



PennState

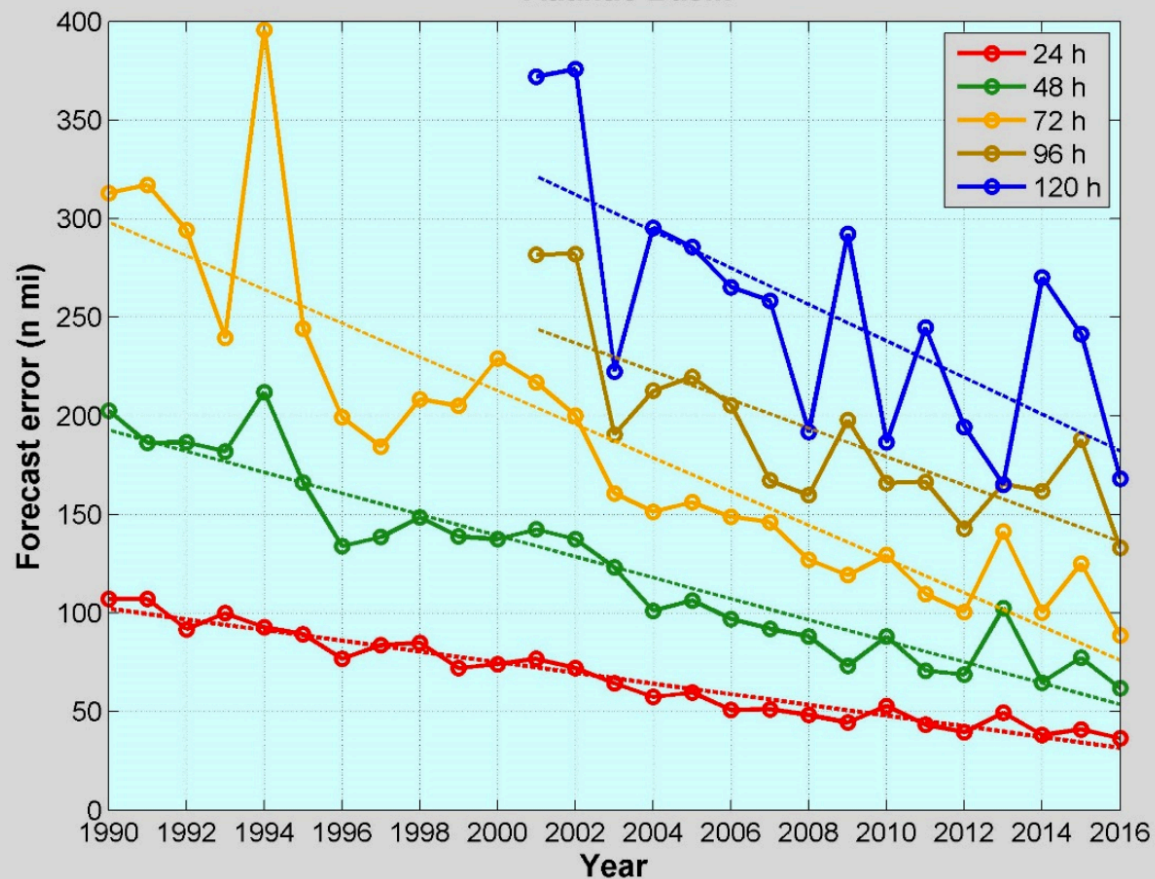


Understanding and Improving the Predictability of Tropical Cyclones Through Ensemble- Based Data Assimilation

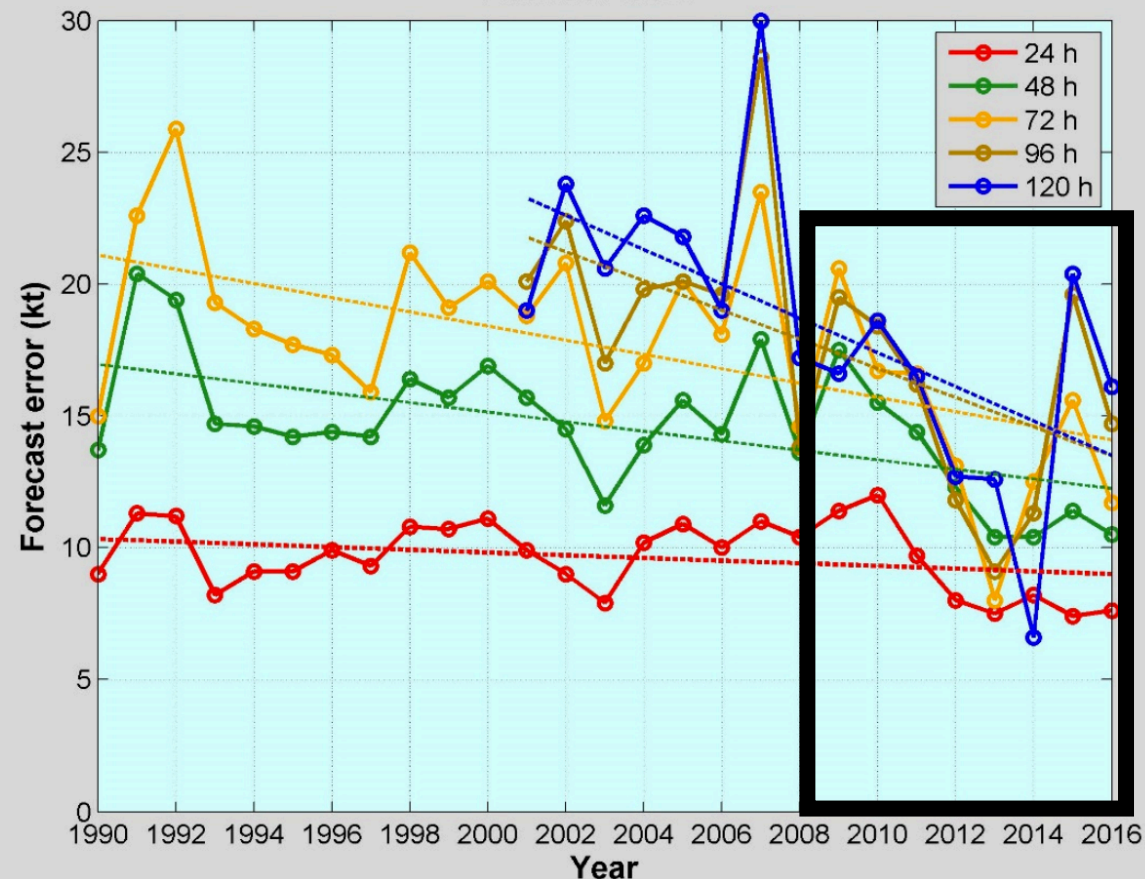
Robert G. Nystrom¹, Fuqing Zhang, Erin B. Munsell, Scott A. Braun, Jason A. Sippel, Yonghui Weng, and Kerry Emanuel

¹Department of Meteorology and Atmospheric Science, and Center for Advanced Data Assimilation and Predictability Techniques, The Pennsylvania State University, University Park, Pennsylvania, USA

**NHC Official Track Error Trend
Atlantic Basin**

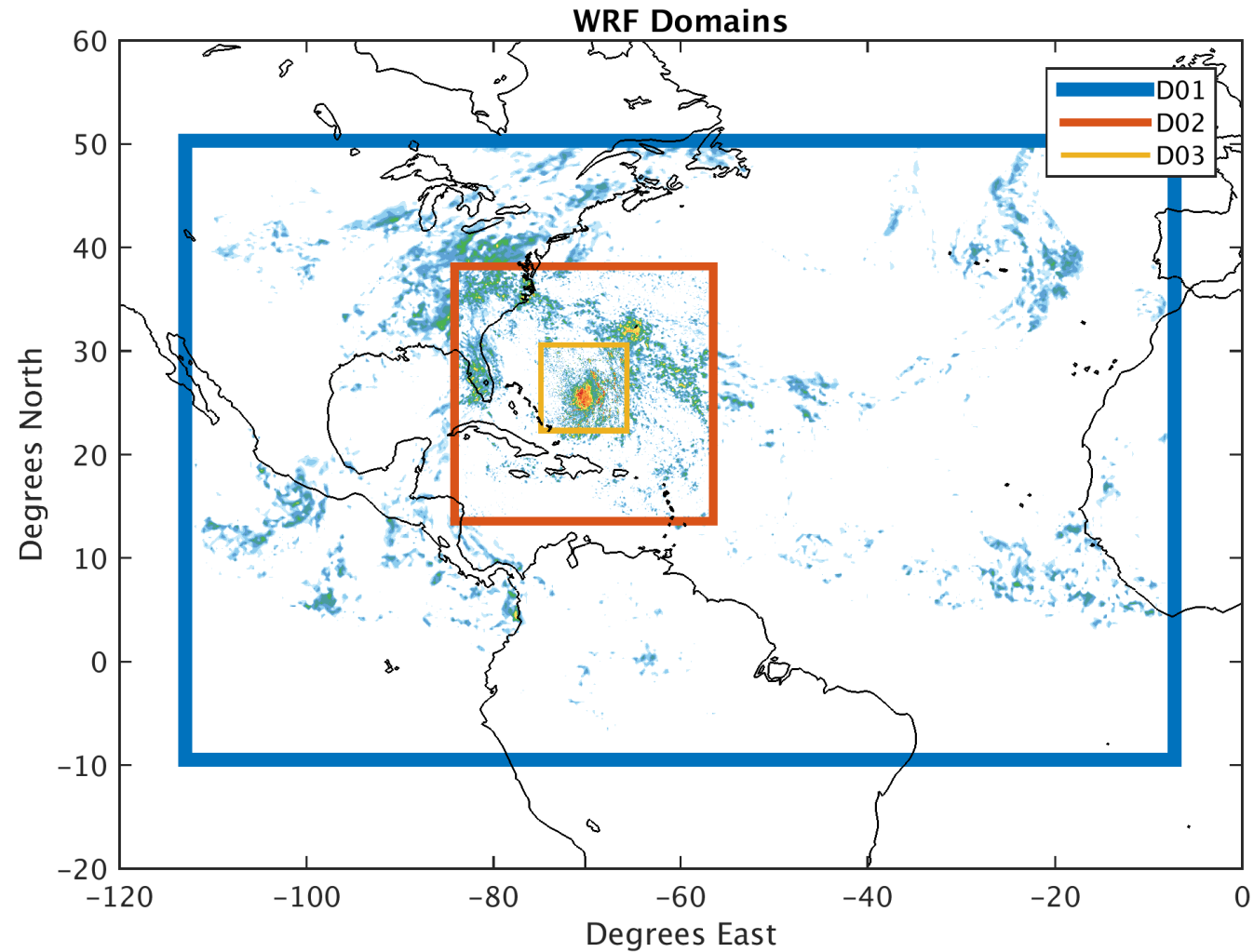


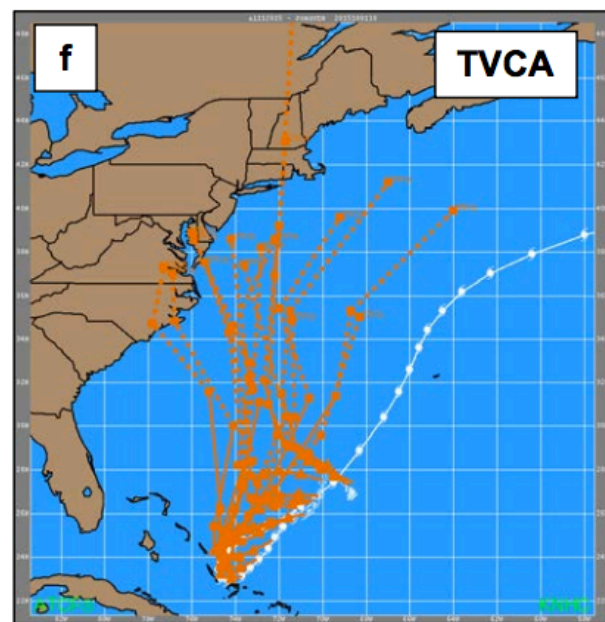
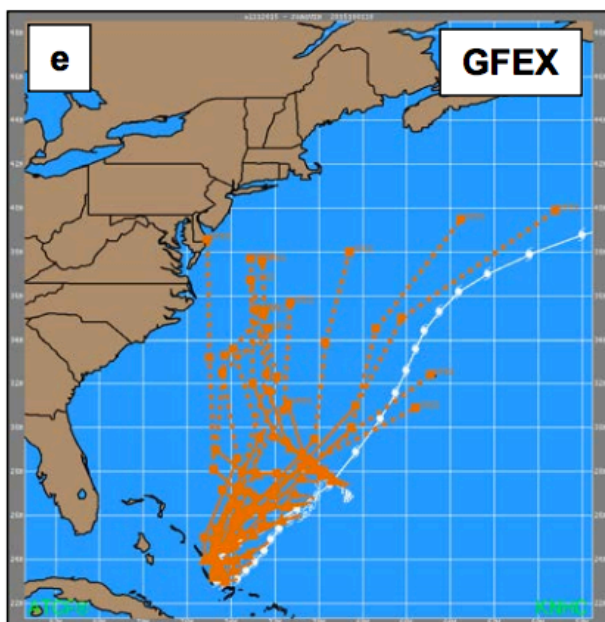
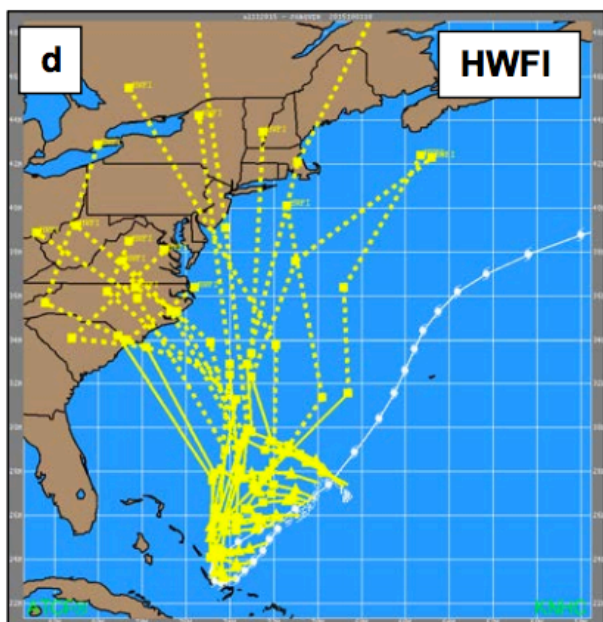
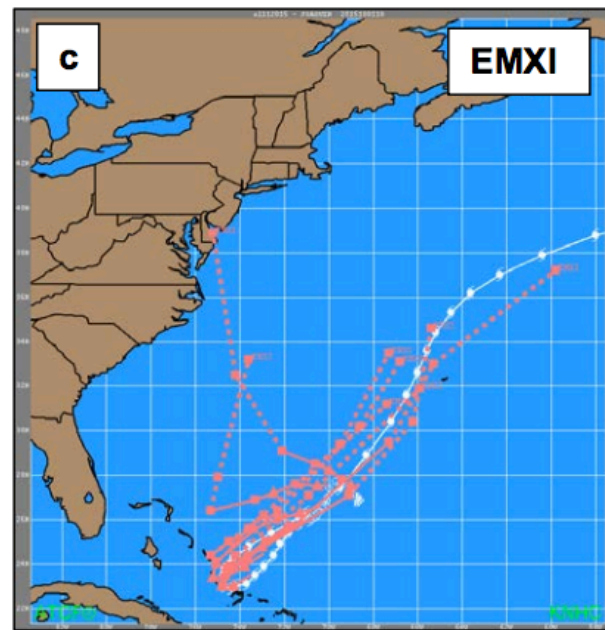
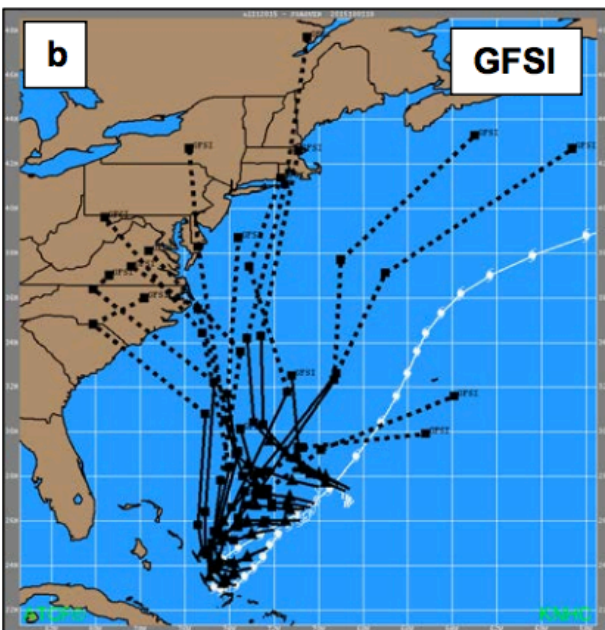
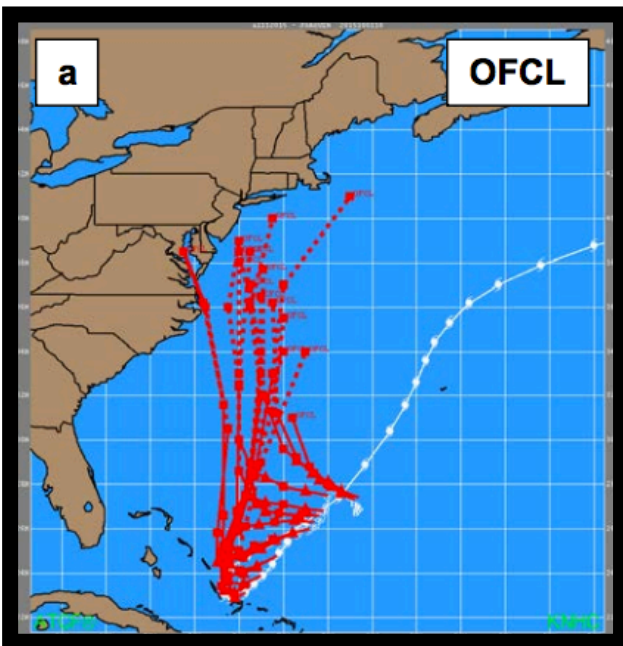
**NHC Official Intensity Error Trend
Atlantic Basin**

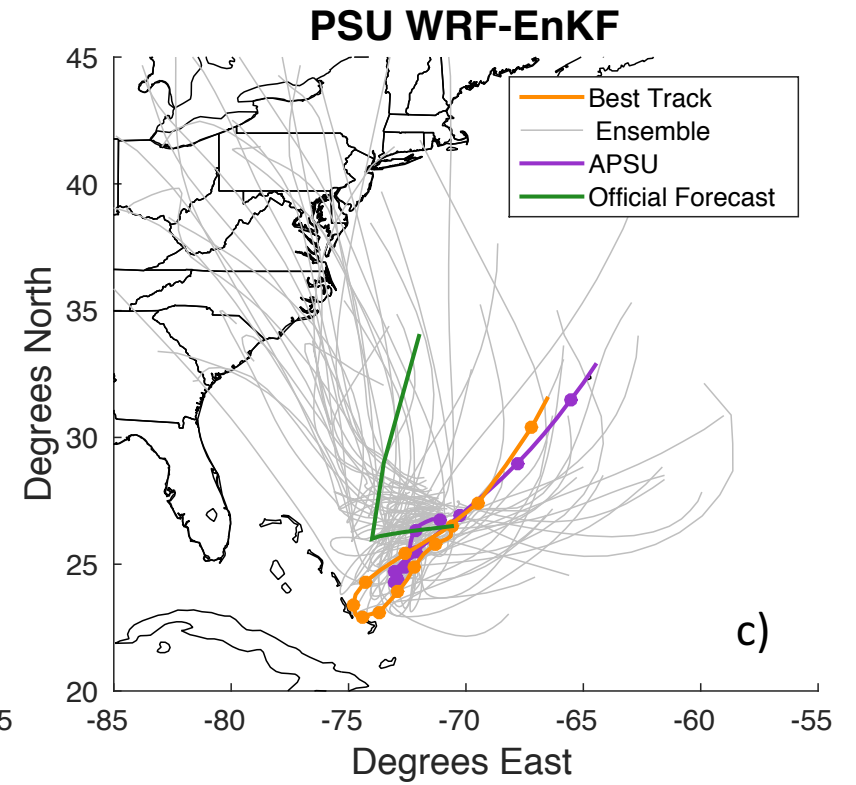
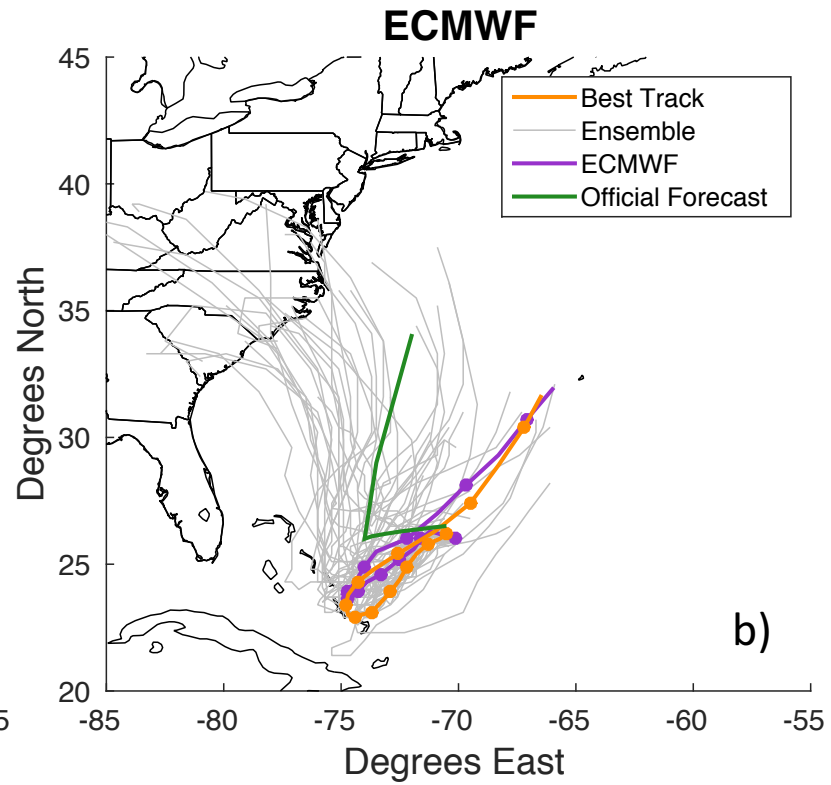
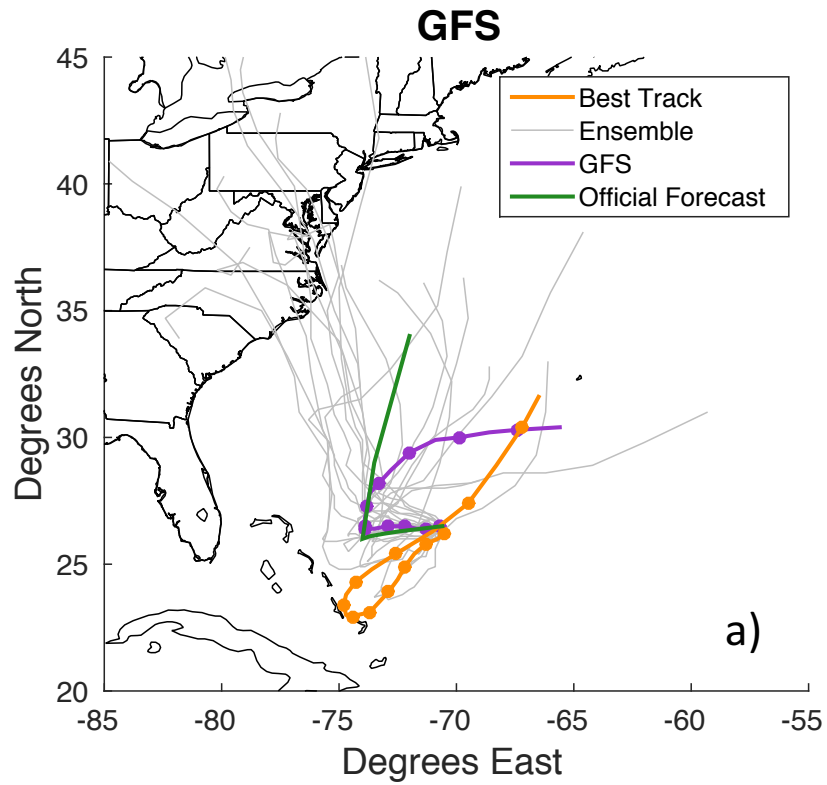


