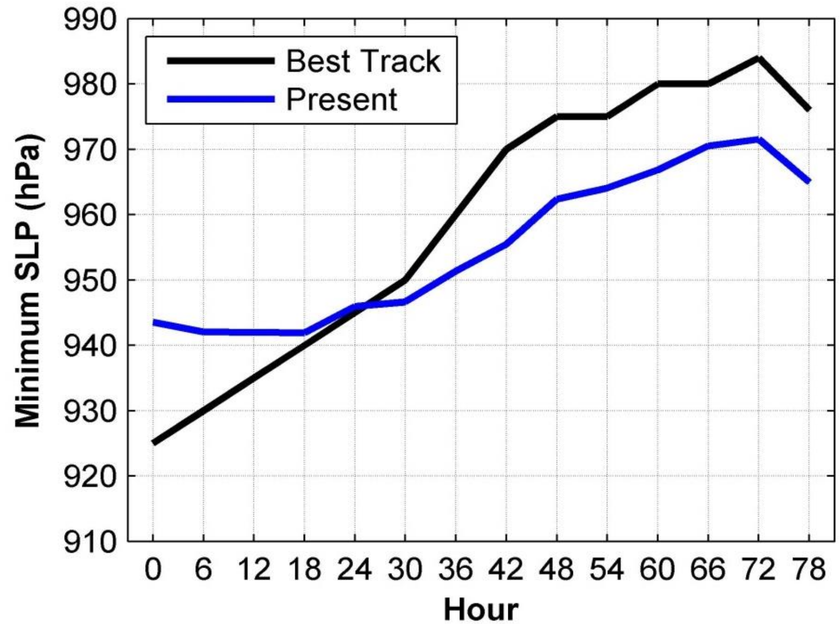
GFS analysis, 250-hPa geopotential height (black) and sea level pressure (shaded), 18 UTC 11 Nov 2014

Buffalo, NY lake-effect snow event, 18 Nov 2014

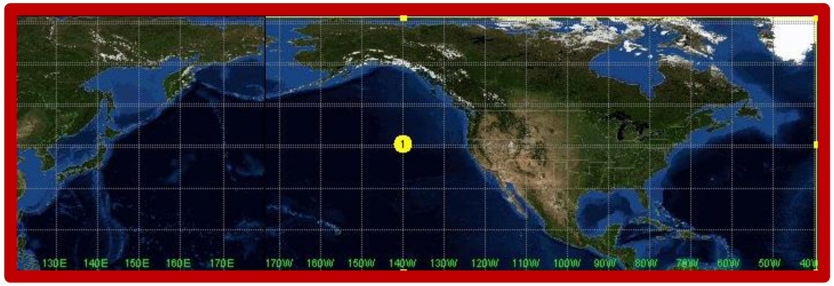
http://f ox41blogs.typepad.com/.a/6a0148c78b79ee970c01b8d0939a20970c-pi

