Climate Change: Mesoscale and Synoptic-Scale Precipitation Events

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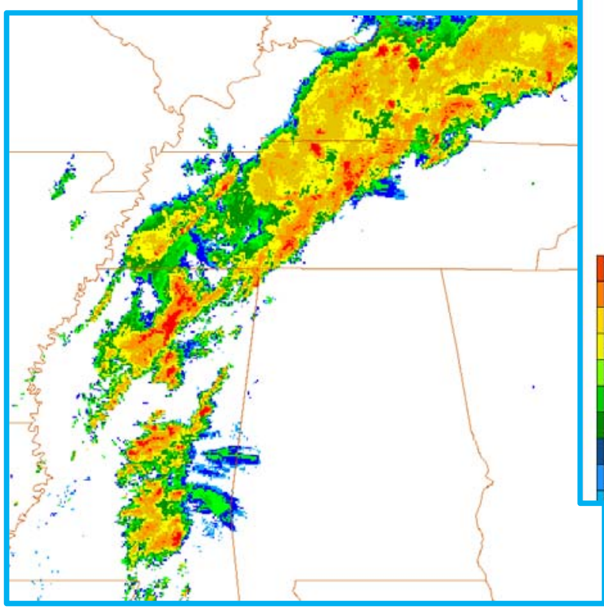
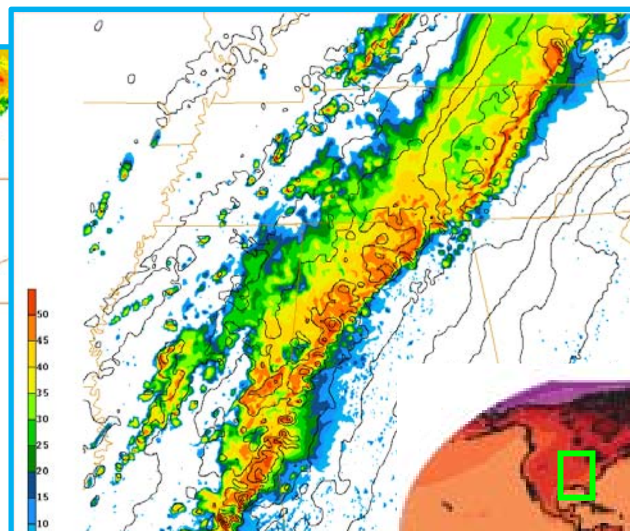
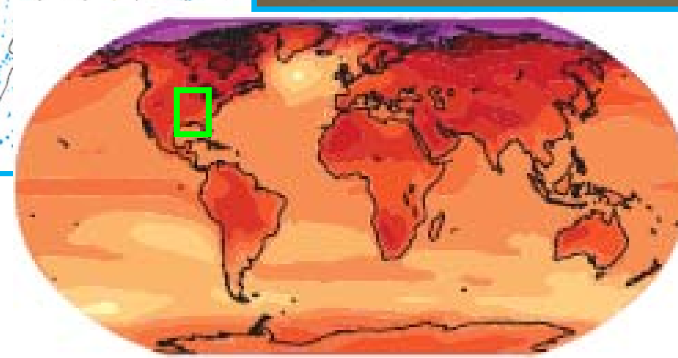
CLIVAR Workshop on LSMPs Associated with Extreme Events
21 August 2013







Outline

1.) Challenges

2.) Methods, Lessons, & Examples

- RCM classification & “pseudo global warming”
- Case studies and monthly/seasonal simulations

3.) Results: Convective Flood Event of May 2010, SE US

- Hypothesis and test
- Analysis of precipitation changes

4.) Conclusions

Downscaling Challenges (familiar to this audience):

- Resolution requirements for simulating extreme precipitation (e.g., < 6 km grid)

- Require global model/GCM for initial conditions (IC) and lateral boundary conditions (LBC)
    - Synoptic precursors to extreme events are often poorly resolved in GCMs

- Difficulty in separating thermodynamic / dynamic aspects of climate change

- [Keeping up with literature in multiple areas]

Categorization of dynamical downscaling techniques:
[Castro et al. (2005), Pielke and Wilby (2011)]

Type 1) Short-term; IC/LBC from operational analyses or re-analyses; IC "remembered"

Type 2) Longer-term; LBC from operational global model analyses or re-analyses; IC "forgotten"

Type 3) IC/LBC provided by GCM forced with specified surface boundary condition (e.g., observed SST)

Type 4) IC/LBC from fully coupled AOGCM

Castro et al. (2005), Pielke and Wilby (2011): Categorization of dynamical downscaling techniques

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Strategy: Combine 1 & ~4 or 2 & ~4

- "Surrogate Global Warming": Apply horizontally uniform climate change fields to analyzed IC, LBC (e.g., Schär et al. 1996; Frei et al. 1998)

- "Pseudo Global Warming (PGW)": Apply spatially varying, GCM-derived changes to IC, LBC [e.g., Hara et al. (2007); Kimura and Kitoh (2007); also "Method R" - Sato et al. (2007)]

Combine 1 & ~4   or   2 & ~4

Advantages:

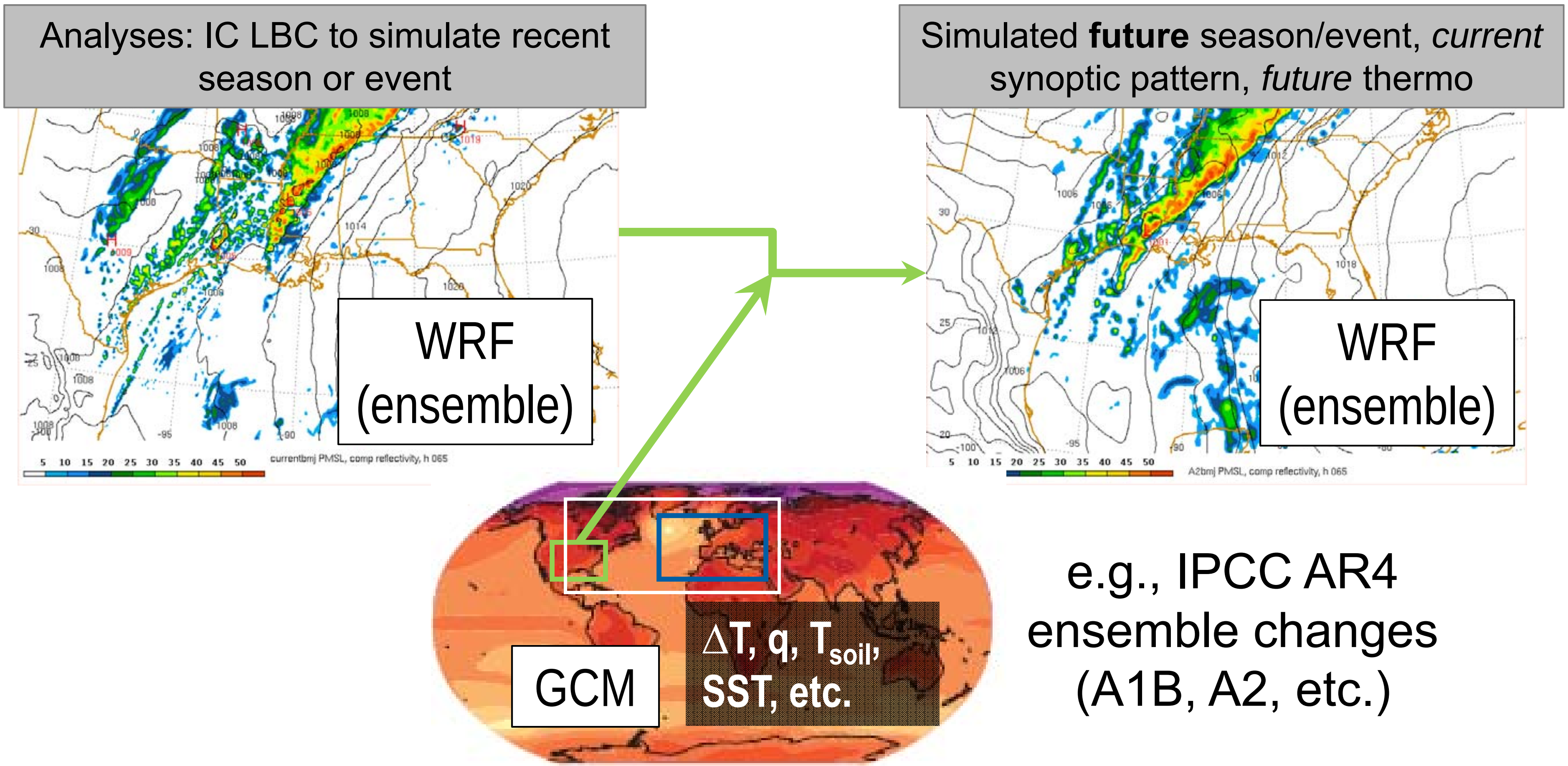
(i) Realism, resolution of synoptic fields

(ii) Direct comparison of current to past/future systems

(iii) Ability to isolate large-scale thermodynamic impacts

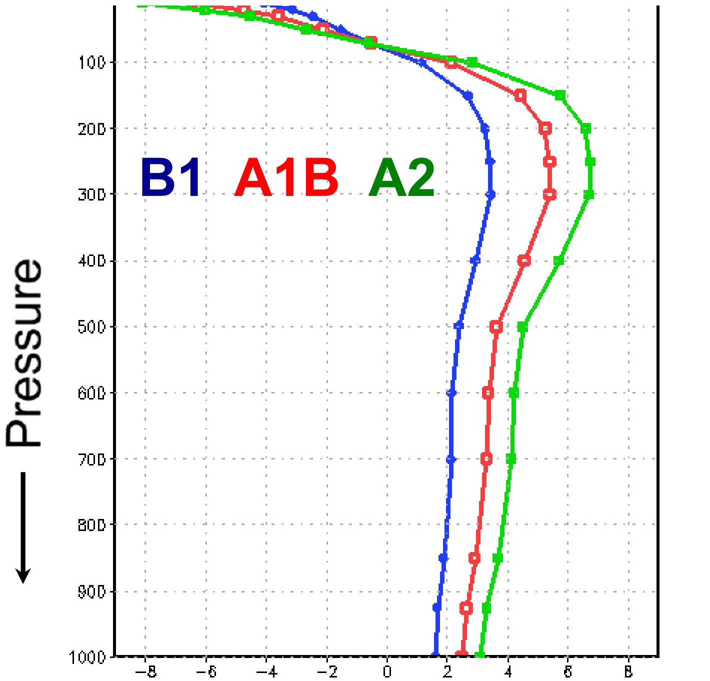
PGW Method: Replication of Current Events

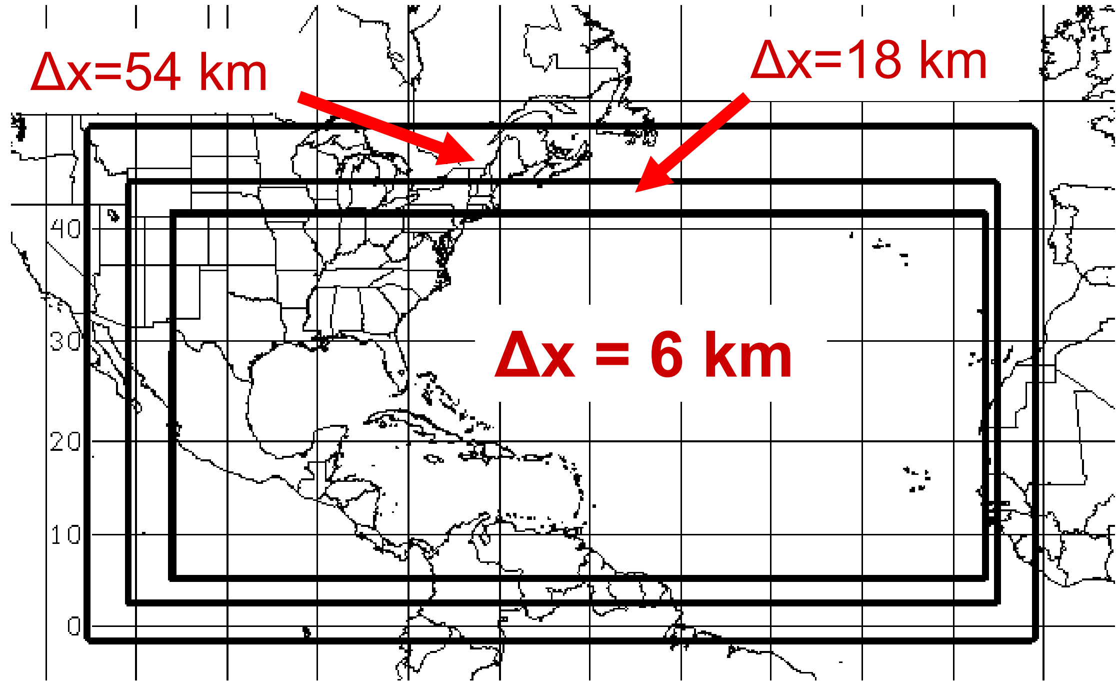
- Apply GCM-derived thermodynamic change to current analyses; uniform (tropics) or spatially varying (higher latitude) – PGW approach
- Replicate current events & seasons, with “future or past thermodynamics”



