Convection-permitting Ensemble Data Assimilation of Doppler Radar Observations for Hurricane Prediction

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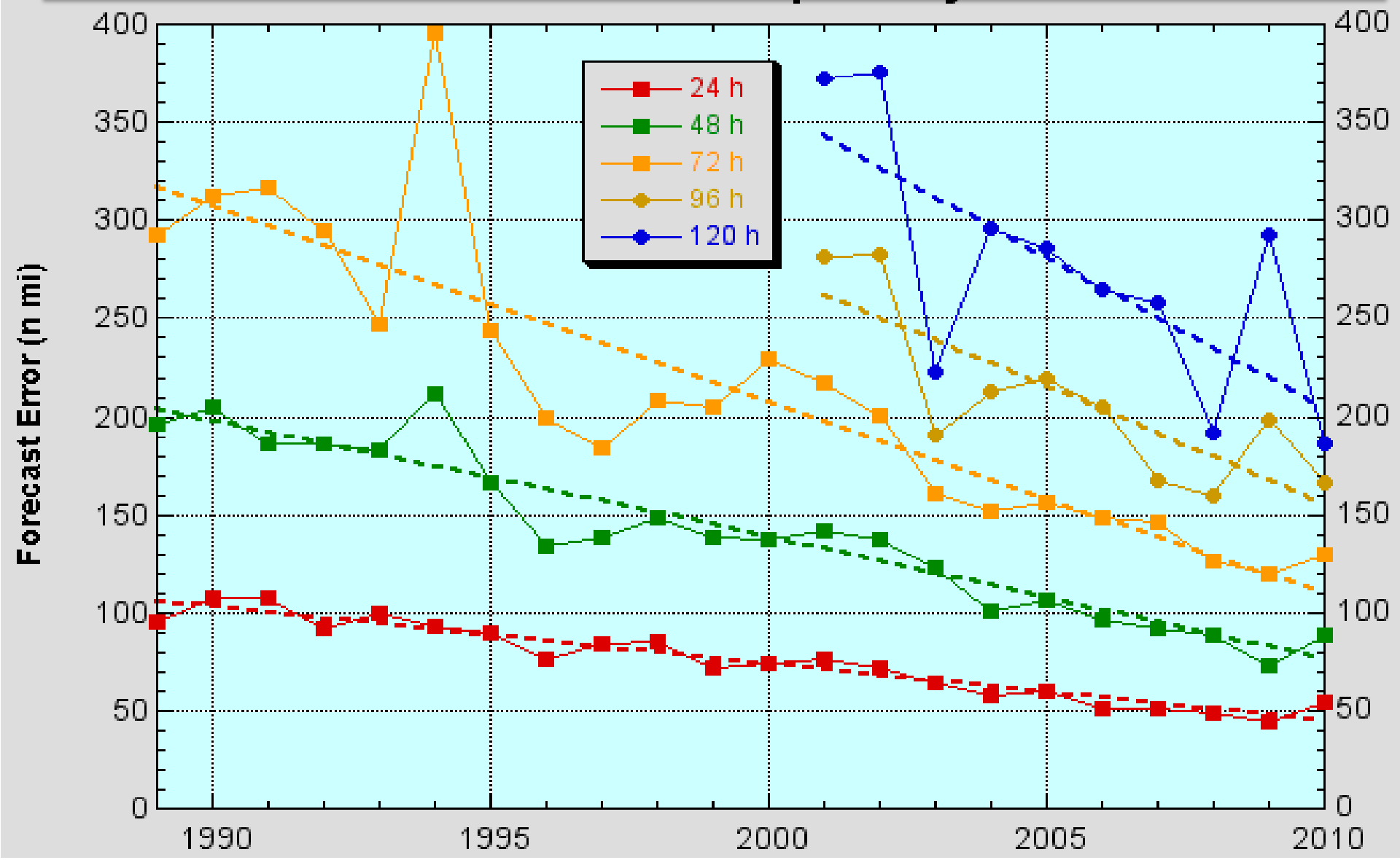
Penn State University

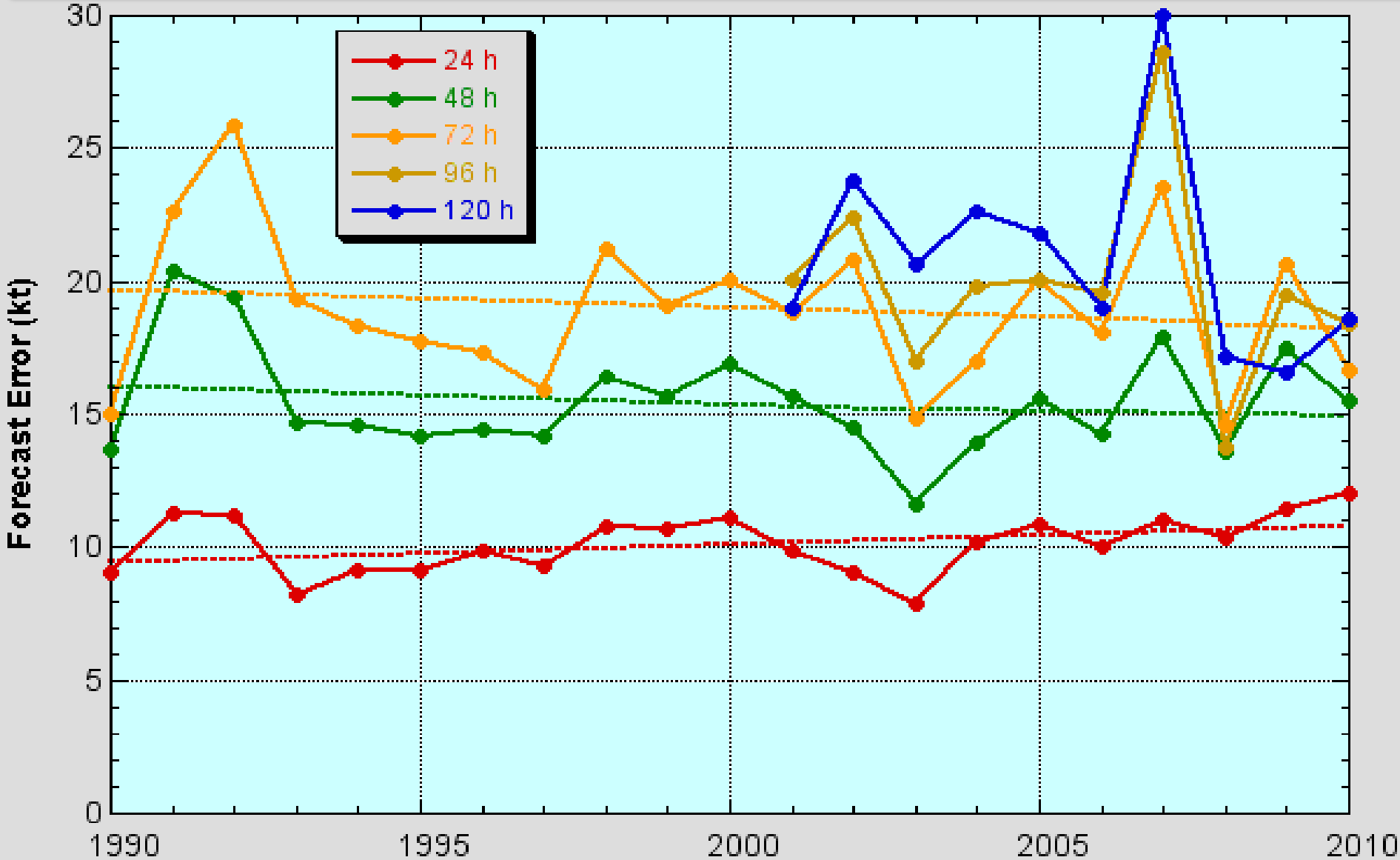
Sponsored by NOAA/HFIP, ONR, NASA and NSF

National Hurricane Center Official Track Errors



Tropical cyclone track is mostly determined by larger-scale environment whose forecast improves with better observations, better models, higher resolution (T80->T382) and 100,000 times faster computers

National Hurricane Center Official Intensity Errors



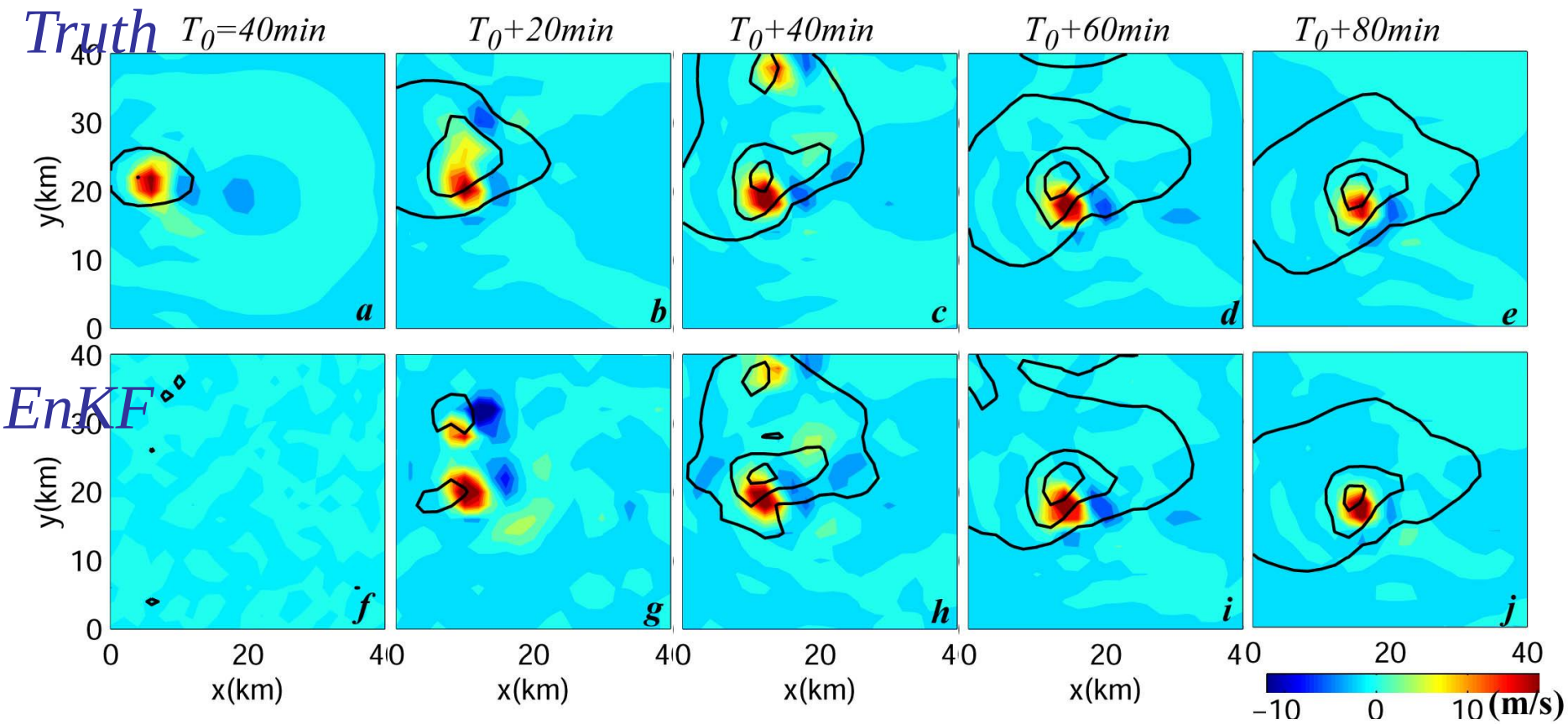
Tropical cyclone intensity is strongly dependent on internal dynamics and moist convection which are smaller in scales, more chaotic, under-observed, under-resolved, and/or intrinsically less predictable?

First Test of EnKF for Limited-area Models: Assimilation of Radar Observations of Supercells

(Snyder and Zhang 2003; Zhang, Snyder and Sun 2004; Dowell, Zhang et al. 2004; all in MWR)

Observations: radial velocity V_r only, available every 5 minutes where reflectivity dBZ>12

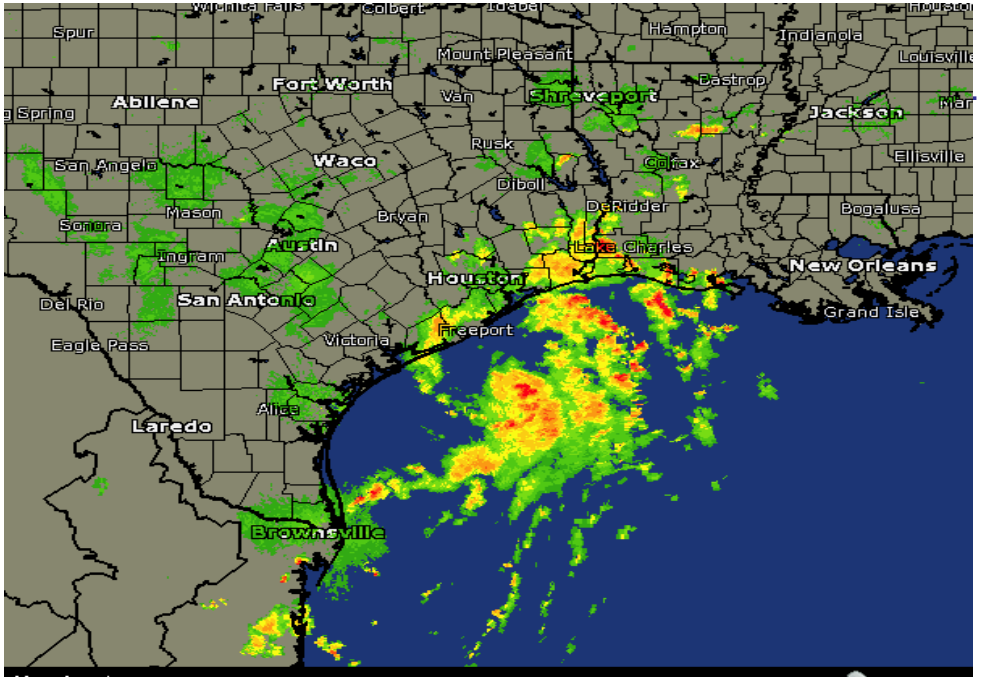
Vertical velocity at 5km (colored) and surface cold pool (black lines, every 2K)

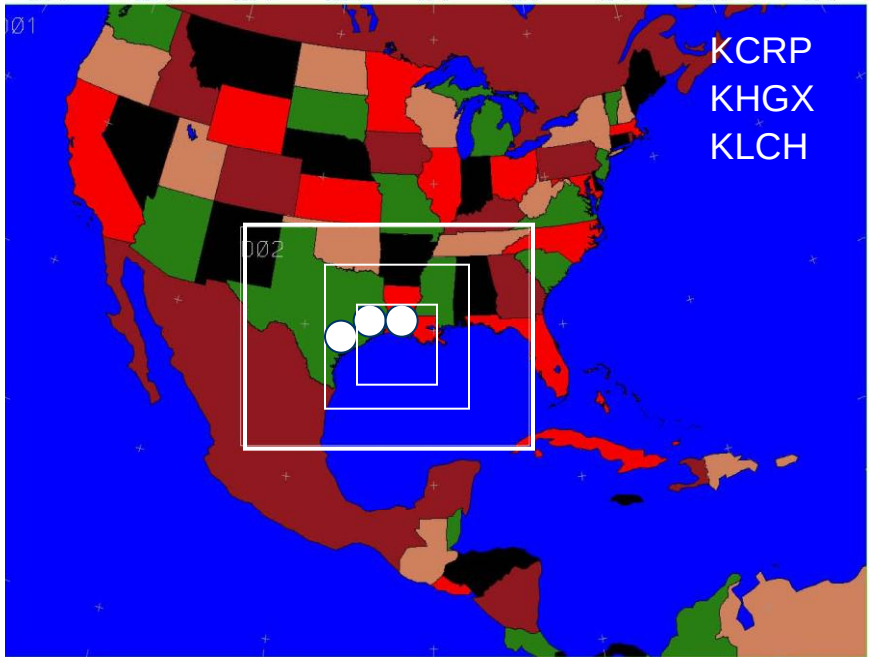


Assimilate W88D Doppler Winds with WRF-EnKF

(Zhang et al. 2009 MWR)

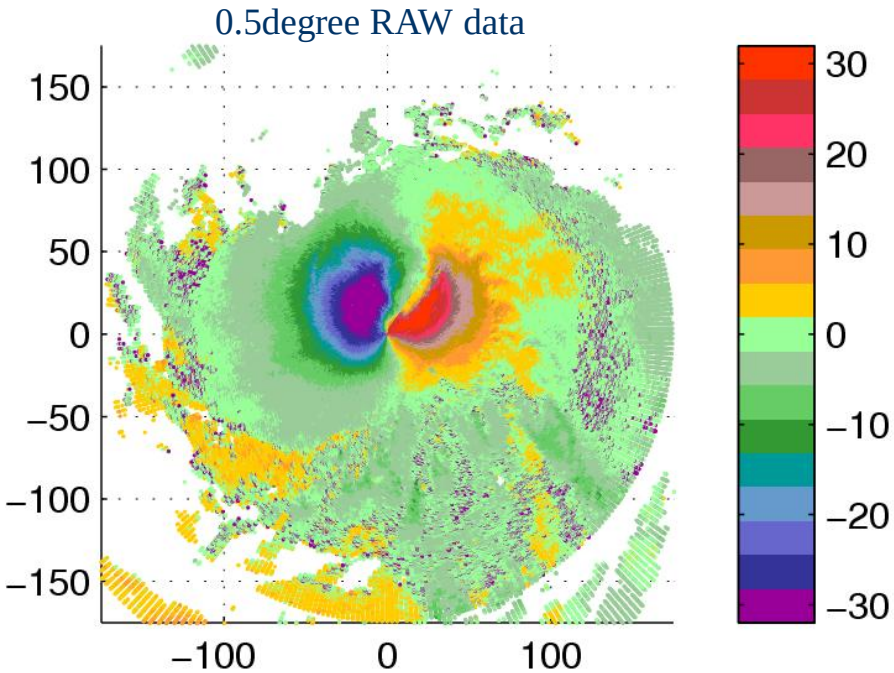
- Model: Weather Research and Forecast Model (WRF) with 4 domains two-way nested and grid sizes of 40.5, 13.5, 4.5, and 1.5km
- Data: Doppler winds from three coastal weather surveillance radars [available routinely for more than 20 years but never used in any NOAA operational models]
- Data assimilation method: Ensemble Kalman Filter (Meng and Zhang 2008a,b)

