Climate Change & Hurricane Sandy

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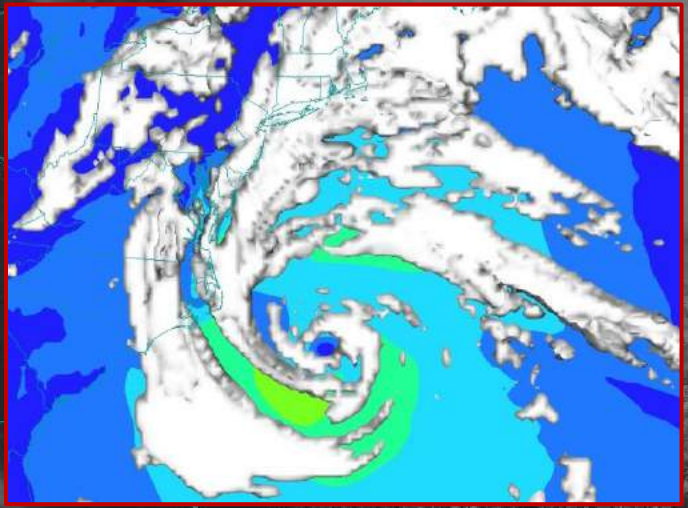
http://www.good.is/posts/so-now-is-probably-a-good-time-to-talk-about-climate-change



30 January 2015

Dept. of Civil & Environmental Engineering

University of Connecticut

Overview, Questions, Goals…

Tropical cyclones (TCs) draw energy from the sea surface; this latent energy is released via condensation in spiraling updrafts

How do TCs change when the environment warms?

Intensity? Frequency? Size? Movement? Impacts?

What, if anything, can we say about how climate change alters (or causes) specific events, like Sandy (2012)?

Two goals: (i) Summarize some previous work on TCs and climate change for context, (ii) Analyze the Sandy event

Methods, then **past work on TC intensity, frequency**, then **Sandy**

Methods: Potential Vorticity (PV)

$$PV = -g\, \varsigma_{a\theta} \frac{\partial \theta}{\partial p}$$

Absolute vorticity

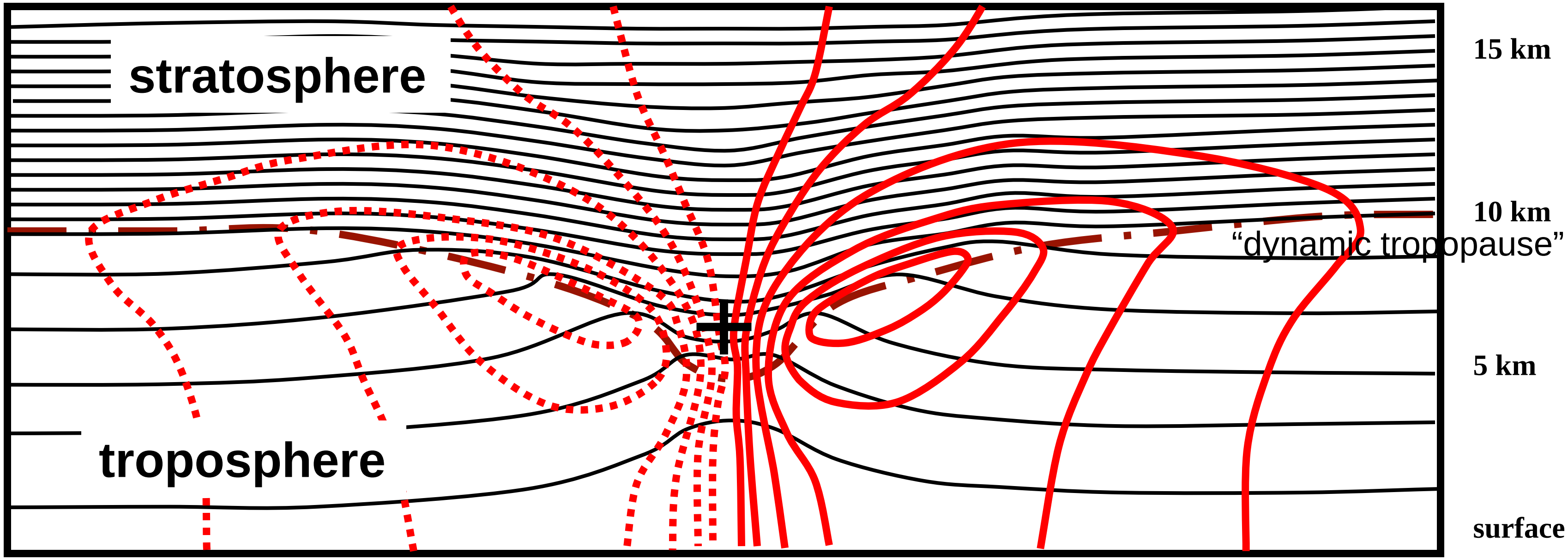
Static stability

- ***Conserved*** for adiabatic, frictionless flow; useful in identifying, quantifying ***diabatic*** processes
- ***Invertible:*** Given boundary conditions, balance relation, can compute piecewise wind, mass fields
- A "marker" of cyclonic (+PV anomaly NH) and anticyclonic (-PV anomaly NH)

Potential Vorticity (PV)

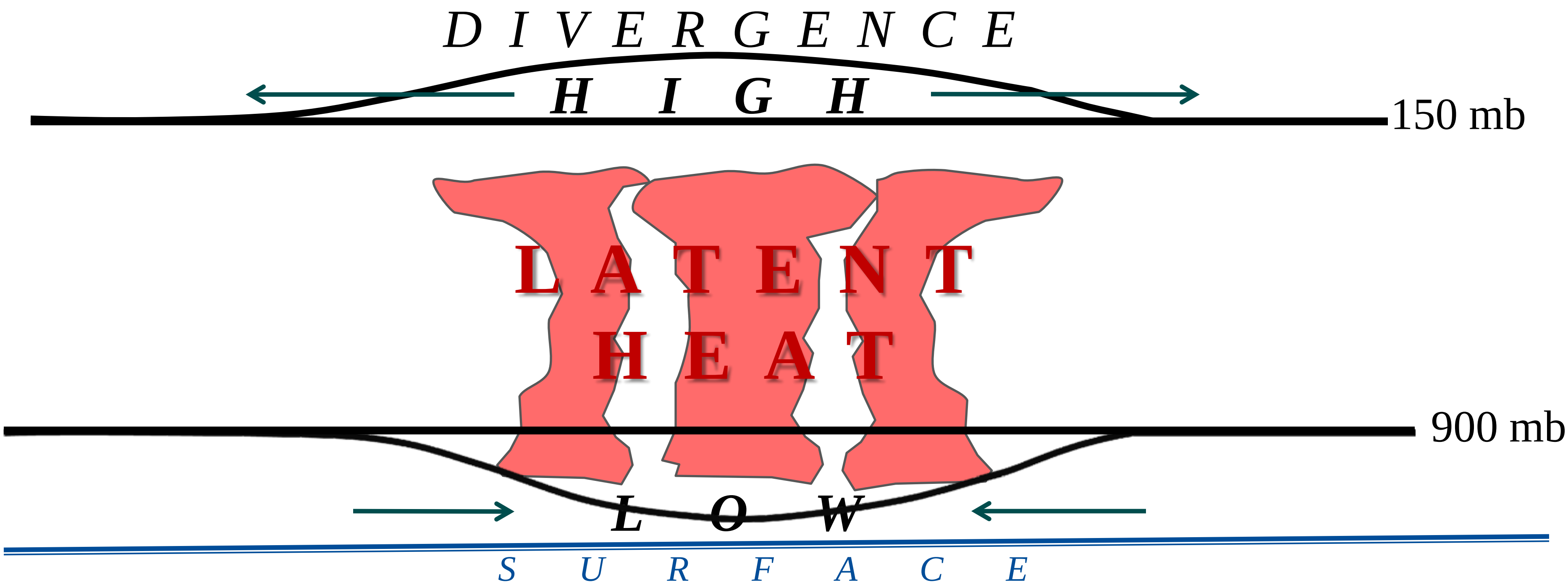
High static stability in stratosphere, large PV there

Regions of lower tropopause = cyclonic PV anomalies



Given PV distribution & boundary conditions, can "invert" to obtain associated wind, temperature, pressure fields

Heating & Pressure Changes

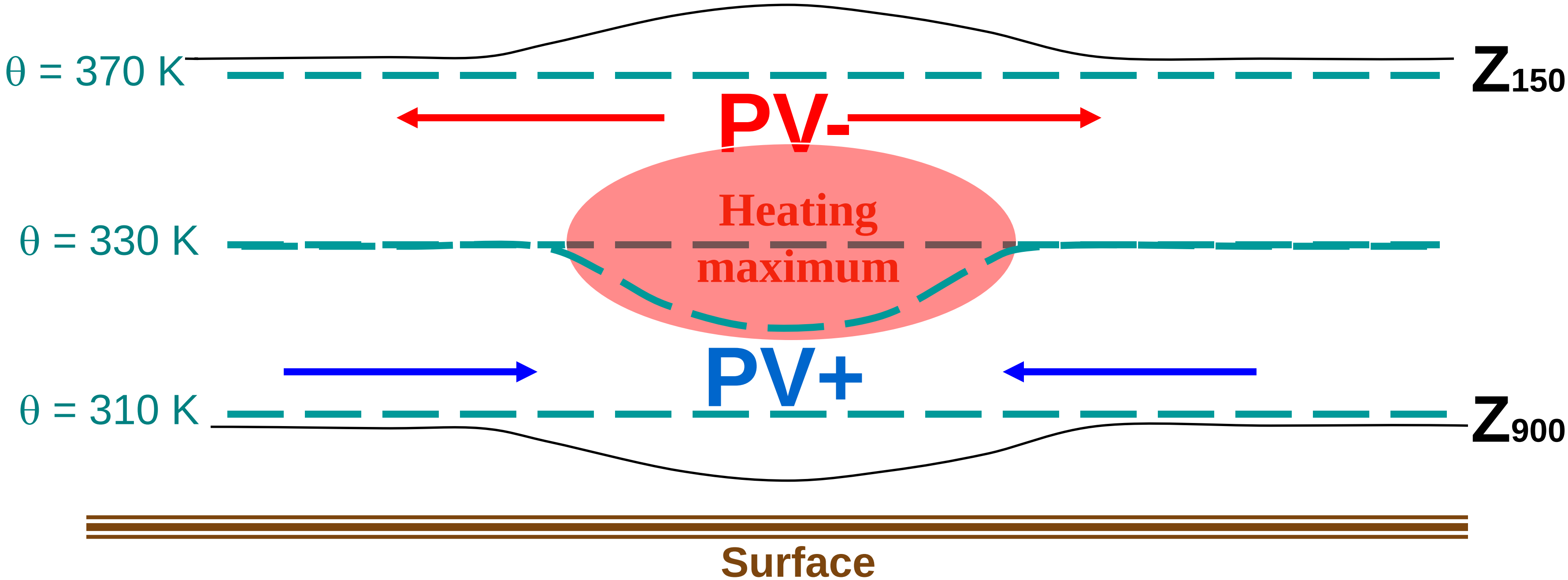


Divergence, anticyclonic tendency above heating

Convergence, cyclonic tendency below heating

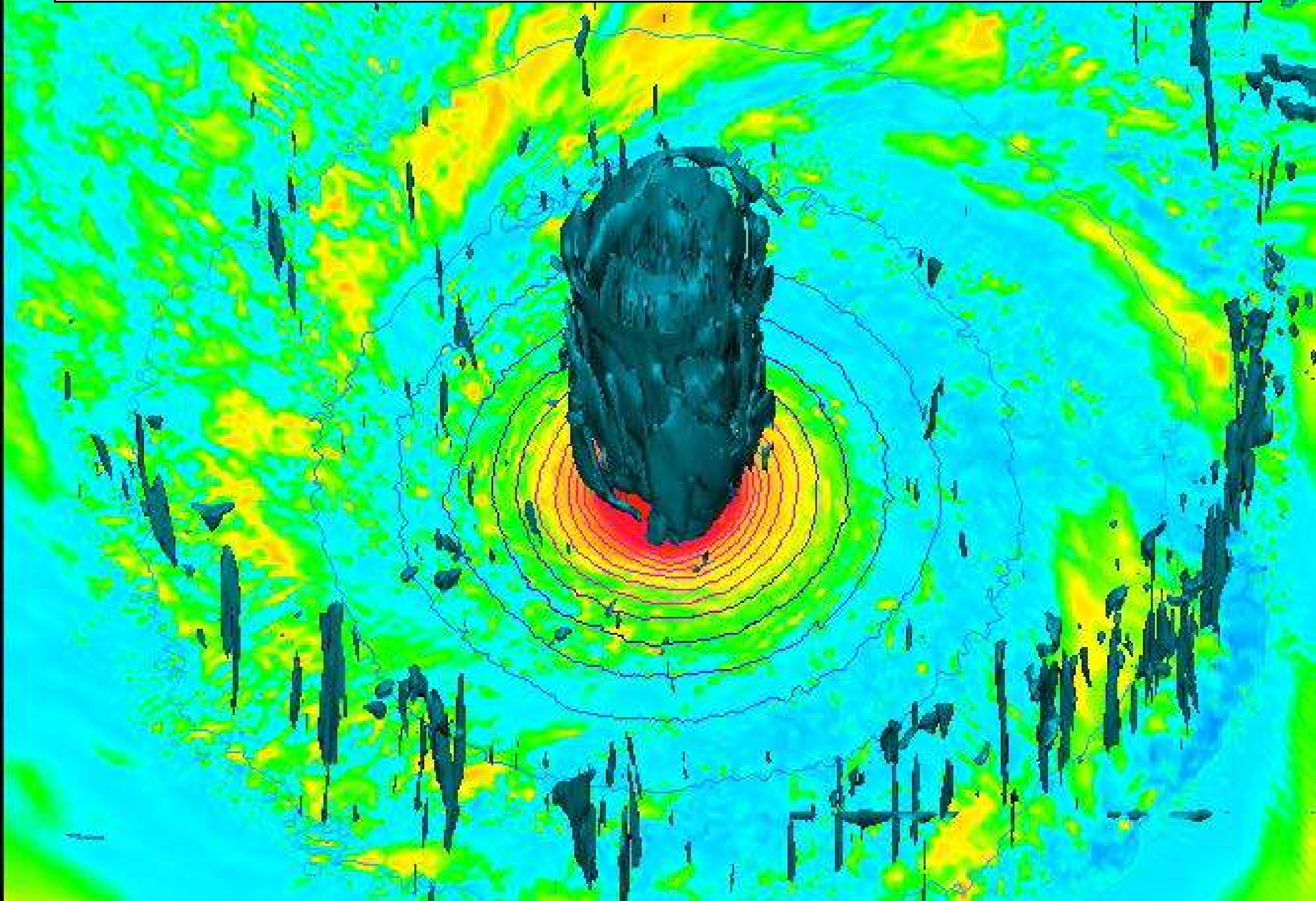
Heating & PV Non-conservation

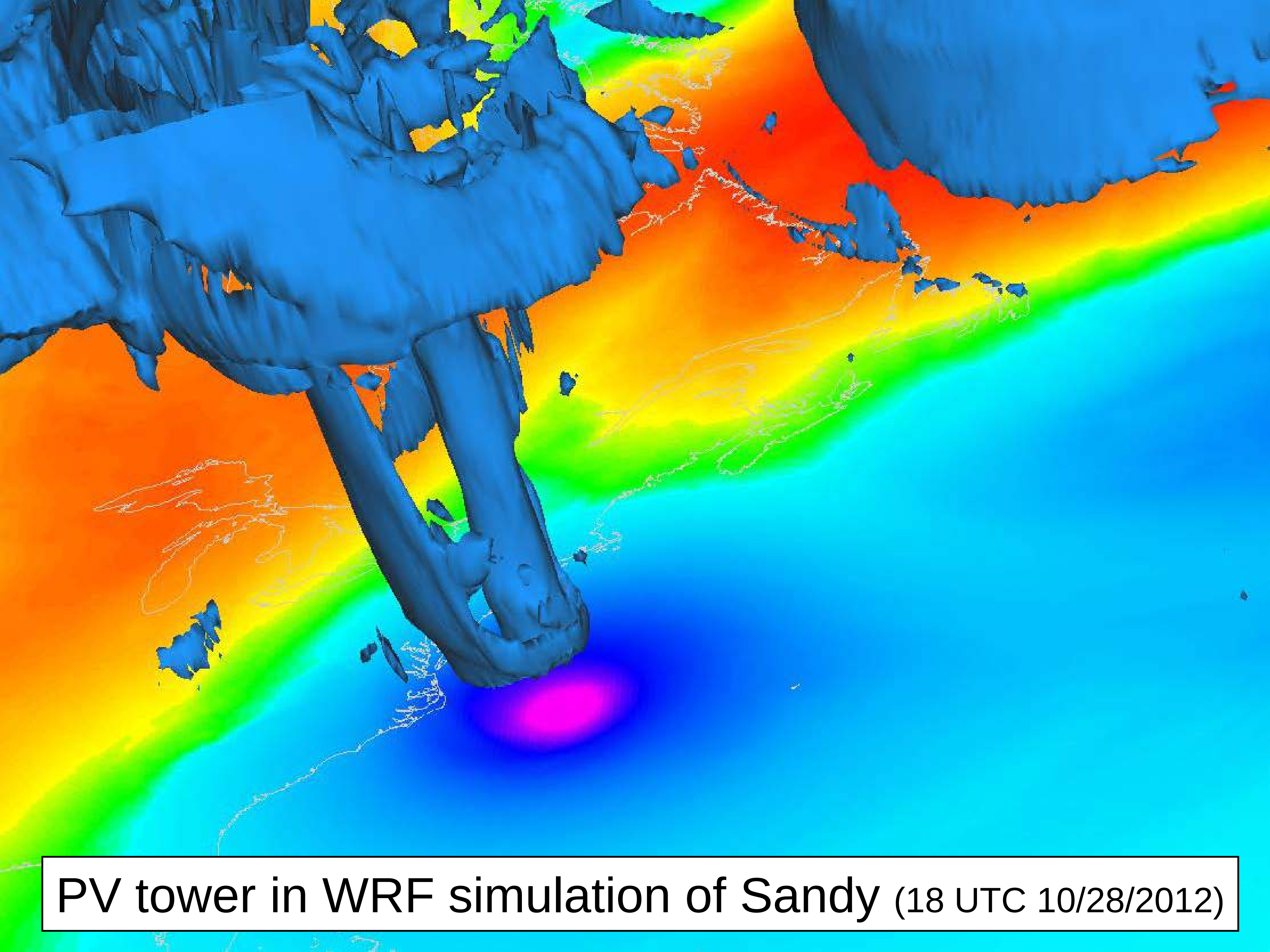
- Isentropes displaced downward near heating maximum
  - Stability increases (decreases) below (above) level of max heating
  - Convergence beneath, divergence above heating maximum: vorticity changes same sign as stability changes: PV change



Slide by Brennan and Lackmann

PV tower in idealized tropical cyclone simulation





PV tower in WRF simulation of Sandy (18 UTC 10/28/2012)

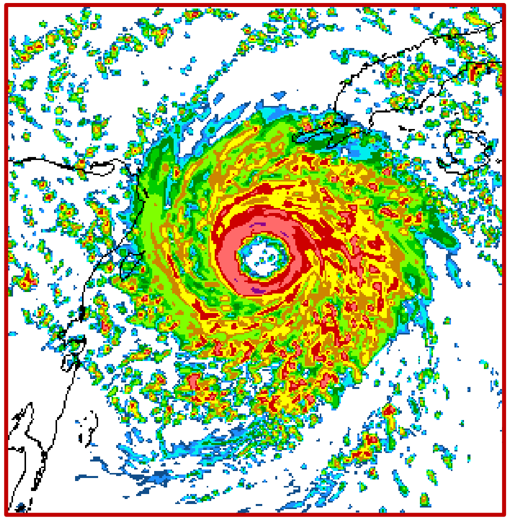
Methods

Numerical models are useful tools with which to test hypotheses…

Weather Research & Forecasting (WRF) model:

- Proven reliable in numerous real-data case studies and forecasting experiments – highly tested

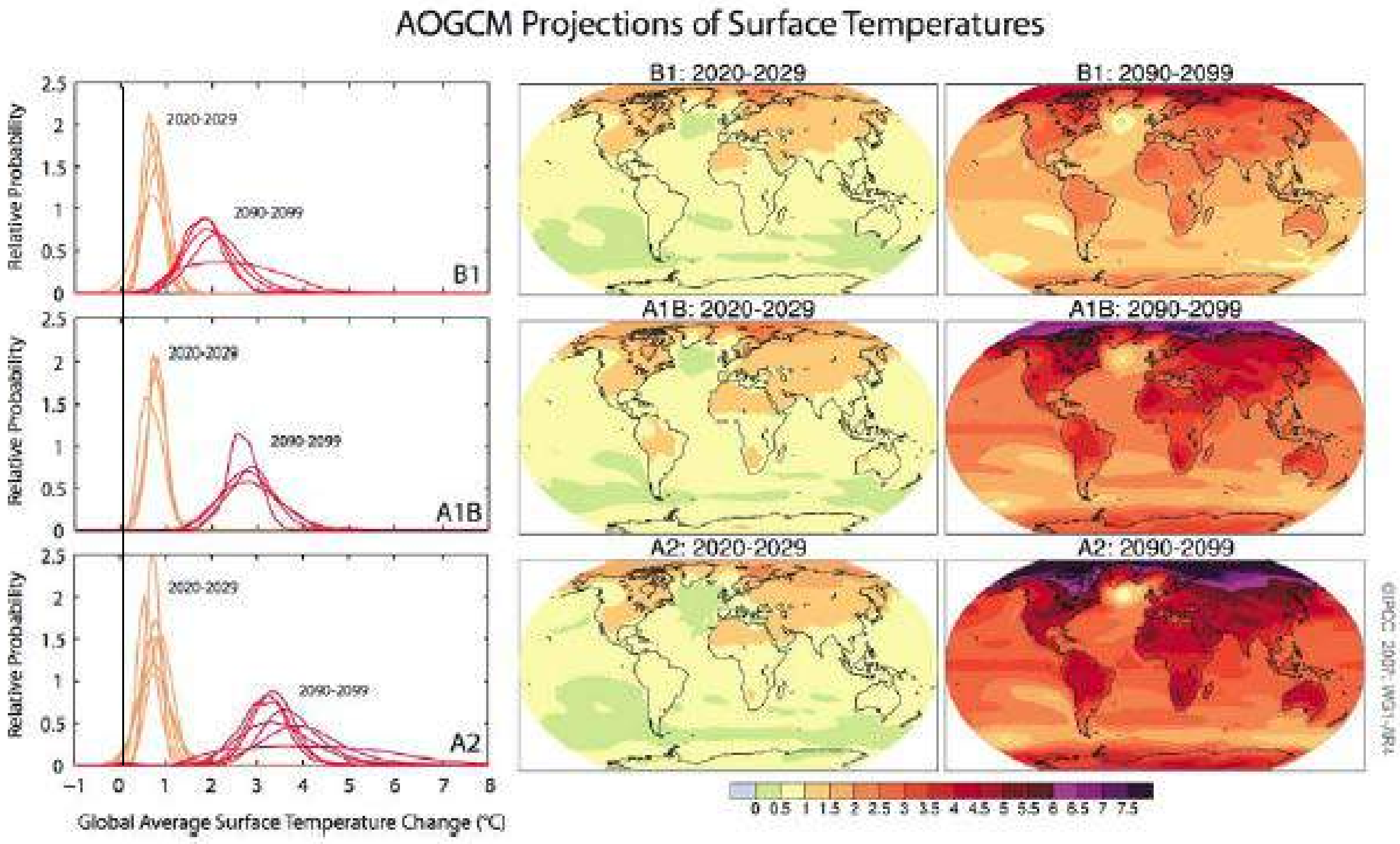
Strategy: For idealized or real-case events, run WRF control + experiments with modified thermodynamic environments



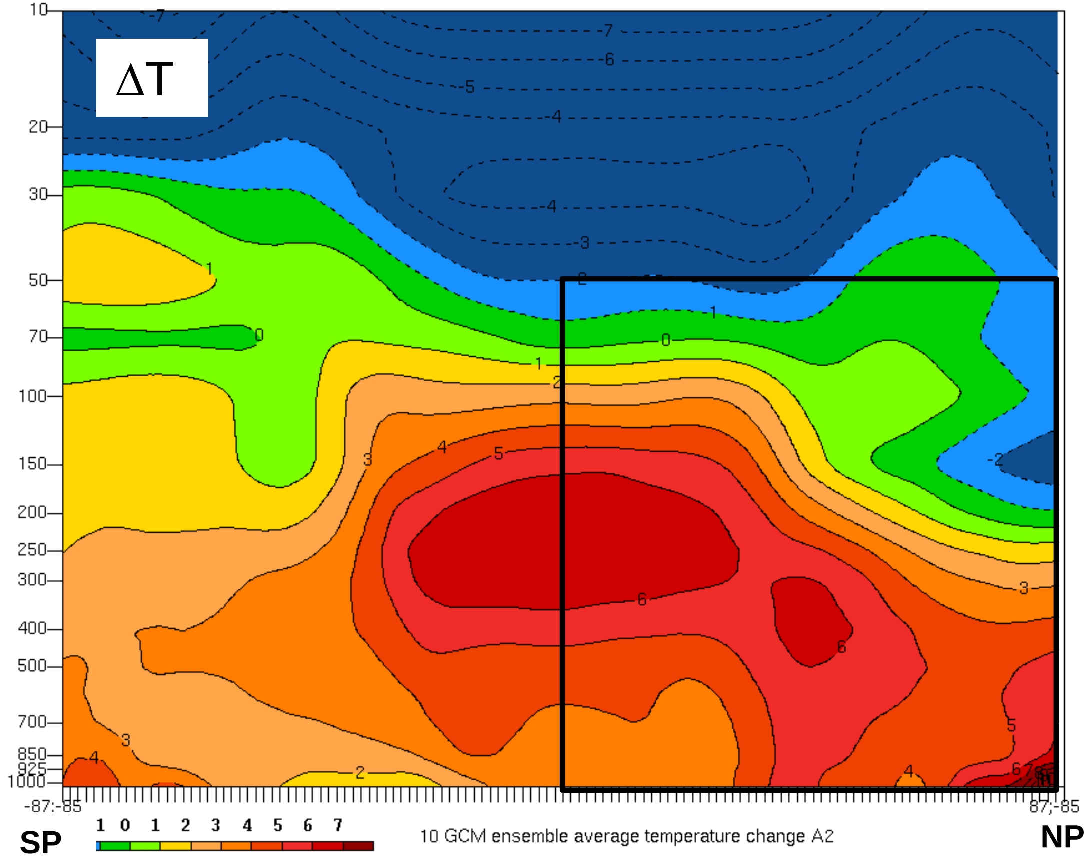
WRF simulated reflectivity for Ivan (2004), 2-km grid length

