PSU HFIP Annual Report
Real-time Convection-Permitting Ensemble Analysis and Prediction

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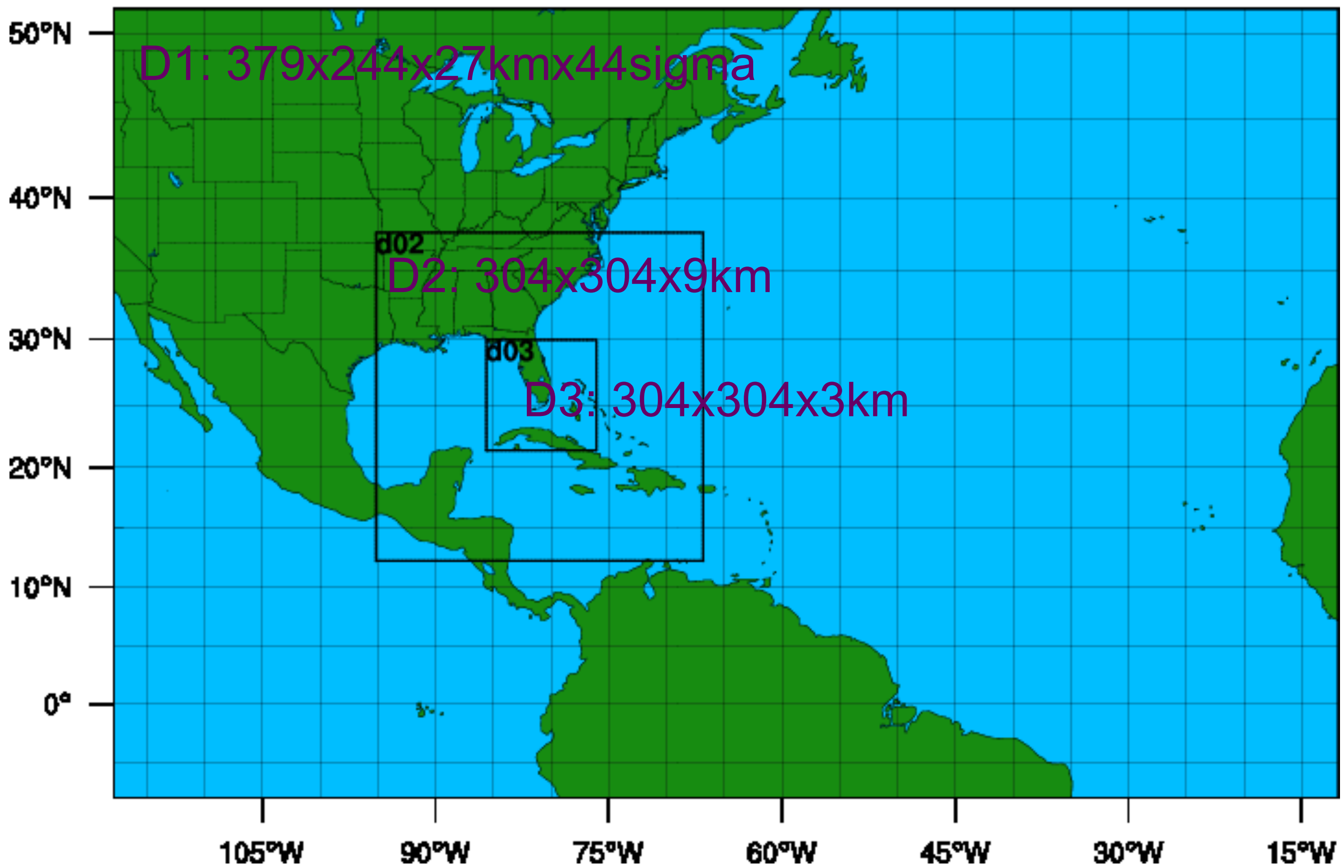
Penn State University