STY Nuri, Best Track and WRF Control





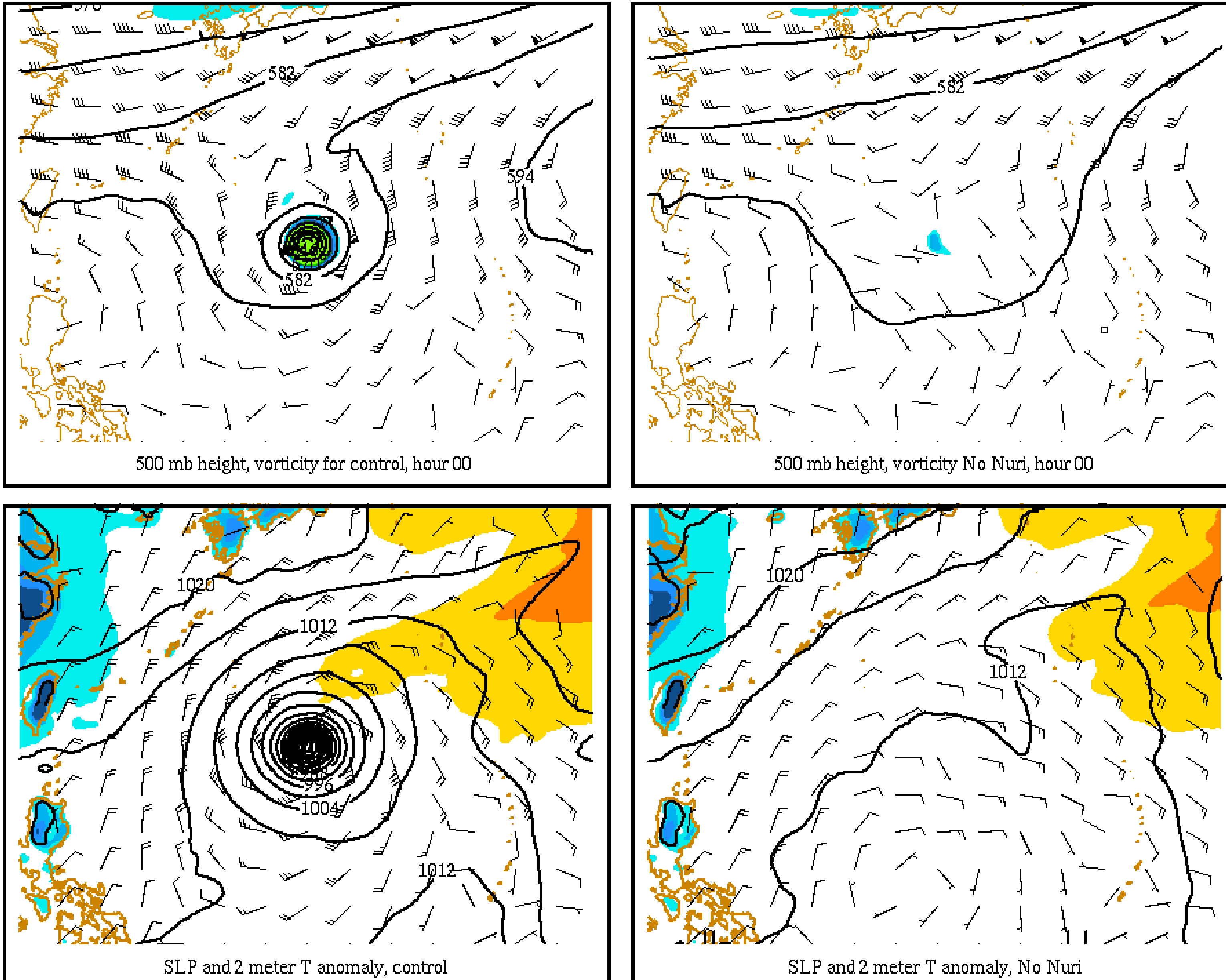
Grid length ~ 39 km



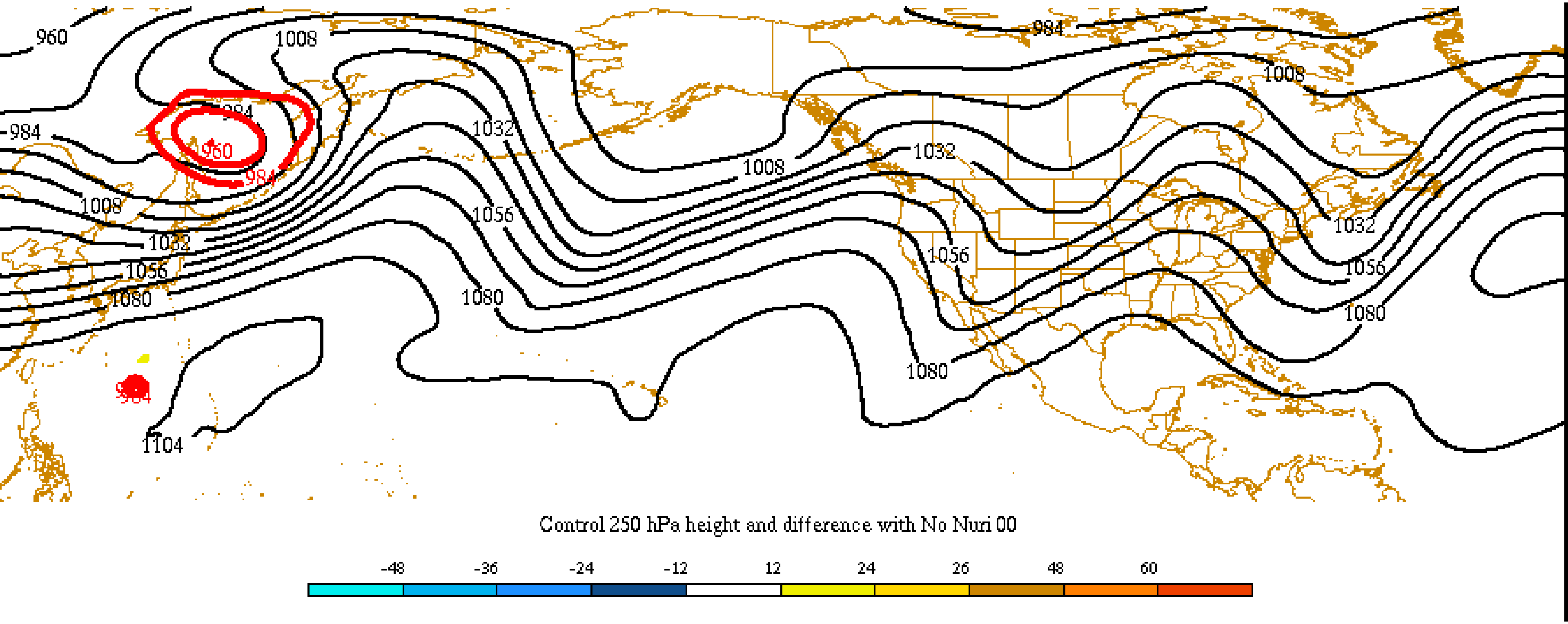
Control (left) and Nuri removed (right)