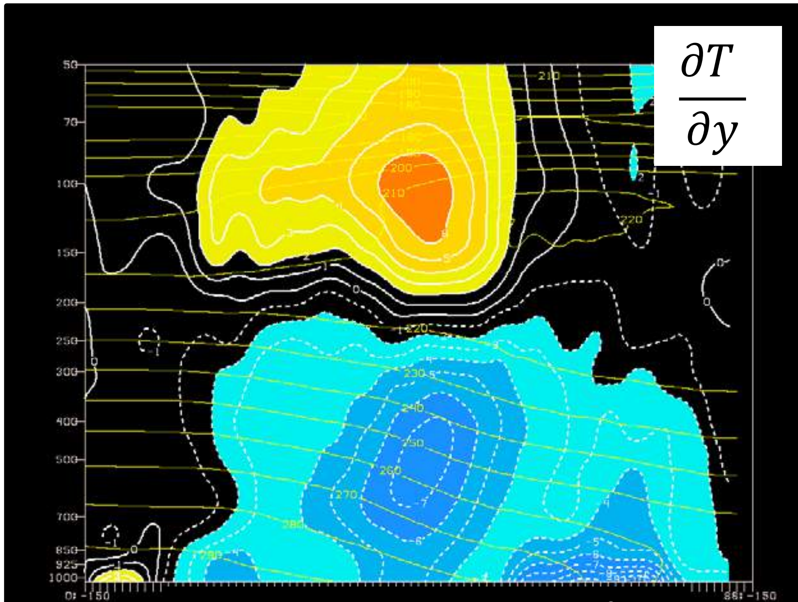
Climate Change Projections

Intergovernmental Panel on Climate Change (IPCC) Assessments: Emission scenarios & Representative Concentration Pathways

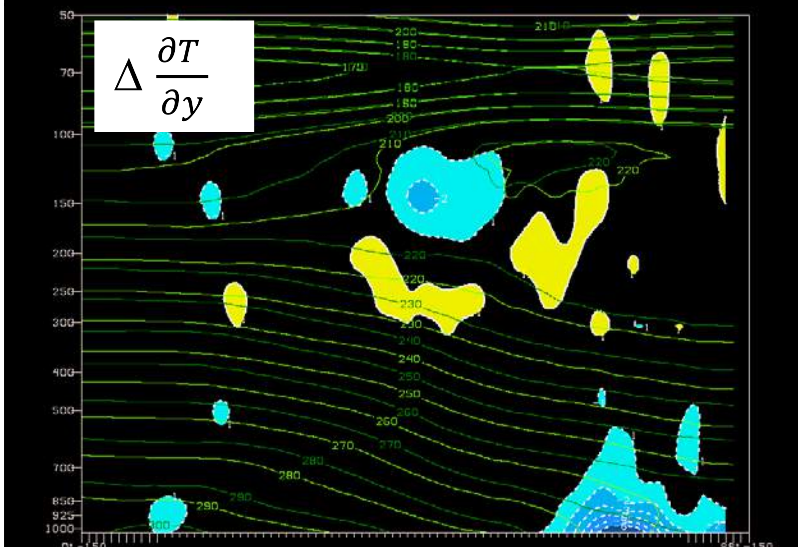


GCM-subset Temp. Change, 2090s – 1990s (October)





1990s October average $\frac{\partial T}{\partial y}$



October average $\Delta \frac{\partial T}{\partial y}$

Shallow weakening of $\frac{\partial T}{\partial y}$ at high NH latitudes

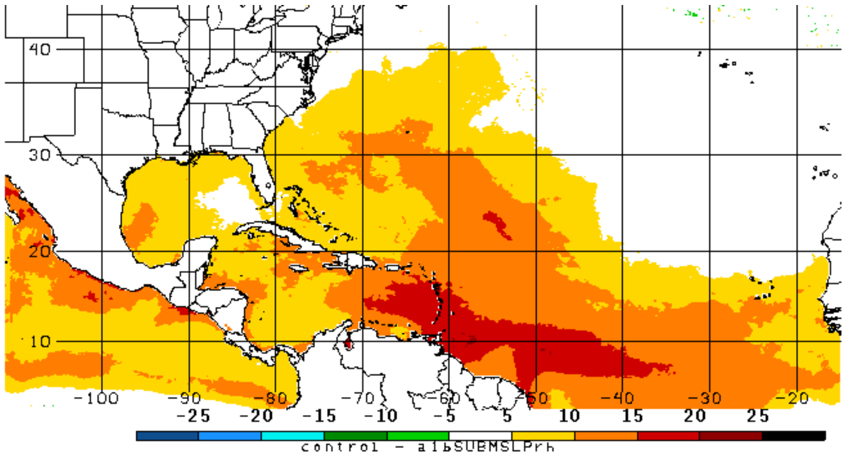
Increased $\frac{\partial T}{\partial y}$ 30-45°N between 200-300 mb

Implications for jet stream changes

Climate Warming and TCs

Favorable

- Increased SST, maximum potential intensity (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

TC Intensity & Climate Change

- Idealized model experiments: Jordan tropical sounding, initial vortex, run to quasi-steady intensity
  - Constant SST, no shear environment

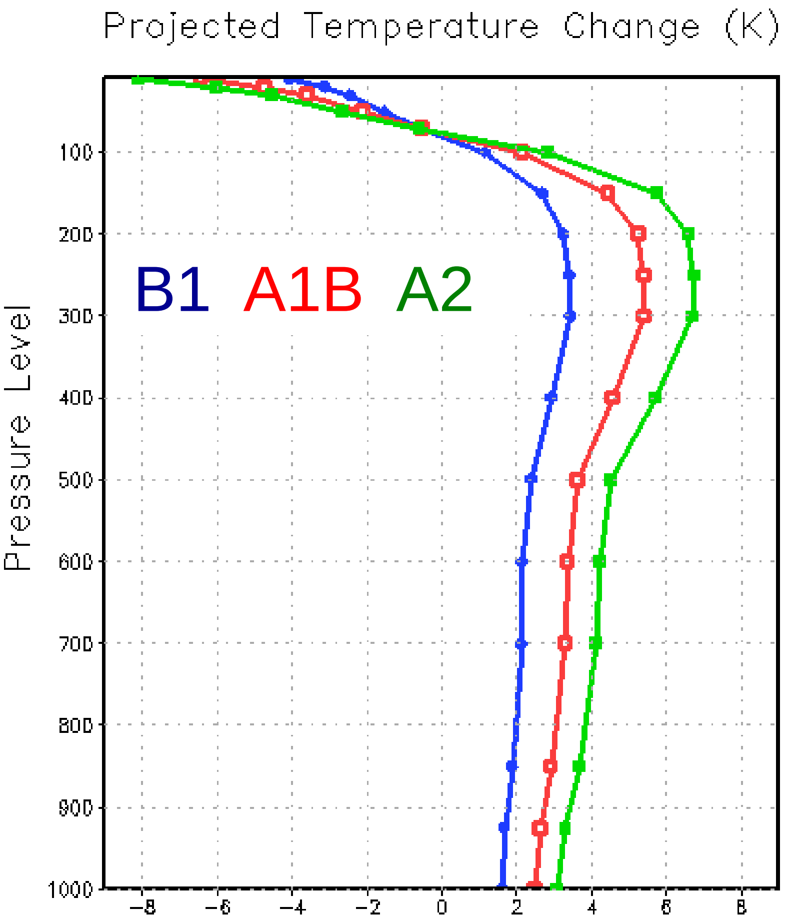
- Compare equilibrium strength using *analyzed current environment* versus *future projections from GCM ensemble*

  Examine:
  - **TC Precipitation**
  - **Intensity**
  - **Frequency**

- See Hill and Lackmann (2011), *J. Climate* for additional details

Thermodynamic Changes

- 20-member IPCC AR4 GCM ensemble
- Difference (2090s – 1990s) in 10-yr spatial Sept. T avg. for tropical N. Atlantic
- Apply to initial, boundary conditions, re-run WRF



- Moisture: Constant relative humidity (RH), calculate mixing ratio at modified temperature

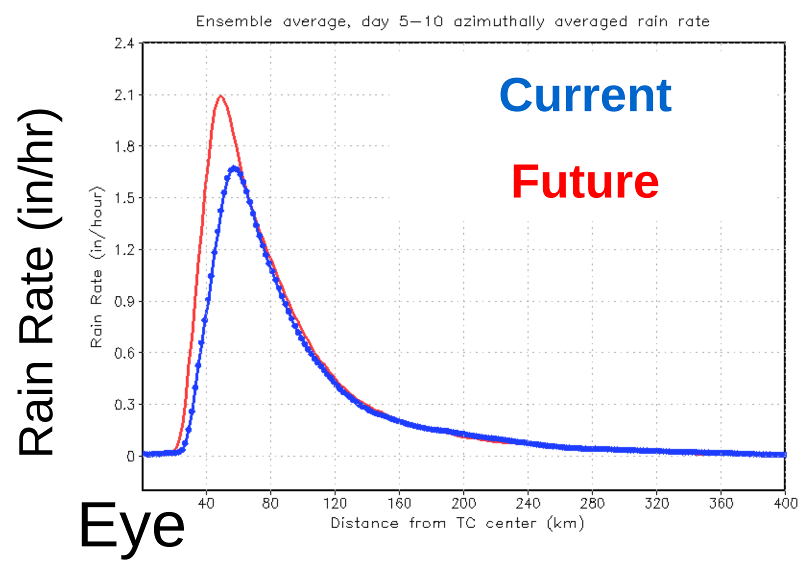
TC Precipitation & Climate Change

Simulation name	Min SLP (hPa)	Increase in SLP deficit (%)	Precipitation (R < 250 km)		MPI change (% relative to control)
Ctrl 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%**

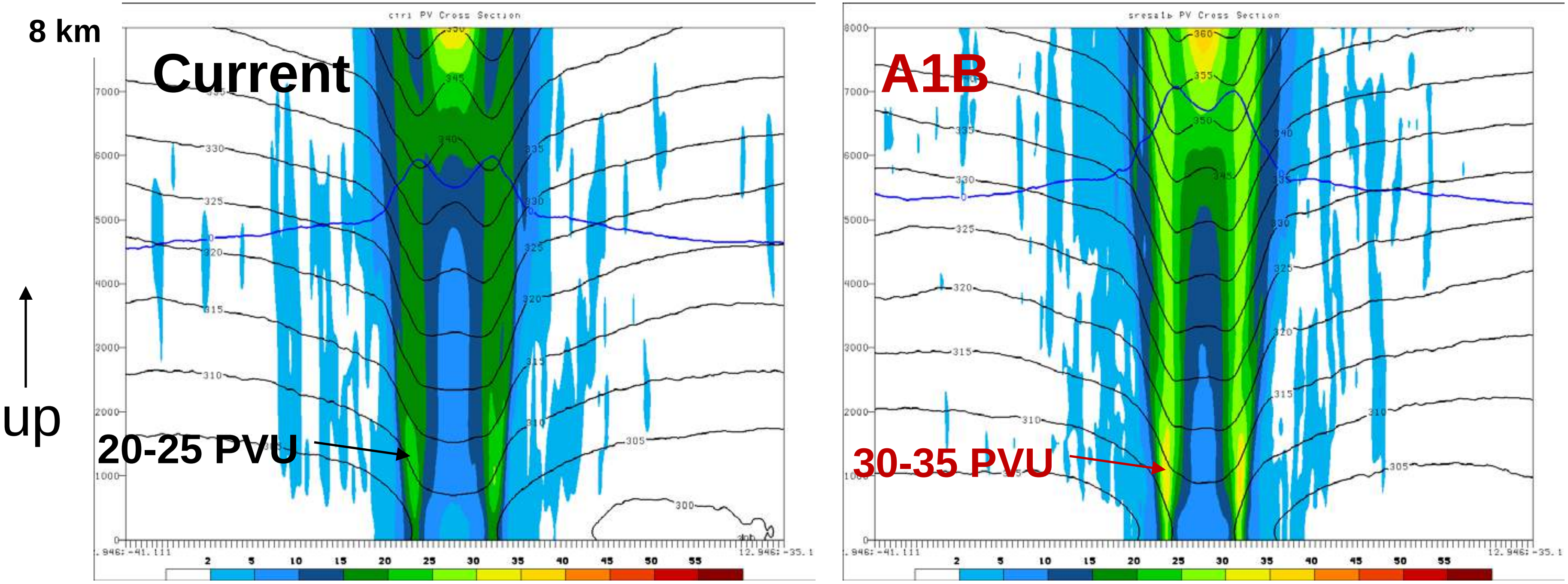
Rainfall increase: Tied to vapor more than updraft, in eyewall



TC Intensity & Climate Change

Heavier precipitation for future TCs:

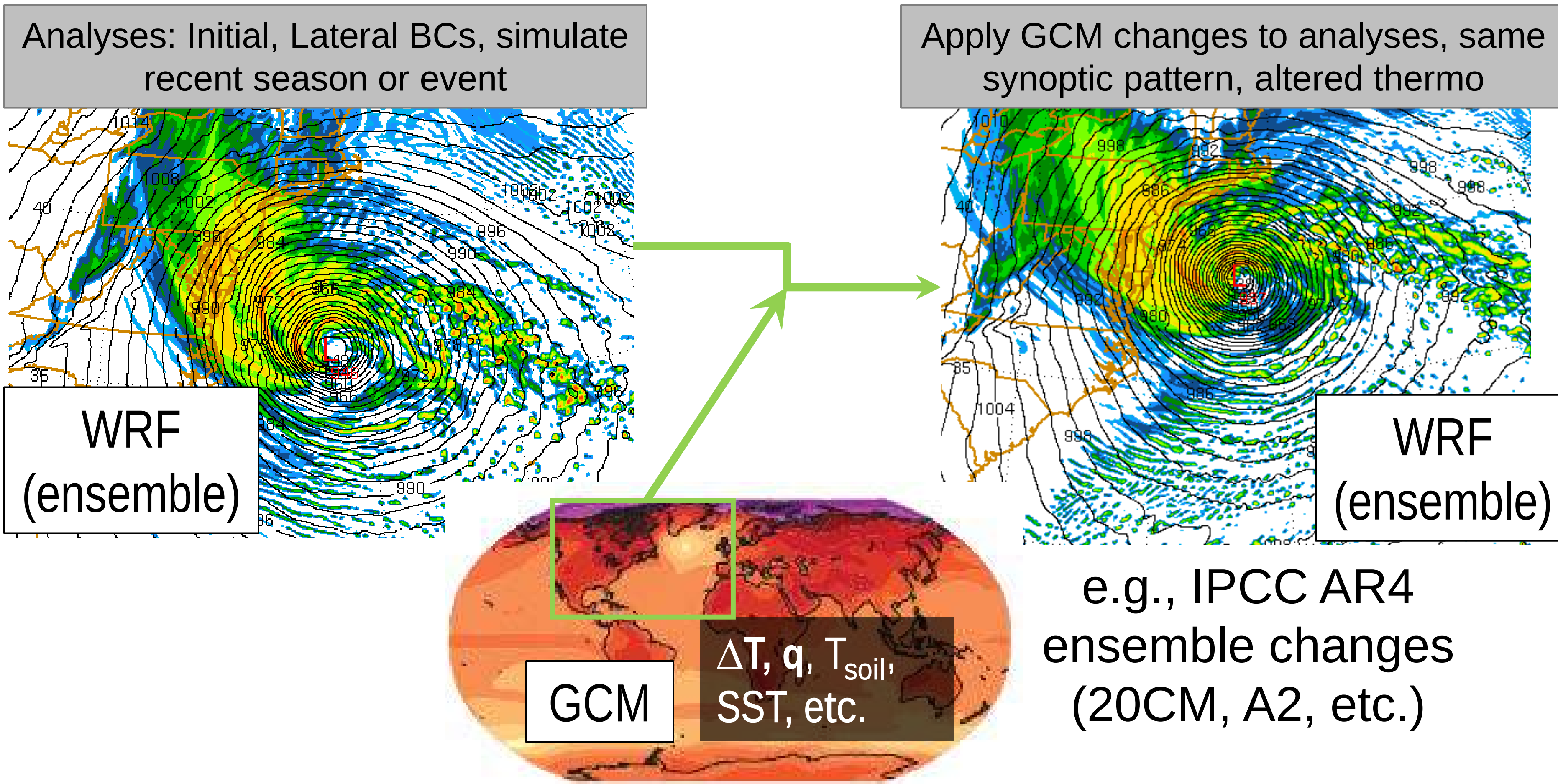
- Strength of steady-state PV tower related to precipitation rate
- Reduced efficiency from warming outflow: Partial compensation



Time, azimuthal average PV cross sections

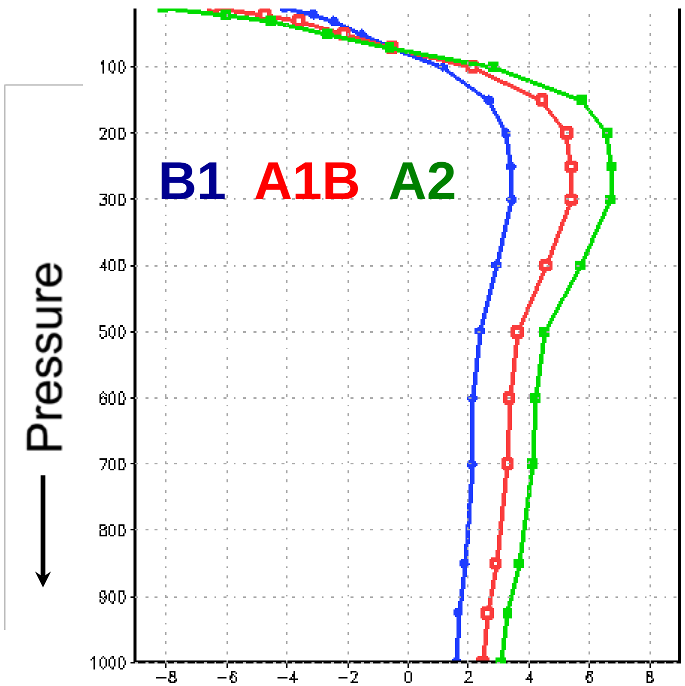
Pseudo Global Warming (PGW) Method

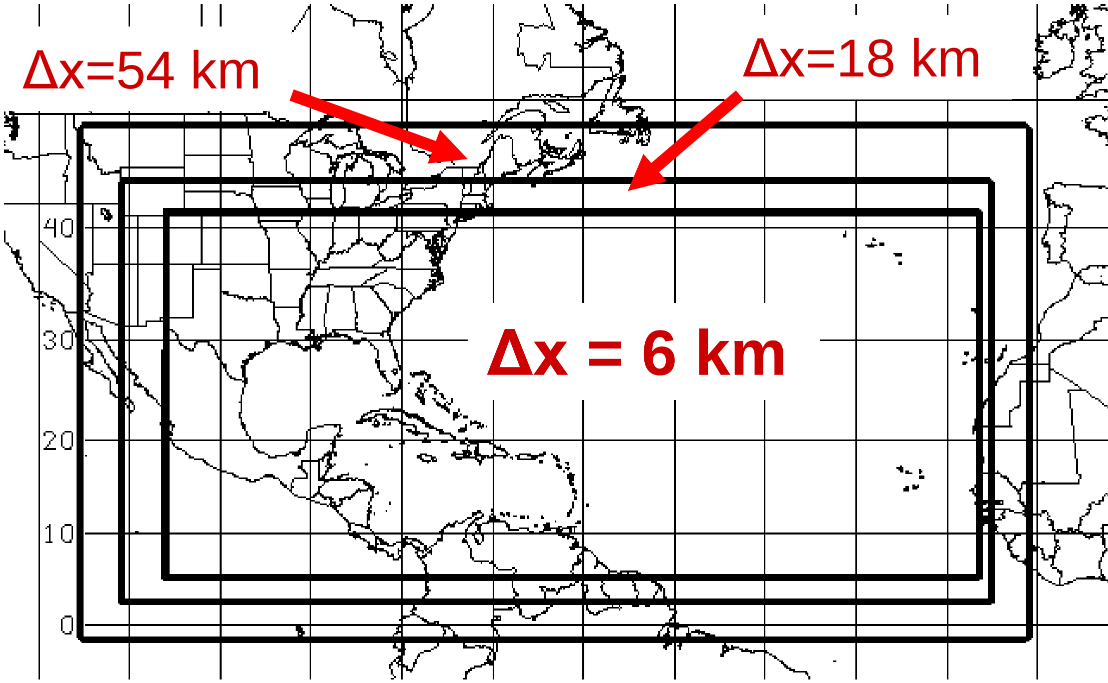
- Apply GCM-derived thermodynamic change to current analyses; uniform (tropics) or spatially varying (higher latitude) (e.g., Kawase et al. 2009)
- Replicate current events & seasons, with "future or past thermodynamics"



Tropical Atlantic Domain, Monthly Simulation

Projected T change, tropical spatial average over subset of domain





Ensemble of GCM projections for change fields; apply to reanalysis IC, LBC

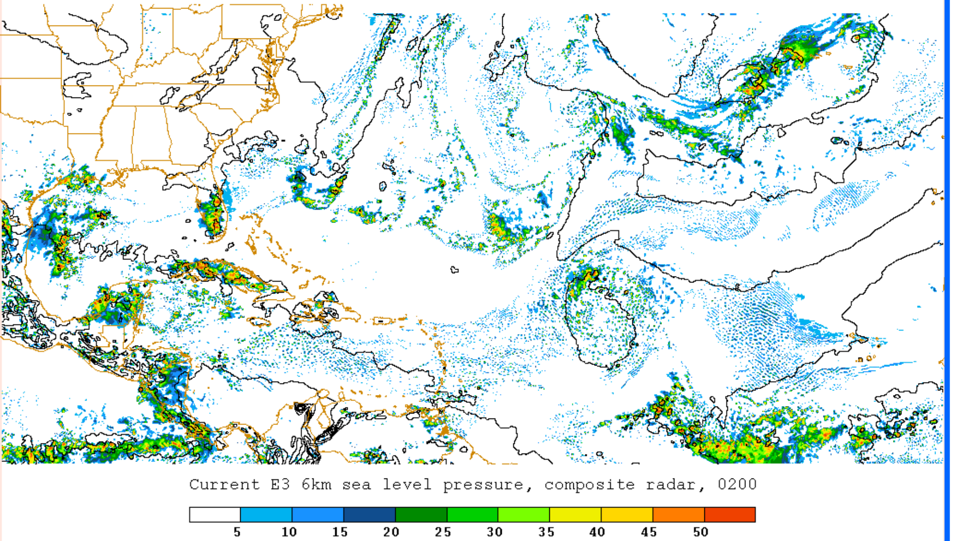
Moisture: Tested both constant RH and GCM-derived changes; similar

Included ocean changes, WRF mixed-layer ocean model

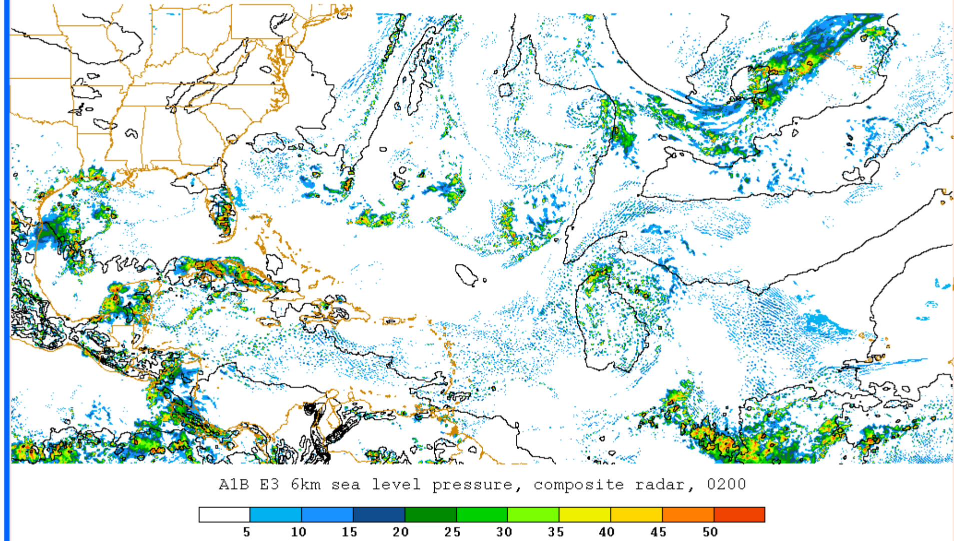
Altered trace gas concentrations in some experiments (> 2 weeks)

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

Recent September



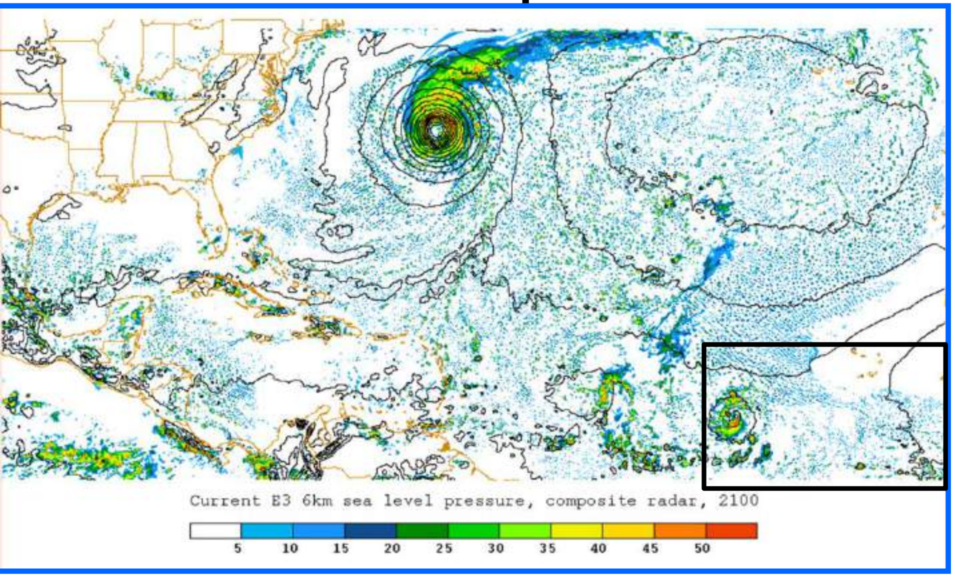
A1B Modified (future)



Future: Reduced TC activity with same pattern

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

Recent September



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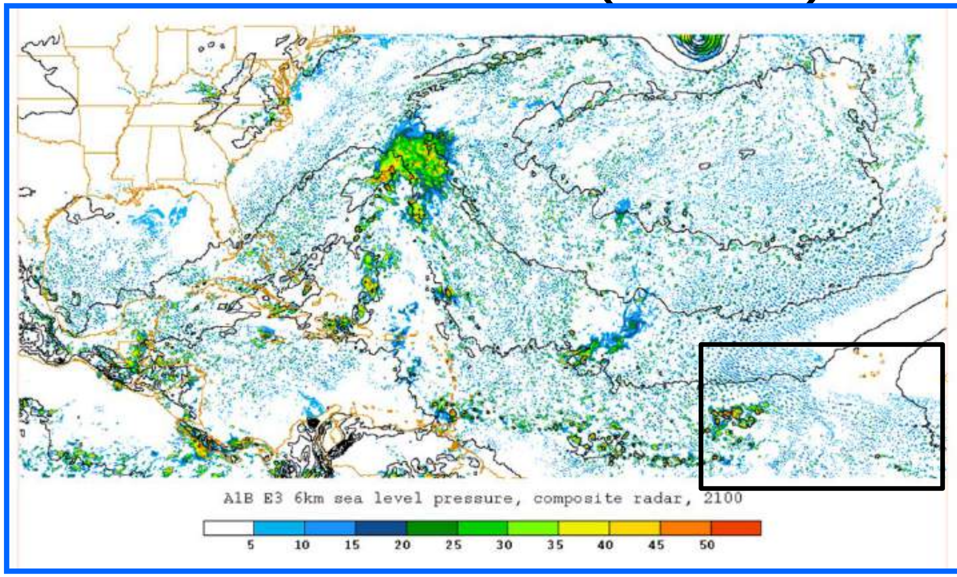


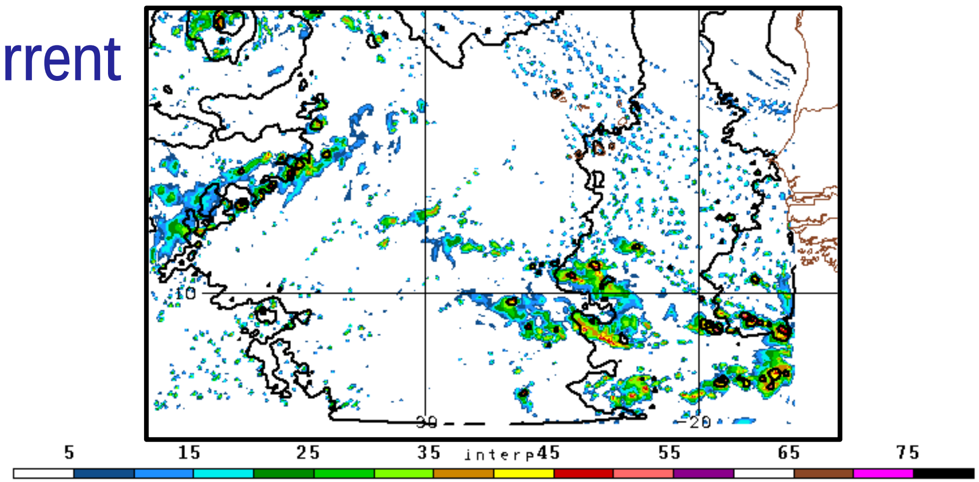
Future: Reduced TC activity with same pattern – Why?