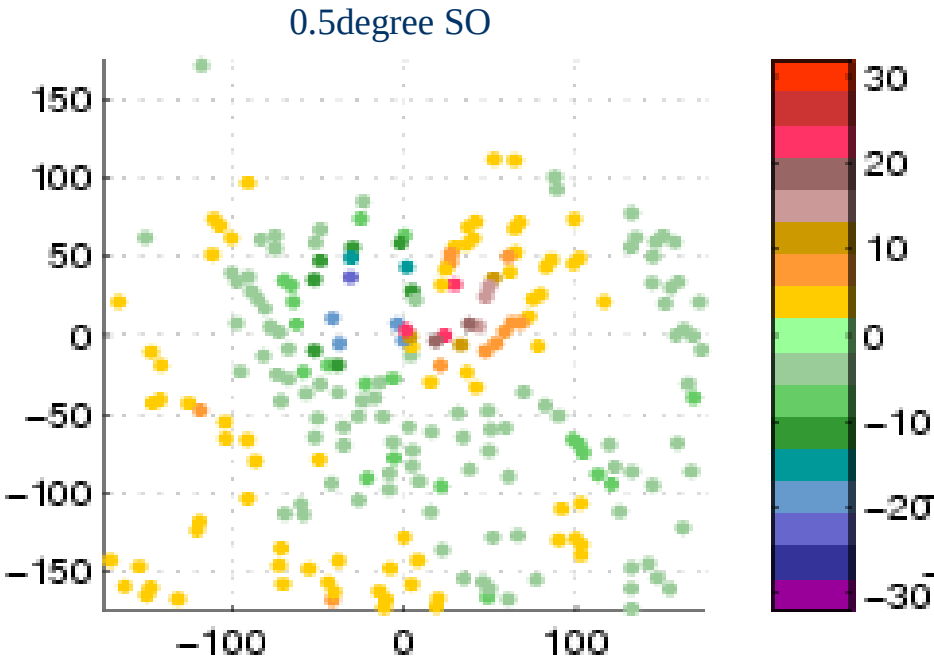




Super-Obs: QC and thinning of WSR-88D Vr Obs

(Zhang et al. 2009 MWR; Weng, Zhang et al 2011 CiSE)

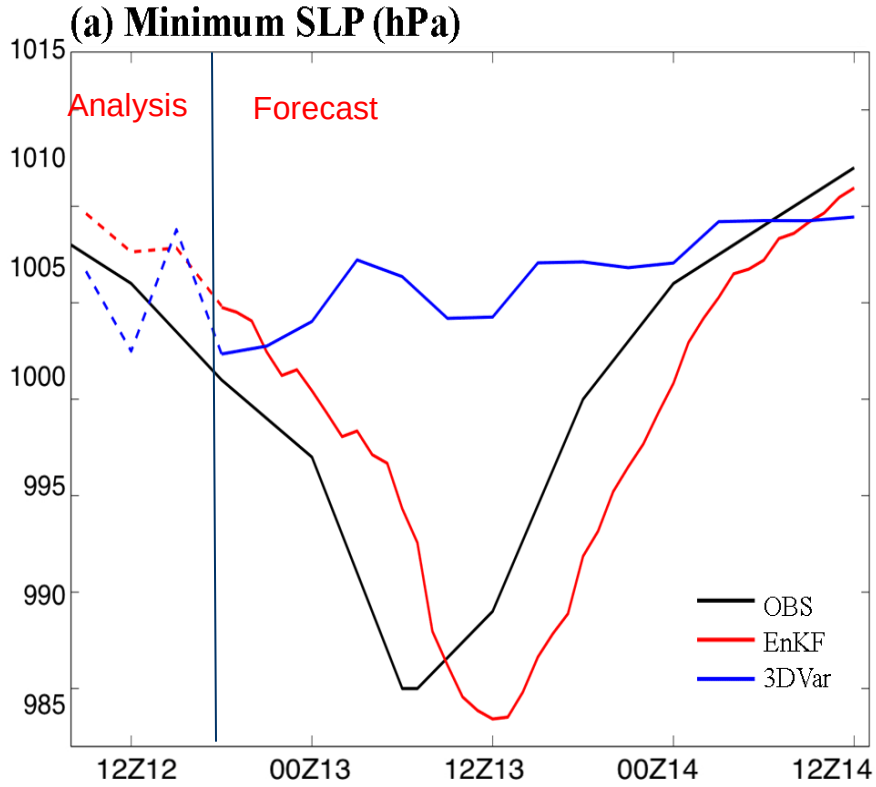


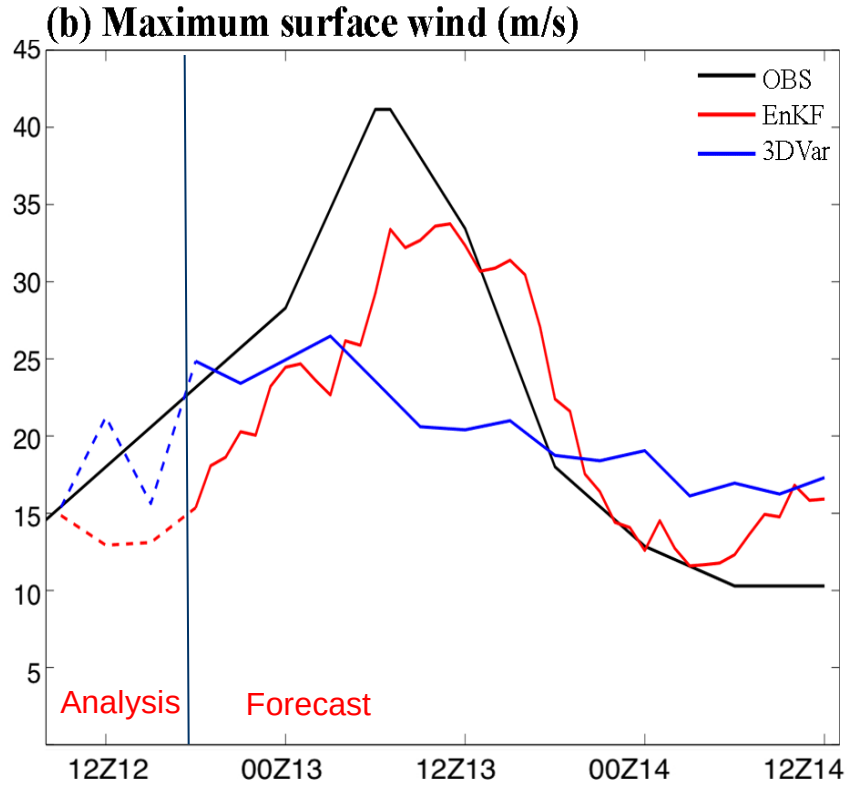


- Define SO position depended on the radial distance
- Average10 nearest data points in the raw polar scan to create a SO
- Averaging bin is 5km max radial range and 5° max azimuthally resolution
- There are at least 4 valid velocity data within an averaging bin.

Assimilate W88D Doppler Vr for Humberto'05

WRF/EnKF Forecast vs. Observations vs. 3DVAR





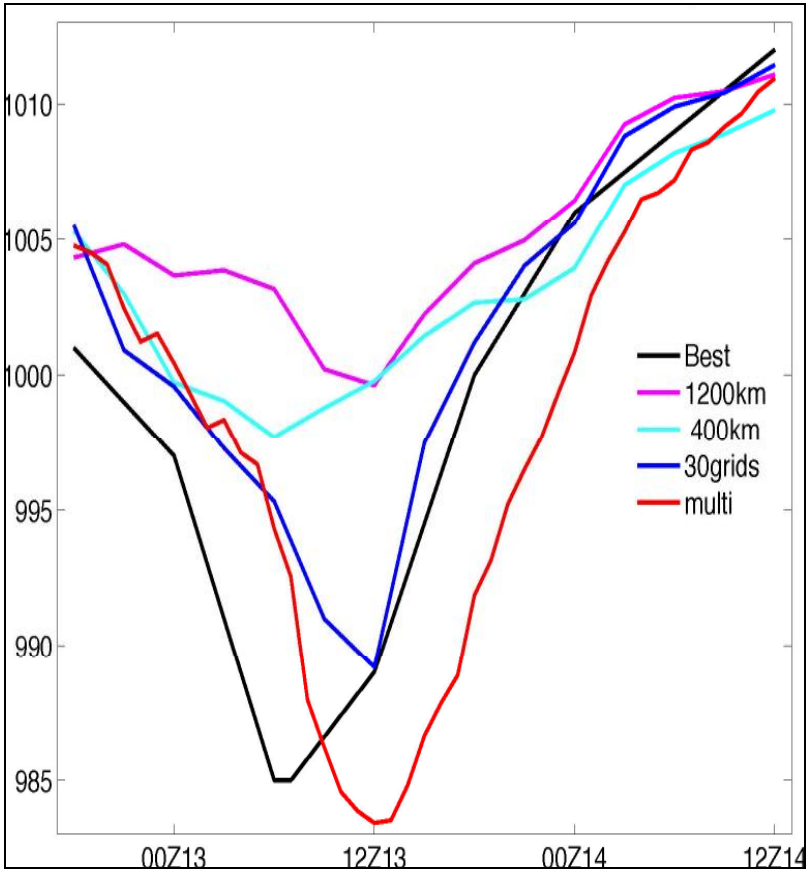
The WRF/3DVAR (as a surrogate of operational algorithm) assimilates the same radar data but without flow-dependent background error covariance, its forecast failed to develop the storm despite fit to the best-track observation better initially

(Zhang et al. 2009 MWR)

Successive Covariance Localization (SCL)

(Zhang et al. 2009 MWR)

- Dense observations contain information of the state at different scales, e.g., hurricanes.
- Rationale: larger-scale errors have larger correlation length scales thus need fewer observations, large radii of influence; more observations with smaller radius of influence are needed to constrain small-scale errors (Zhang et al. 2006).
- SCL has some similarity to successive correction method (SCM) used in some earlier empirical objective analysis schemes (e.g., Barnes 1964), though subgrouping of observations is used in the EnKF so the same observation not used twice.

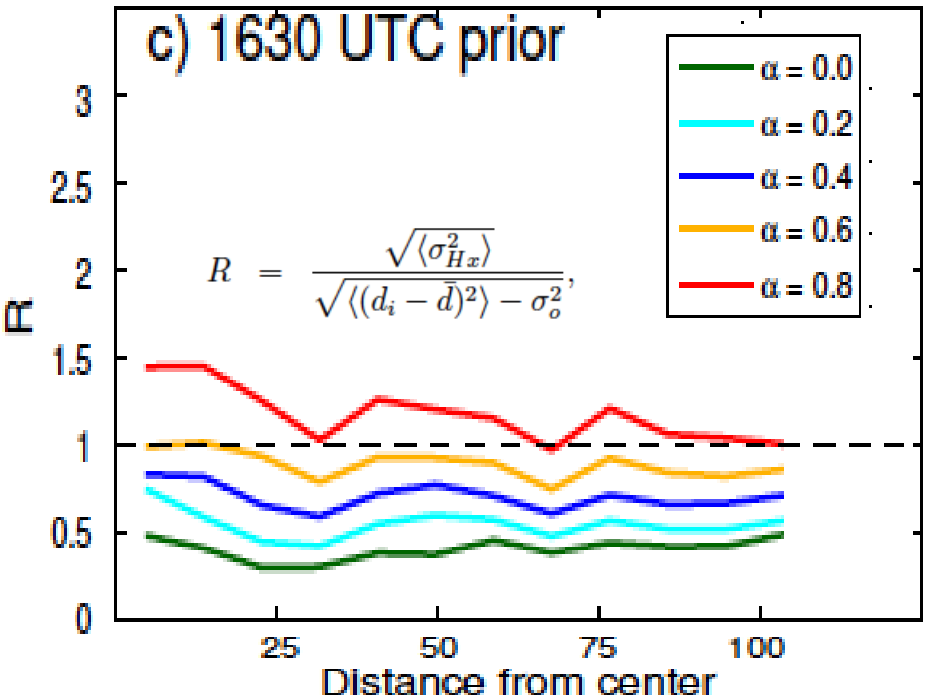


Covariance Relaxation: Inflation through Relaxation to Prior

(Zhang, Snyder and Sun 2004 MWR)

$$(x'^{a})_{new} = \alpha\, x'^{f} + (1-\alpha)\, x'^{a}$$

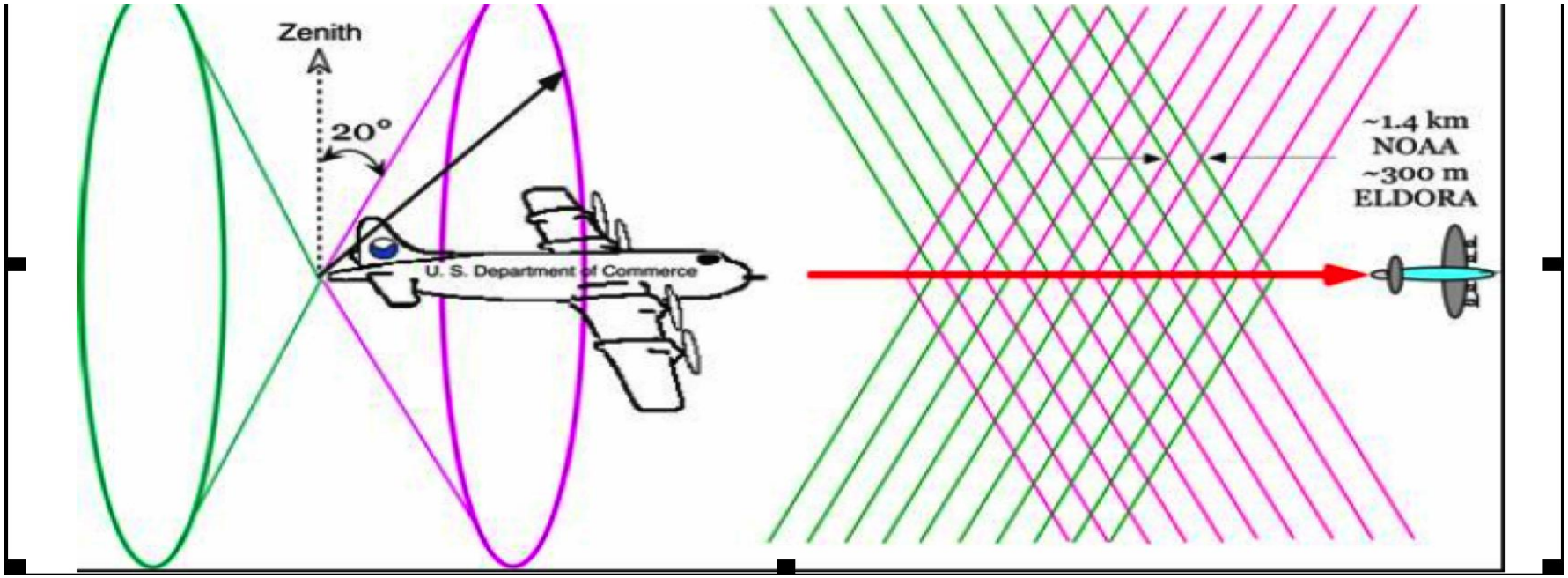
- α is the relaxation or mixing coefficient
- Treats sampling issues with respect to both model error and ensemble size
- More inflation in the area of denser observations while no inflation if no obs
- The method is adopted from the commonly used relaxation method in interactive numerical solver
- It is the 1st known adaptive covariance inflation method



(Poterjoy, Zhang & Weng, 2014 MWR)

Assimilate Airborne Doppler Winds with WRF-EnKF

(Weng and Zhang 2012 MWR)



Superobservations: 1. Separate forward and backward scans; 2. treat every 3 adjacent full scans as one fixed-space radar (translation<5km); 3. thinning ---one bin for 2 km in radial distance and 3 degree in scanning angle; 4. use medium as SO after additional QC checking 5. similar to the super-obing procedure for WSR88D Vr in Zhang et al. (2009 MWR)

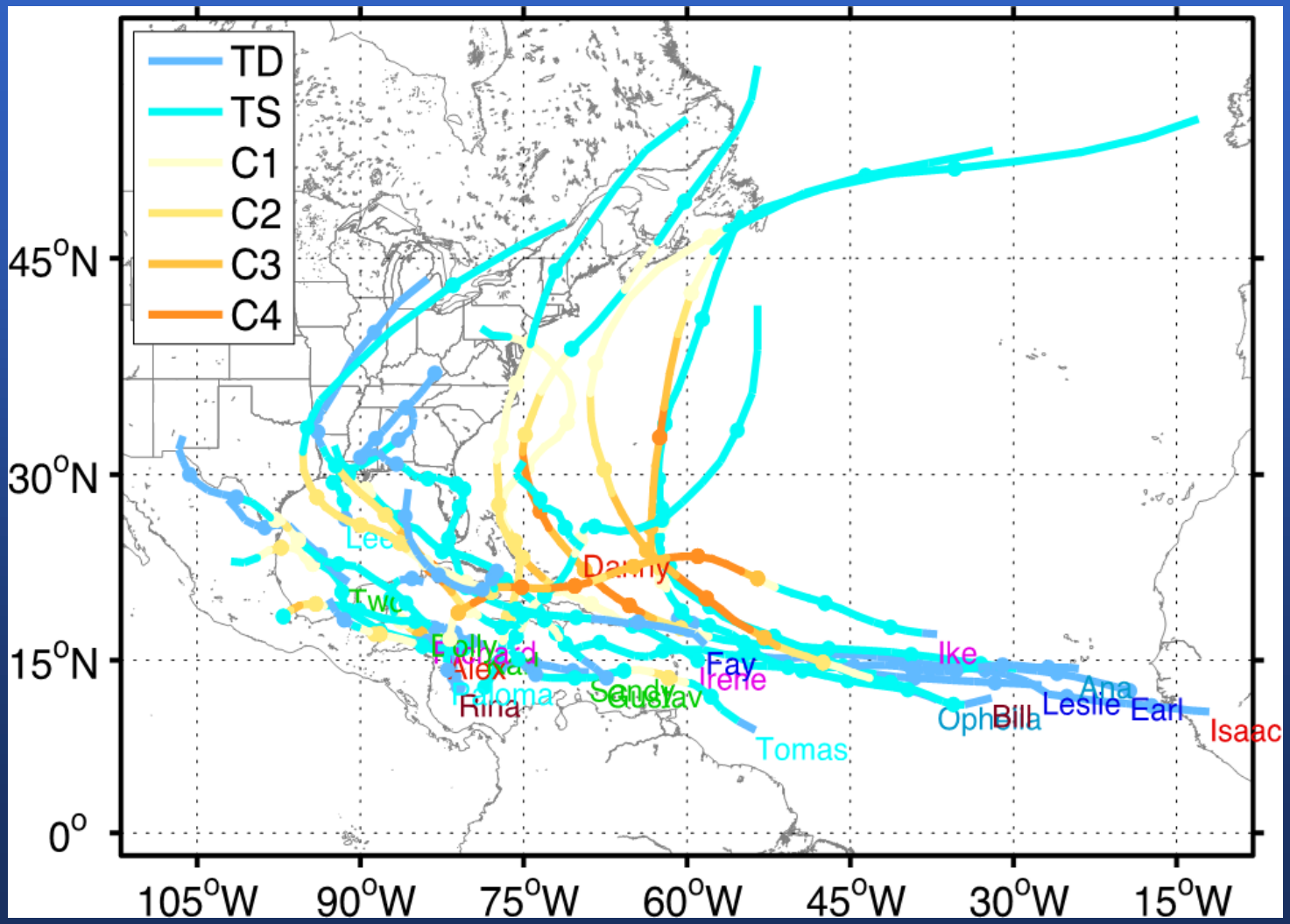
Thanks to John Gamache at HRD, these SOs are generated on flight of NOAA P3's and G4, transmitted to ground in real-time; adopted by HWRF in first operational assimilation 2013