PSU WRF-EnKF

- 60 member ensemble
- 3 hour continuous cycling EnKF
- Assimilates conventional and Airborne radial velocity SOs
- WRF v3.5.1
- 3 two-way nested domains
- 27/9/3 km grid spacing
- Boundary conditions provided by GFS
- Initial ensemble perturbations provided by background error covariance
- WSM6 microphysics
- YSU PBL
- Dudhia Shortwave
- Grell-Dévényi Cumulus (D01 Only)
- Green and Zhang (2013) surface flux scheme

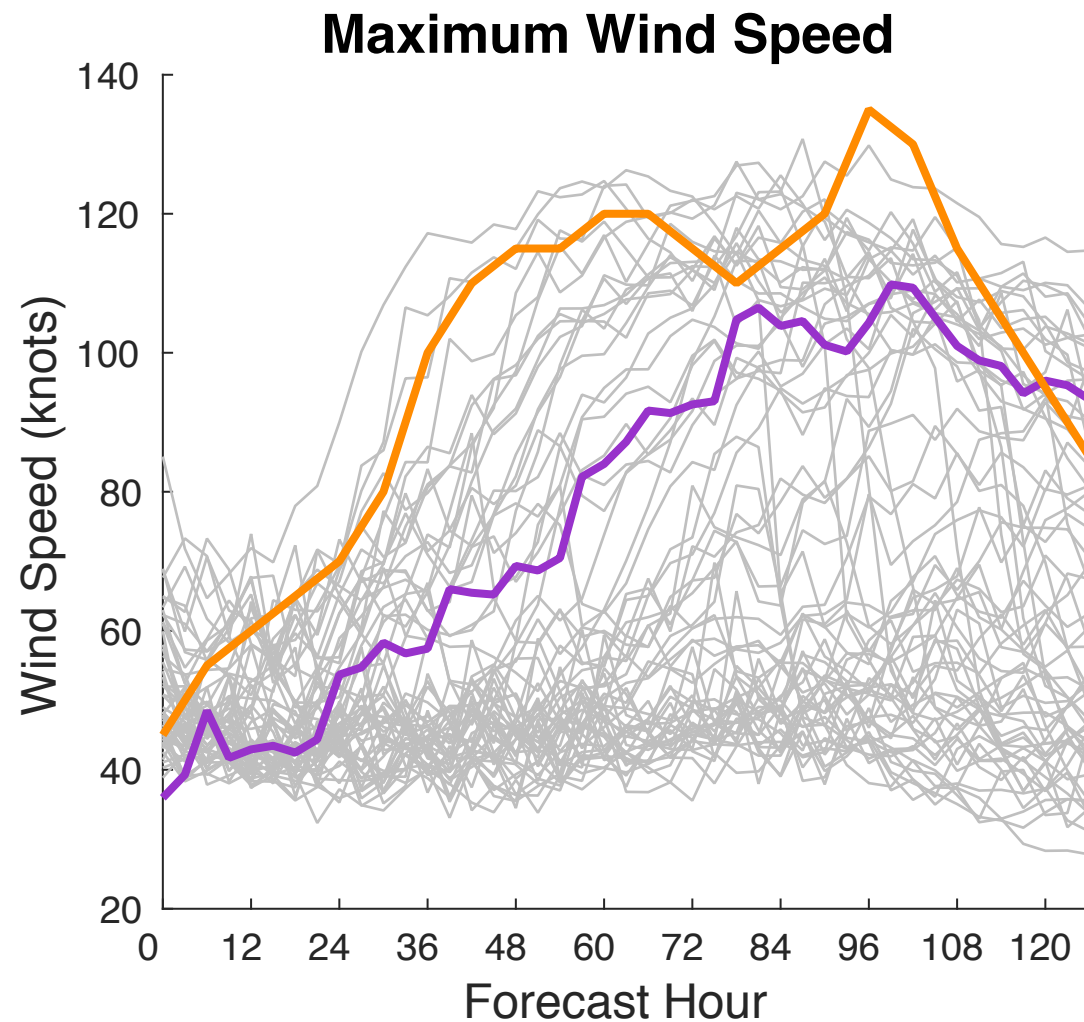
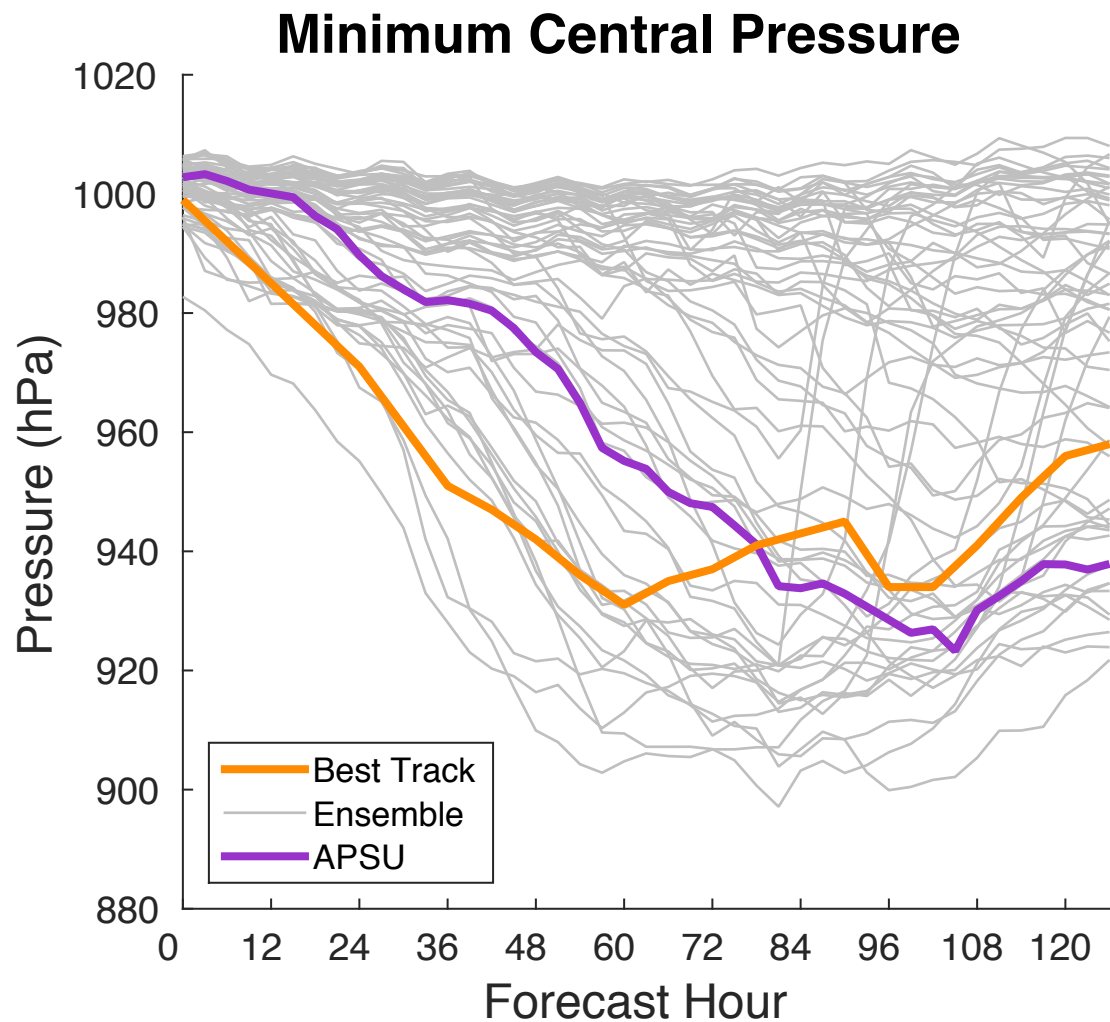






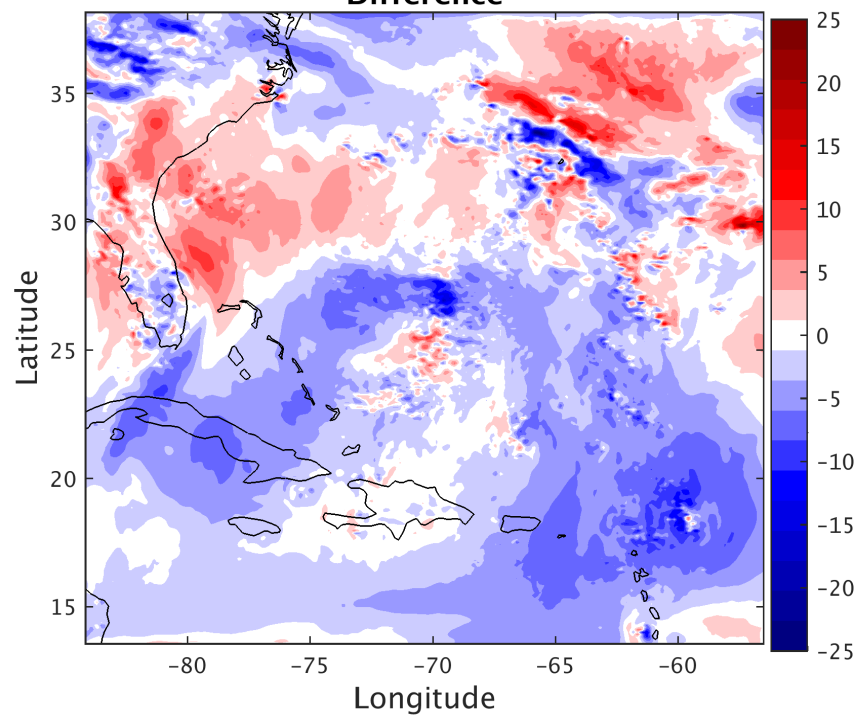
U.S. Landfall?

Out to sea?



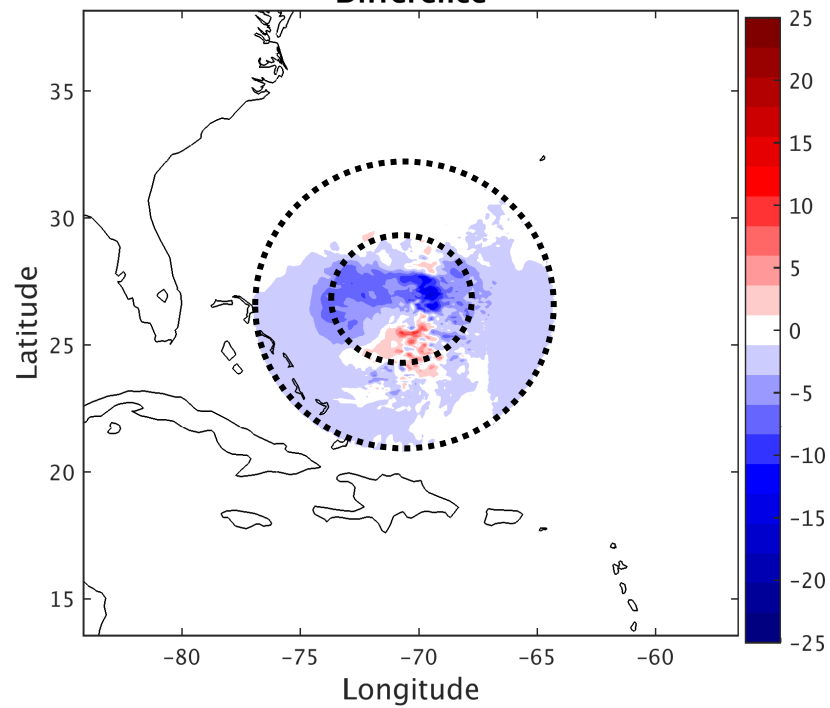
Major Hurricane? Tropical Storm?

UNRL
Difference



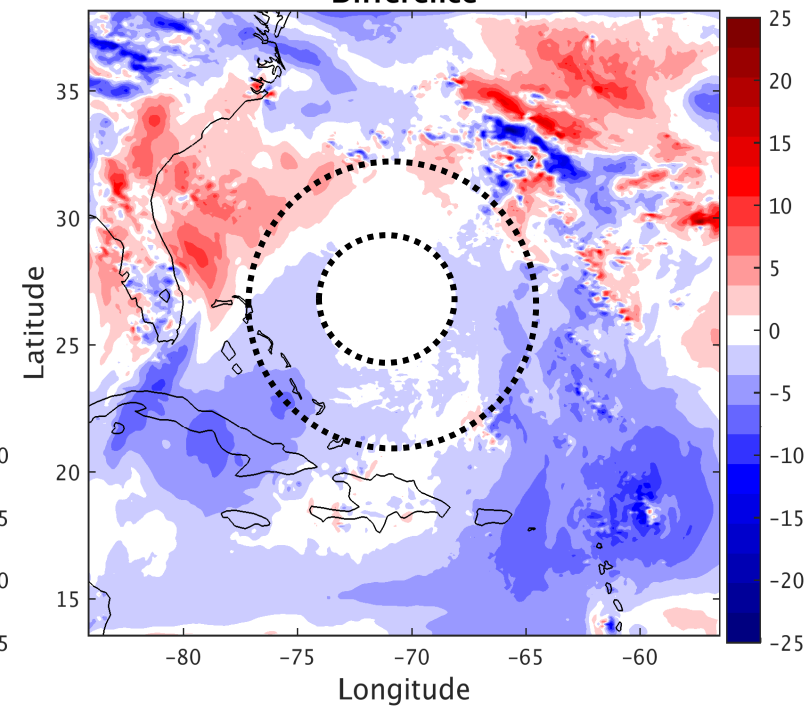
IC differences everywhere

RENV
Difference

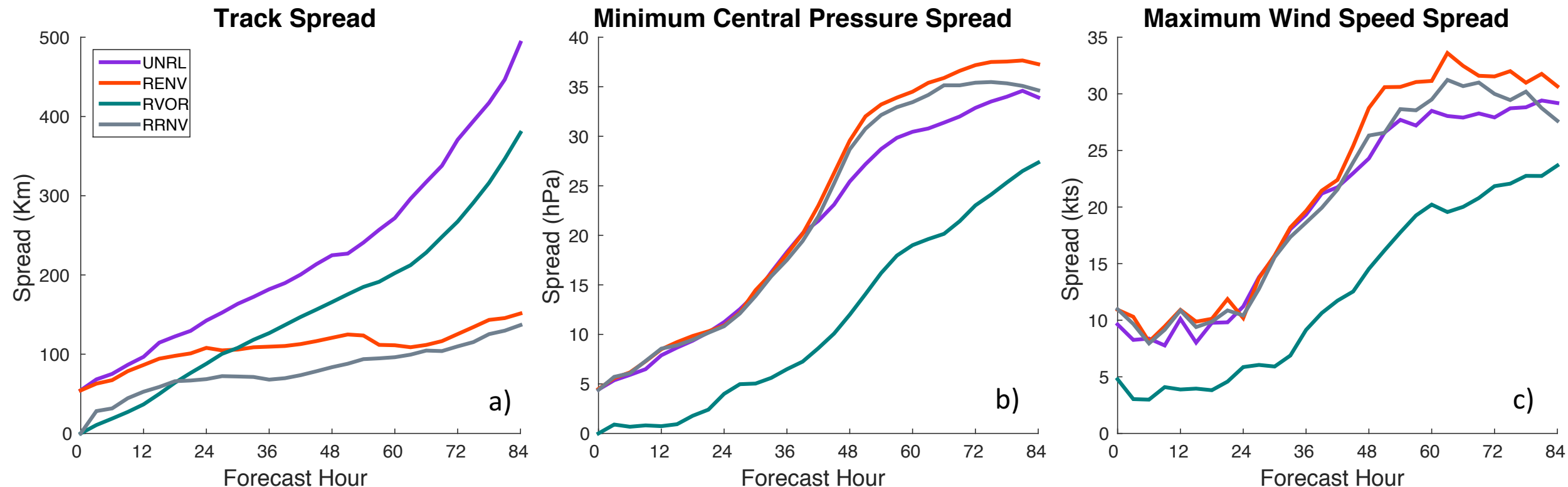


IC differences Vortex only

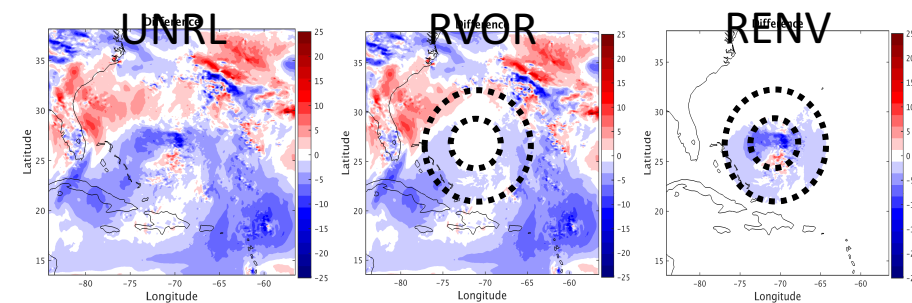
RVOR
Difference



IC difference Environment

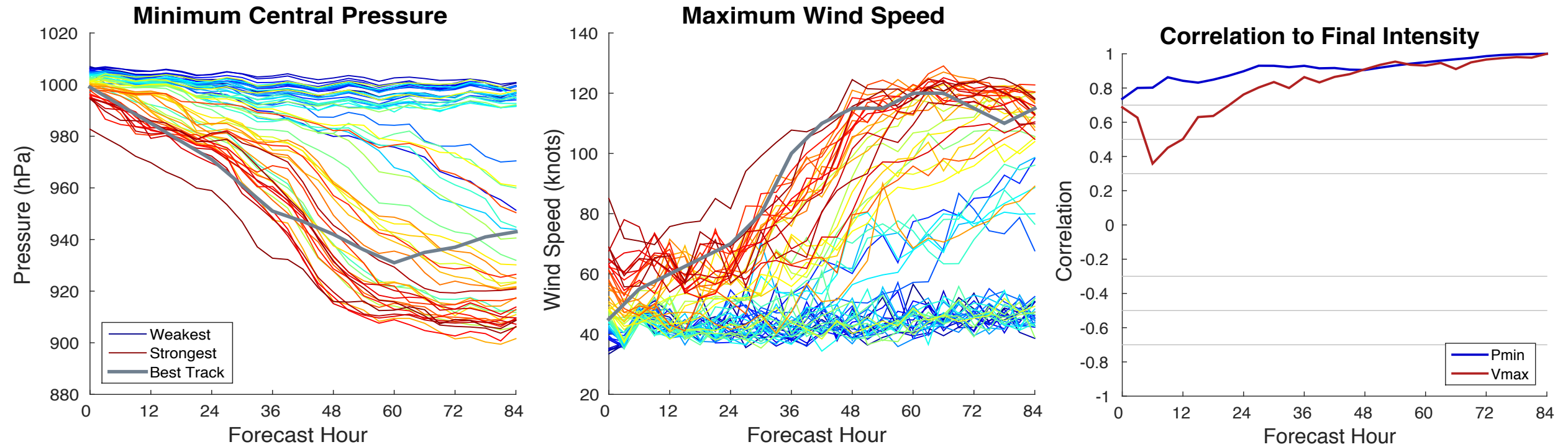


- RVOR only ensemble whose track spread approaches that of UNRL
- RENV/RRNV track spread only slightly increases
- RENV/RRNV can reproduce UNRL intensity spread
- RVOR intensity spread still growing at 84 h

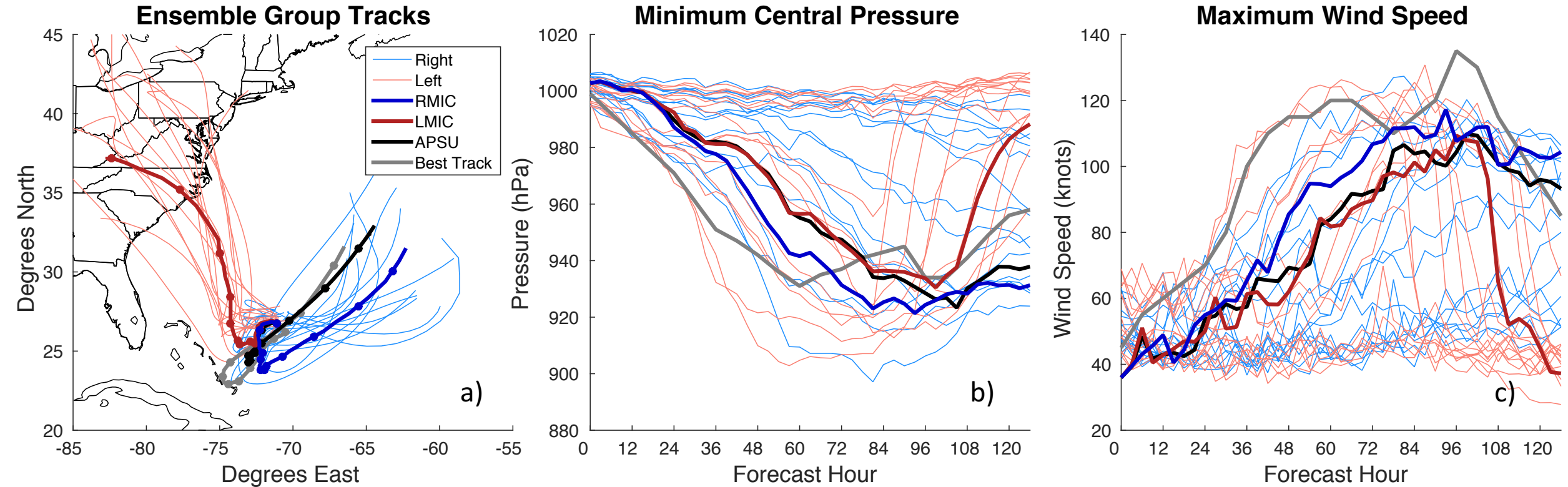


Initial intensity is very important!

