

Adjoint Sensitivity Diagnosis of the Intensification of Hurricane Harvey

Zoë Brooke Zibton¹, Michael Morgan¹, and Brett Hoover²

¹University of Wisconsin-Madison, ²Cooperative Institute for
Meteorological Satellite Studies

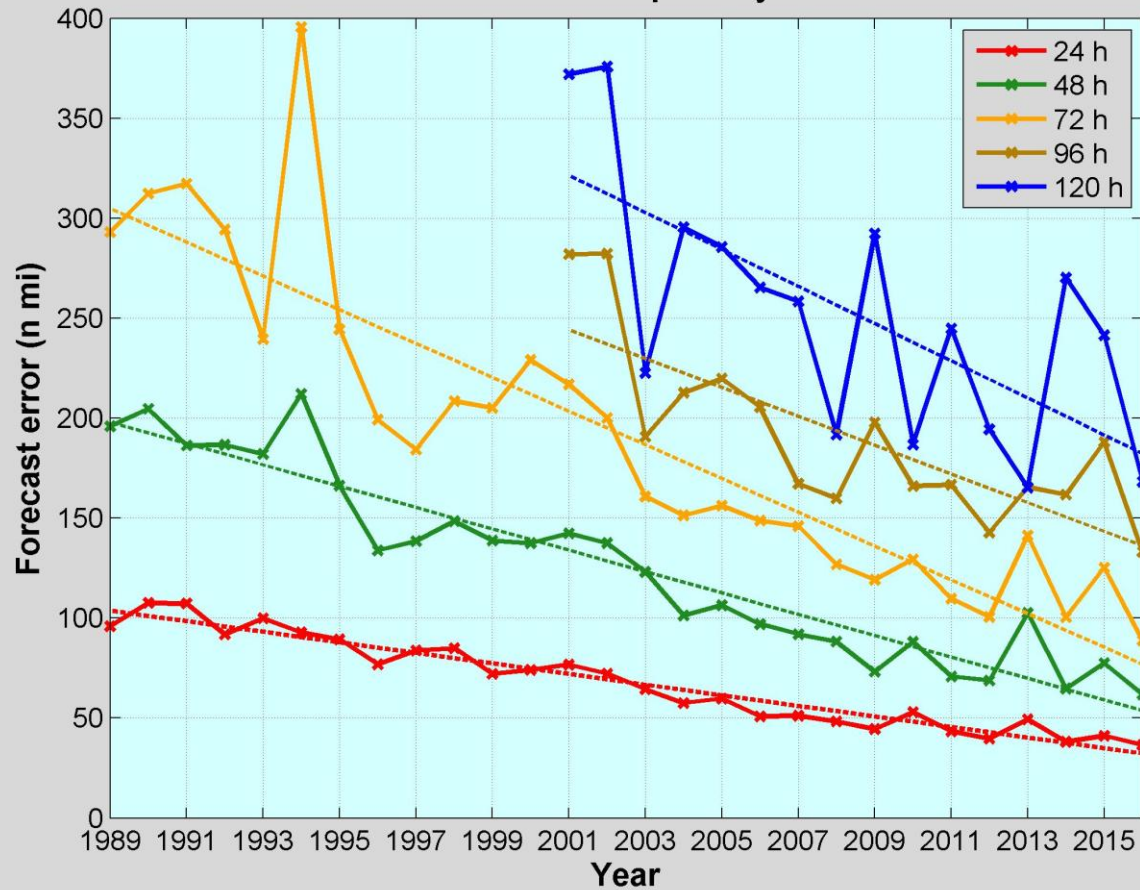
2 July 2018

Motivation

- TC intensity change forecasts remain a challenge
- Sensitivity studies can help understand impact of IC errors and uncertainties
- Sensitivity techniques
 - Past studies
 - Ensemble Sensitivity (Brown and Hakim 2015)
 - Adjoint Sensitivity (Doyle et al 2012)
- Apply adjoint-derived diagnostics to study Hurricane Harvey

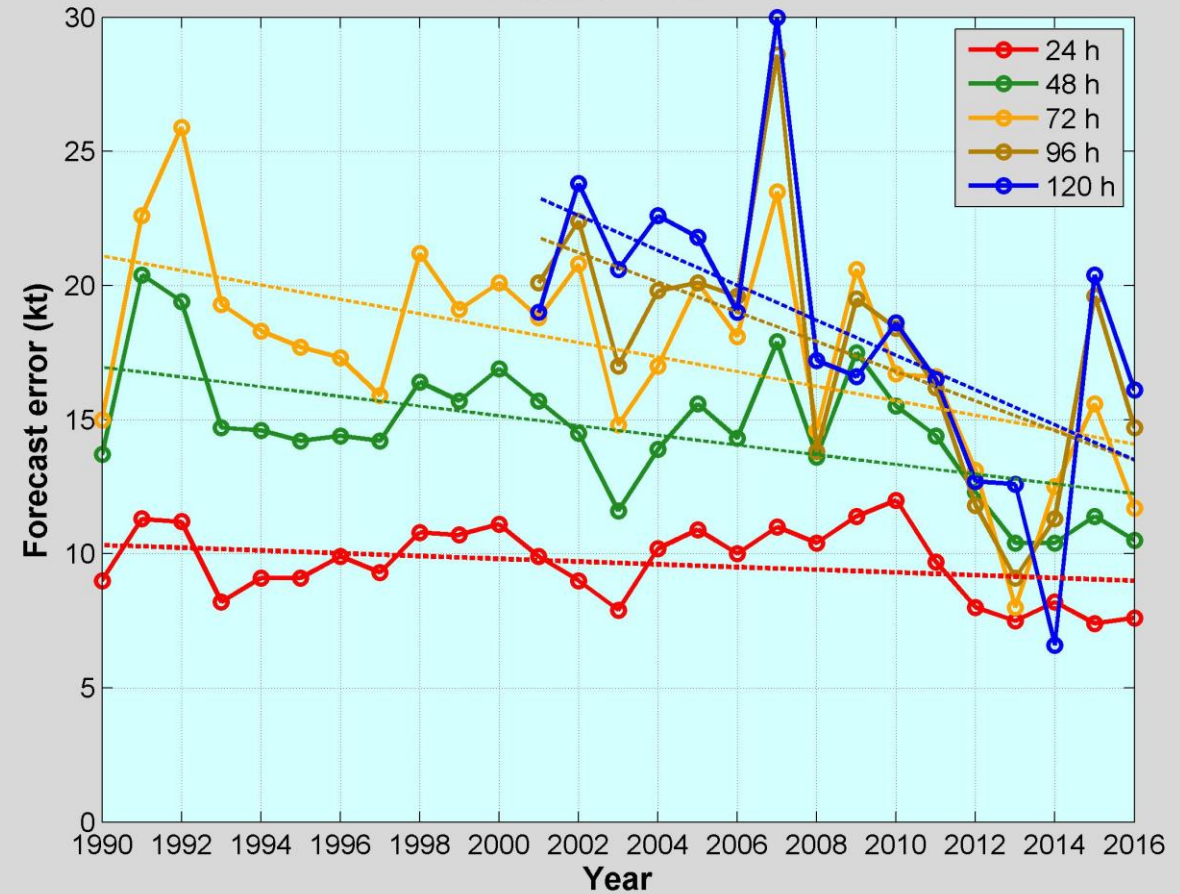
Track

NHC Official Annual Average Track Errors
Atlantic Basin Tropical Cyclones

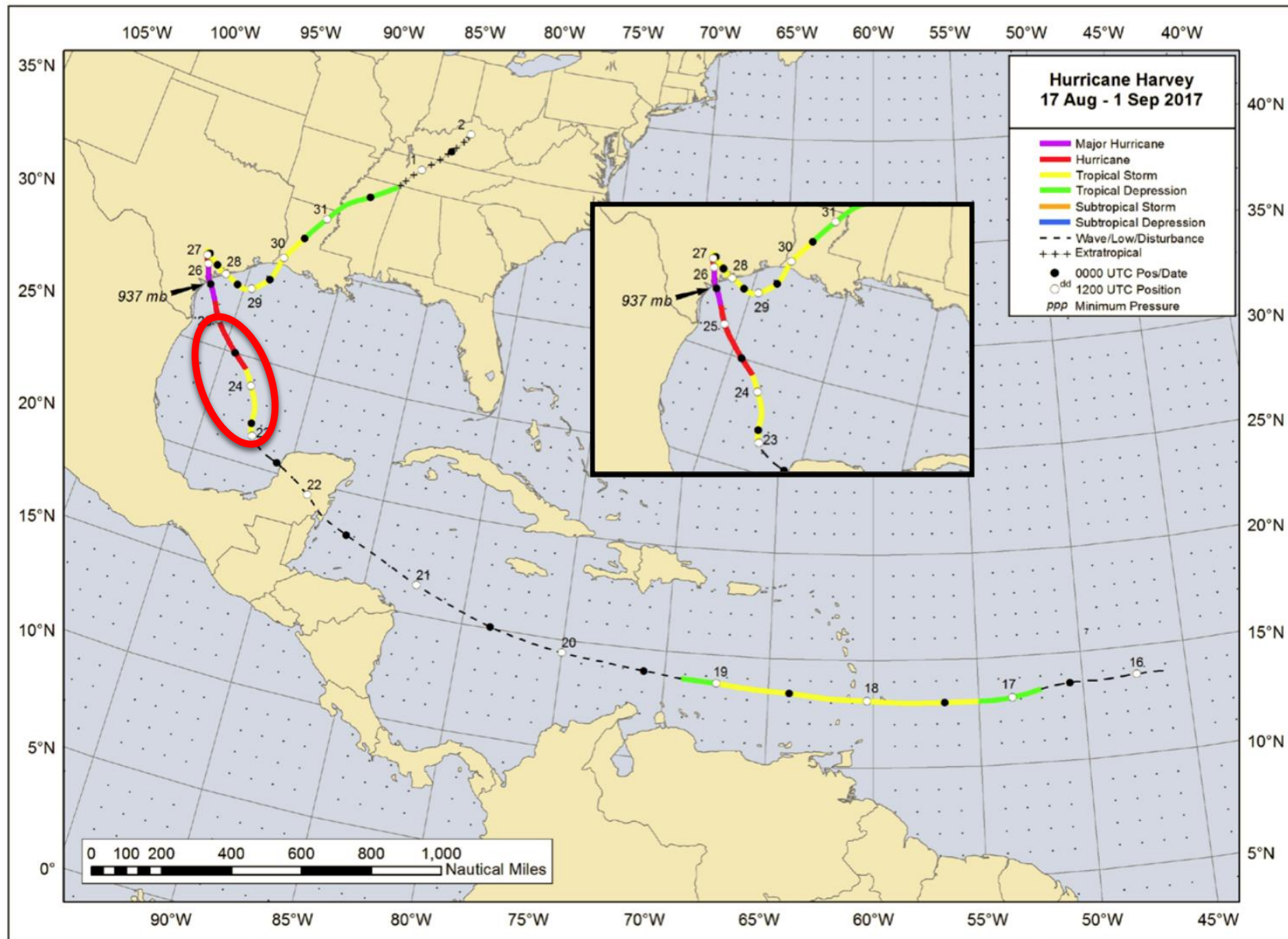


Intensity

NHC Official Intensity Error Trend
Atlantic Basin



Hurricane Harvey 2017

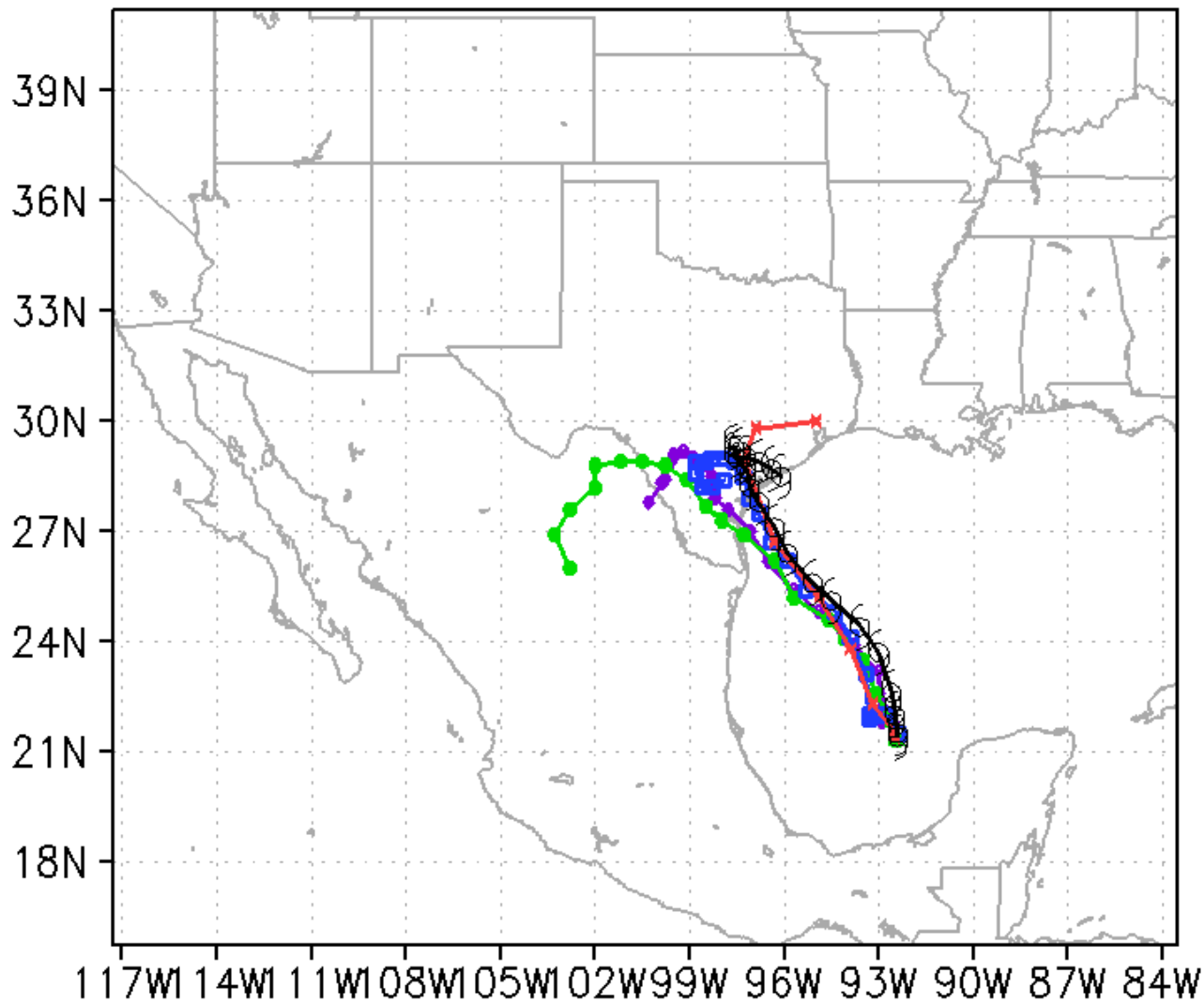


Source:
NHC Tropical
Cyclone Report
Hurricane Harvey

Operational HWRF: TC Tracks

Storm: HARVEY (09L) valid 2017082312

- ◆ HWRF: HWRF
- AVNO: Oper. GFS
- ✦ OFCL: NHC Official
- BEST: Best Track
- ◆ HM0N: Oper.
- NVGM: NVGM model
- ◆ CTCX: COAMPS-TC w/GFS



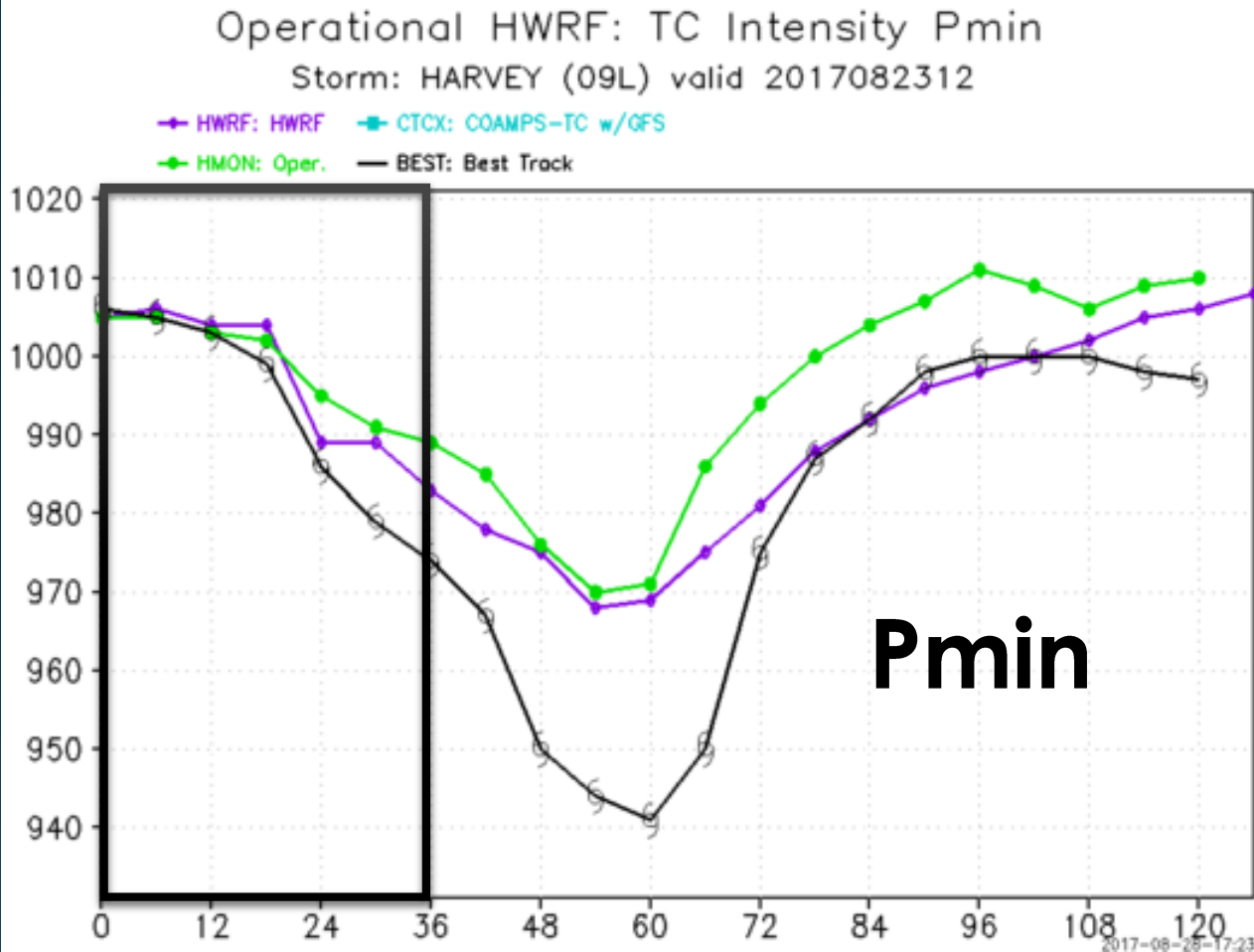
2017-08-28-17

Forecasts
initialized:
1200 UTC 23
August 2017

Agreement
between observed
and model forecast
tracks

Source: <http://www.emc.ncep.noaa.gov>

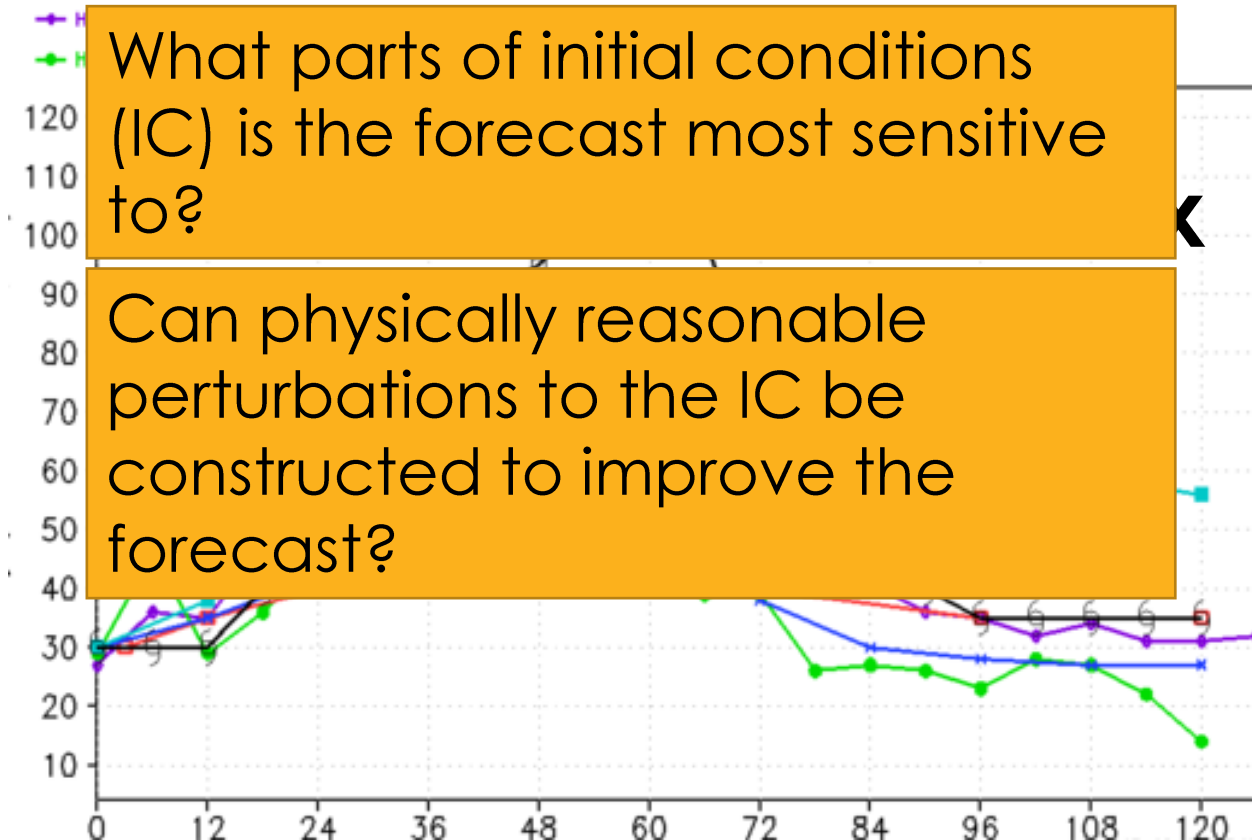
Forecasts initialized: 1200 UTC 23 August 2017



What lead to the underforecast?

What parts of initial conditions (IC) is the forecast most sensitive to?

Can physically reasonable perturbations to the IC be constructed to improve the forecast?