WRF-EnKF Performance Assimilating Airborne Vr

all 100+ P3 TDR missions during 2008-2012

Quasi-operational evaluation by NHC since 2011 as HFIP stream 1.5 run

WRF-EnKF: 3 domains (27, 9 , 3km), 60-member ensemble, PSU TC flux scheme



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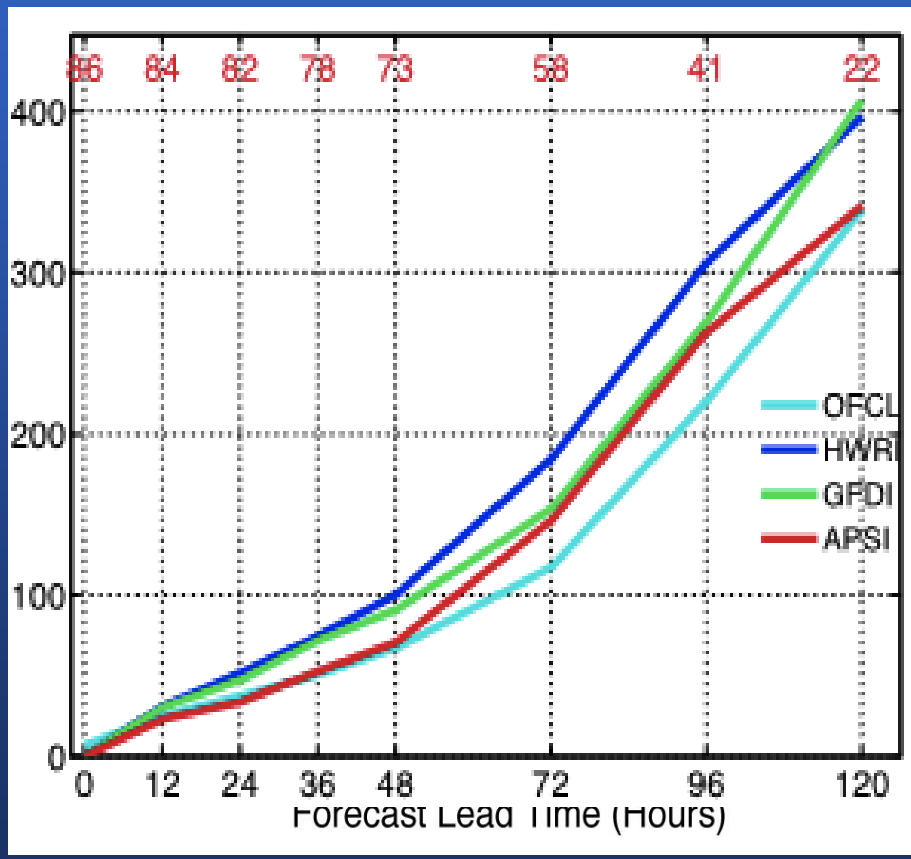
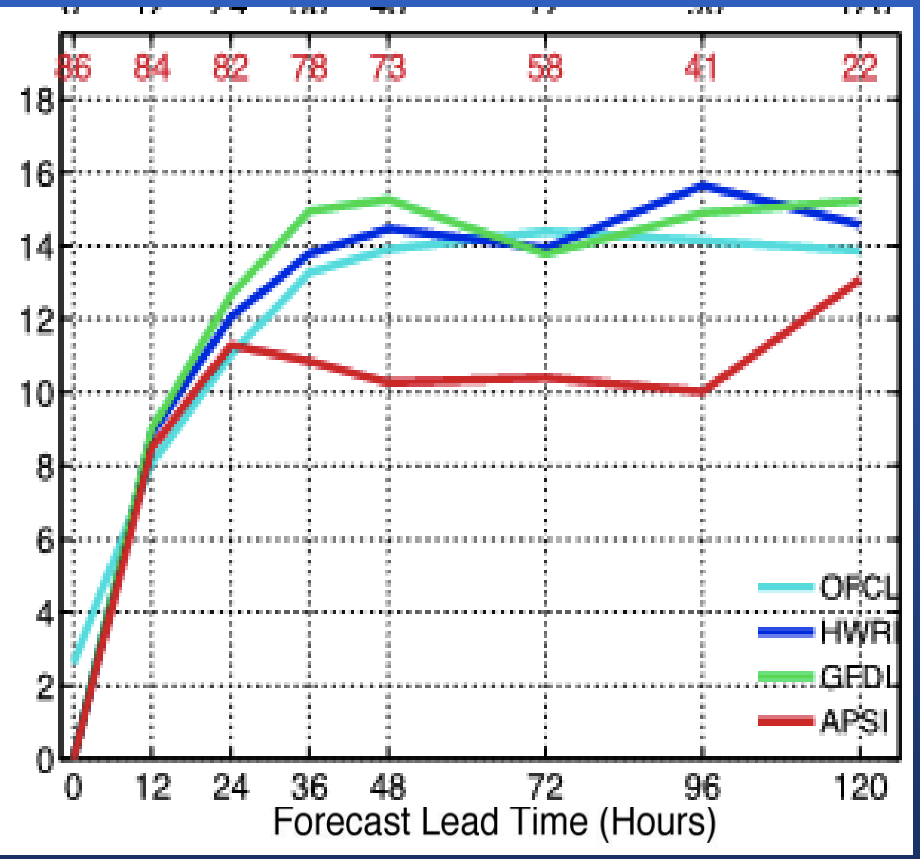
Position error (km)

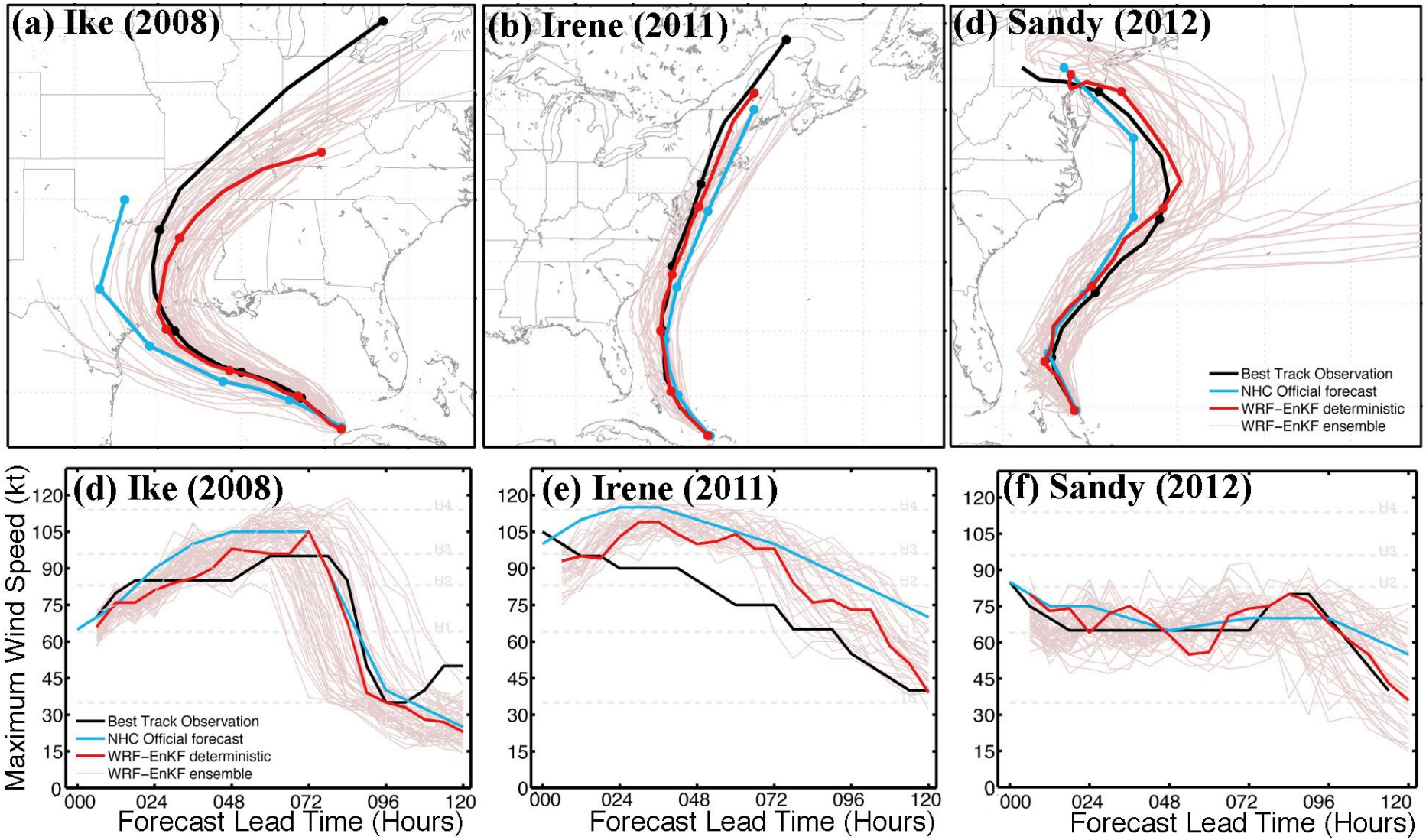


Intensity error (knots)

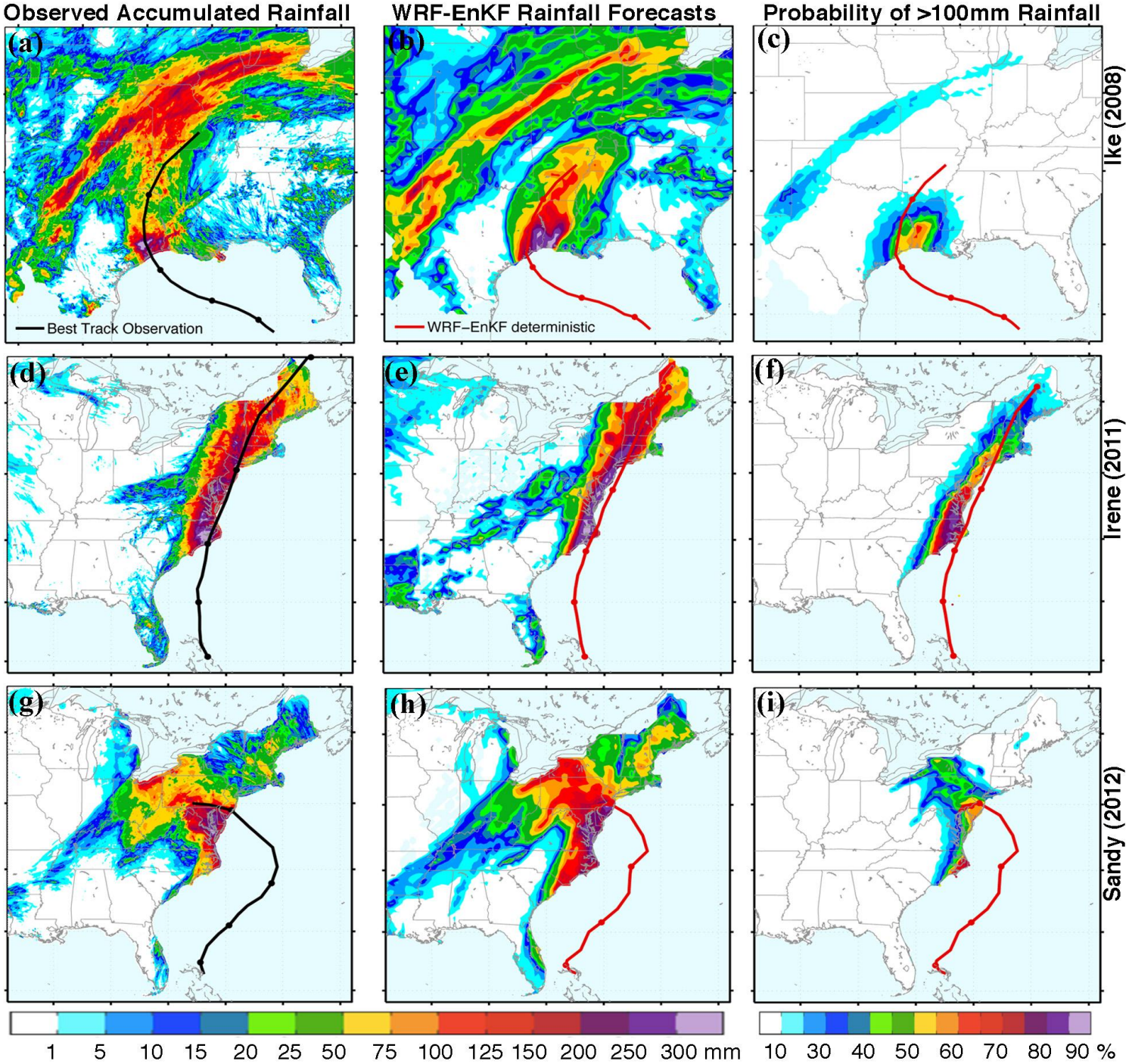


(Zhang et al. 2011 GRL; Zhang and Weng, BAMS, in review)

PSU Real-time EnKF Assimilation of Airborne Doppler Winds for Hurricane Forecasts