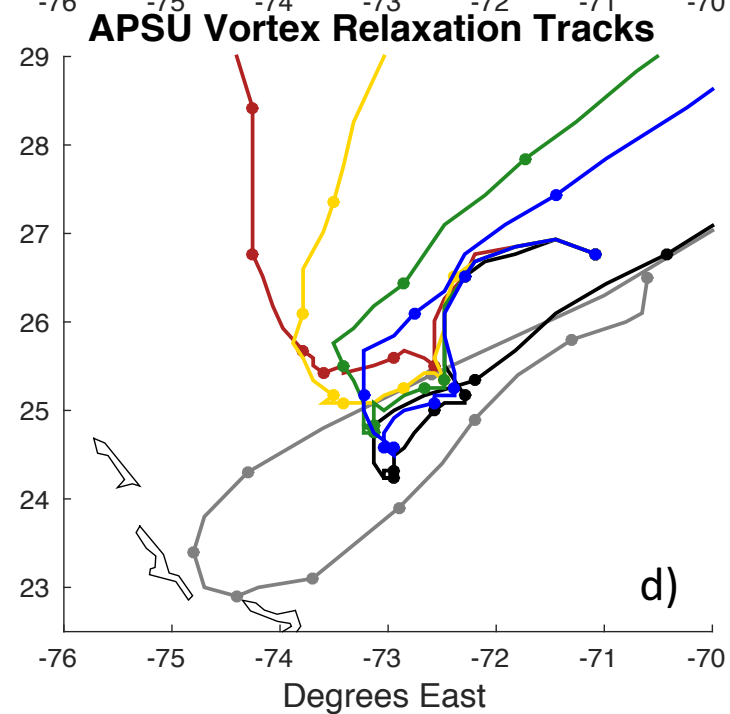
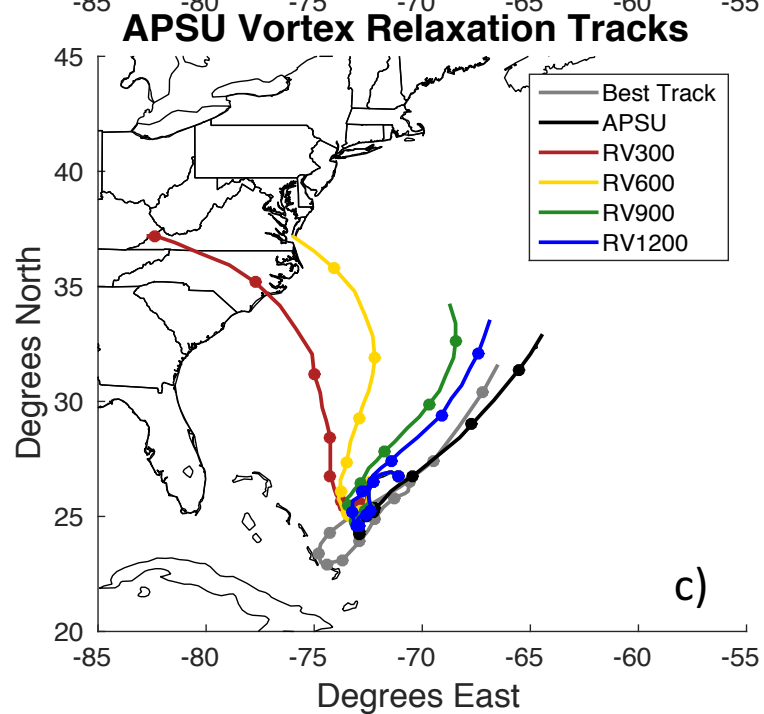
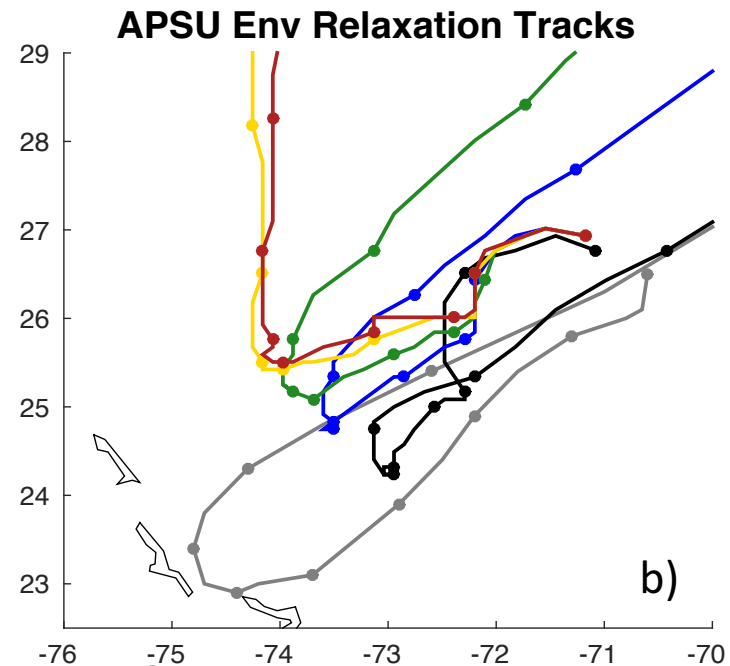
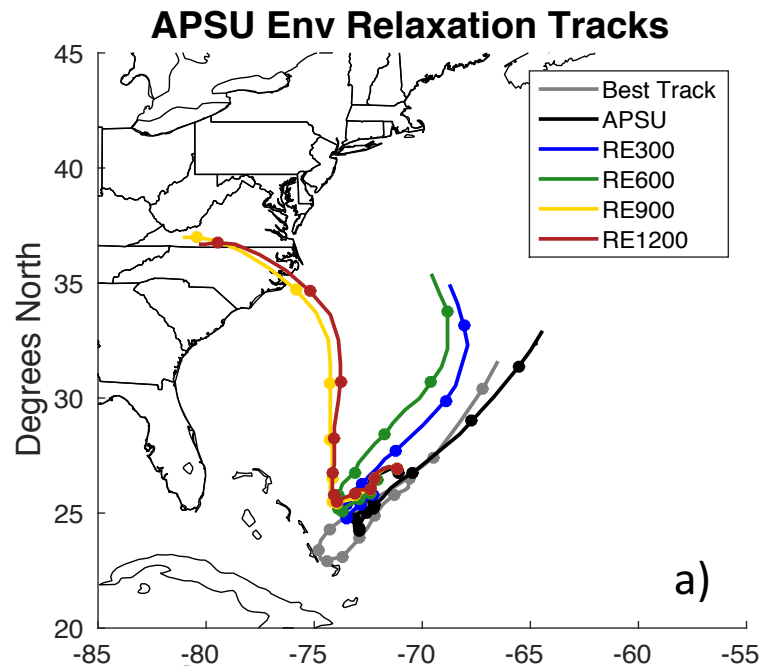
From RRNV Ensemble:



Forecast track insensitive to intensity!



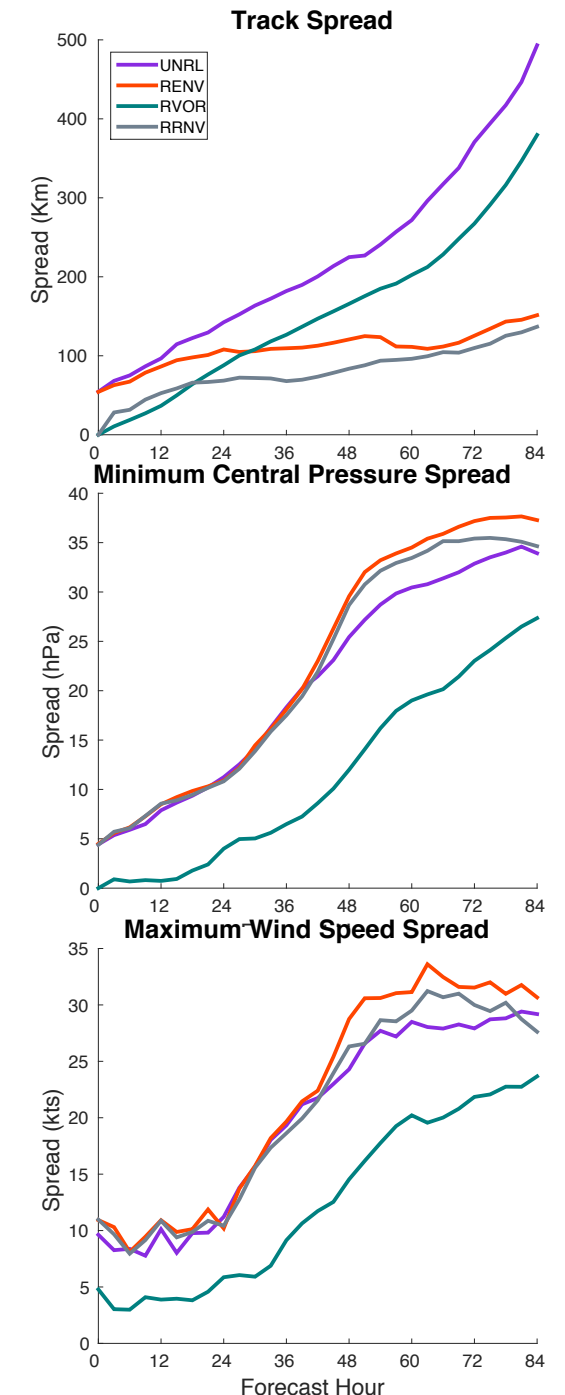
What in the environment influences storm track?



Summary

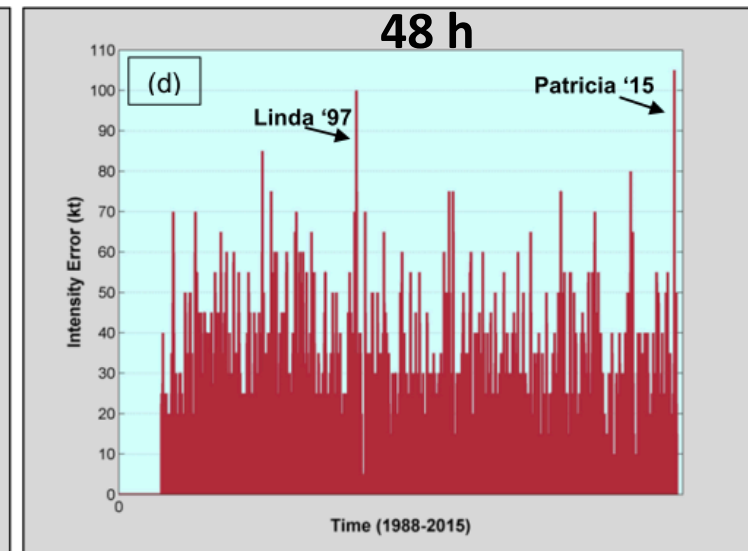
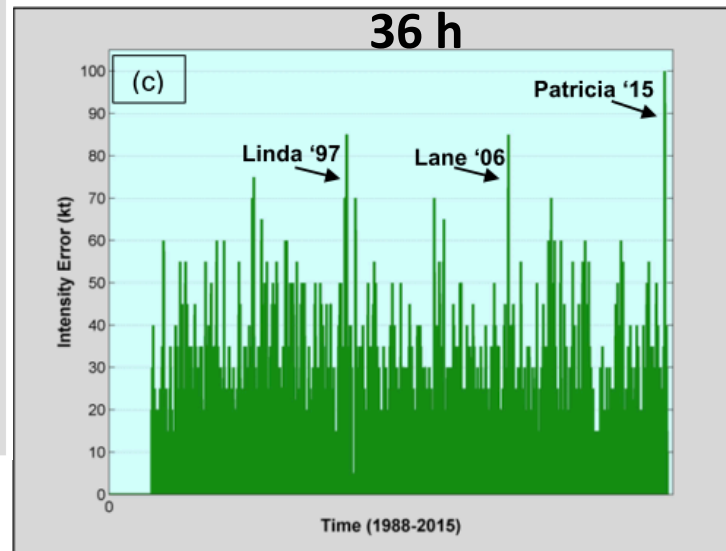
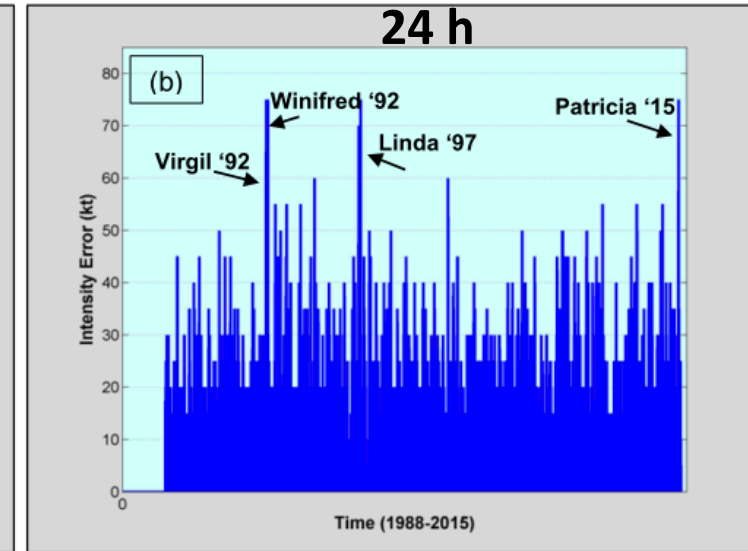
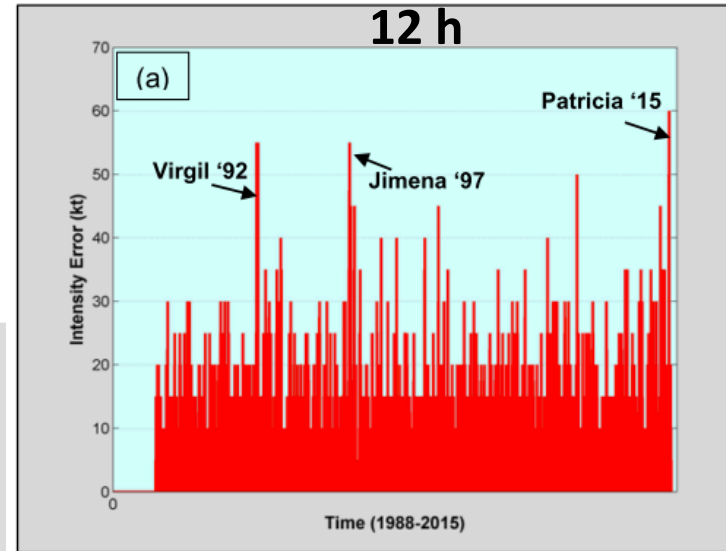
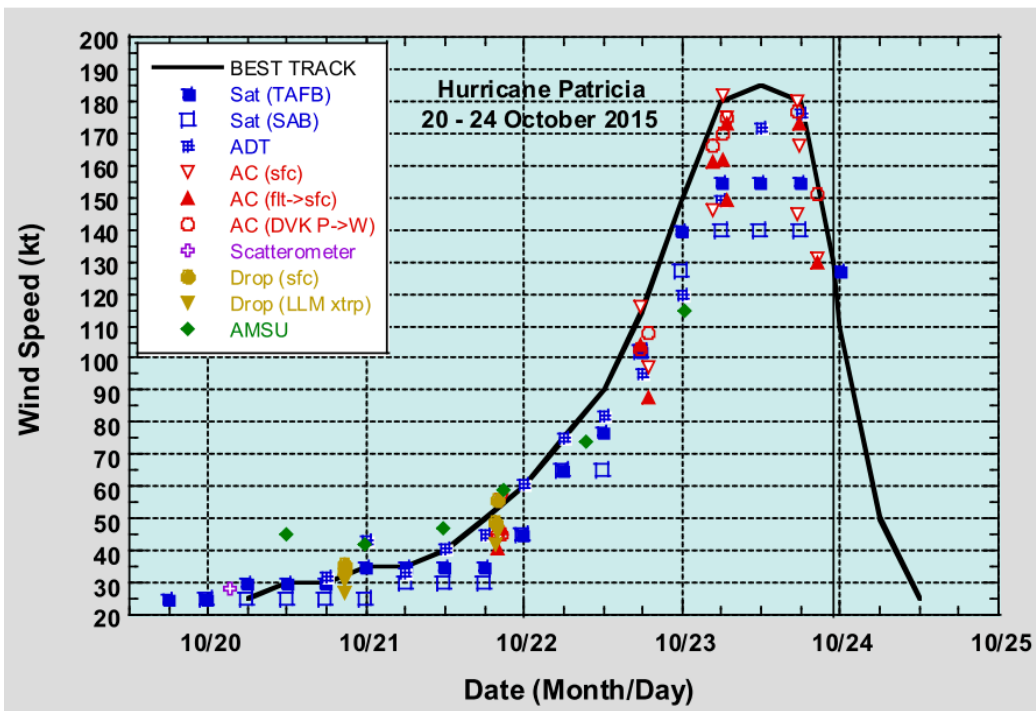
- Ensemble forecasts of Joaquin had very large intensity and track spread
- Intensity spread saturates most rapidly as a result of IC differences to the storm vortex (within 300 km)
 - Initial intensity large determining factor in final intensity
strong initial storm -> strong final storm
weak initial storm -> weak final storm
- Track spread dominated by IC differences to the environment (beyond 300 km)
 - Track bifurcation insensitive to storm intensity
 - Mid to low-level steering wind differences appear to have resulted in track divergence
 - IC differences between 600-900 km from initial storm location important!

Nystrom et al. 2017

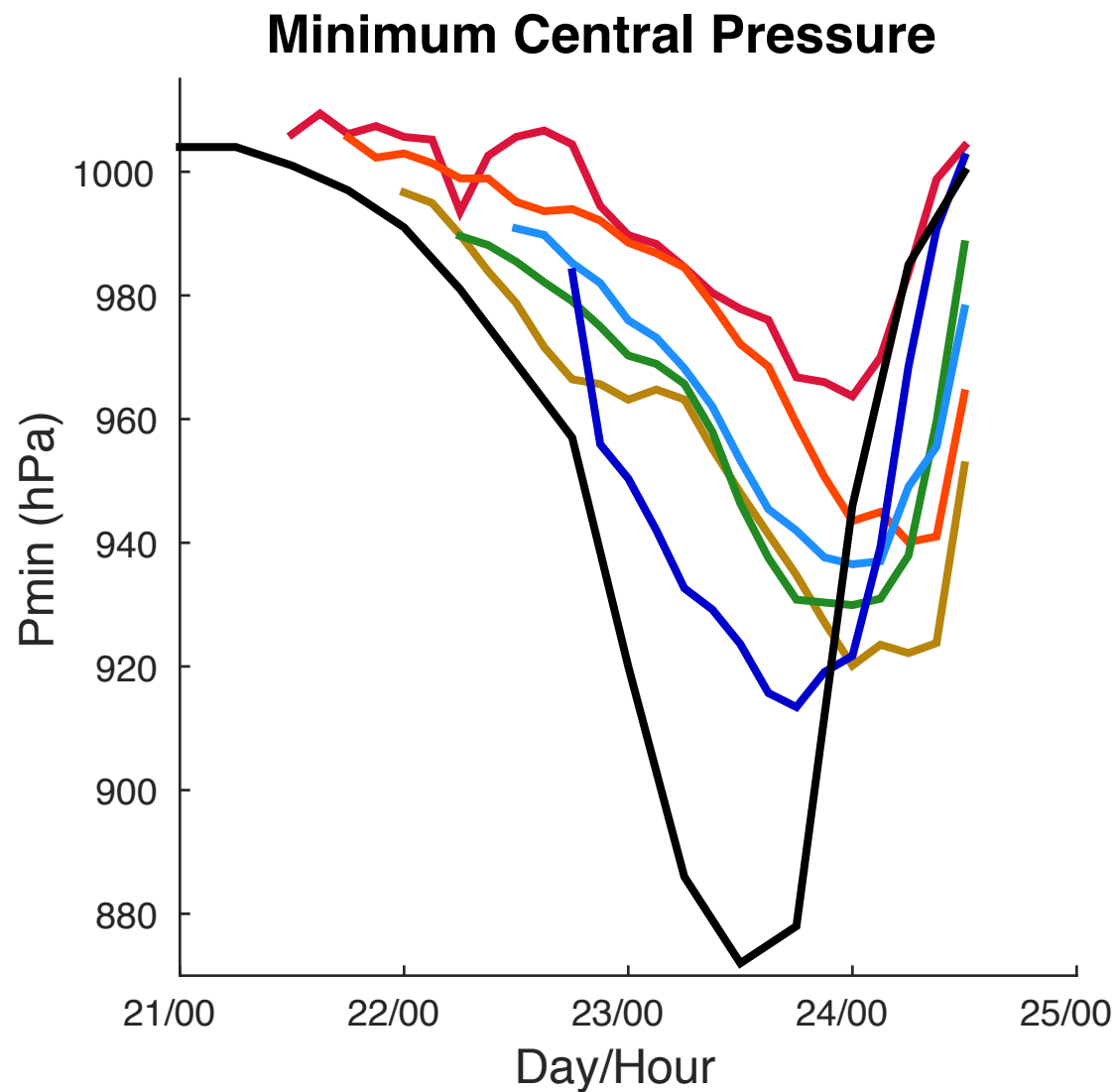
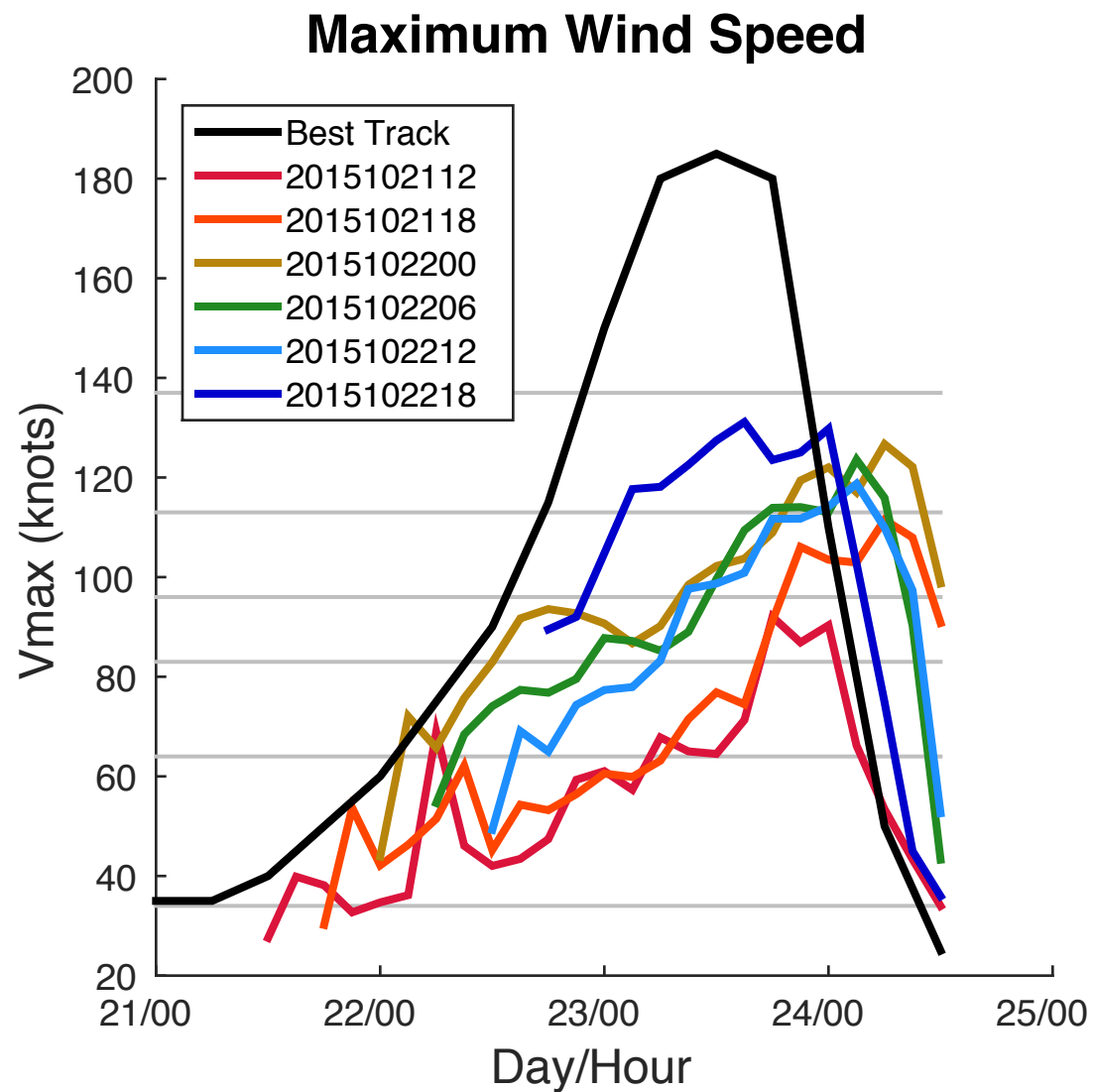