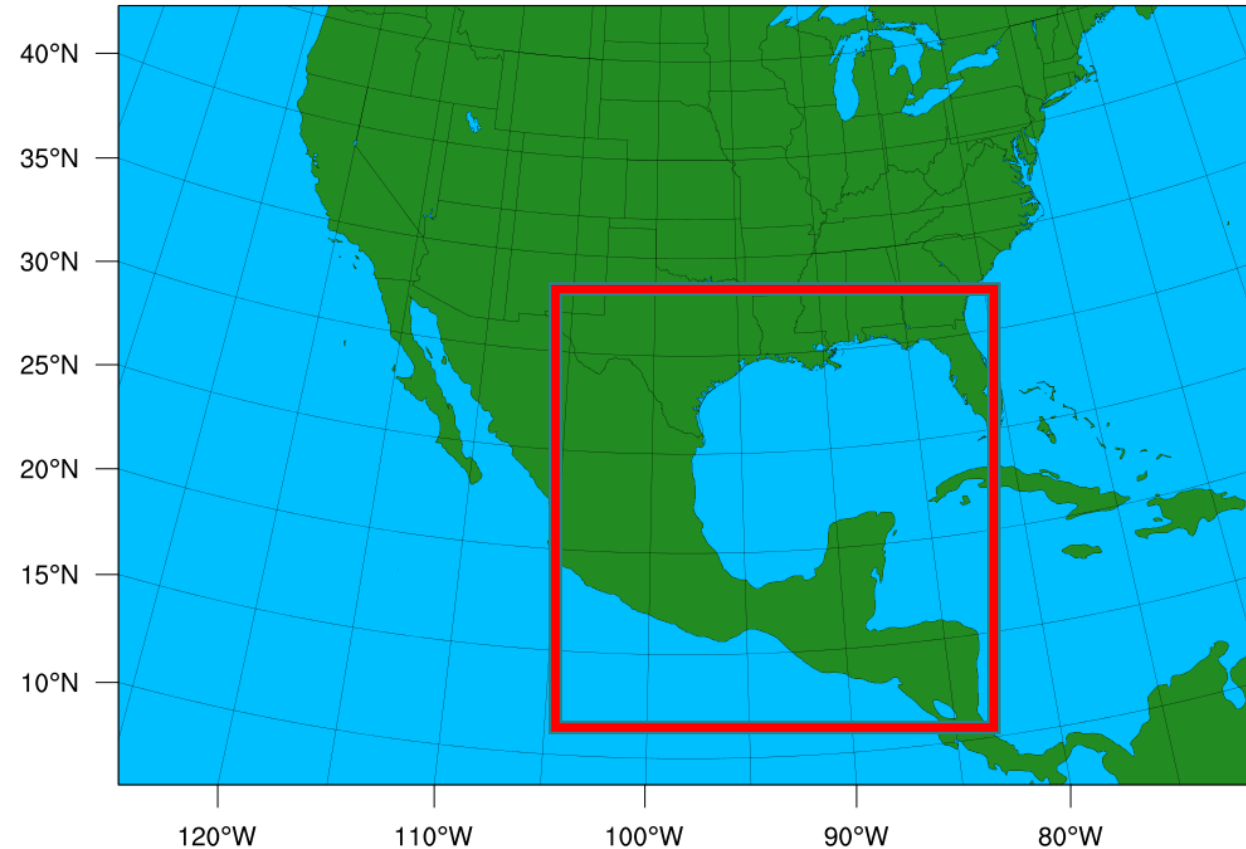
Forecasts deviate significantly from observed after ~20 hours

Model

- WRF-ARW V3.8.1 and its adjoint
- 30 km grid spacing
- 41 evenly spaced vertical levels
- 0.25° GFS final analysis global data
- 36 hour forecast and adjoint integration

Near Environment

WPS Domain Configuration

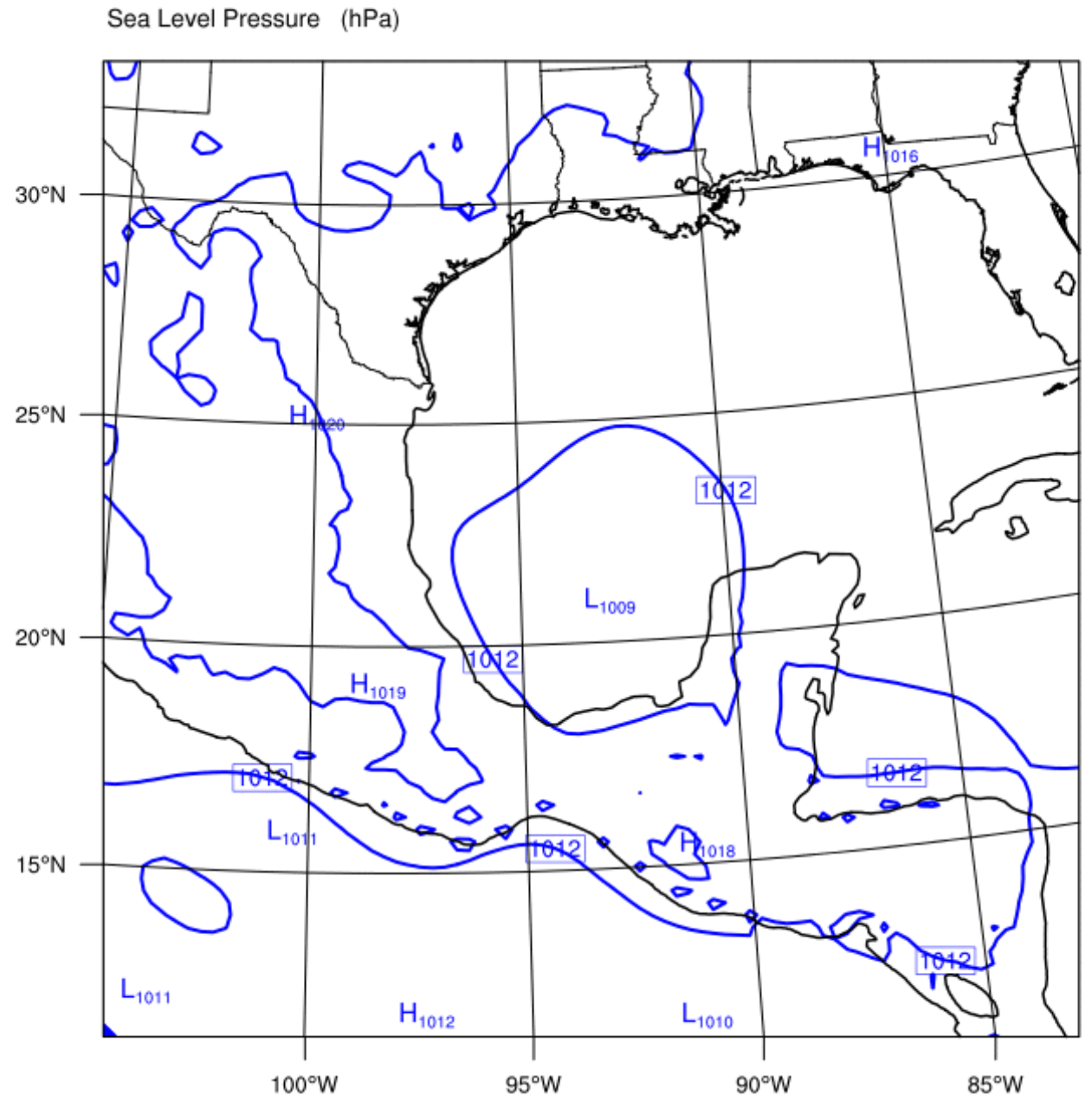


Simulation initialized: 1200 UTC 23 August 2017

Shown:
Near Environment

Contour:
MSLP [hPa]

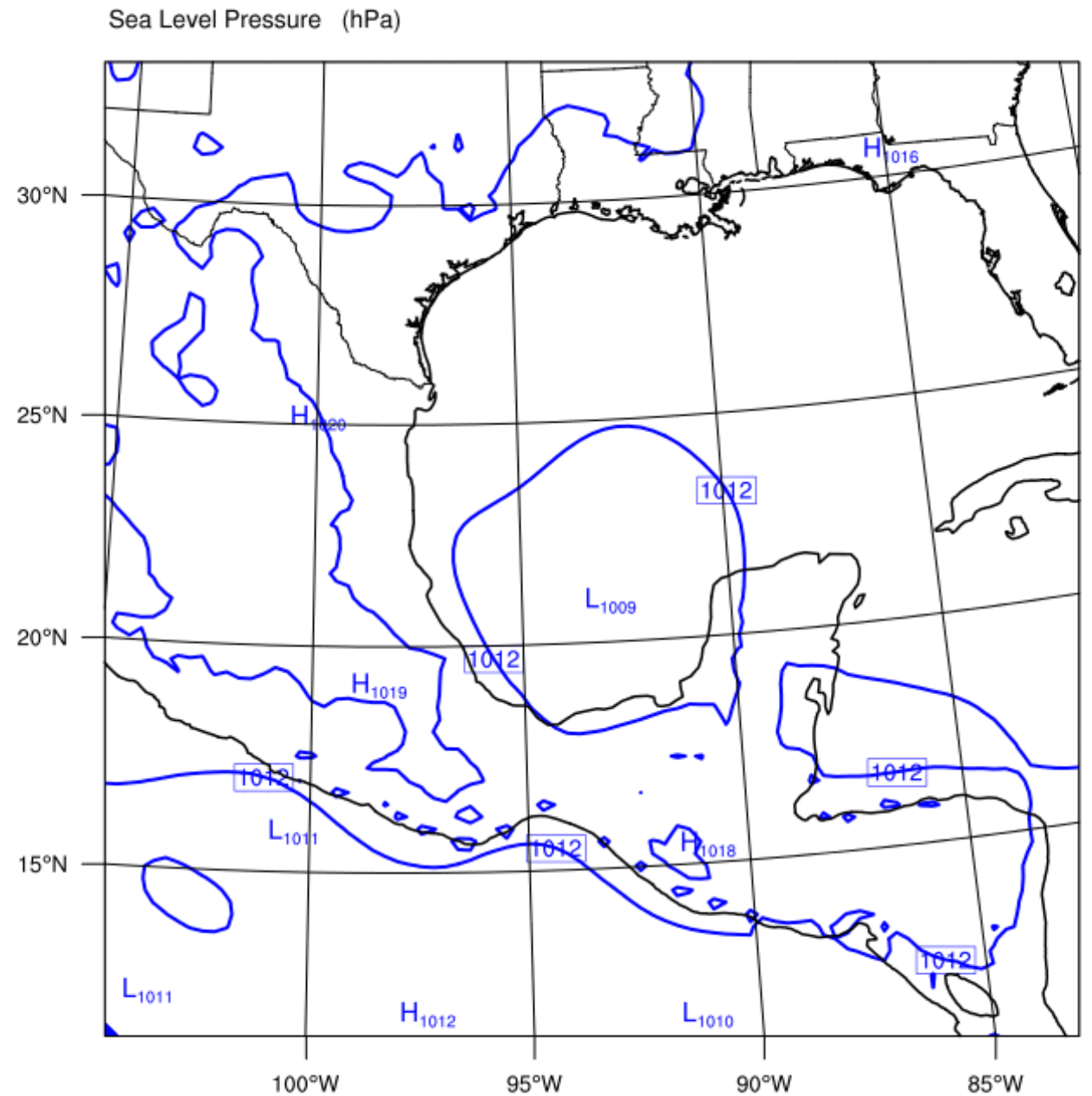
Minimum pressure:
WRF: 1008.9 hPa
OBS: 1006.0 hPa



**Simulation
initialized:
1200 UTC 23
August 2017**

Shown:
Near Environment

Contour:
MSLP [hPa]



36h simulation:

Valid: 0000 UTC
25 August 2017

Shown:

Near Environment

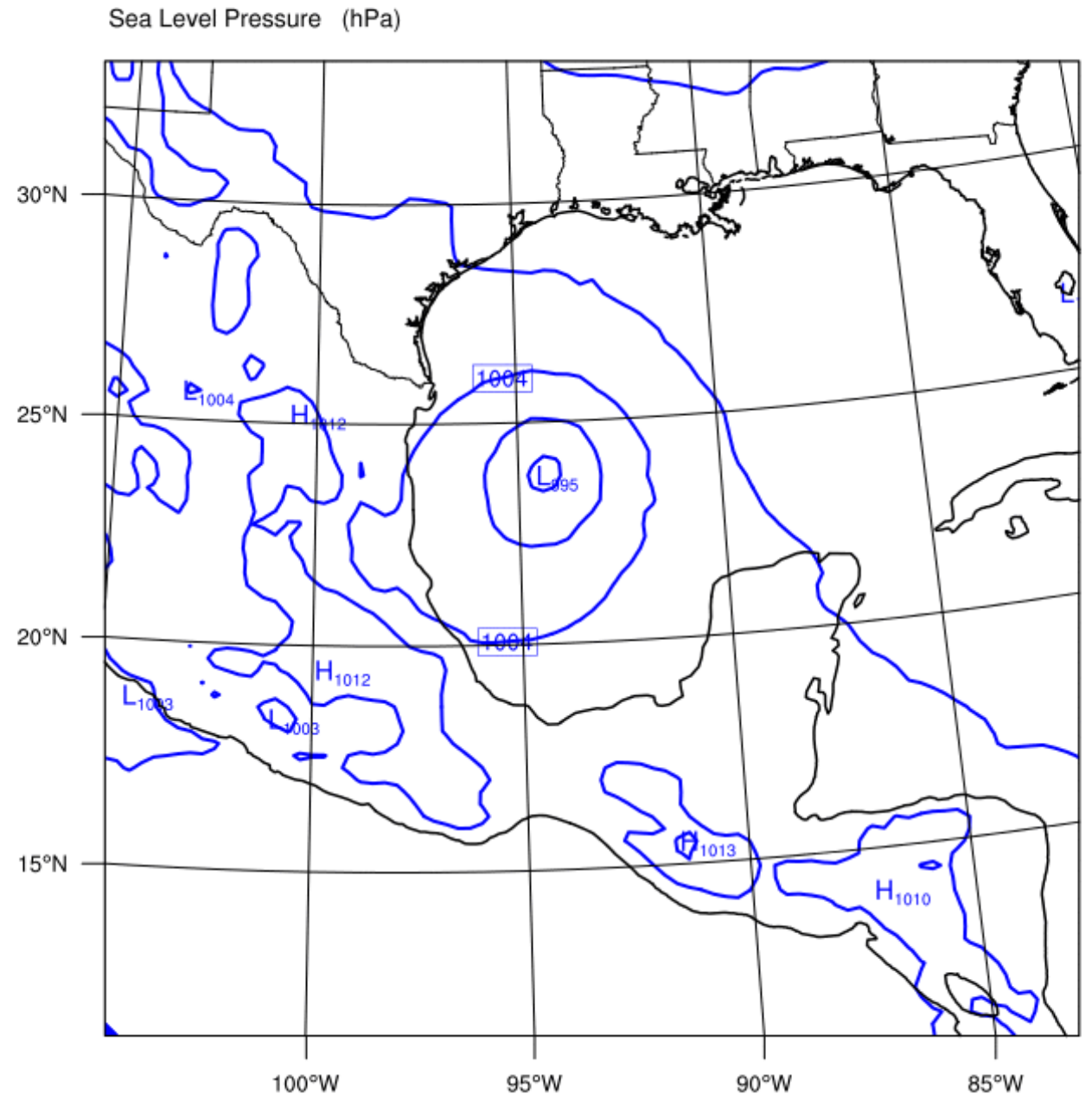
Contour:

MSLP [hPa]

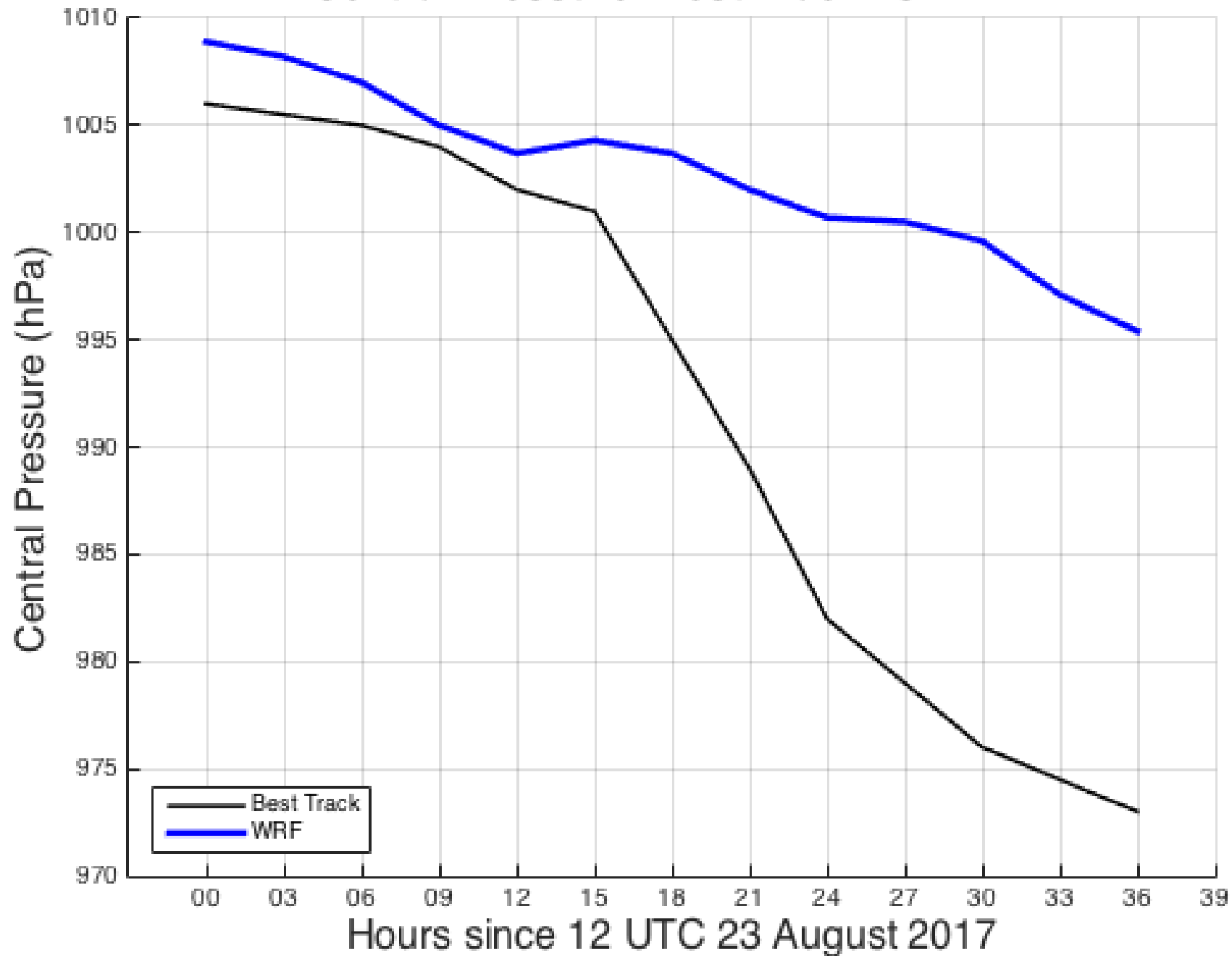
Minimum pressure:

WRF: 995.4 hPa

OBS: 973.0 hPa



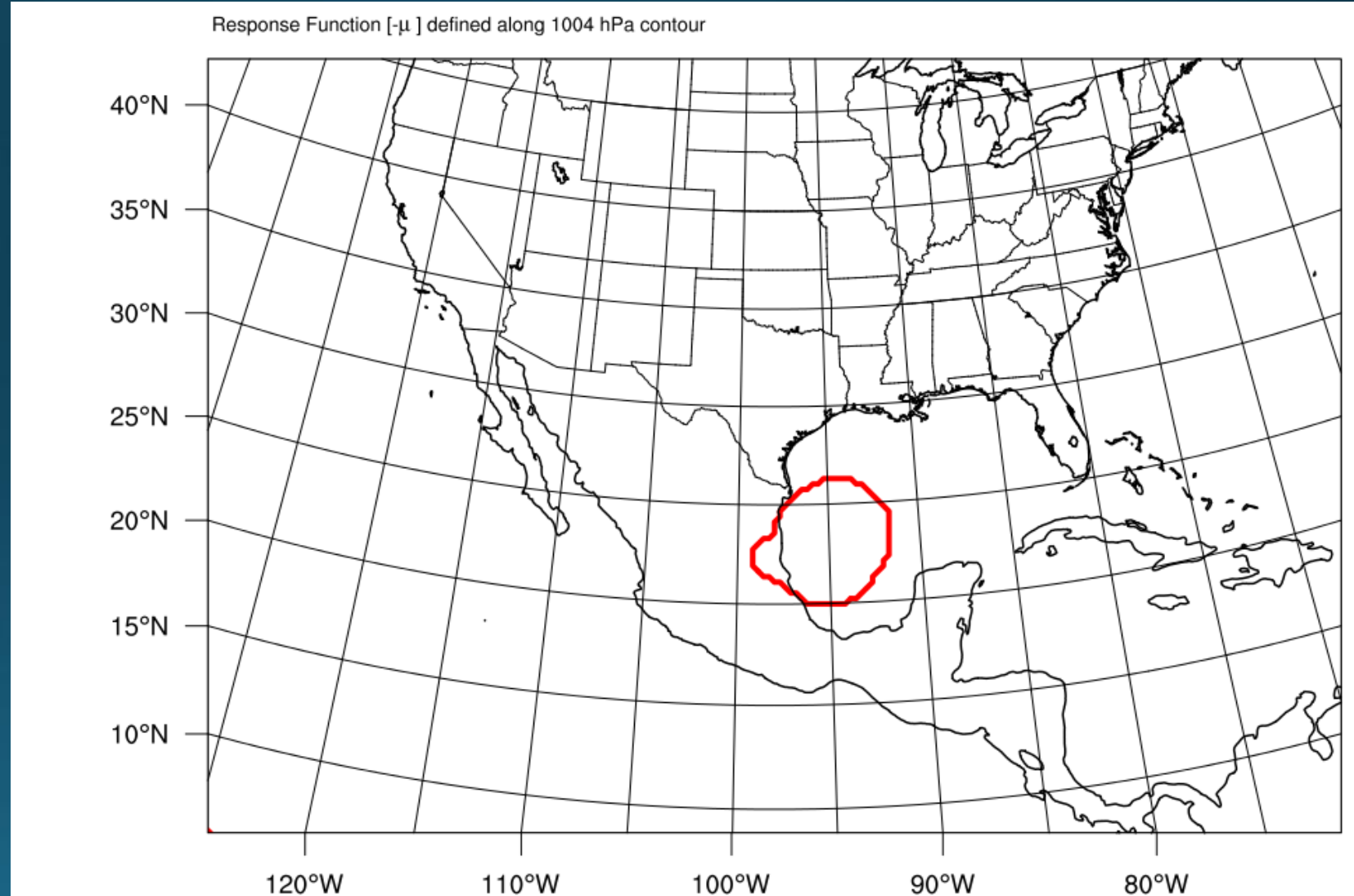
Central Pressure: Best Track vs. WRF



Response Function (R)

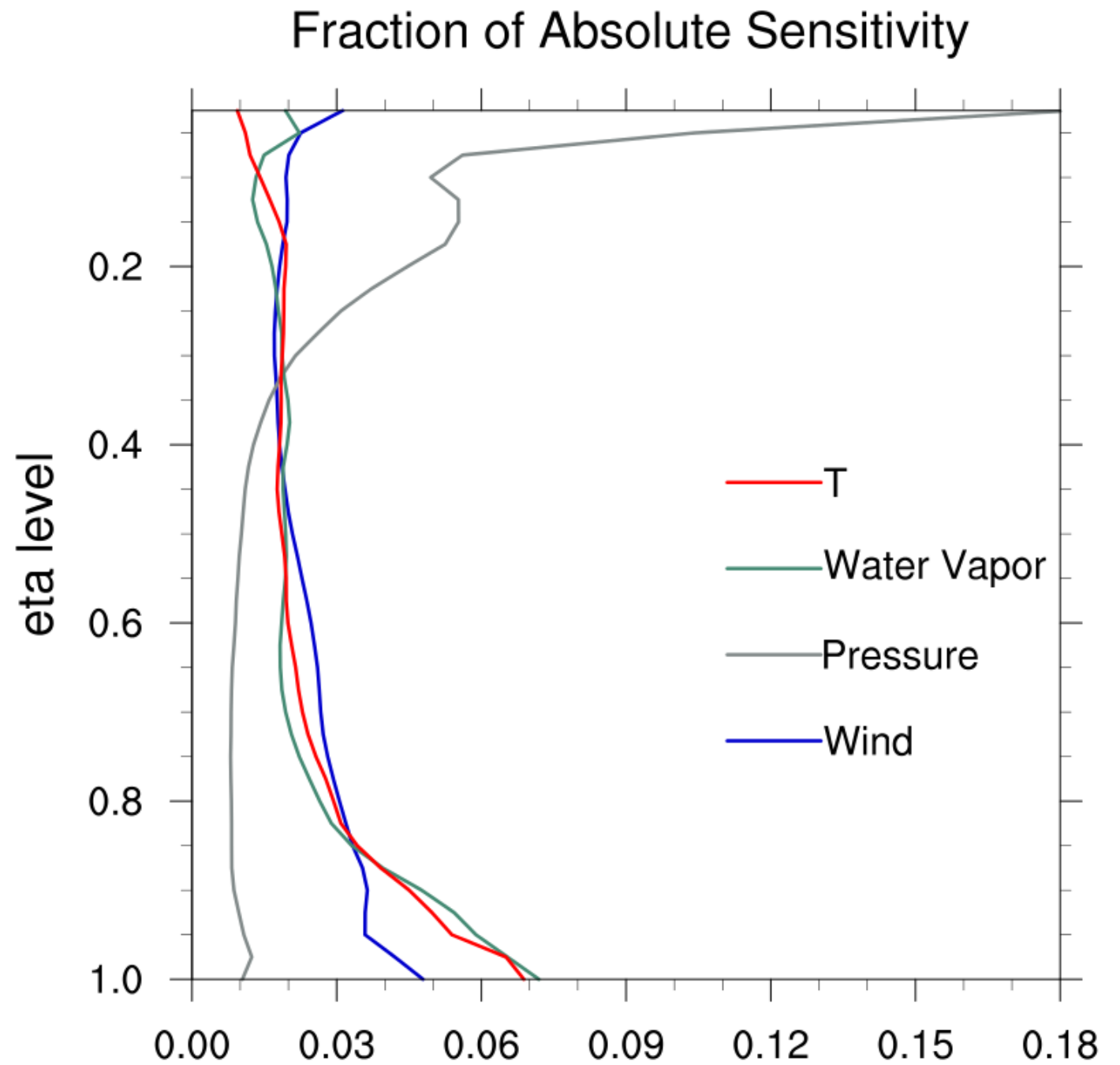
$R = -\bar{\mu}$
within 1004 hPa
contour