Ex. 1: Tropical Atlantic Domain, Monthly Simulation

Projected T change, tropical spatial average over subset of domain (AR4)





Ensemble of GCM projections for change fields

Change fields applied to reanalysis fields used for IC, LBC

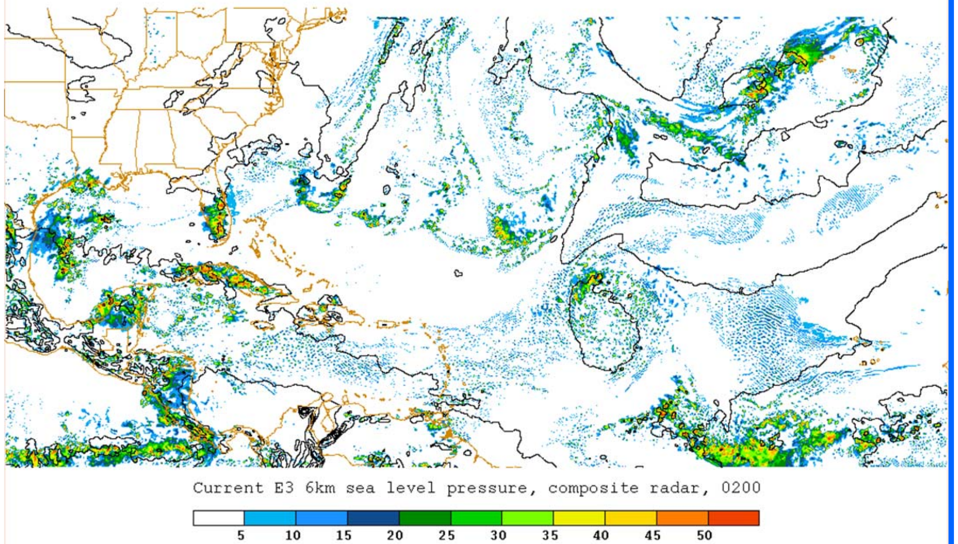
Moisture: Tested both constant RH and GCM-derived changes; similar

Included ocean changes, WRF mixed-layer ocean model

Altered trace gas concentrations in some experiments

High-Resolution (6-km grid) Simulations
Side-by-Side Ensemble Member E3

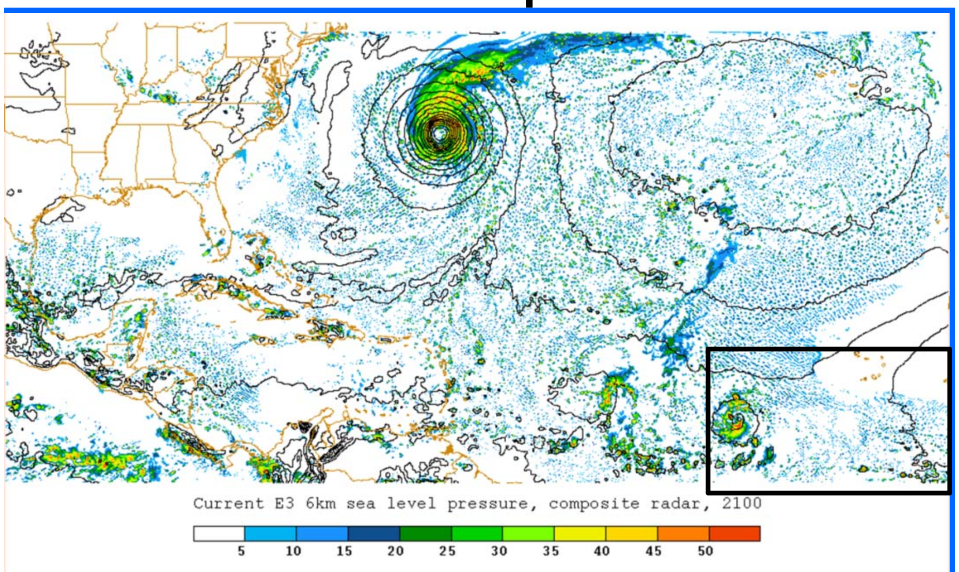
Recent September



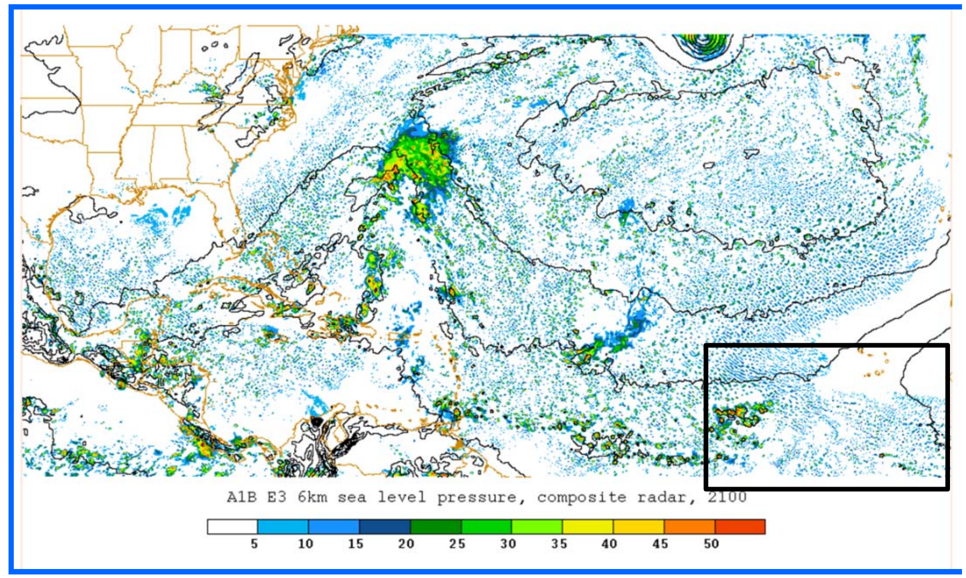
Future: Reduced TC activity with same pattern

High-Resolution (6-km grid) Simulations
Side-by-Side Ensemble Member E3

Recent September



A1B Modified

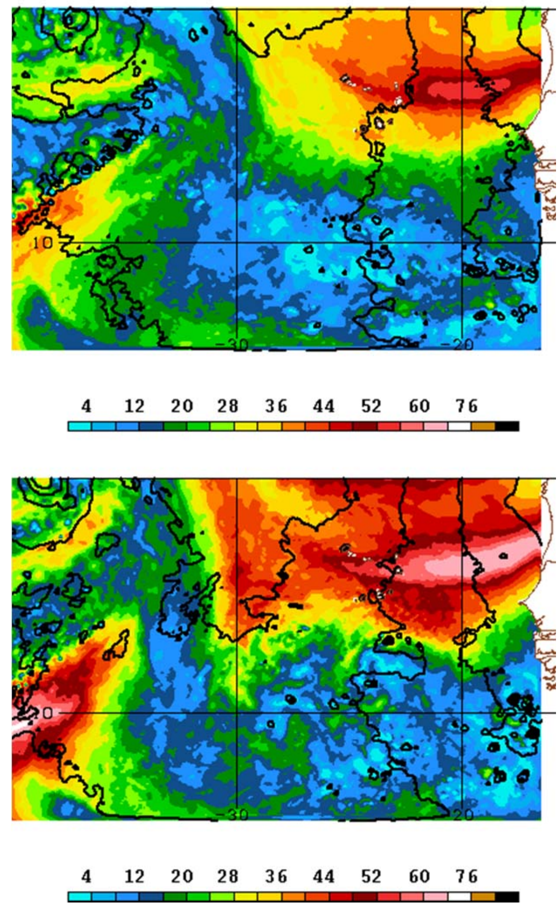


Future: Reduced TC activity with same pattern – Why?

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

Subset Case 1: Developing / Non-Developing

- Initial disturbance enters marginal humidity environment
- **Current: Convection moistens environment, TC forms**
- **Future: Requires more moistening to saturate, convection dissipates**



Current

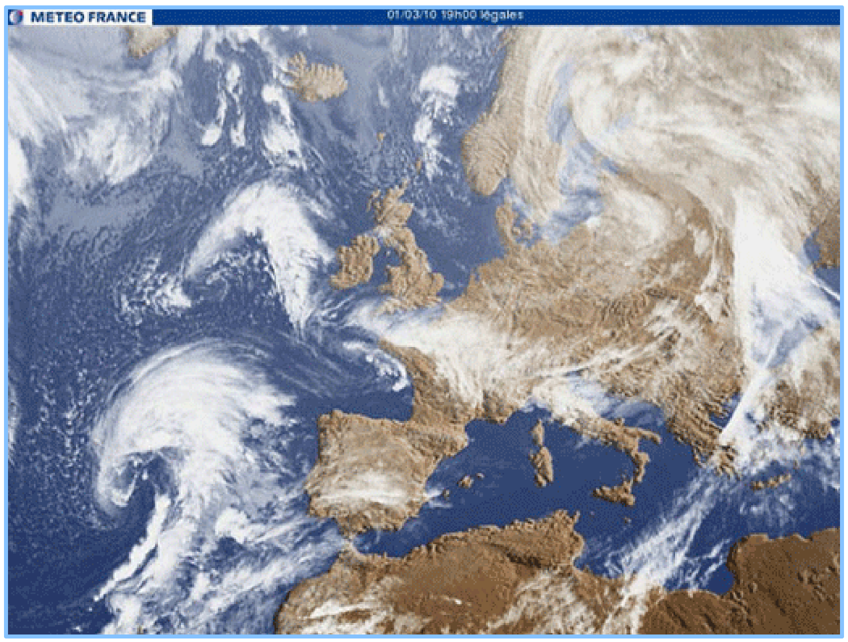
Future

Measure of mid-level saturation deficit (shaded), with SLP (contours)

χ_{mid}

Ex. 2: Extratropical Cyclone Xynthia

Xynthia – February 2010
>60 fatalities
€ 1.3-3B



If synoptic pattern accompanying Xynthia were repeated in a warmer climate, how would surface winds (& cyclone) compare?