2012 PSU ARW-EnKF Configurations



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 and Zhang

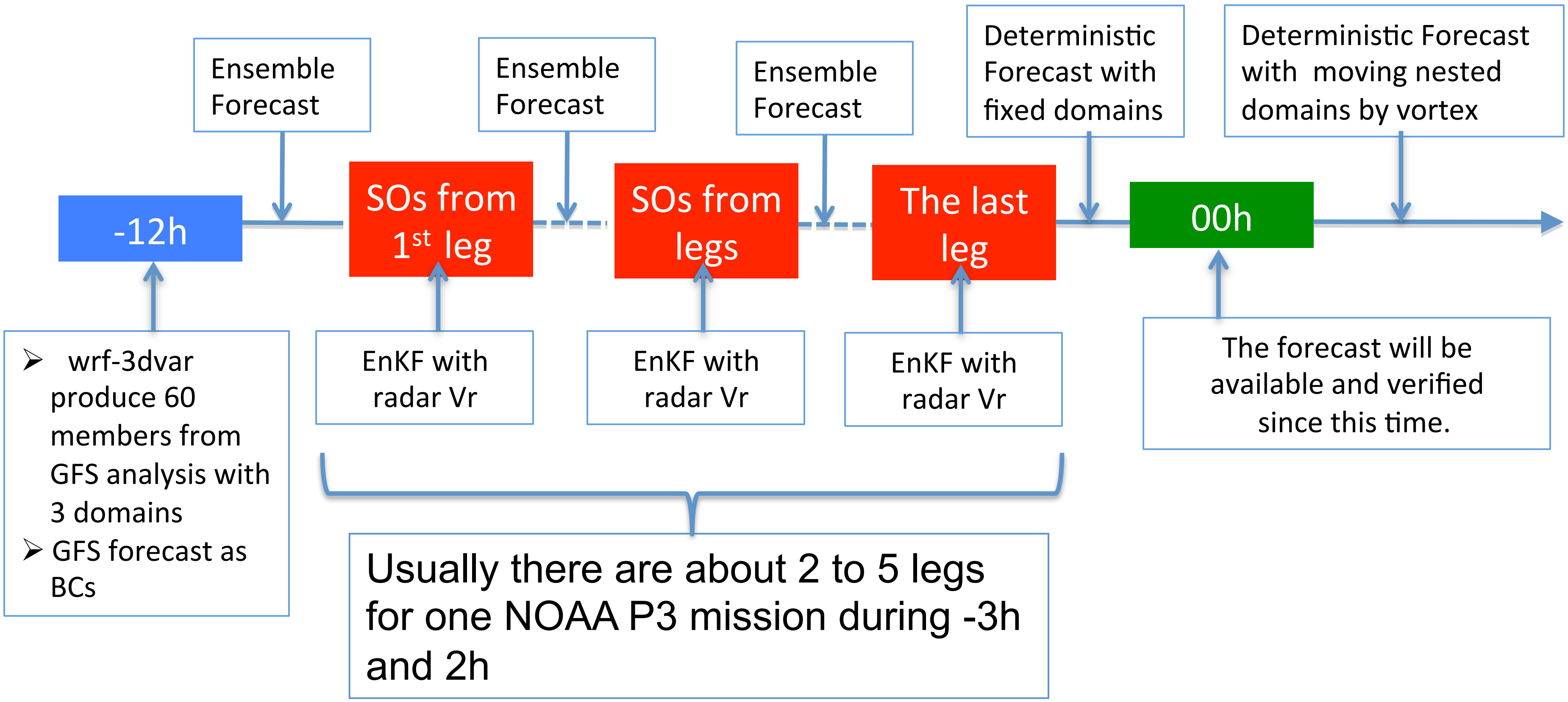
- 60-member ensemble
- Gaspairi & Cohn 99' covariance localization with varying RoI
- IC & BC: GFS using 3DVAR background uncertainty
- Hourly assimilation with TDR over all 3 domains

ATCF ID:

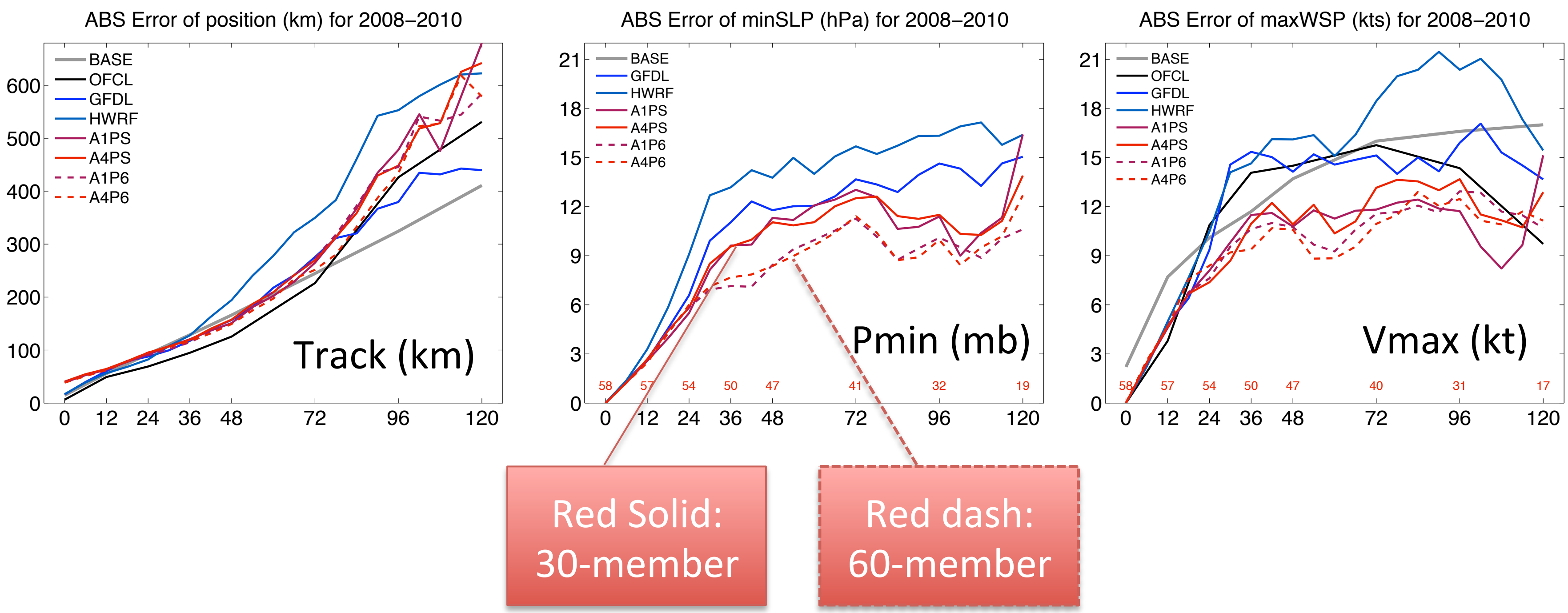
APSU: stream 1.5, ARW 3-km deterministic forecast initialized with TDR assimilation;

ANPS: stream 2.0, ARW 3-km deterministic forecast initialized with operational GFS Analysis.