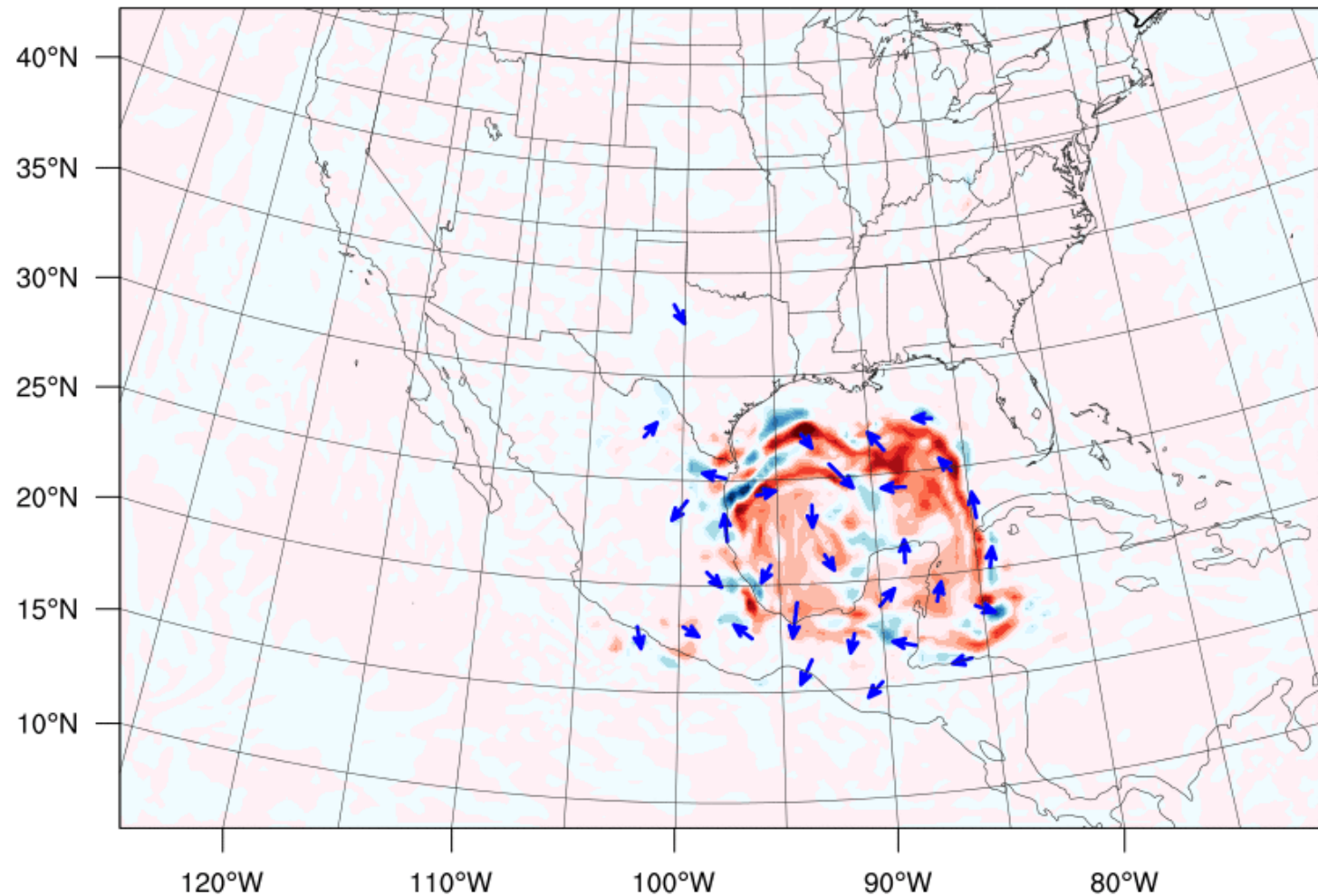
μ : perturbation
dry air mass in
column



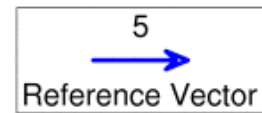
Sensitivities

- Greatest sensitivities occur under the 0.8 eta level
- Pressure peak near top of domain

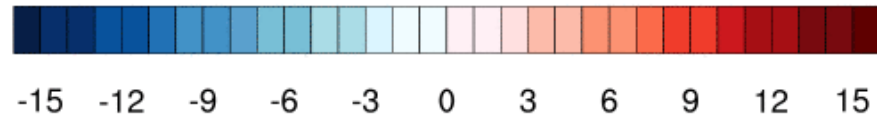


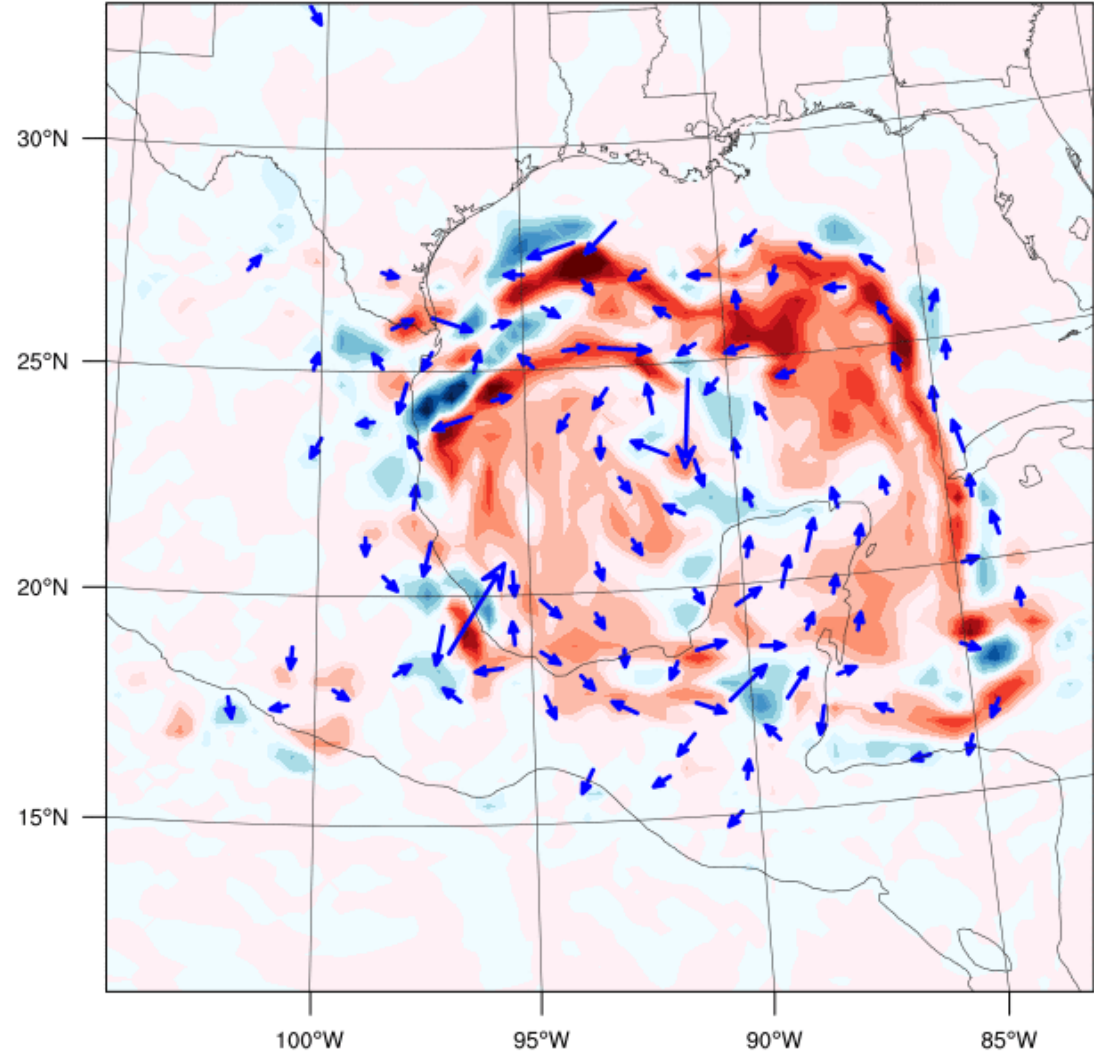


Sea Level Pressure Contours: 1004 to 1100 by 1000

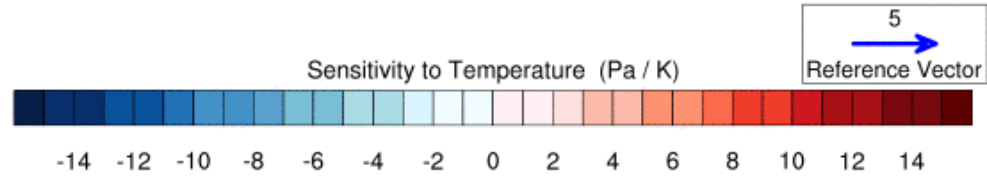


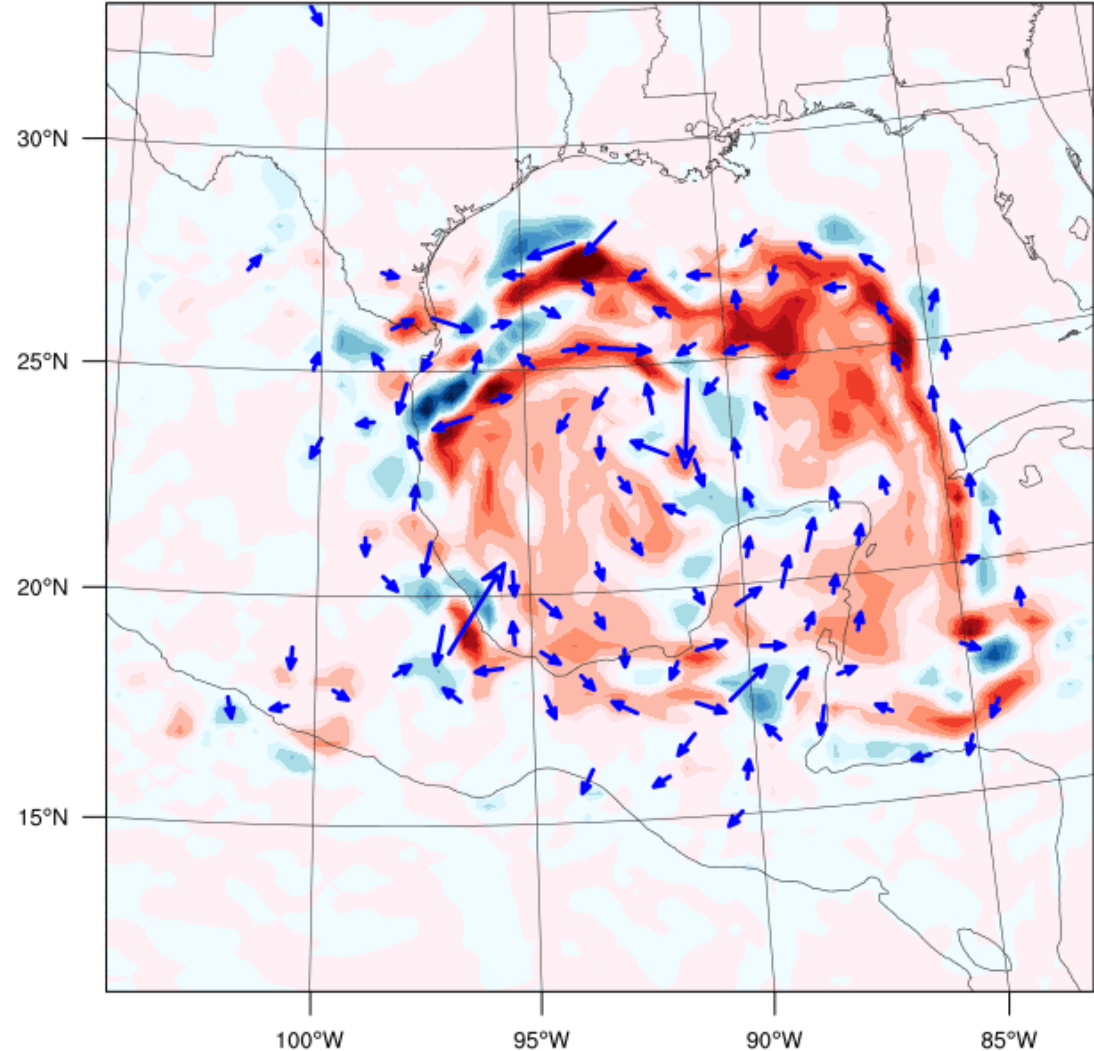
Sensitivity to Temperature (Pa / K)



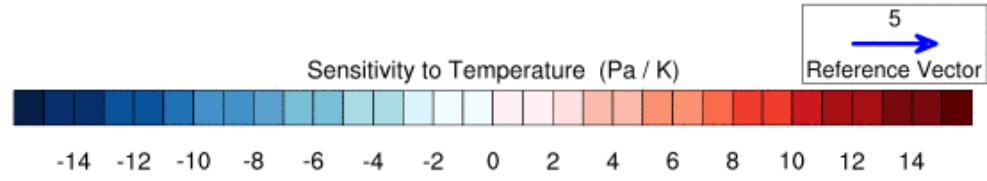


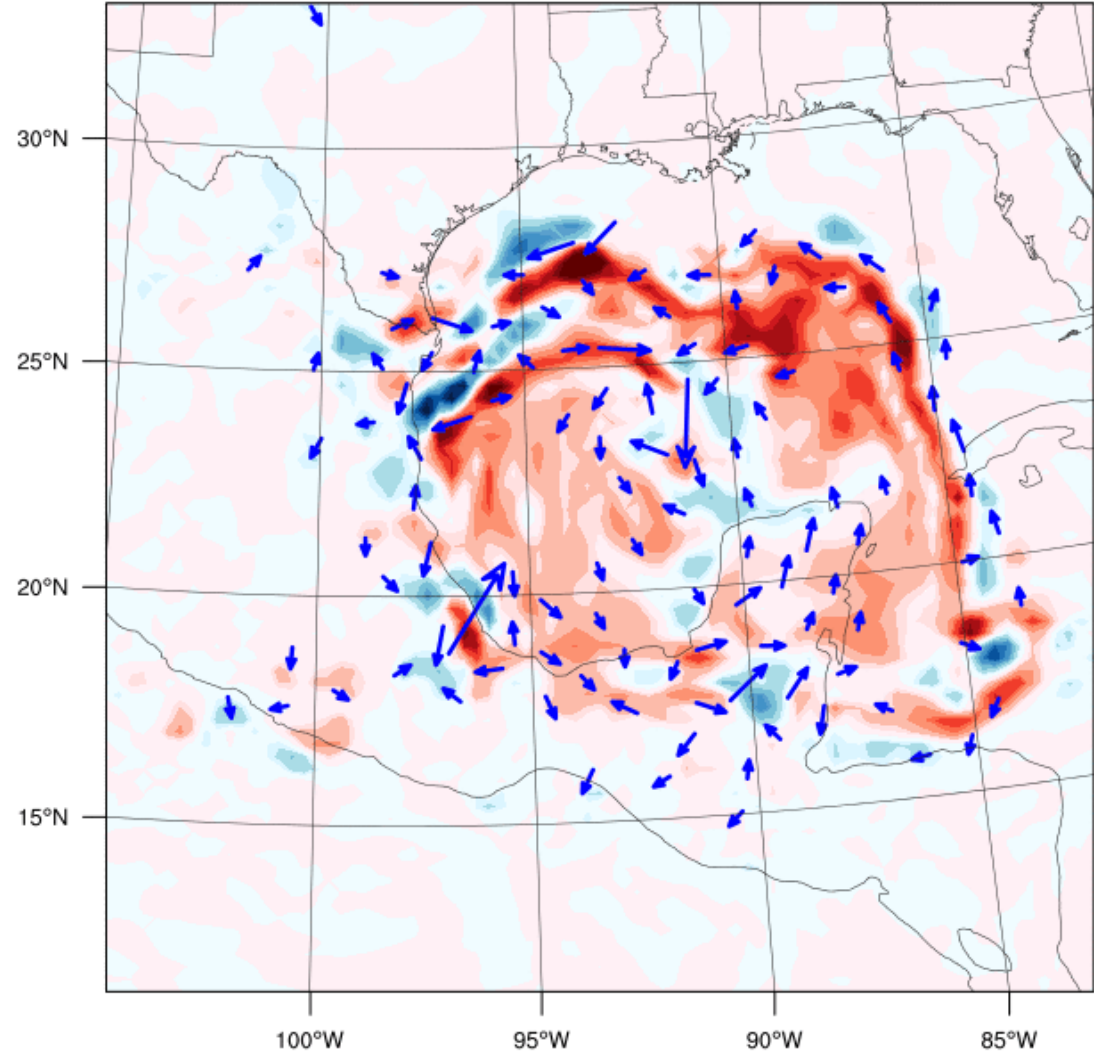
Sea Level Pressure Contours: 1004 to 1100 by 1000



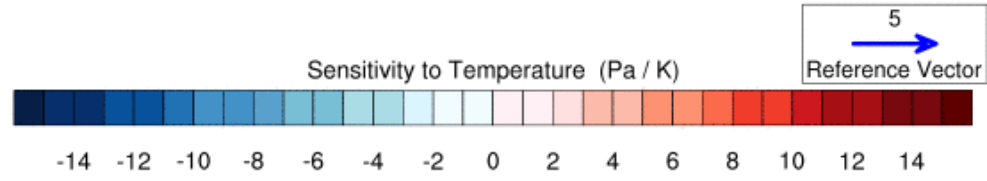


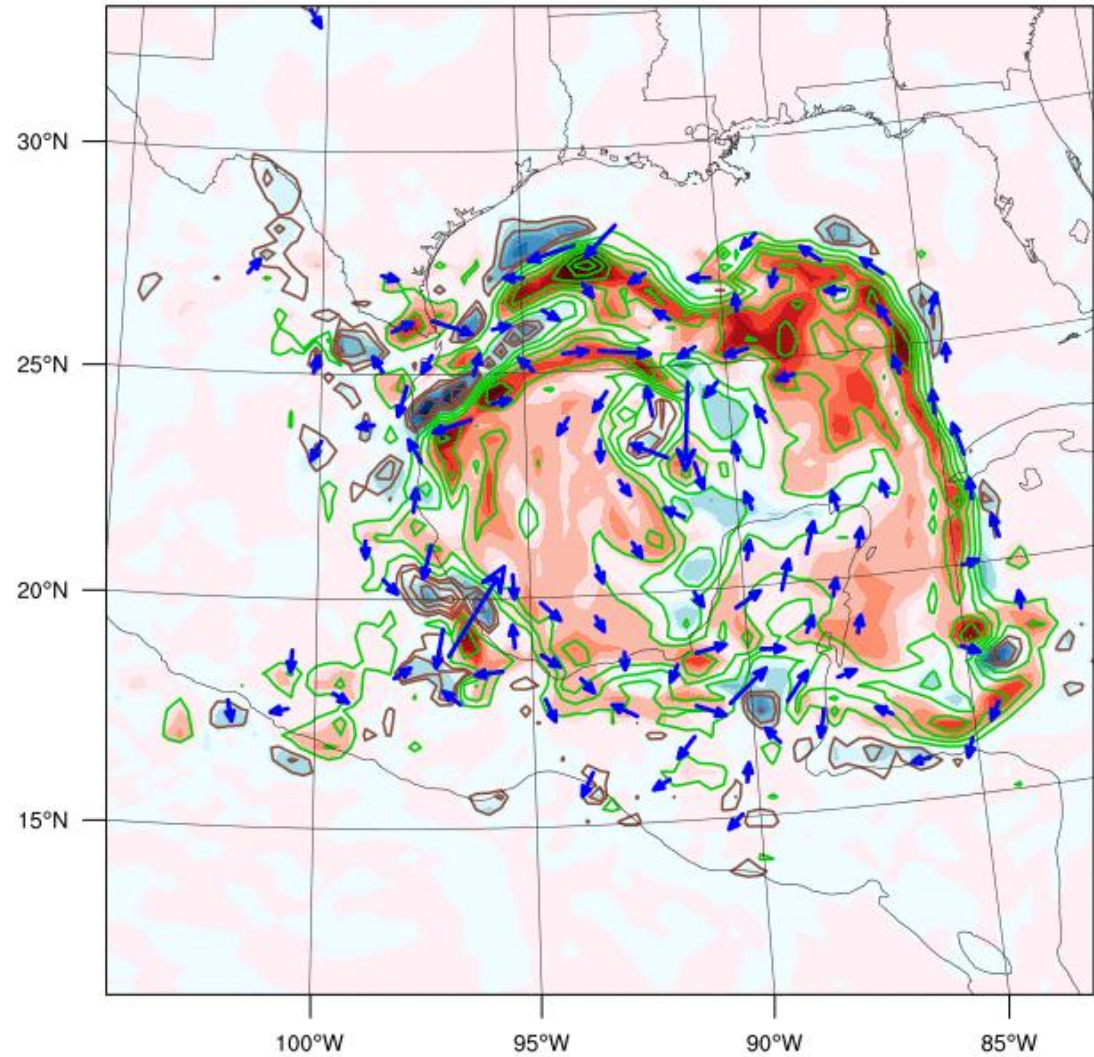
Sea Level Pressure Contours: 1004 to 1100 by 1000



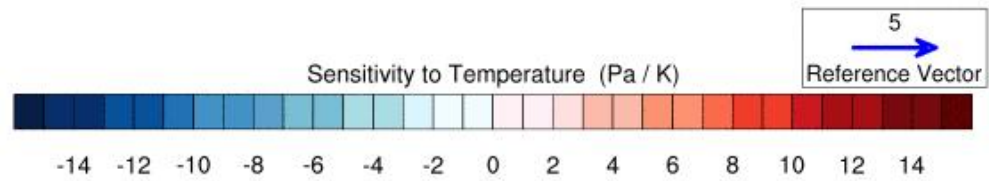


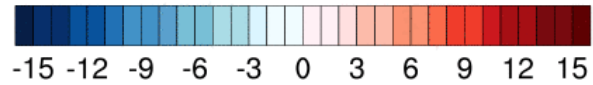
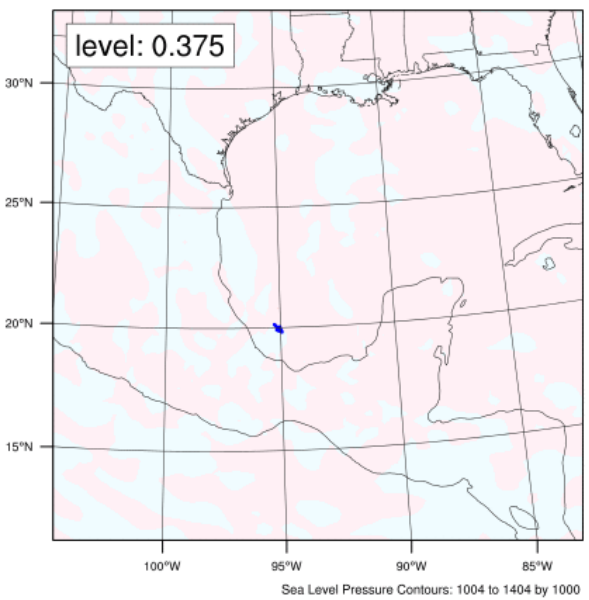
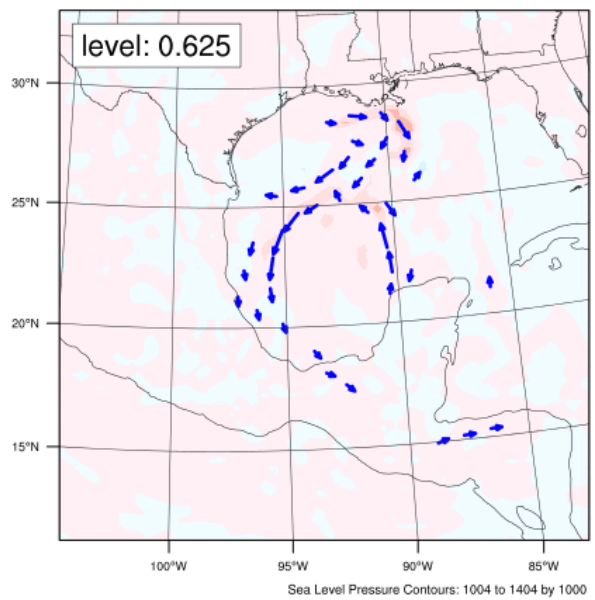
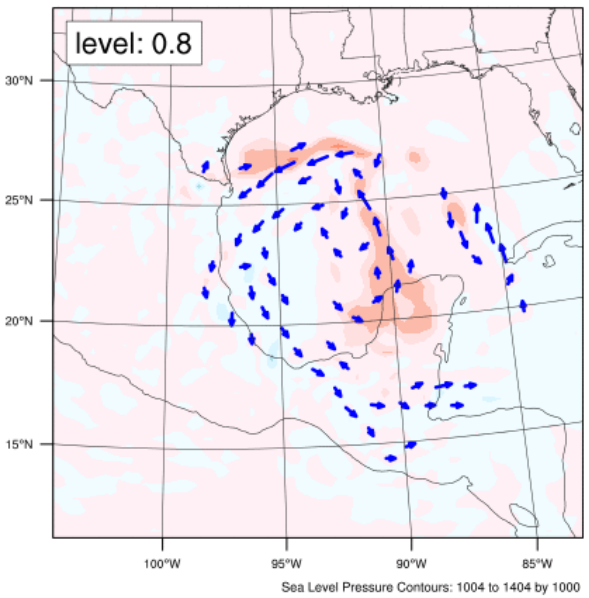
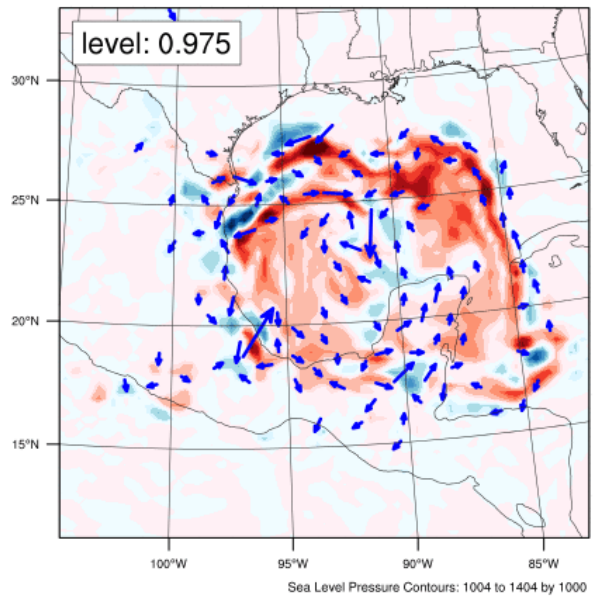
Sea Level Pressure Contours: 1004 to 1100 by 1000