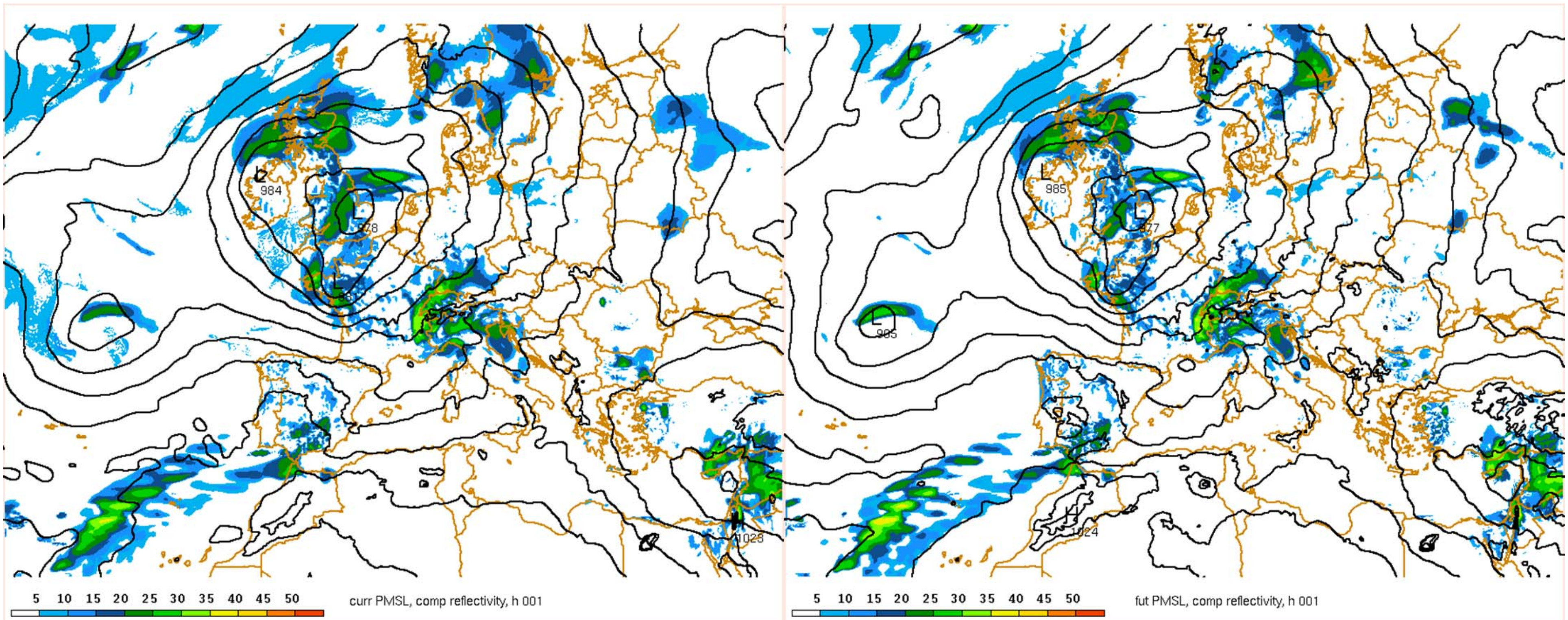
http://www.eqecat.com/images/s/U5q6plOEvE6YMJ94AJ752A/20100228-1-1-xynthia.gif

http://www.wunderground.com/blog/JeffMasters/comment.html?entrynum=1440

Xynthia, high resolution domain – 6.6 km grid

Current simulation

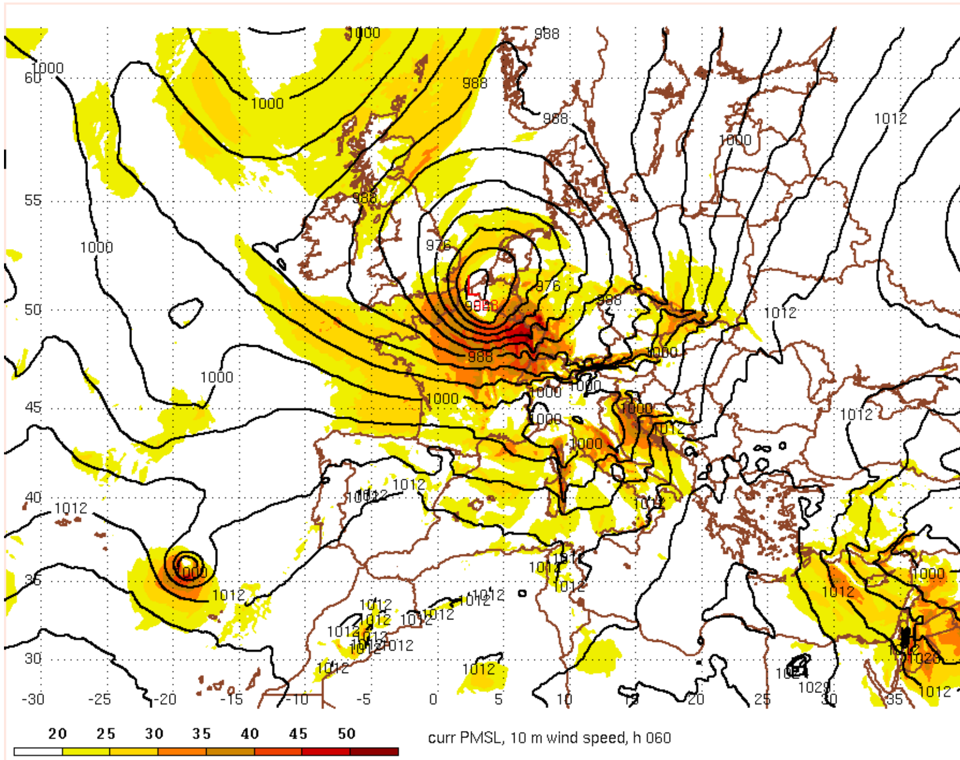
Future simulation



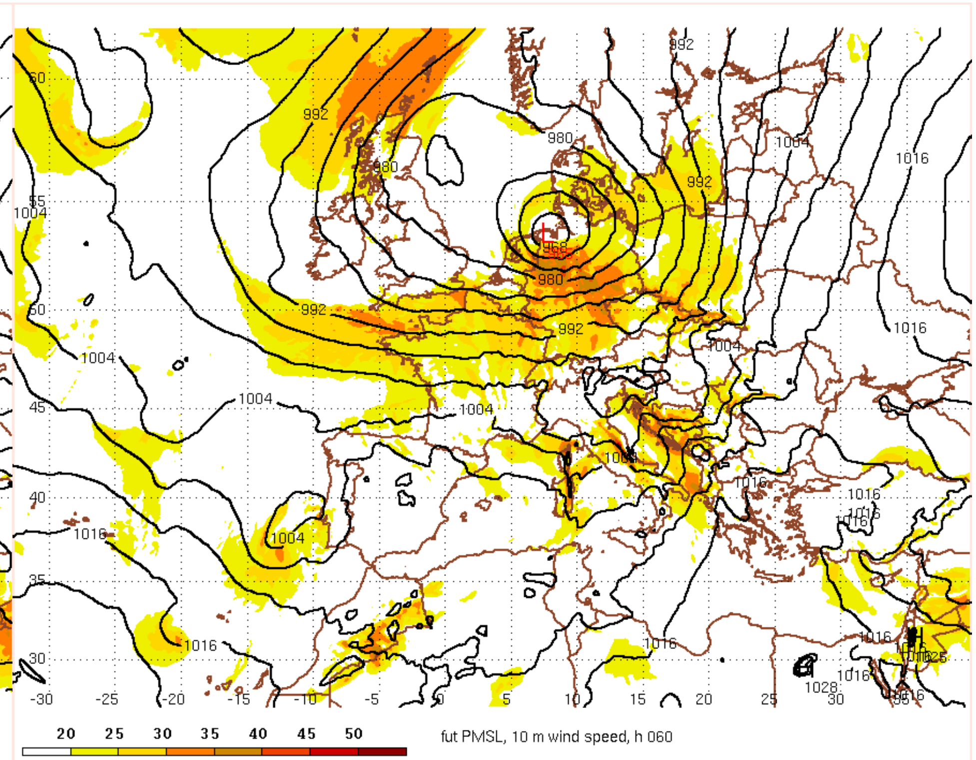
Sea-level pressure (black contours),
simulated radar (shading)

Xynthia, 6.6 km grid, hour 60

Current simulation



Future simulation



Sea-level pressure (black contours),
10-m wind speed (m/s, shaded)
Valid 12 UTC 28 February 2010

PGW simulations of extreme cyclone events:

For many single-case simulations, “future” cyclone *weaker*, despite heavier precipitation

Upper wave moves faster (with upper jet)

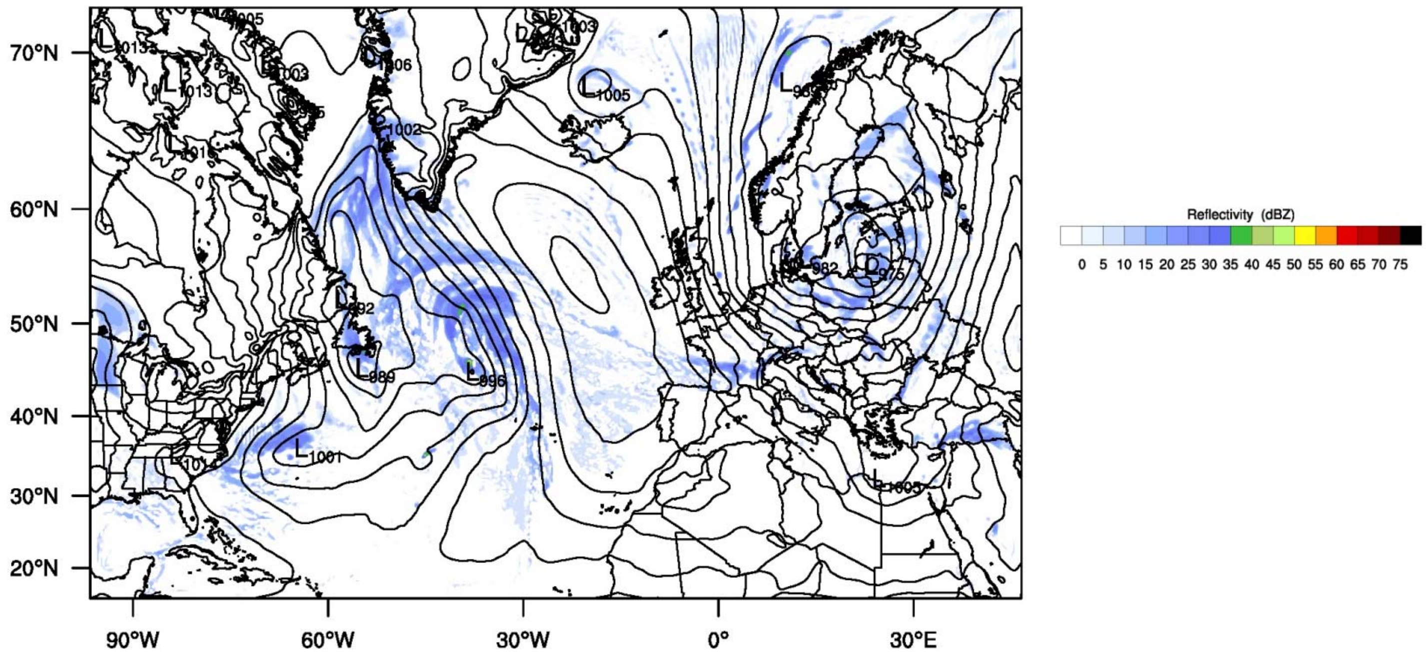
Reduced vertical coupling?