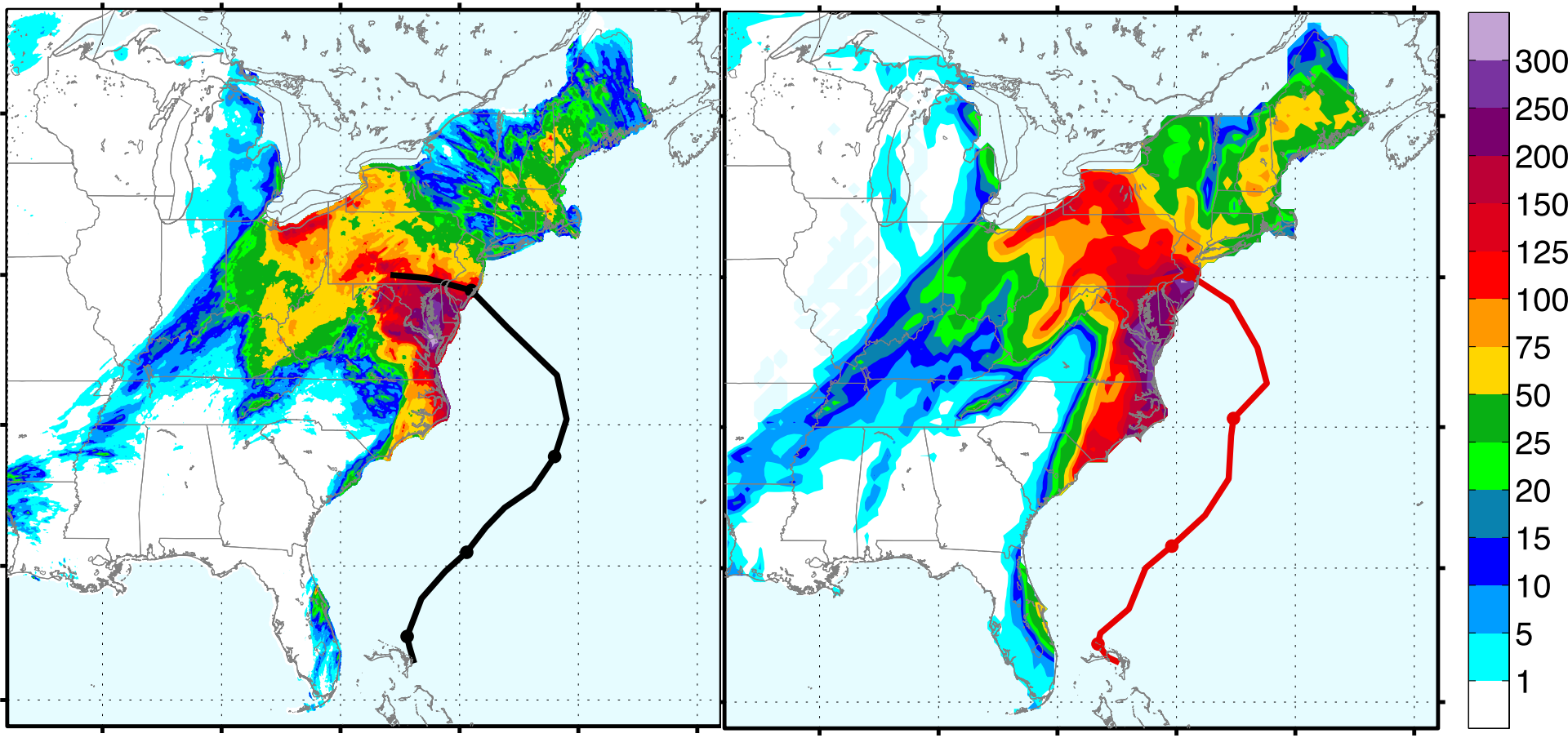
Rainfall Forecasts with PSU WRF-EnKF



PSU WRF-EnKF 4-day Rainfall Forecast from 00Z/26 Oct

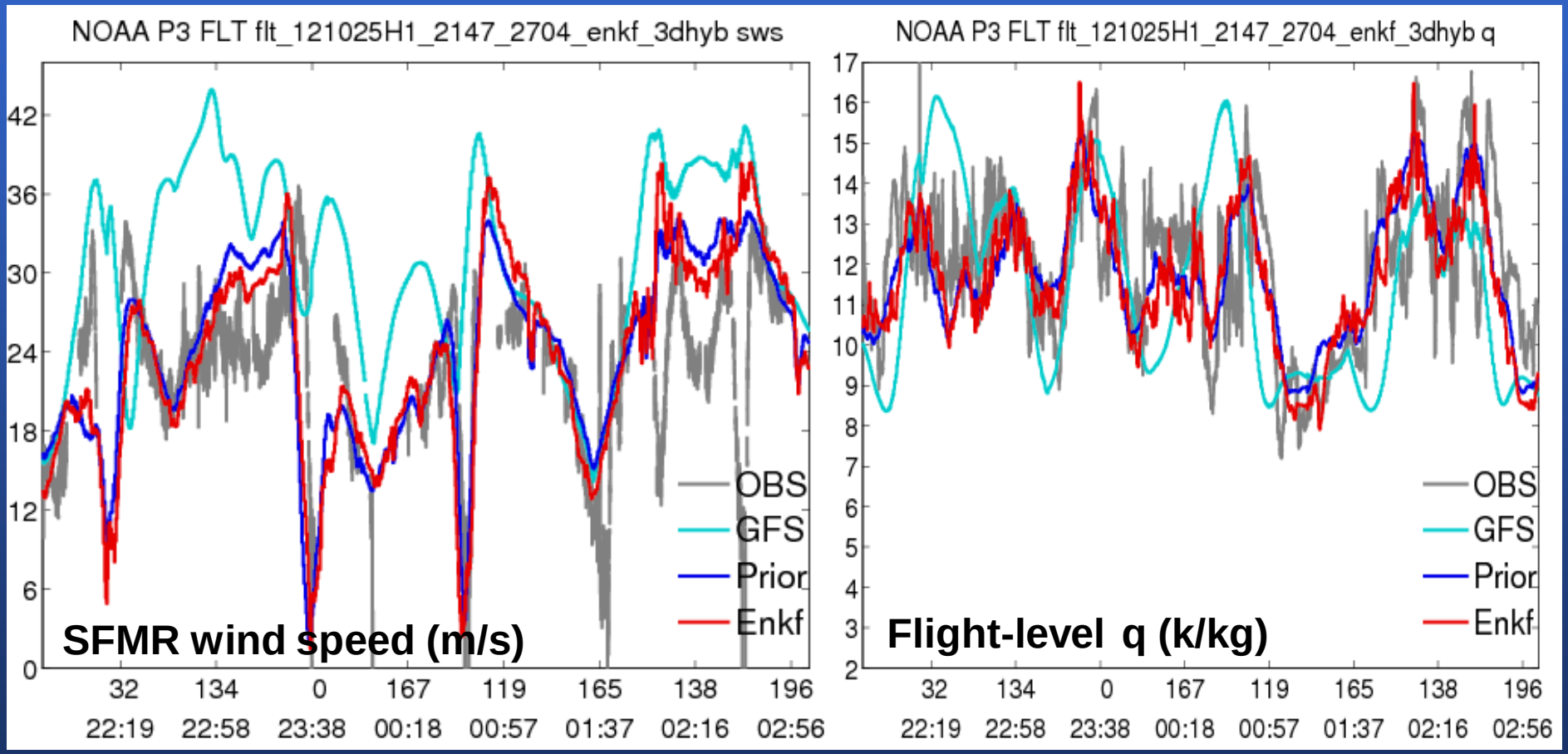
NWS 4km 96-h rainfall

APSU 96-h deterministic rainfall forecast



PSU WRF-EnKF Performance for Superstorm Sandy

EnKF analysis vs. independent observations from SFMR and flight-level obs



PSU WRF-EnKF Performance for Superstorm Sandy

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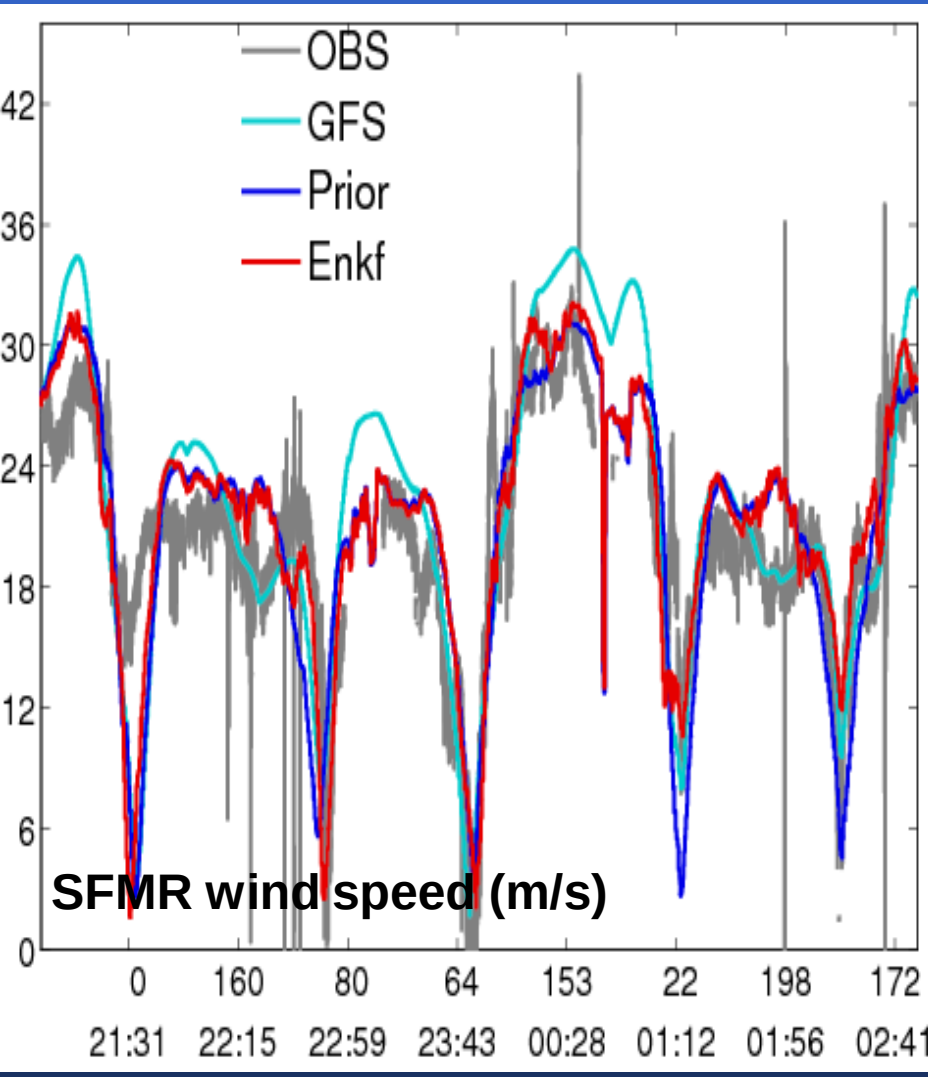
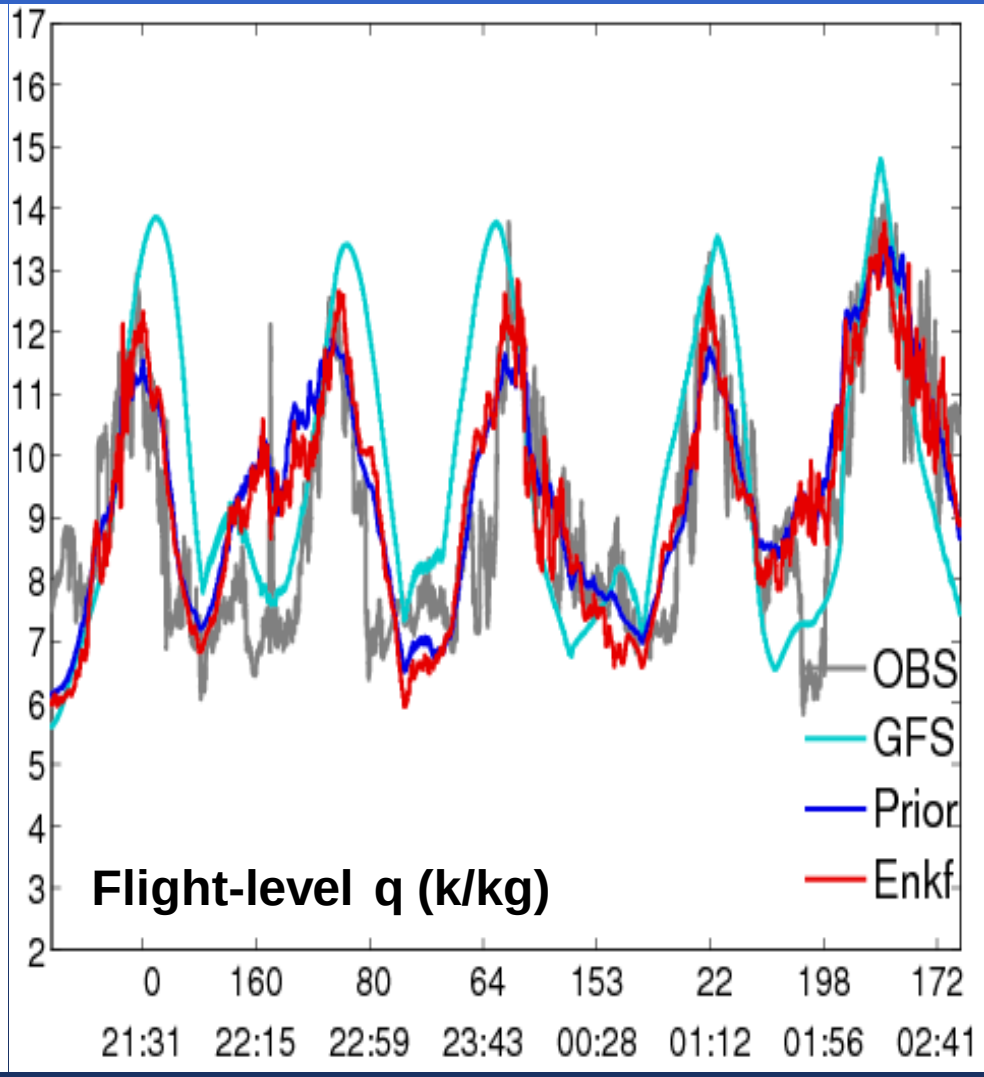
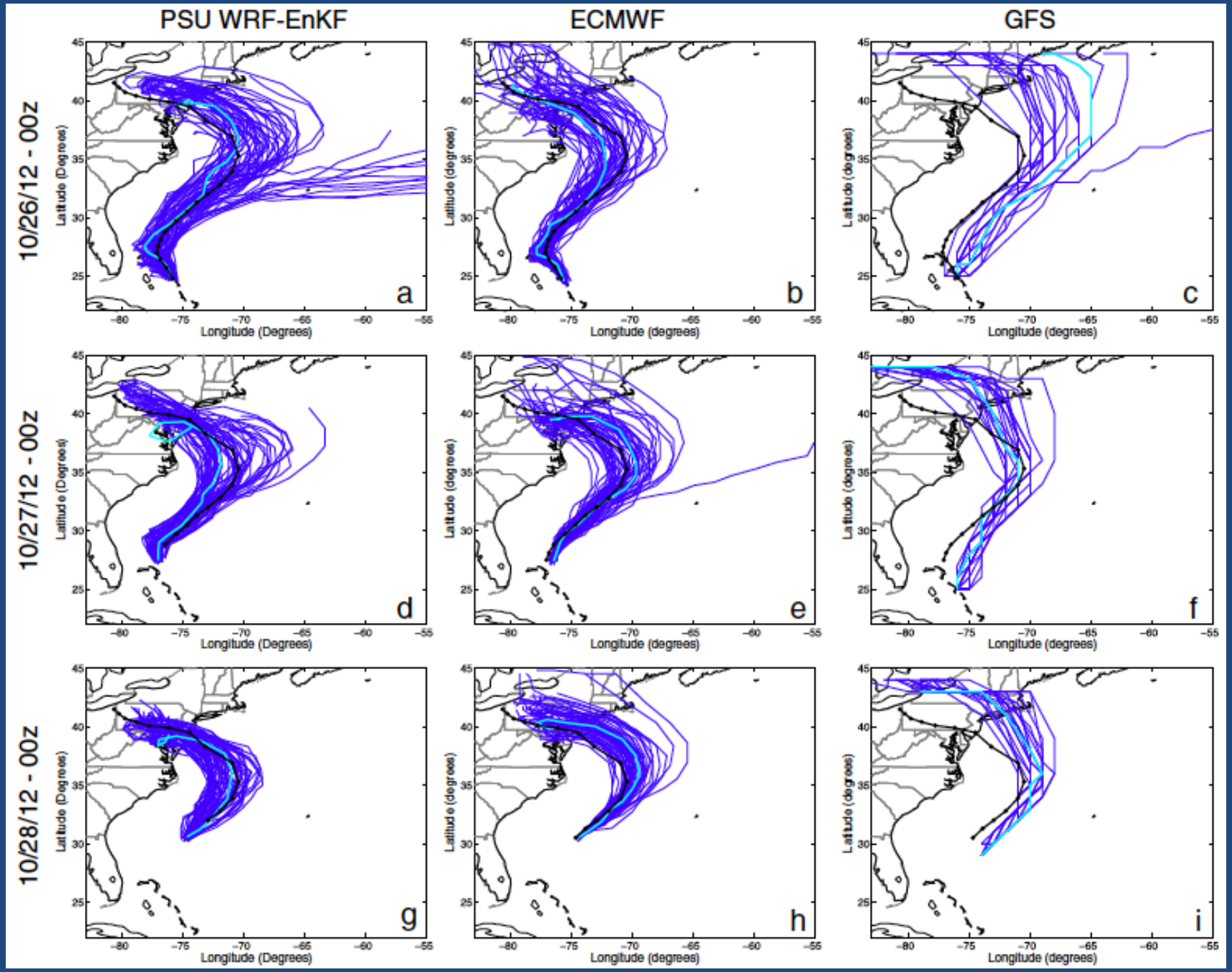






(Munsell & Zhang 2014 JAMES)

High Resolution Ensemble Storm Surge Predictions for Superstorm Sandy Around the New York City Region

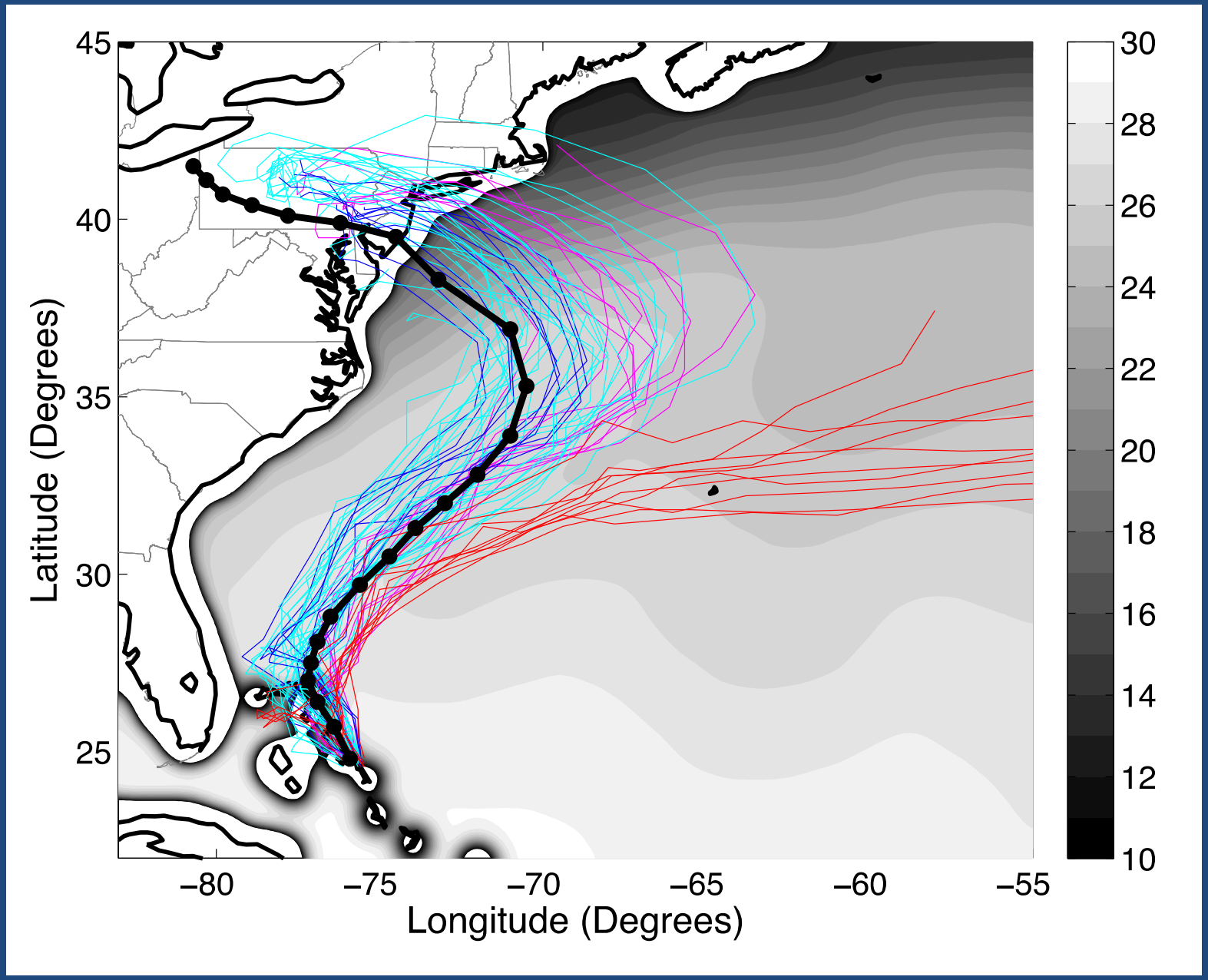
Brian A. Colle, Jian Kuang, Hamish Bowman, Malcolm Bowman, and Charles Flagg