Sea Level Pressure Contours: 1004 to 1100 by 1000





Valid: 2017-08-23_12:00:00

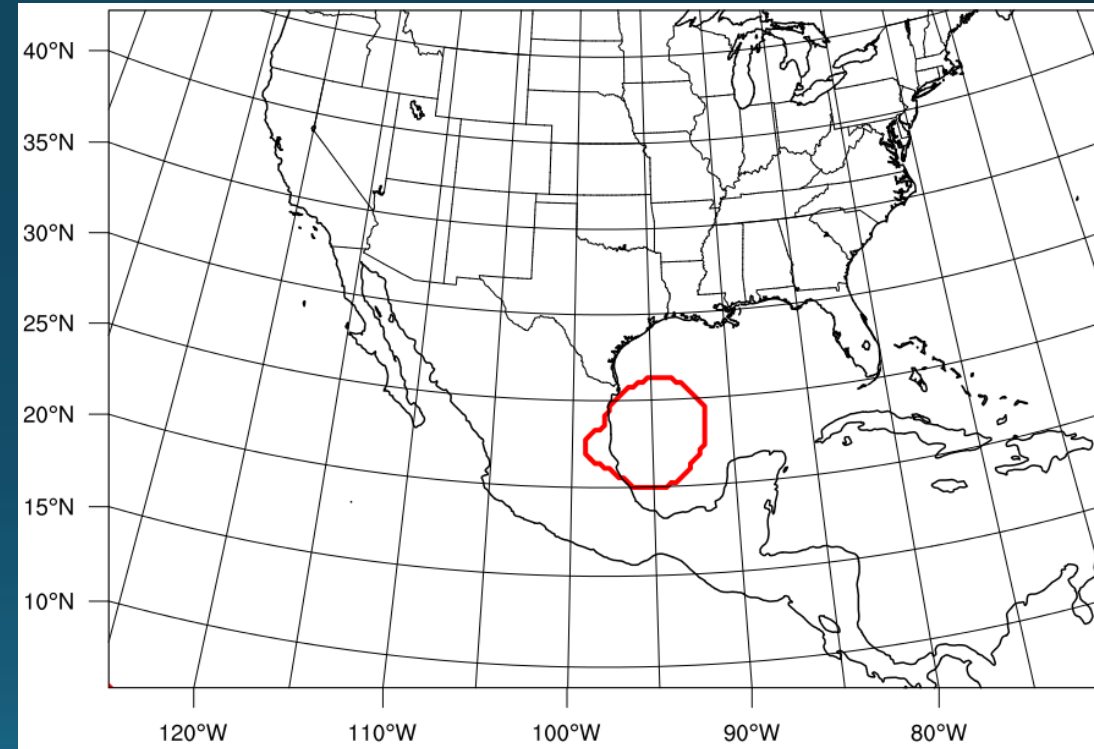
Optimal Perturbation

Seek to minimize energy needed at initial time to make the prescribed change at final time

Prescribed change (δR) 1 hPa decrease in pressure over response function domain

Perturbations are calculated based on prescribed change and the sensitivity gradients at the initial time

- Perturbations:
- Max V-wind: 11.0 m/s
- Max U-wind: 3.7 m/s
 - Less than 0.2% of perturbations greater than 1m/s

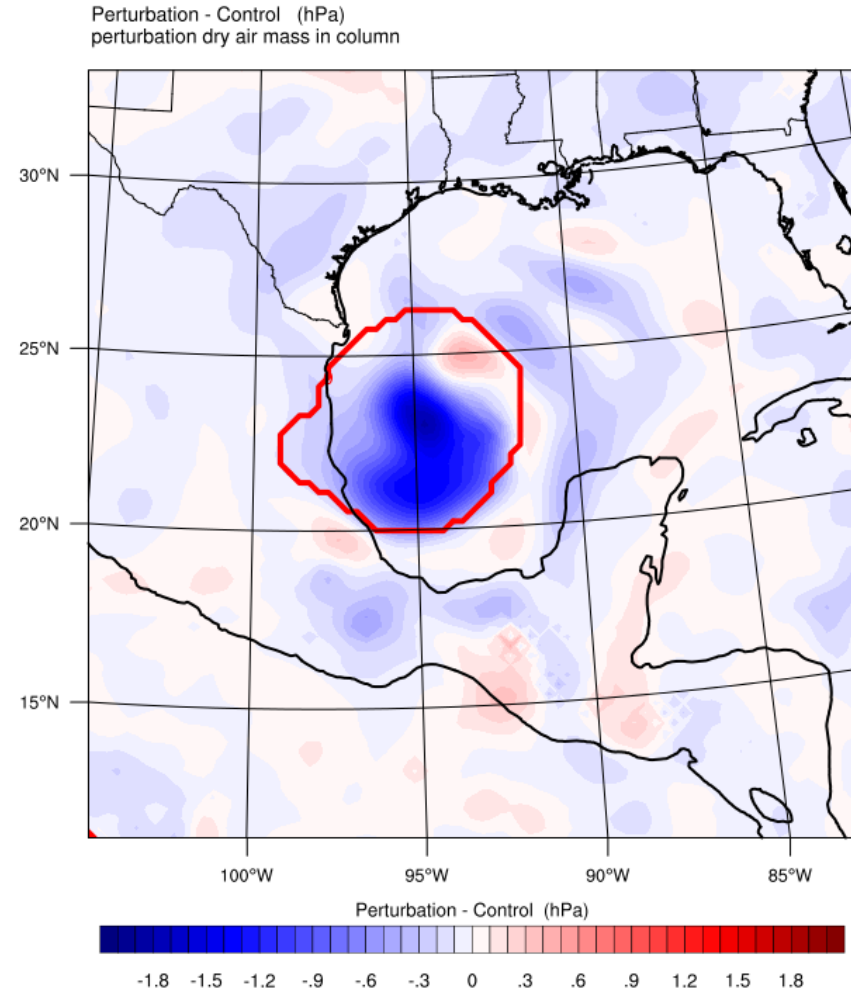


Optimal Perturbation to u and v

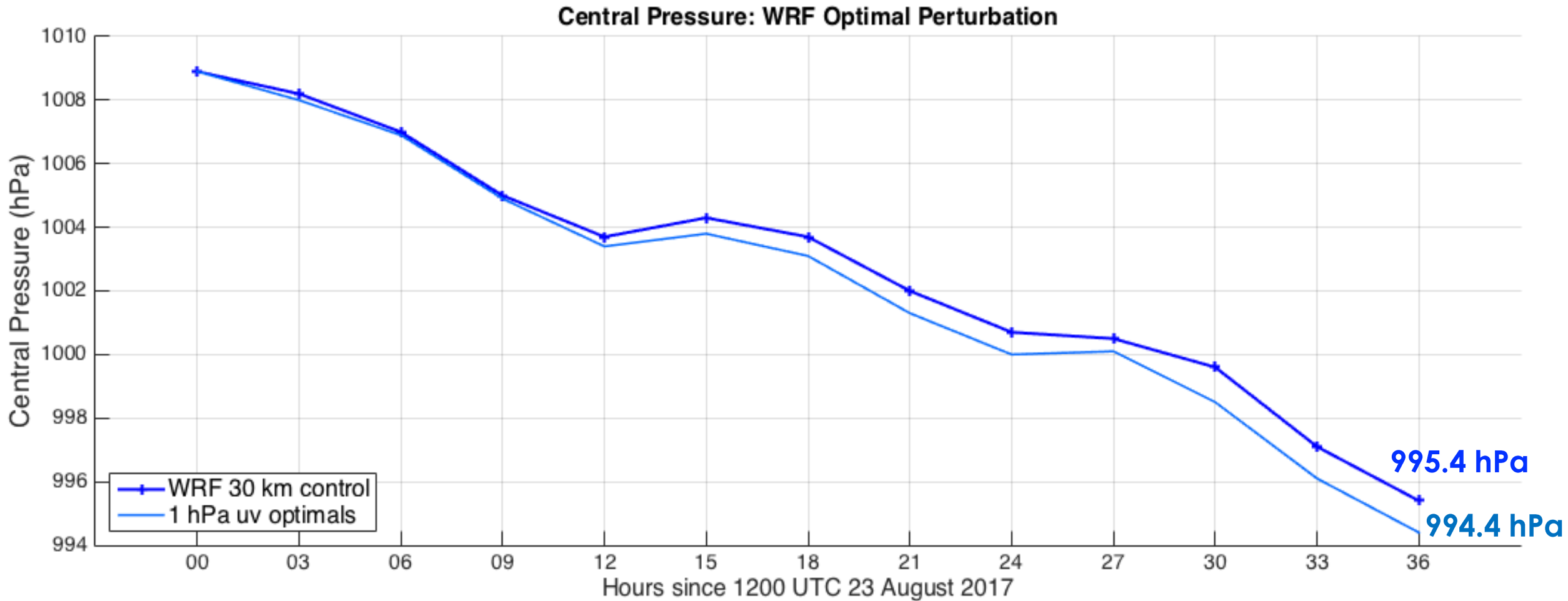
$$\delta R = 1 \text{ hPa}$$

$$t = 36 \text{ h}$$

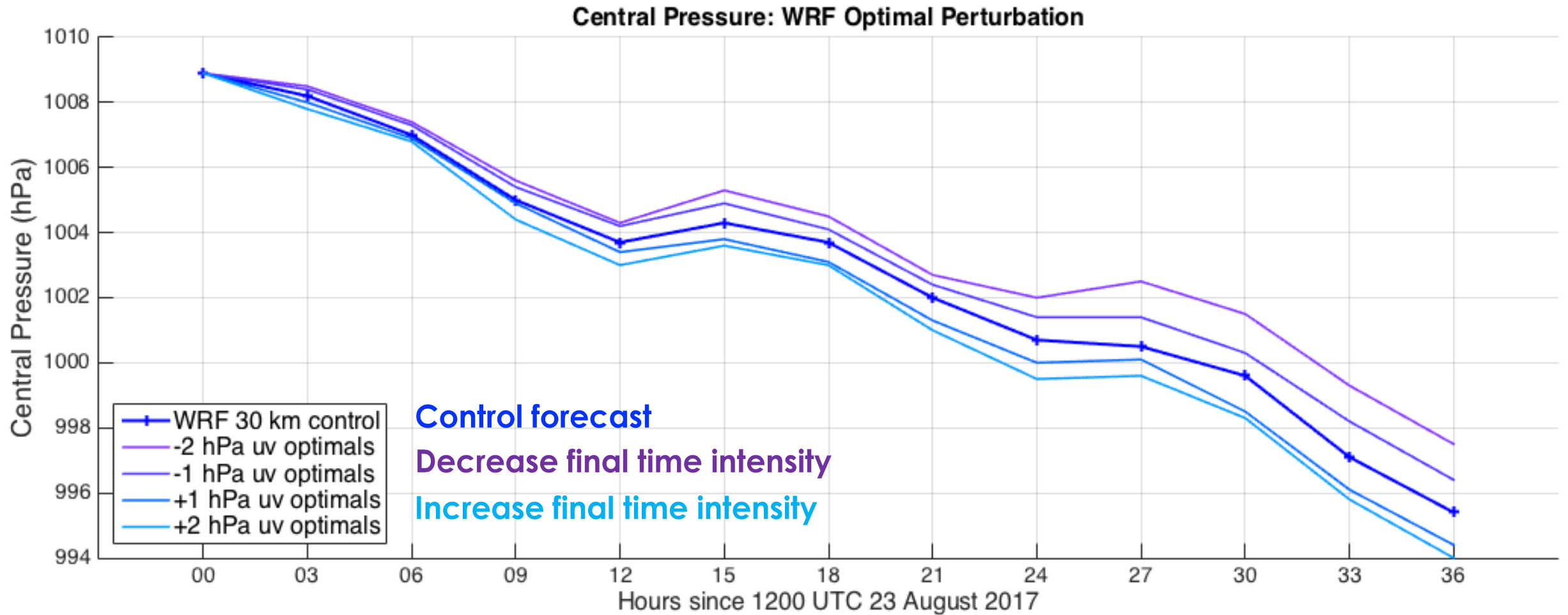
Difference in μ (fill)



Central Pressure

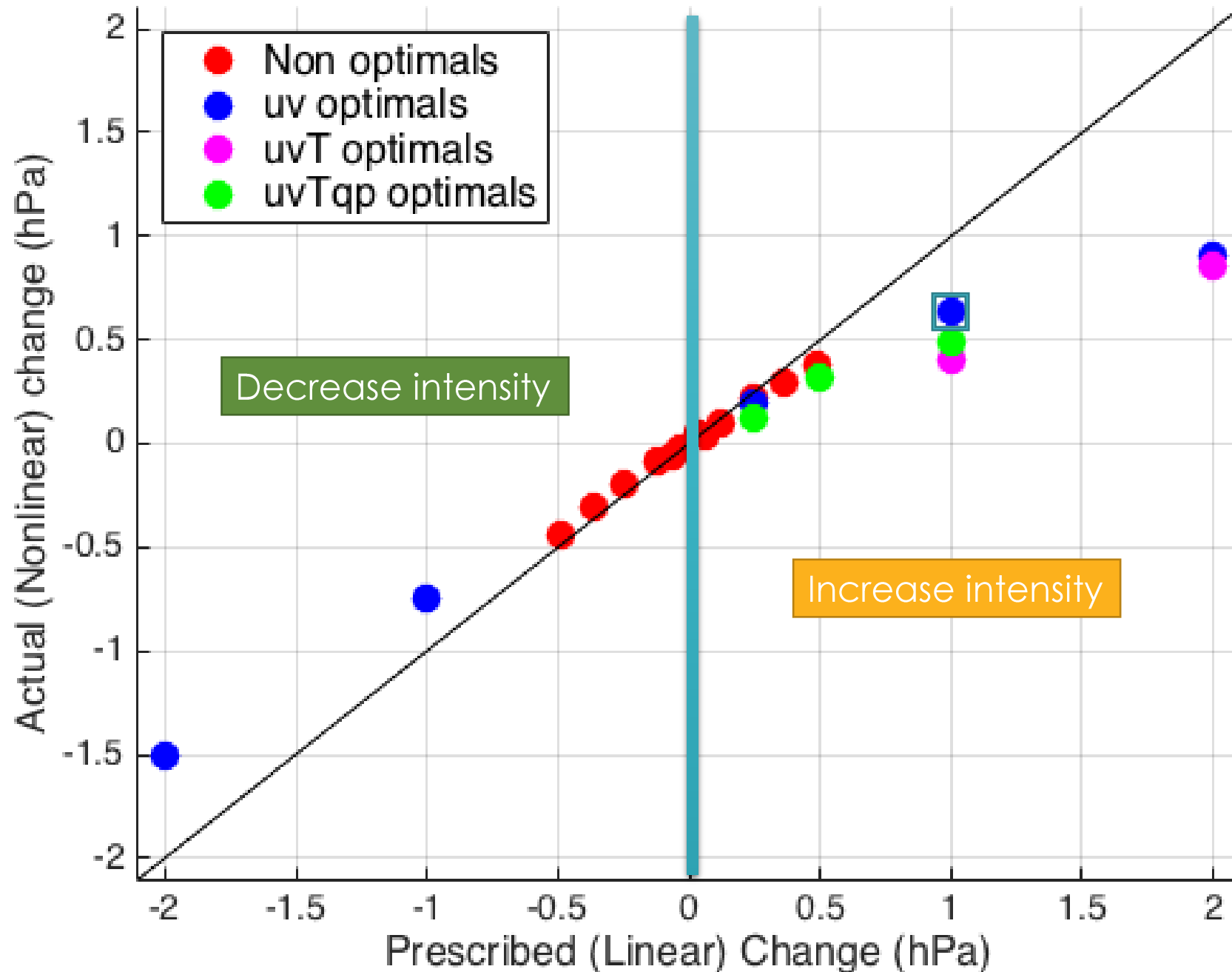


Central Pressure



Linearity

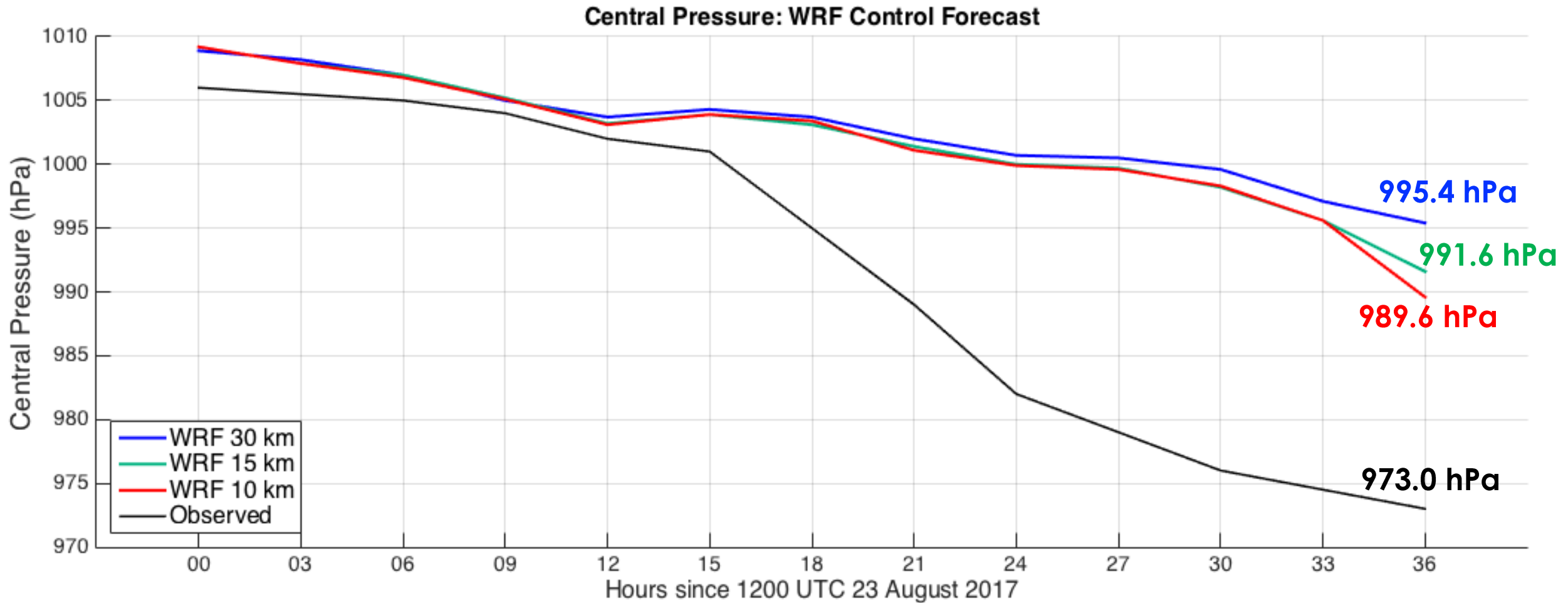
Boxed:
case study shown



Resolution Impacts

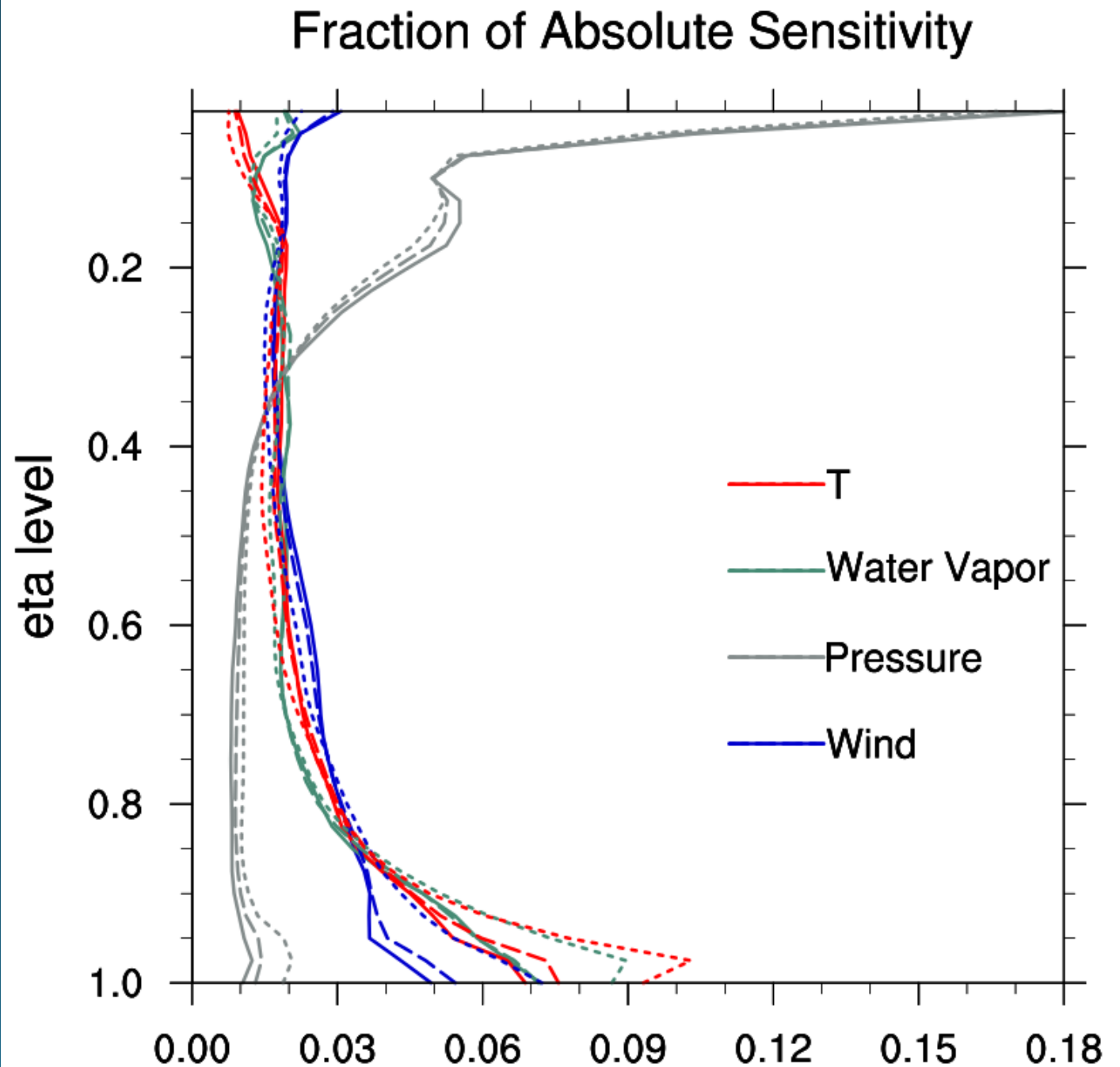
- Re-ran WRF forward trajectory at:
 - 15 km grid spacing (time step = 90s)
 - 10 km grid spacing (time step = 45s)
- Keeping all other variables/configurations the same
- Response function: $-\bar{\mu}$ within 1004 hPa contour
 - Comparable size of domain as 30 km grid spacing