500-hPa Z, vorticity

SLP, T anomaly

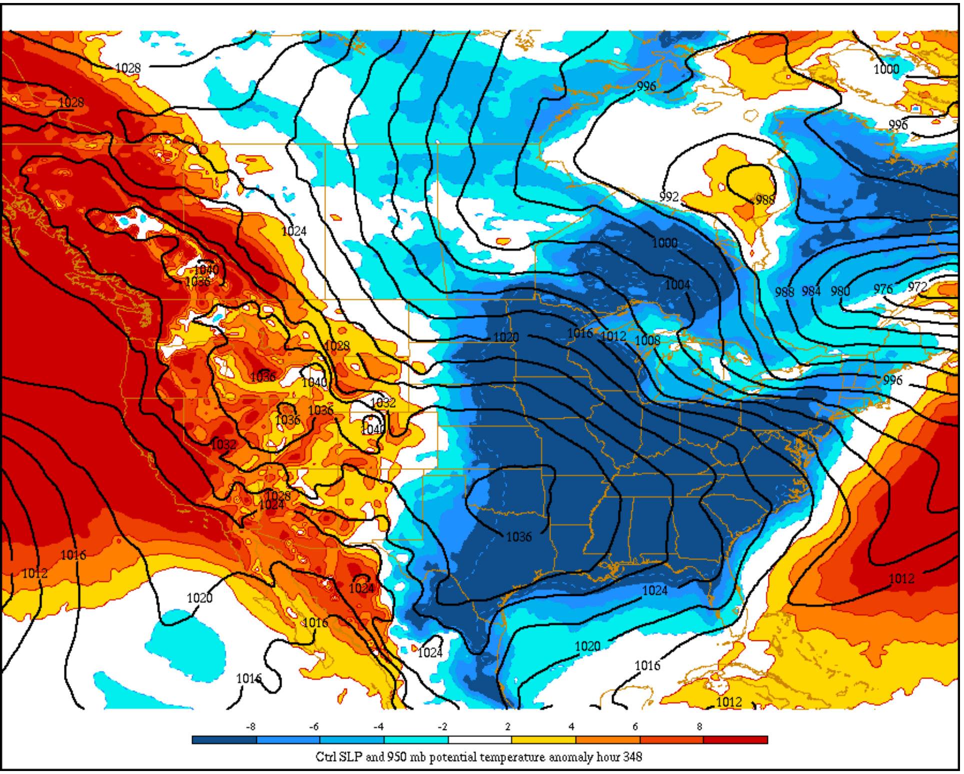


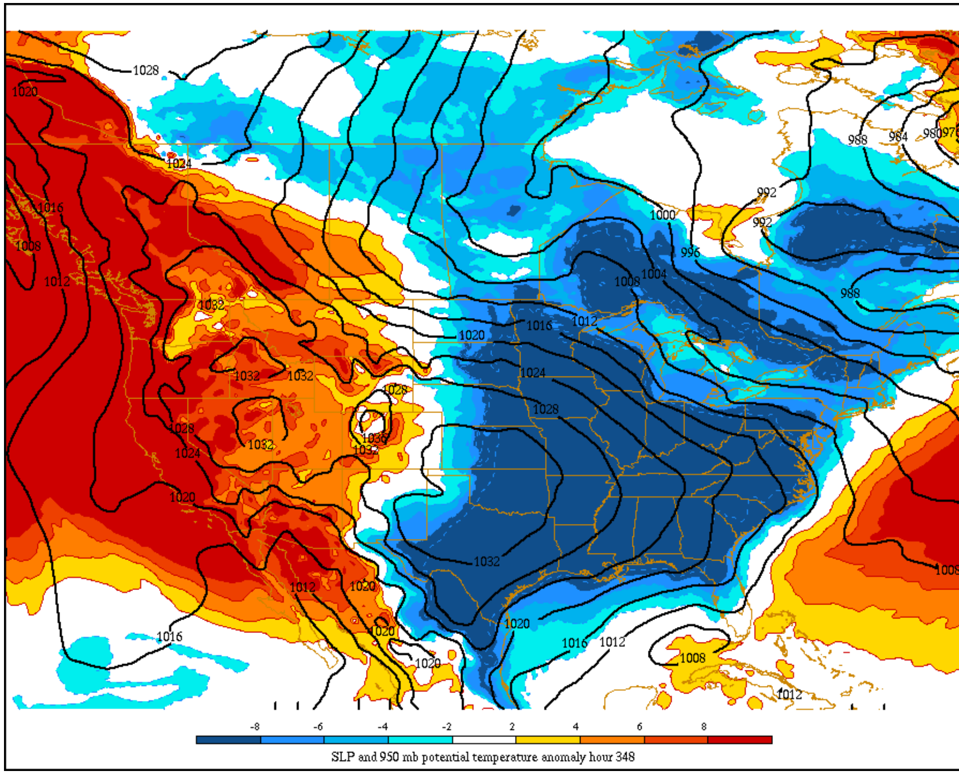
Control 250 hPa height and difference (shaded), SLP < 984 (red) control minus no Nuri (regional)



Control

NoNuri