Stony Brook University/SoMAS

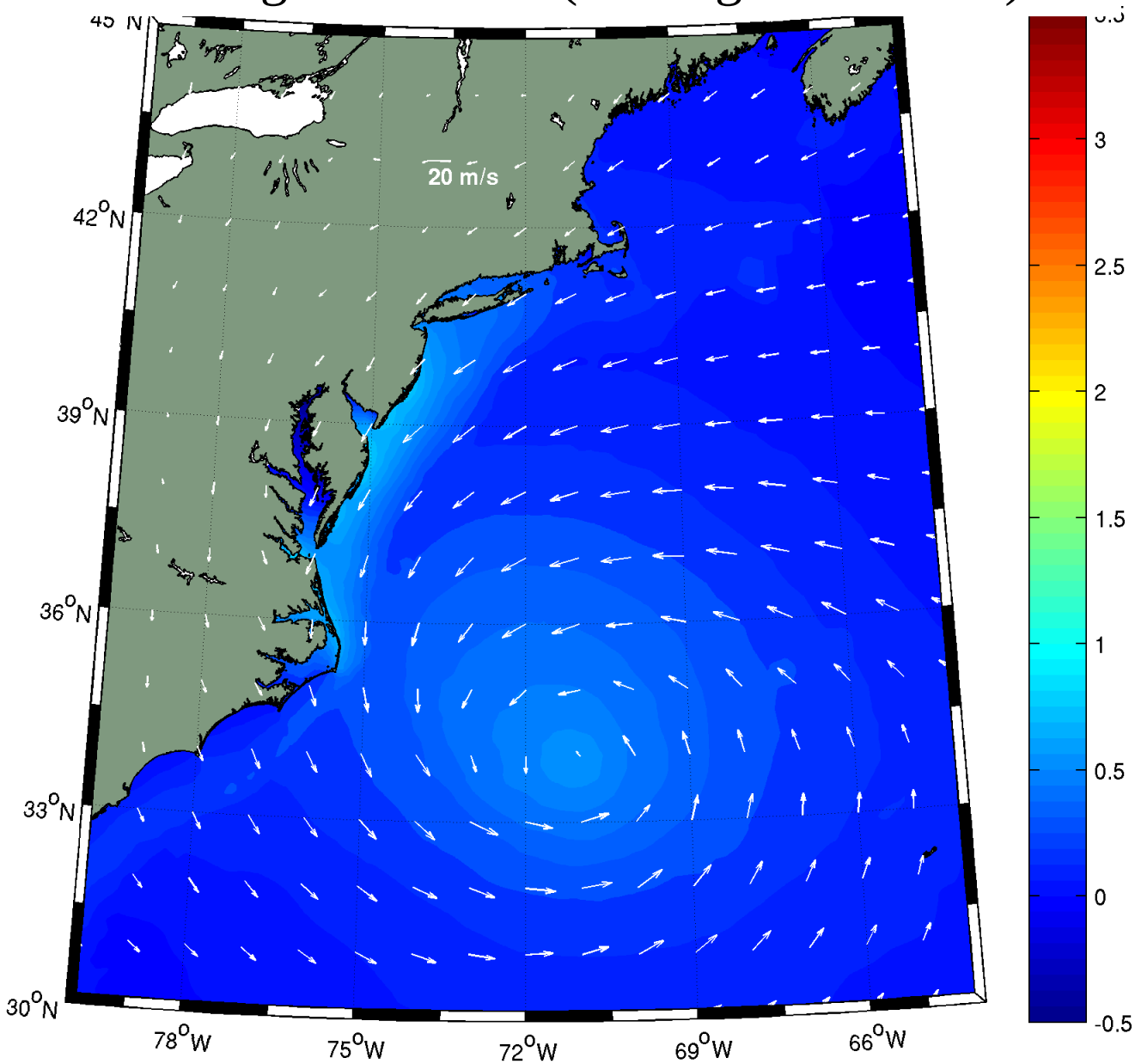
Fuqing Zhang, Yonghui Weng, and Erin Munsell

Pennsylvania State University

PSU Ensemble Tracks 4.5-d before landfall (10/26/12 – 00Z)

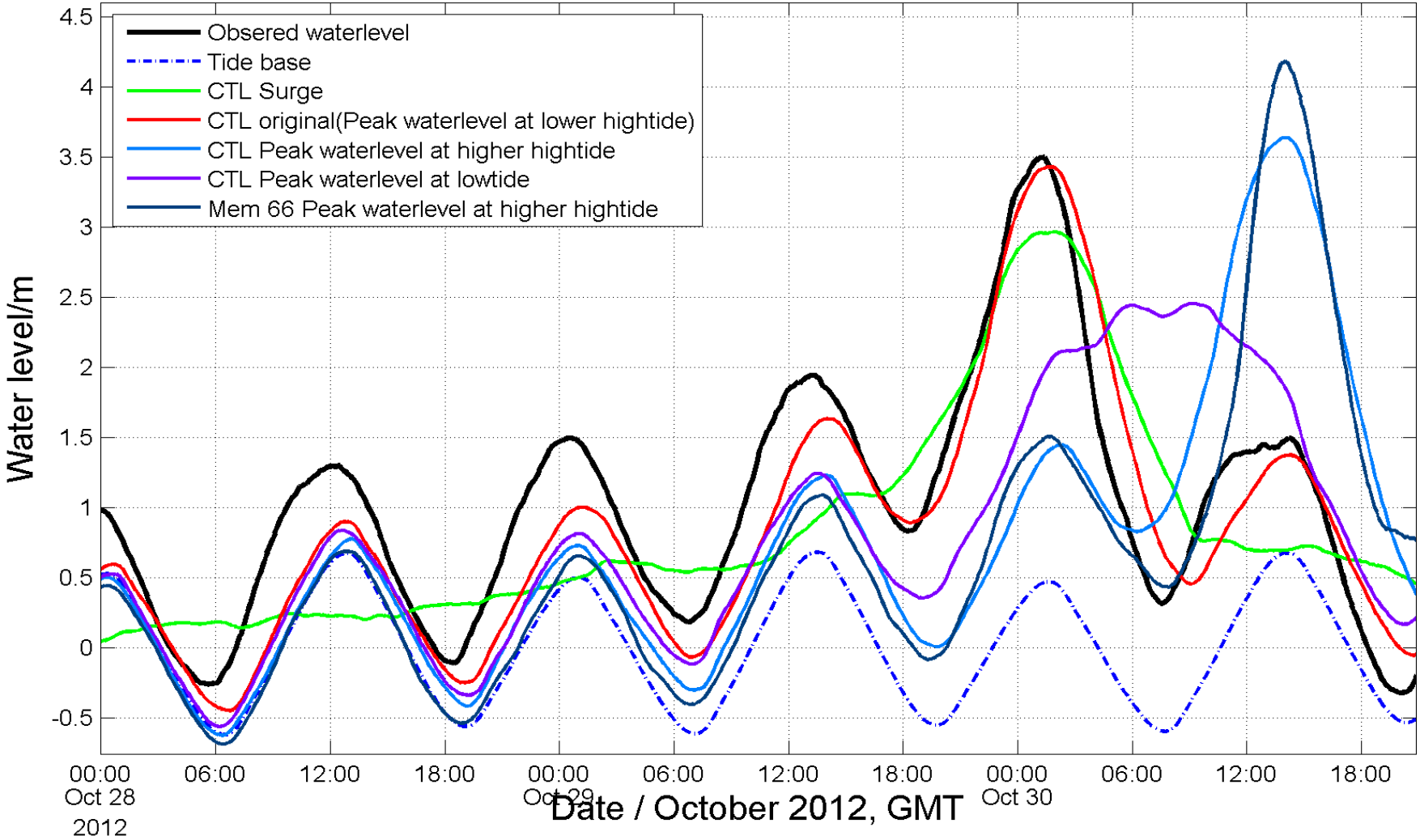


CTL surge animation (starting 29/00 UTC)



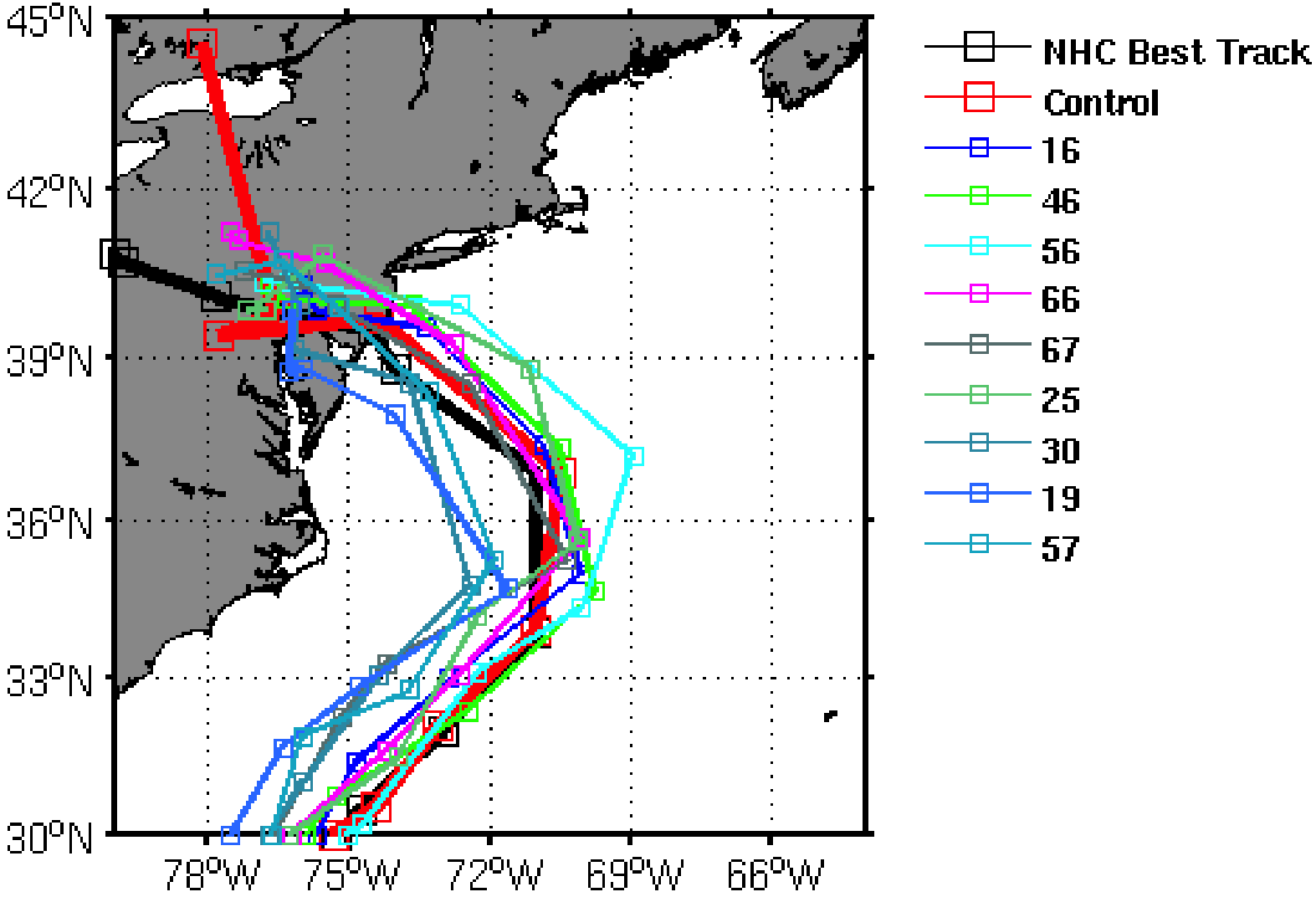
(meters)

Battery: Total Water Level (Shift to Low and High Tide)

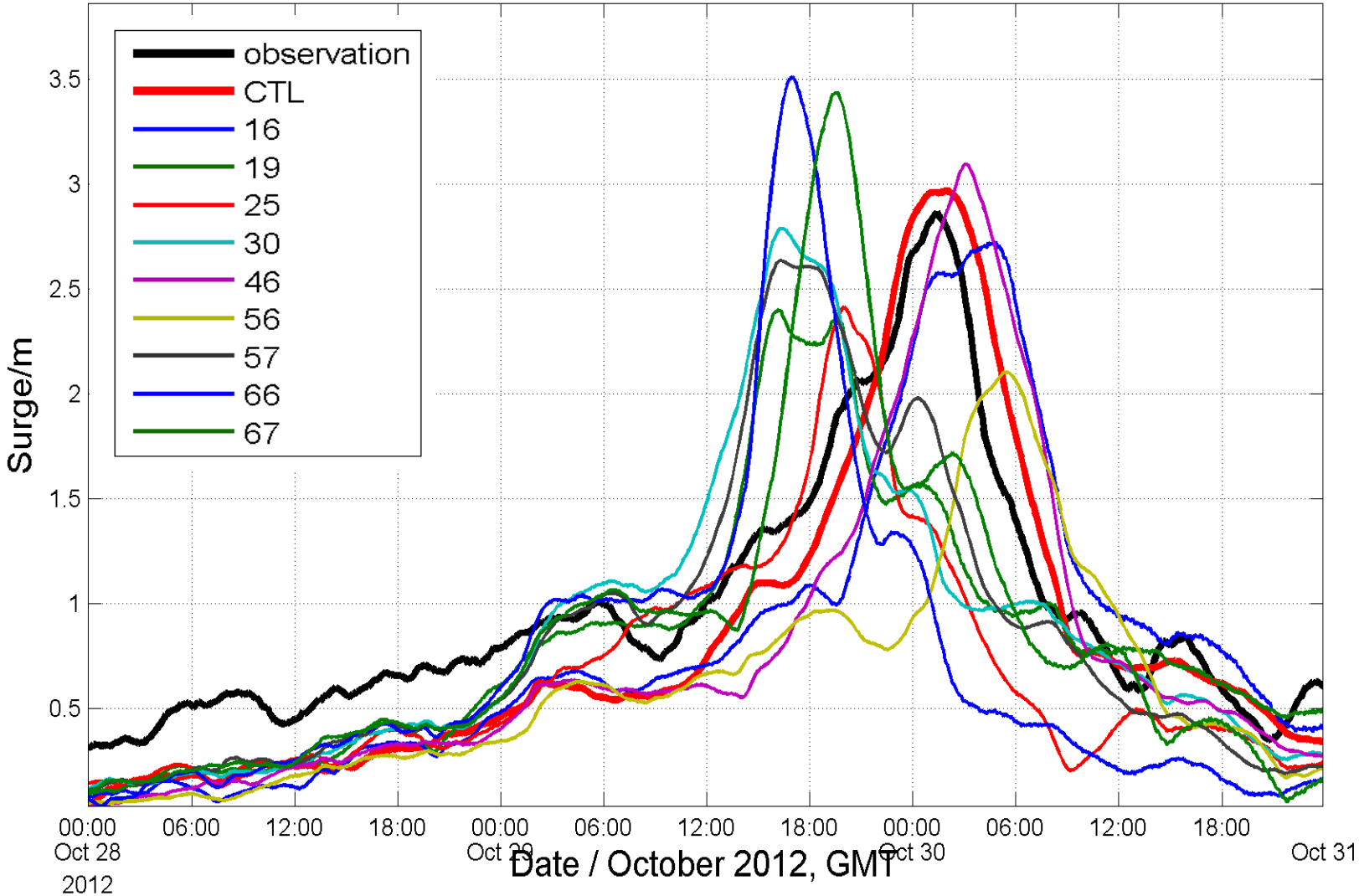


EnKF Runs Analyzed

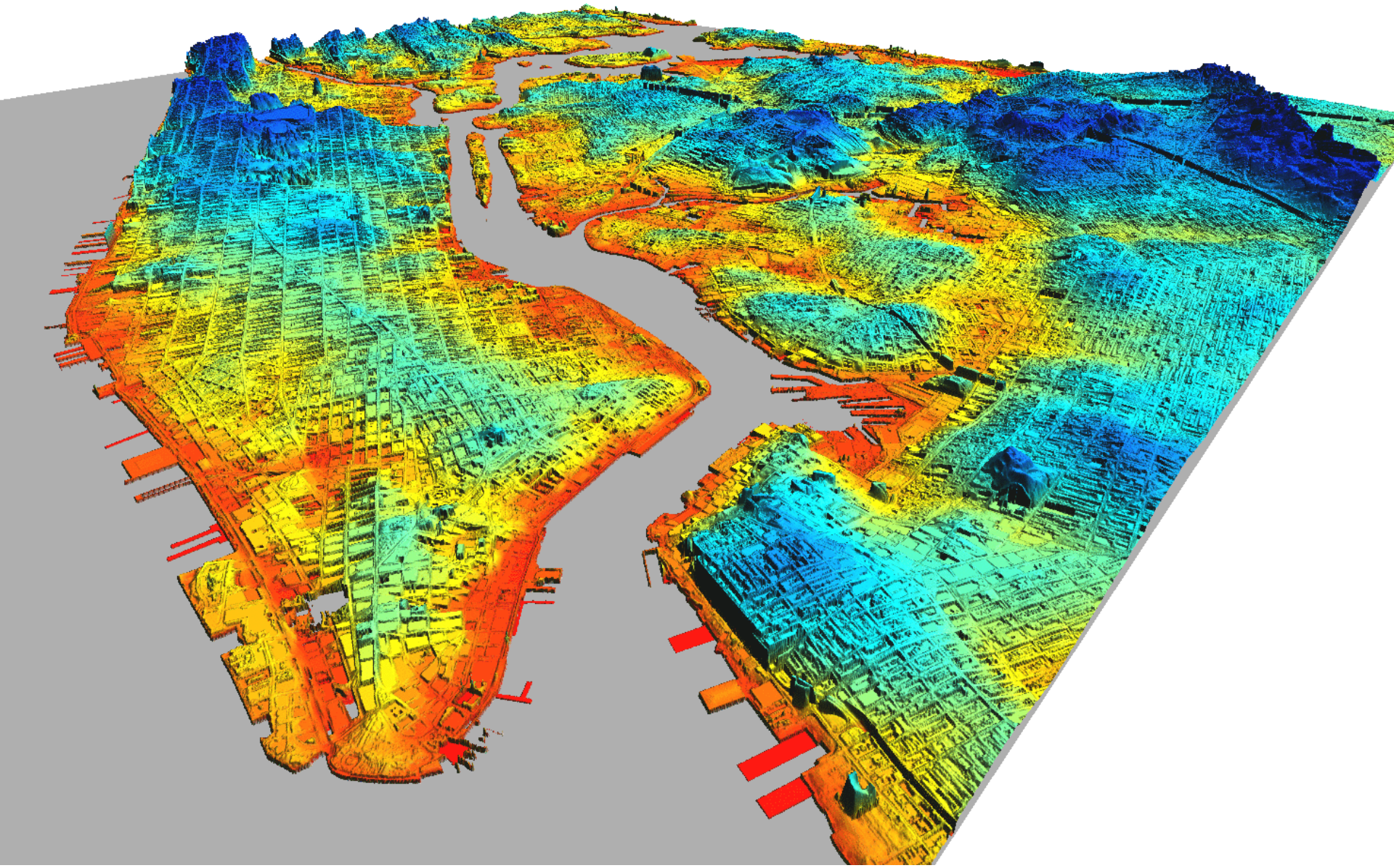
- Control: 26/00Z – 28/00Z + 28/00-31/00Z Runs
  - 9 "Good" Members from 26/00Z