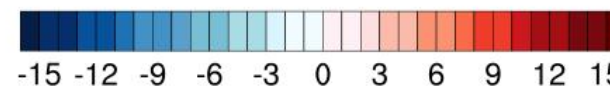
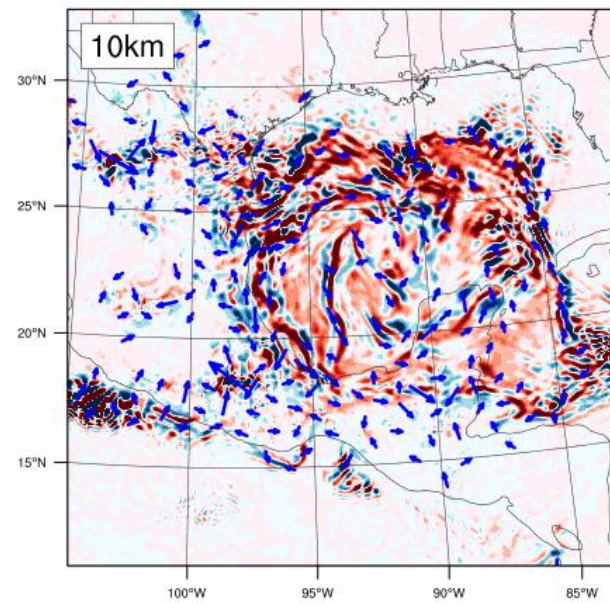
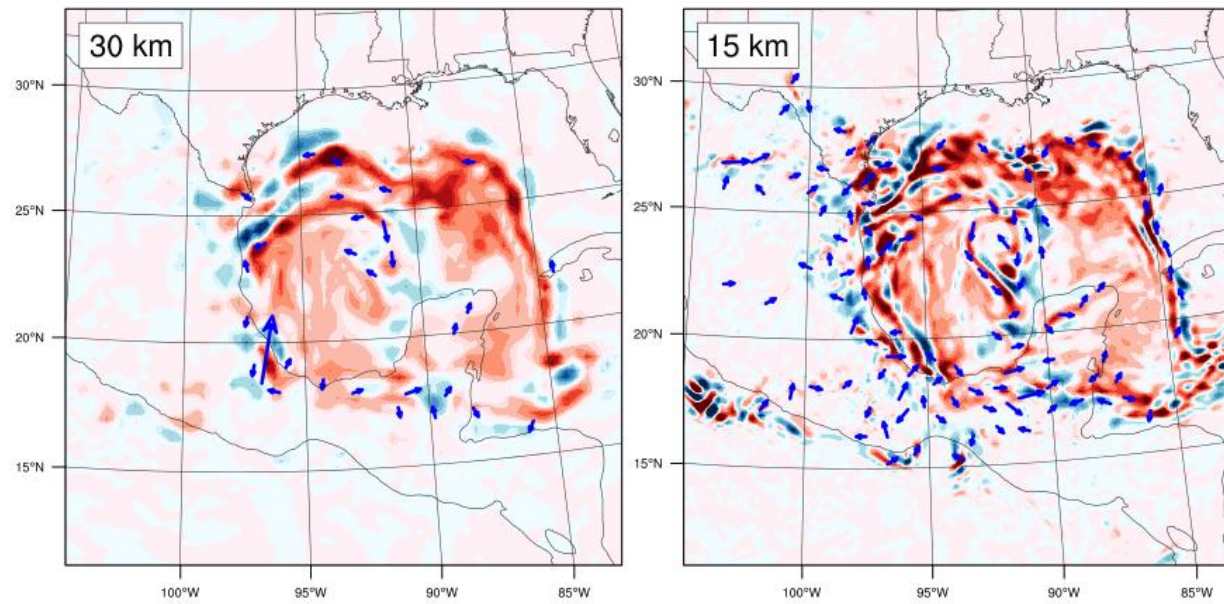
Central Pressure



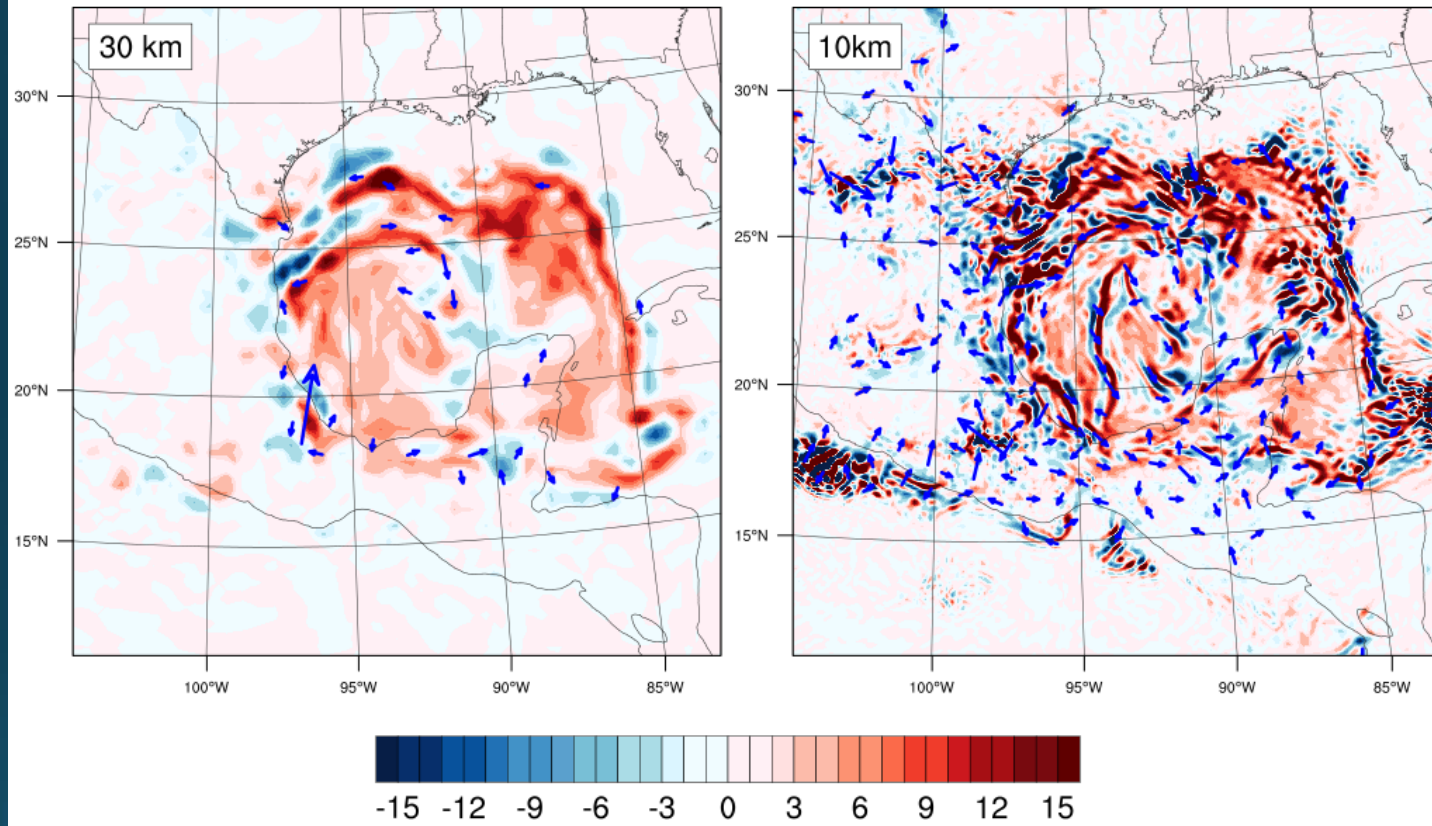
Sensitivities

- Greatest sensitivities occur under the 0.8 eta level
- Pressure peak near top of domain
- Finer grid spacing result in increased low level sensitivity fraction





Valid: 2017-08-23_12:00:00, Eta Level: 0.975



Valid: 2017-08-23_12:00:00, Eta Level: 0.975

Summary

- Initial diagnostics show sensitivities concentrated in lower levels
 - T, q, u, v
 - Consistent with previous studies (Doyle et al. 2012; Brown and Hakim 2015)
- Smaller prescribed changes (δR) to initial conditions evolve to intensify Harvey and behave linearly
- Larger δR and perturbations to thermodynamic fields deviate from linearity
- Finer grid spacing results in increased low level sensitivities fraction
- Greater detail in finer grid spacing sensitivities

Future work

- Increase model resolution impact
 - Does increasing resolution lead to greater insight to structure of sensitivities/perturbations
- Explore different response functions
 - Circulation around box
 - Intensification rate
 - $P_{\text{obs}} - P_{\text{MPI}}$
- Explore other tropical cyclone cases



Acknowledgements

- Special thanks to the organization committee for funding me to attend this conference
- Dr. Michael Morgan
- Dr. Brett Hoover
- Pete Pokrandt
- Morgan and Martin Lab Groups
- Zhaoxiangrui He, optimal perturbation code

References:

Brown, B. R., and G. J. Hakim, 2015: Sensitivity of intensifying Atlantic hurricanes to vortex structure. *Quart. J. Roy. Meteor. Soc.*, 141, 2538-2551.

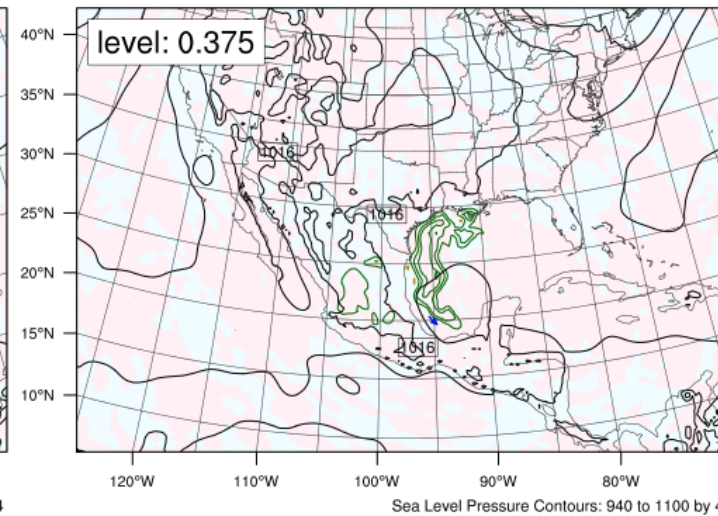
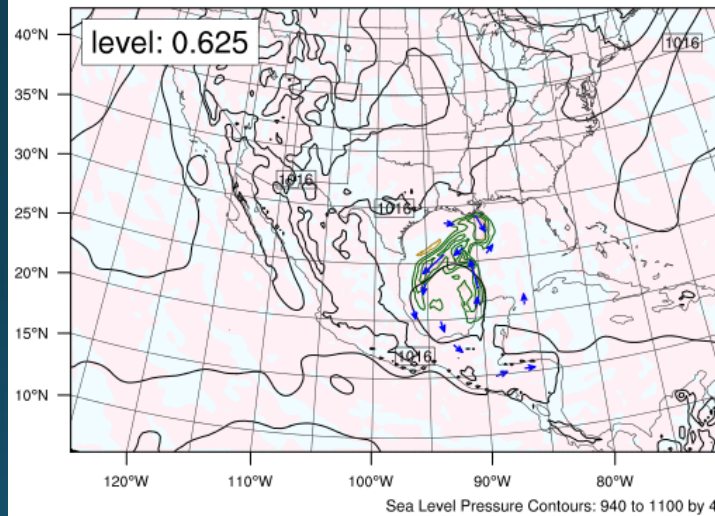
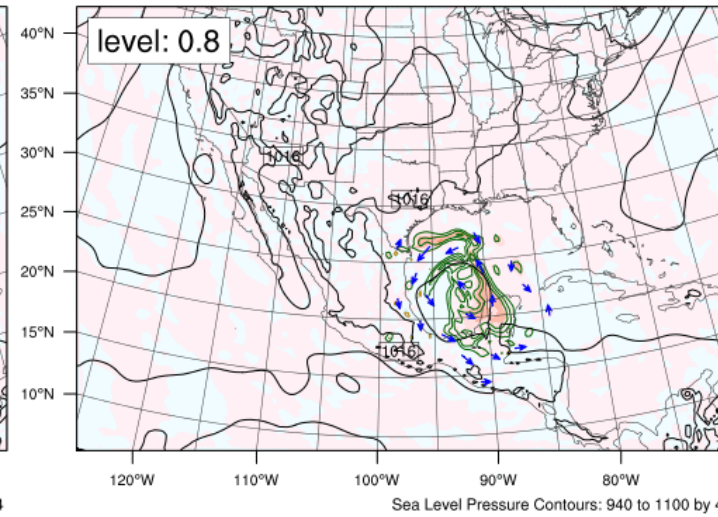
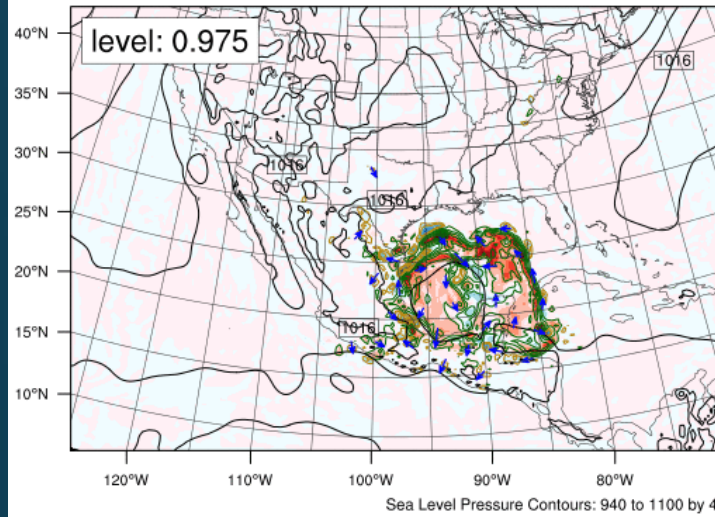
Doyle, J. D., C. A. Reynolds, C. Amerault, and J. Moskaitis, 2012: Adjoint sensitivity and predictability of tropical cyclogenesis. *J. Atmos. Sci.*, 69, 3535–3557

Errico, R., 1997: What is an adjoint model? *Bull. Amer. Meteor. Soc.*, 78, 2577–2591



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Space Science Engineering
Center

Extra Slides



Valid: 2017-08-23_12:00:00 Sensitivity to Temperature (fill)
 Sensitivity to wind (vectors) and Water Vapor (contour) and Sea Level Pressure (black contour)

Perturbations

$$\delta R = \left\langle \frac{\partial R}{\partial \mathbf{X}_0}, \delta \mathbf{X}_0 \right\rangle$$

$$\delta R \cong \Delta R = R(\mathbf{X}_f^c + \mathbf{X}'_f) - R(\mathbf{X}_f^c)$$

$$\mathbf{X}_0^p = \mathbf{X}_0^c + \alpha \frac{\partial R}{\partial \mathbf{X}_0}$$

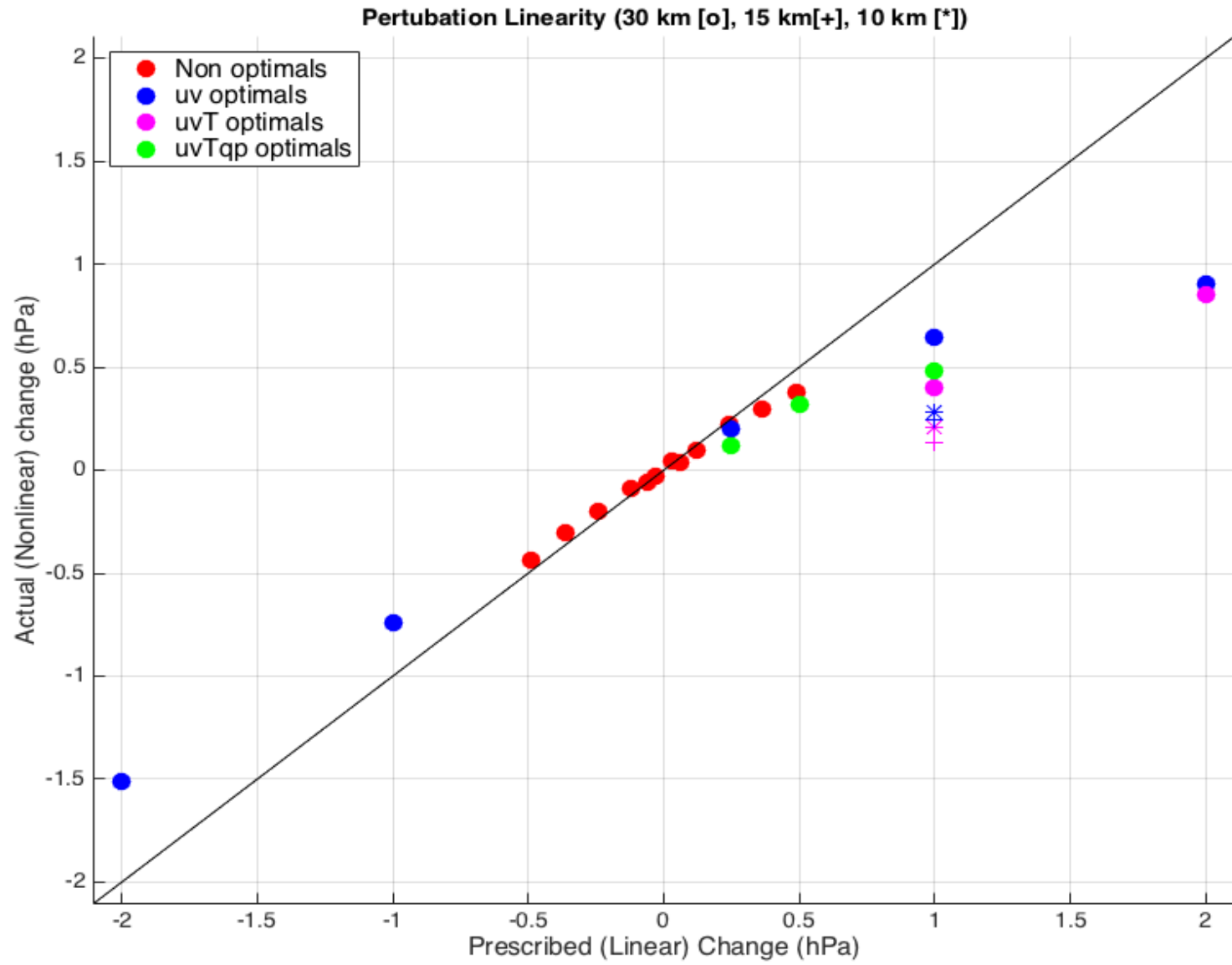
Optimal Perturbations*

$$(\delta \mathbf{X}_0) = \lambda \mathbf{W}^{-1} \frac{\partial R}{\partial \mathbf{X}_0}$$

$$\lambda = \delta R \left(\frac{\partial R}{\partial \mathbf{X}_0} \mathbf{W}^{-1} \frac{\partial R}{\partial \mathbf{X}_0} \right)^{-1}$$

*special thanks to Zhaoxiangrui He

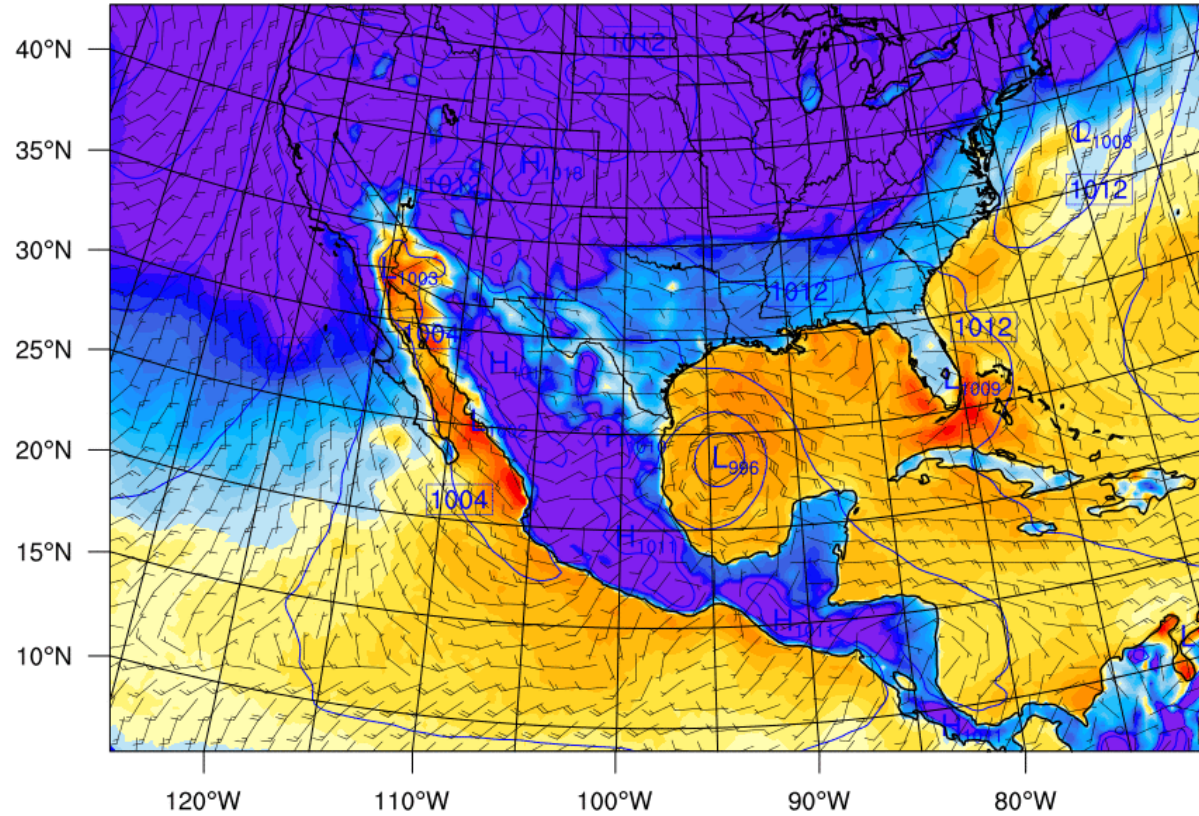
Linearity



REAL-TIME WRF

Init: 2017-08-23_12:00:00
Valid: 2017-08-25_00:00:00

Sea Surface Temperature (C)
Sea Level Pressure (hPa)
Wind (kts)



Sea Level Pressure Contours: 900 to 1100 by 4

Sea Surface Temperature (C)



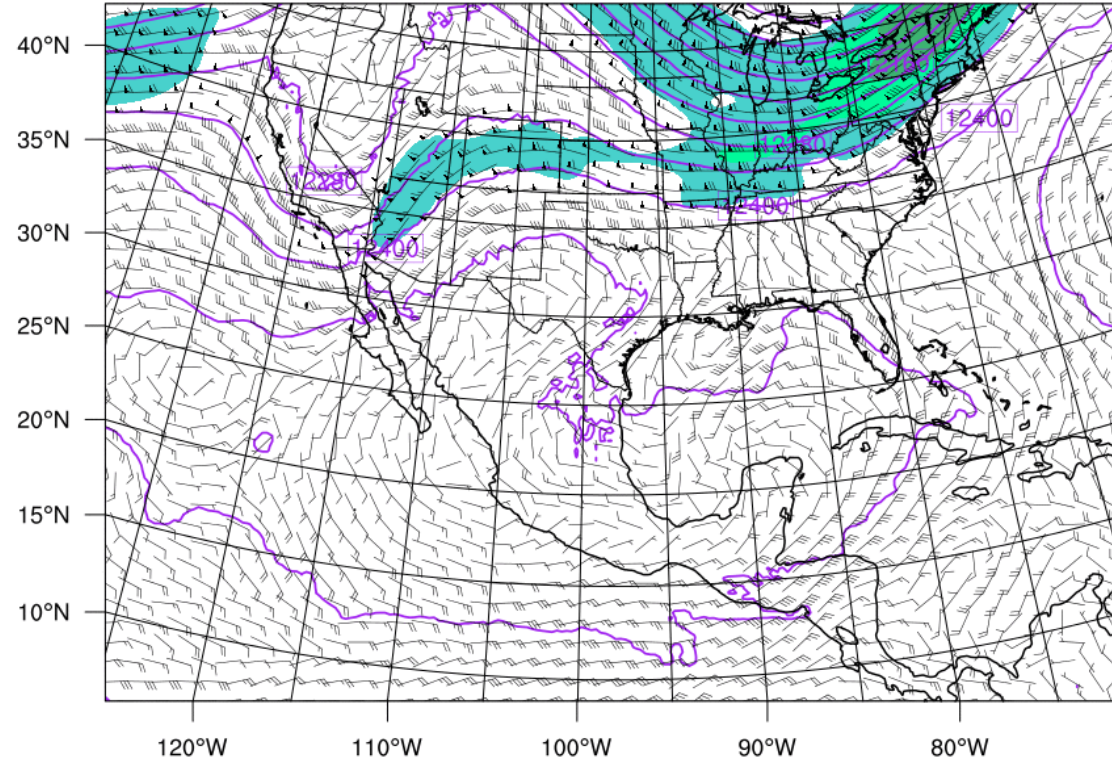
20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35

OUTPUT FROM WRF V3.8.1 MODEL
WE = 210 ; SN = 144 ; Levels = 41 ; Dis = 30km ; Phys Opt = 7 ; PBL Opt = 1 ; Cu Opt = 1

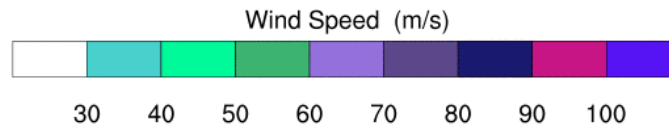
REAL-TIME WRF

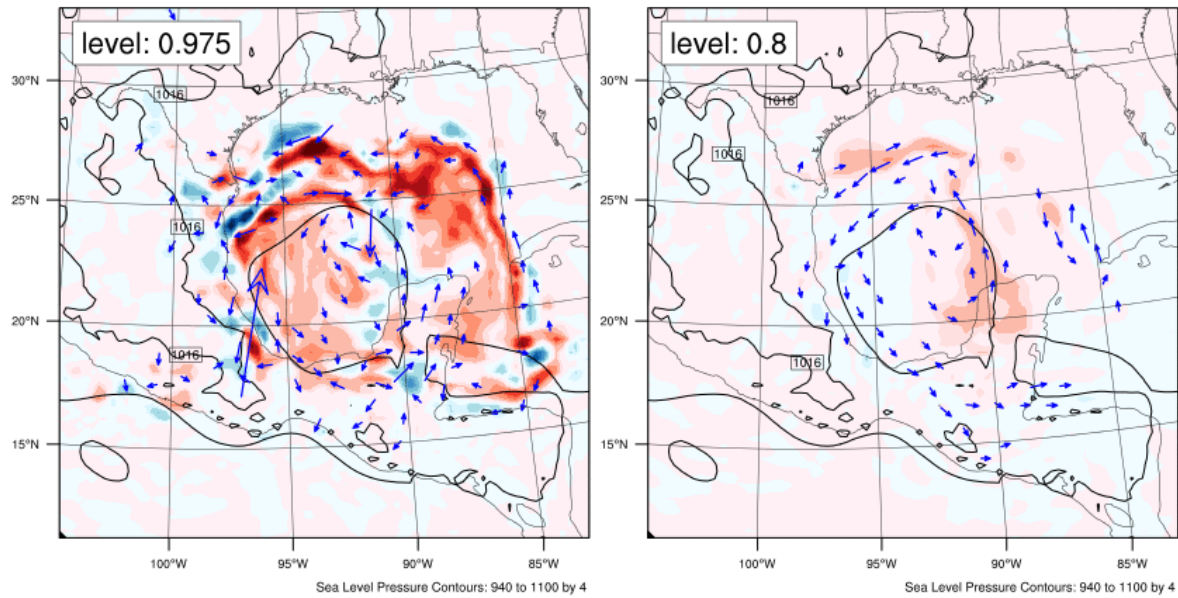
Init: 2017-08-23_12:00:00
Valid: 2017-08-23_12:00:00