Must exercise caution when extrapolating conclusions from high-impact current cases…

Ex. 3: Seasonal PGW Simulations

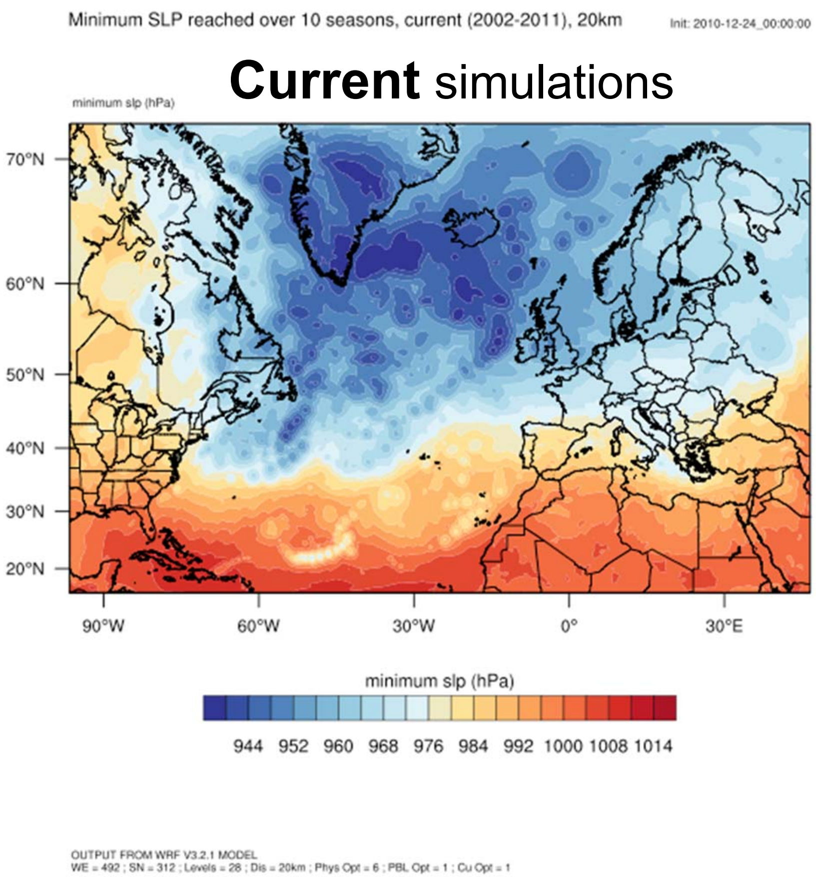
10 North Atlantic basin winter simulations

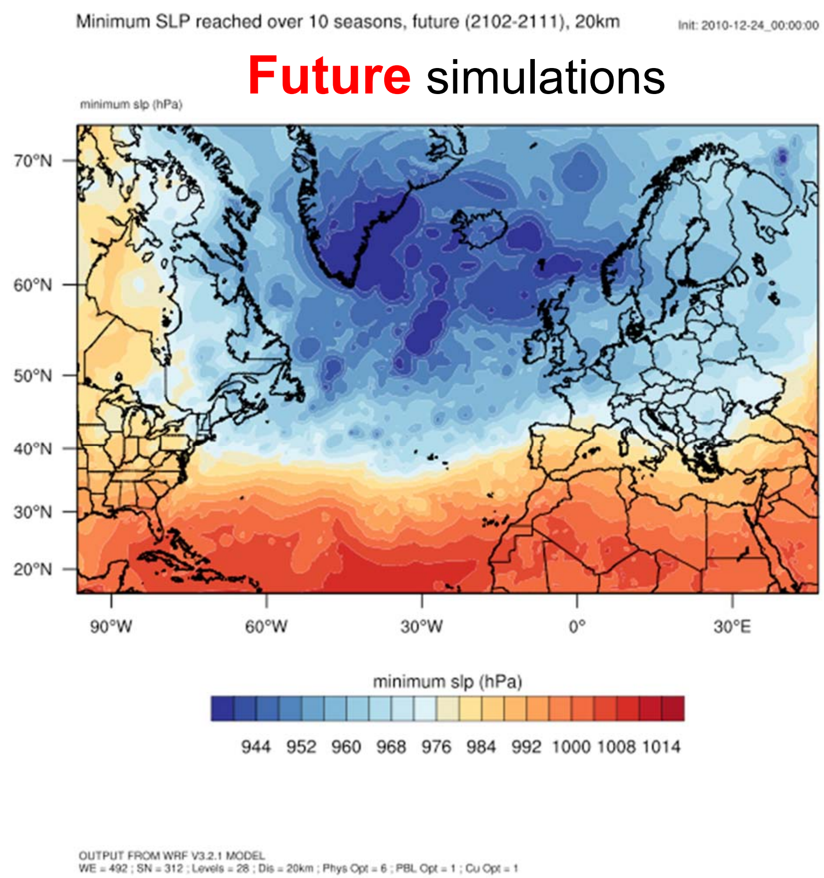
- 24 Dec – 7 Apr, years 2001-2011, Current & Future
- 20 km grid length, Kain-Fritsch convective scheme
- SST updated weekly from RTG 0.5° analysis, GFS FNL for IC, LBC
- Climate change as for case-study simulations but alter trace gases
- External & sea ice forcing excluded by design



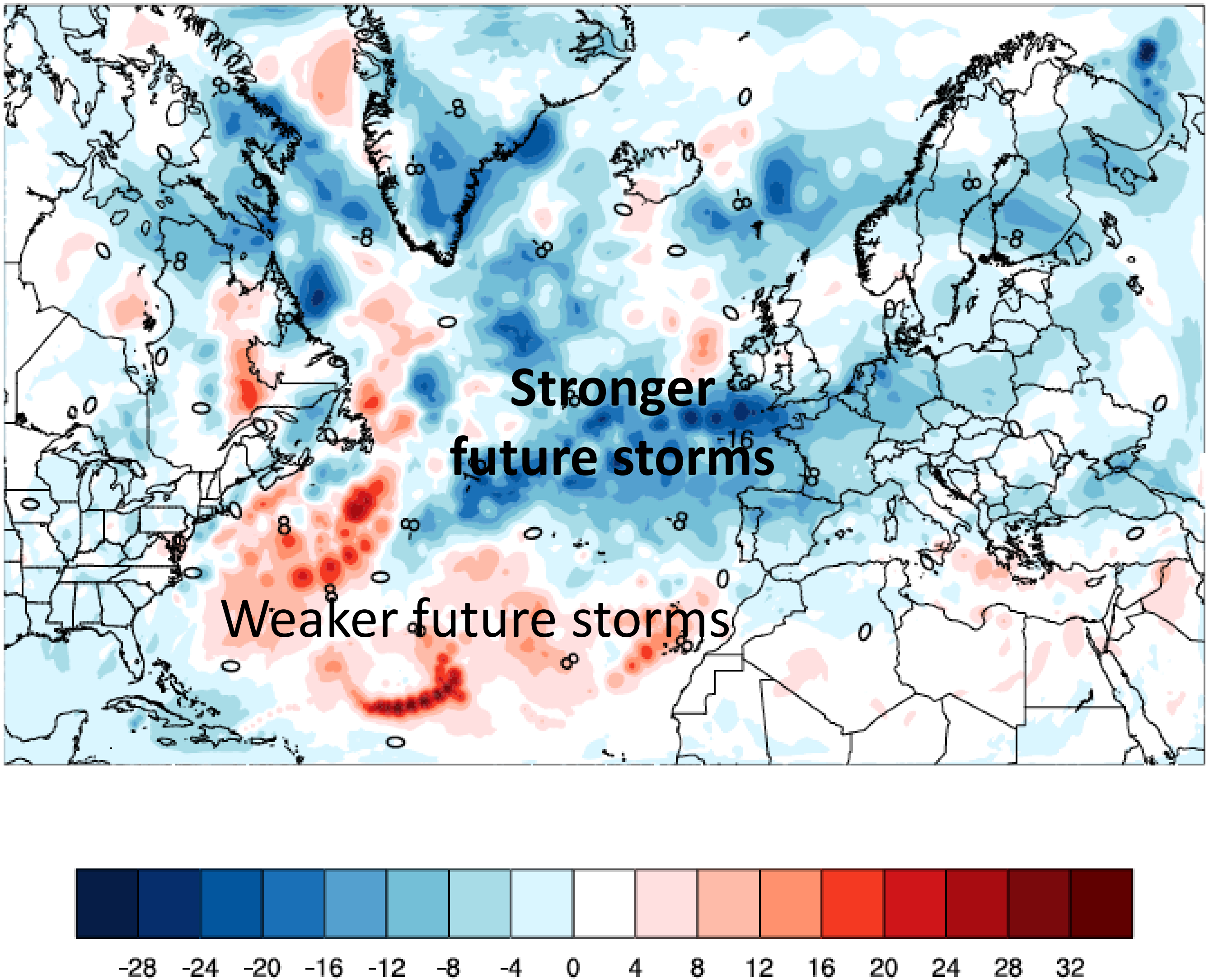
Seasonal Simulations

Lowest value of sea level pressure over entire 10 seasons of simulation (4,194 output times per set)





Difference in minimum sea level pressure, 10 winters



Strongest storms weaken in southern portion of storm track, strengthen to north, east

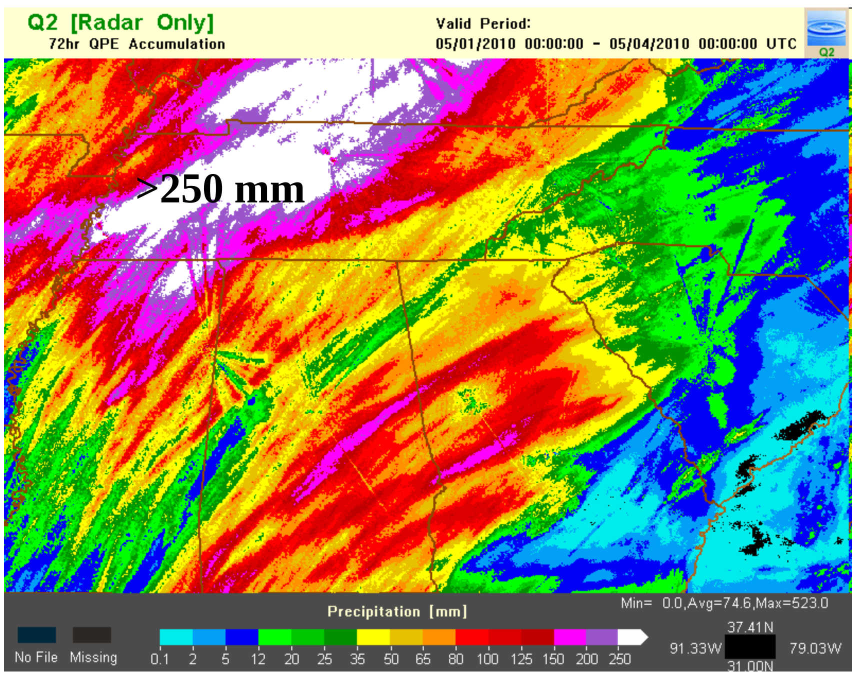
Current minus future

Application of PGW approach to Convective Flooding Event (May 2010)

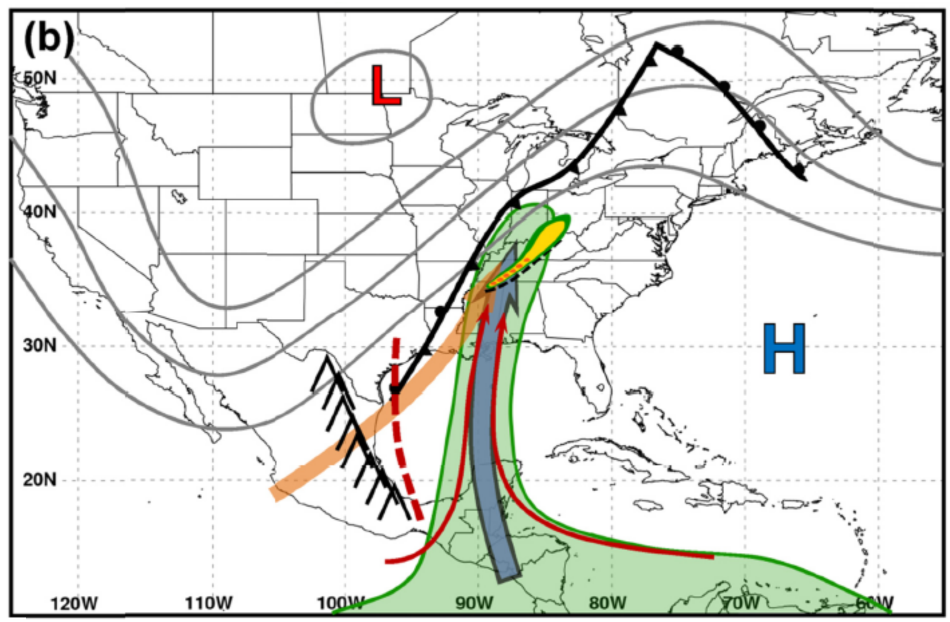
Damage exceeded $2B USD (Durkee *et al.* 2012)

3-d precipitation > 250 mm over substantial area of TN, KY, LA

Impressive low-level jet, tropical moisture plume, persistence



3-d total radar-derived rainfall (mm)
Maximum: 523 mm



Moore et al. (2011)

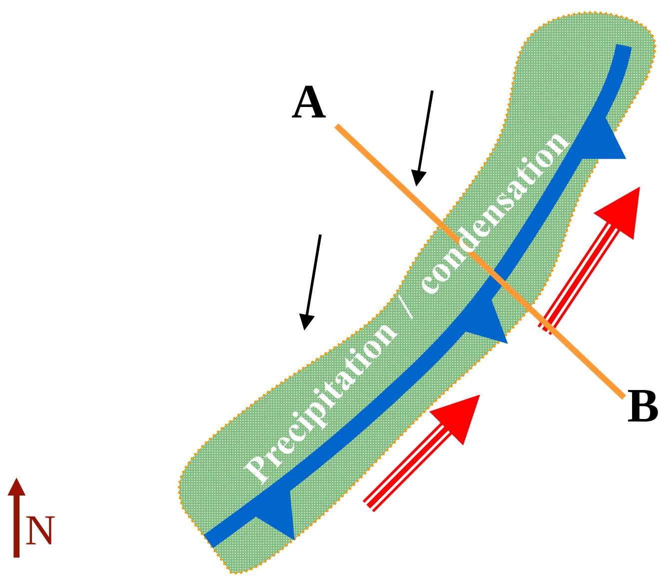
Dynamical moisture effect?