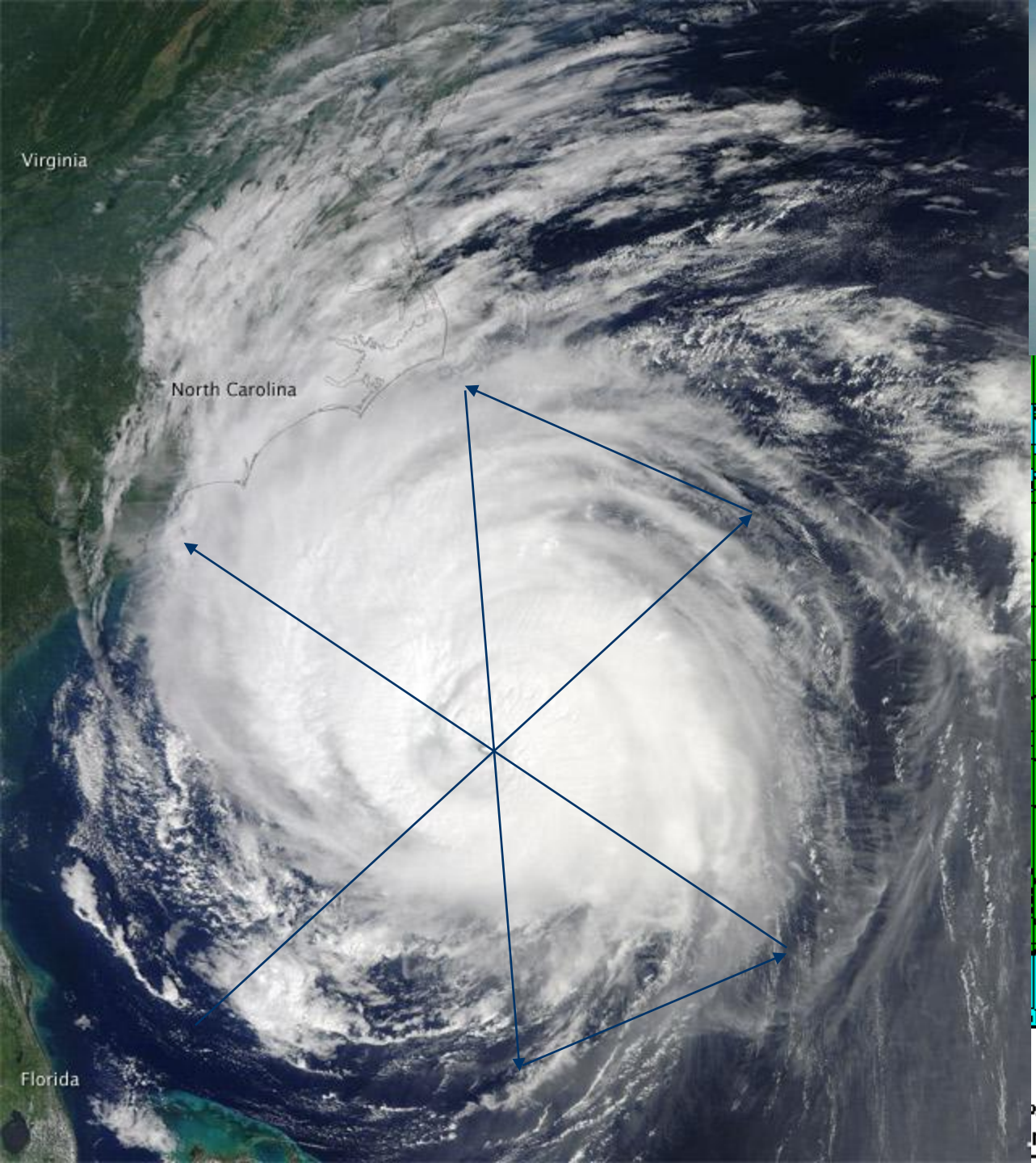
Battery: Ensemble Storm Surge

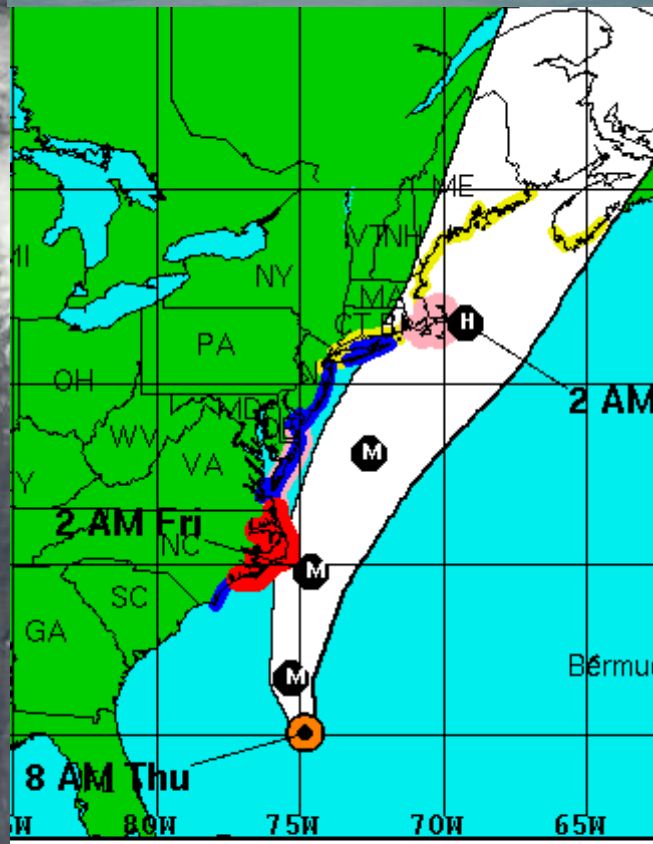


ADCIRC larger surge #66 at high tide



My Eye-Penetration Experience into the Cat-4 Hurricane Earl





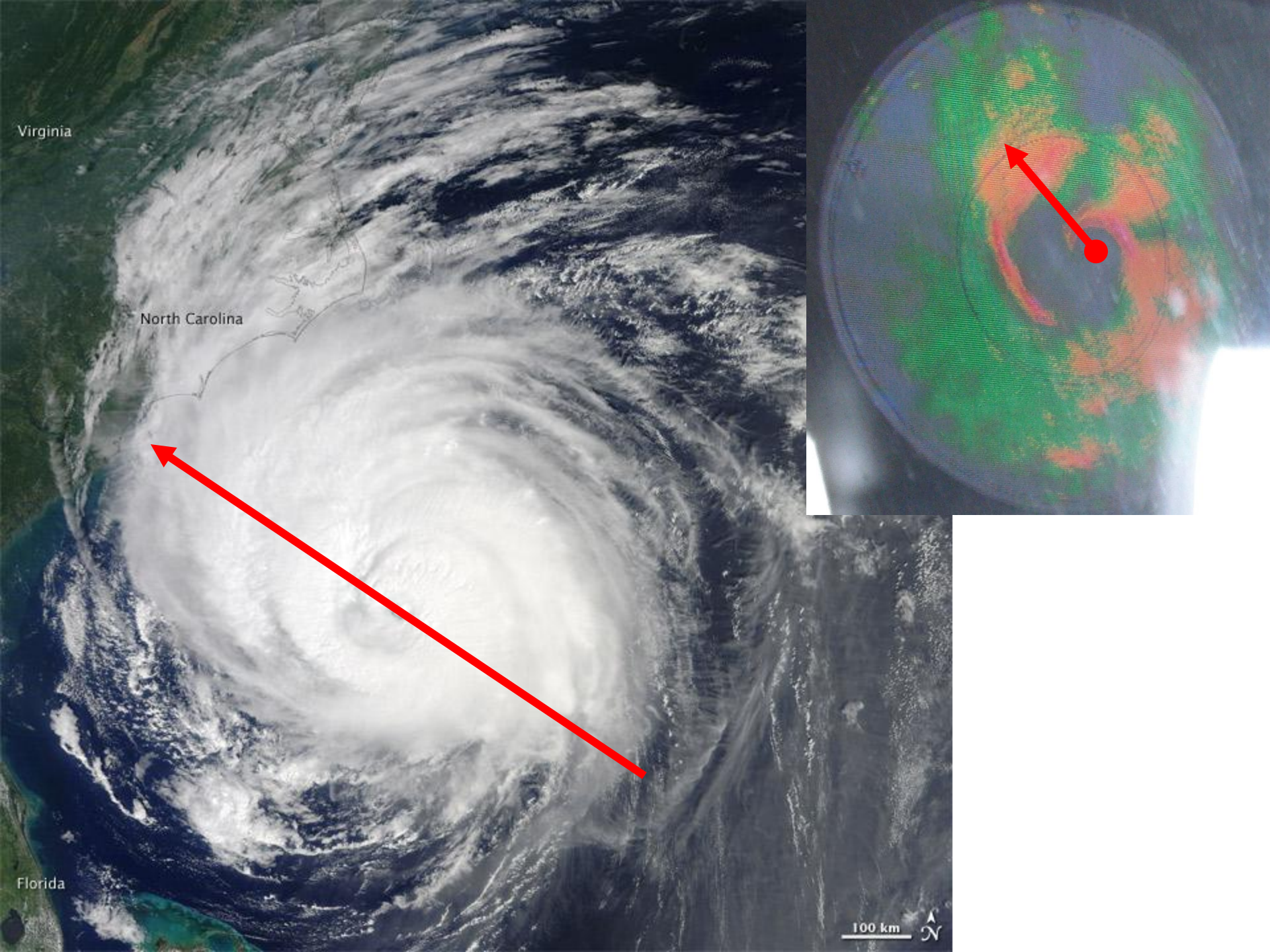
Current Information:

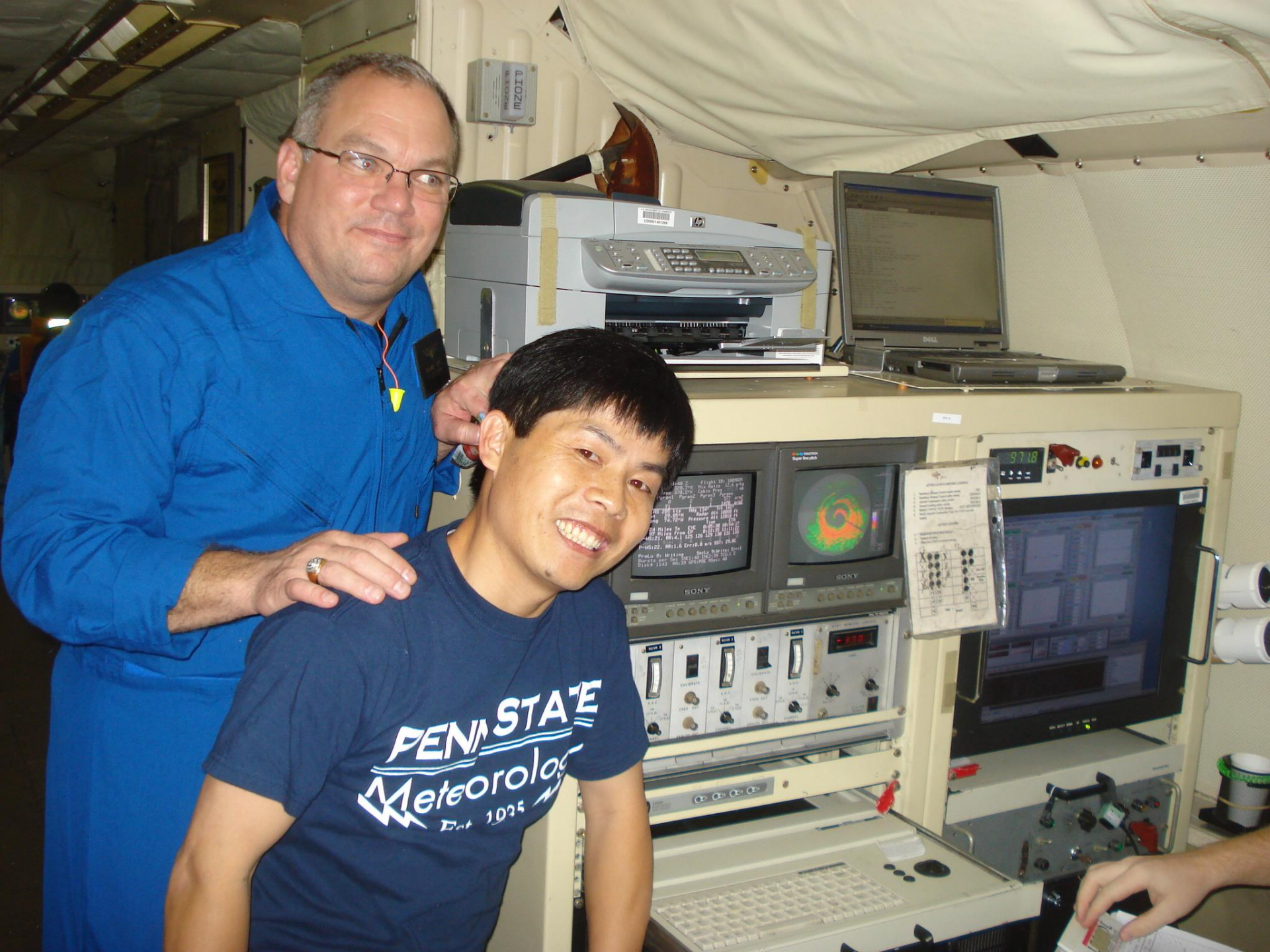
Center Location 30.1 N 74.8 W

Max Sustained Wind 145 mph

Movement NNW at 18 mph

RESCUE
FLORIDA STATE
SEMINOLES
PENN STATE
Meteorology


Virginia
North Carolina
Florida
100 km
N


PENNSTATE
Meteorolog
SONY
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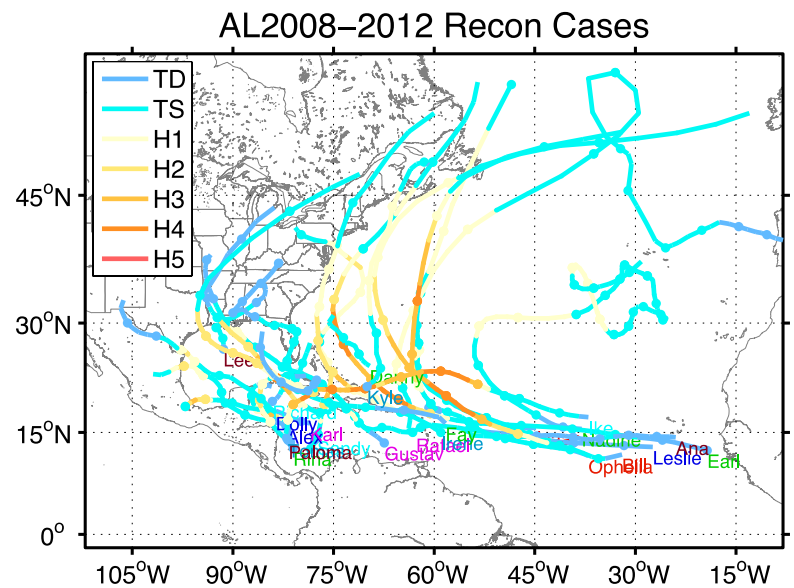
President Barack Obama receives an update on Hurricane Irene in the Situation Room of the White House, August 28, 2011. Clockwise starting to the left of Obama, Transportation Secretary Ray LaHood; Richard Reed, Special Assistant to the President for Homeland Security; Nick Shapiro, senior policy advisor to John Brennan; John Brennan, Assistant to the President for Homeland Security; and Chief of Staff Bill Daley. Onscreen are FEMA Administrator Craig Fugate and Homeland Security Secretary Janet Napolitano. Joining by phone are Vice President Joe Biden, Treasury Secretary Tim Geithner and Energy Secretary Steven Chu. (Official White House Photo by Pete Souza)

Airborne Reconnaissance Inner-core Data Impacts beyond Doppler Vr (HFIP/RDITT)

Aircraft ReconCcases for the 2008-2012 Atlantic Storms (by NHC)

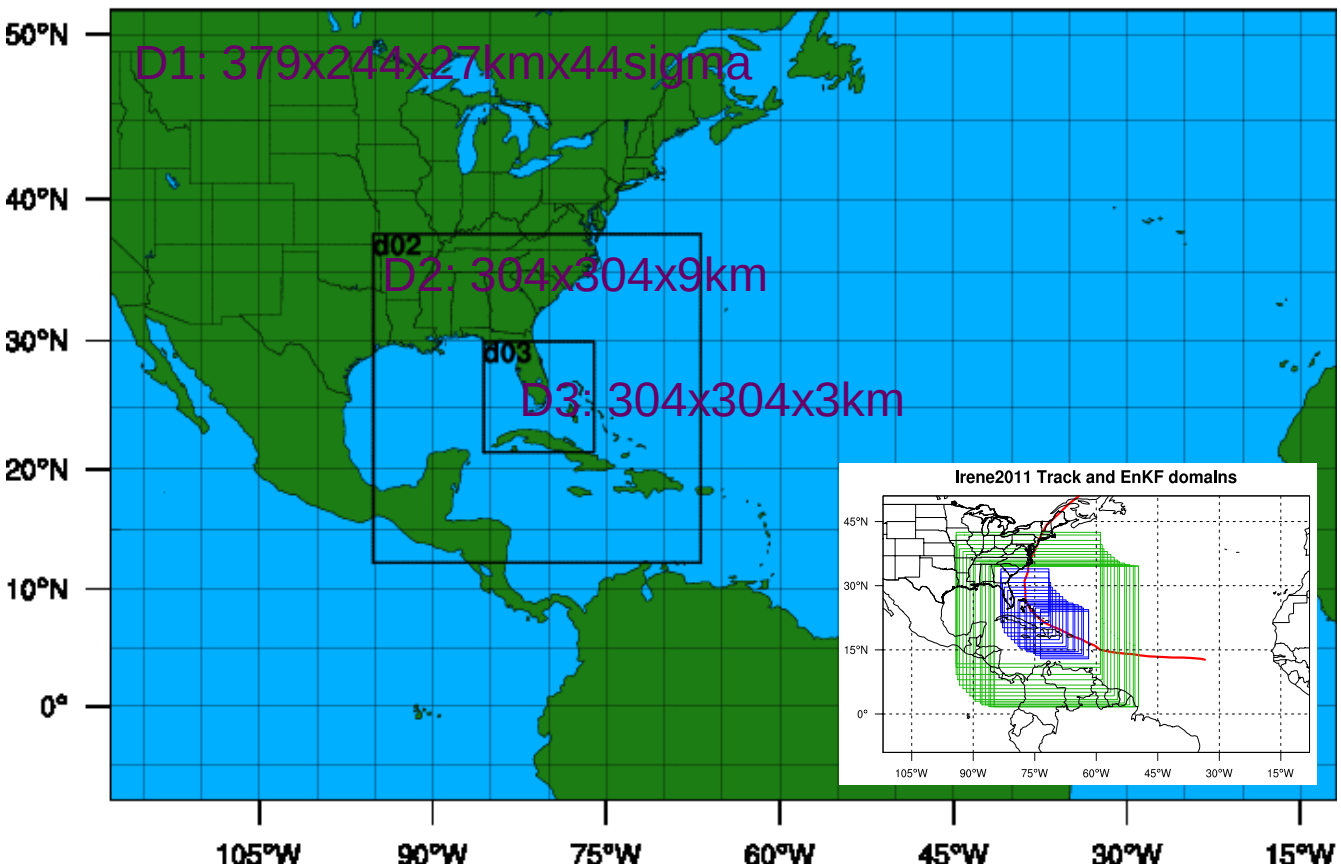
Year	Storm	APCT MMDDHH-MMDDHH	APRC MMDDHH-MMDDHH
2008	04-Dolly	072012-072418	072012-072418
	06-Fay	081400-082400	081400-082400
	07-GUSTAV	082512-090200	082512-090200
	09-Ike	090200-091312	090512-091312
	11-Kyle	092300-092812	092318-092812
	17-Paloma	110600-111000	110600-111000
2009	02-Ana	081200-081700	081612-081700
	03-Bill	081600-082312	081812-082312
	05-Danny	082612-082900	082612-082900
2010	01-Alex	062512-070112	062512-070112
	07-Earl	082600-090400	082712-090400
	13-Karl	091412-091800	091412-091800
	19-Richard	102012-102600	102012-102600
	21-Tomas	102912-110806	102912-110806
2011	09-Irene	082000-082900	082012-082900
	13-Lee	090200-090612	090200-090612
	16-Ophelia	092100-100218	092312-092900
	18-Rina	102212-102818	102312-102800
2012	09-Isaac	082000-083018	082112-082906
	12-Leslie	083000-091100	090712-090812
	14-Nadine	091000-100318	091118-100318*
	17-Rafael	101300-101718	101300-101718
	18-Sandy	102100-103018	102212-102918
Total	23 storms	758 cases	636 cases

* NASA Globe-Hawk dropsondes.