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

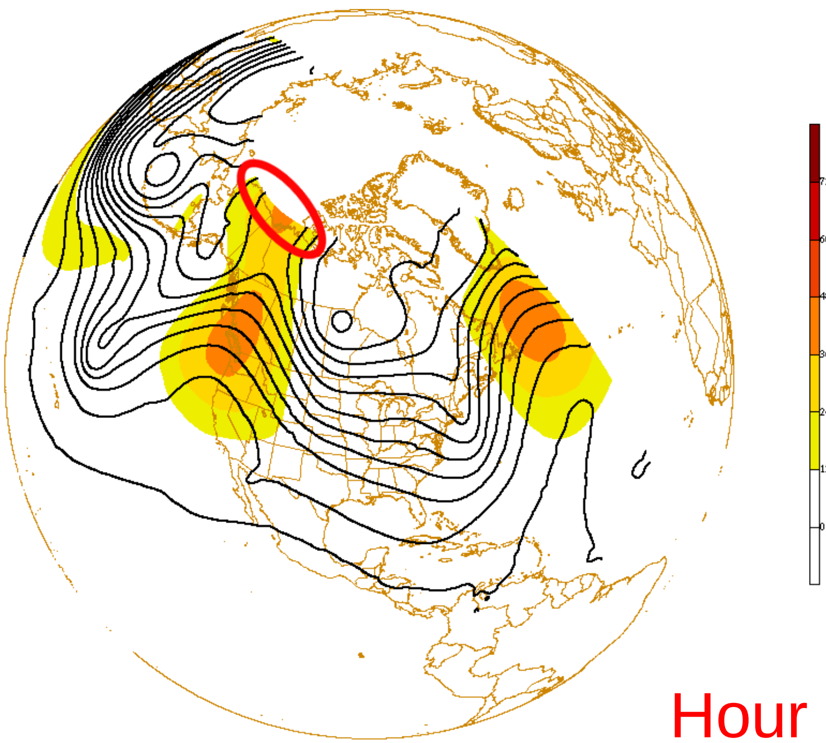
Or, is this result a figment of our methods?

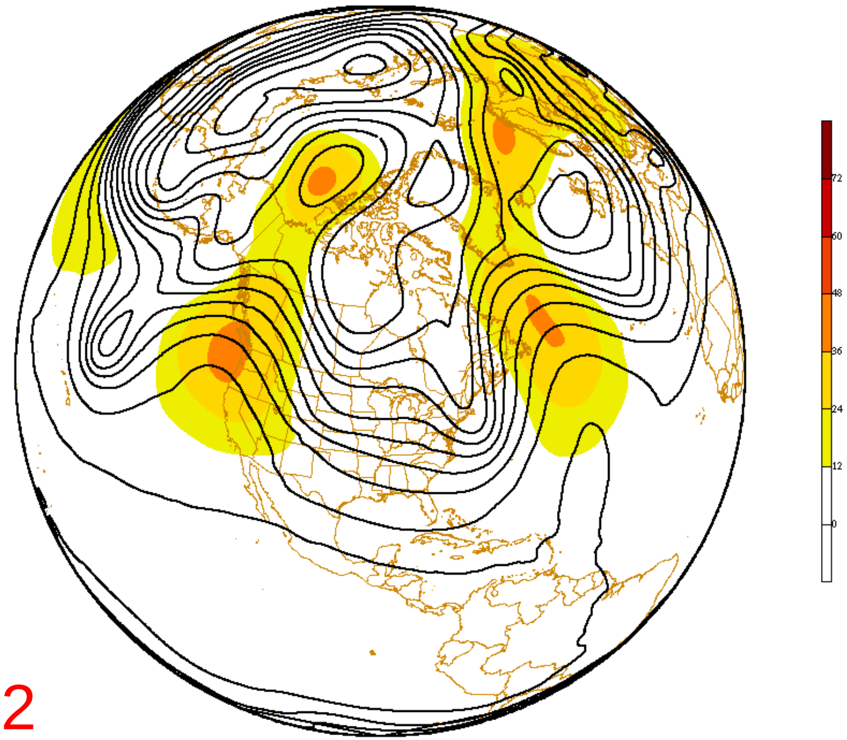
- Use of analyzed lateral boundary conditions: Locked in ridge at northern edge of domain