Wind Speed (m/s)
Height (m) at 200 hPa
Wind (kts) at 200 hPa



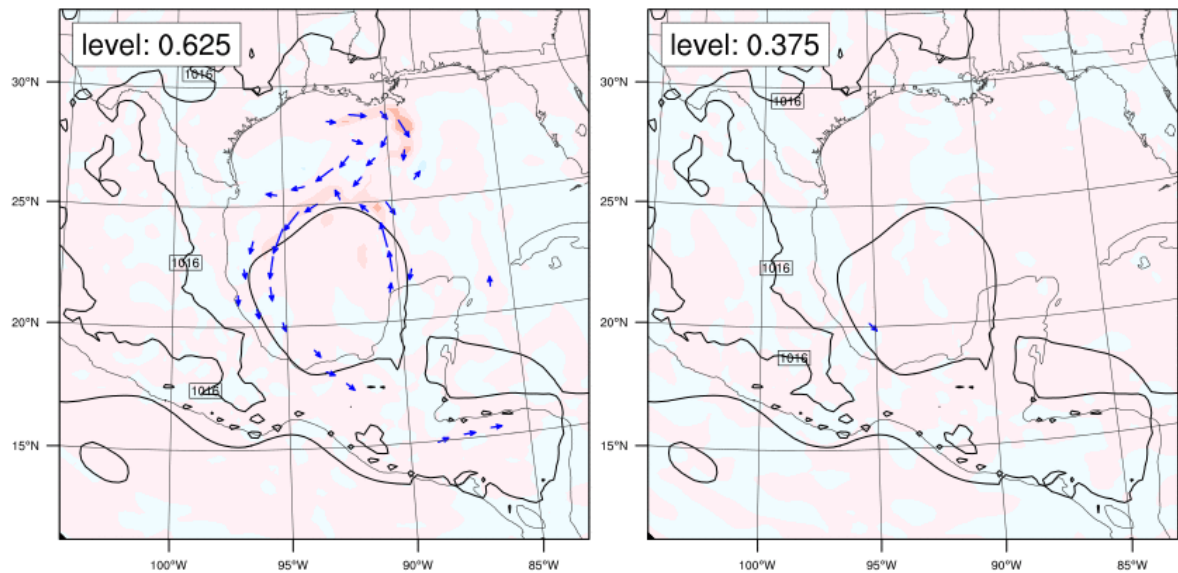
Height Contours: 11800 to 12640 by 60





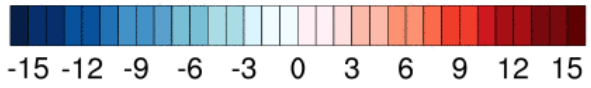
Sea Level Pressure Contours: 940 to 1100 by 4

Sea Level Pressure Contours: 940 to 1100 by 4

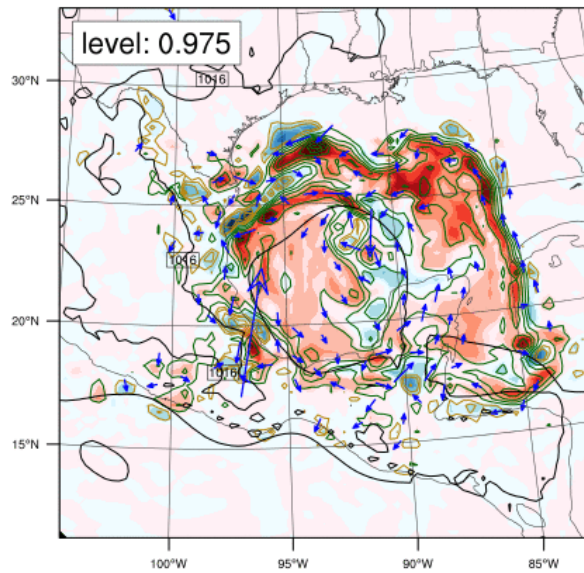


Sea Level Pressure Contours: 940 to 1100 by 4

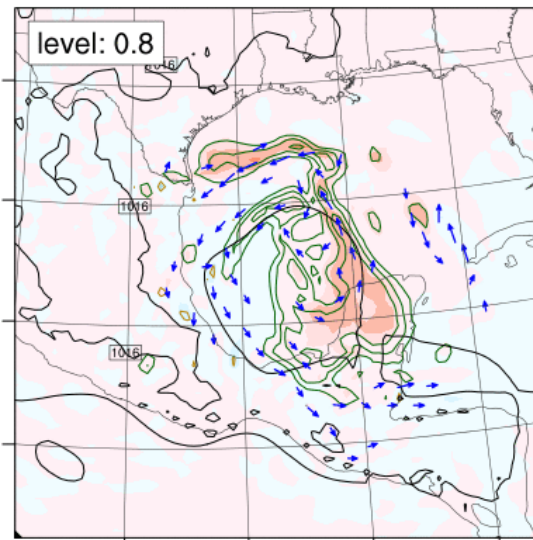
Sea Level Pressure Contours: 940 to 1100 by 4



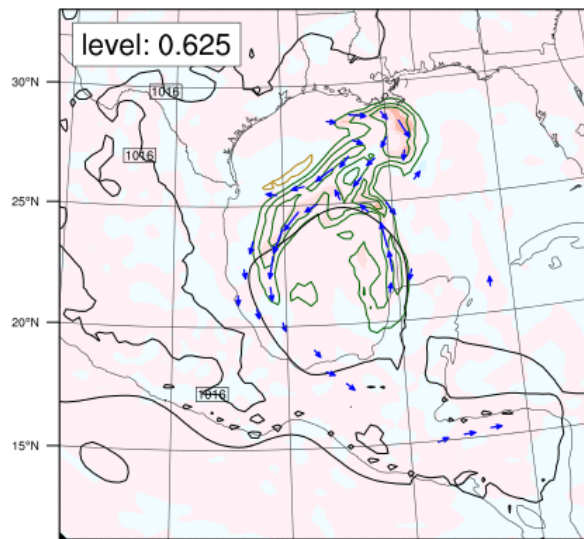
Valid: 2017-08-23_12:00:00 Sensitivity to Temperature (fill)
 Sensitivity to wind (vectors) and Sea Level Pressure (black contour)



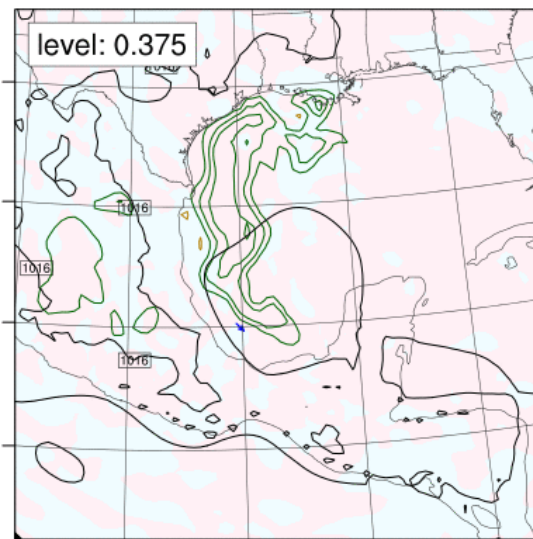
Sea Level Pressure Contours: 940 to 1100 by 4



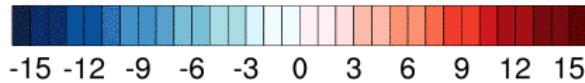
Sea Level Pressure Contours: 940 to 1100 by 4



Sea Level Pressure Contours: 940 to 1100 by 4

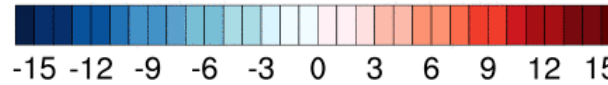
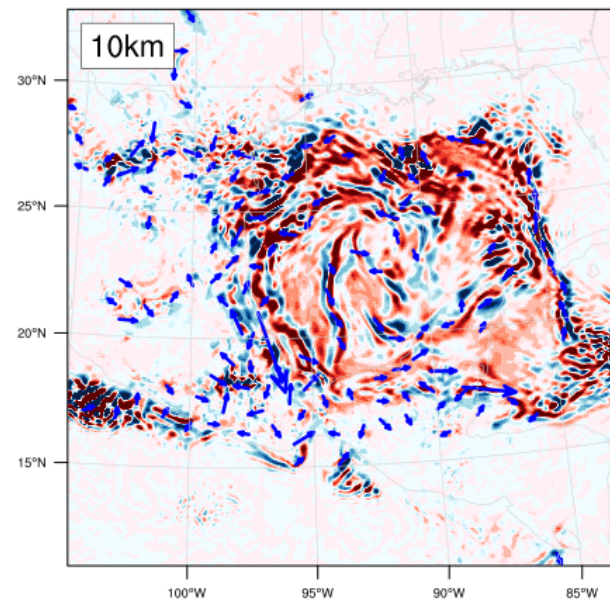
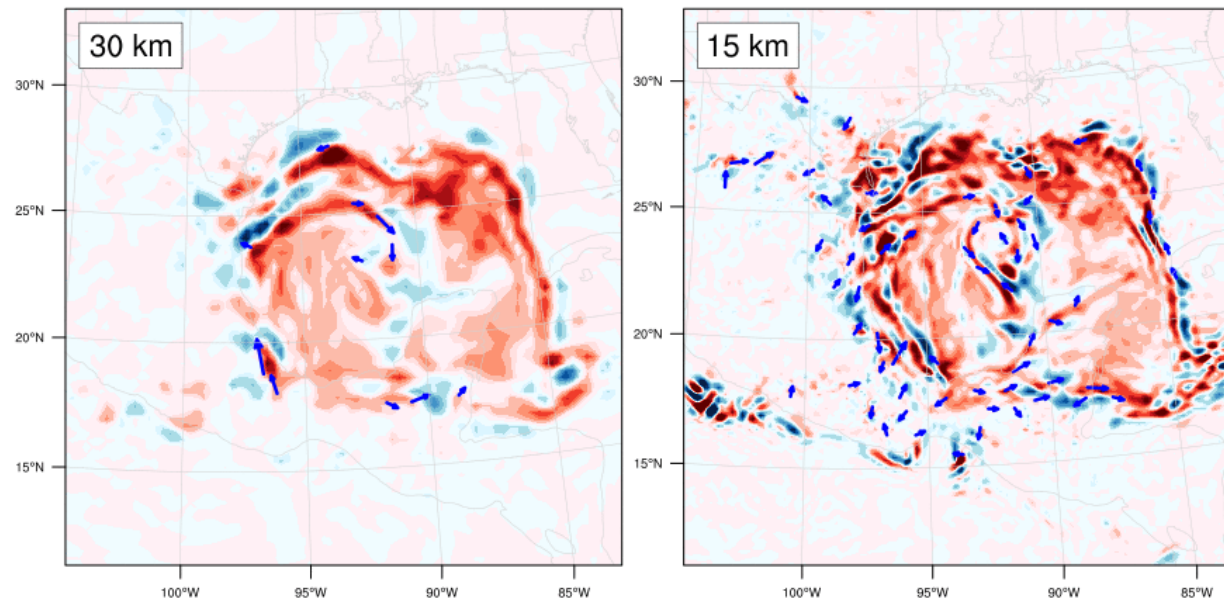


Sea Level Pressure Contours: 940 to 1100 by 4



Valid: 2017-08-23_12:00:00 Sensitivity to Temperature (fill)

Sensitivity to wind (vectors) and Sea Level Pressure (black contour)



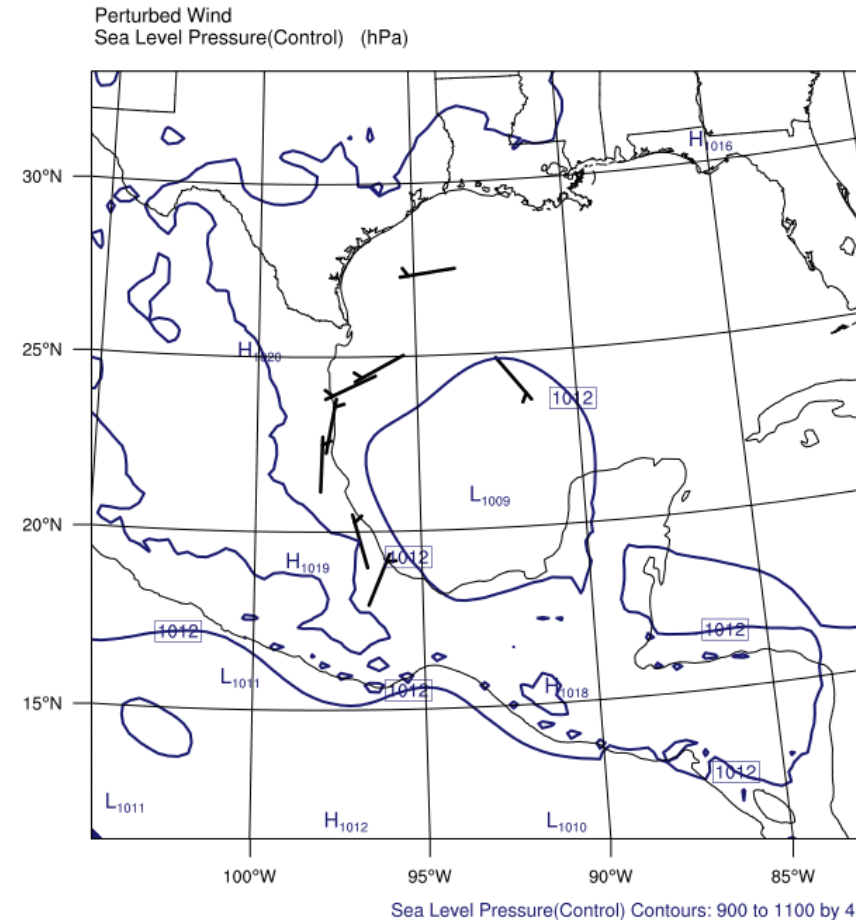
Valid: 2017-08-23_12:00:00, Eta Level: 0.975
Sensitivity to Temperature (fill) and Sensitivity to wind (vectors)

Optimal Perturbation to u and v

$$\delta R = 1 \text{ hPa}$$

$$t = 0 \text{ h}$$

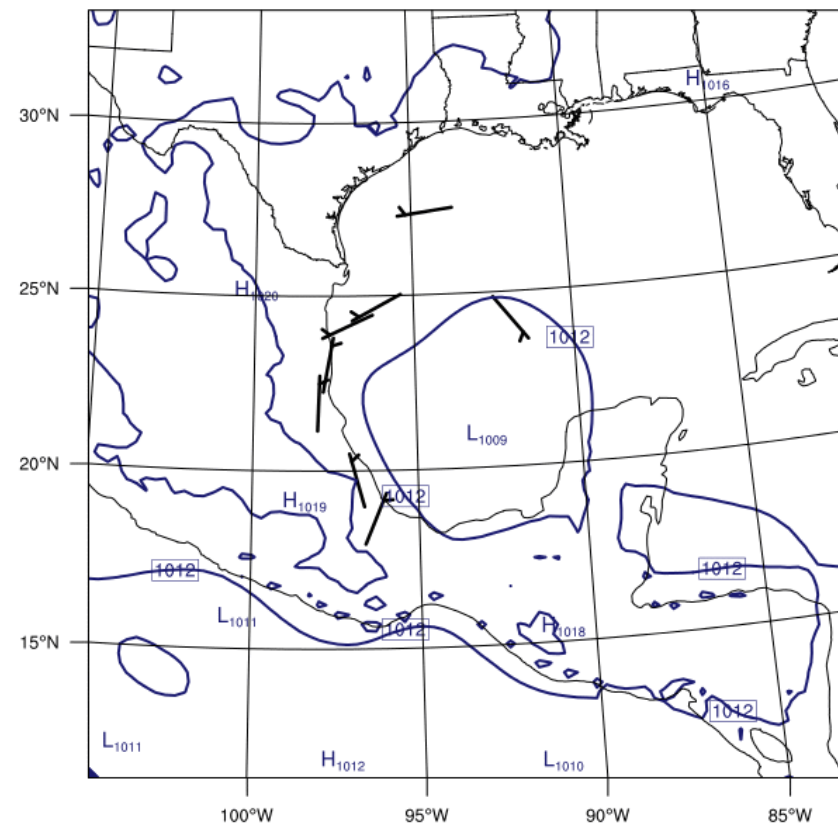
Difference in MSLP
(fill), and u, v
(barbs)



Optimal Perturbation to u and v

$$\delta R = 1 \text{ hPa}$$

Perturbed Wind
Sea Level Pressure(Control) (hPa)



Sea Level Pressure(Control) Contours: 900 to 1100 by 4

Difference in MSLP, u, v

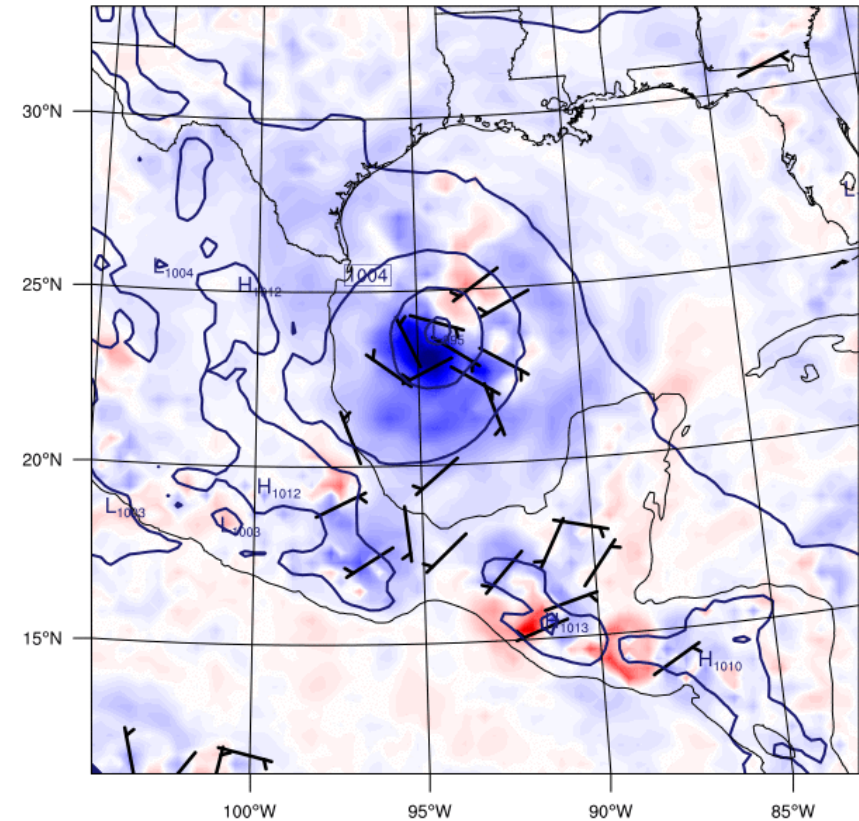
Optimal Perturbation to u and v

$$\delta R = 1 \text{ hPa}$$

$$t = 36 \text{ hr}$$

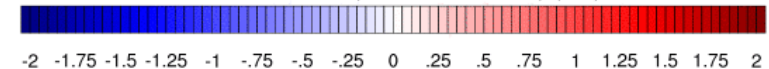
Difference in MSLP, u , v

Sea Level Pressure (Perturbation - Control) (hPa)
Perturbed Wind
Sea Level Pressure(Control) (hPa)

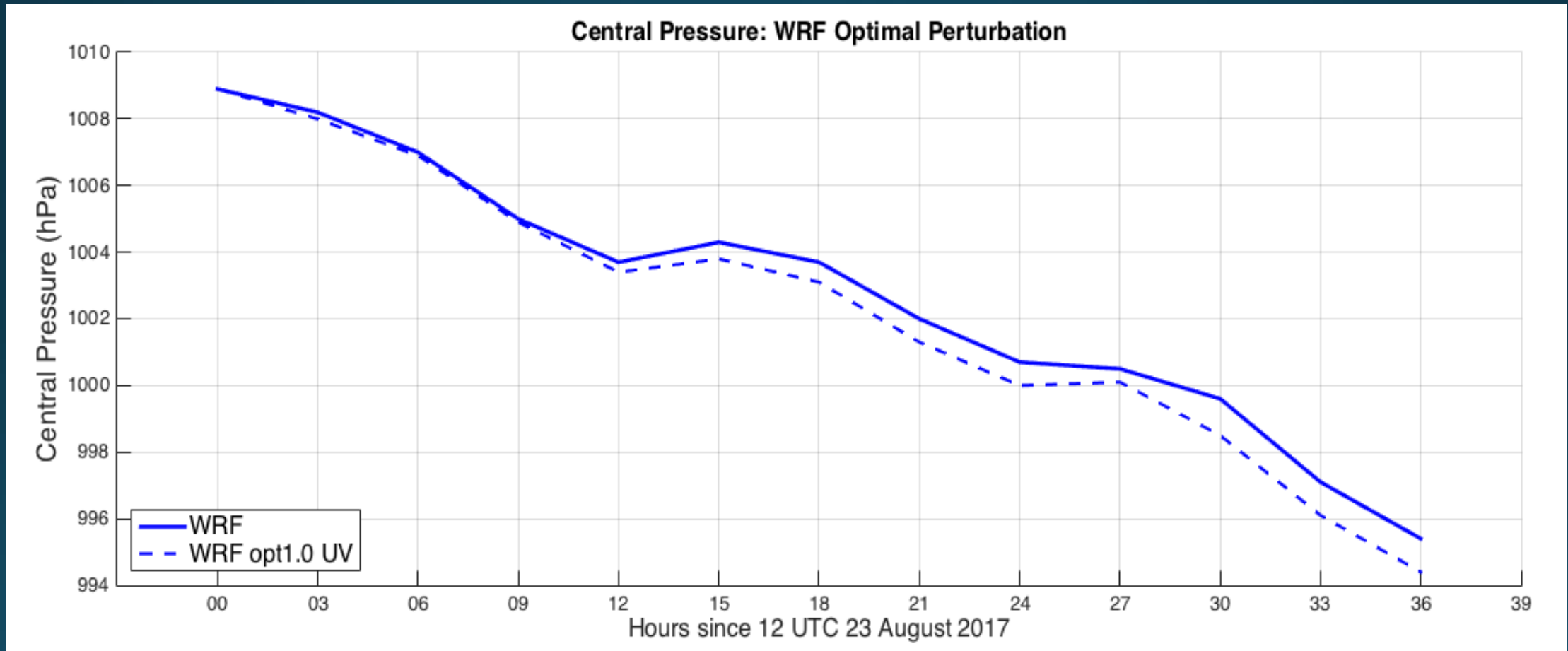


Sea Level Pressure(Control) Contours: 900 to 1100 by 4

Sea Level Pressure (Perturbation - Control) (hPa)



Central Pressure



Adjoint

- Adjoint-based sensitivity studies involve the evaluation of the sensitivity of a **specific** function (R) of model output (\mathbf{x}_f) to changes in the model initial conditions (\mathbf{x}_0)

$$\frac{\partial R}{\partial \mathbf{x}_0}$$

- Given this *sensitivity gradient*, one can compute the changes to R (δR) attributed to small changes in initial conditions ($\delta \mathbf{x}_0$):

$$\delta R = \left\langle \frac{\partial R}{\partial \mathbf{x}_0}, \delta \mathbf{x}_0 \right\rangle$$

$$\mathbf{x} = (\mathbf{u}, \mathbf{v}, \mathbf{w}, \mathbf{T}, \mathbf{p}', \mathbf{q}_v)$$

R – forecast aspect (intensity)



$$\frac{\partial R}{\partial \mathbf{x}_0} = \left(\frac{\partial R}{\partial \mathbf{u}_0}, \frac{\partial R}{\partial \mathbf{v}_0}, \frac{\partial R}{\partial \mathbf{w}_0}, \frac{\partial R}{\partial \mathbf{T}_0}, \frac{\partial R}{\partial \mathbf{p}'_0}, \frac{\partial R}{\partial \mathbf{q}_{v,0}} \right)$$