Hurricane Patricia (2015)

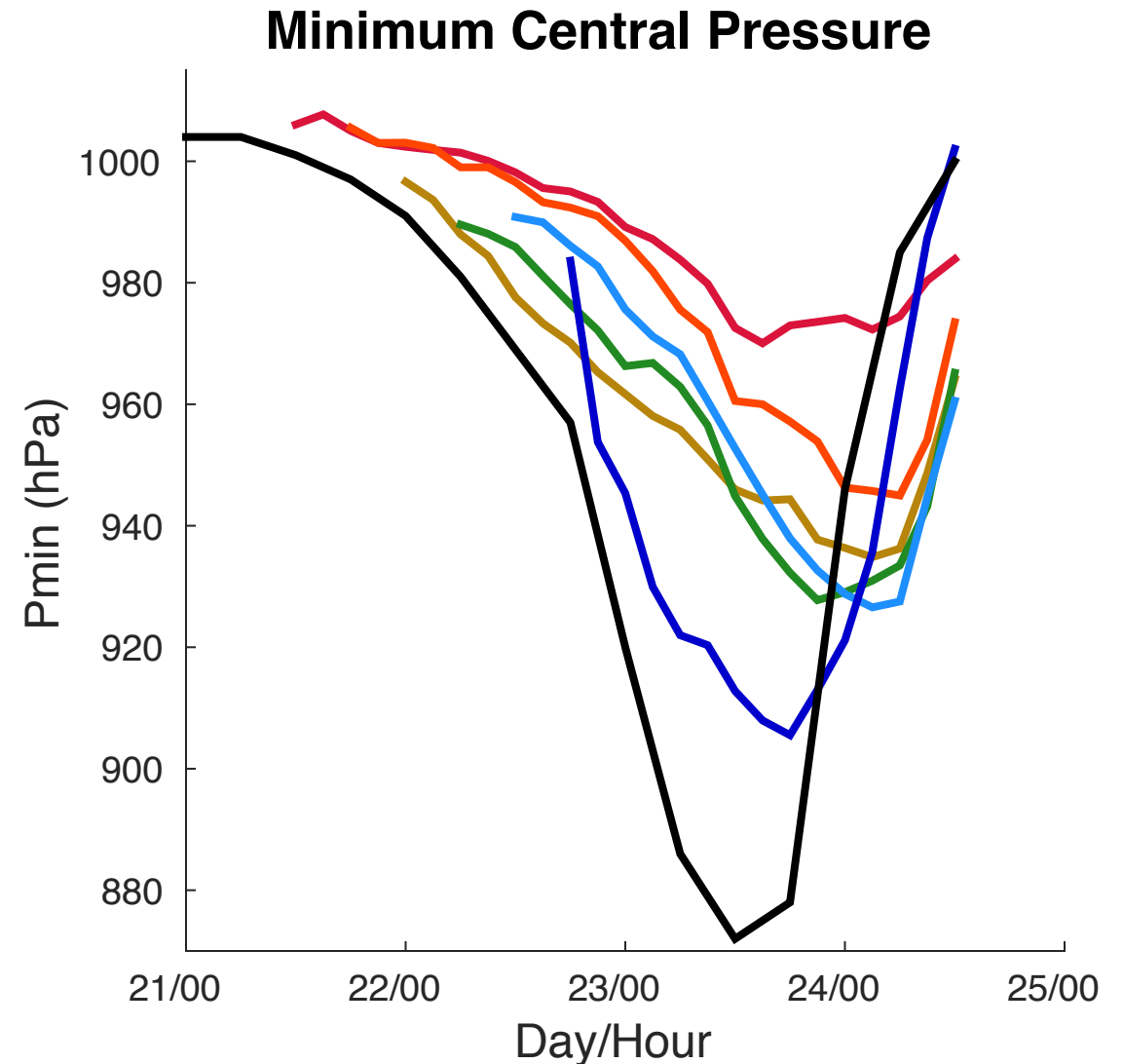
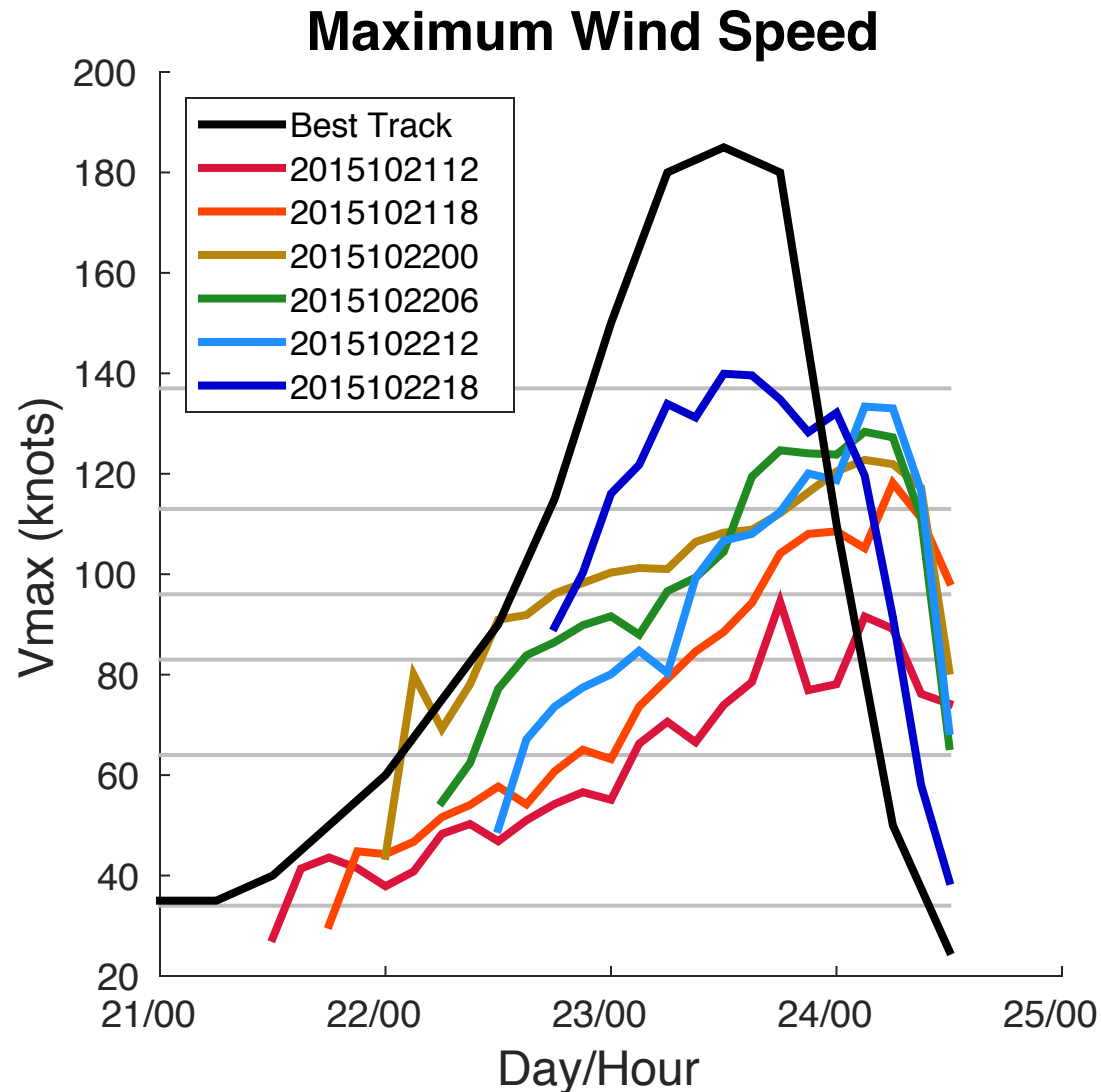
- Historical record setter
- Very large forecast errors!



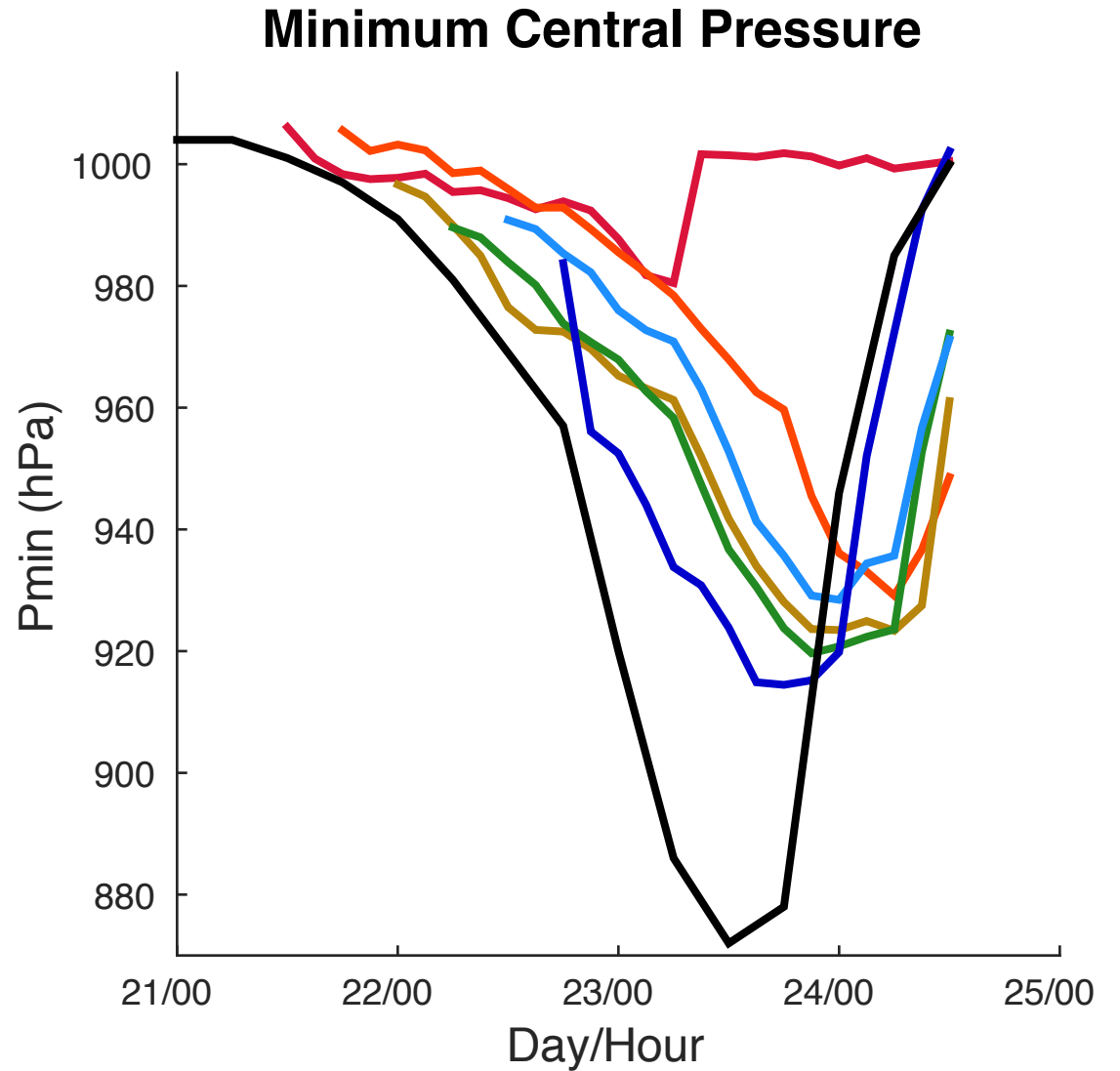
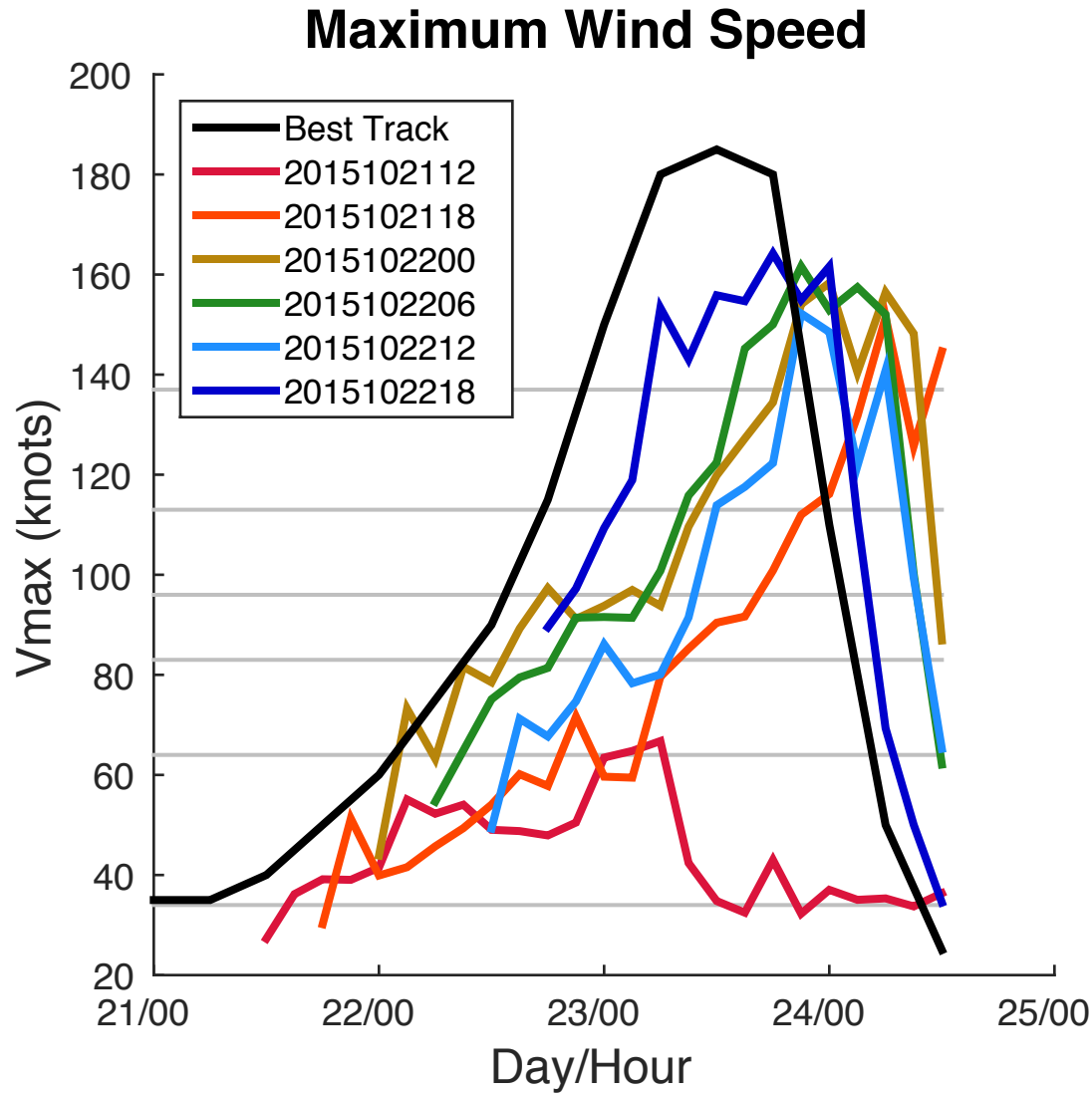
Retrospective PSU-WRF EnKF runs



Retrospective PSU-WRF EnKF runs (1 km)



Retrospective PSU-WRF EnKF runs (sfc flux)



Summary and Future Work

- Forecasts of Patricia struggle to capture timing and rate of RI
- 1 km forecast demonstrate slight improvement
- New sfc flux scheme helps capture high intensity [Yingjian et al. 2017]
- PSU WRF-EnKF demonstrates improvement from NHC forecasts

How can we further improve forecasts?

- Assimilate Coplane obs instead of SOs [Melhauser and Zhang 2016]
- Assimilate GOES-13 All-Sky radiances and possibly microwave observations
- Examine ensemble forecasts

3 km

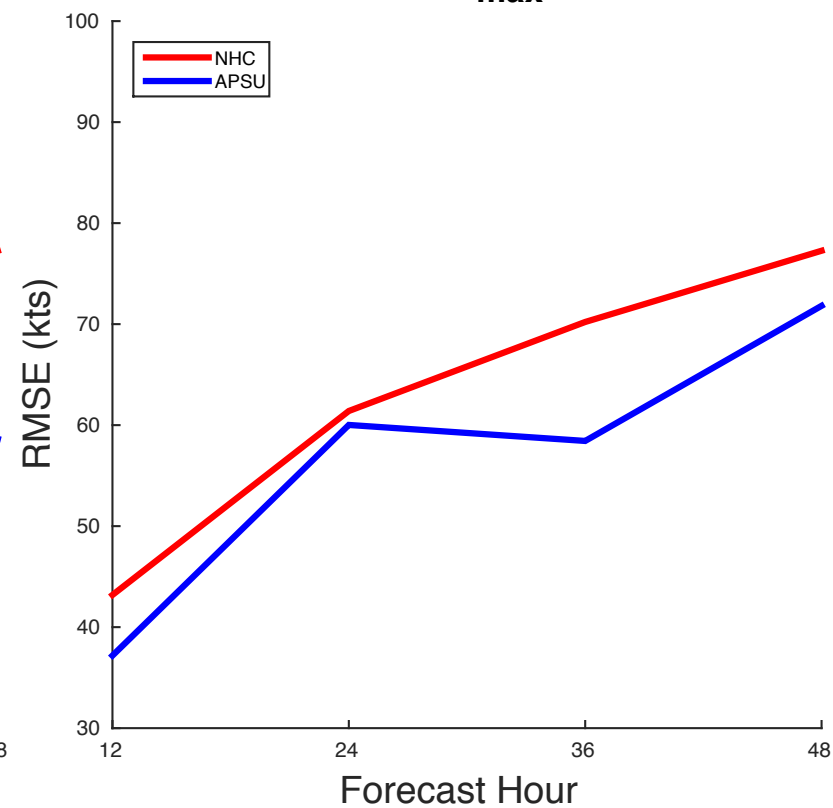
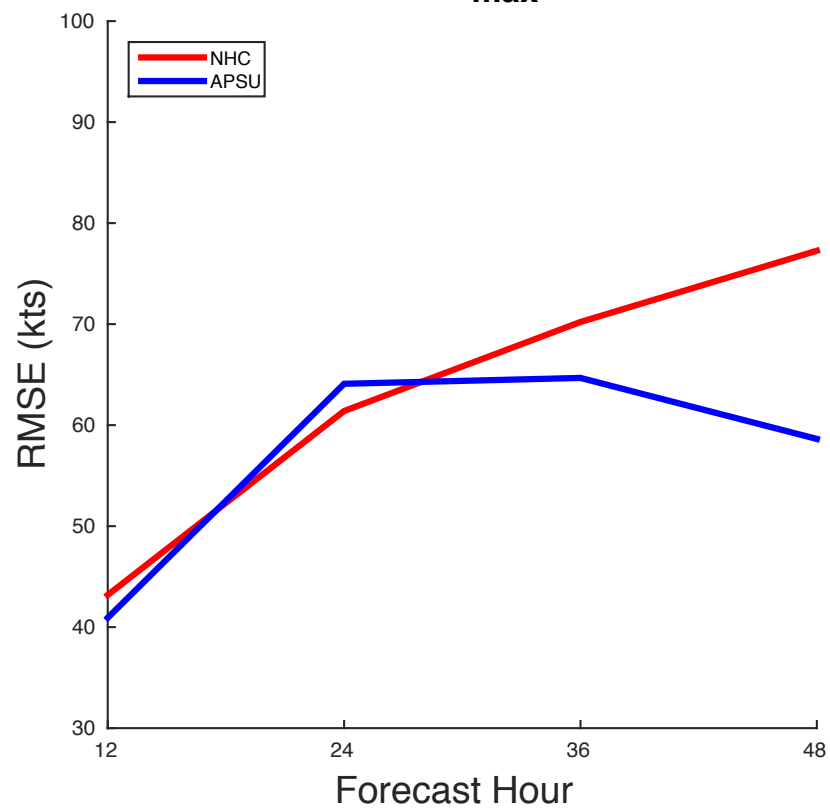
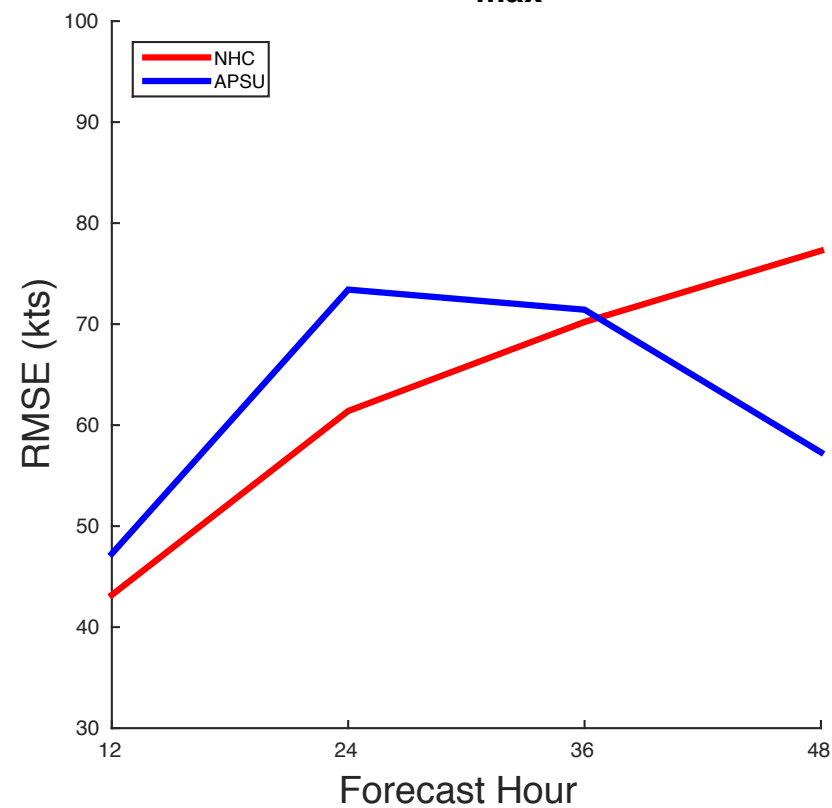
1 km