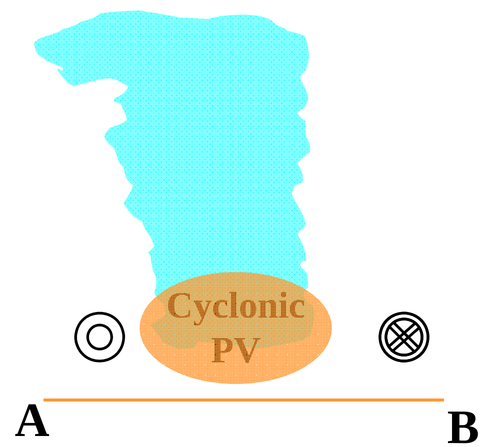
Warming climate: Increased water vapor, roughly 6.5% specific humidity increase per °C warming

Precipitation *in heavy rain events* increases at this rate or larger

Windstorms can occur with low-level jet located ahead of cold fronts

Condensation (heating) with cold-frontal precipitation strengthens this jet; H: More condensation, stronger winds in low-level jet ahead of front





Flood Event Simulation

GFS analyses for initial, lateral boundary conditions (1.0°)

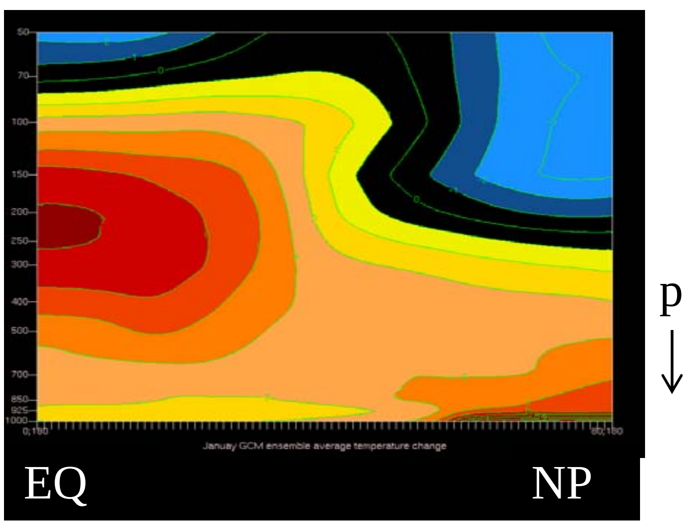
Initialize 00 UTC 30 April, run 96 h to 00 UTC 4 May 2010

54/18/6 km grid spacing, 1-way nesting

Parameterized convection (BMJ) outer 2 domains, explicit inner

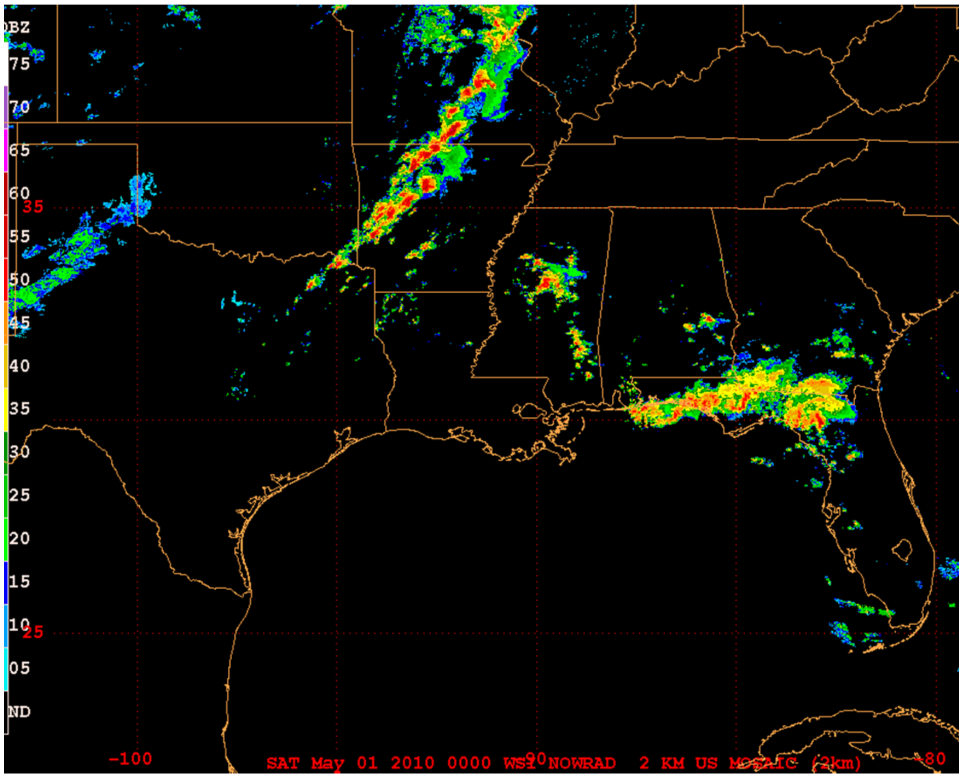
- WSM6 microphysics
- YSU PBL, surface layer
- NOAH LSM