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

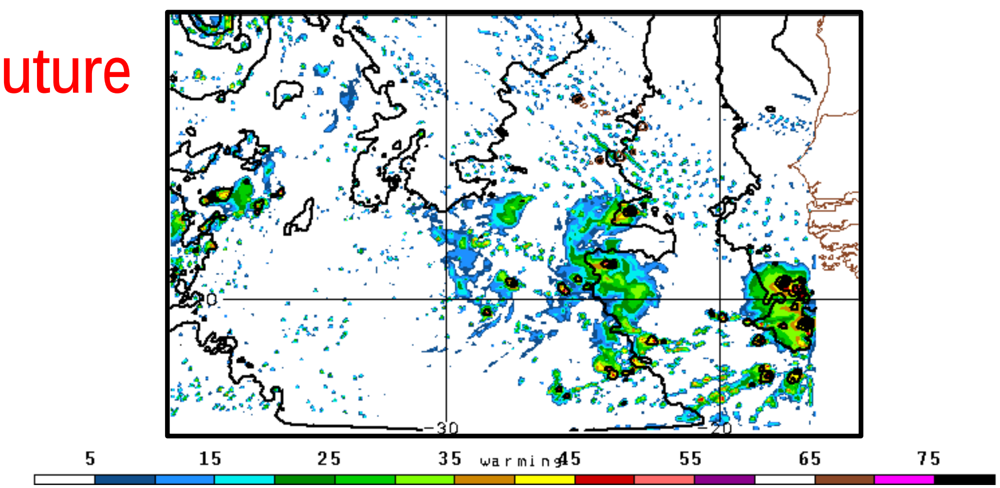
Developing / Non-Developing Event

- Initial disturbance appears as closed low, convection to east, south
- **Current**: convection persists, TC genesis
- **Future**: **convection dissipates**

Current

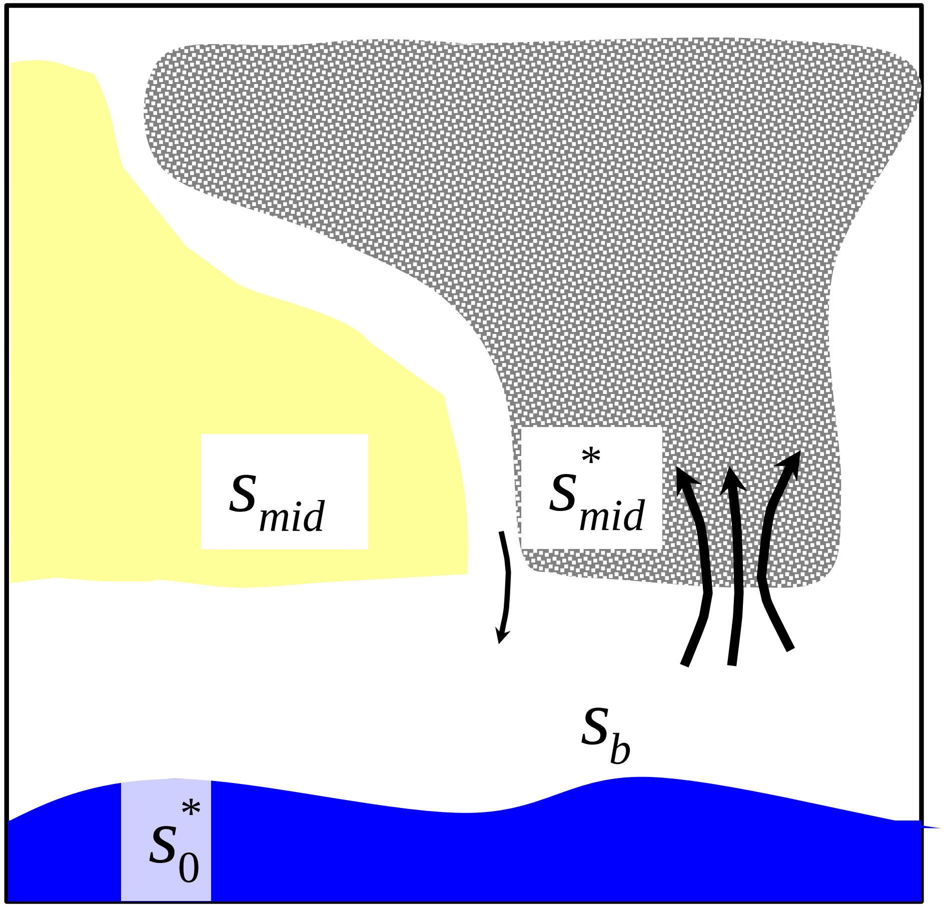


Future



Model simulated radar & sea-level pressure (every 2 hPa) 5-day period in September, 1st ensemble member

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:

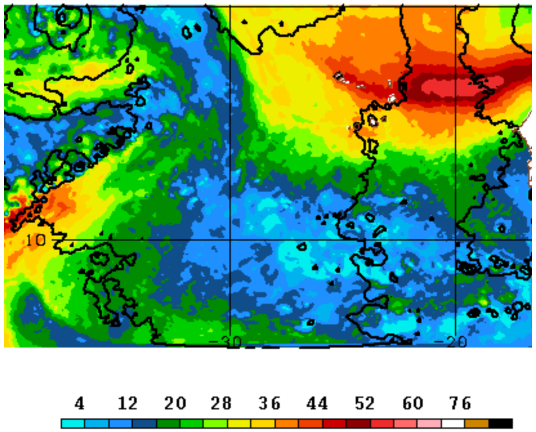
- Larger midlevel saturation deficit: more sub-saturated downdrafts
- Near saturation is a necessary condition for TC genesis
- ***Warming: Delayed TC genesis, reduced TC frequency***

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

See Emanuel 1989, 1995, Emanuel *et al. 2008*, Rappin *et al. 2010; Mallard et al. 2013a,b*

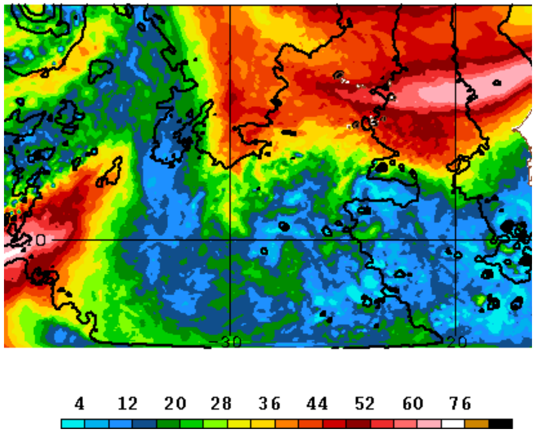
Developing / Non-Developing Event

- Initial disturbance enters marginally favorable humidity environment
- **Current: Convection moistens environment, TC forms (barely)**
- **Future: Requires more moistening to saturate, convection dissipates**



Current

χ_{mid}



Future

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

Summary

- *Intensity*: Despite competing thermodynamic processes, strongest storms strengthen with future warming
  - Heavier precipitation stronger effect than lapse rate stabilization
- *Frequency:* Thermodynamic consequence of warming is increased saturation deficit, greater moistening required
- *Reduction in future TC frequency:*
  - Basin dependence? Atlantic TCs more often "moisture limited"
  - The "weaklings" fail to develop in future simulations with warming
- Hill and Lackmann (2011), Mallard et al. (2013a,b) *J. Climate* for details

Hurricane Sandy

Did Climate Change Cause Hurricane Sandy?

By Mark Fischetti | October 30, 2012 | 89

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Capital Weather Gang

The inside scoop on weather in the D.C. area and beyond

When it comes to climate change and its effect on Superstorm Sandy, it seems many of the loudest voices fall into two camps: 1) the all-in camp: climate change is making the weather more extreme, and Sandy is the poster child for that. We can and should blame climate change for the storm's terrible toll and it's a sign of things to come. 2) the no effect camp: climate change played no role in Superstorm Sandy and there's no cause for concern about the future.

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doubt run across a journ
explaining why it's diffic
climate change could be
storms like Sandy. Well
is.

Posted at 11:12 AM ET, 11/15/2012

The whole truth about Superstorm Sandy and climate change

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Experts argue global warming's impact on Sandy's unusual path to N.J.

By Star-Ledger Staff
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on November 12, 2012 at 7:15 AM, updated November 12, 2012 at 9:27 AM

By Amy Ellis Nutt and Stephen Stirling/The Star-Ledger

Polar Amplification & Weather Extremes

Model projections of atmospheric steering of Sandy-like superstorms

Elizabeth A. Barnes[a,b,1], Lorenzo M. Polvani[b,c], and Adam H. Sobel[b,c]

[a]Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523; [b]Division of Ocean and Climate Physics, La Observatory, Palisades, NY 10964; and [c]Department of Applied Physics and Applied Mathematics and Department of Earth and En Columbia University, New York, NY 10027

Edited* by Kerry A. Emanuel, Massachusetts Institute of Technology, Cambridge, MA, and approved August 2, 2013 (received for

Evidence linking Arctic amplification to extreme weather in mid-latitudes

Jennifer A. Francis[1] and Stephen J. Vavrus[2]

Received 17 January 2012; revised 20 February 2012; accepted 21 February 2012; published 17 March 20

GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L06801, doi:10.1029/2012GL051000, 2012

GCM: Decrease in frequency, persistence of easterly flow of type leading to Sandy's track

Future conditions less likely than at present to propel storms westward to coast

Slower eastward Rossby wave propagation due to weakened zonal wind, increased amplitude

This increases weather pattern persistence, perhaps increased probably of extreme weather

Sandy & Climate Change

"Did large-scale thermodynamic change make Sandy worse than it would otherwise have been?"

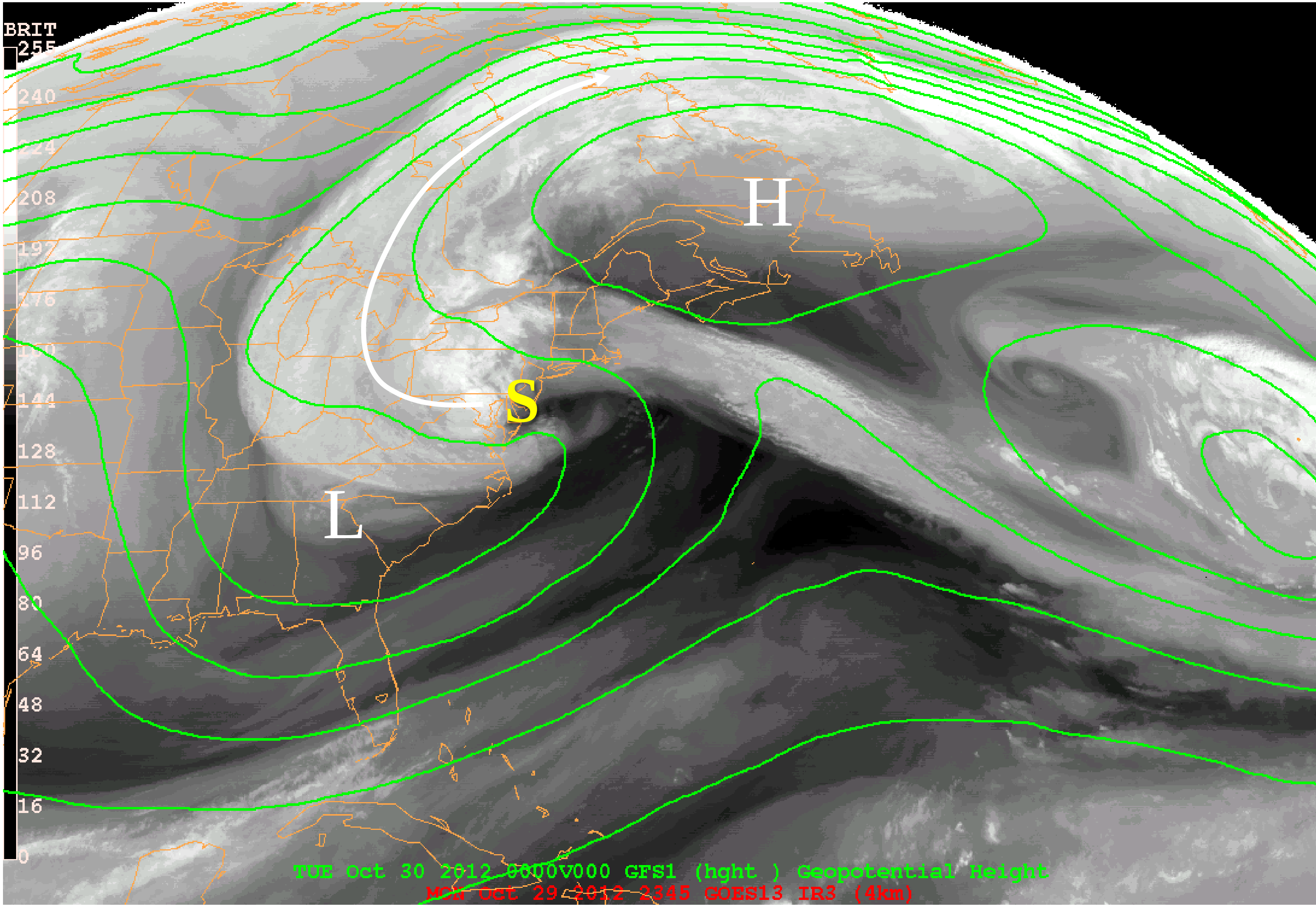
"How and why would a past or future version of Sandy differ from what was observed?"

Focus on changes in track and intensity

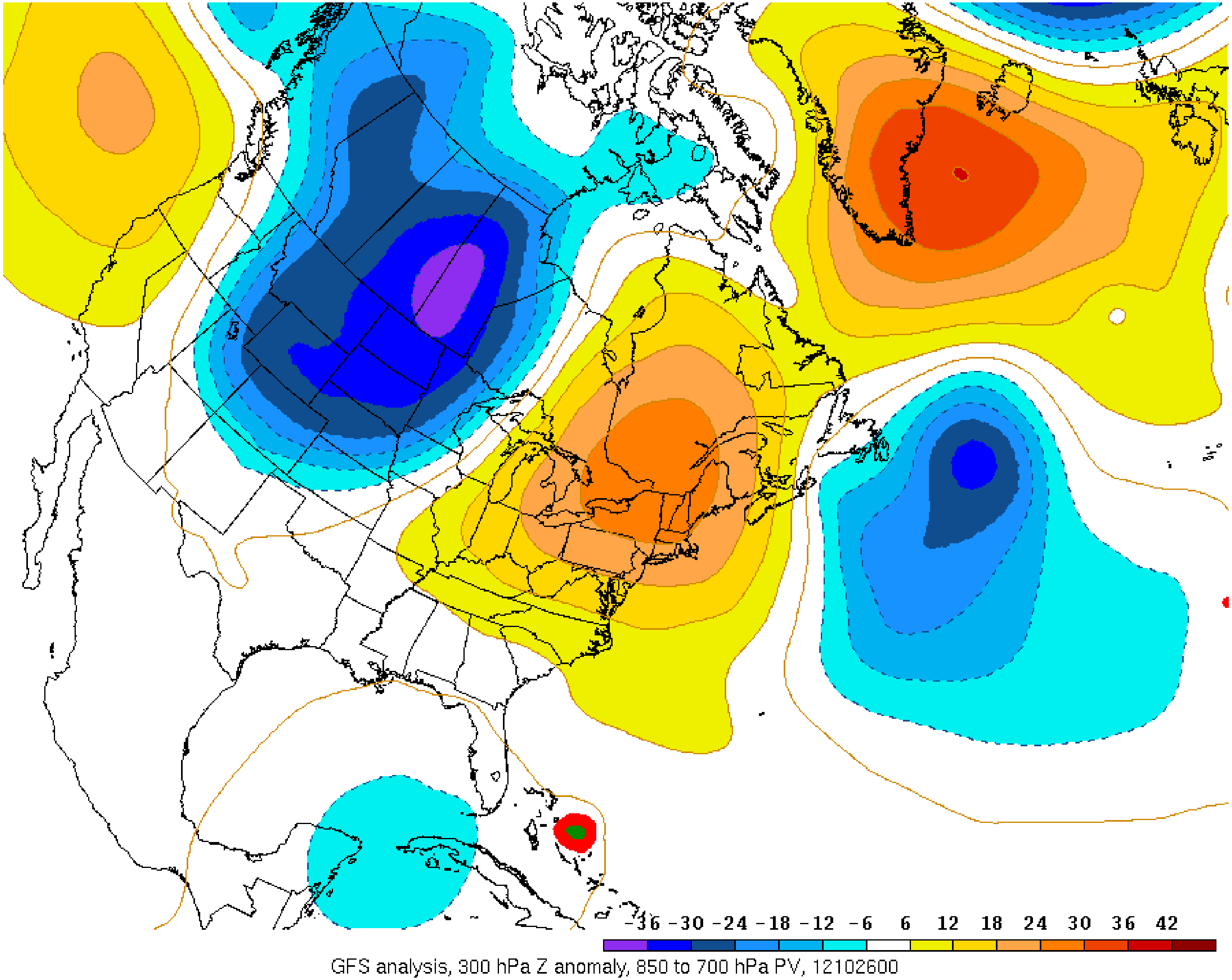
Study does not address frequency of this synoptic type

See Lackmann (2015, BAMS) for details

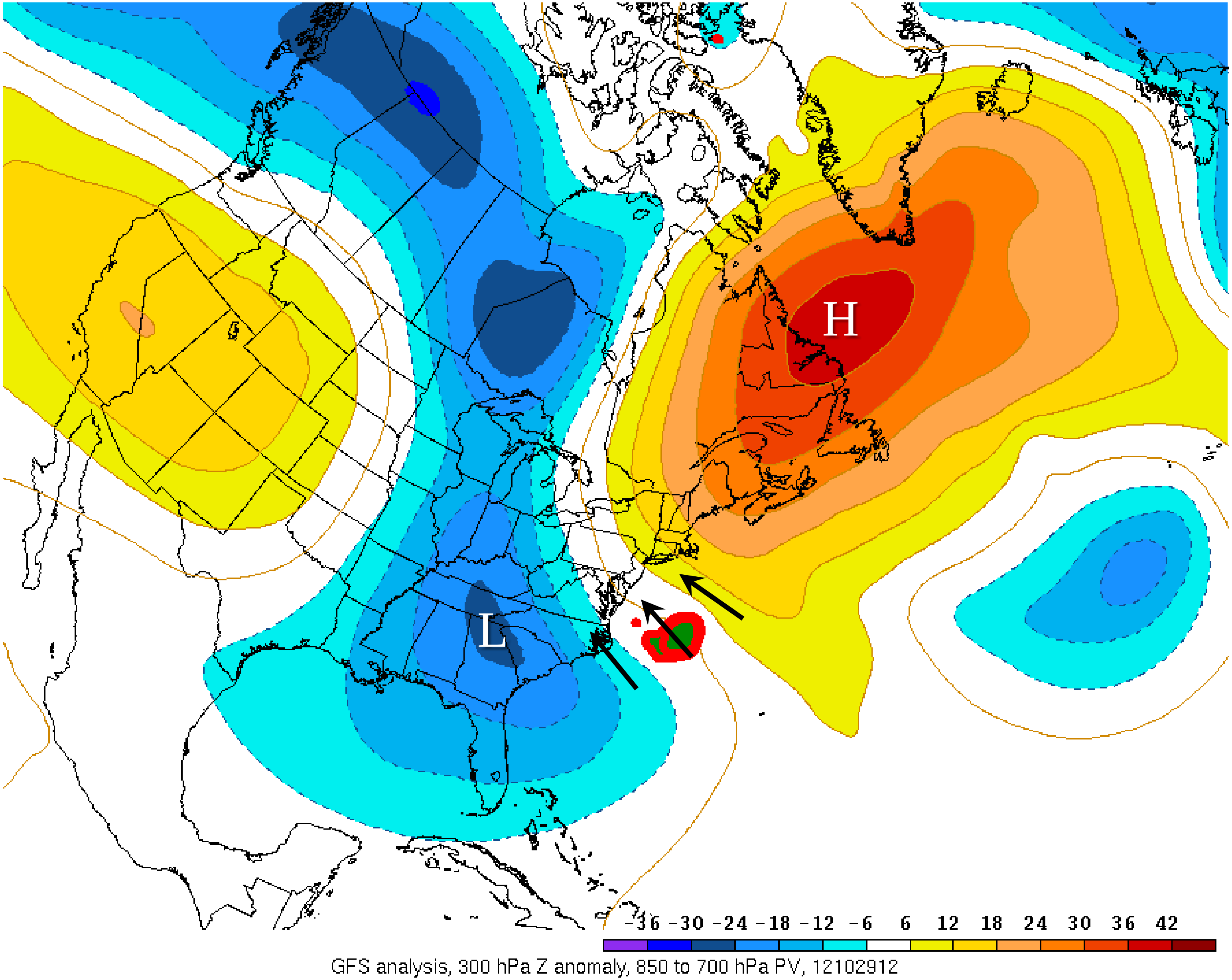
GOES 13 WV, GFS 250 hPa Height Analysis
00 UTC 30 October 2012



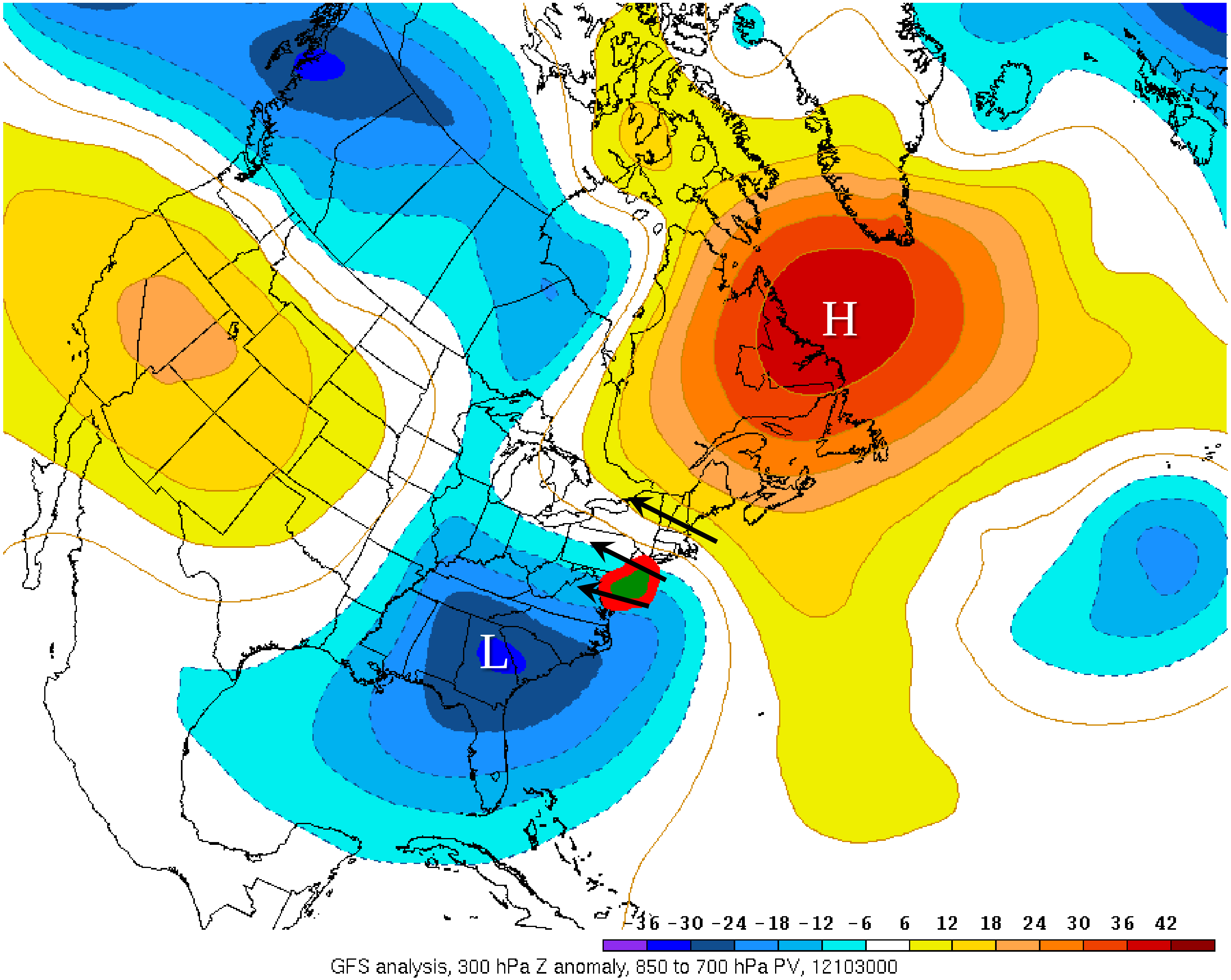
GFS 300 hPa Height Anomaly, 850-700 hPa PV
00 UTC 26 Oct – 06 UTC 30 Oct 2012