Simulation
initialized:
1200 UTC 23
August 2017

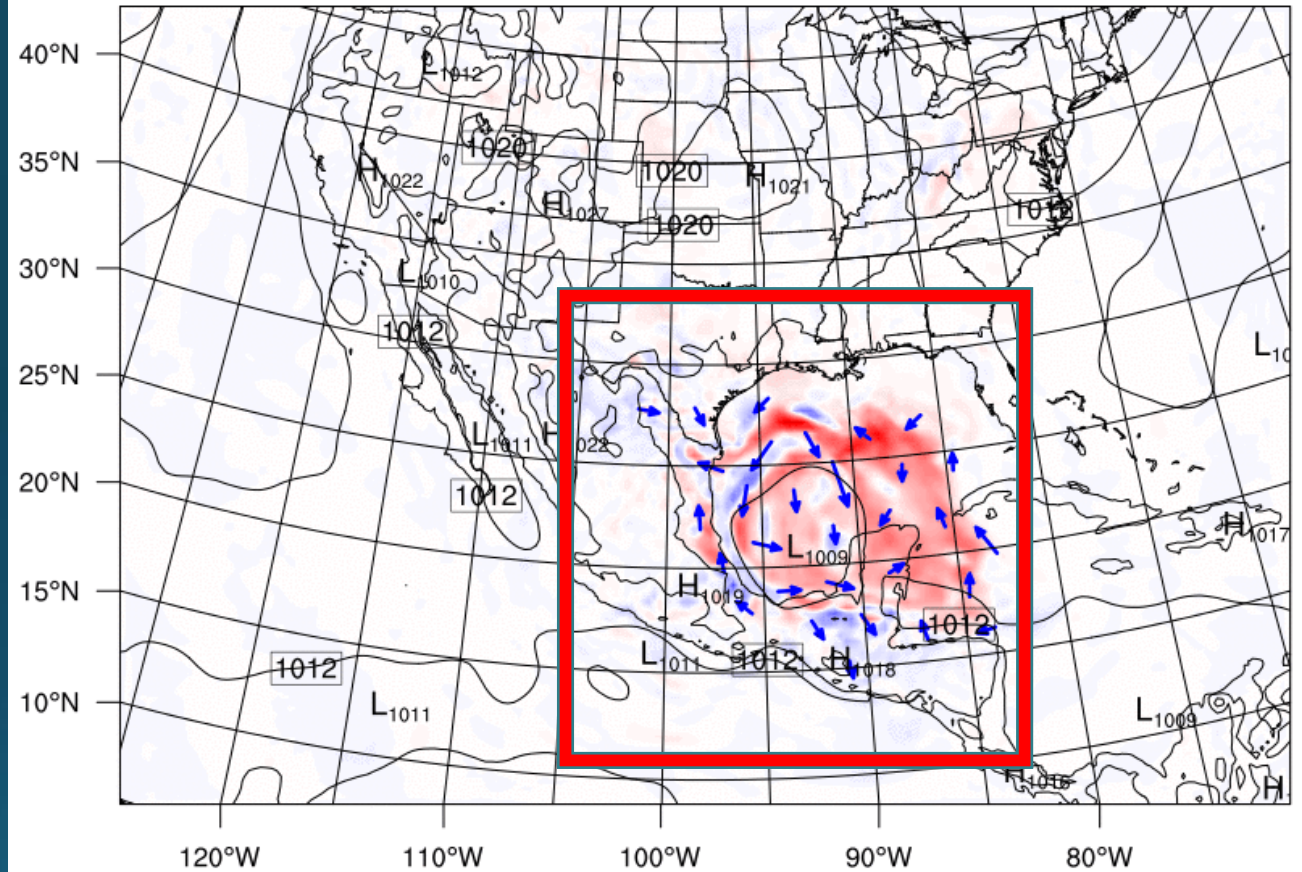
$t = 0$ h

Sensitivity to
Temperature (fill)
and Wind (arrows)

REAL-TIME WRF: Hurricane Harvey

Init: 2017-08-23_12:00:00
Valid: 2017-08-23_12:00:00

Sensitivity to Temperature (Pa / K)
Sensitivity to Wind (m s⁻¹)
Sea Level Pressure (hPa)



Sea Level Pressure Contours: 900 to 1100 by 4

5
Reference Vector

Sensitivity to Temperature (Pa / K)



-15 -12 -9 -6 -3 0 3 6 9 12 15

REAL-TIME WRF: Hurricane Harvey

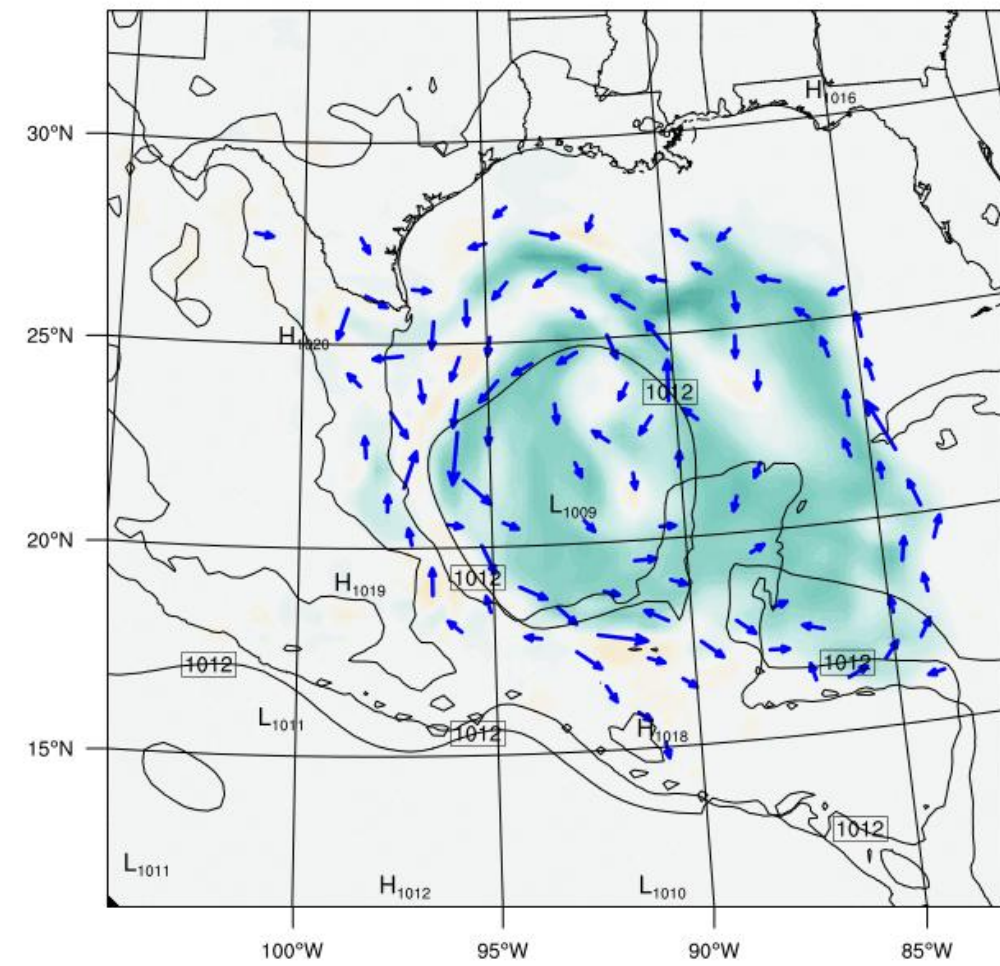
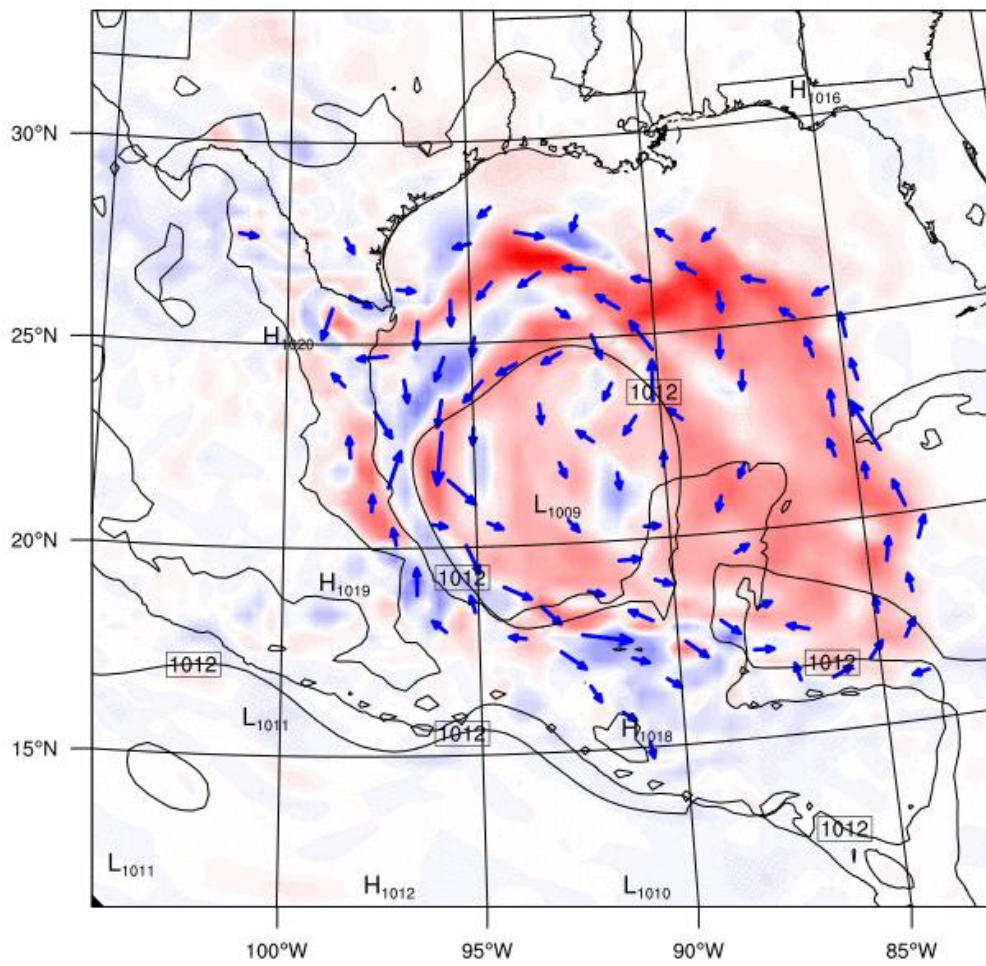
Init: 2017-08-23_12:00:00
Valid: 2017-08-23_12:00:00

REAL-TIME WRF: Hurricane Harvey

Init: 2017-08-23_12:00:00
Valid: 2017-08-23_12:00:00

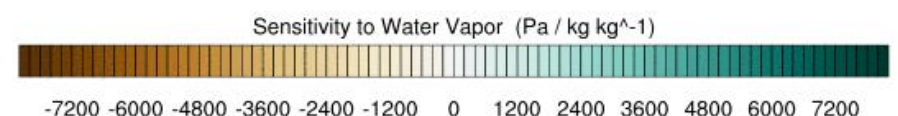
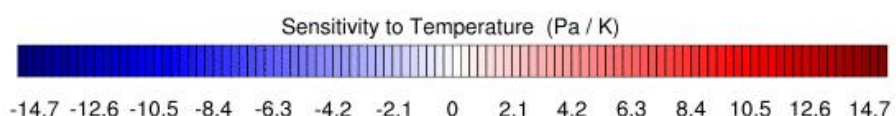
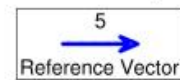
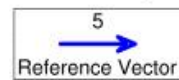
Sensitivity to Temperature (Pa / K)
Sensitivity to Wind (m s⁻¹)
Sea Level Pressure (hPa)

Sensitivity to Water Vapor (Pa / kg kg⁻¹)
Sensitivity to Wind (m s⁻¹)
Sea Level Pressure (hPa)

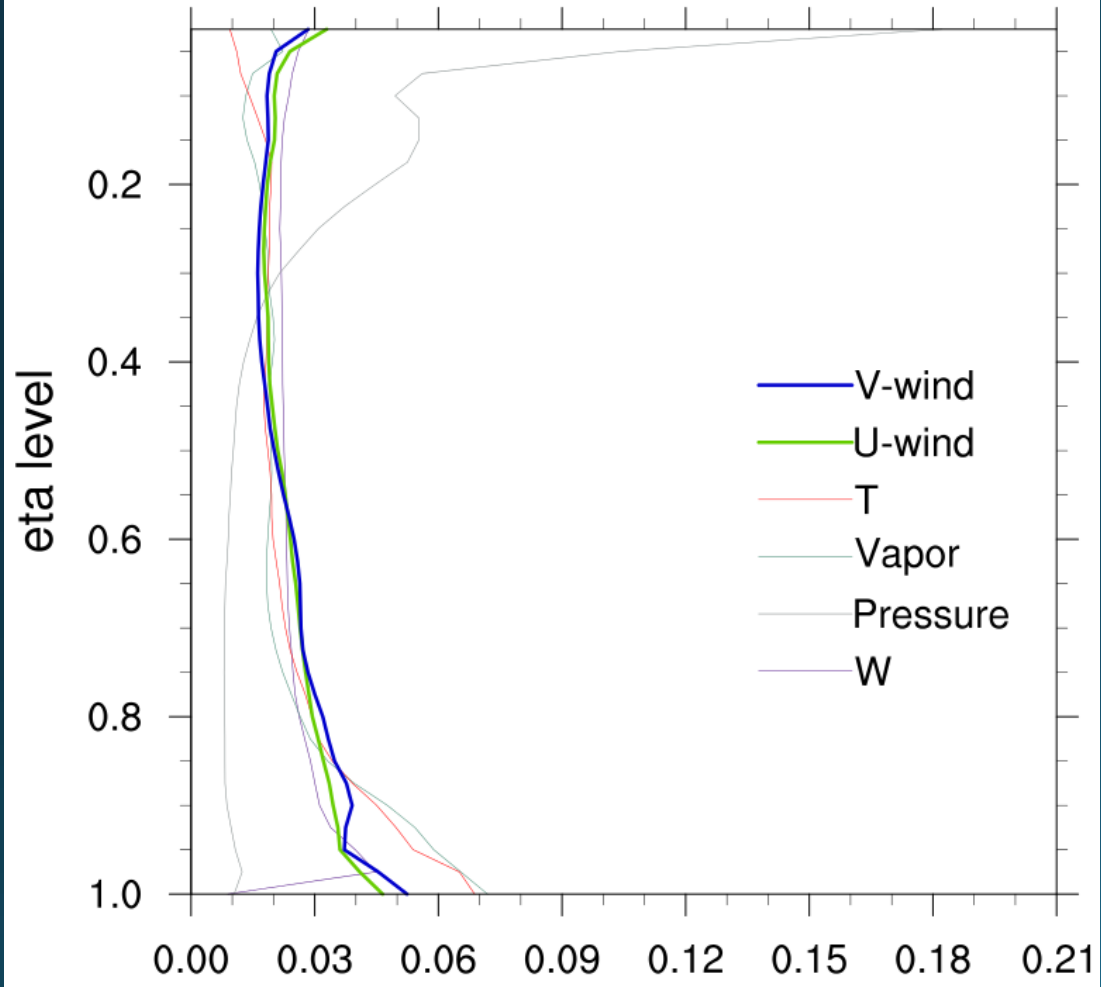


Sea Level Pressure Contours: 900 to 1100 by 4

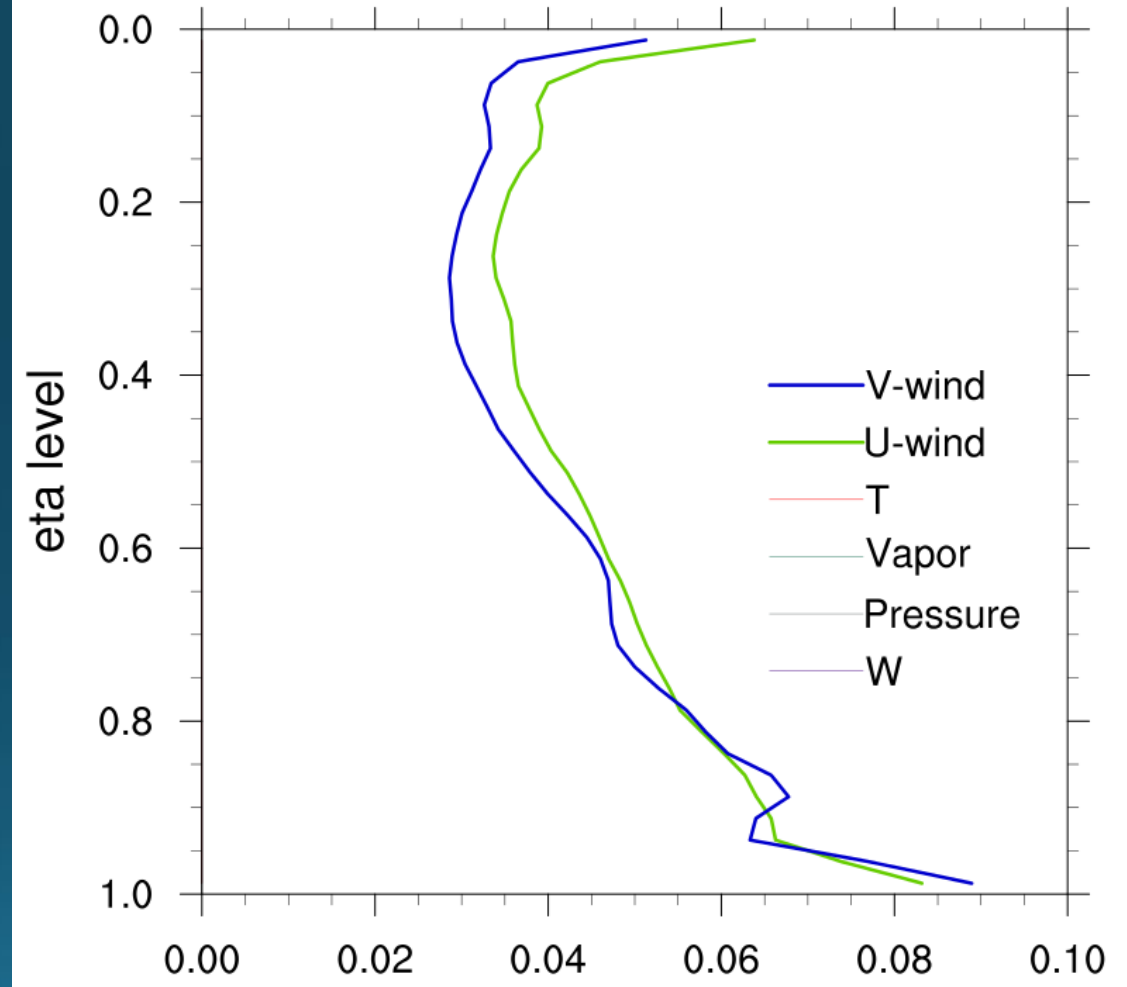
Sea Level Pressure Contours: 900 to 1100 by 4



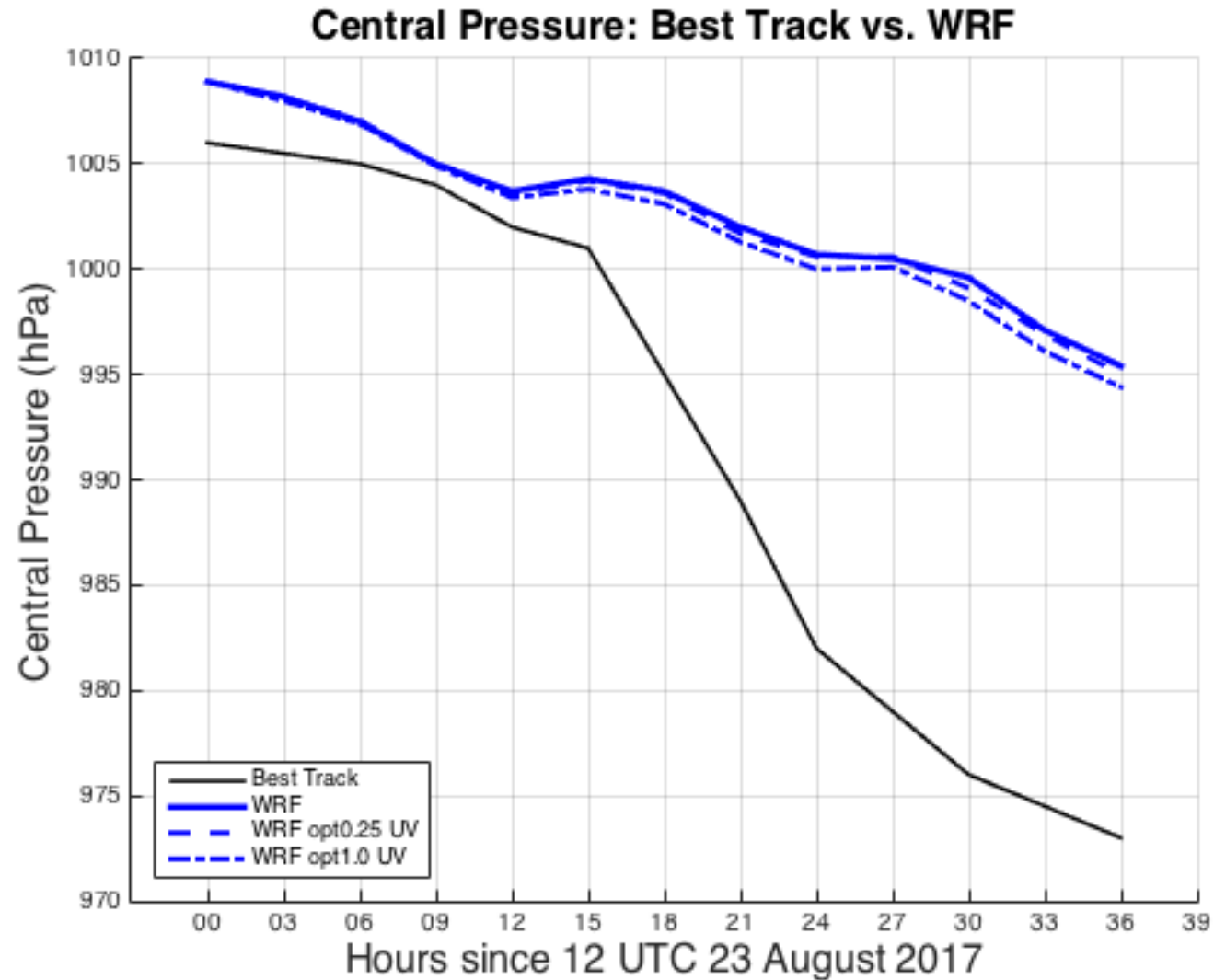
Fraction of Absolute Sensitivity

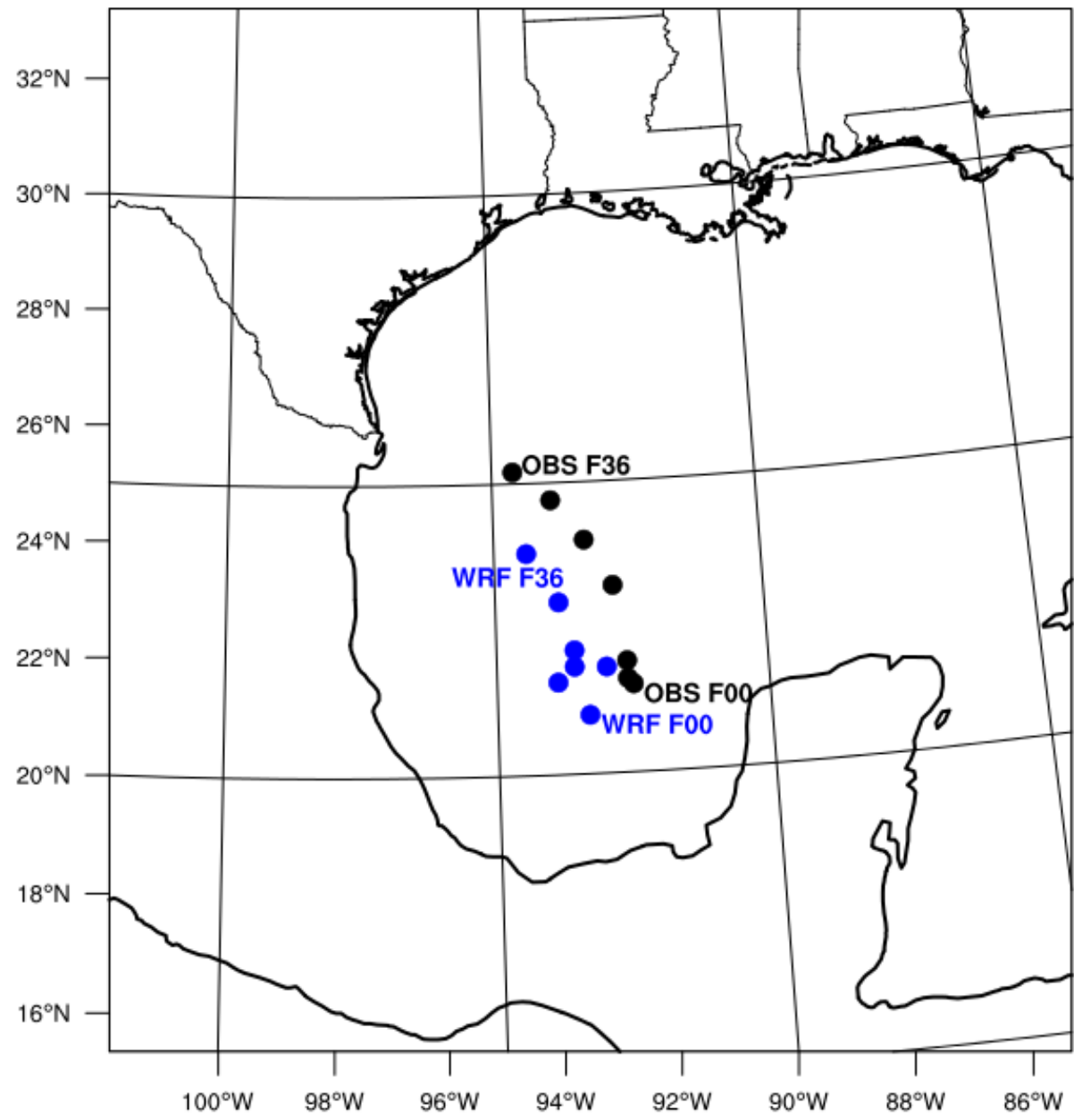


Optimal Perturbation: Average Vertical Structure



Central Pressure





Optimal Perturbation to u' and v'