Spatially varying GCM change

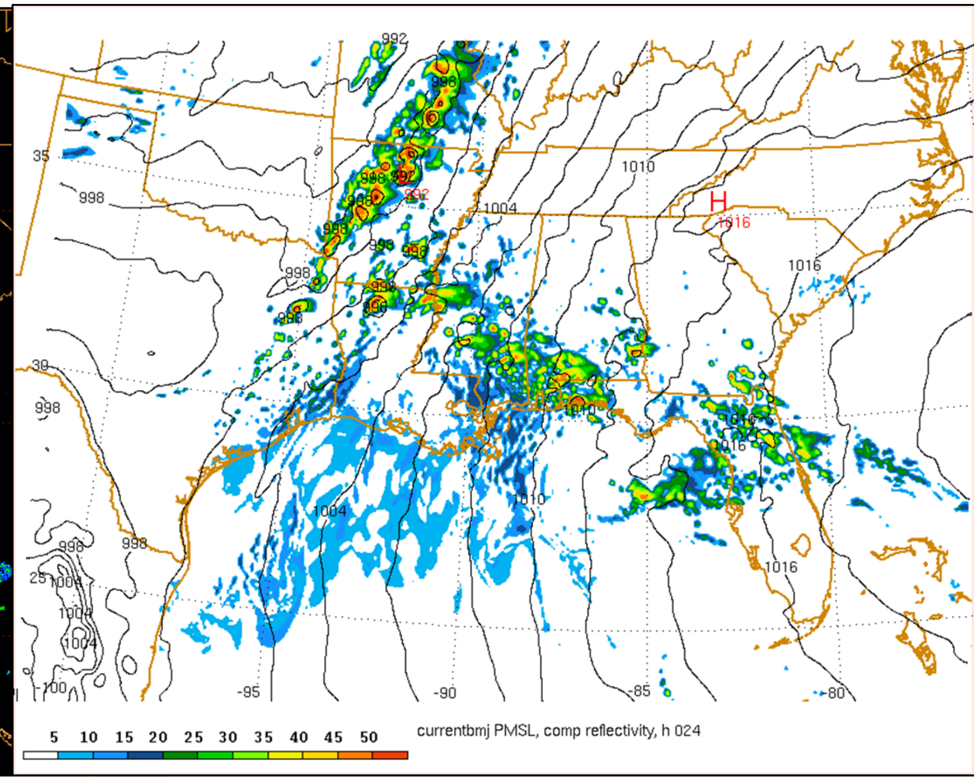


Control Simulation

Control simulation: Qualitatively credible reproduction of MCS



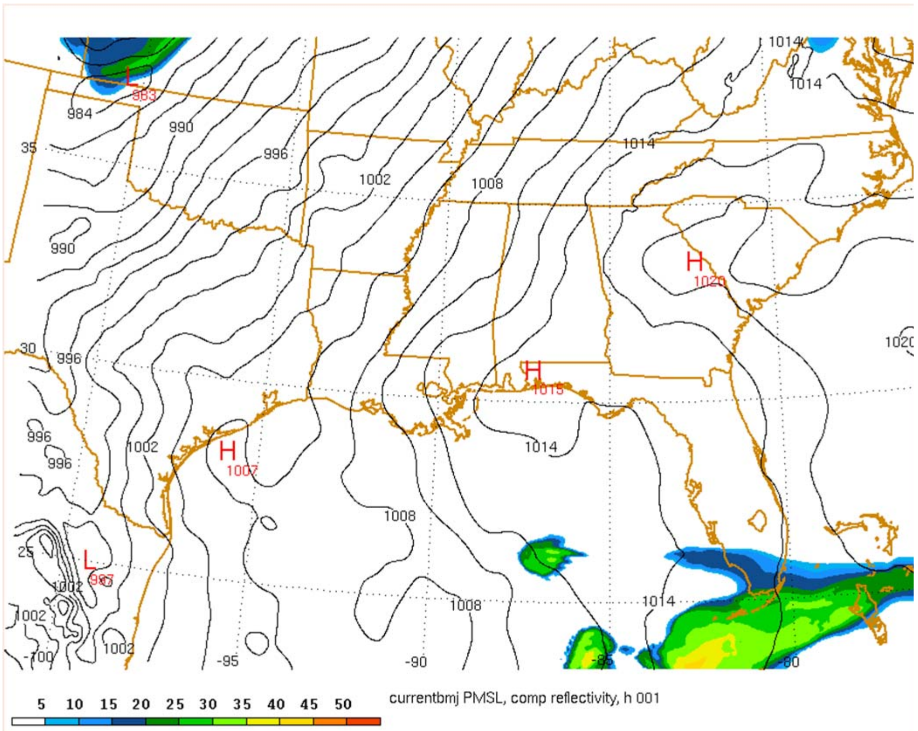
Observed Radar, 00Z 5/1-23Z 5/3



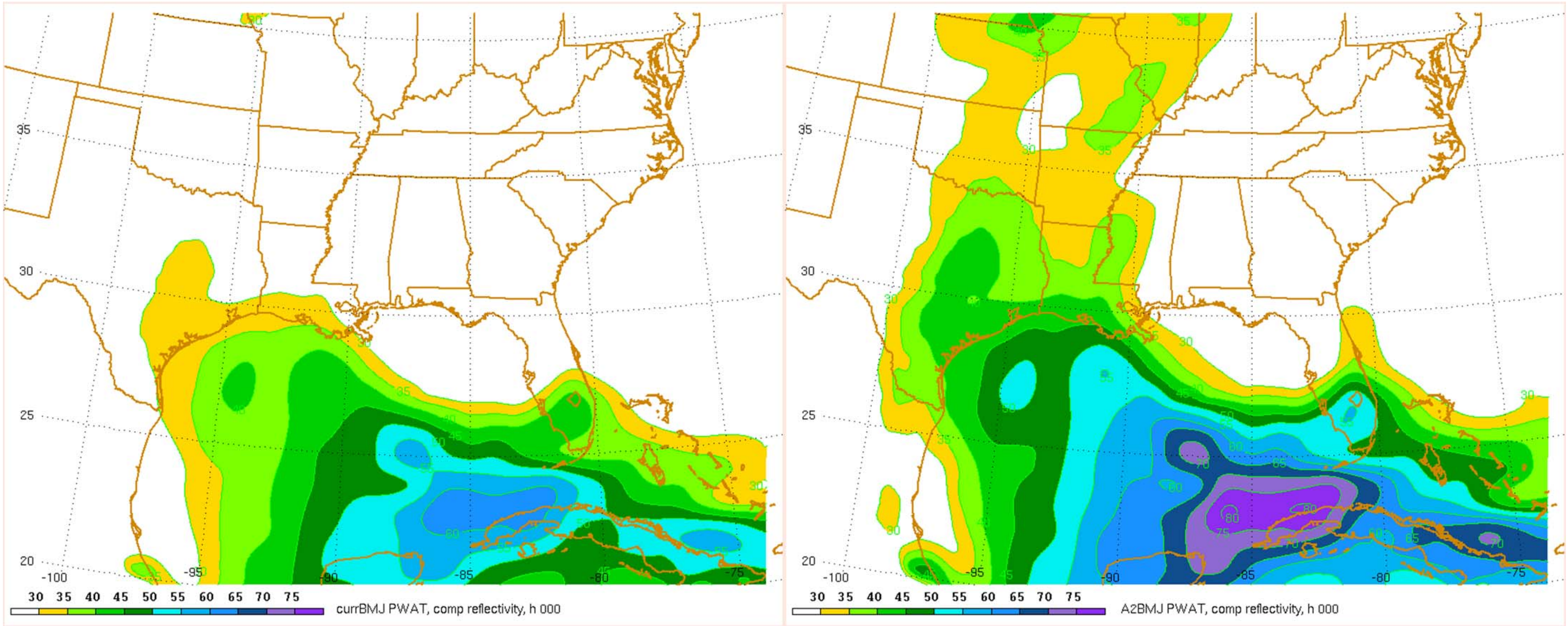
WRF 6-km control simulation

SLP, Simulated Composite Reflectivity

Current



Precipitable Water (shaded), Reflectivity (black contours)

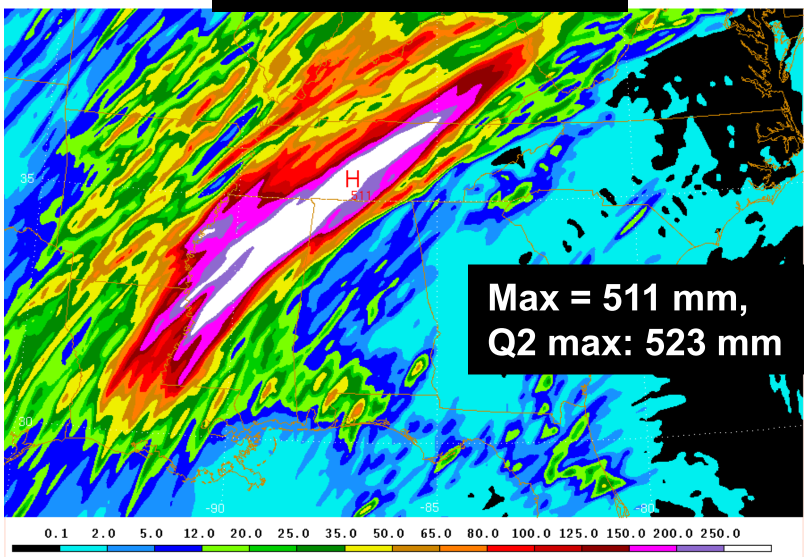


Current

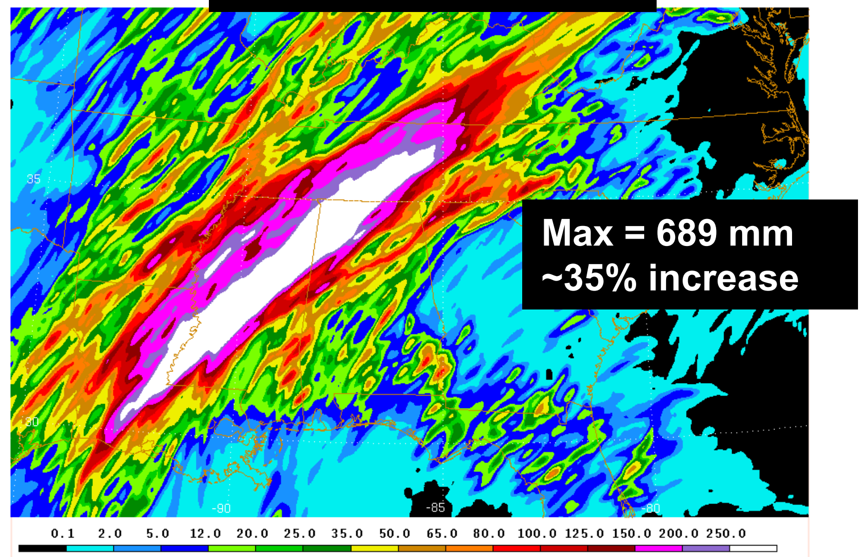
Future (A2)

72-h Precipitation Total: Current vs Future

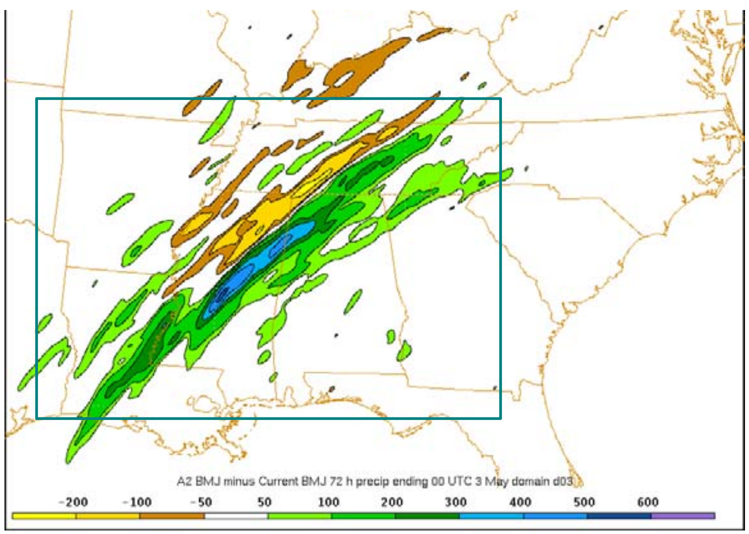
6 km **Current**



6km A2 **Future**



6 km Difference (Future – Current)



Maximum difference > + 500 mm, due mostly to south/eastward shift

Flood Event Precipitation Change & Clausius-Clapeyron

Average over 96-h simulation, region of heavy rain (30;-95;37;-82)

Compute changes in temperature, vapor, precipitation:

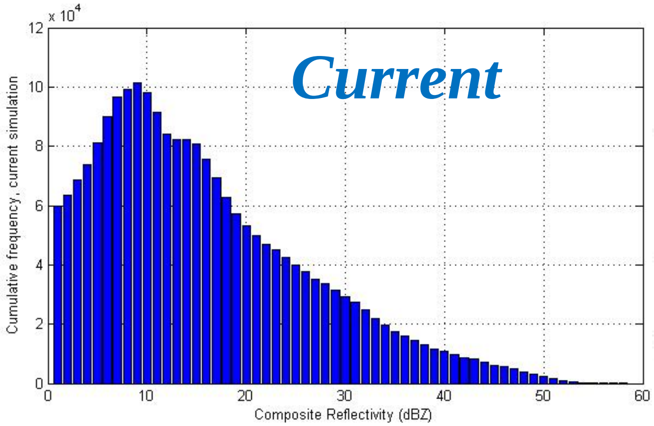
Parameter	Current	Future	Difference	Actual % change	C-C Prediction	C-C % Change
850 hPa T	289.14 K	292.68 K	**3.54 K**			

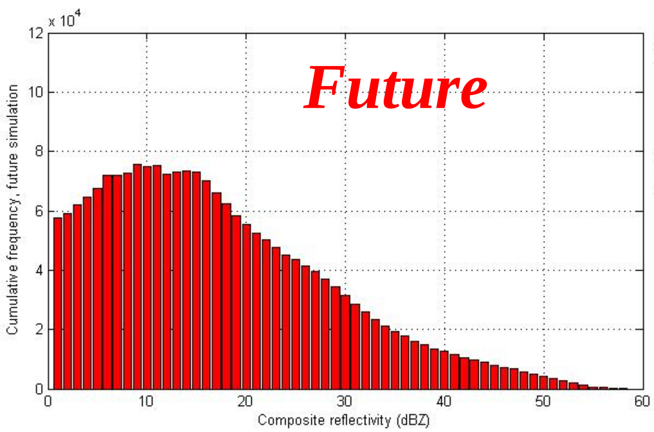
Precipitation increase exceeds that of vapor for this event (super Clausius-Clapeyron)

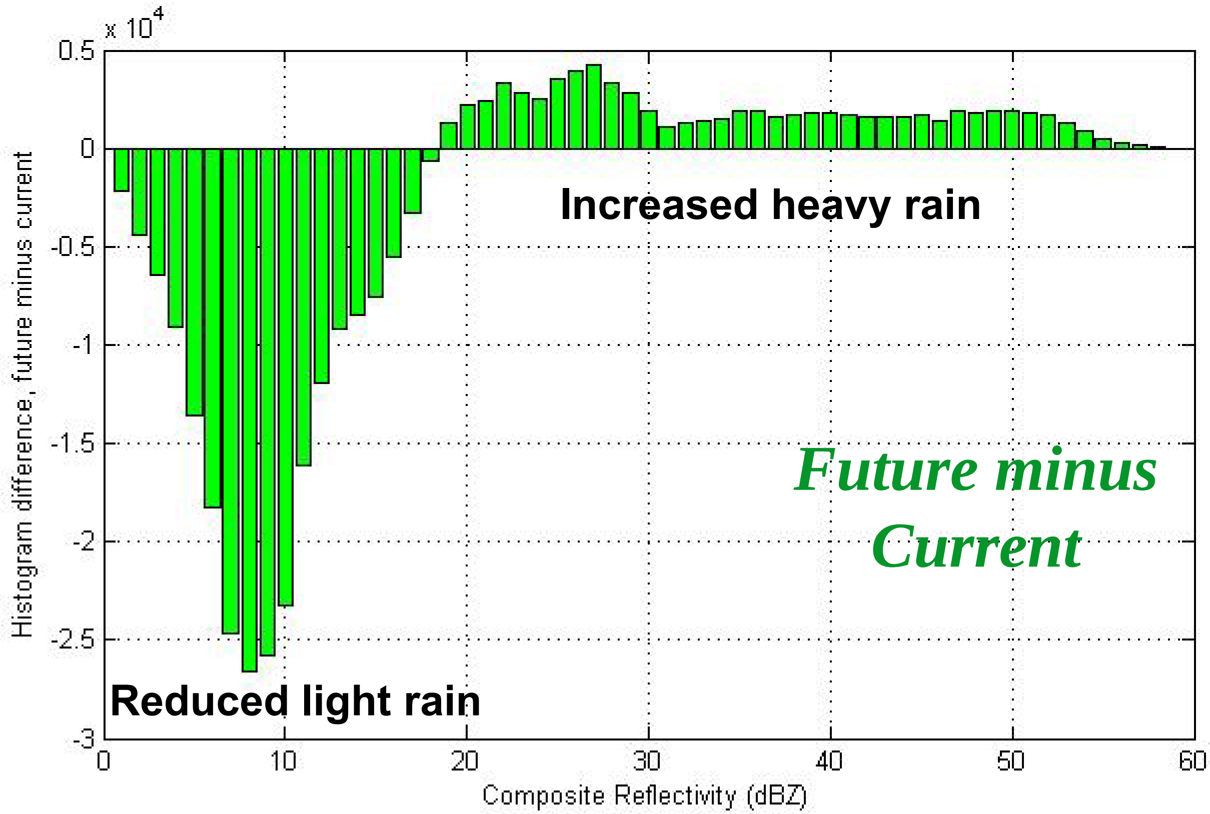
Flood Event Histograms: Simulated Reflectivity