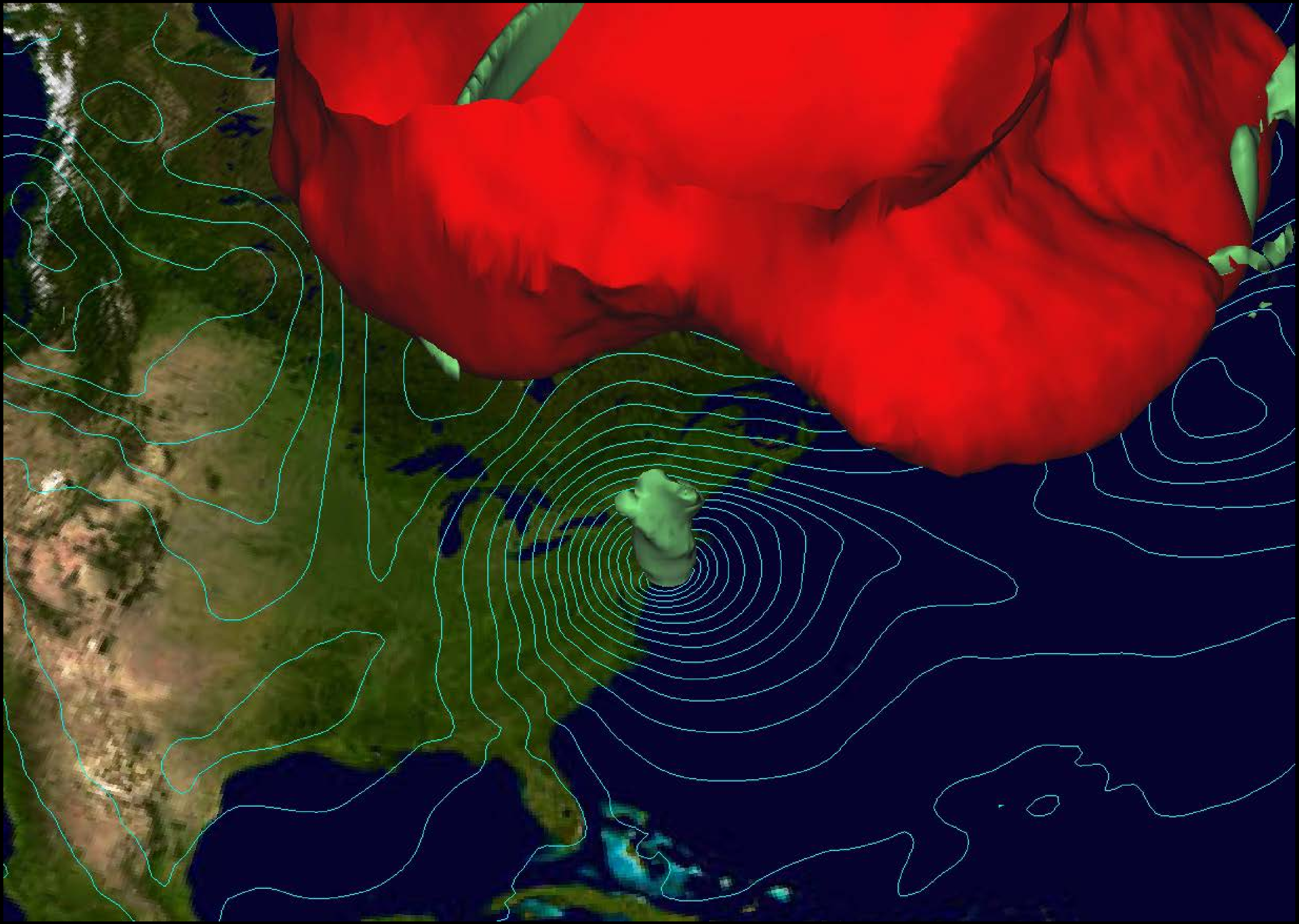
GFS 300 hPa Height Anomaly, 850-700 hPa PV
12 UTC 29 Oct 2012



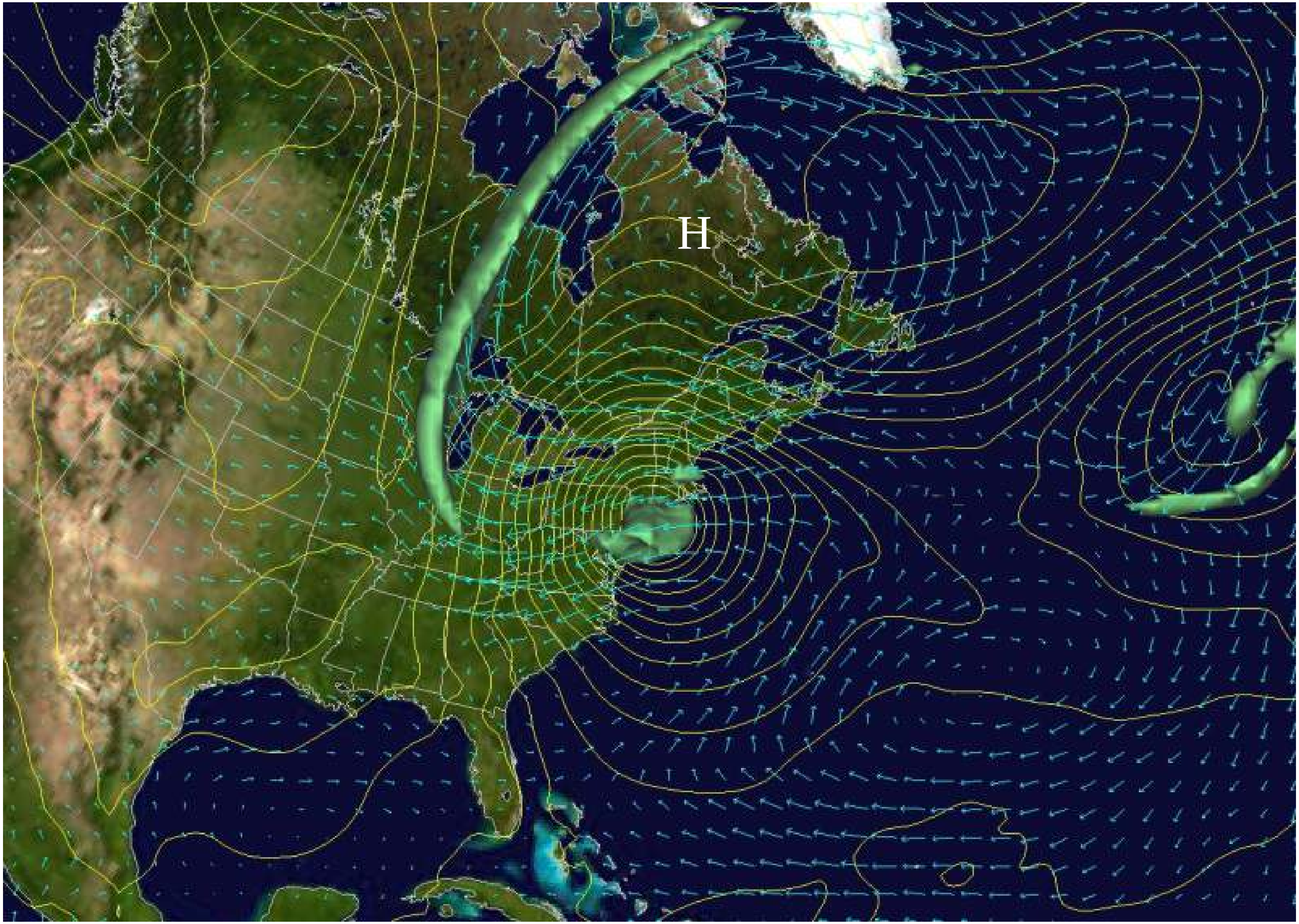
GFS 300 hPa Height Anomaly, 850-700 hPa PV
00 UTC 30 Oct 2012



SLP, vorticity, and 180 m Δ Z isosurface



Diabatic Wind Component, SLP, vorticity isosurface, WRF simulation for 00 UTC 30 Oct 2012



Sandy & Climate Change: Offsetting Processes

Climate change & *intensity*:

- Vapor increase: Stronger
- Stronger upper jet, more shear: TC bad, ETC good
- Tropical warming aloft: Weakening influence (Hill & Lackmann 2011)

Climate change & *track*:

- Increased outflow, stronger ridge, more *westward* track
- Stronger upper jet, more *eastward* track

Compensating processes, numerical simulations needed

Model Methods

WRF simulations (current climate):

- **ECMWF Interim for IC/LBC (0.7°)**
- **Ensemble (physics + GCM change fields)**
- **Nested 54/18/6 km simulations**
- **WRFV3.2.1**, 3.4.1, 3.5, 3.5.1, 3.6

Isolate Sandy's outflow ridge:

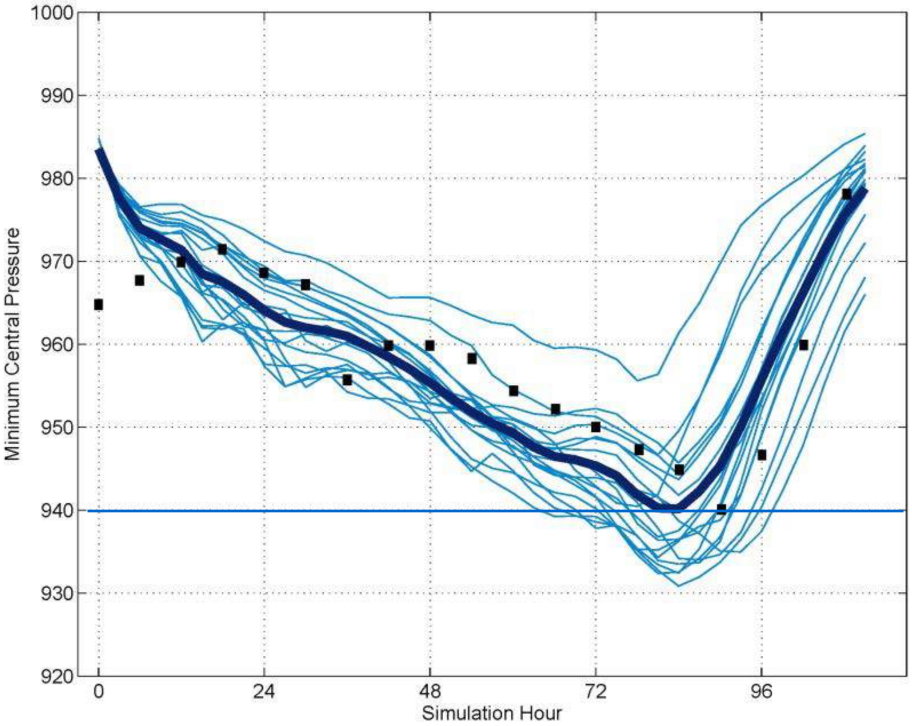
- **Run without latent heating, compute difference**

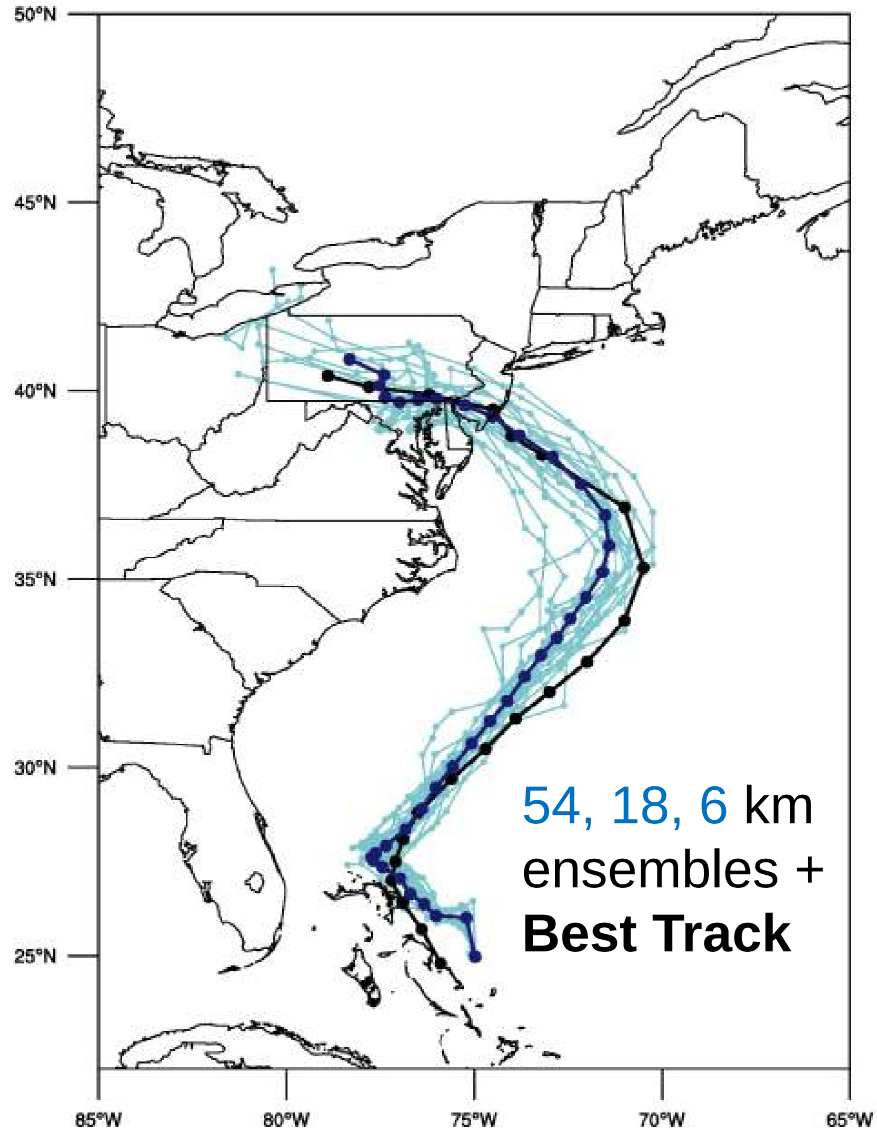
Simulations

Run	Grid Length (km)	Climate (P, C, F)	Model
Ctrl (noTCflx)	54, 18, 6	P, C, F: 5 GCM avg, 26/0	WRFV321
With TCflx	54, 18, 6	P, C, F: 5 GCM avg, 26/0	WRFV321
Goddard uphys	54, 18, 6	P, C, F: 5 GCM avg, 26/0	WRFV321
WDM6 uphys	54, 18, 6	P, C, F: 5 GCM avg, 26/0	WRFV321
Morrison uphys	54, 18, 6	P, C, F: 5 GCM avg, 26/0	WRFV321
BMJ CP (MYJ)	54, 18, 6	P, C, F: 5 GCM avg, 26/0	WRFV321
Tiedtke CP	54, 18	P, C, F: 5 GCM avg, **24/0**	WRFV36, 351
DFI Ctrl	54	P, C, F: 5 GCM avg, 26/0	WRFV321
DFI Ctrl	54, 18, 6	P, C, F: 5 GCM avg, 26/0	WRFV36

NOAH LSM, Dudhia radiation, YSU PBL, Kain-Fritsch (outer), w_damping = 1
Also WRFV3.6, 3.5.1, 3.4.1, + individual GCM changes

Current Ensemble Intensity, Track





Initial intensity weak, rapid adjustment

Too deep (~5 hPa) until landfall

Intensity at landfall close to observed

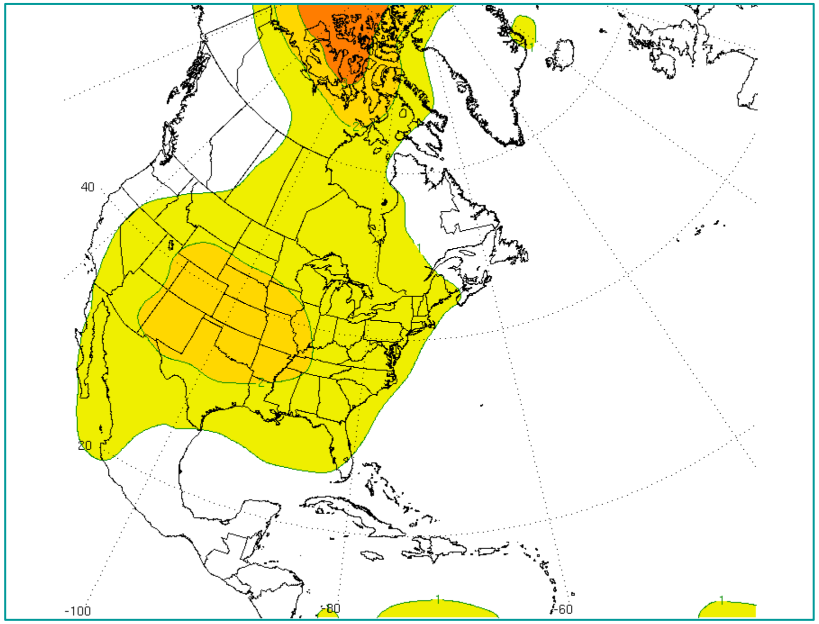
Landfall within 15 km of observed

Sandy in the 1880s?

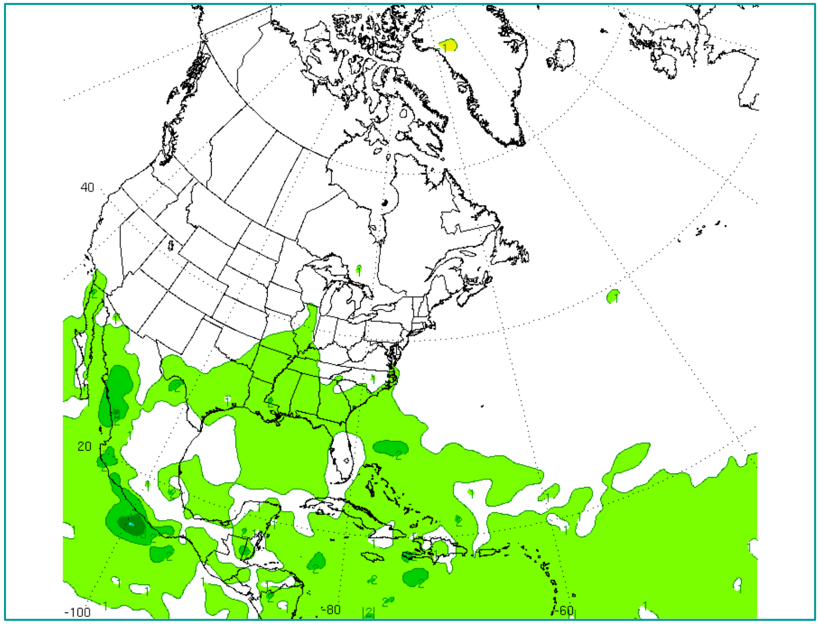
October decadal averages, compute Δ fields

- CMIP3 GCM historical run averages, Δ 1880s to 2010s
- Apply Δ to EC analyses, simulate with altered IC, LBC
- Could also use reanalysis data, other sources

Cooler, less moisture in past: Expect less diabatic ridging to north; Sandy out to sea?

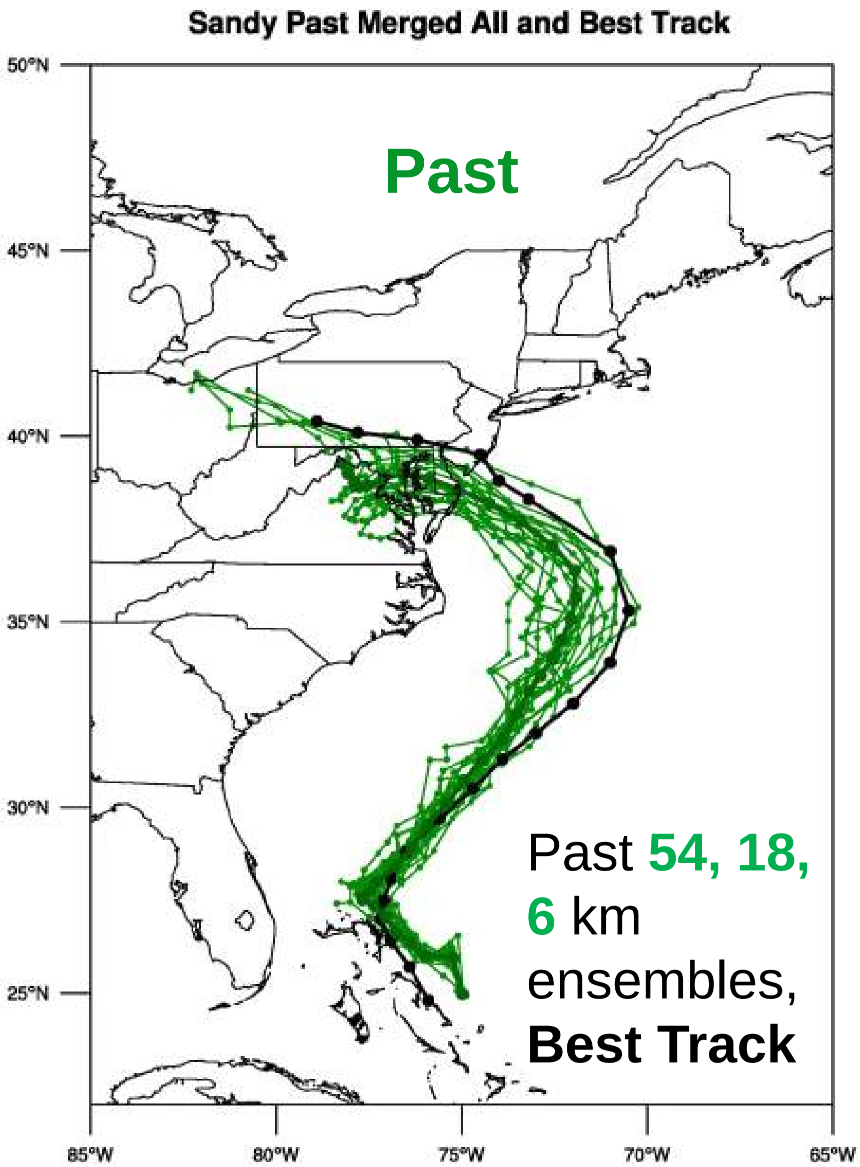


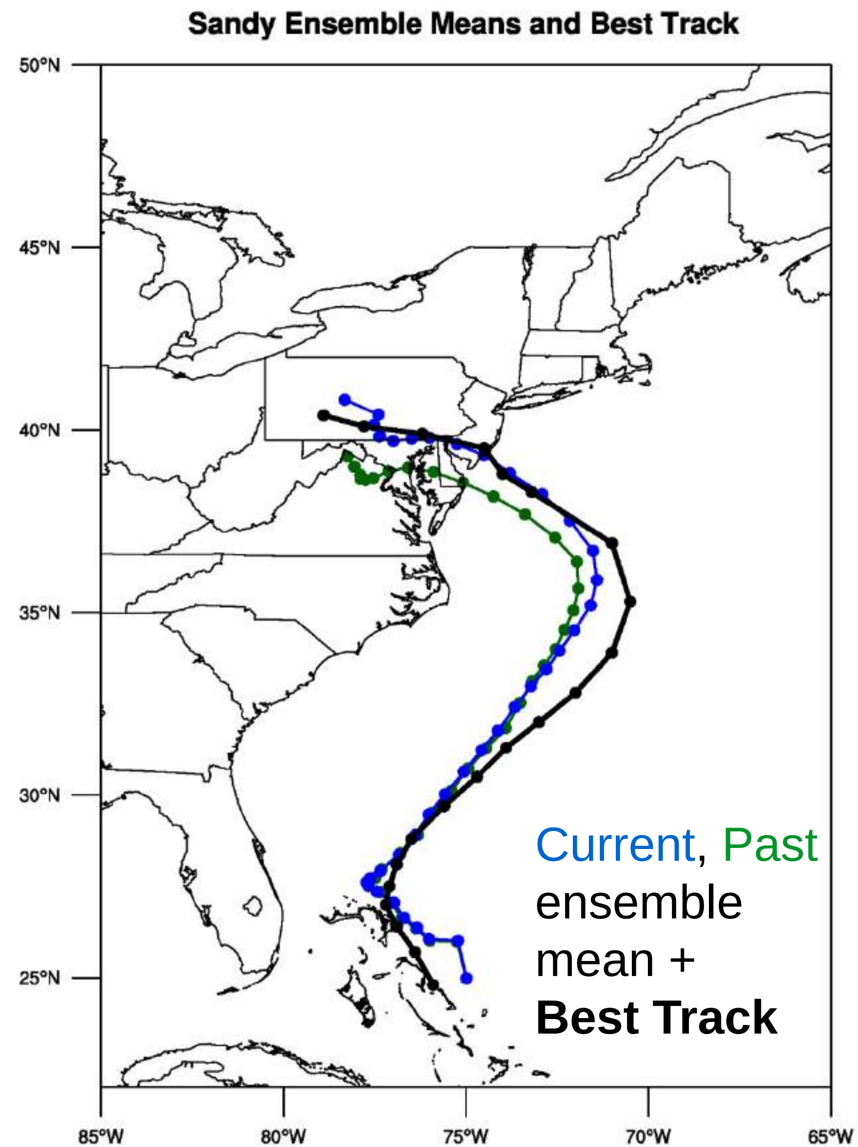
(Current – past) 2-m Temperature



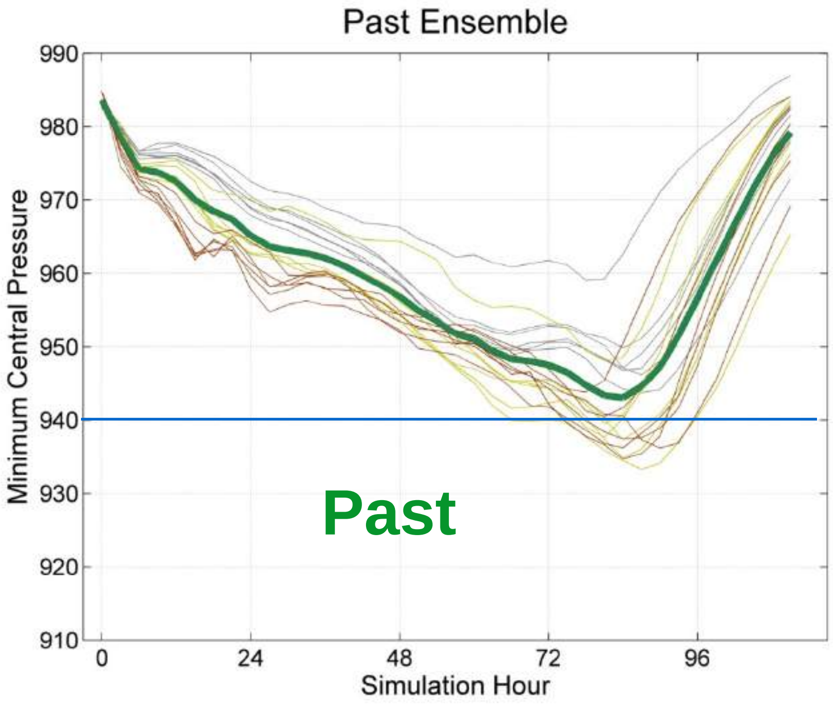
(Current – past) 950-hPa water vapor

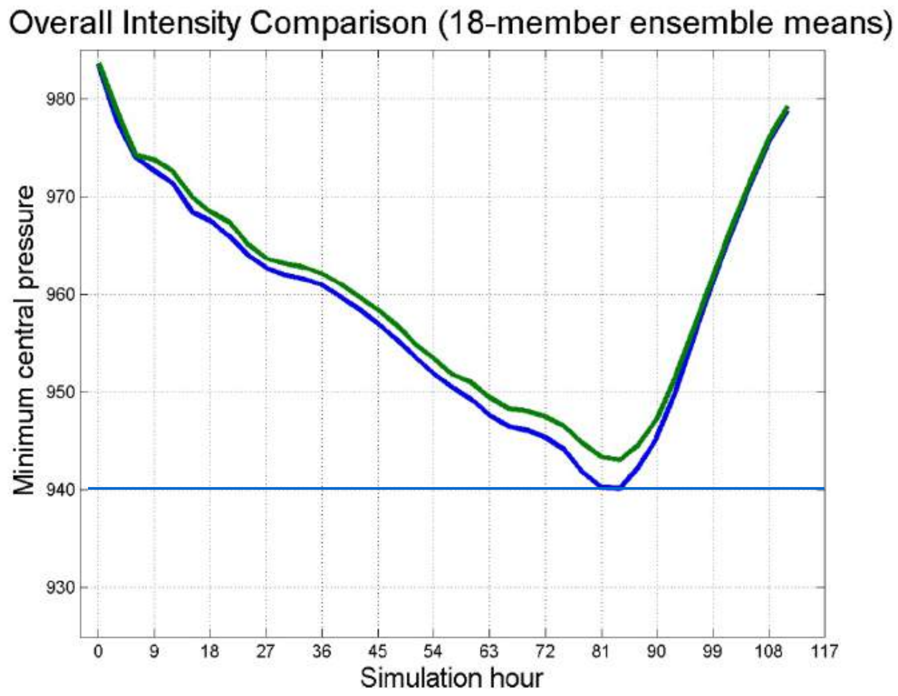
Ensemble Track Comparison: Past & Current

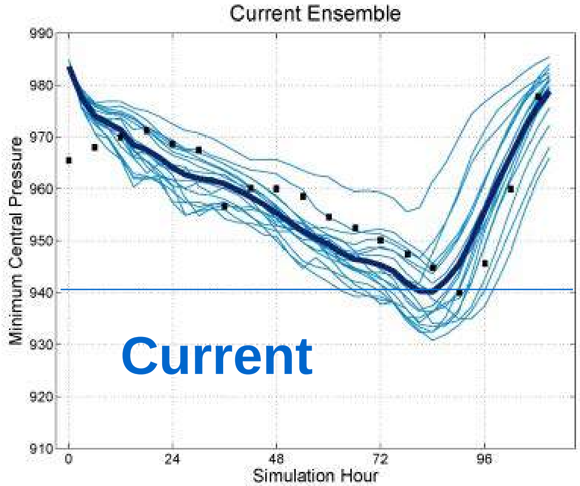




Intensity- Past & Current







Past ensemble mean intensity slightly weaker

Differences fail t-test for significance

Sandy in 2112?