Atlantic storm tracks with recon missions during 2008-2012

WRF-ARW Configurations for the PSU Cycling EnKF



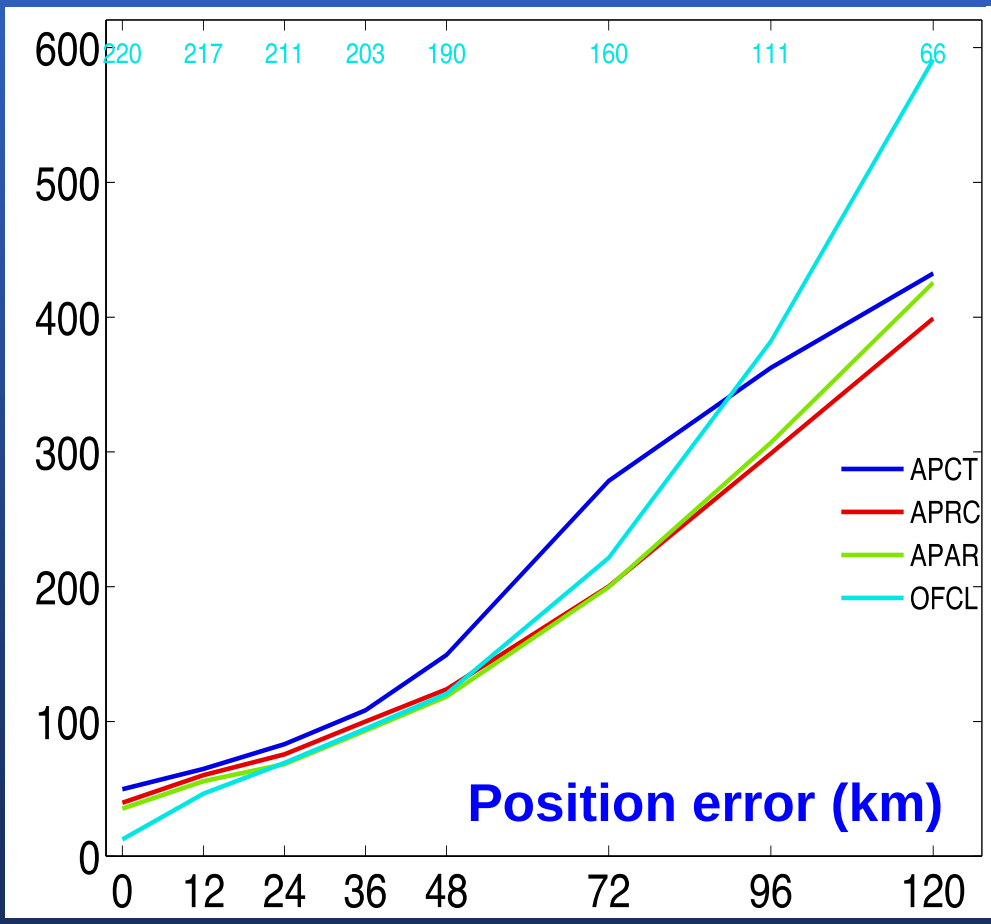
ARW	V3.4.1
Cumulus	Grell-Devenyi ensemble (27 km domain only)
Microphysics	WSM 6-class graupel
PBL	YSU
Surface Layer	Monin-Obukov
Land Surface	thermal diffusion
Radiation	Rrtm / Dudhia
Air-sea flux	Green&Zhang (2013 MWR)
Ocean	NO
• 60-member ensemble	
• Gaspairi & Cohn 99' covariance localization with varying RoI	
• IC & BC: GFS using 3DVAR background uncertainty	
• Observation window: 3hrs cycling	

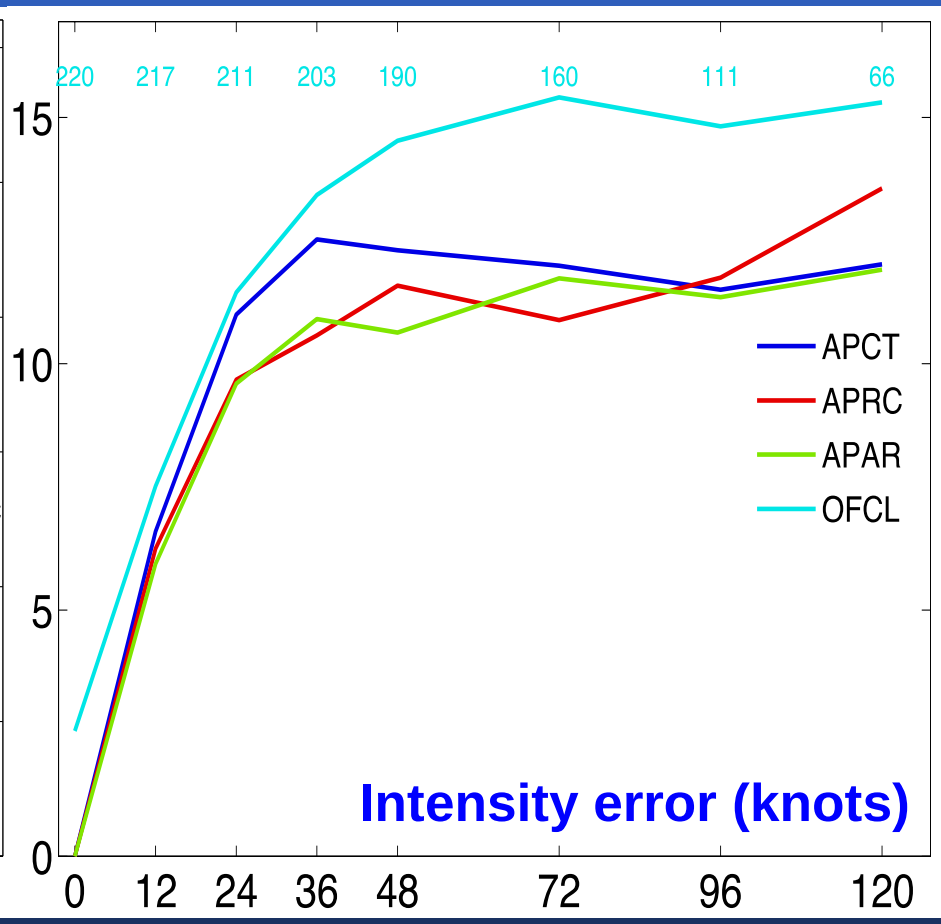
ANPS – no EnKF assimilation: WRF is initialized with operational GFS analysis
APCT – control run: EnKF assimilation of conventional data only
APRC – recon run: APCT + flight-level and dropsonde observations
APAR – recon with TDR run: APCT + flight-level and dropsonde obs + TDR Vr

Further Updates: Cycling WRF-EnKF Retrospective Runs Assimilating Airborne Dropsonde, Flight-level and/or TDR Vr Observations at NHC's Request

NOAA/HFIP Tiger Team RECON tests and evaluation for 2013 stream 1.5 run

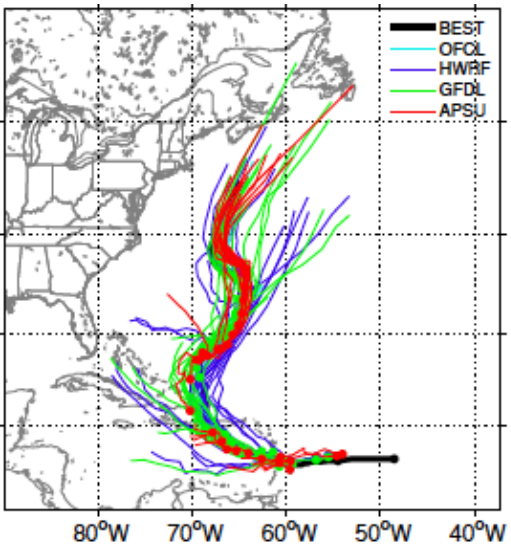
Cycling WRF-EnKF: 3 domains (27, 9 , 3km), 60-member ensemble, PSU TC flux

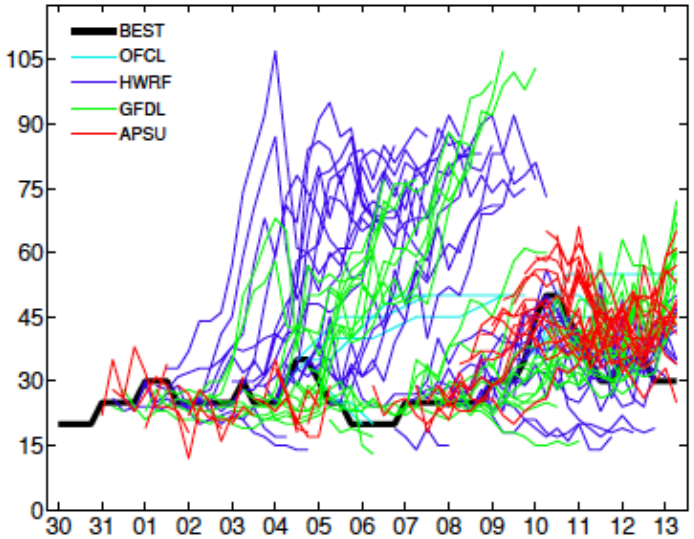


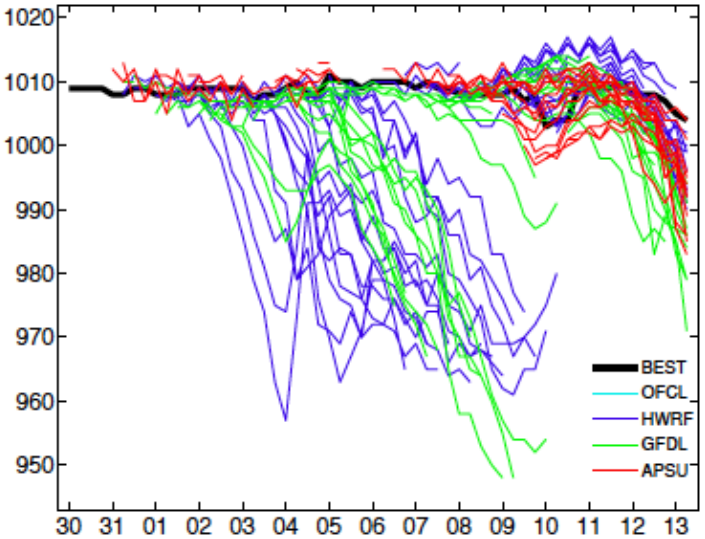


PSU WRF-EnKF 2013 Realtime Stream-1.5 Run

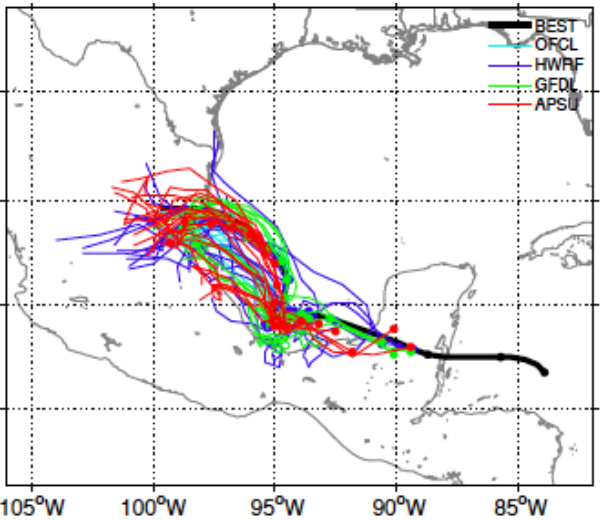
Tropical Storm Gabriel from 12Z/Aug29 to 12Z/Sep13 including 3 HS3 GH missions

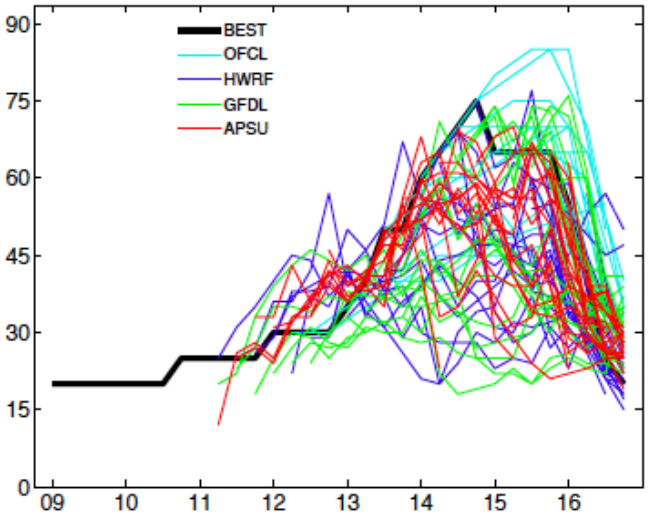


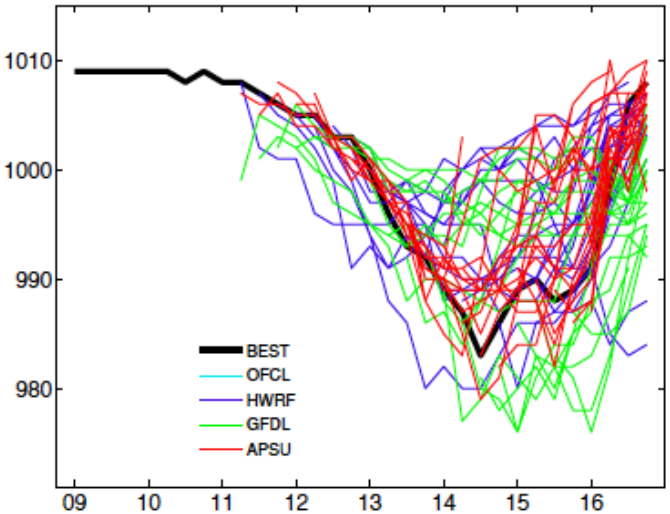




Hurricane Ingrid from 12Z/Sep8 to 00Z/Sep17 including 1 HS3 GH missions

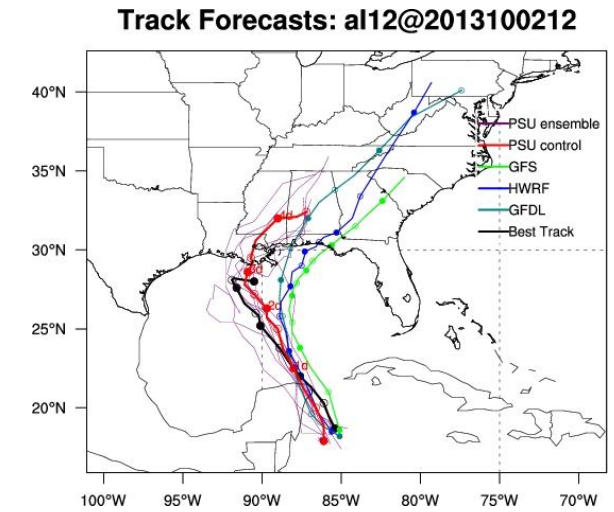


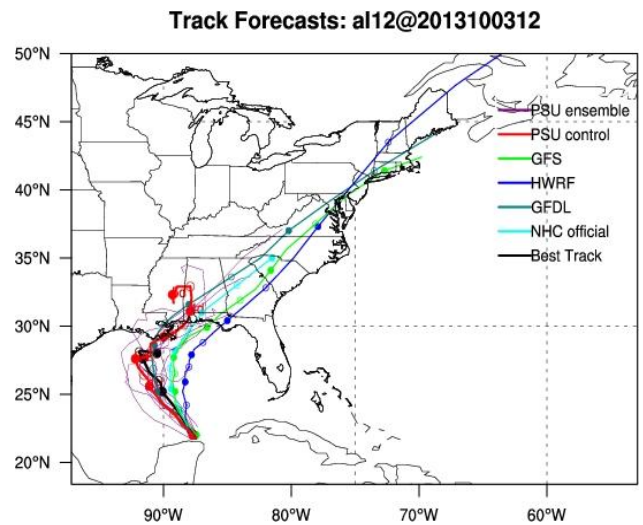


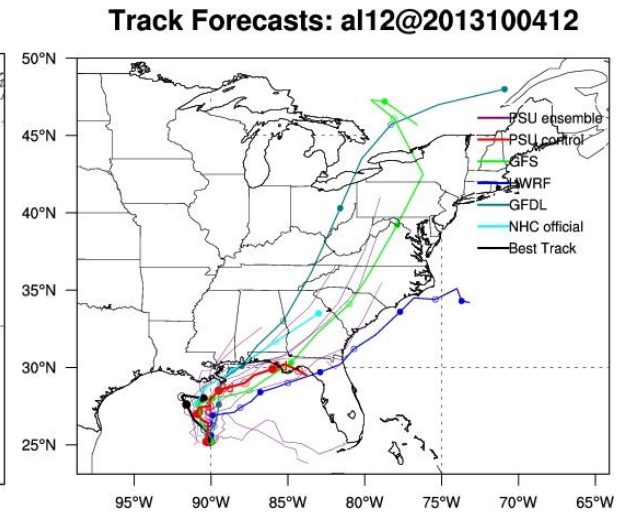


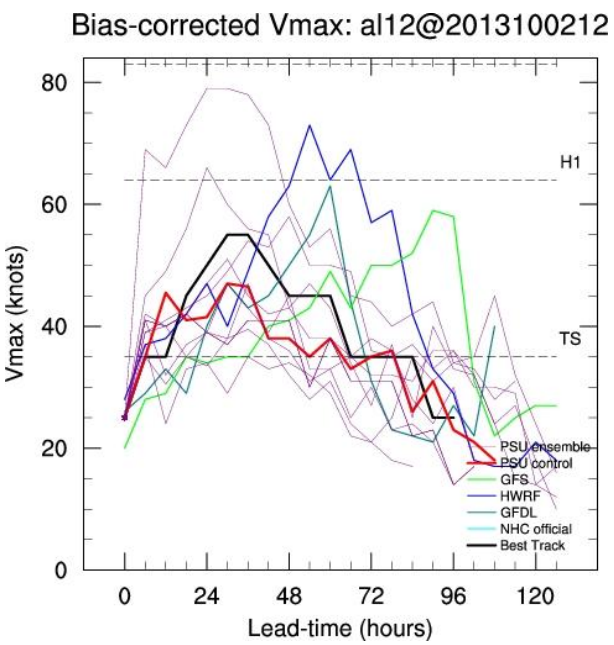
PSU WRF-EnKF 2013 Realtime Stream-1.5 Run