Histograms of simulated composite reflectivity over entire model grid, 96-h simulation (>12M grid cells)

Decrease in frequency of reflectivity below ~ 18 dBZ



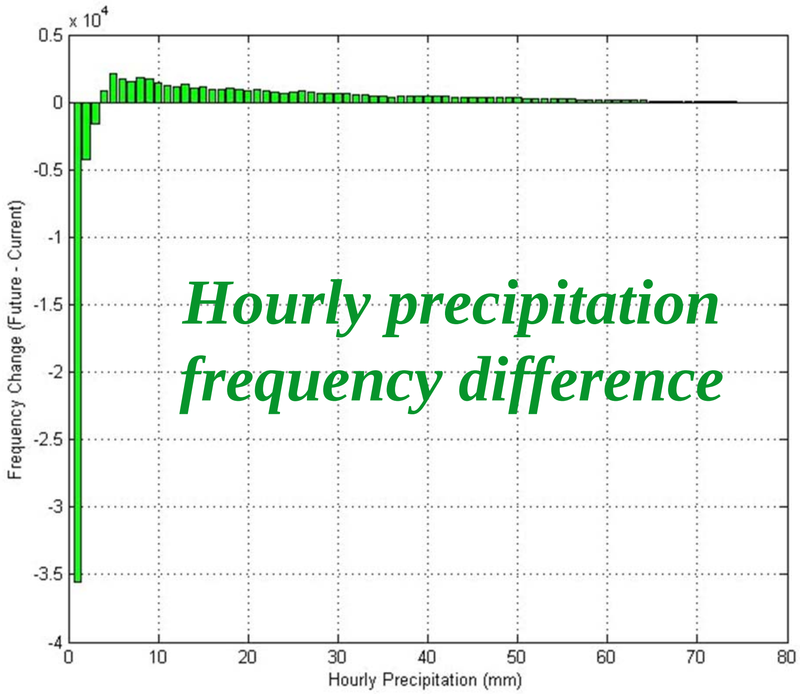


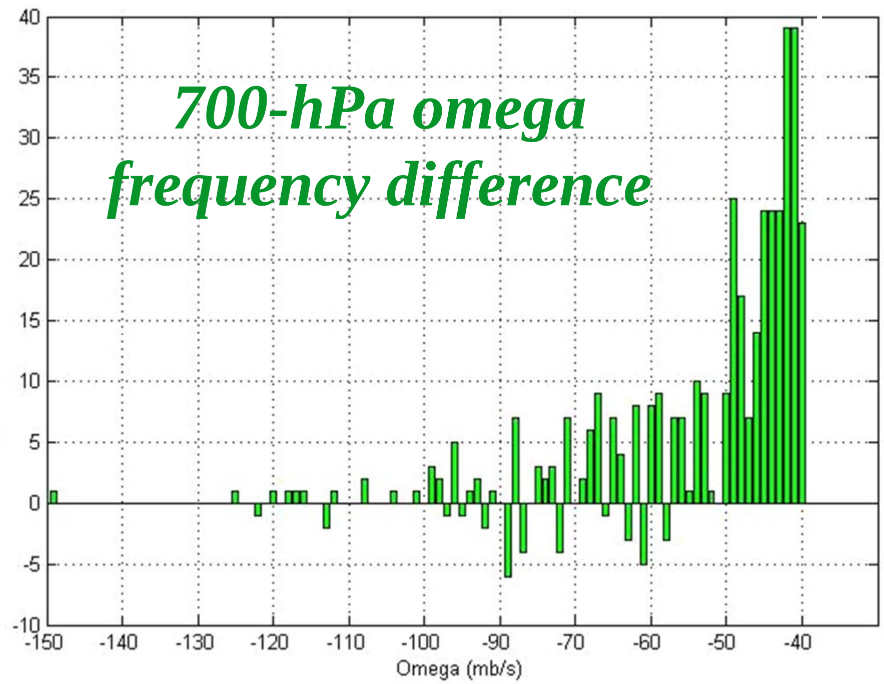


Flood Event: Hourly Precipitation, Ascent

Hourly rain rate histogram consistent with reflectivity:
- Decrease in frequency < 5 mm h^{-1}; increase for > 5 mm h^{-1}

Increases in convective-scale ascent, consistent with larger CAPE in future



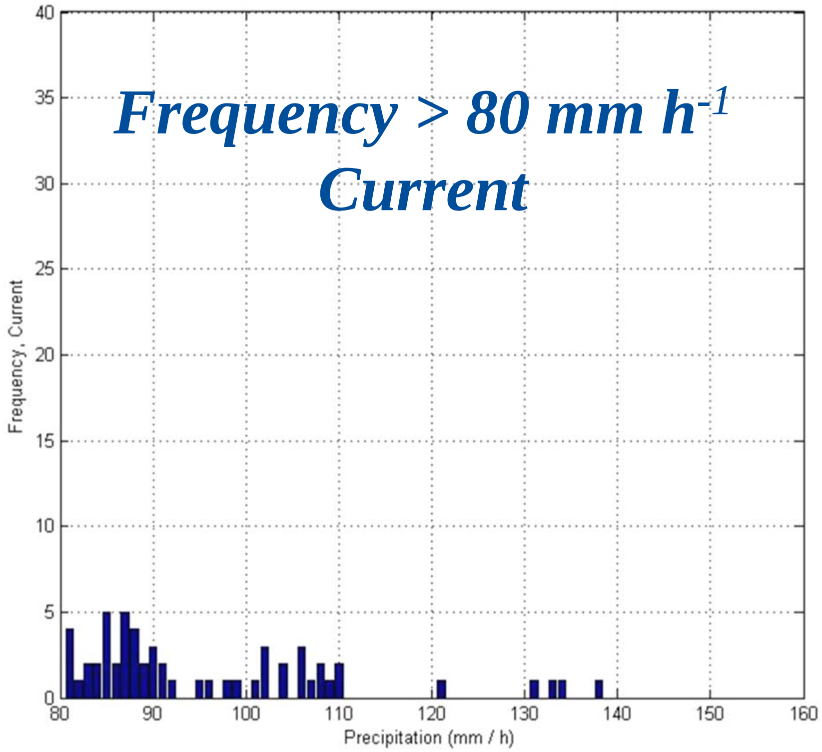


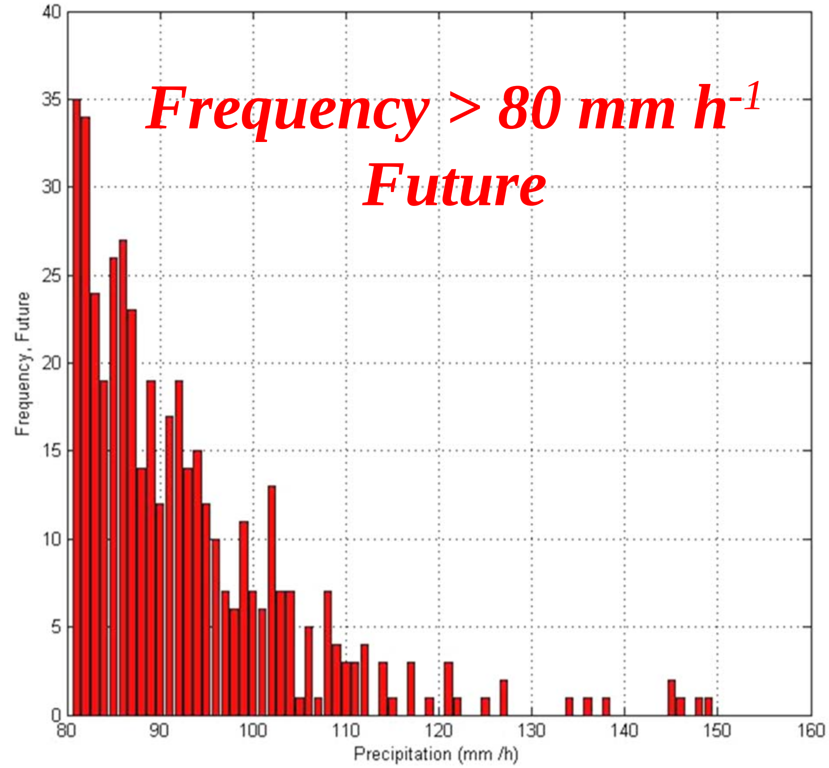
Histogram Comparisons: Hourly Precipitation

Consider grid-cell frequency of precipitation rates > 80 mm h^{-1}

Largest frequency increases evident up to 100 mm h^{-1} (4” h^{-1})

Flash flooding implications



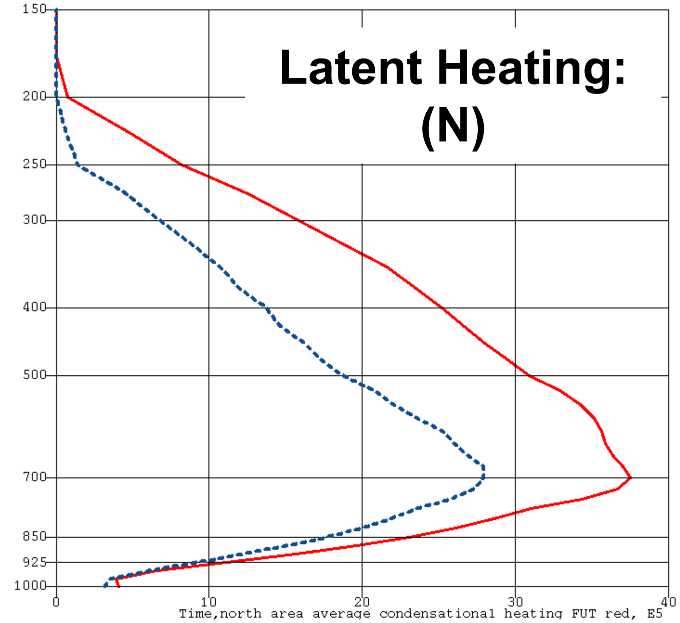


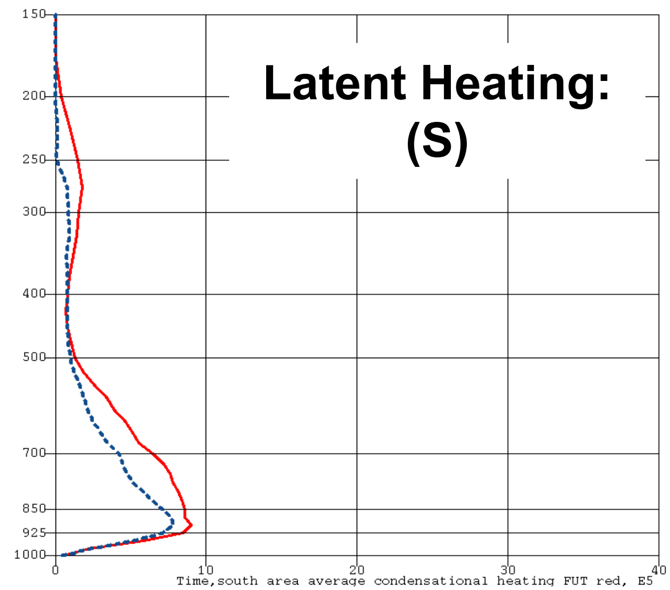
What about the LLJ hypothesis?