October decadal averages, compute Δ fields

- CMIP3 5-GCM subset average (BCCR, CNRM, INMCM, MPI, UKMO)
- A2 emission scenario, Δ 1990s to 2090s
- Apply Δ to EC analyses, simulate with altered IC, LBC
- Same mini-physics ensemble for more robust results

Warmer, more moisture in future: Expect stronger diabatic ridging to north, more westward track?

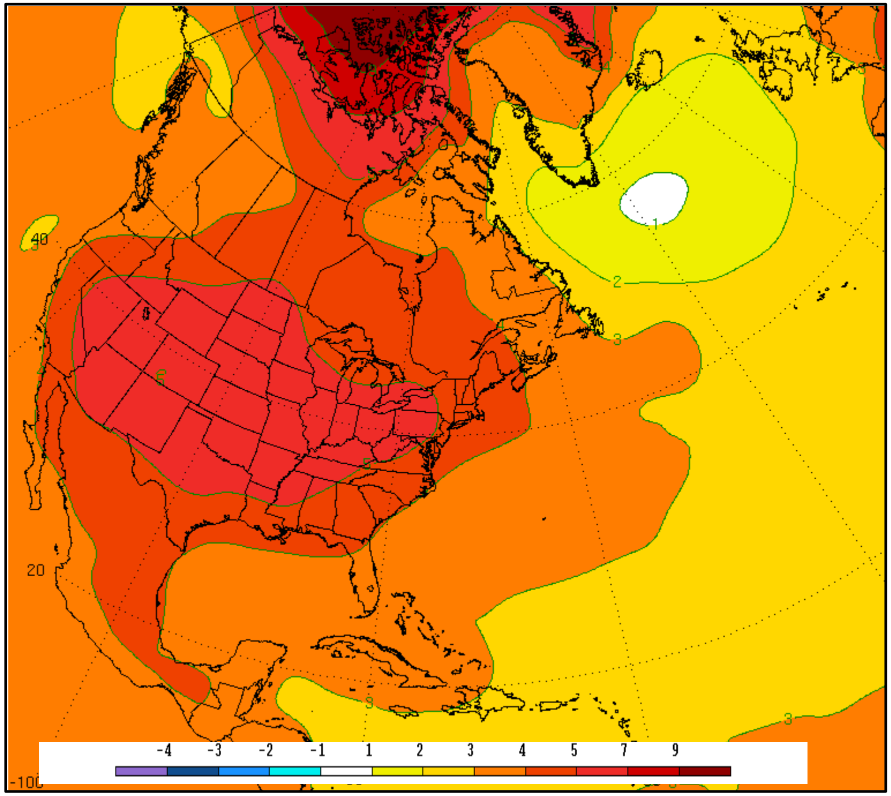
Increased westerly jet: More eastward track?

More diabatic weakening of trough to west: Eastward?

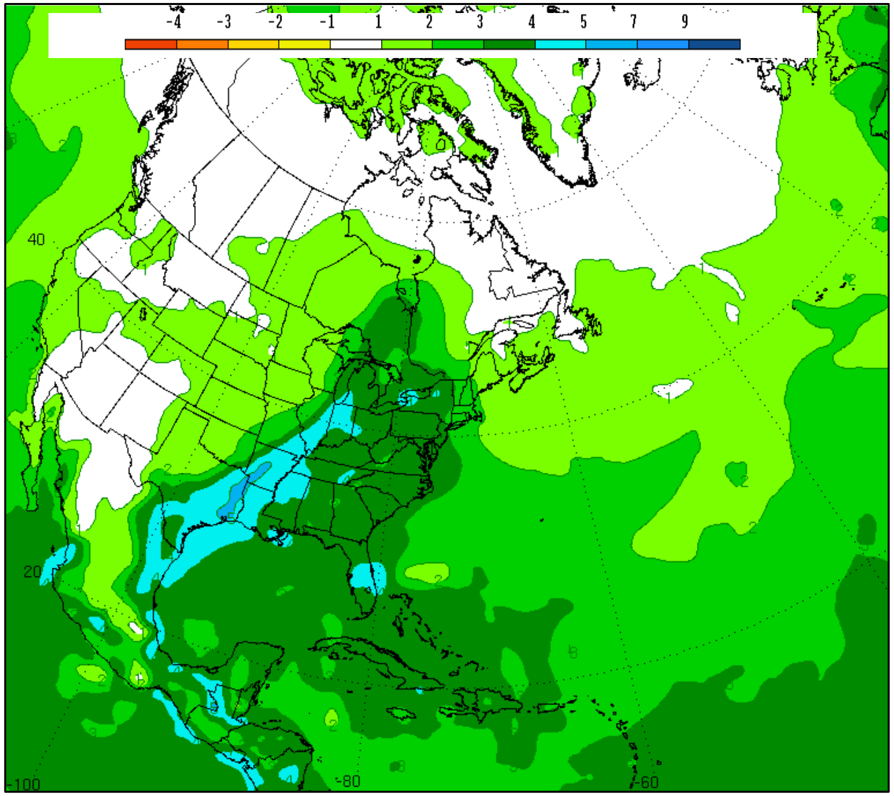
Change fields, 5-GCM mean**, present to future (A2)**

October decadal averages, compute Δ fields

Also with individual GCMs, additional ensemble members

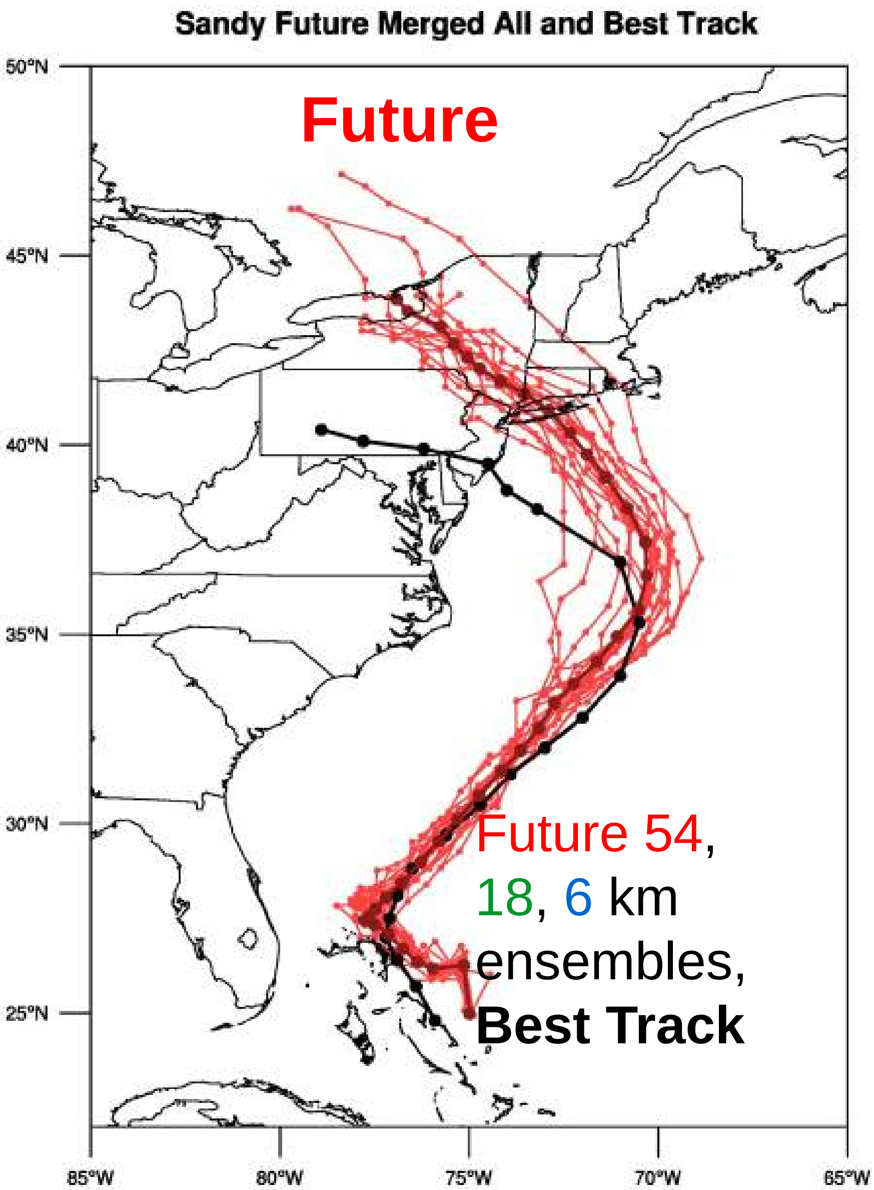


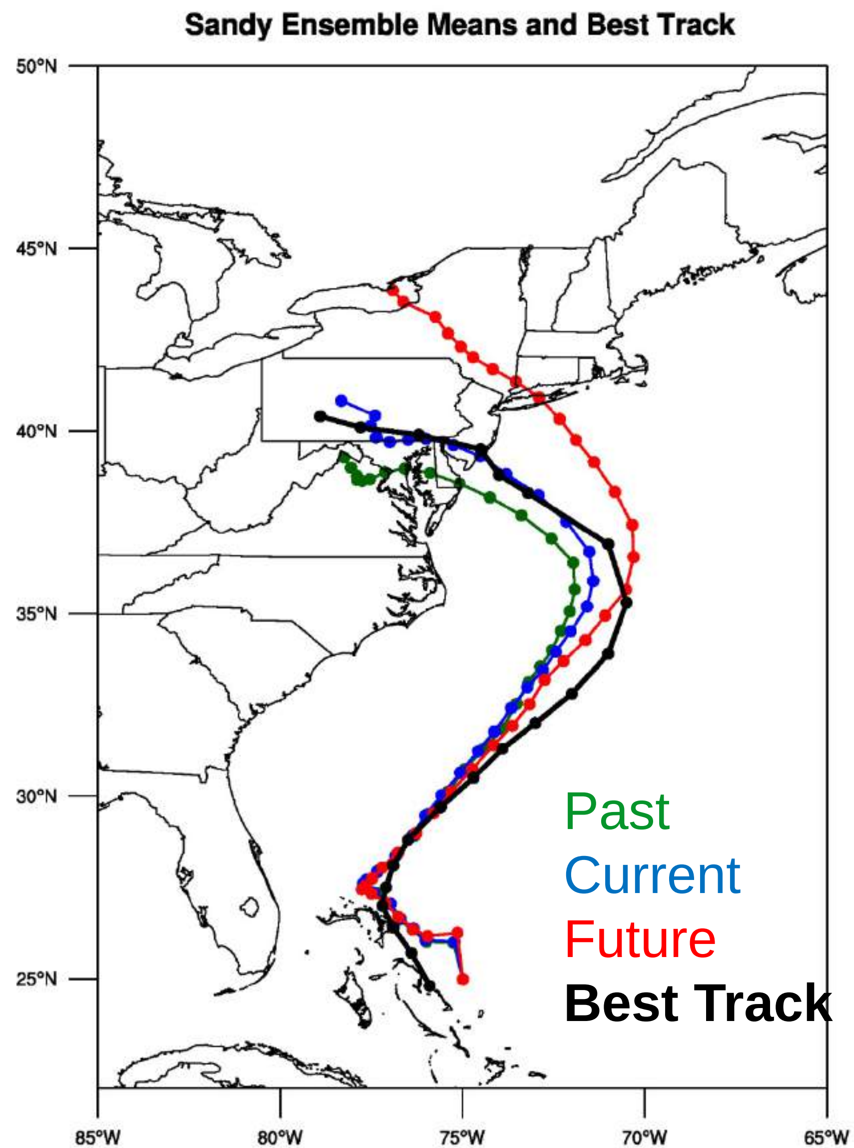
(Future – current) 2-m Temperature



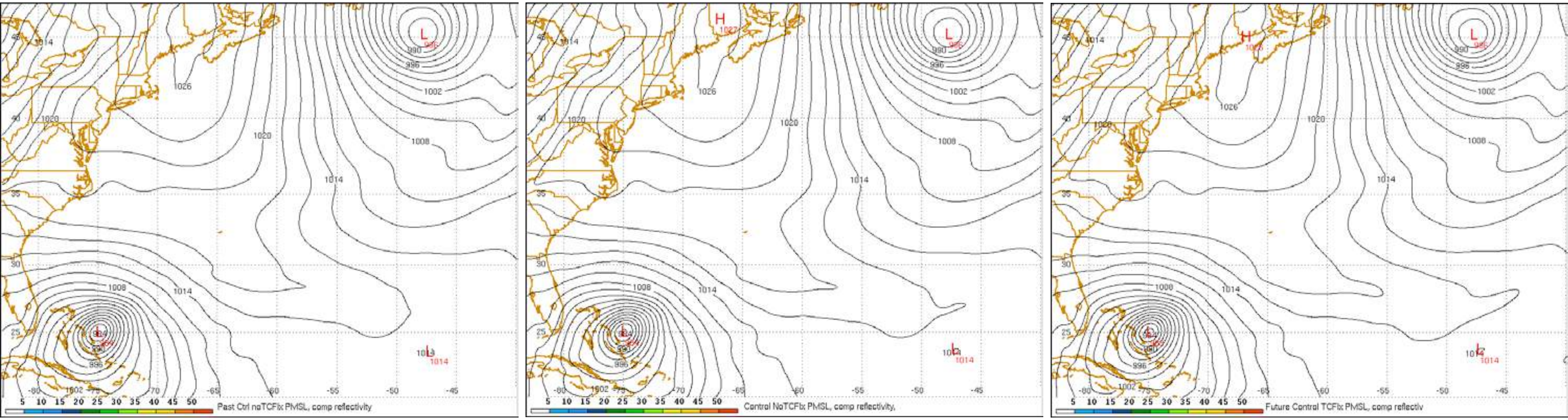
(Future – current) 950 hPa water vapor change (g/kg)

Ensemble Track Comparison: Past, Present, & Future

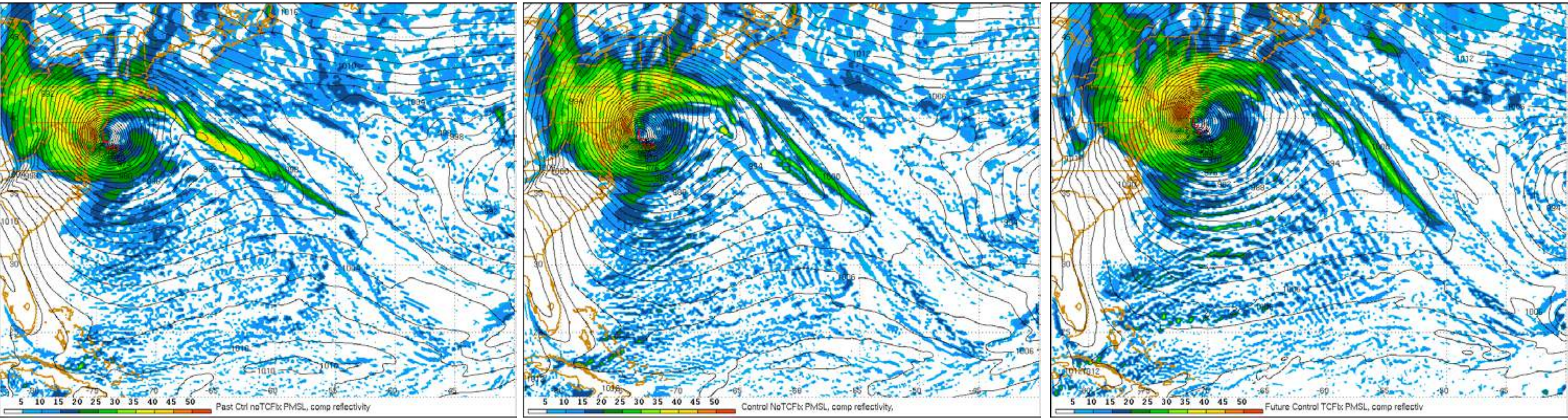




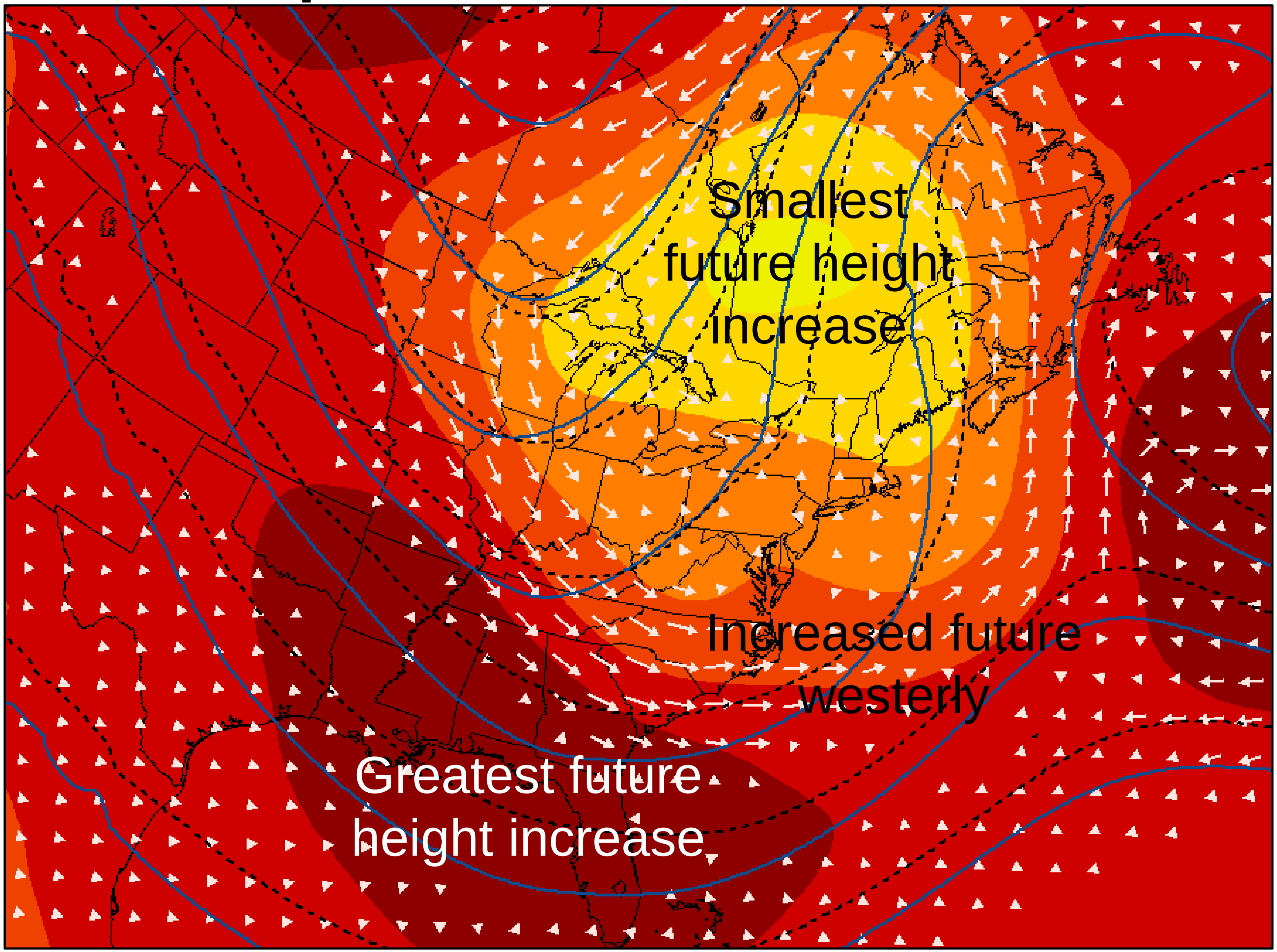
Comparison – 18 km simulations



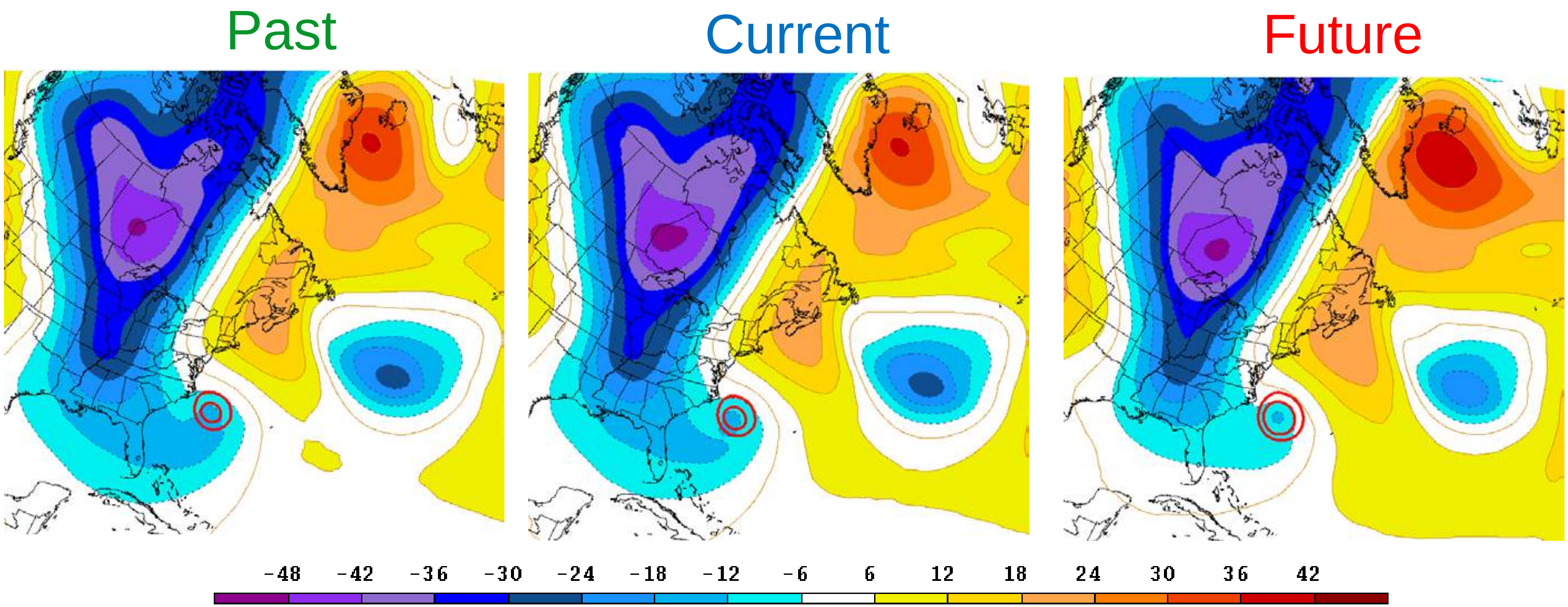
Past **Current** **Future**



Time-averaged 300 hPa changes, **future minus present,** 12Z 26th to 00Z 28th



Scaled 300 hPa Z', **hour 60 (12Z 28th)**

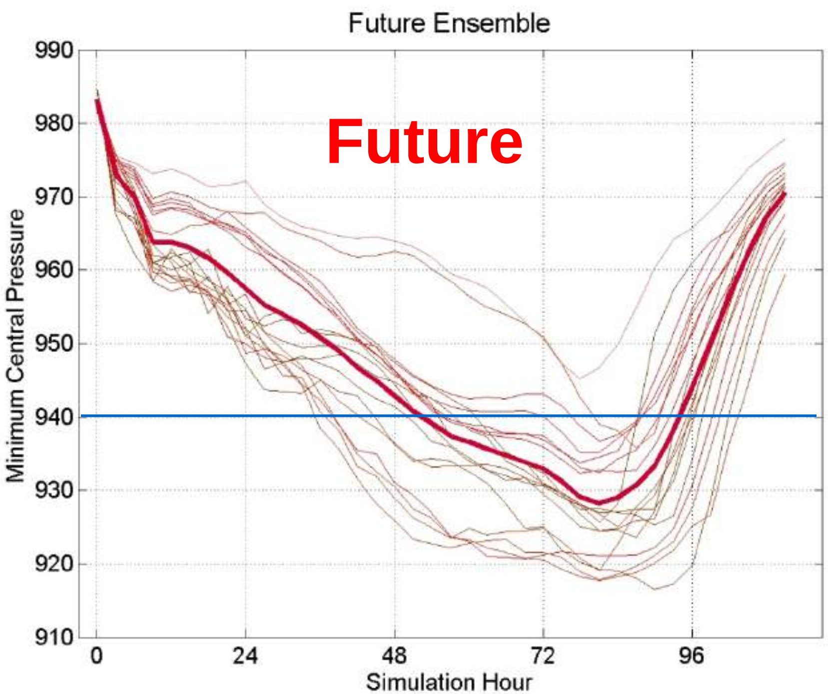


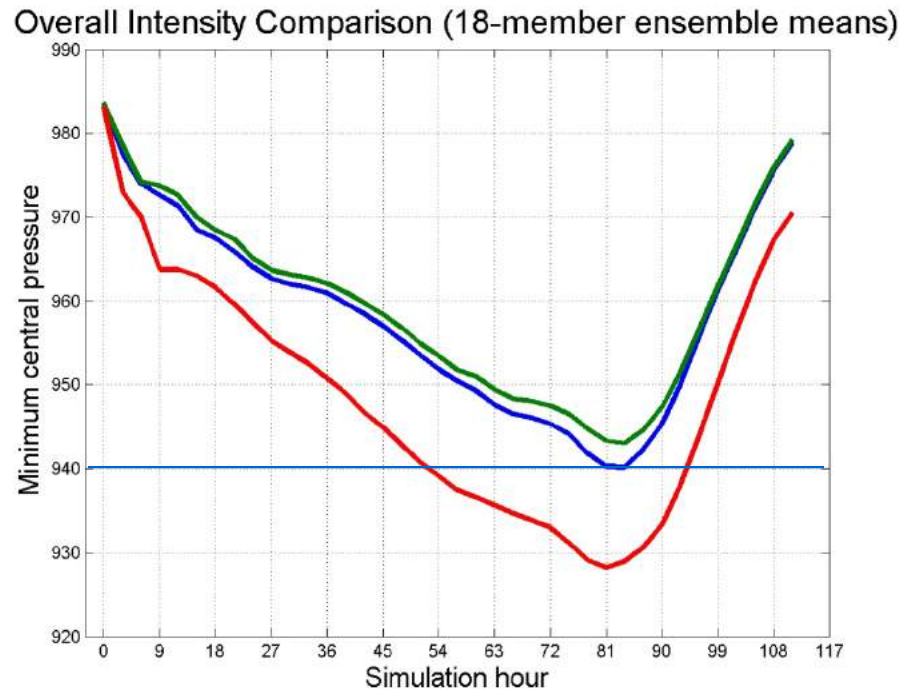
Anomaly defined relative to re-scaled GFS global zonal average