Sfc Flux

Average $V_{\max}$ RMSE

Average $V_{\max}$ RMSE

Average $V_{\max}$ RMSE

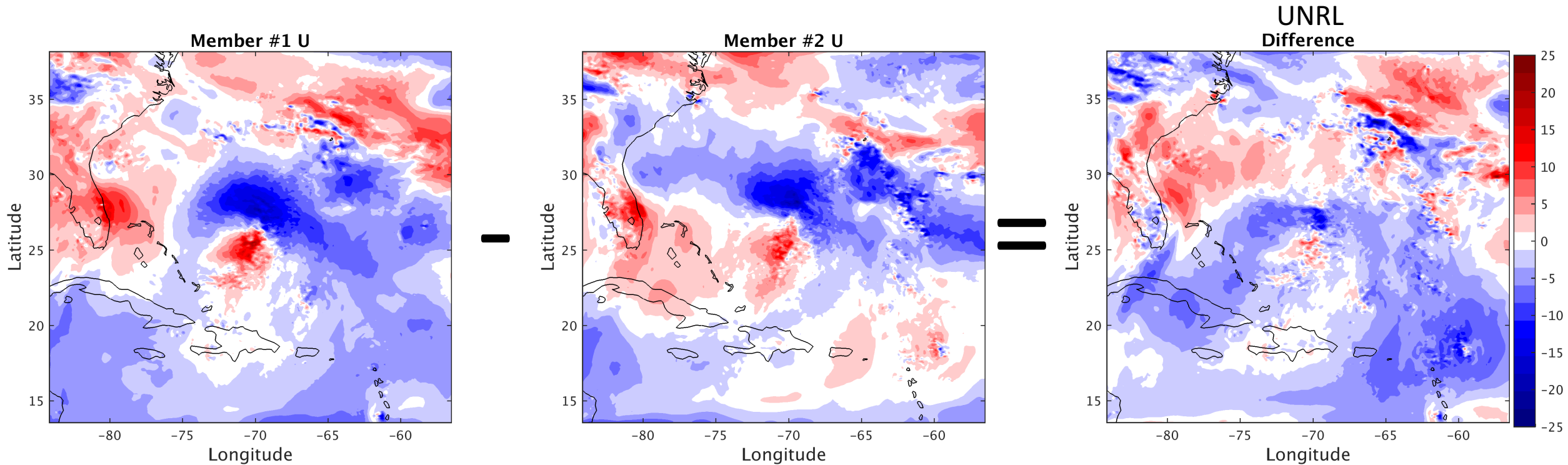


Relaxation Procedure

$$\text{RENV} \left\{ \begin{array}{l} a = (R_{\max} - r) / (R_{\max} - R_{\min}) \text{ (if } R_{\min} \leq r \leq R_{\max}) \\ a = 1.0 \text{ (if } r < R_{\min}) \\ a = 0 \text{ (if } r > R_{\max}) \\ \text{RENV} = \text{UNRL} * a + \text{GFS} * (1 - a) \end{array} \right.$$

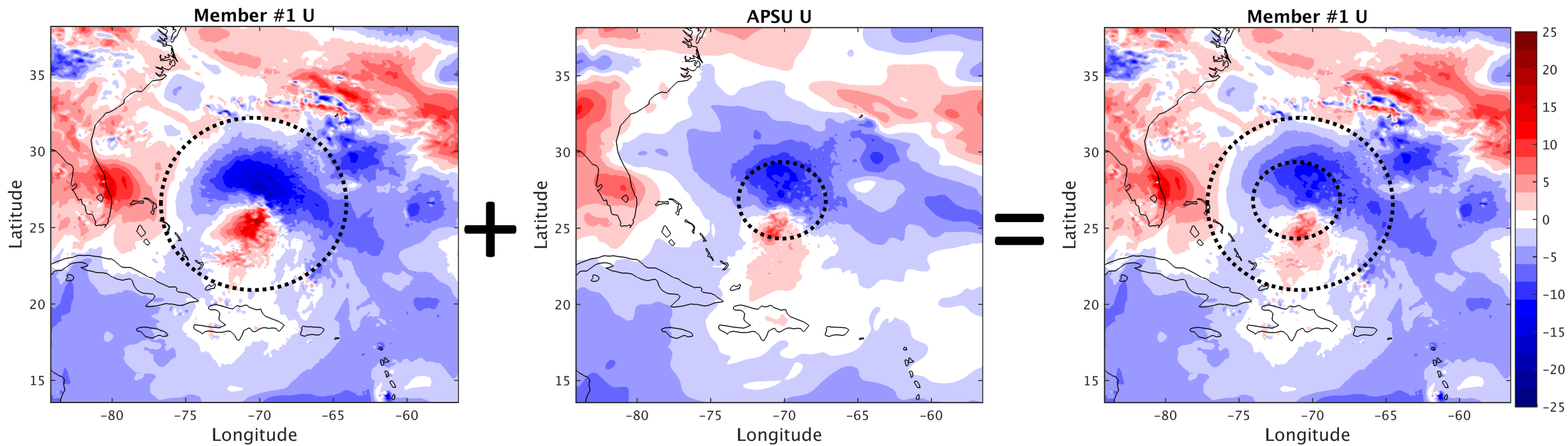
$$\text{RVOR} \left\{ \begin{array}{l} a = (R_{\max} - r) / (R_{\max} - R_{\min}) \text{ (if } R_{\min} \leq r \leq R_{\max}) \\ a = 1.0 \text{ if } r < R_{\min} \\ a = 0 \text{ if } r > R_{\max} \\ \text{RVOR} = \text{UNRL} * (1 - a) + \text{APSU} * a \end{array} \right.$$

Initial Condition differences exist in many location!



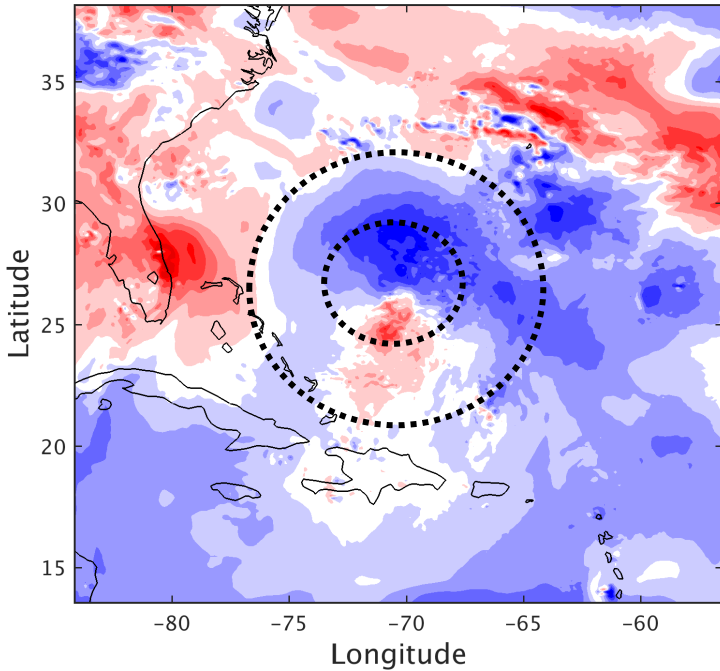
Where are these initial conditional differences most important?
How do they impact the forecast?

Relaxed to APSU vortex (RVOR)

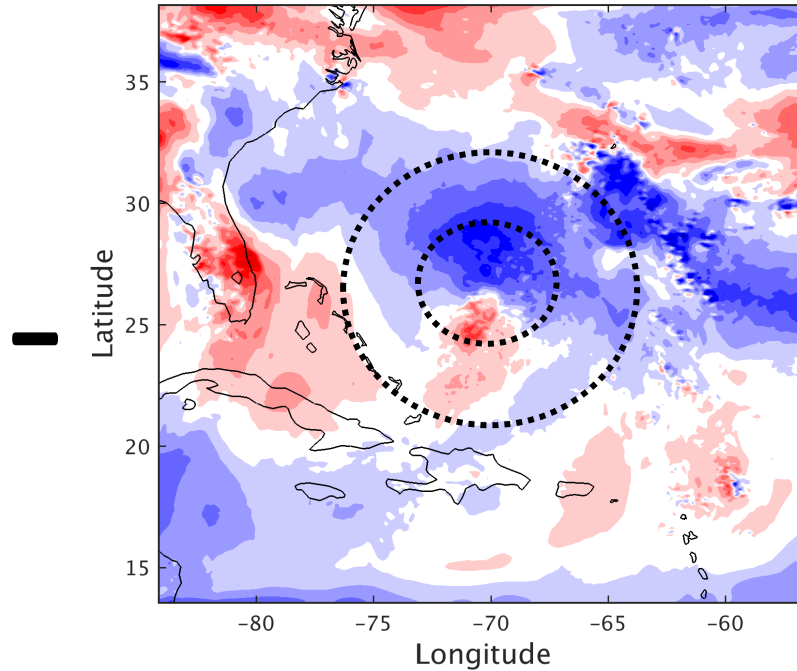


Initial Condition differences to the inner core
are removed!

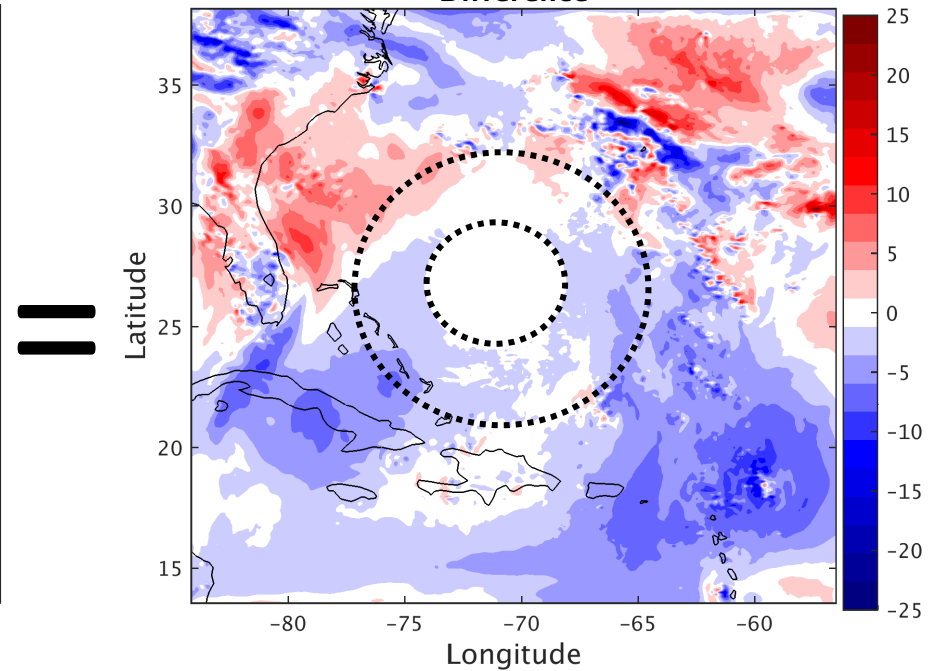
Member #1 U

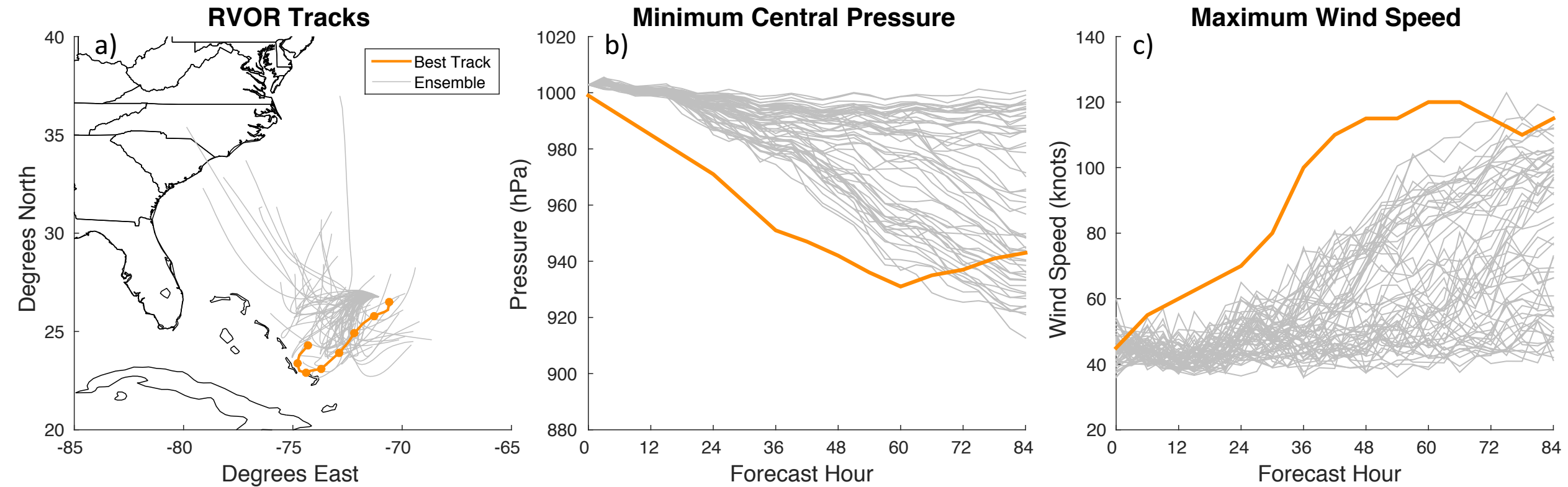


Member #2 U



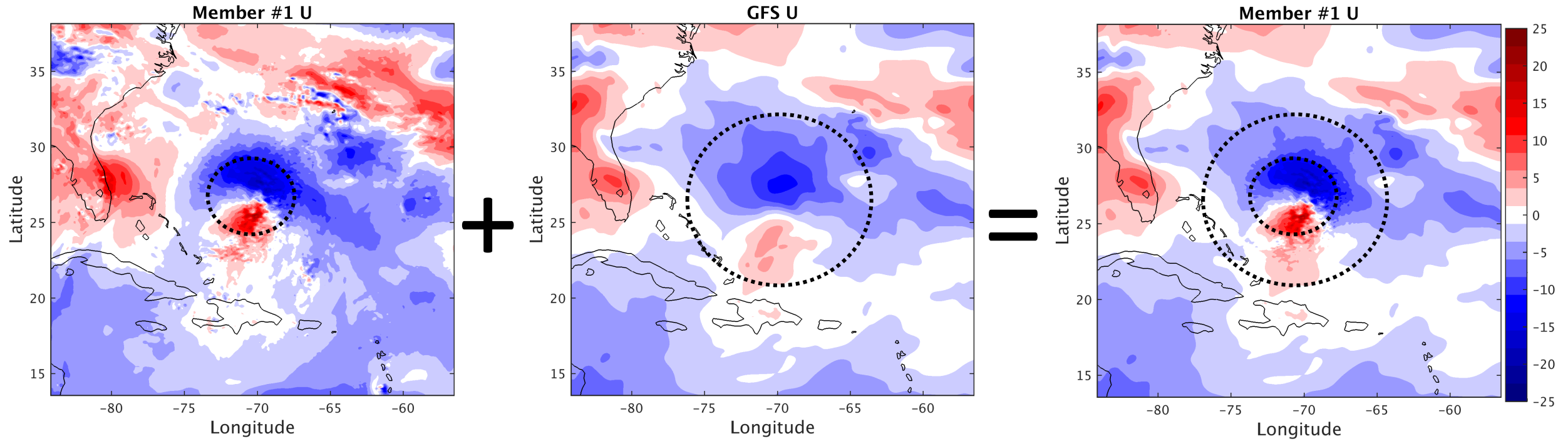
RVOR
Difference



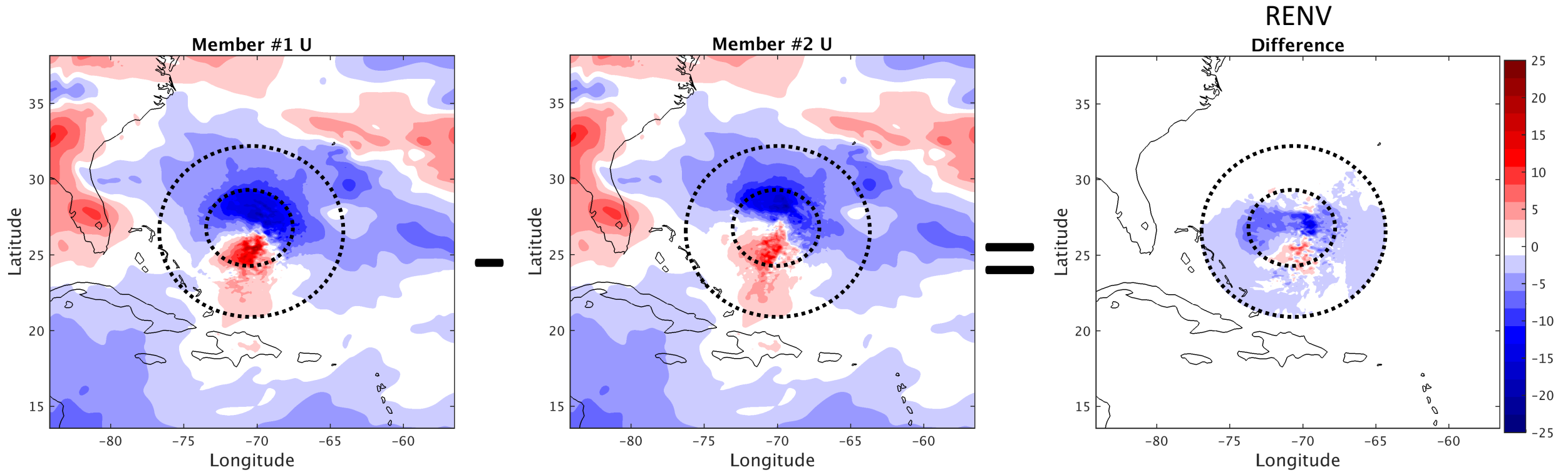


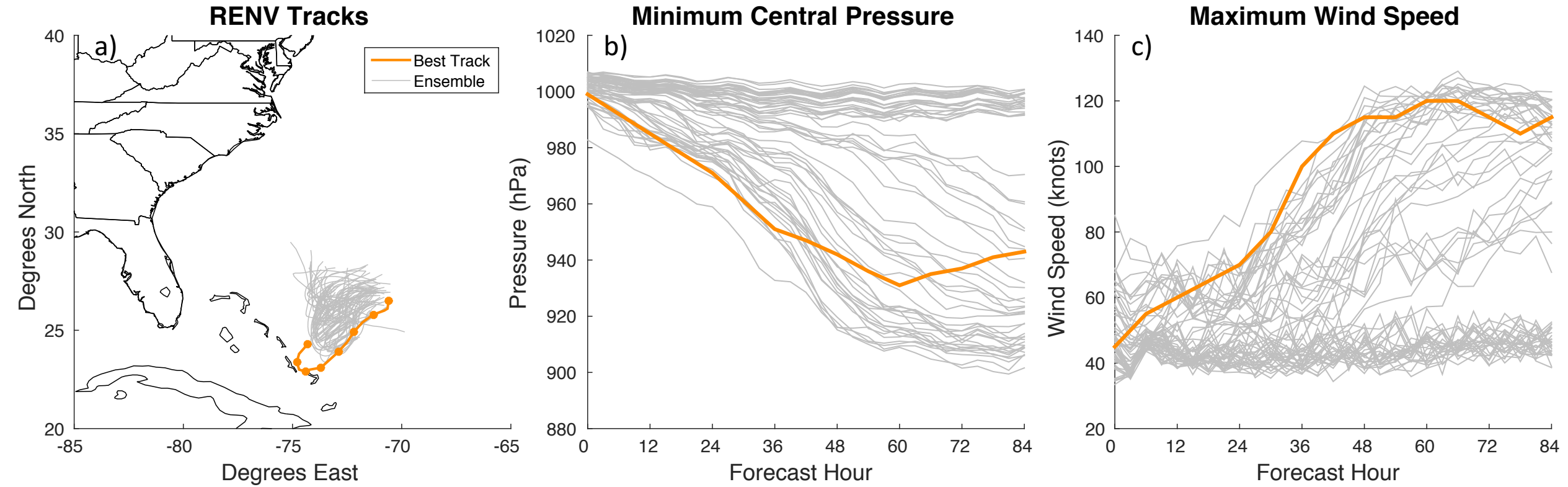
- Large track spread remains
- Intensity spread reduced for first 84 h
- Delay in intensity spread growth

Relaxed to GFS environment (RENV)

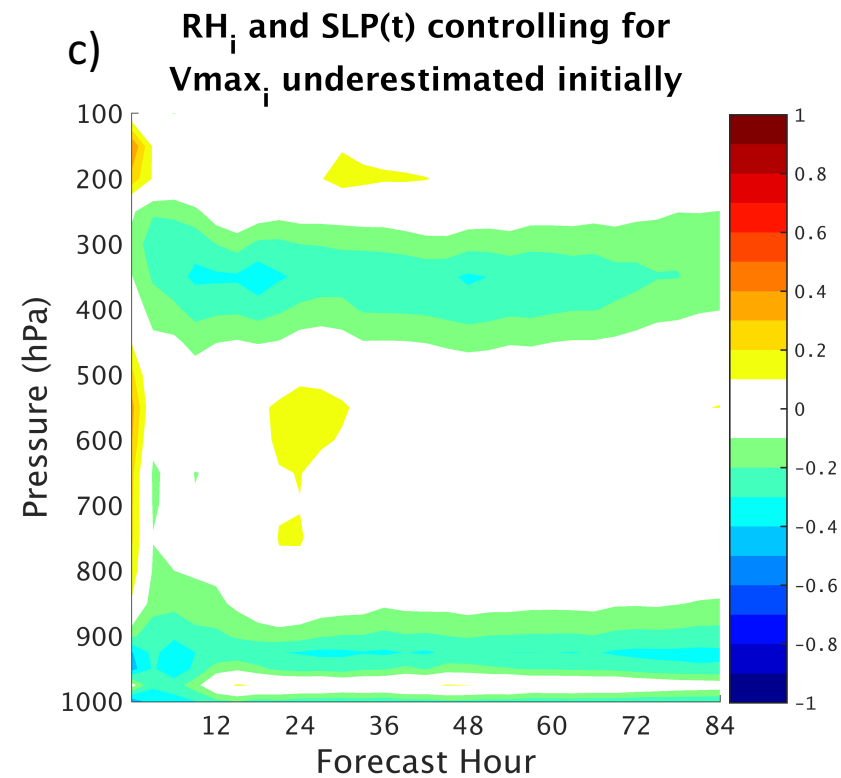
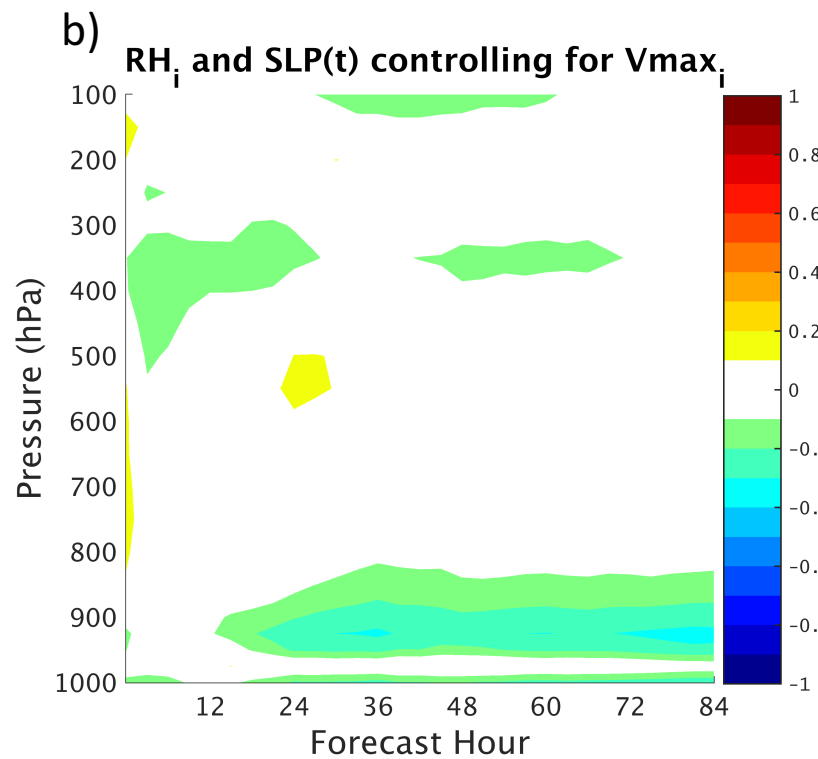
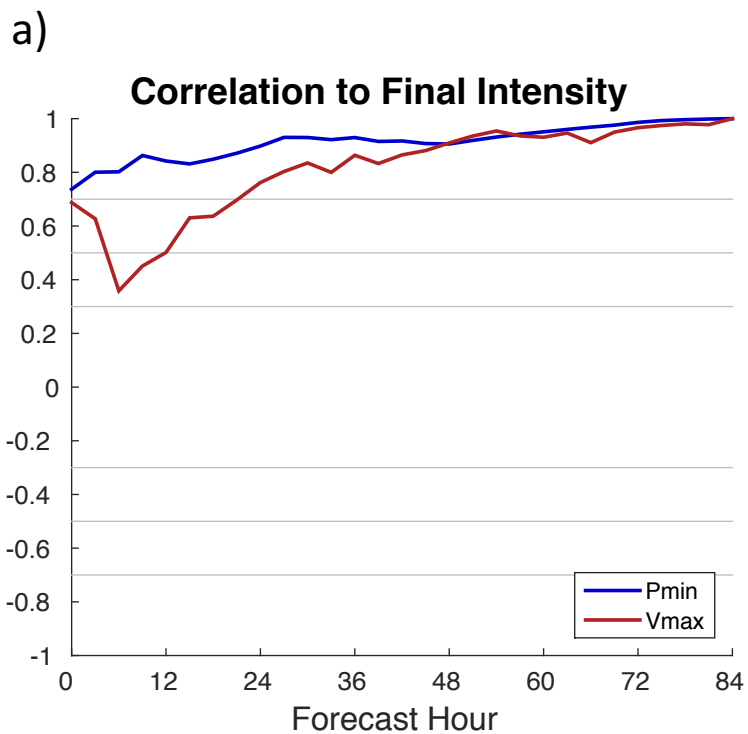


Initial Condition differences to the environment
are removed!