Spatial & Temporal Average Comparison

Future: Stronger latent heating to north, less difference to south

Expect insignificant diabatic PV tendency difference over Gulf of Mexico (LLJ location)



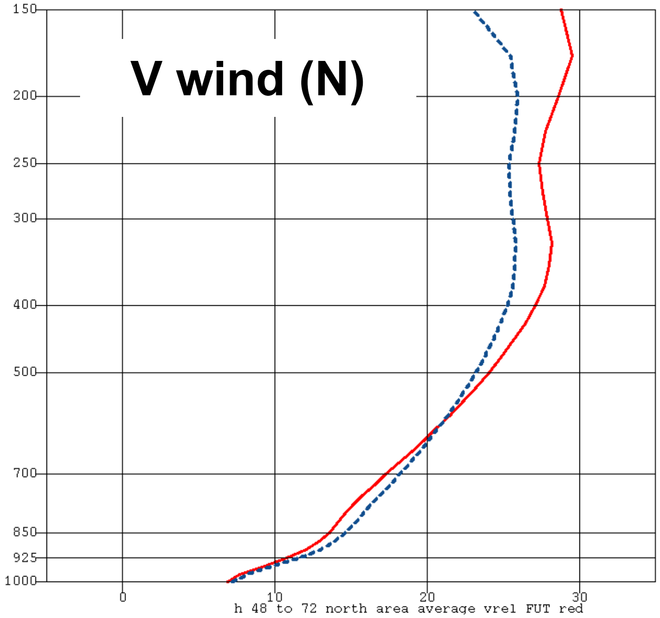


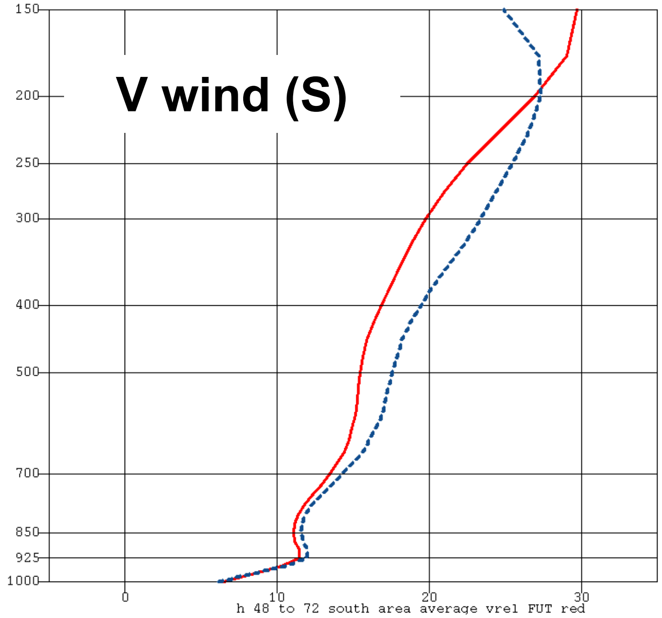
Spatial & Temporal Average Comparison

V-wind component slightly stronger aloft (N), slightly weaker near surface in north

In southern region, V-wind component generally weaker in future simulation

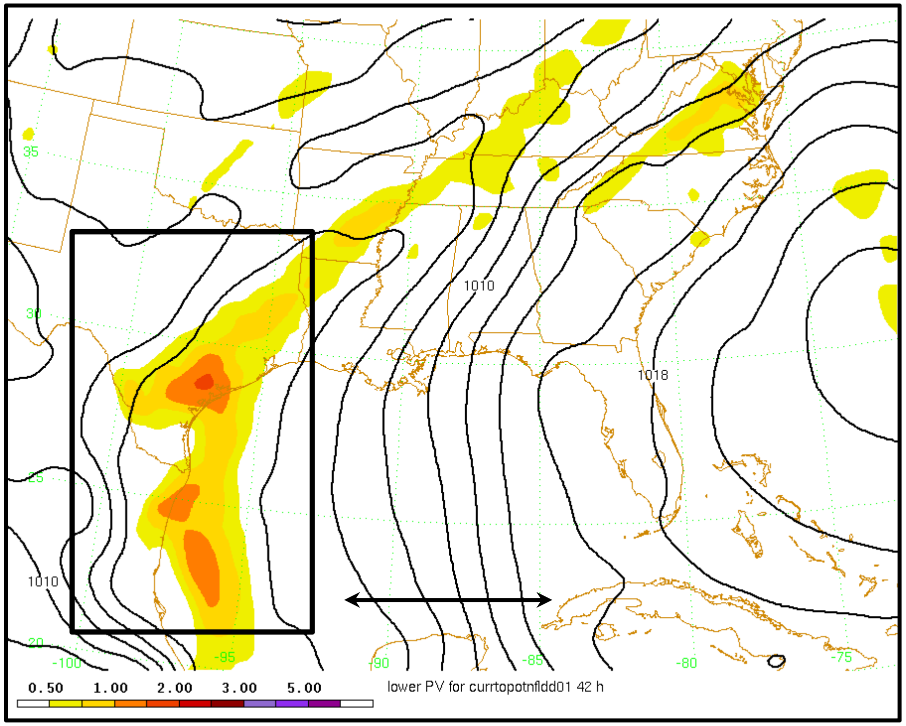
Little evidence for stronger LLJ in future for this case…. Why?



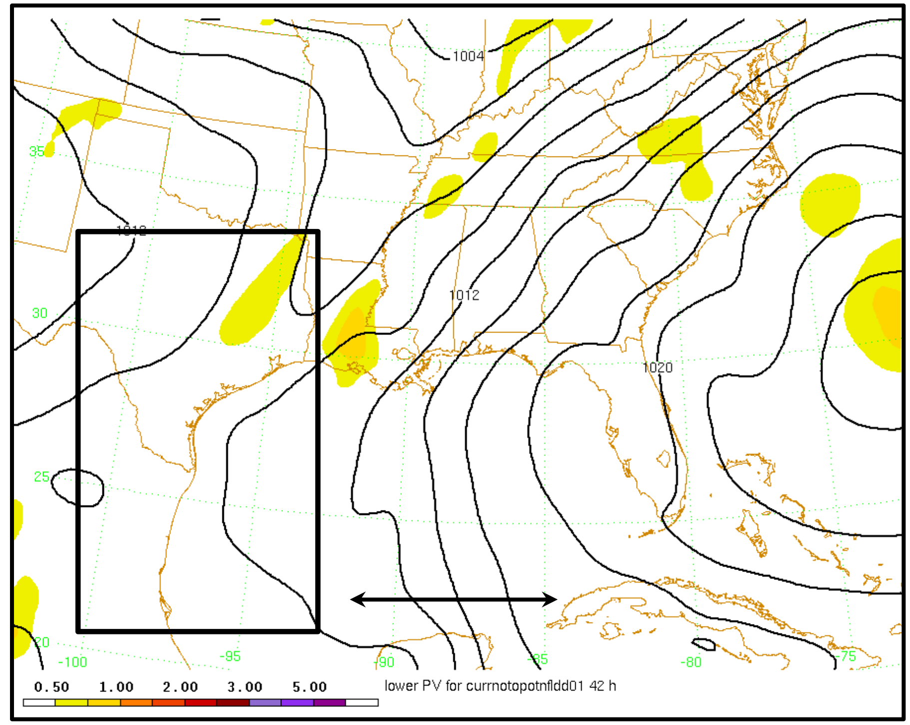


800-900 mb PV (shaded) SLP (contours)

Control D01



***No Terrain** D01*

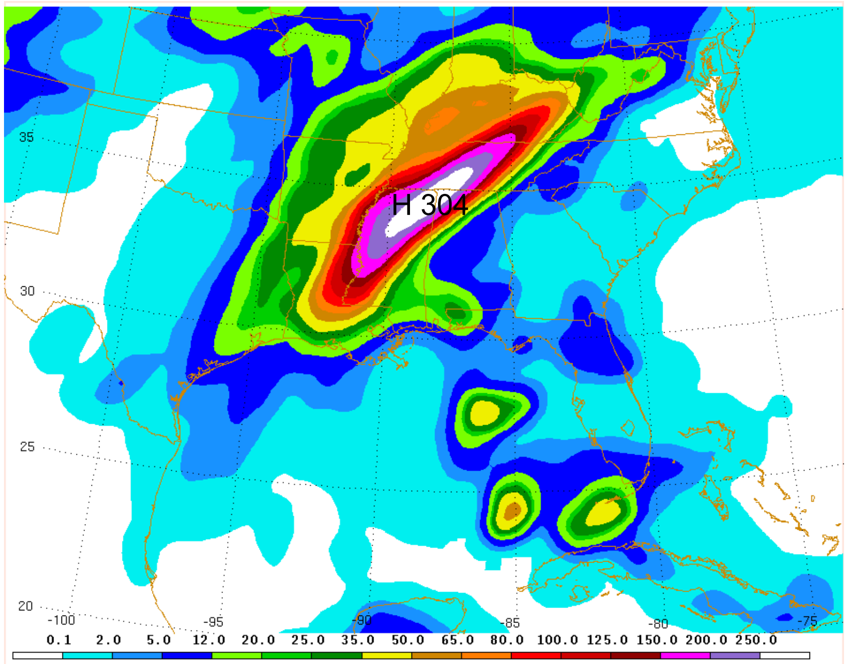


Removing terrain results in higher pressure in western Gulf, weaker LLJ and southerly flow

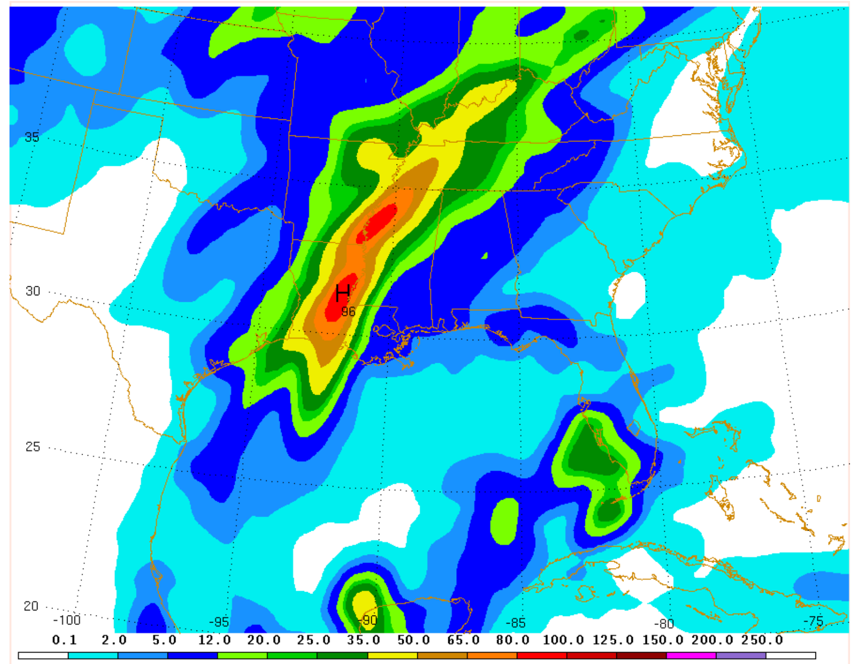
Suggests orographic effects, lee trough more important than condensational heating for southern portion of LLJ

Precipitation, with/without terrain (coarse domain)

Control D01



***No Terrain** D01*



Much heavier precipitation in flood zone in control relative to no-terrain simulation (304 mm versus 96 mm for Domain 1)

Lee trough, Mexican terrain critical during this event, but no climate change for this aspect

Summary: Flooding Case

Future A2 simulations:

- Shift in character of precipitation towards higher rain rates
- Precipitation increase exceeds vapor increase
- Increases in ascent, vertical & horizontal $H_2O_{(v)}$ transport

No systematic strengthening of LLJ despite heating increase:

- Topographic role in LLJ enhancement (western Gulf) less affected by climate change than latent-heat driven LLJ
- Larger CAPE, stronger upward vertical motion, low stability- lessen dynamical response of LLJ (also limited stratiform precipitation)

Future work: Examine cases with condensation-driven LLJ; extend analysis of this case (terrain, system-relative budget)

See: Lackmann, G. M., 2013: The south-central US flood of May 2010: Present and future. *J. Climate*, **26**, 4688–4709.

Summary: Method

Conservative “PGW” approach:

- Repeat past analyzed synoptic patterns, apply GCM ensemble mean thermodynamic changes
- Guarantees “realistic” synoptic pattern at operational resolution
- Allows “apples to apples” comparison of specific events
- Adding GCM ensemble mean may underestimate future extremes
- Limited in ability to address synoptic pattern changes

Significant changes result from thermodynamic signal alone

Useful to understand process changes for specific events / phenomena (context for larger GCM change studies)

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The hurricane research represents a portion of Megan Mallard's PhD dissertation

Jeff Willison, Michelle Cipullo, **Chris Marciano**, **Walt Robinson**, and **Fred Semazzi** all contributed to this work

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