APSU workflow



APSU system updates before 2012 demo: from 30 to 60 ensemble members

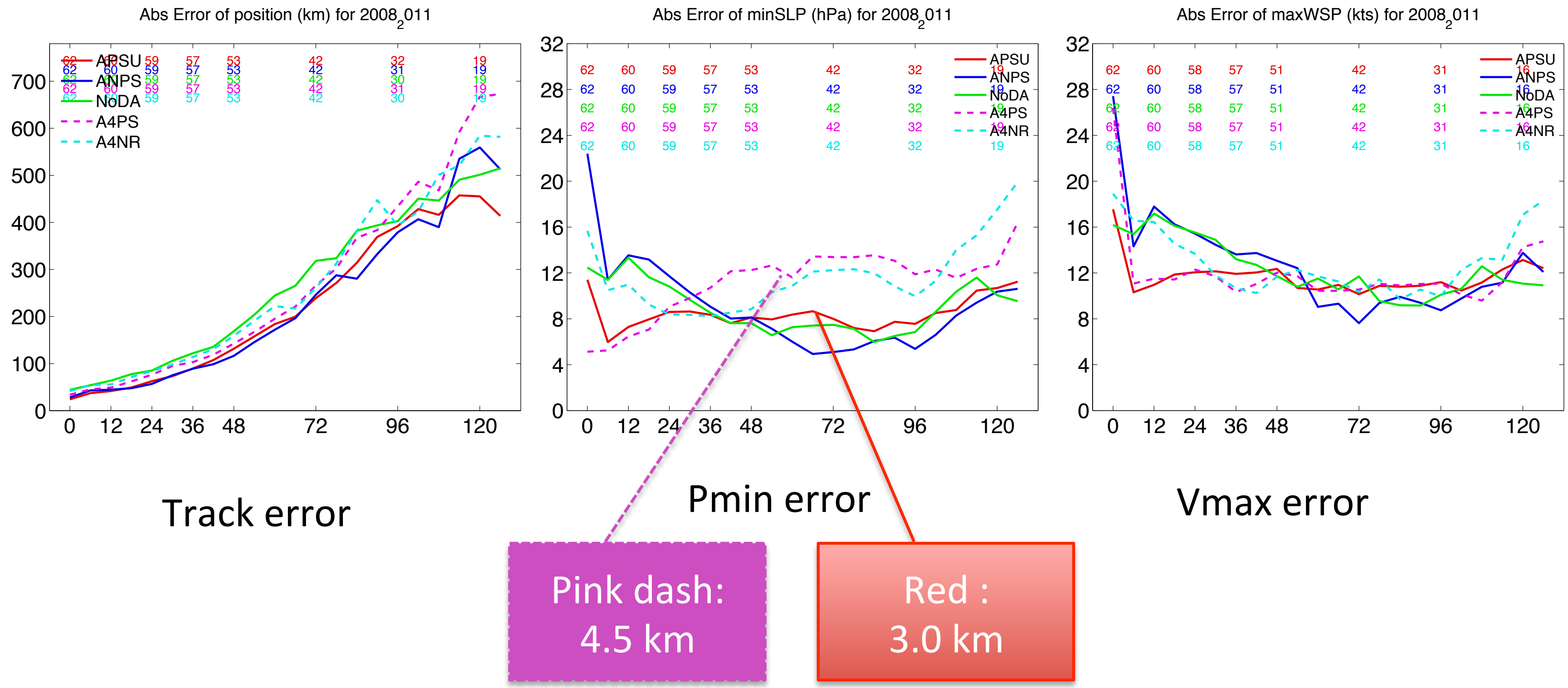


Mean absolute forecast errors homogeneously averaged for 2008-2010 TDR cases.

BASE: HFIP baseline;
A4PS: 4.5-km EnKF with 30 members;
A4P6: 4.5-km EnKF with 60 members

$$Bias\_corrected = (Best - Forecast)_{t=00h} \frac{(30 - t_{t<30h})}{30} + Forecast$$

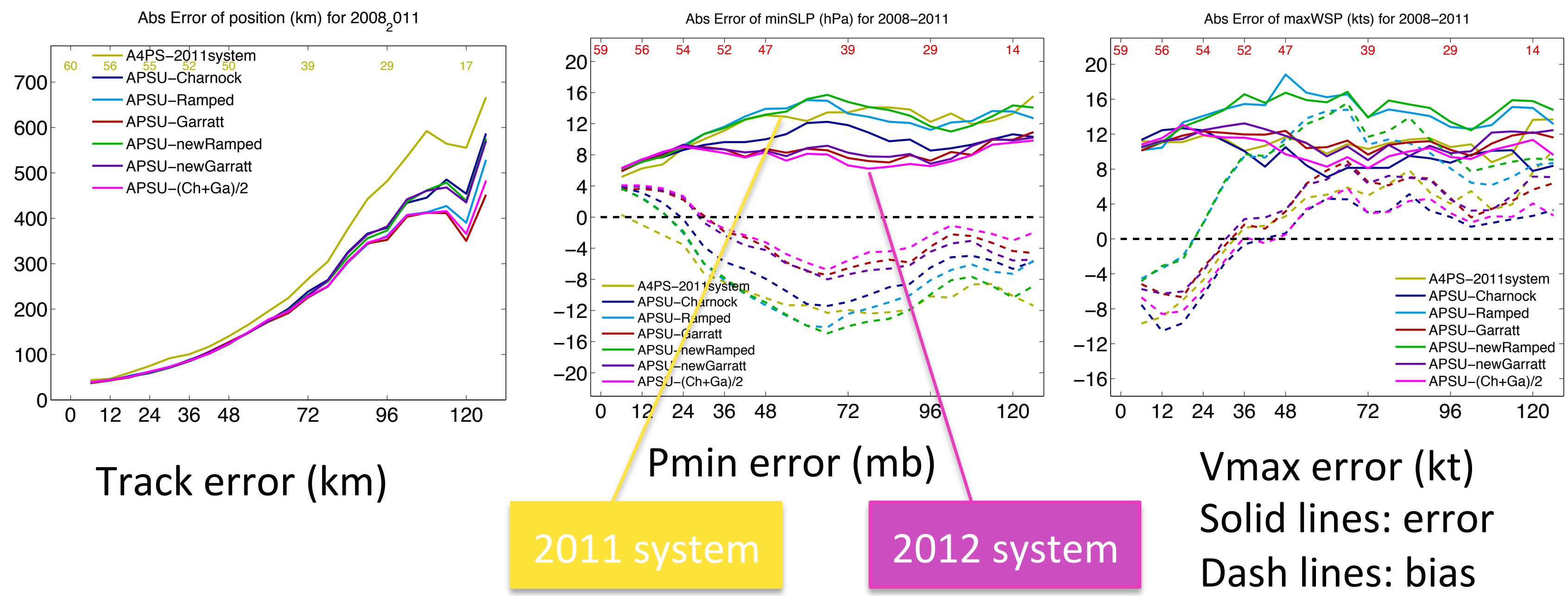
APSU system updates before 2012 demo: from 4.5 km/35 levels to 3.0 km/43 levels