- 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





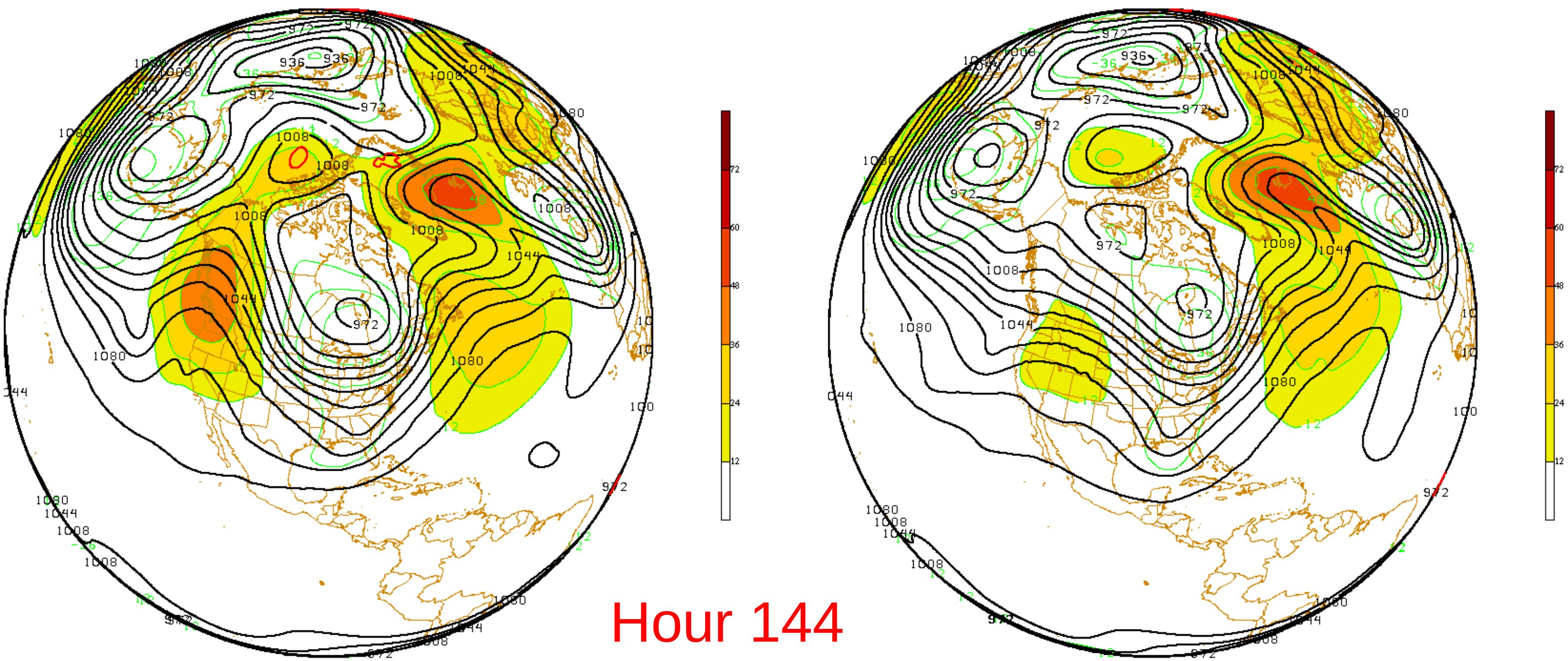
Hour 102

Regional Control

Global Control

Does Global WRF Provide Consistent Results?

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



Global, Control, SST update

Global, NoNuri, SST update

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?

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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

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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)

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