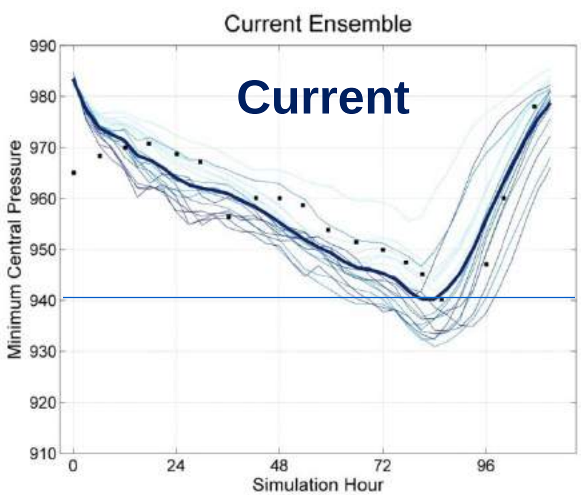
Slightly stronger ridge to north of Sandy

Also weakened trough to south

Intensity- Past, Current & Future





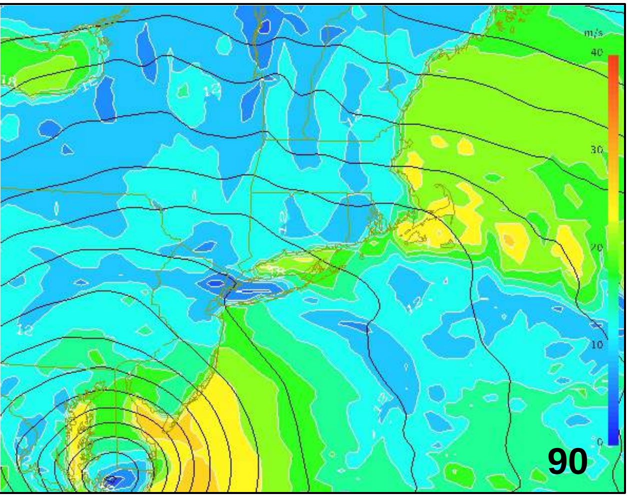


Future ensemble mean intensity stronger

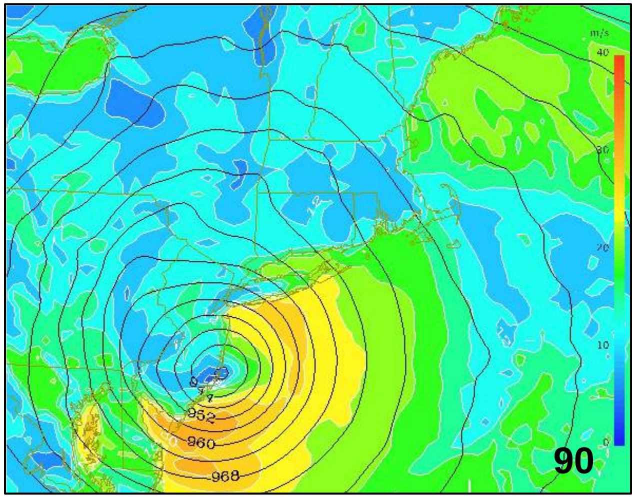
Differences pass t-test for significance (95%)

10-m wind speed comparison, **hour 90 (18Z 29th)**

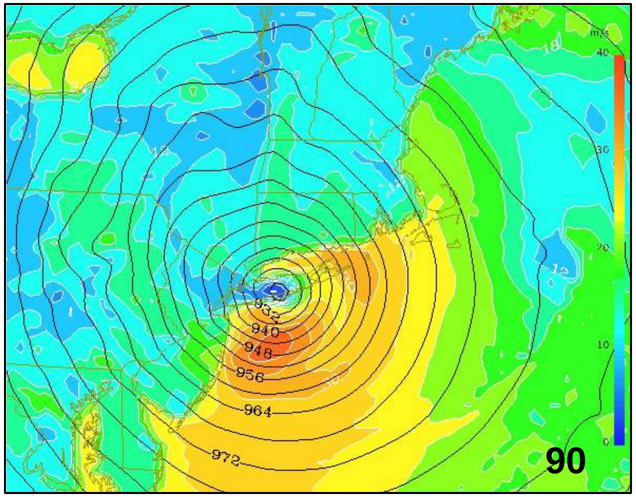
Past



Current



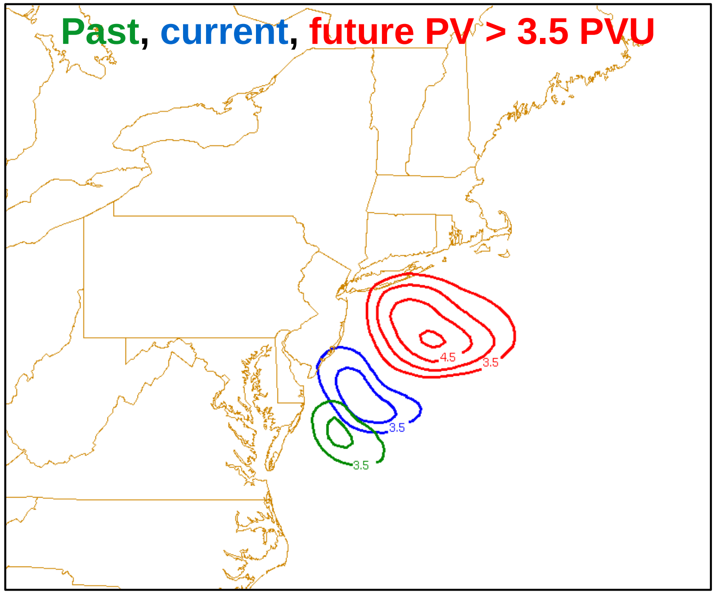
Future



10-meter wind speed (shaded, m/s), sea level pressure contours

Why is Future Sandy Stronger?

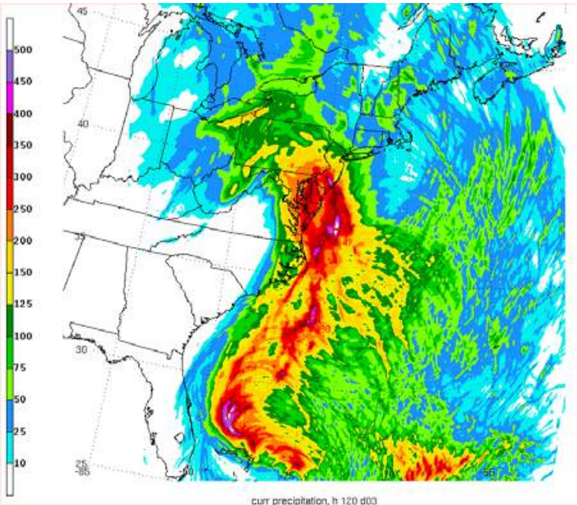
Ensemble mean 850-700 hPa potential vorticity

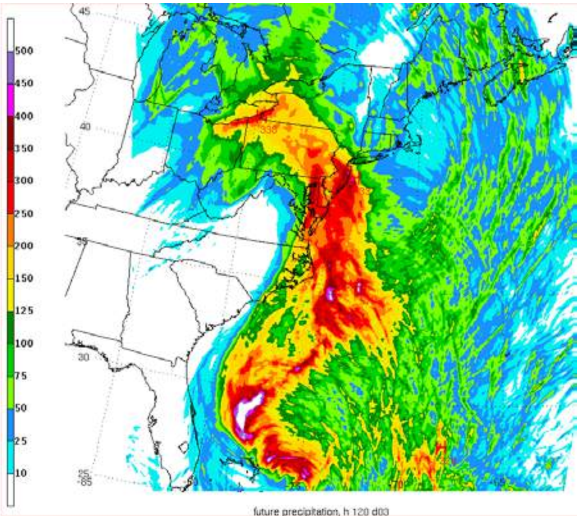


Larger future rain rates (not shown) yield stronger lower-tropospheric PV

Results consistent with Knutson & Tuleya (2004); Hill & Lackmann (2011), others

Point rainfall totals not drastically higher due to faster future storm motion





Summary

Thermodynamic changes alter Sandy substantially, even in a highly similar synoptic pattern

Past version of Sandy:

- Slightly weaker, more southerly landfall location
- Changes not statistically significant

Suggests that thermodynamic climate change since 1880s had modest direct influence on Sandy’s track and intensity

Study **does not** address:

- Change in frequency of this type of synoptic pattern
- Sea-level rise, land use changes

Summary

Future version of Sandy:

- Landfall location shifts significantly to north, east
- Future storm considerably stronger (P_{min} < 930 hPa)
- Changes ***are*** statistically significant
- A2 (~RCP8.5) emission scenario tested here – high end

Heavier precipitation, more condensational heating, stronger cyclonic PV (consistent with Hill and Lackmann 2011)

Stronger diabatic ridging *does not* lead to more westward track, strengthened westerly flow dominates track change

Additional factors not considered here (e.g., sea-level rise) would likely increase severity of impacts

Additional Work and Acknowledgements

Additional work:

- Explore other datasets for past, future change
- Analyze changes in landfall timing, rainfall, storm motion
- Consider genesis, other parts of storm life cycle

Acknowledgements:

Dr. Marina Astitha and **U. Conn**. for this invitation; you for your interest & attention

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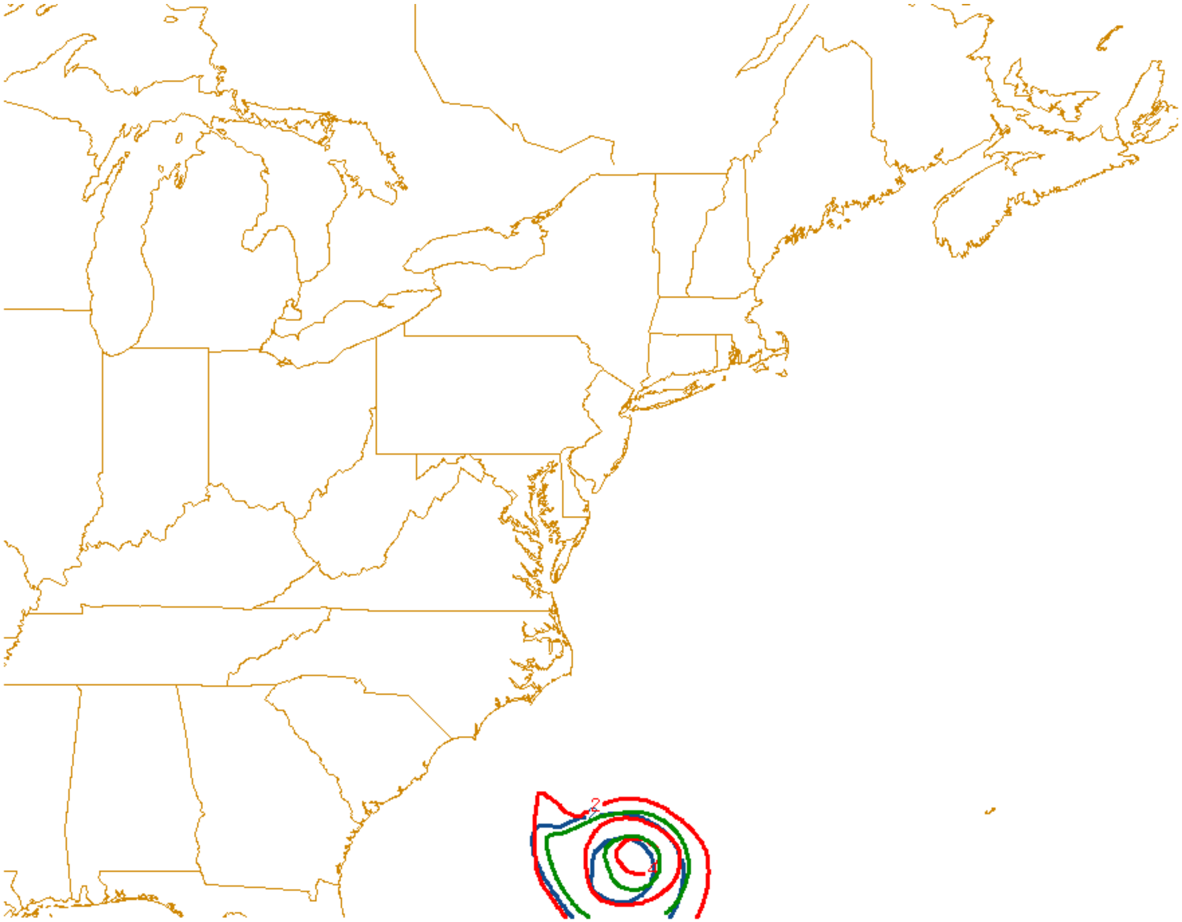
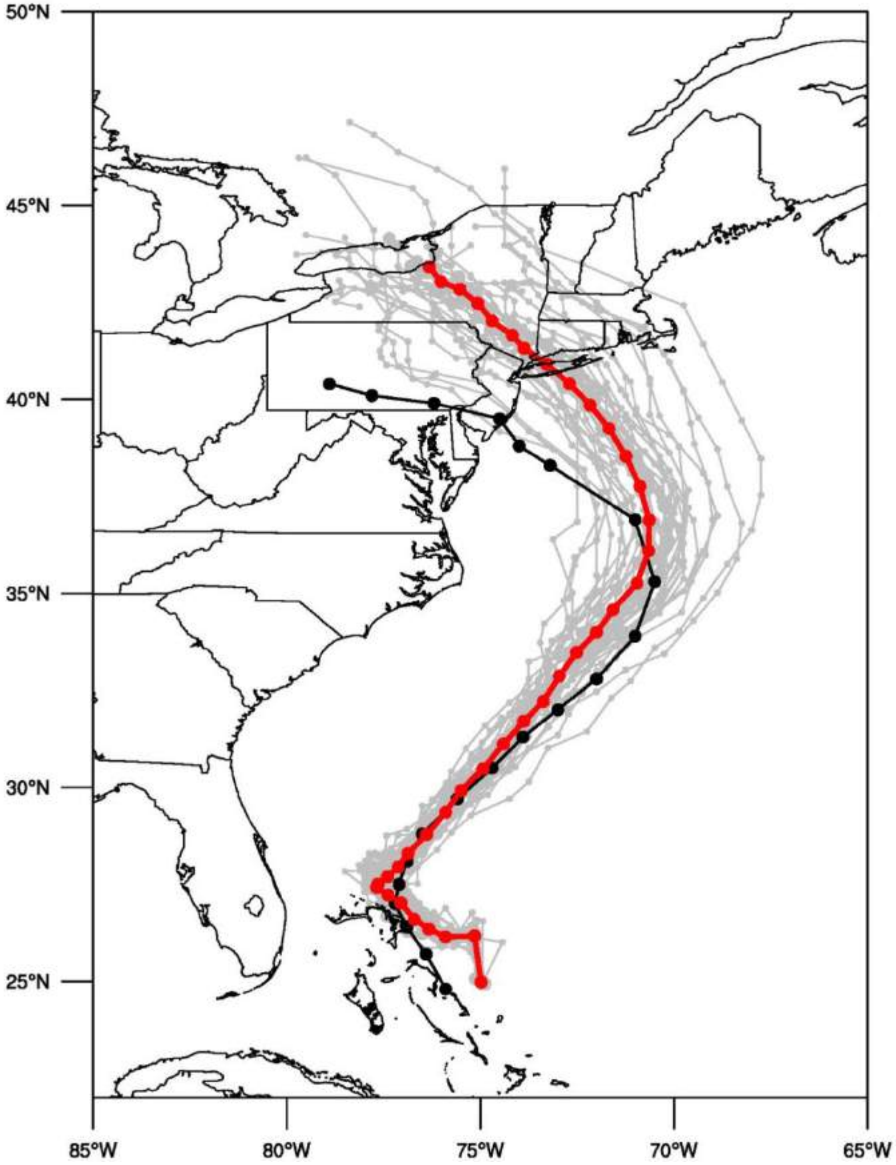
Ensemble mean 850-700 hPa potential vorticity

Past, current, future PV > 2 PVU



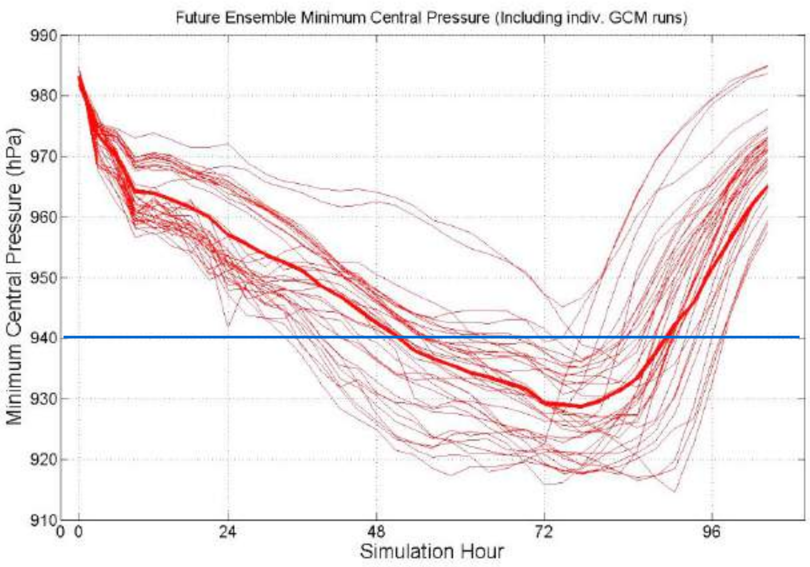
Future Ensemble, including individual GCM changes



Change fields from individual GCMs: 15 additional simulations

Greater spread than physics ens.

Full ensemble mean track, intensity nearly identical to previous



Earlier Initial Time?

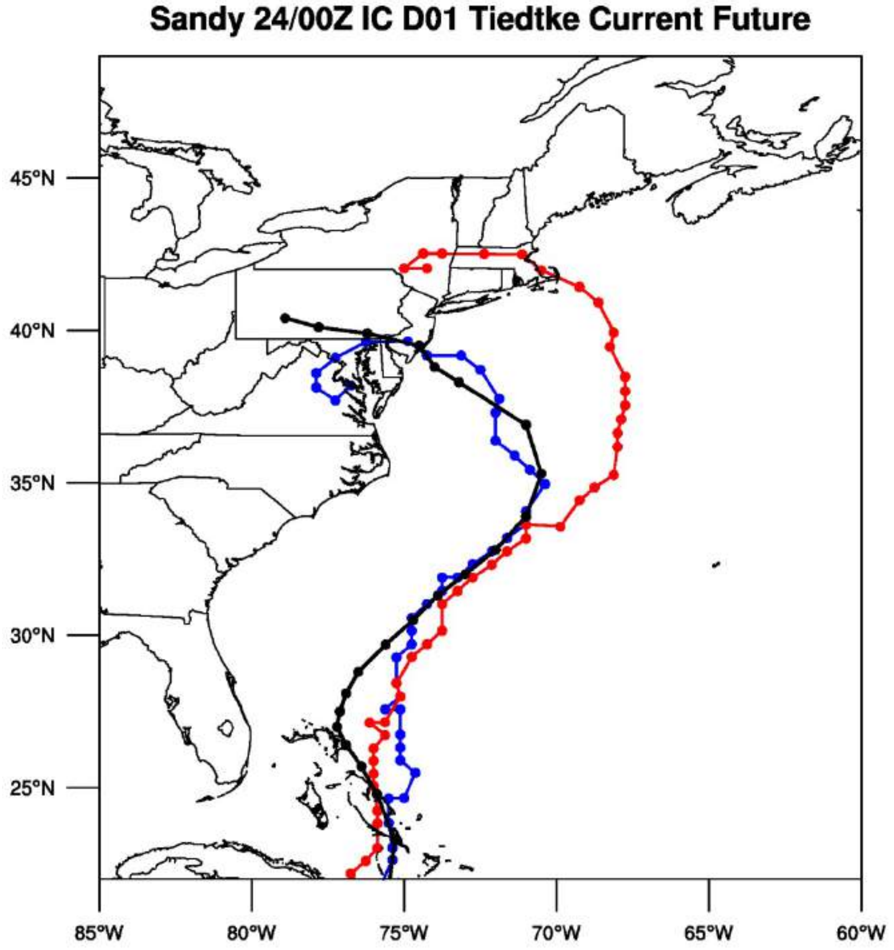
What would happen if initialized at an earlier time? There was more variability earlier.

Initialized 00Z 24^{th}

WRFV3.6, Tiedtke CP

Similar trend in results, by far best results with Tiedtke CP scheme (see Bassill 2014)

What about genesis?

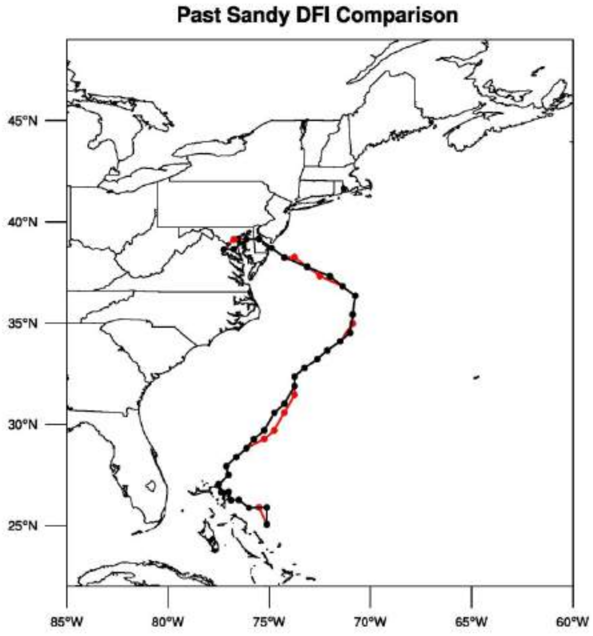


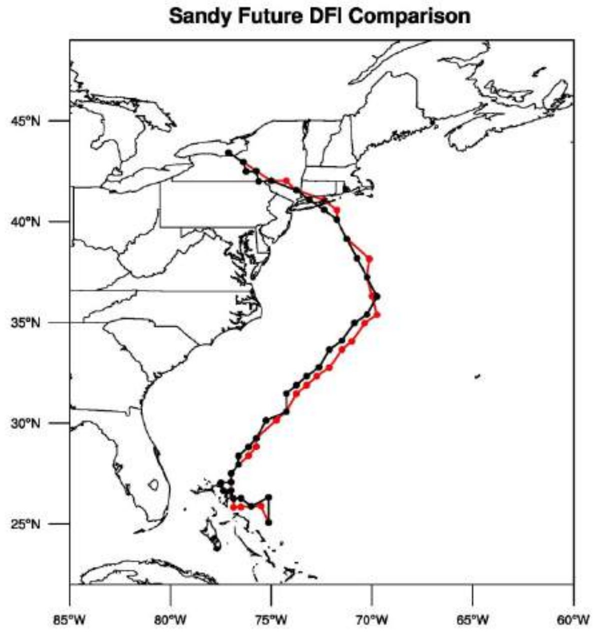
Balanced Initial Wind Fields

Didn't initialize with a wind field that was completely balanced – only changed T, q, and Z at time zero

Utilized WRF DFI capability (Lynch and Huang 1994)

DFI runs produce highly similar tracks to non-DFI runs



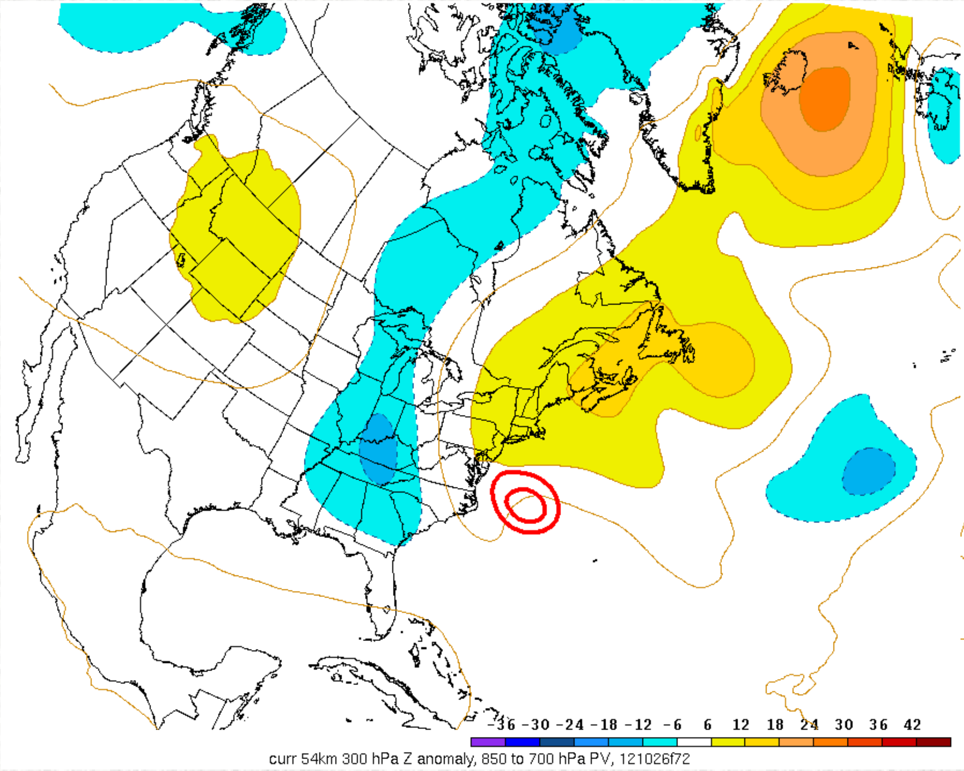


Did the upper ridge get stronger?