Mean absolute forecast errors homogeneously averaged for 2008-2011 TDR cases

A4PS: 4.5-km EnKF
APSU: 3.0-km EnKF

APSU system updates before 2012 demo: use of an ad hoc air-sea surface flux scheme



Track error (km)

Pmin error (mb)

Vmax error (kt)
Solid lines: error
Dash lines: bias

Mean absolute forecast errors homogeneously averaged for 2008-2011 TDR case.

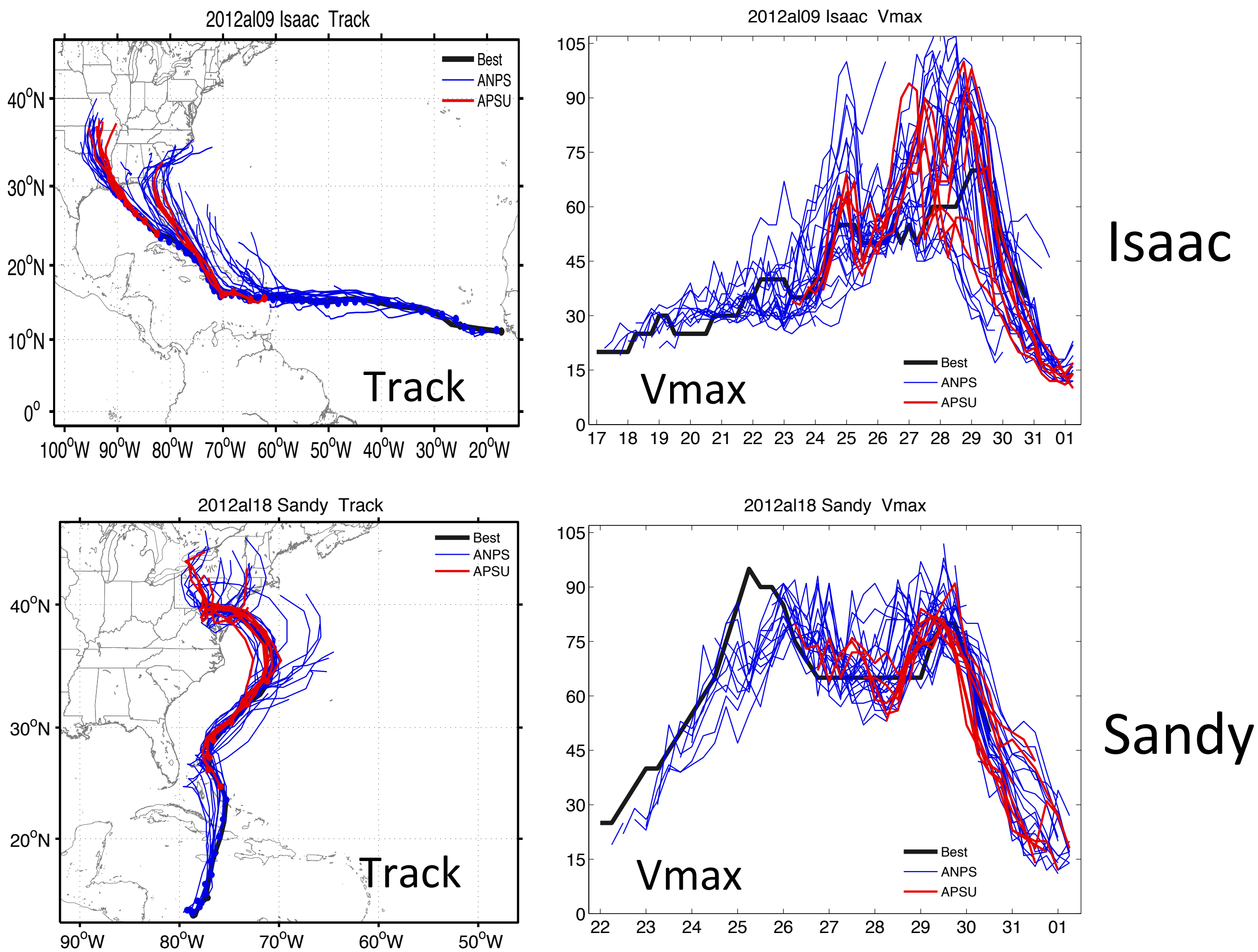
A4PS-2011 system (yellow) : PSU 2011 stream-1.5 system, which has 4.5 km horizontal resolution and Charnock TC surface flux scheme.