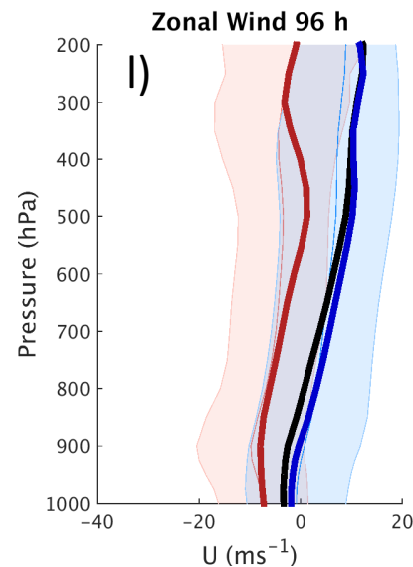
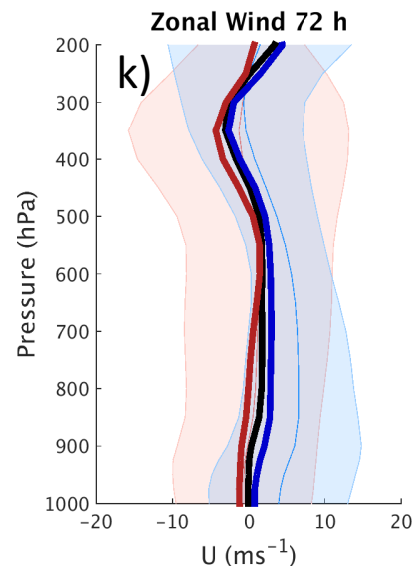
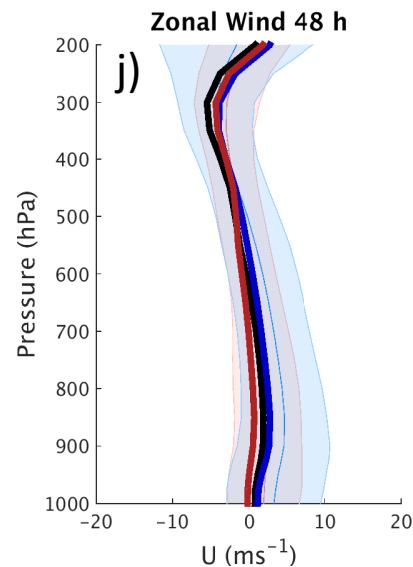
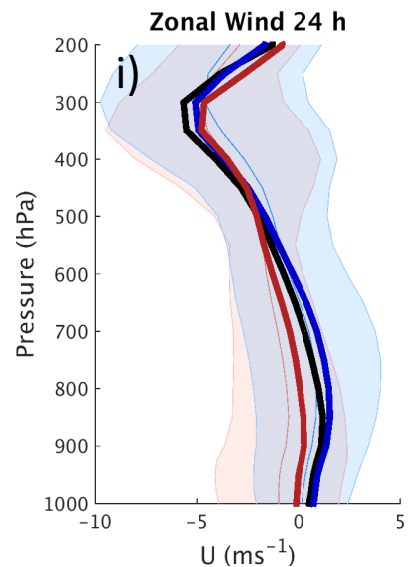
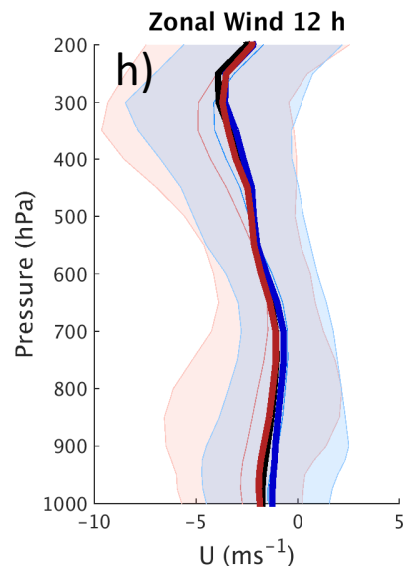
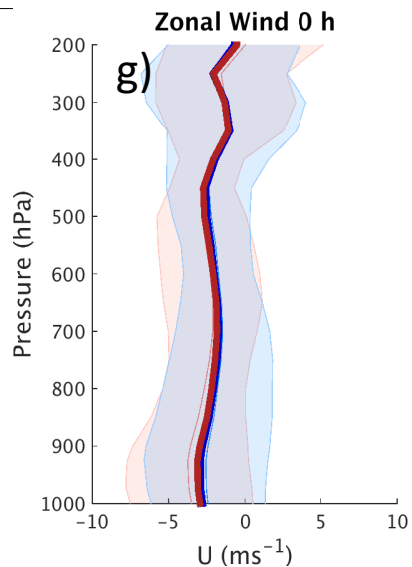
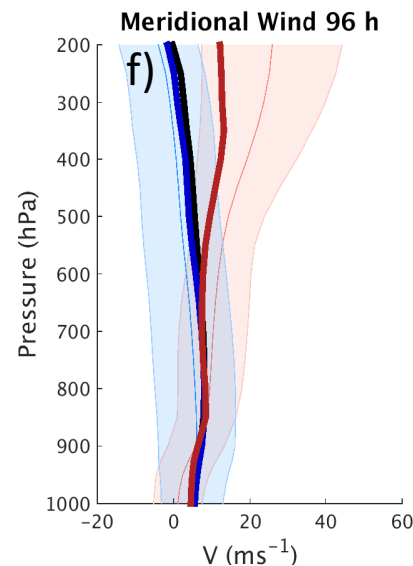
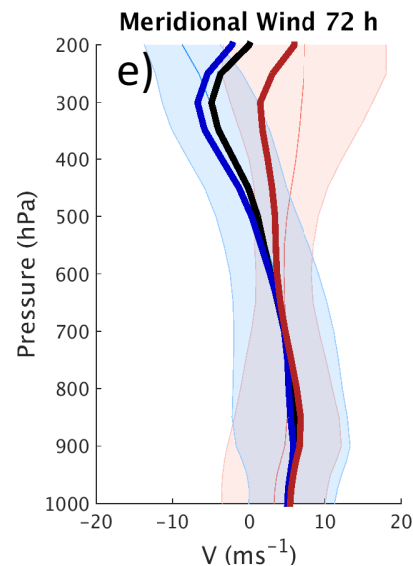
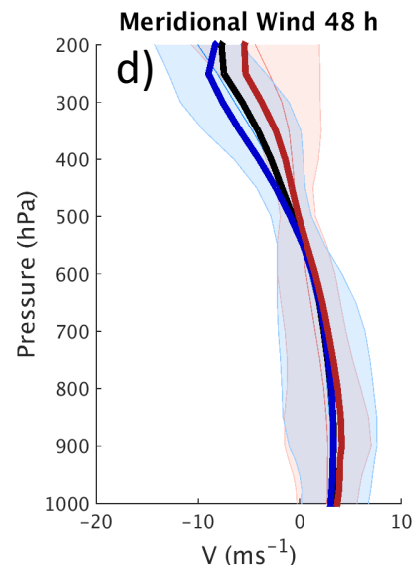
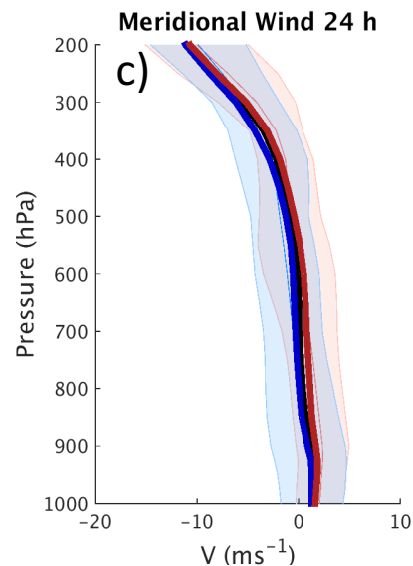
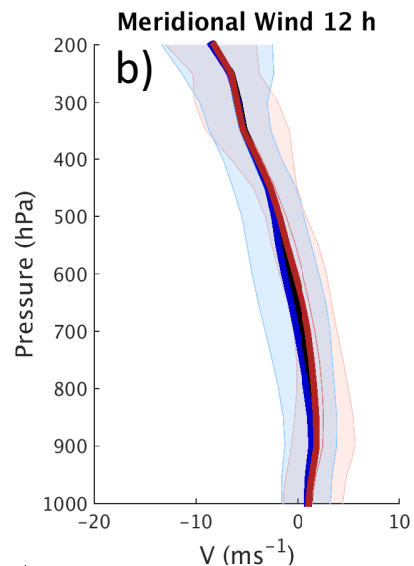




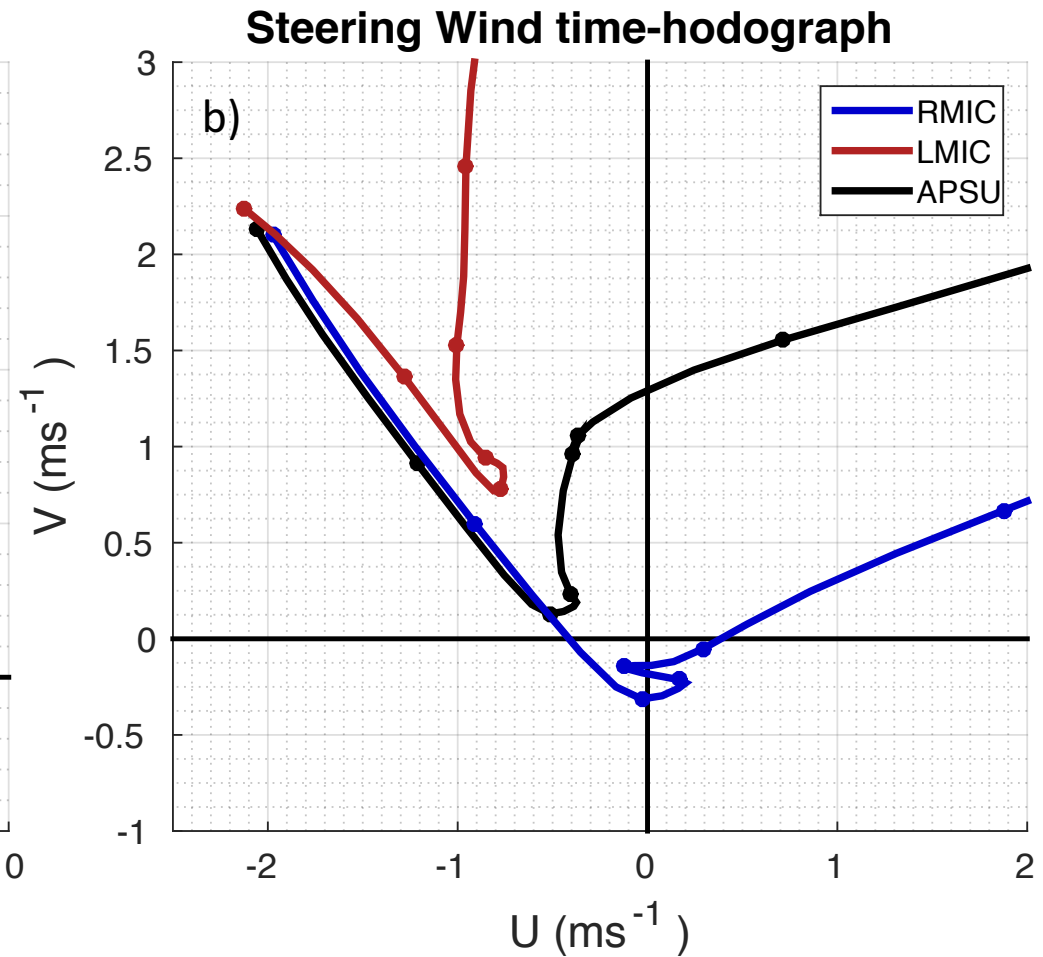
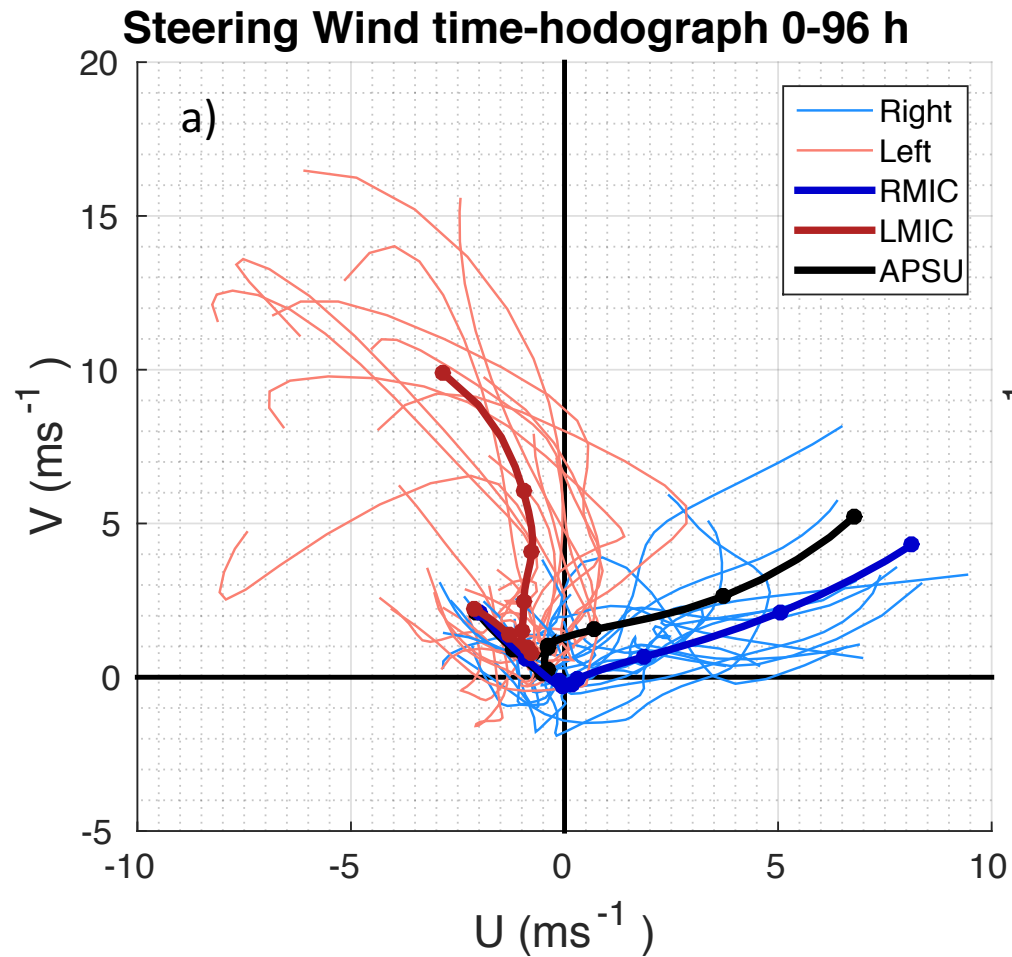
- Track spread greatly reduced
- Large intensity spread remains

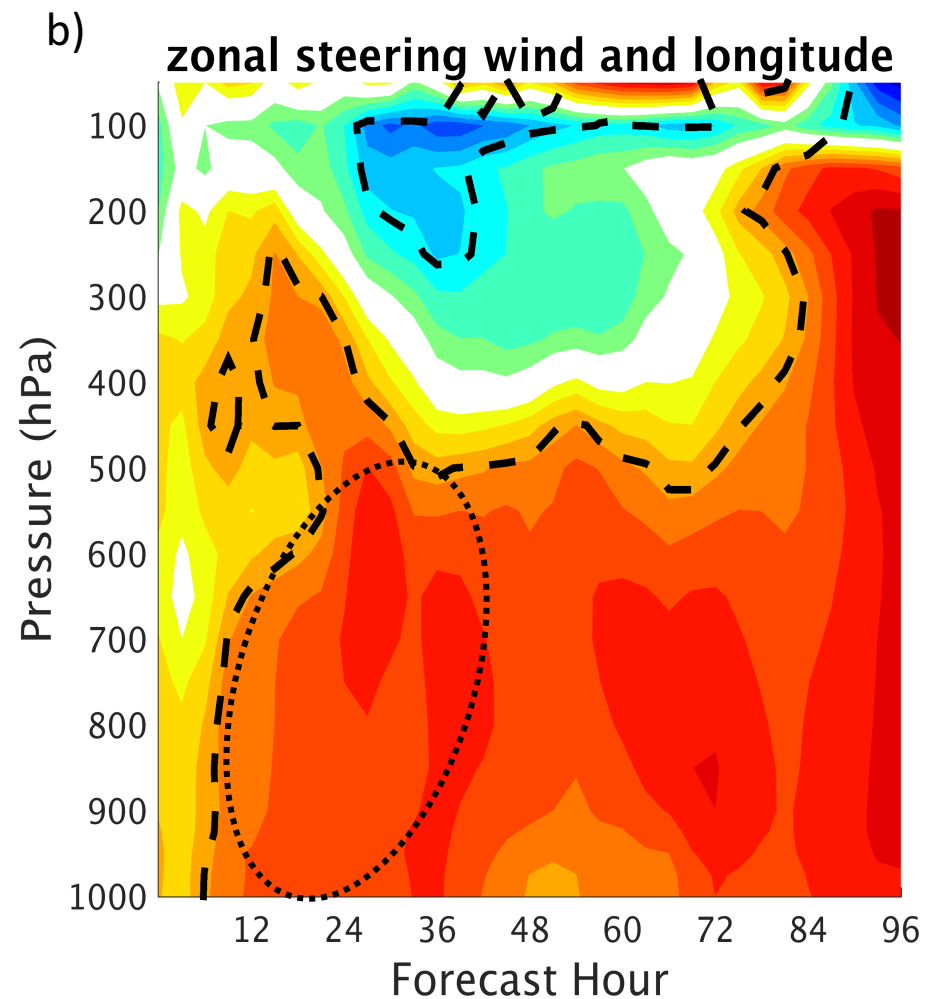
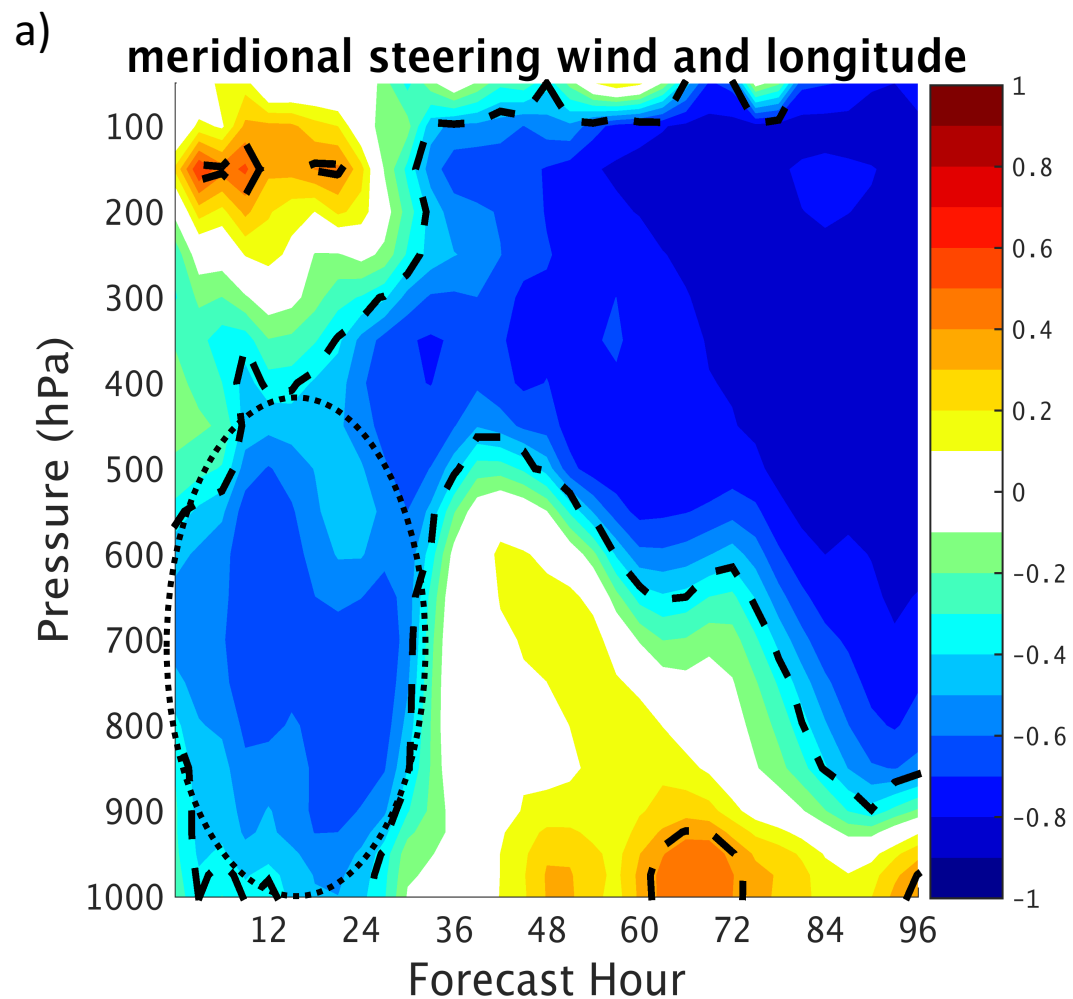