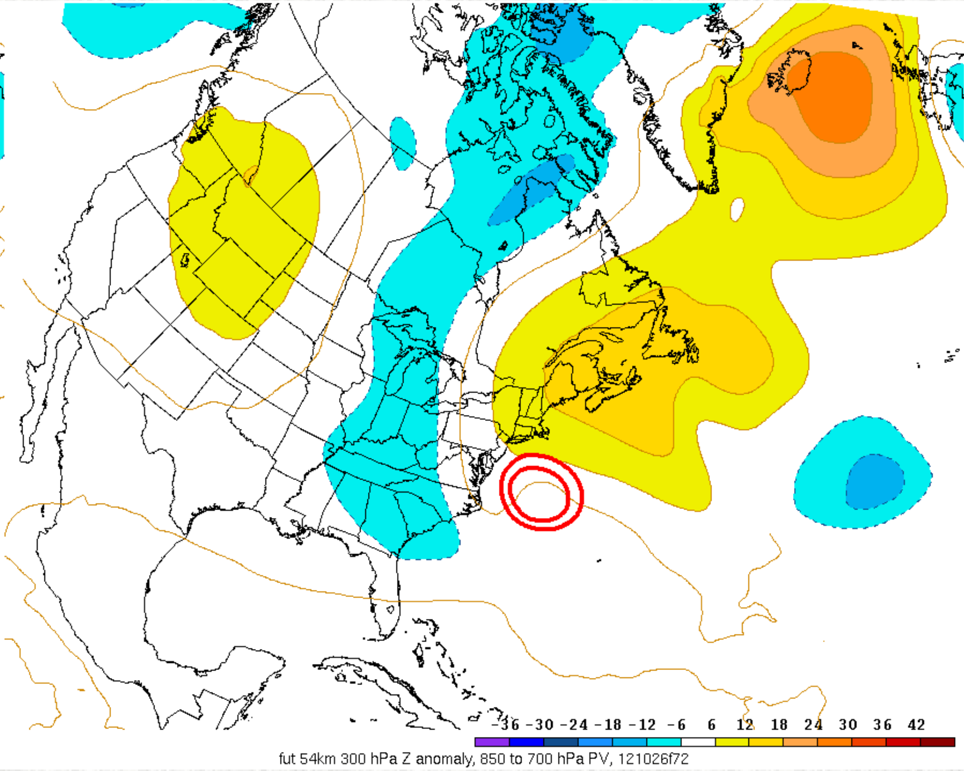
Slightly stronger ridge to north of Sandy

Also weakened trough to south

Current

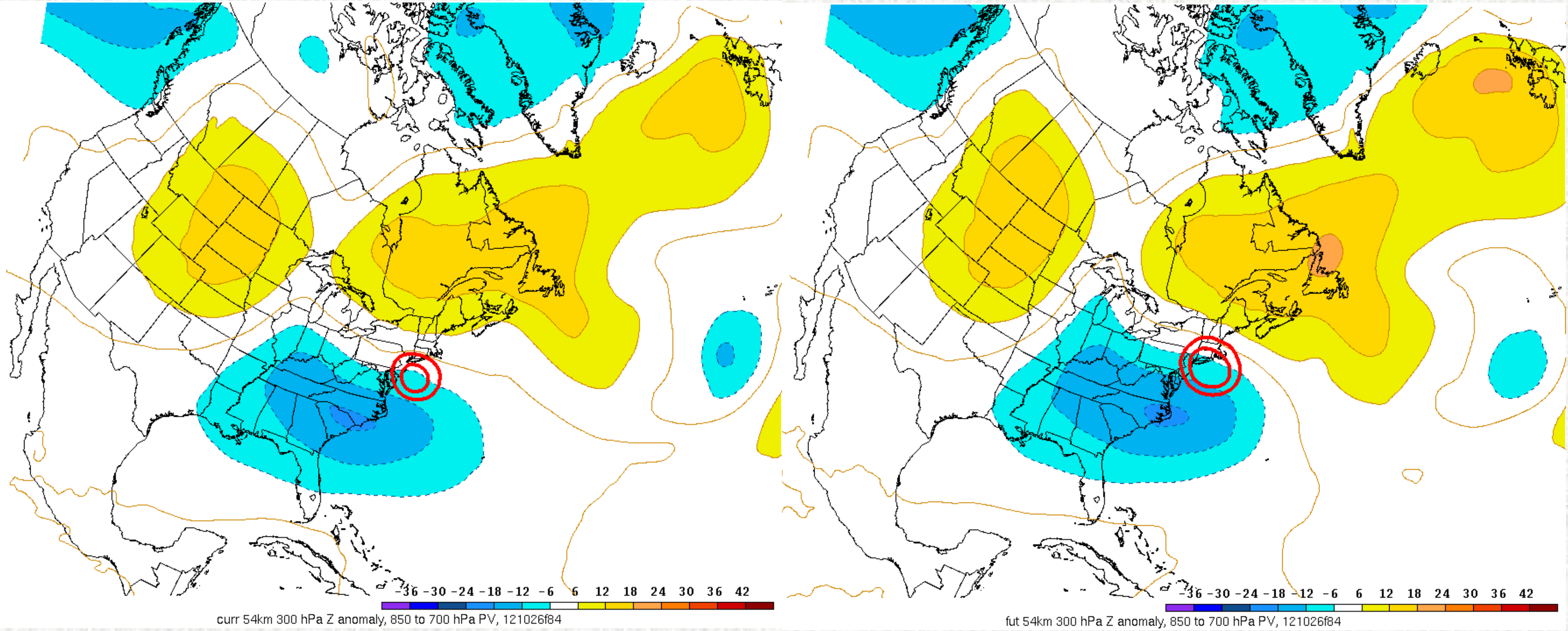


Future



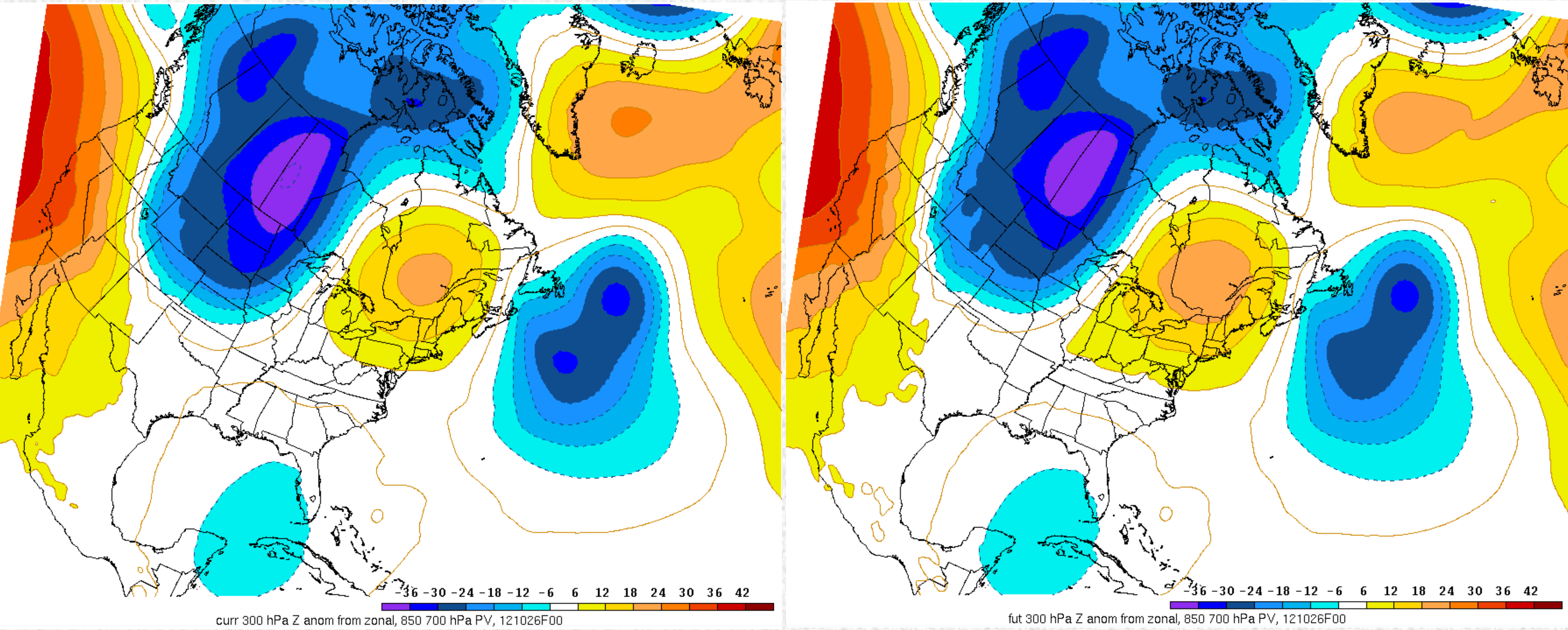
300 Z anomaly defined relative to 144 h time averages

Did the upper ridge get stronger?



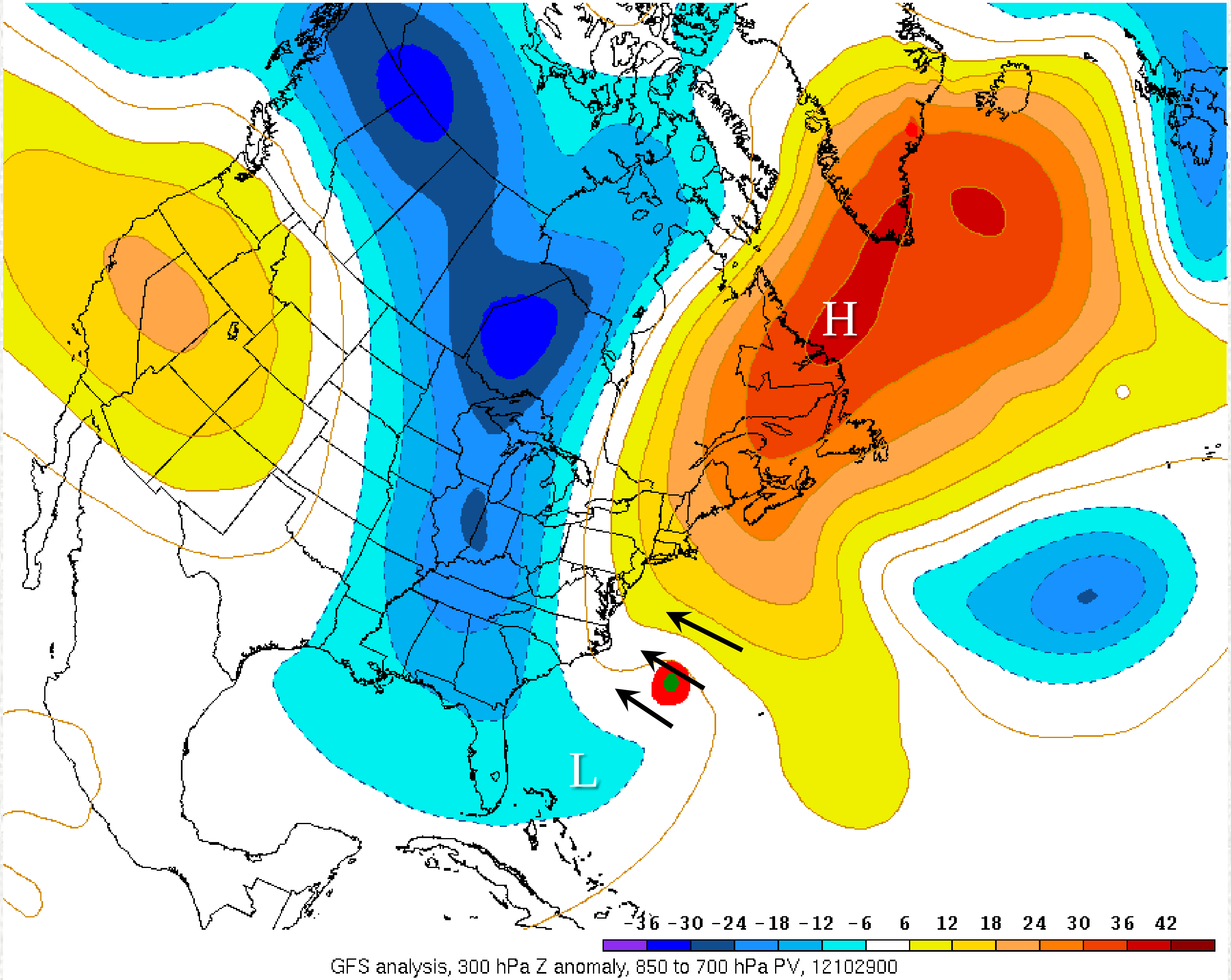
Anomaly defined relative to 144 h time averages

Did the upper ridge get stronger?



Anomaly defined relative to adjusted GFS global zonal average

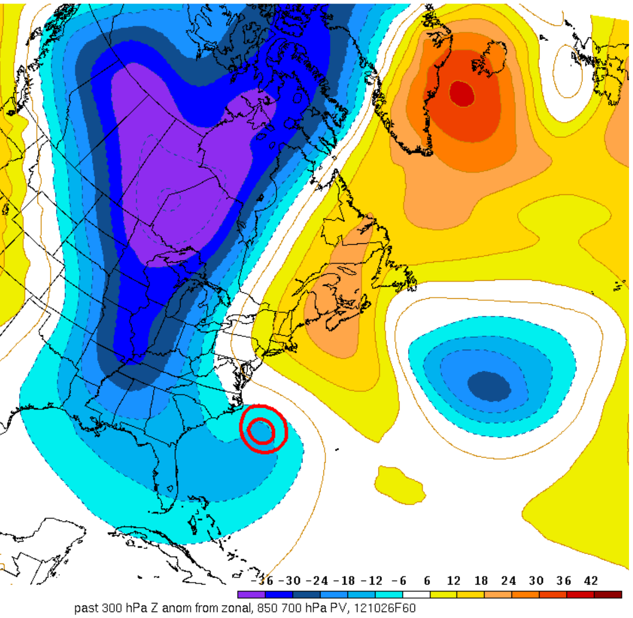
GFS 300 hPa Height Anomaly, 850-700 hPa PV
00 UTC 29 Oct 2012



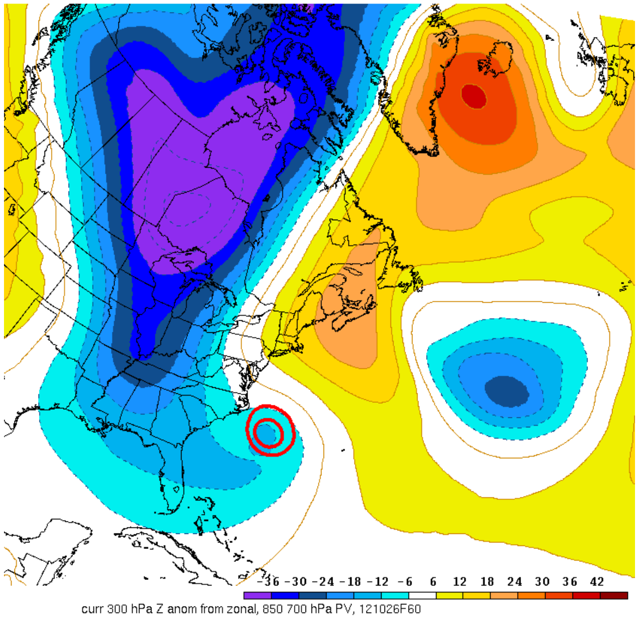
Did upper ridge strengthen? 300 Z anomaly, h 60

Slightly stronger ridge to north of Sandy

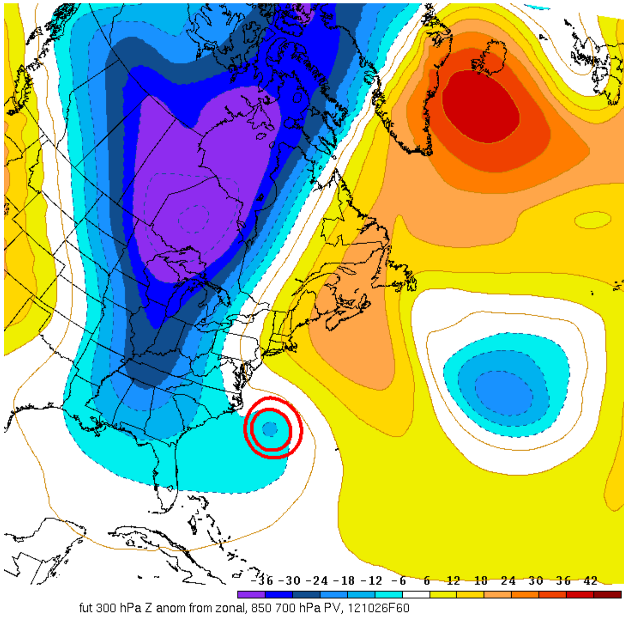
Also weakened trough to south



Past



Current



Future

Anomaly defined relative to re-scaled GFS global zonal average

Basic Ensemble

Run	Climate	Grid length (km)	CP scheme	Microphysics	IC time	PBL/TC flux
1	P, C, and F	54, 18, 6	KF, KF, none	WSM6	26/00Z	YSU/No
2	P, C, and F	54, 18, 6	KF, KF, none	WSM6	26/00Z	YSU/Yes
3	P, C, and F	54, 18, 6	KF, KF, none	Goddard	26/00Z	YSU/Yes
4	P, C, and F	54, 18, 6	KF, KF, none	WDM6	26/00Z	YSU/Yes
5	P, C, and F	54, 18, 6	KF, KF, none	Morrison	26/00Z	YSU/Yes
6	P, C, and F	54, 18, 6	BMJ, BMJ, none	WSM6	26/00Z	MYJ/Yes
7-11	F (GCM)	54, 18, 6	KF, KF, none	WSM6	26/00Z	YSU/Yes
13	C	54, 18, 6	None	No MP heat	26/00Z	YSU/Yes
14DFI	P, C, and F	54	KF	WSM6	26/00Z	YSU/Yes
15DFI	P, C, and F	54, 18, 6	KF, KF, none	WSM6	26/00Z	YSU/Yes
16	P, C, and F	54	KF, KF, none	WSM6	24/00Z	YSU/Yes
17	C and F	54, 18, 6	T, T, none	WSM6	24/00Z	YSU/Yes

NOAH LSM, Dudhia radiation, YSU PBL, Kain-Fritsch (outer), w_damping = 1
Also WRFV3.6, 3.5.1, 3.4.1, + individual GCM changes

Vapor change

Air temperature changes in of themselves not biggest threat

Sea-level rise, ocean acidification, hydrologic cycle changes…

Consider impact of warming on vapor, precipitation

Clausius-Clapeyron (C-C): Saturation vapor pres (e_s) as *f* (T)

$$\frac{d \ln e_s}{d T} = \frac{L_v}{R_v T^2}$$

Observations: RH nearly constant with T over wide ranges, including seasonal change (e.g., Dai 2006 and others)

Modeling studies reveal same: Vapor increase mostly governed by Clausius-Clapeyron relation

Water Vapor and Precipitation Changes

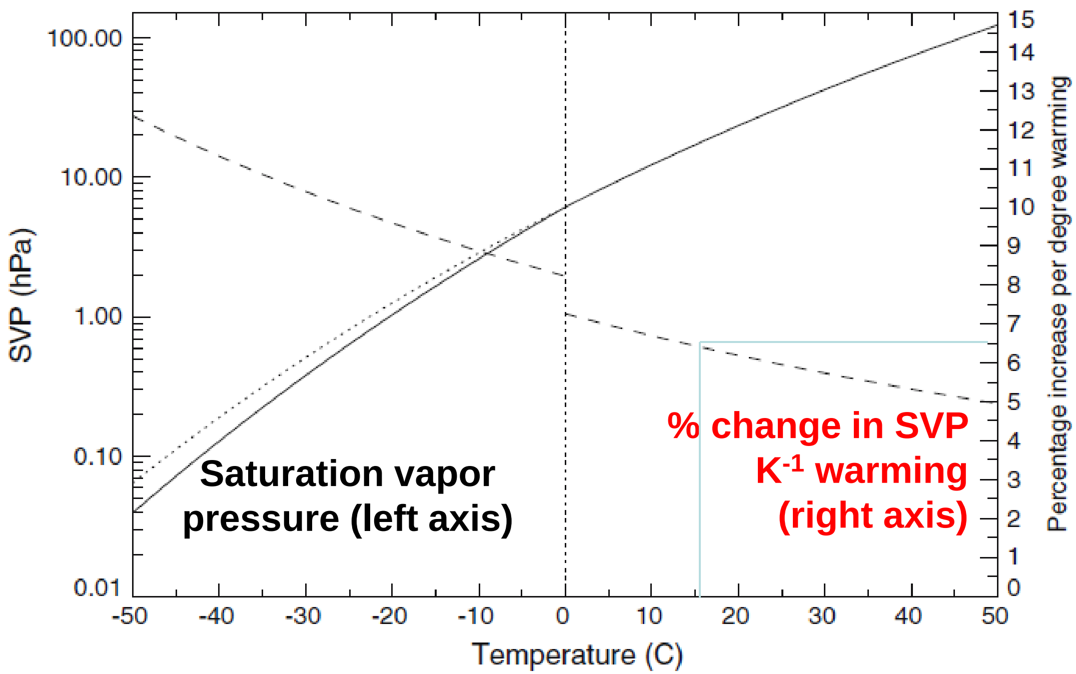


Fig. 6 Relationship between SVP, percentage SVP change, and temperature. SVP (*solid curve*) is expressed on a log scale (*left hand axis*). The *vertical dotted line* separates the vapour–liquid and vapour–ice transition regimes (above and below the triple point of water respectively), with the *dotted curve* showing the deviation of the SVP for the vapour–ice transition from the SVP of a hypothetically continuing vapour–liquid phase transition. The percentage increase in SVP per degree warming (*dashed curve*) is given on a linear scale (*right hand axis*) and has a discontinuity at the triple point, due to the change in regime. For warmer regions, the increase is smaller than for cooler regions

Pall et al. 2007, *Climate Dynamics*

Vapor Change and Global Precipitation

Should precipitation increase at the same rate as vapor?

Is this observed?

NO

Why not?

Water Vapor and Precipitation Changes

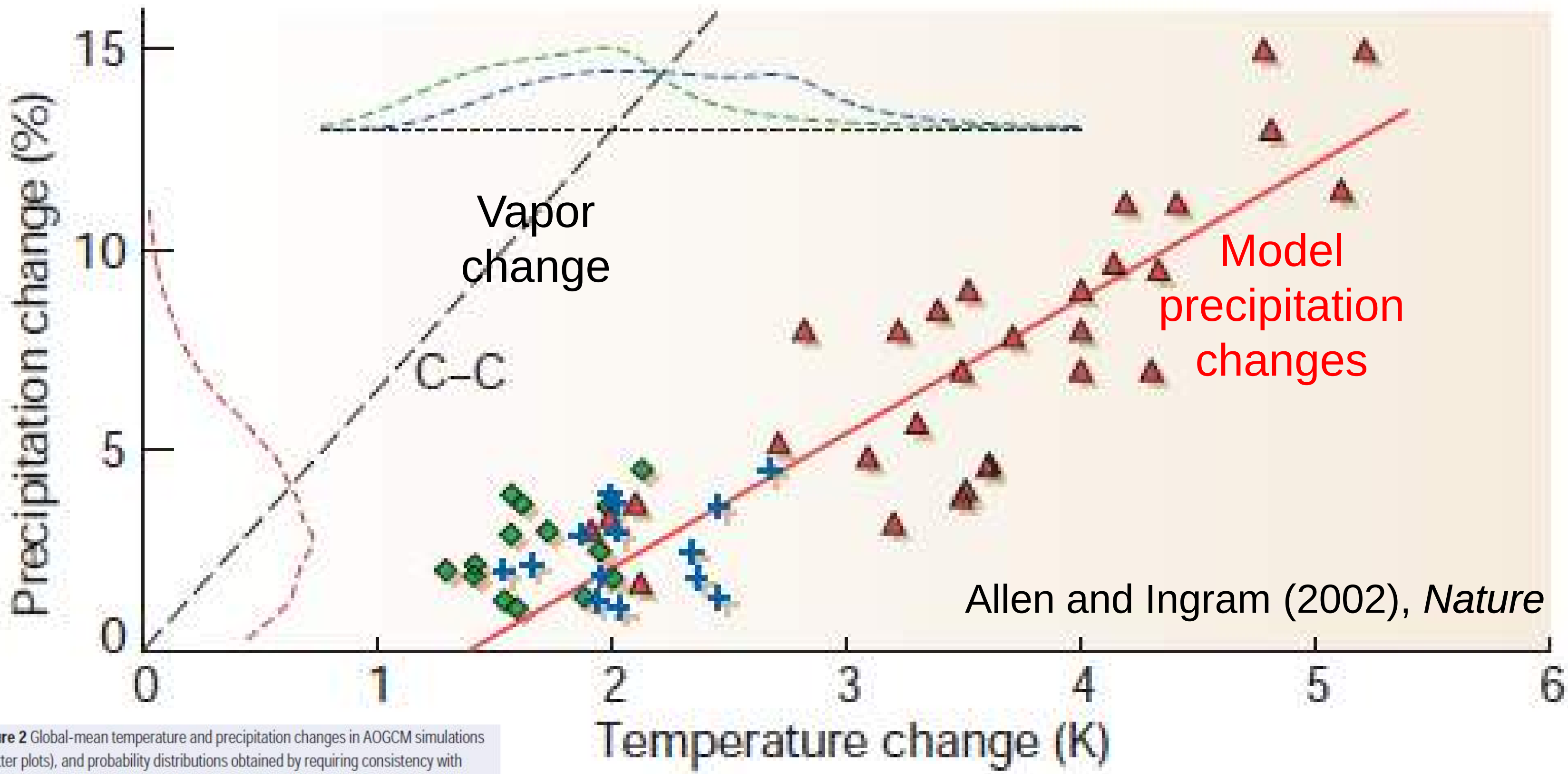
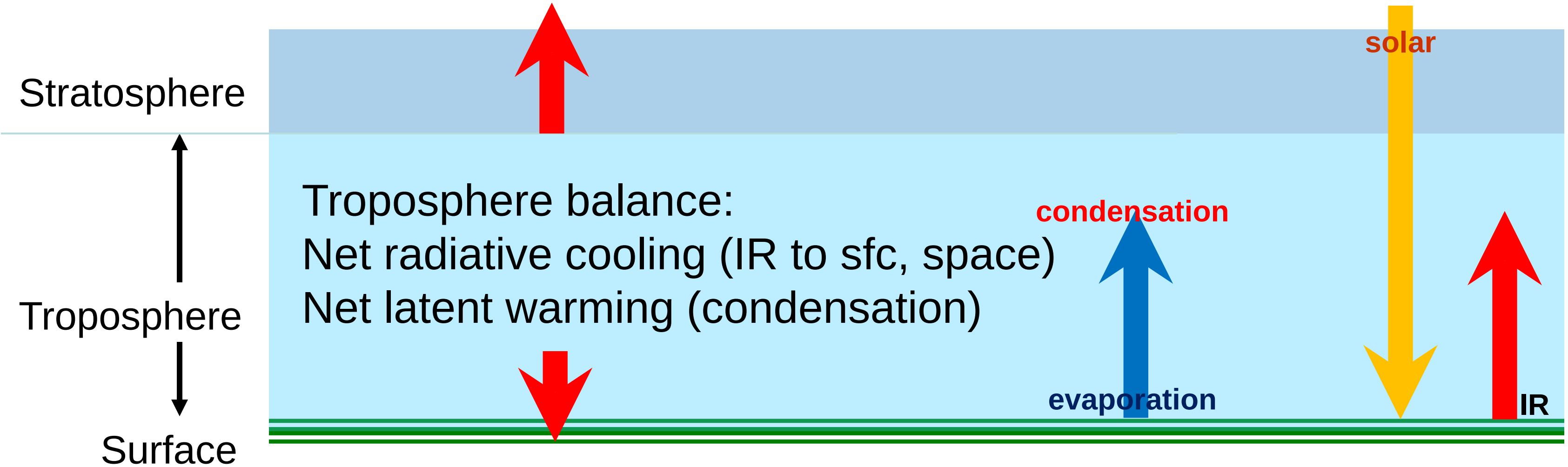


Figure 2 Global-mean temperature and precipitation changes in AOGCM simulations (scatter plots), and probability distributions obtained by requiring consistency with recent observations (curves). Red triangles show global-mean temperature and precipitation changes in a wide range of equilibrium CO_2-doubling experiments with simple thermodynamic ('slab') oceans[4,45], with the red line showing the best-fit (least squares) linear relationship. Green diamonds show the same, at the time of CO_2 doubling, for those CMIP-2 models for which the data are available[25]. Blue crosses are the green diamonds adjusted for disequilibrium in the CMIP-2 runs by adding $\kappa F_S/k_T$ to ΔT (equation (2)), with a single value of κ ($\simeq 1$) estimated from the data to remove the bias with the best-fit line through the 'slab' experiments. All these points would lie on the dashed line labelled C–C if precipitation were to follow the Clausius–Clapeyron relation[44]. The green dashed curve is the observationally constrained estimate of the distribution of global-mean temperature change at the time of CO_2 doubling from Fig. 1. The blue curve is the same, but adjusted for disequilibrium like the blue crosses. The red curve shows the distribution of global-mean precipitation changes implied by the blue curve, assuming the same straight-line relationship observed in the 'slab' experiments, with the same amount of scatter (assumed Gaussian).