APSU: PSU 2012 stream-1.5 system: Cd is half way between the Charnock and the updated Garratt schemes

APSU 2012 stream 1.5: deterministic forecast

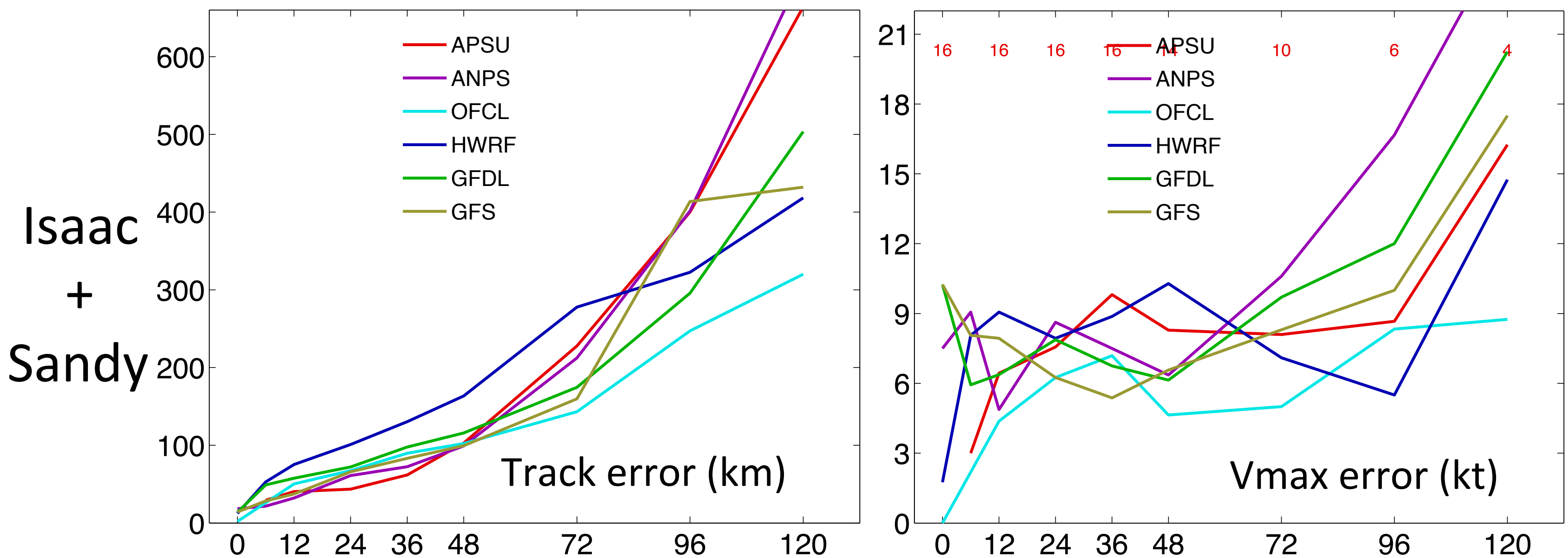
2012 NOAA TDR cases: Alberto (1), Isaac (9), Leslie (3) and Sandy (7).

Due to NOAA Jet computing resource issue, we only operated 16 missions for hurricane Isaac and Sandy in real-time.