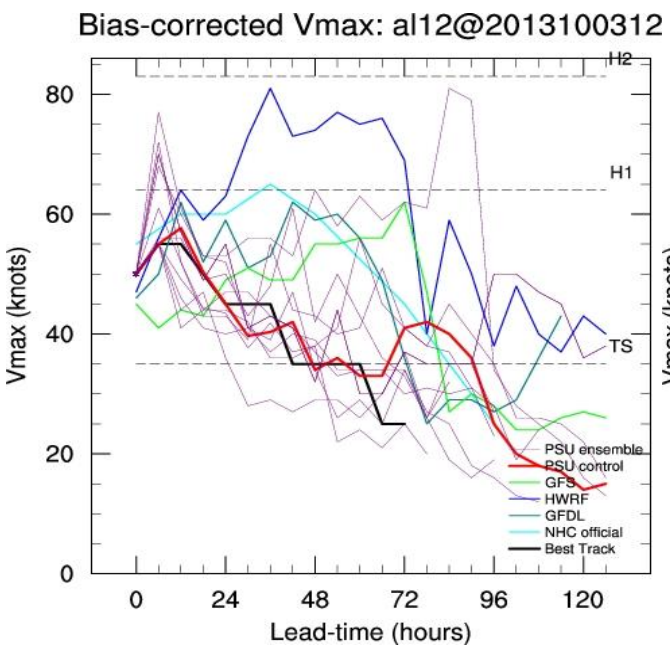
3 sample Forecasts for Tropical Storm Karen (12Z of 2, 3, 4 Oct)

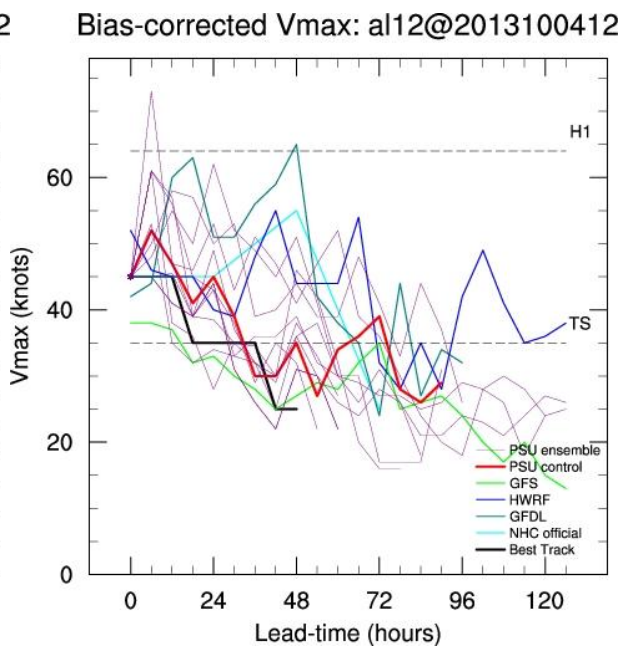




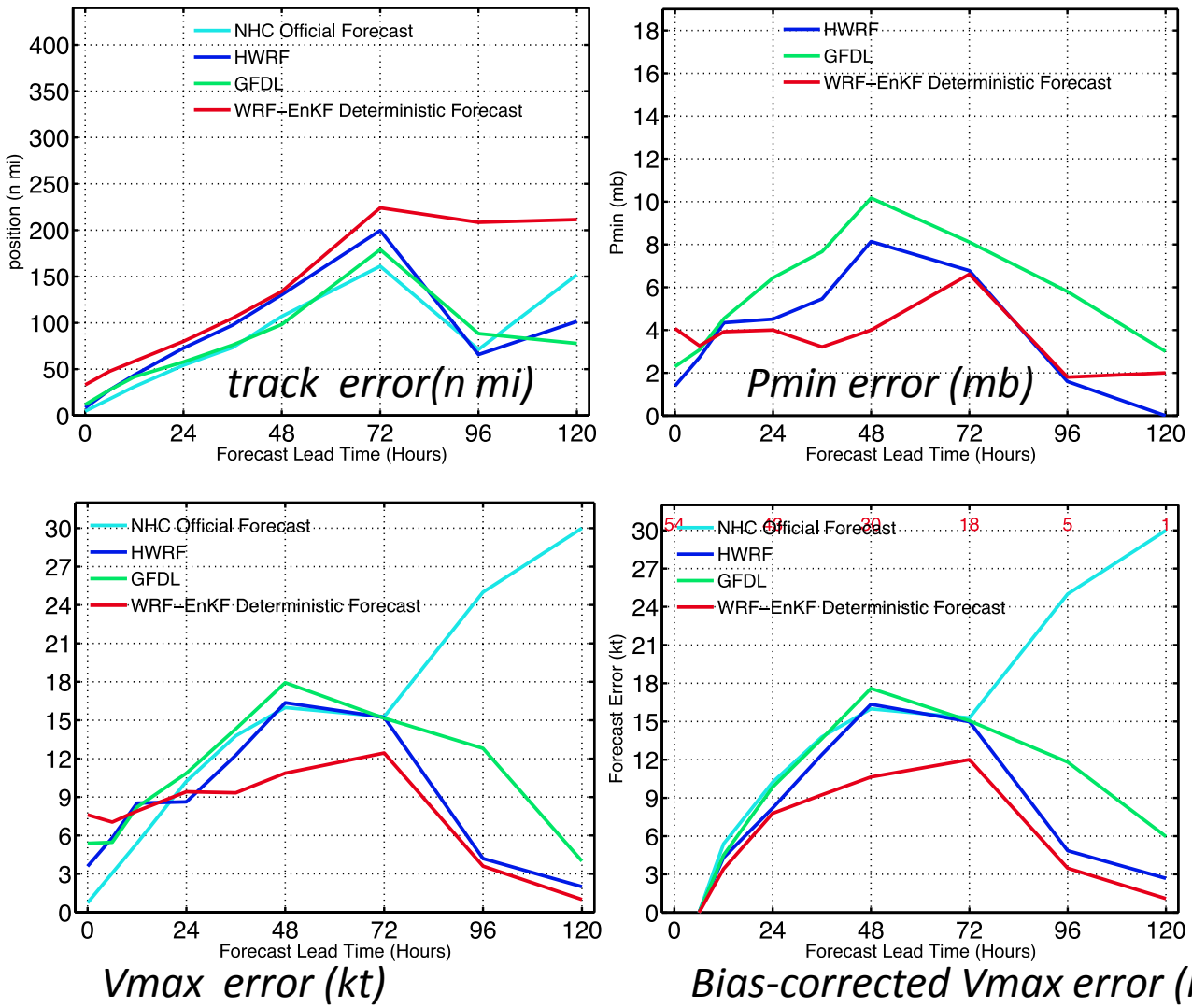








PSU WRF-EnKF 2013 Real-time Performance



Mean absolute forecast errors homogeneously averaged for 2013 stream 1.5 APSU (red), operational OFCL (cyan), HWRF (blue) and GFDL (green).

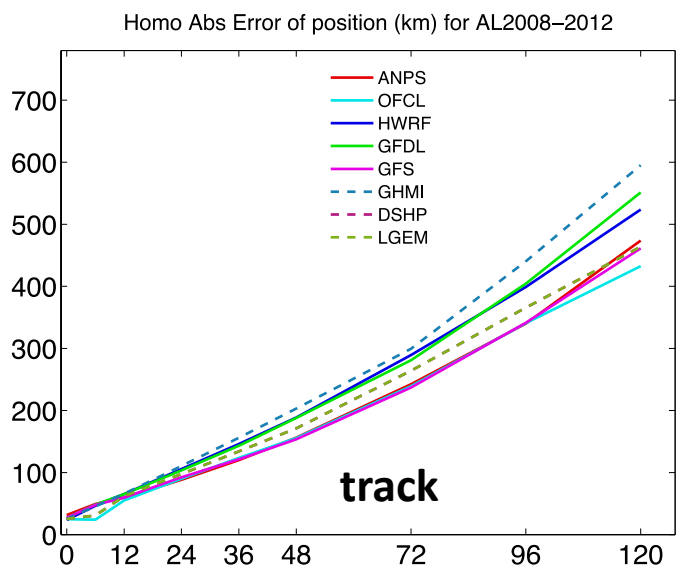
Concluding Remarks

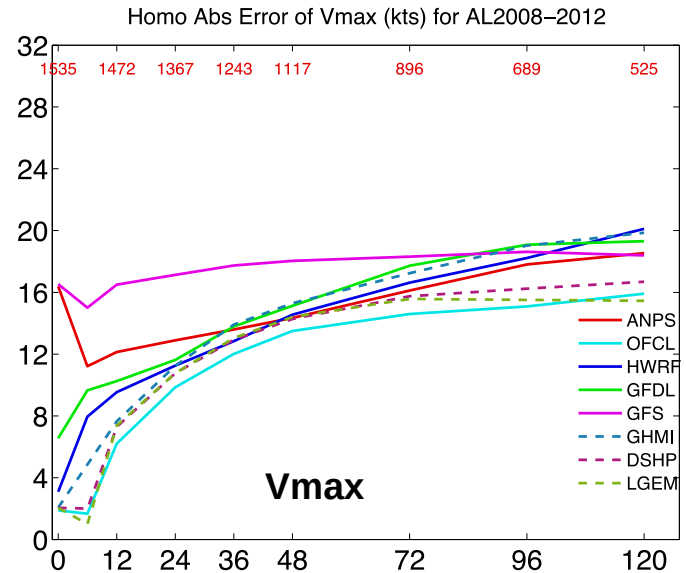
- Hurricane intensity prediction can be improved by advanced ensemble-based assimilation of airborne inner-core observations into convection-permitting models

- Beyond the reach of routine airborne surveillance, future improvement in TC forecasts will likely come from better assimilation of satellite based observations including cloudy radiance

- Further improvement may also come from more advanced data assimilation systems such as coupling of EnKF and 4DVar

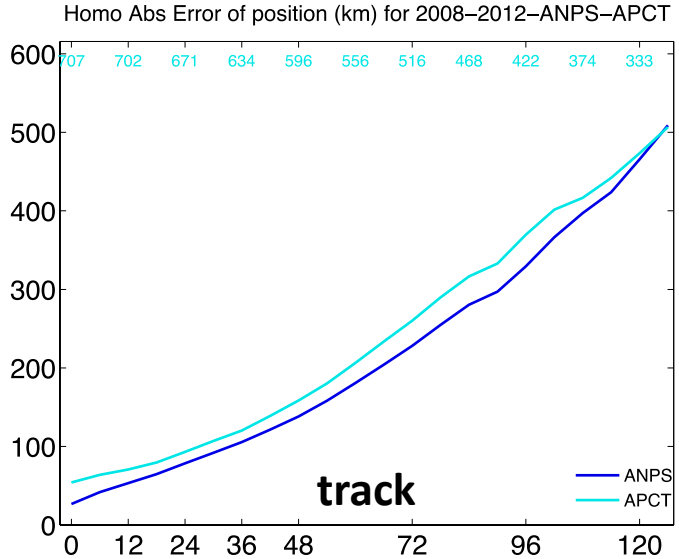
Baseline tests (ANPS): ARW forecasts started from operational GFS analyses

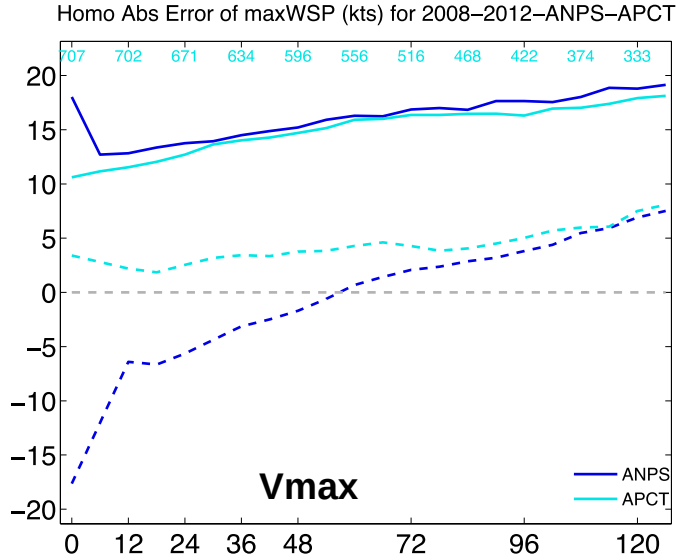


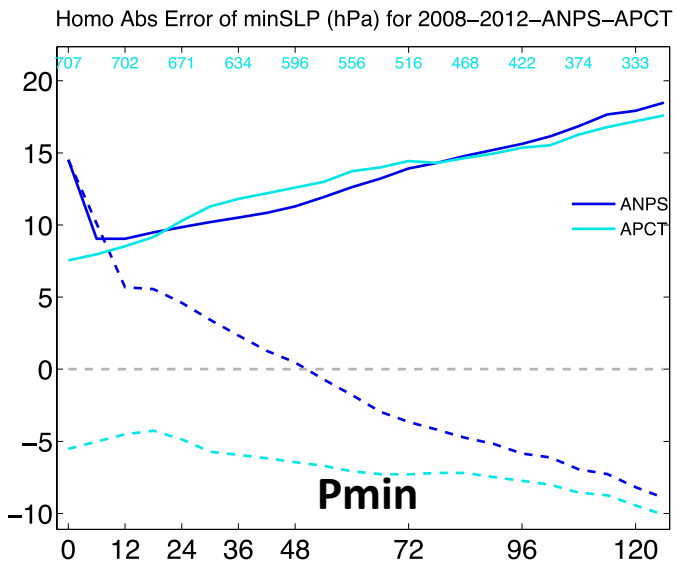


Mean absolute forecast errors averaged over all Atlantic storms during 2008-2012 against the NHC Best Track by homogeneously verified with the WRF deterministic forecasts initialized with operational GFS analysis. The numbers of homogeneously samples are list on the top of the intensity error panels.

PSU Cycling WRF-EnKF with Conventional Data (APCT) *in comparison to WRF from GFS analysis (ANPS)*

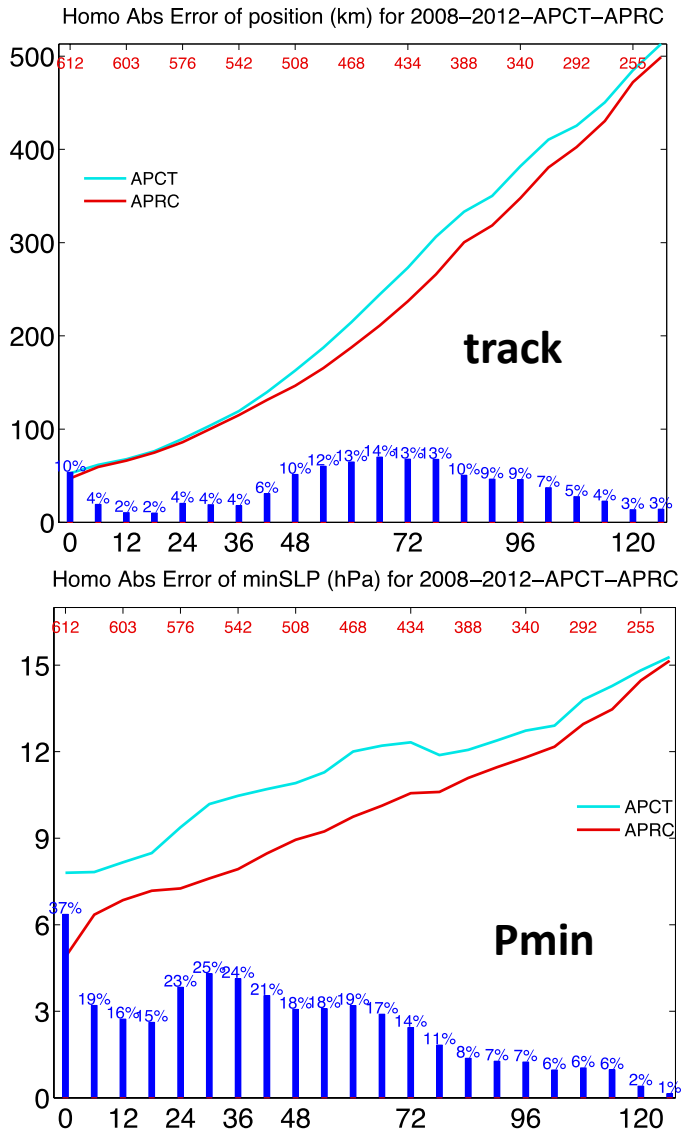


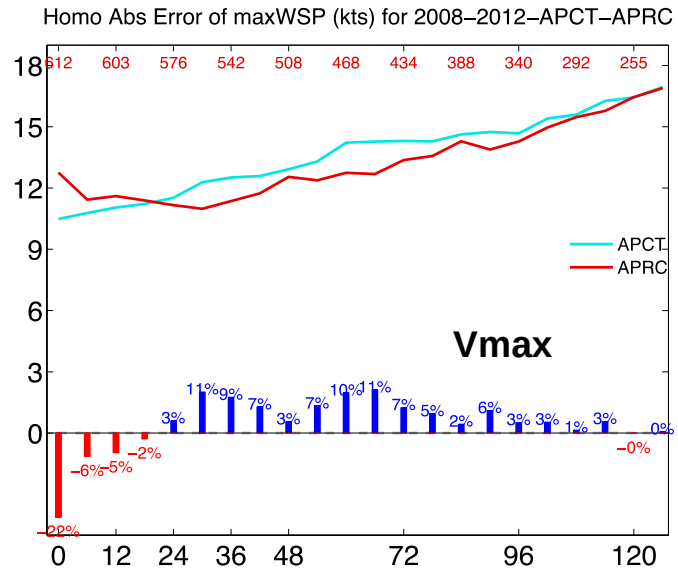




Mean absolute forecast error (solid lines) and bias (dash lines) averaged over all 758 APCT cases during 2008-2012 for the WRF deterministic forecasts initialized with operational GFS analysis ("ANPS", blue) and the WRF deterministic forecasts initialized with the cycling WRF-EnKF analysis with conventional observation assimilation ("APCT", cyan) .

PSU Cycling WRF-EnKF with Aircraft Recon and Conventional Data (APRC) versus "No Recon" (APCT)





Mean absolute forecast error homogeneously averaged over all 636 APRC cases during 2008-2012 for APCT (cyan) and APRC (red). The blue bar on the bottom of each panel means the improvement of APRC in percent over APCT, while the red bar means APRC is worse than the APCT. The numbers of homogeneously samples are list on the top of each panel.