$$\delta R = 1 \text{ hPa}$$

$$\sigma = 0.887$$

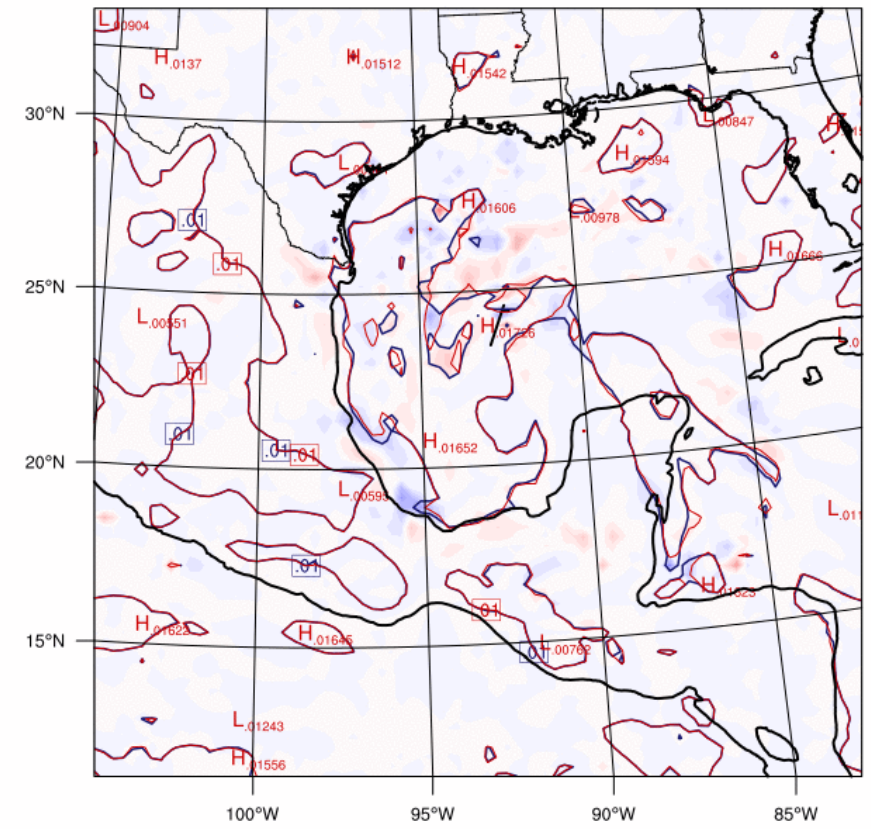
Difference in T, u, v

REAL-TIME WRF: Hurricane Harvey

Init: 2017-08-23_12:00:00

Valid: 2017-08-23_15:00:00

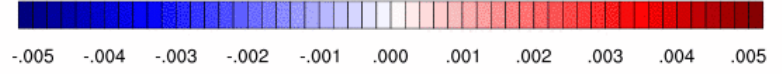
Water vapor mixing ratio (Perturbation - Control) (kg kg⁻¹)
Sea Level Pressure (hPa)
Wind
Water vapor mixing ratio(Control) (kg kg⁻¹)
Water vapor mixing ratio(Perturbation) (kg kg⁻¹)



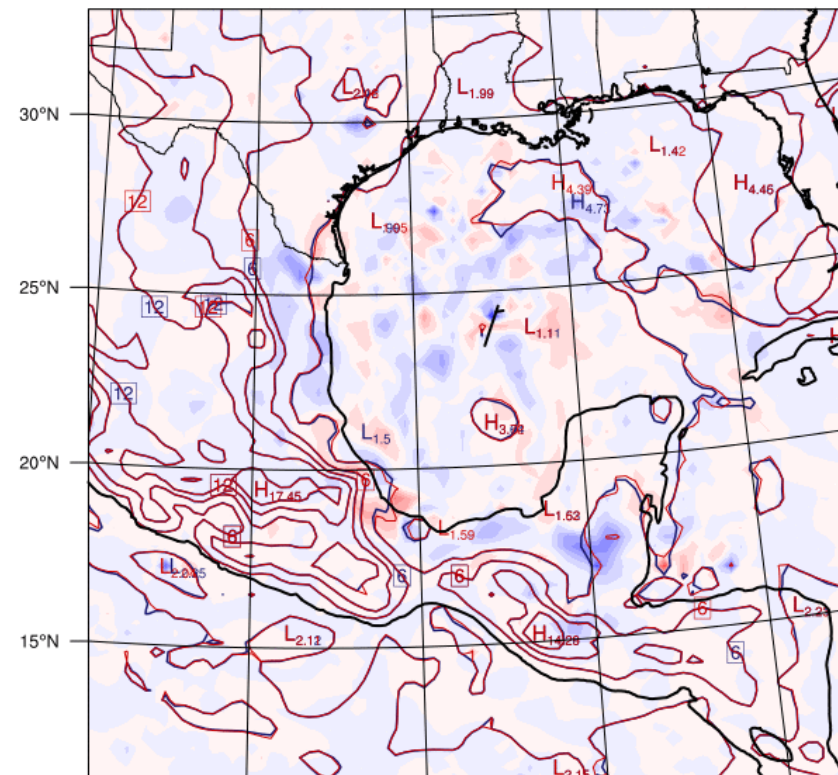
Water vapor mixing ratio(Control) Contours: .00 to .025 by .005

Water vapor mixing ratio(Perturbation) Contours: .00 to .025 by .005

Water vapor mixing ratio (Perturbation - Control) (kg kg⁻¹)



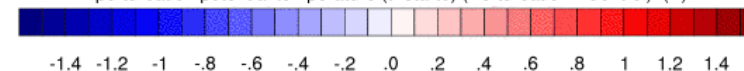
perturbation potential temperature (theta-t0) (Perturbation - Control) (K)
Wind
perturbation potential temperature (theta-t0)(Control) (K)
perturbation potential temperature (theta-t0)(Perturbation) (K)



perturbation potential temperature (theta-t0)(Control) Contours: 0 to 150 by 3

perturbation potential temperature (theta-t0)(Perturbation) Contours: 0 to 150 by 3

perturbation potential temperature (theta-t0) (Perturbation - Control) (K)



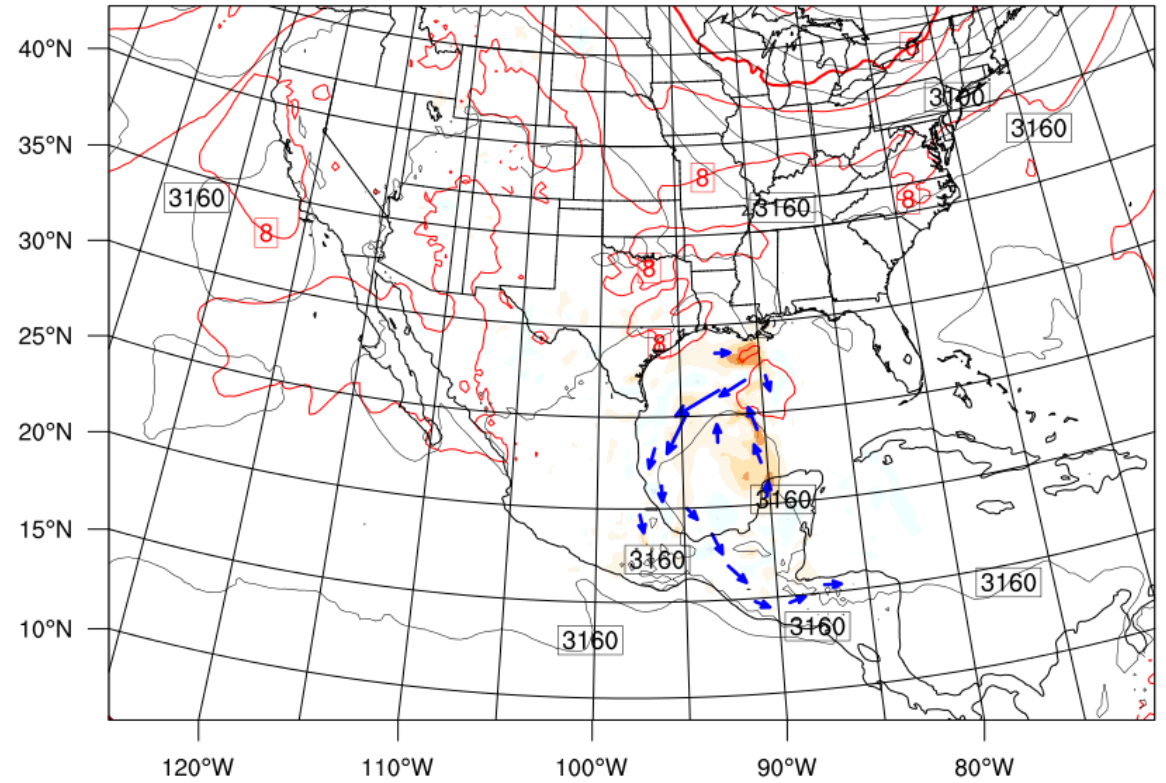
Optimal Perturbation to u' and v'

$$\delta R = 1 \text{ hPa}$$

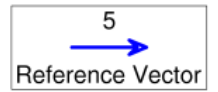
$$\sigma = 0.887$$

Difference in q, u, v

Sensitivity to Temperature (Pa / K) at 700 hPa
Temperature (C) at 700 hPa
Height (m) at 700 hPa
Sensitivity to Wind (Pa / m s-1) at 700 hPa



Height Contours: 2920 to 3250 by 30
Temperature Contours: -12 to 24 by 4



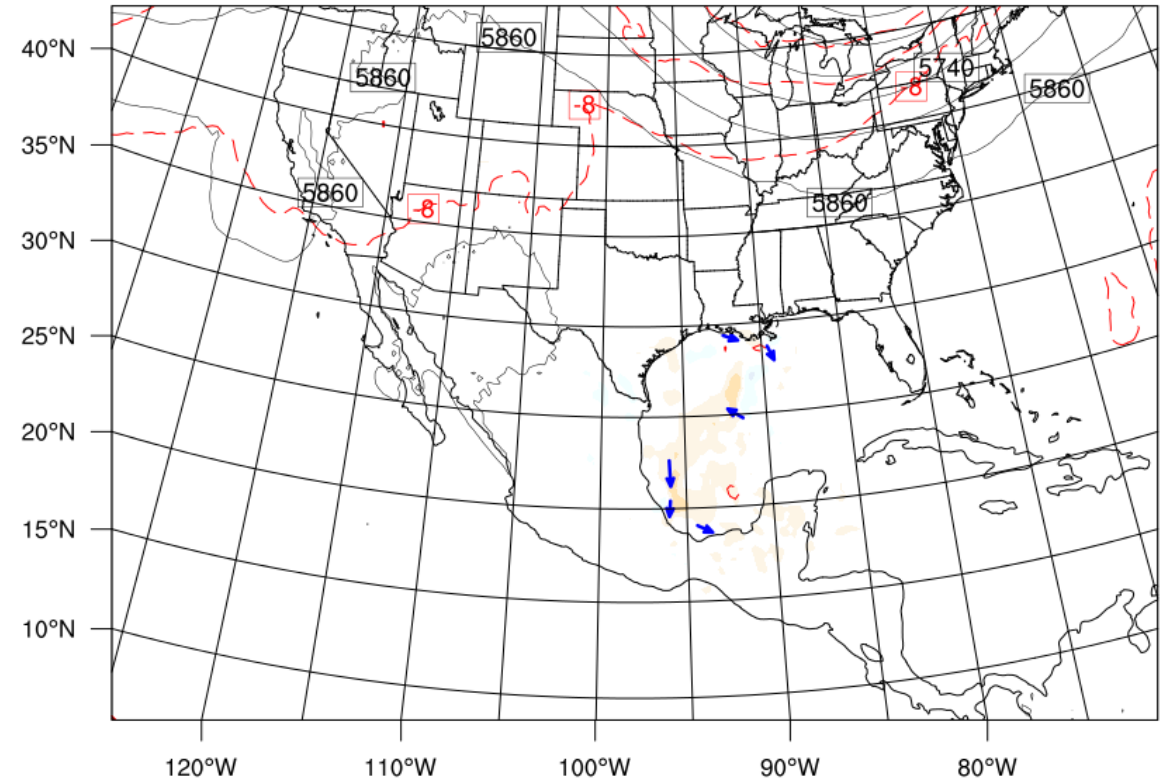
Sensitivity to Temperature (Pa / K)



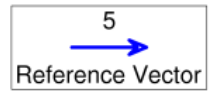
-9.6 -8 -6.4 -4.8 -3.2 -1.6 0 1.6 3.2 4.8 6.4 8 9.6

Sensitivity to Temperature

Sensitivity to Temperature (Pa / K) at 500 hPa
Temperature (C) at 500 hPa
Height (m) at 500 hPa
Sensitivity to Wind (Pa / m s-1) at 500 hPa



Height Contours: 5500 to 6040 by 60
Temperature Contours: -24 to 4 by 4



Sensitivity to Temperature (Pa / K)



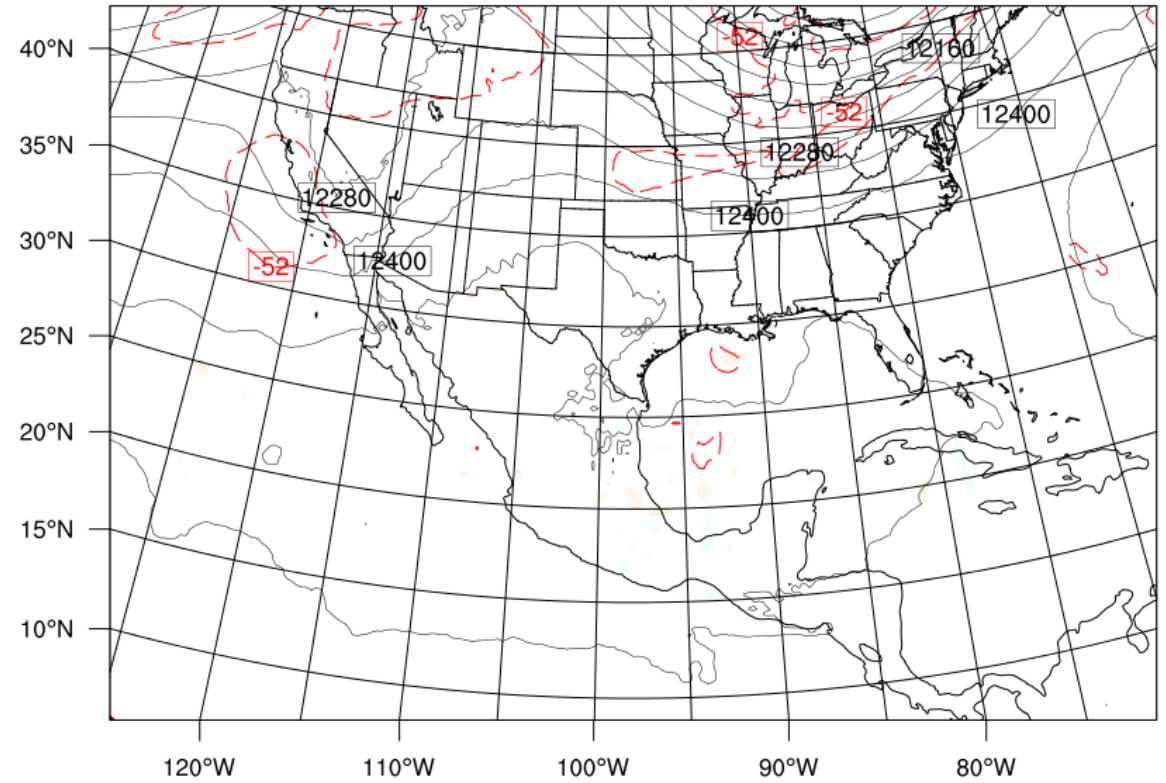
-9.6 -8 -6.4 -4.8 -3.2 -1.6 0 1.6 3.2 4.8 6.4 8 9.6

Sensitivity to Temperature

REAL-TIME WRF: Response Function - μ

Init: 2017-08-23_12:00:00
Valid: 2017-08-23_12:00:00

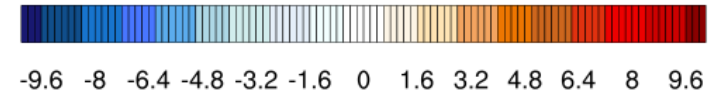
Sensitivity to Temperature (Pa / K) at 200 hPa
Temperature (C) at 200 hPa
Height (m) at 200 hPa
Sensitivity to Wind (Pa / m s-1) at 200 hPa



Height Contours: 11800 to 12640 by 60
Temperature Contours: -64 to -36 by 4

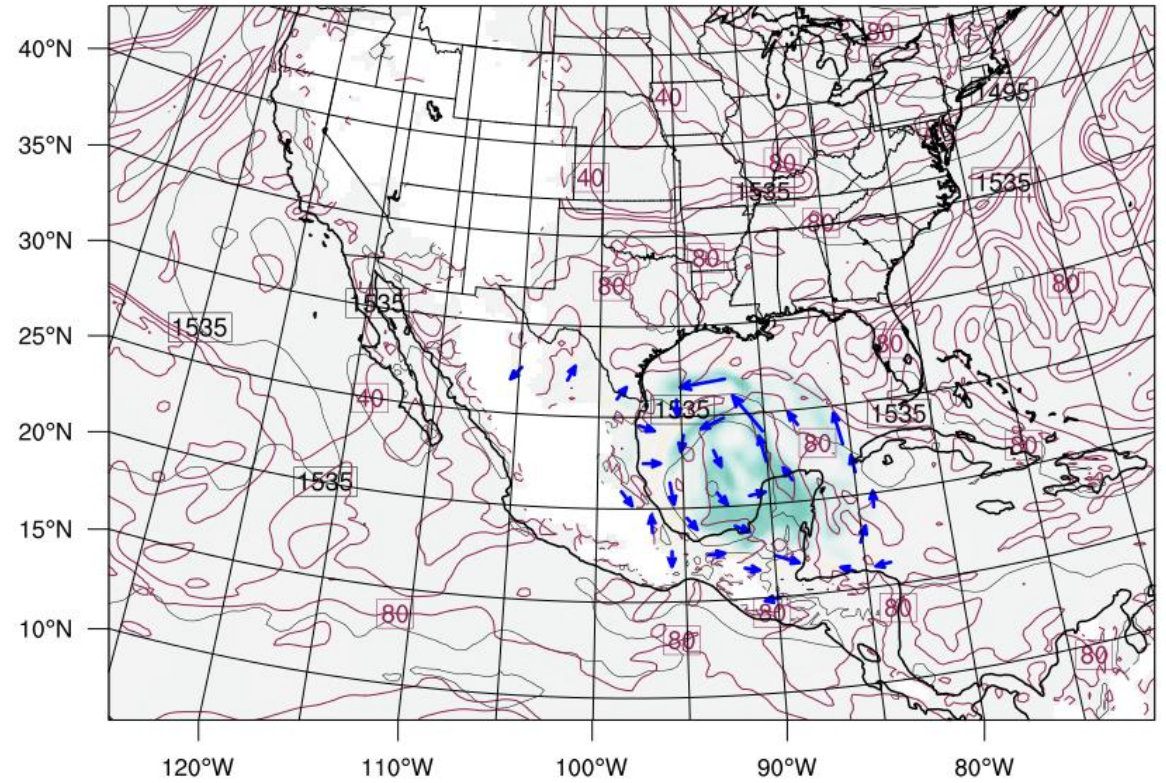


Sensitivity to Temperature (Pa / K)

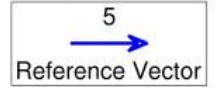


Sensitivity to Temperature

Sensitivity to Water Vapor (Pa / kg kg-1) at 850 hPa
Height (m) at 850 hPa
Relative Humidity (%) at 850 hPa
Sensitivity to Wind (Pa / m s-1) at 850 hPa



Height Contours: 1375 to 1615 by 20
Relative Humidity Contours: 40 to 100 by 20



Sensitivity to Water Vapor (Pa / kg kg-1)



-7200 -5400 -3600 -1800 0 1800 3600 5400 7200

Sensitivity to Water Vapor

Optimal Perturbation to u' and v'

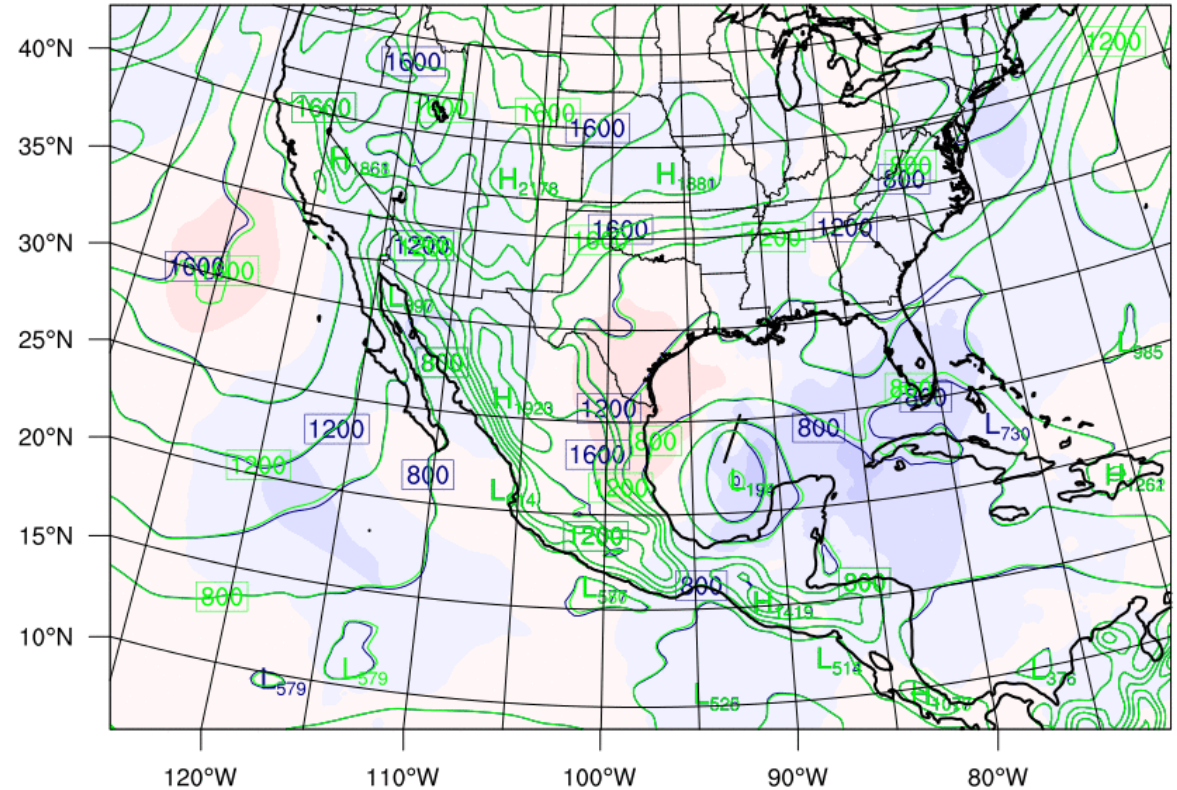
$$\delta R = 1 \text{ hPa}$$

Difference in μ

REAL-TIME WRF: Hurricane Harvey Track

Init: 2017-08-23_12:00:00
Valid: 2017-08-23_15:00:00

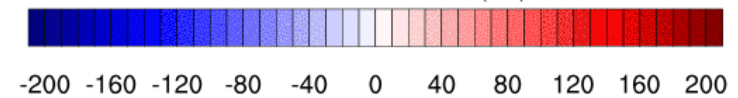
Perturbation - Control (Pa)
Wind
Perturbation Dry Air Mass in Column (Control) (Pa)
Perturbation Dry Air Mass in Column (Perturbation) (Pa)



Perturbation Dry Air Mass in Column (Control) Contours: -1000 to 2300 by 200

Perturbation Dry Air Mass in Column (Perturbation) Contours: -1000 to 2300 by 200

Perturbation - Control (Pa)



OUTPUT FROM WRF V3.8.1 MODEL
WE = 210 ; SN = 144 ; Levels = 41 ; Dis = 30km ; Phys Opt = 7 ; PBL Opt = 1 ; Cu Opt = 1