Vapor increase ~ 7% per K warming

Precipitation increase ~ 3.5% per K warming

Why does precipitation increase at a slower rate (per K warming) than vapor?



Surface balance:
Net radiative heating (solar – IR)
Net latent cooling (evaporation)

$$\Delta R_C + \Delta R_T = L \Delta P$$

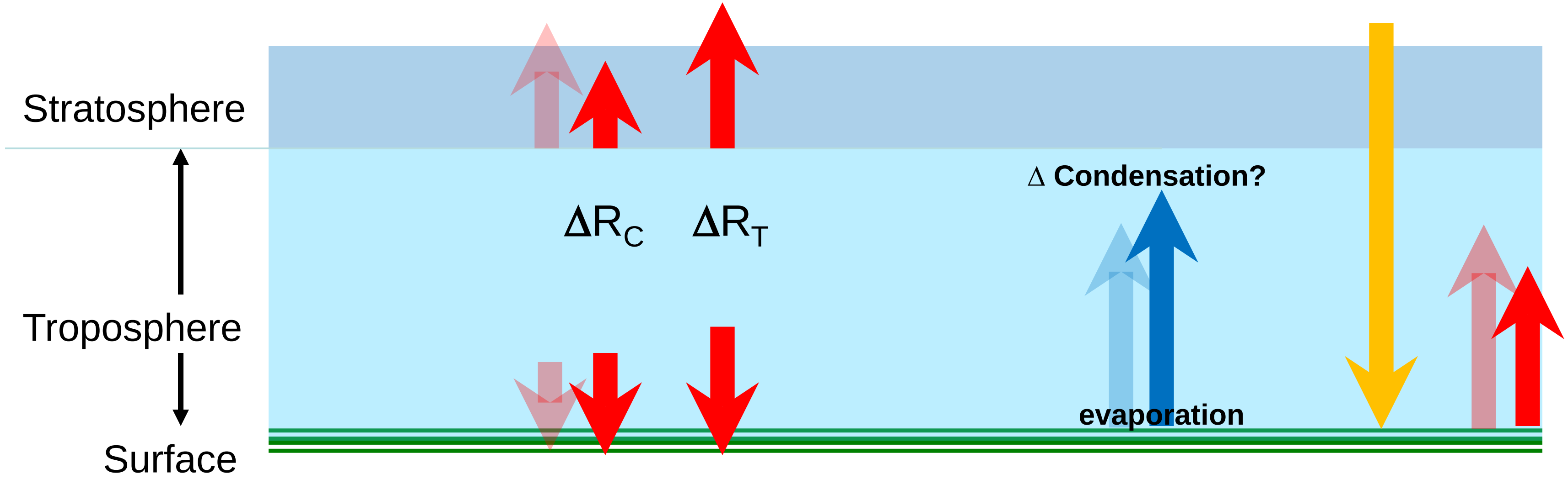
Changes in hydrologic cycle not constrained by moisture, but by energy balance

Limiting factor: Ability of troposphere to radiate away latent heat from precipitation

Tropospheric balance: Change in radiation (ΔR) $\propto$ change in precipitation (ΔP)

Radiation changes: T independent (ΔR_C) versus those a function of T (ΔR_T)

Consider case of doubling CO_2



If no T change, reduce upward IR 3-4 W m^{-2}, increase downward IR ~1 W m^{-2}

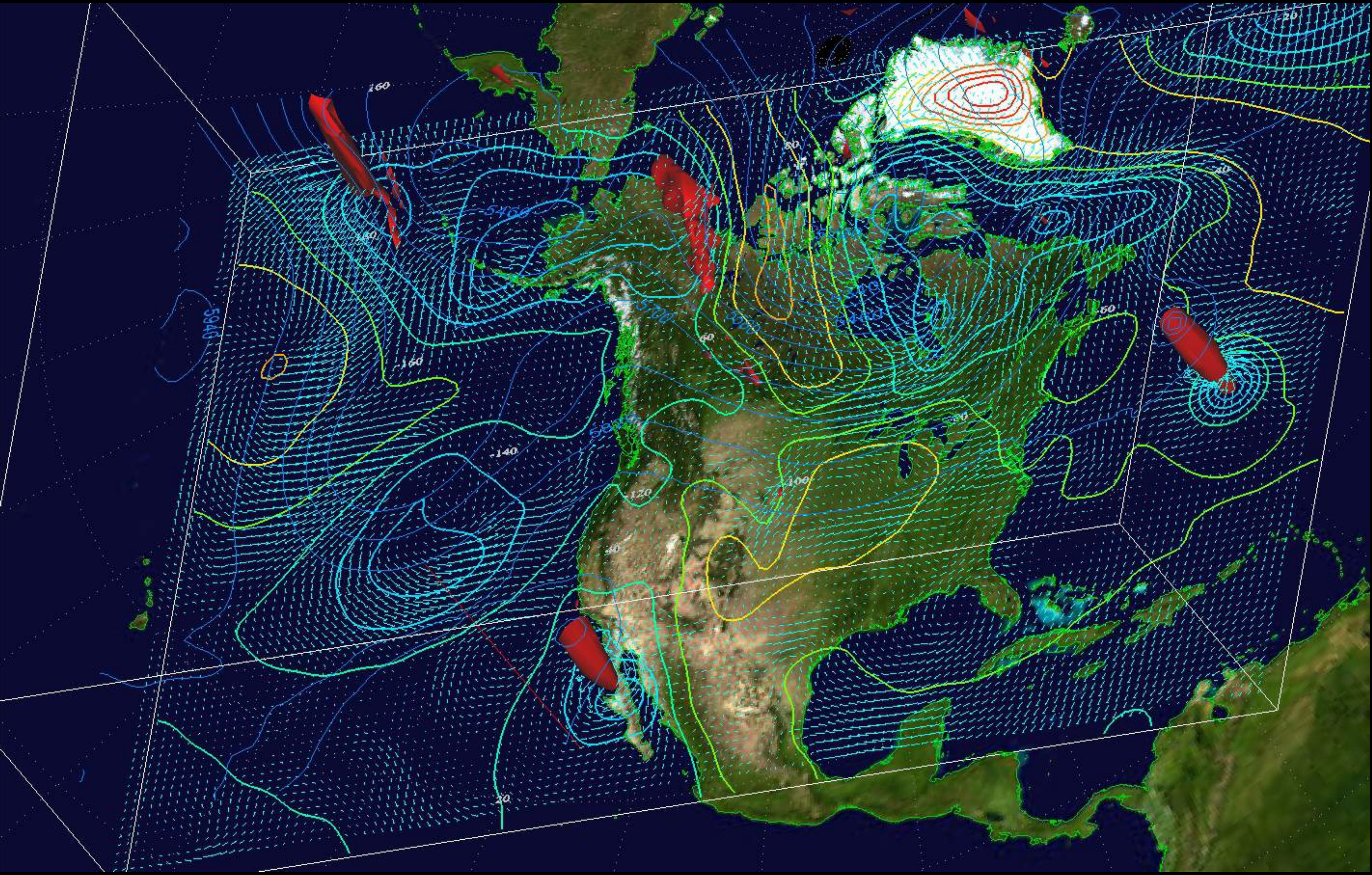
Net $\mathbf{\Delta R_C}$ -2 to -3 W m^{-2}, weaken hydrologic cycle significantly (- ΔP required)

But $\mathbf{\Delta R_T}$ also changes: Increased IR cooling, so ΔP > 0, but < vapor increase

$$\Delta R_C + \Delta R_T = L\Delta P$$

< 0 > 0 >0

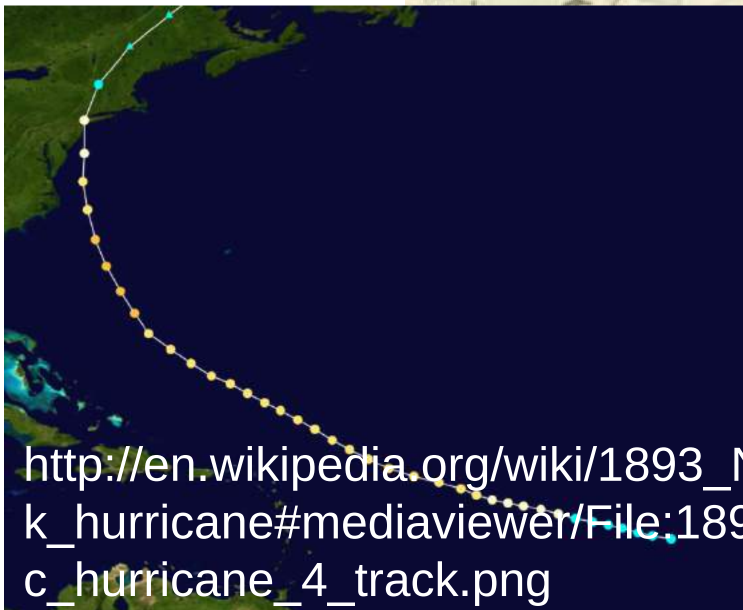
Odile, Edouard



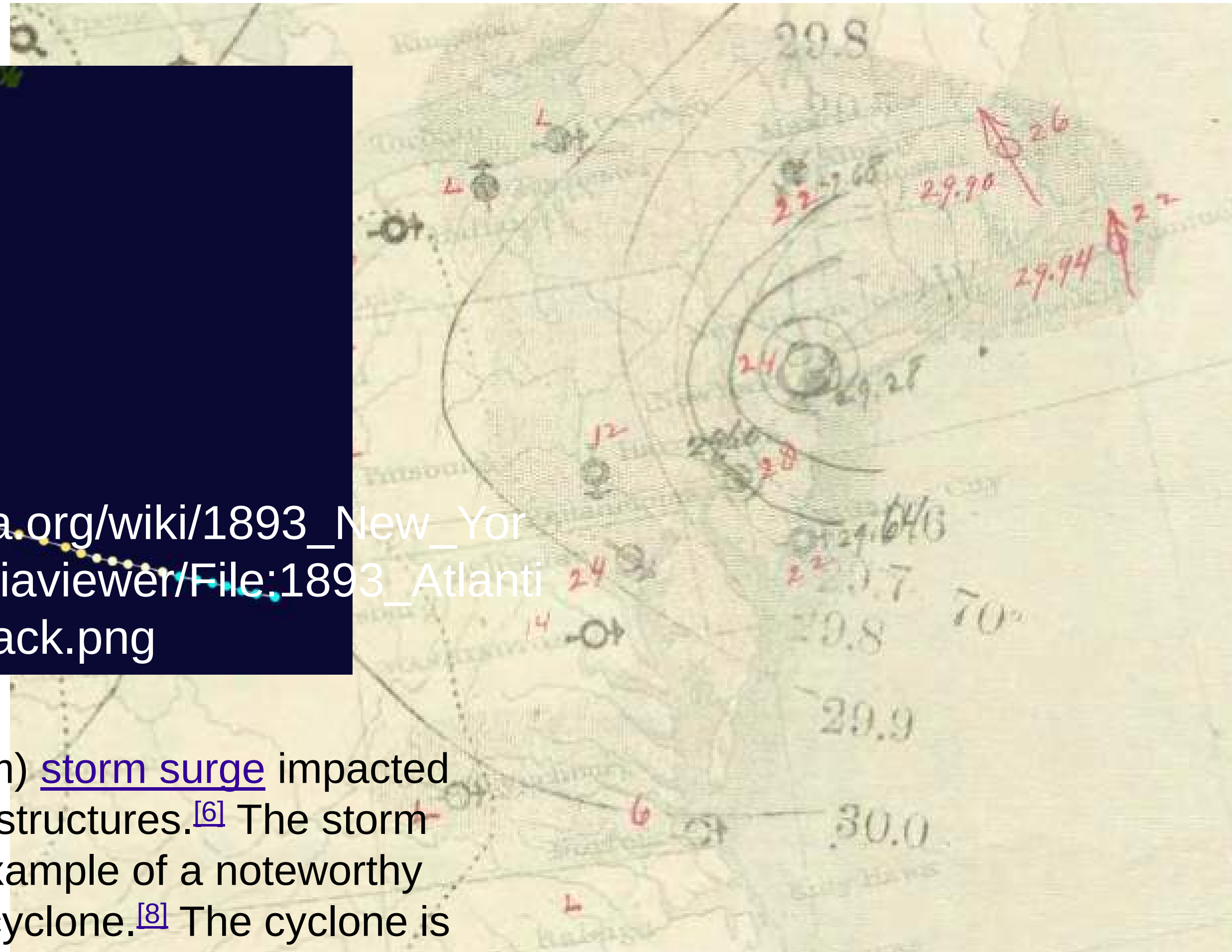
Historic New England Hurricanes

Bob Gaza:
“Then, the historic hurricanes such as Diane in 1955, which dropped 20" of rain on the south coast, just a week after Hurricane Connie had saturated the ground with heavy rains leading to extreme floods all across southern New England. And, as has been noted, the great Hurricane of 1938 with 120 mph sustained winds at Blue Hill - gusts to 187 mph - leading to 2 billion trees blown down. Providence was under water due, in part, to a phenomenal storm surge (~50 ft?). I just read about the Hurricane of 1893 in which storm tides reached 30 ft. in NYC (5 years after the Blizzard of 1888)! Ludlam reminds us of 4 hurricanes hitting New England between in 1954 and 1955, including the infamous Hurricane Carol and its 130 mph gusts on Block Island and extensive flooding and damage.

Hurricane of 8/24/1893



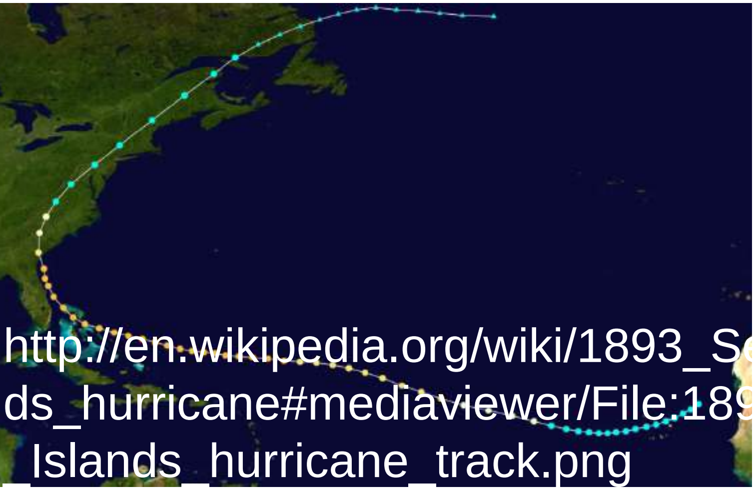
http://en.wikipedia.org/wiki/1893_New_York_hurricane#mediaviewer/File:1893_Atlantic_hurricane_4_track.png



Wikipedia: A 30 ft (9.1 m) storm surge impacted the shore, demolishing structures.[6] The storm has been cited as an example of a noteworthy New York City tropical cyclone.[8] The cyclone is known for largely destroying Hog Island, a developed island that existed south of the modern-day Long Island coast. The island peaked in size during the 1870s at about 1 mi (1.6 km) long.[9]

NOAA Central Library Silver Spring, Maryland NOAA Central Library Data Imaging Project

“Sea Islands” Hurricane of 8/24/1893



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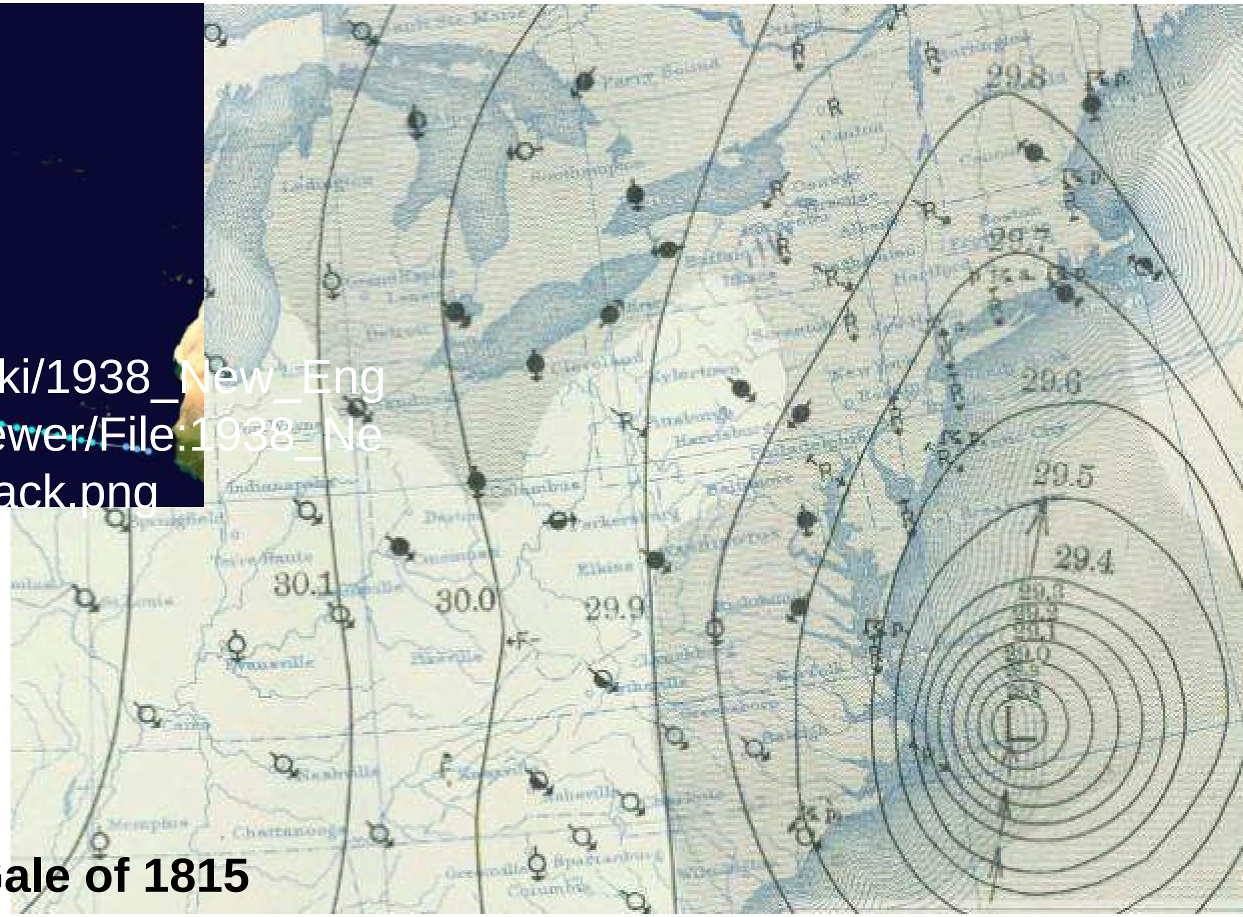
New England Hurricane of 9/21/1938

http://en.wikipedia.org/wiki/1938_New_England_hurricane#mediaviewer/File:1938_New_England_hurricane_track.png

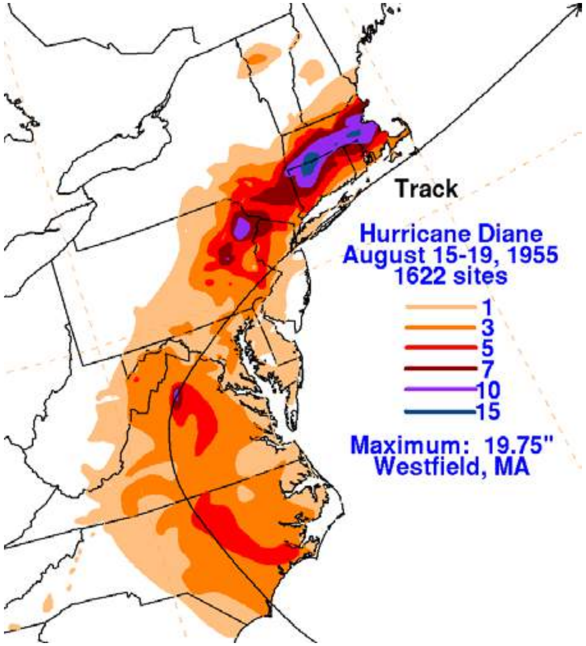


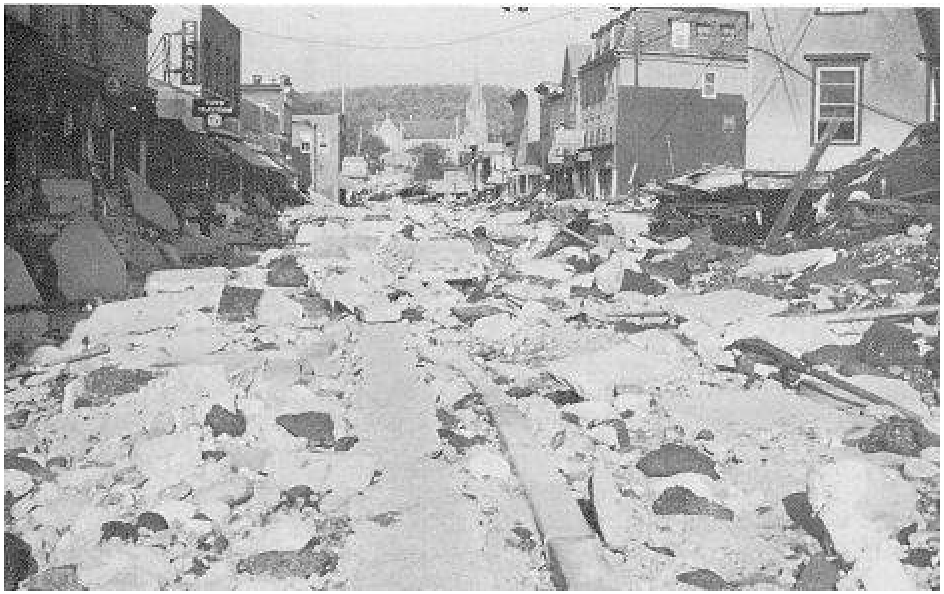
Great September Gale of 1815
NYC 9/23/1815

1821 Norfolk and Long Island Hurricane

[NOAA Central Library Data Imaging Project](http://docs.lib.noaa.gov/rescue/dwm/1938/19380921.djvu)
http://docs.lib.noaa.gov/rescue/dwm/1938/19380921.djvu

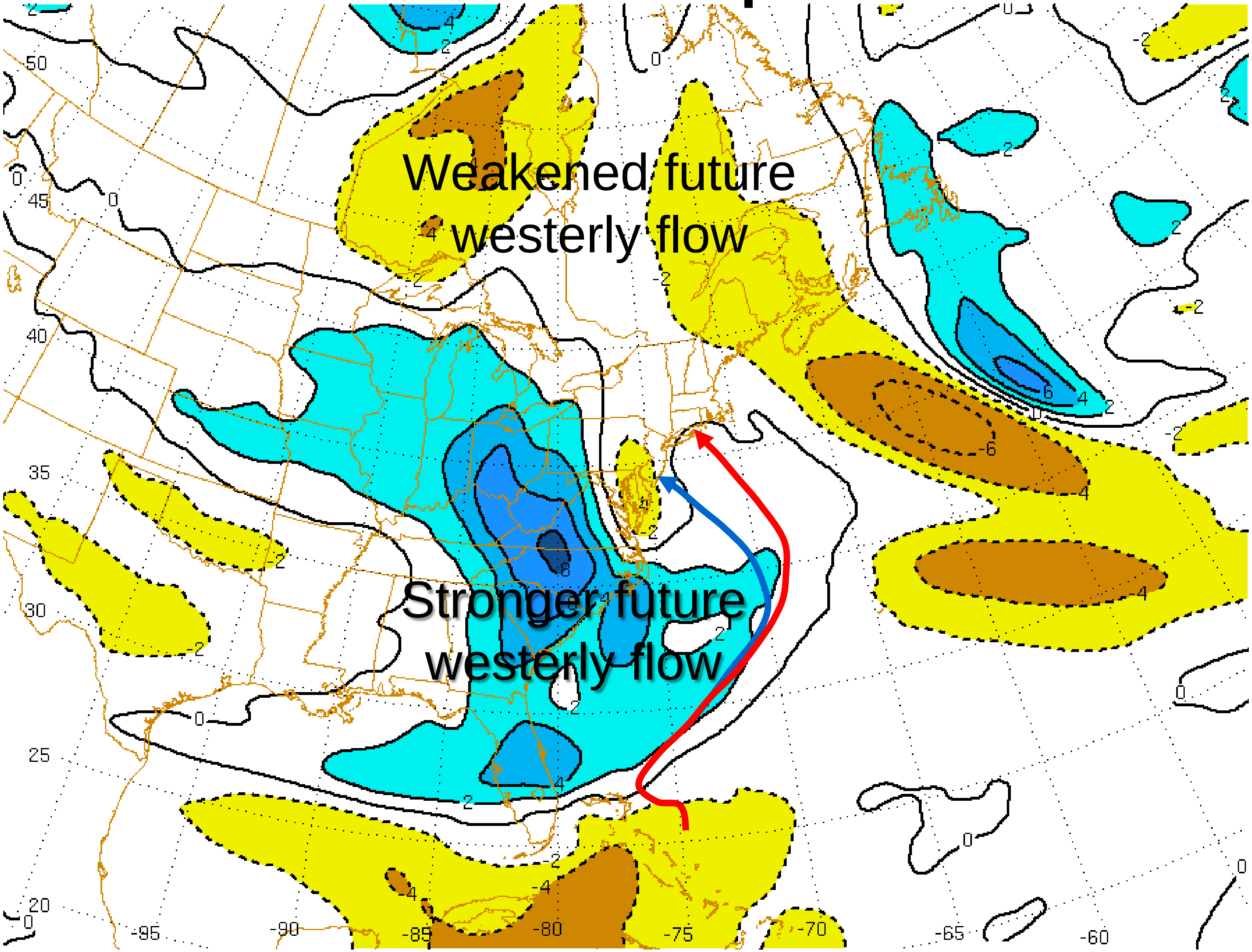
Diane, 1955





http://en.wikipedia.org/wiki/Hurricane_Diane

Time-averaged 300 hPa zonal wind change, **future minus present**



TAUREL 300 future minus current