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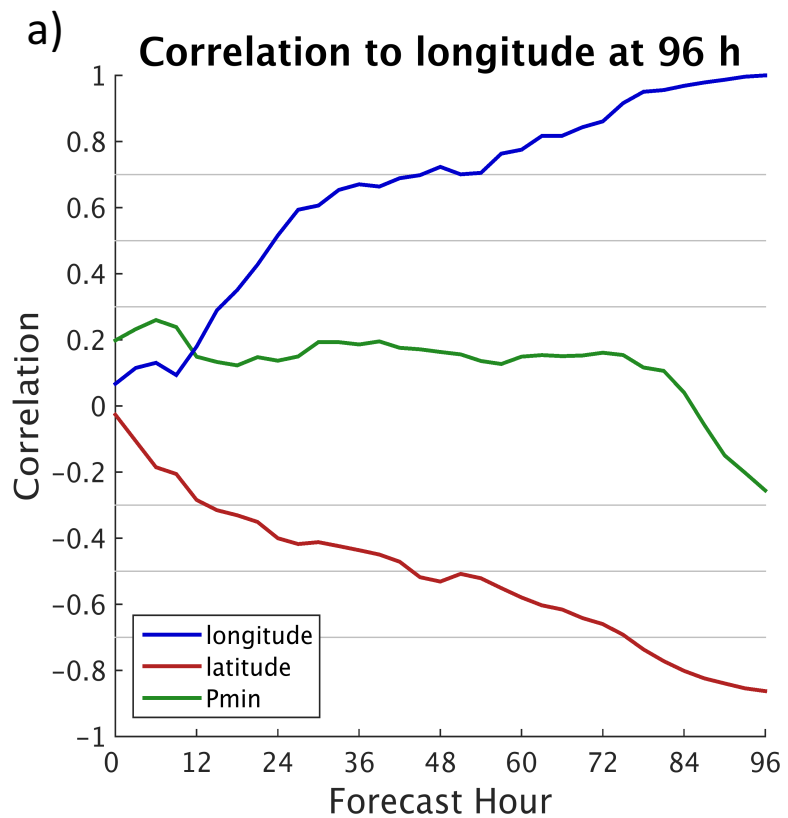


Intensity specific steering flow through time

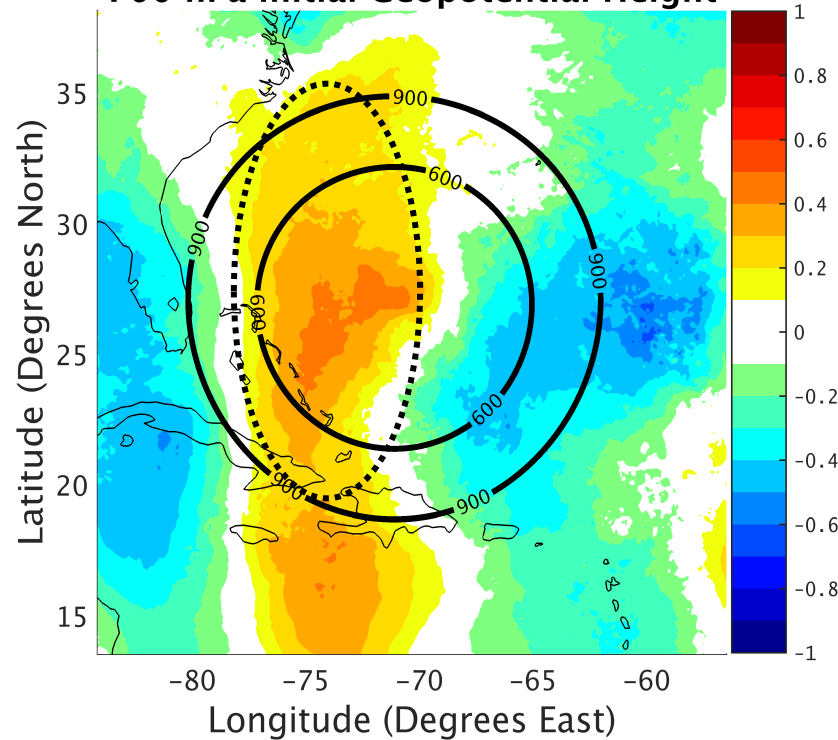




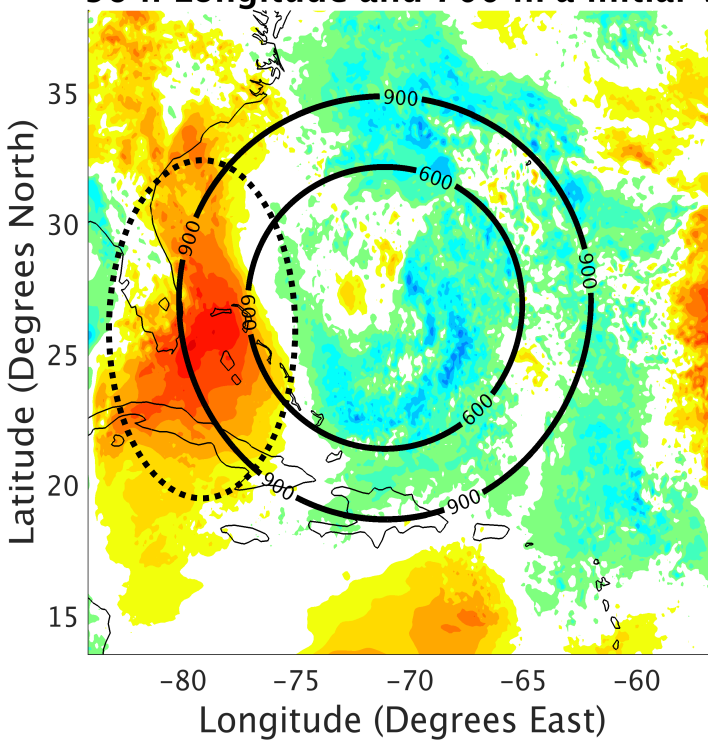
Pmin>1000 hPa	999>Pmin _≥ 990 hPa	989>Pmin _≥ 970 hPa	969>Pmin _≥ 950 hPa	949>Pmin _≥ 940 hPa	Pmin<940 hPa
700-850 hPa	500-850 hPa	400-850 hPa	300-850 hPa	250-850 hPa	200-850 hPa



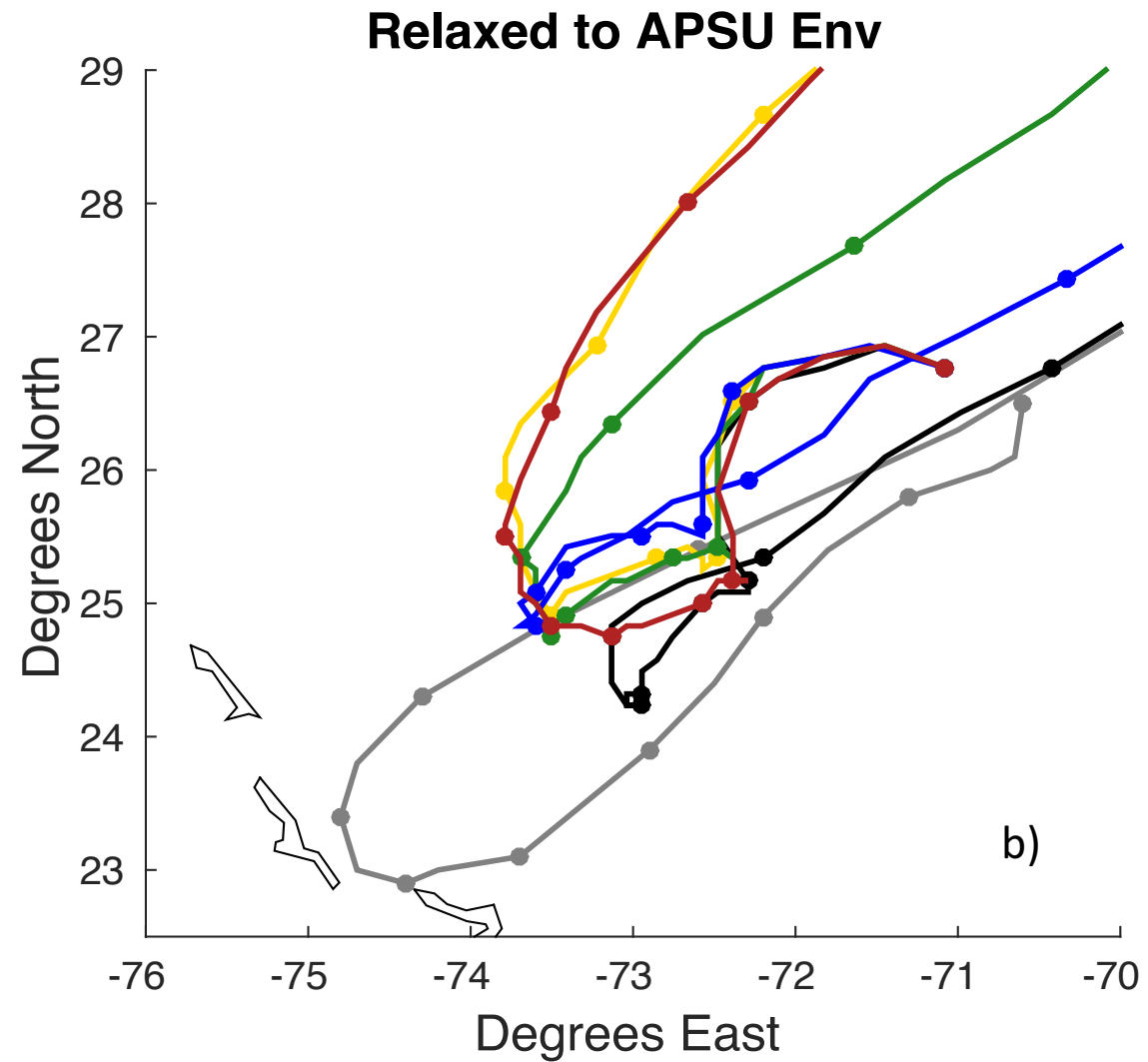
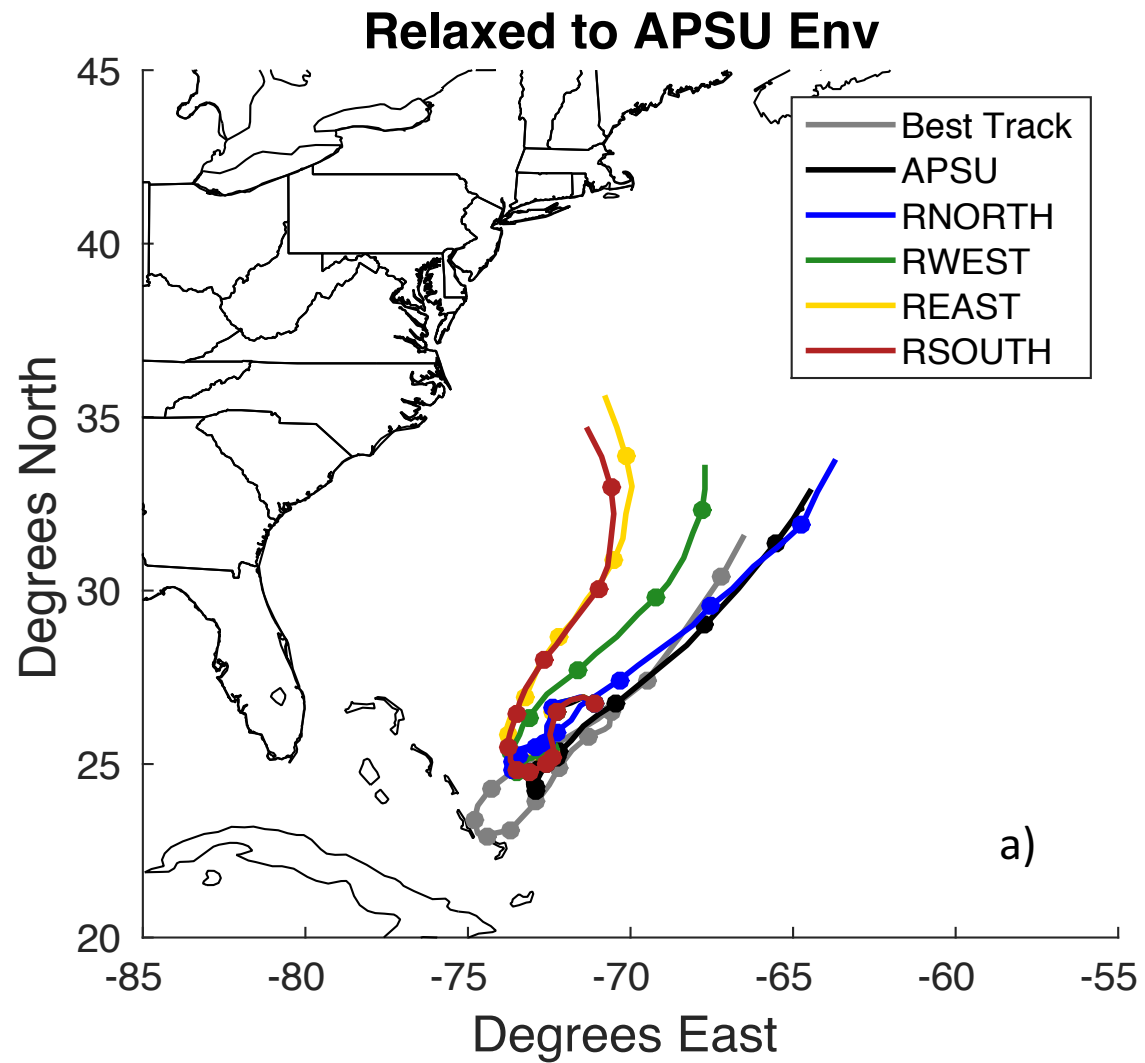
b) **96 h Longitude and 700 hPa initial Geopotential Height**



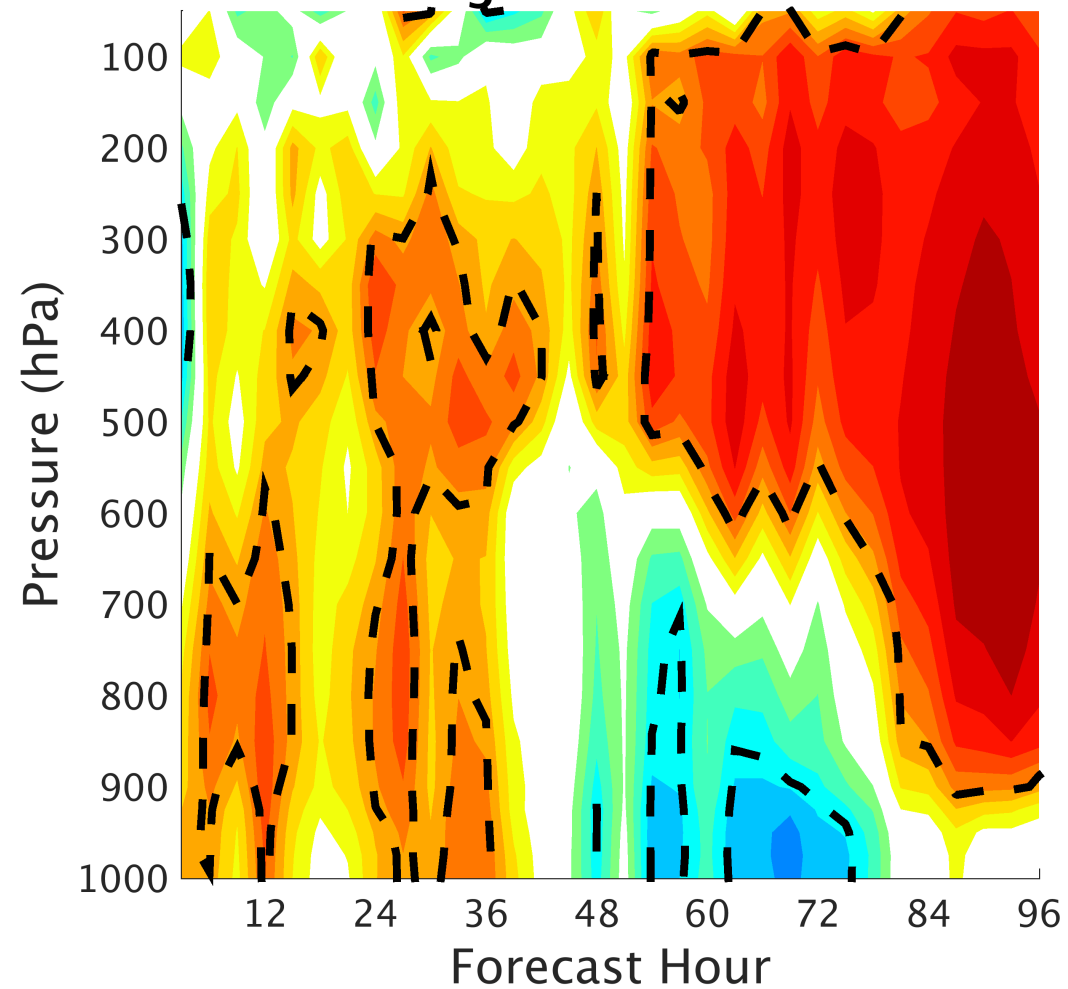
c) **96 h Longitude and 700 hPa initial V**



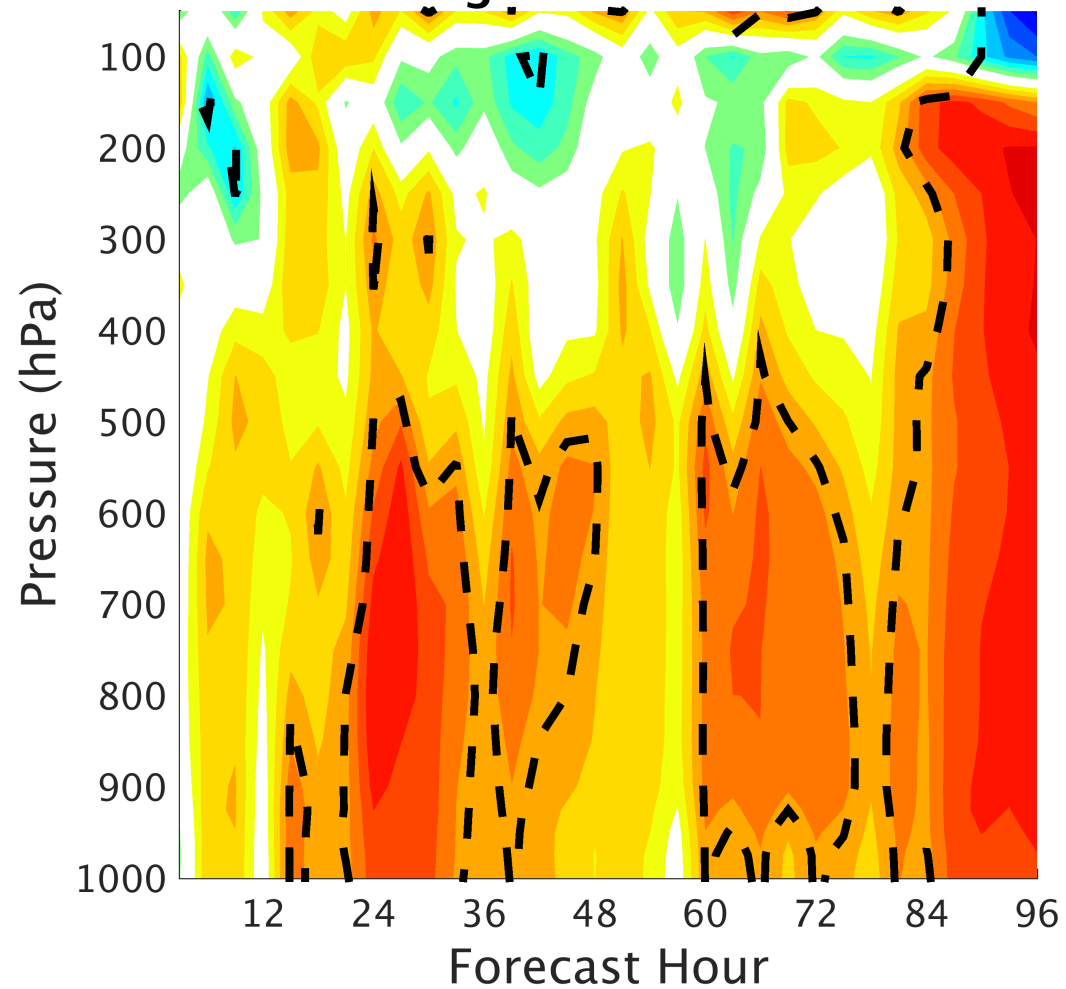
Ridging to the East and North of initial location Important?

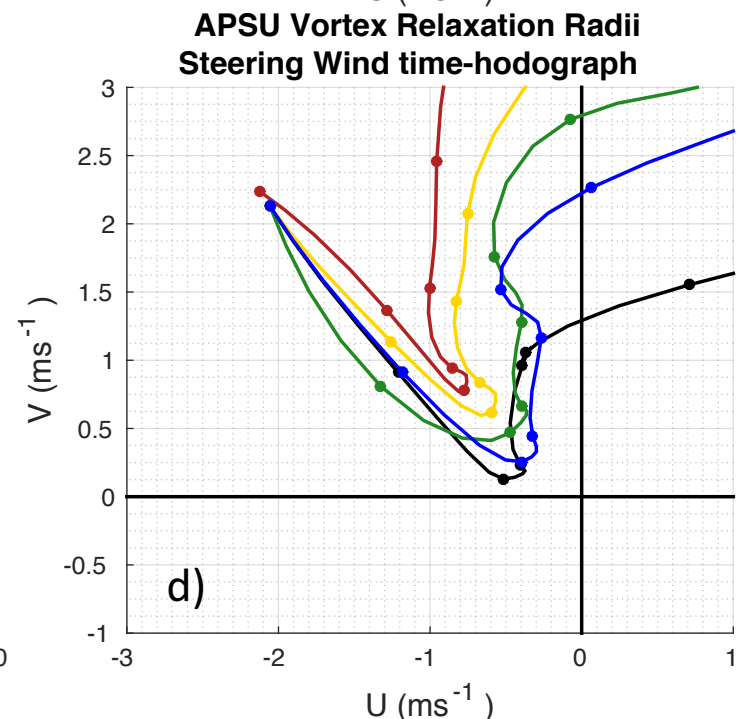
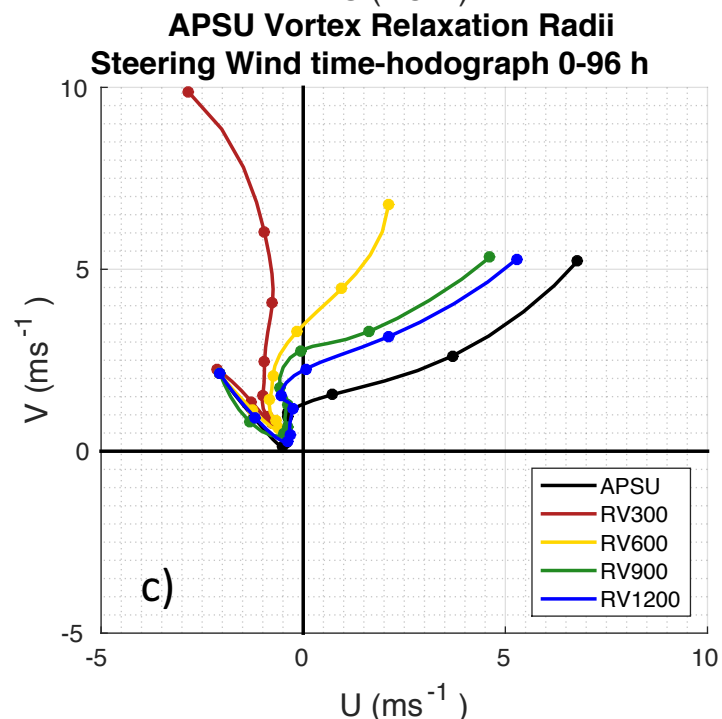
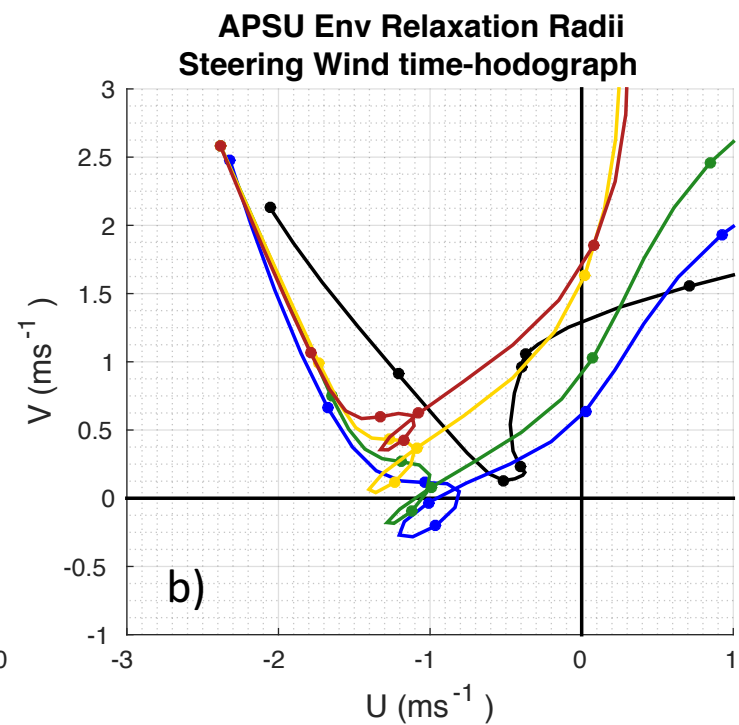
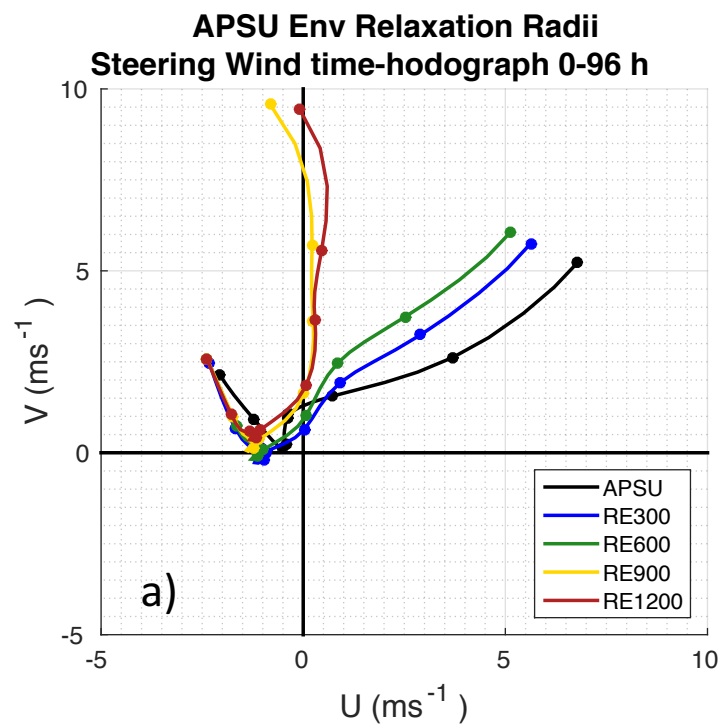


meridional steering wind and meridional motion



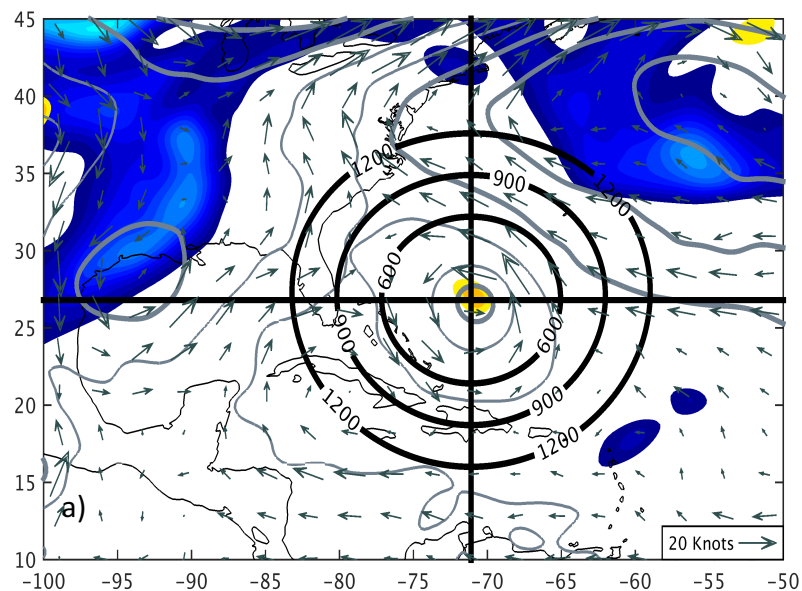
zonal steering wind and zonal motion



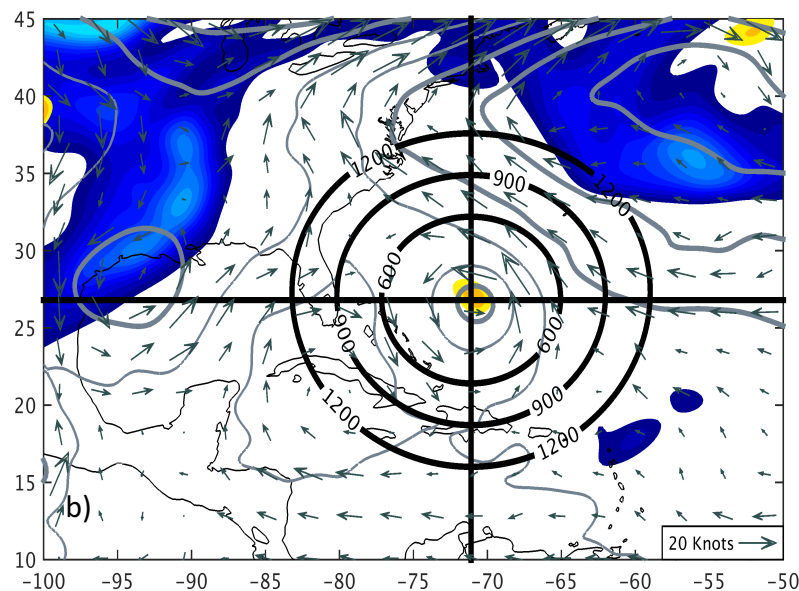


Forecast Hour 0

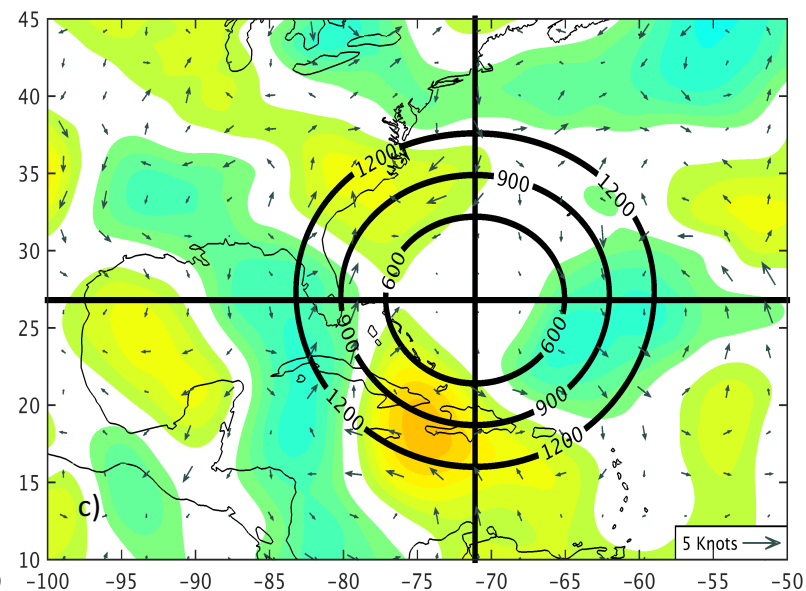
APSU



LMIC



APSU – LMIC



1 2 3

850 hPa Potential Vorticity (PVU)

2 4 6 8

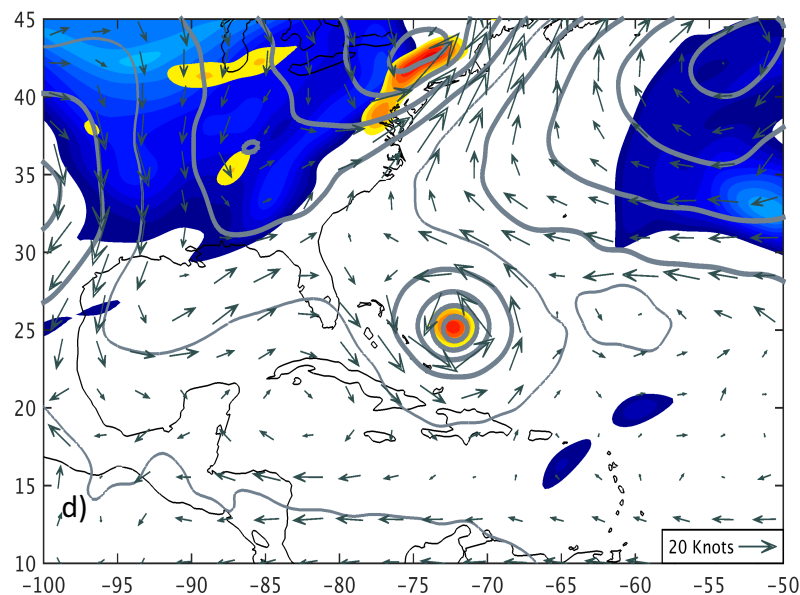
200 hPa Potential Vorticity (PVU)

20 -10 0 10 20

700 hPa Geopotential Height Difference (m)

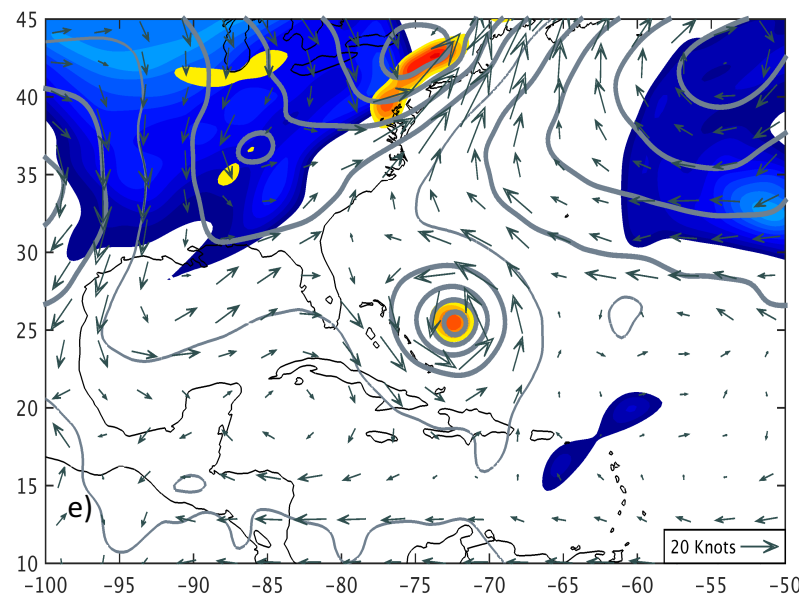
Forecast Hour 24

APSU



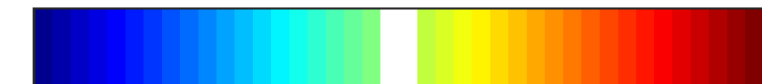
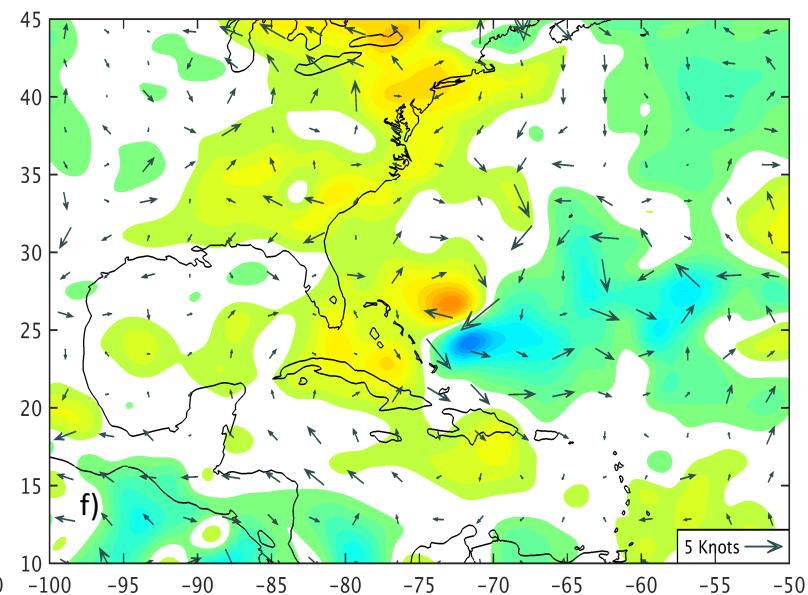
850 hPa Potential Vorticity (PVU)

LMIC



200 hPa Potential Vorticity (PVU)

APSU – LMIC



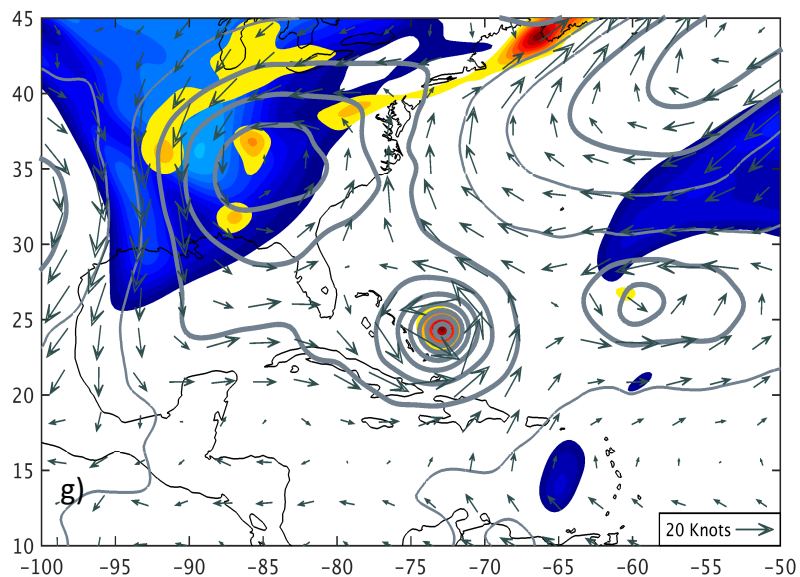
700 hPa Geopotential Height Difference (m)

APSU

LMIC

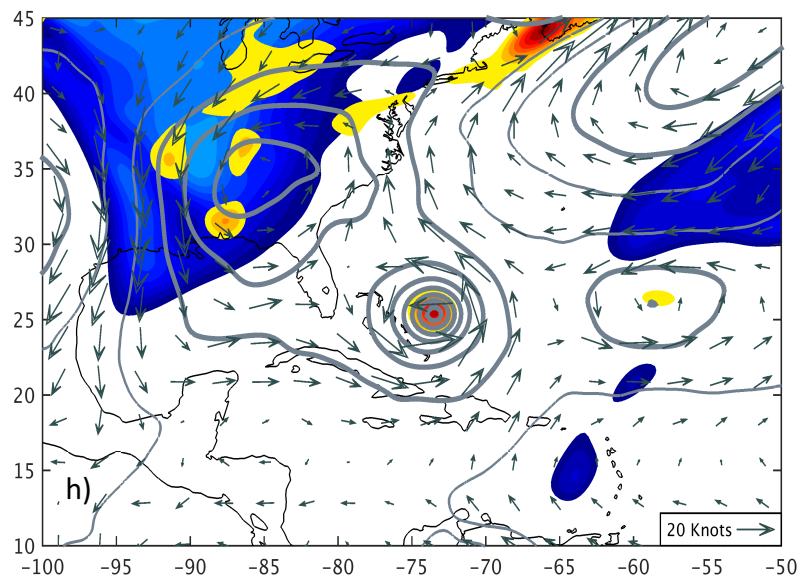
APSU – LMIC

Forecast Hour 48



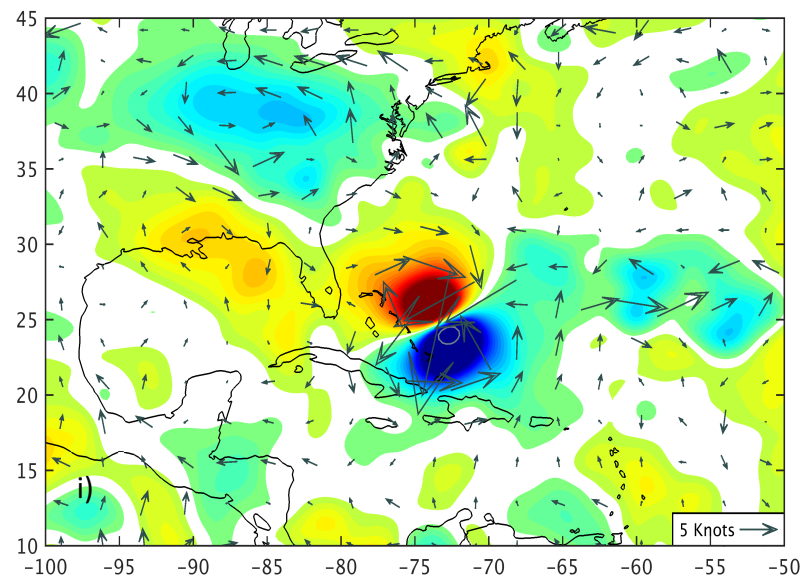
1 2 3

850 hPa Potential Vorticity (PVU)



2 4 6 8

200 hPa Potential Vorticity (PVU)

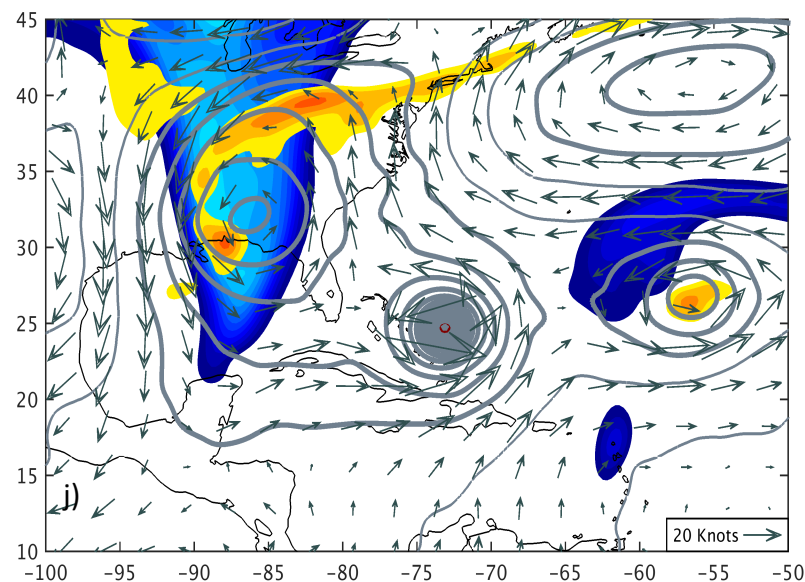


20 -10 0 10 20

700 hPa Geopotential Height Difference (m)

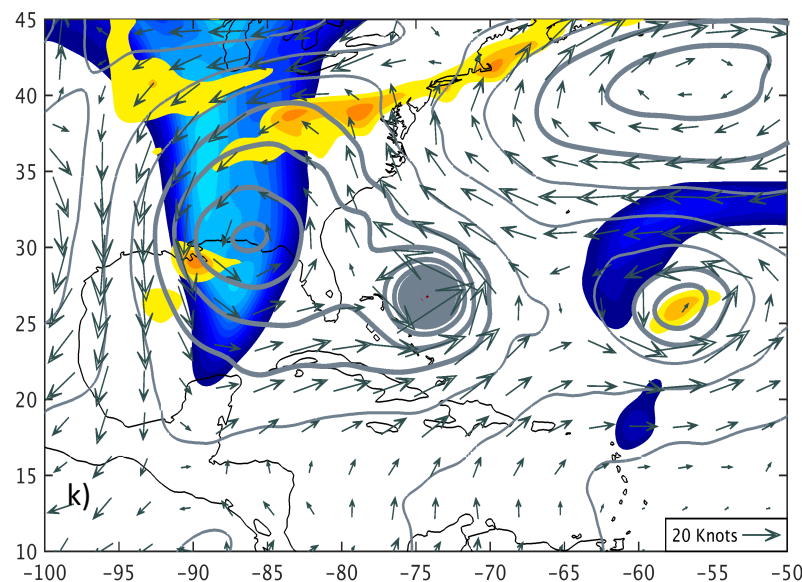
Forecast Hour 72

APSU



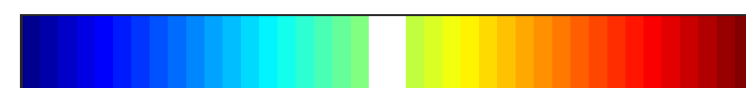
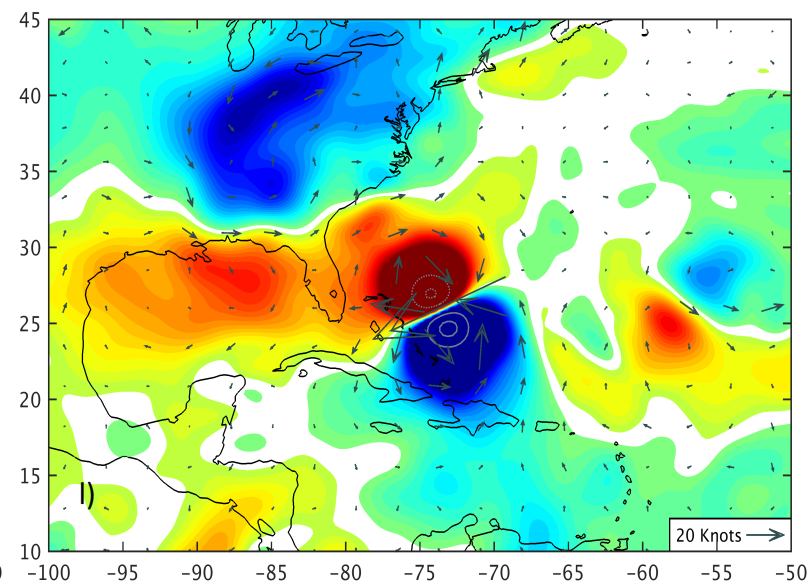
850 hPa Potential Vorticity (PVU)

LMIC



200 hPa Potential Vorticity (PVU)

APSU – LMIC



700 hPa Geopotential Height Difference (m)