PSU ARW-EnKF 2012 demo system real-time forecasts for hurricane Isaac (up) and Sandy (down). ANPS is the ARW forecast without data assimilation, while APSU is the PSU ARW-EnKF forecast initialized with the EnKF analysis by assimilating NOAA airborne radar observations.

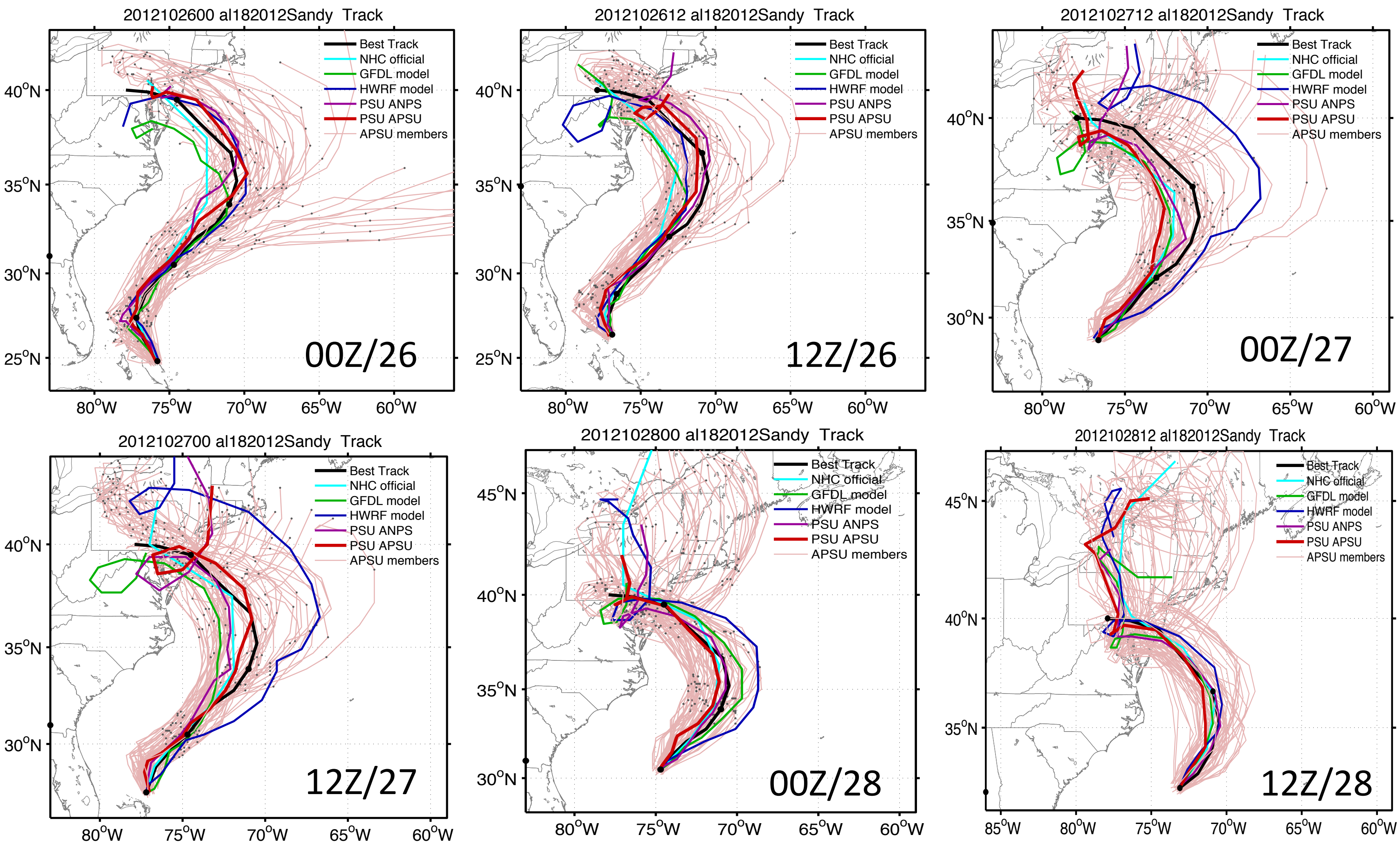
APSU 2012 stream 1.5: deterministic forecast error



Track and Intensity forecast error for PSU 2012 stream 1.5 runs.

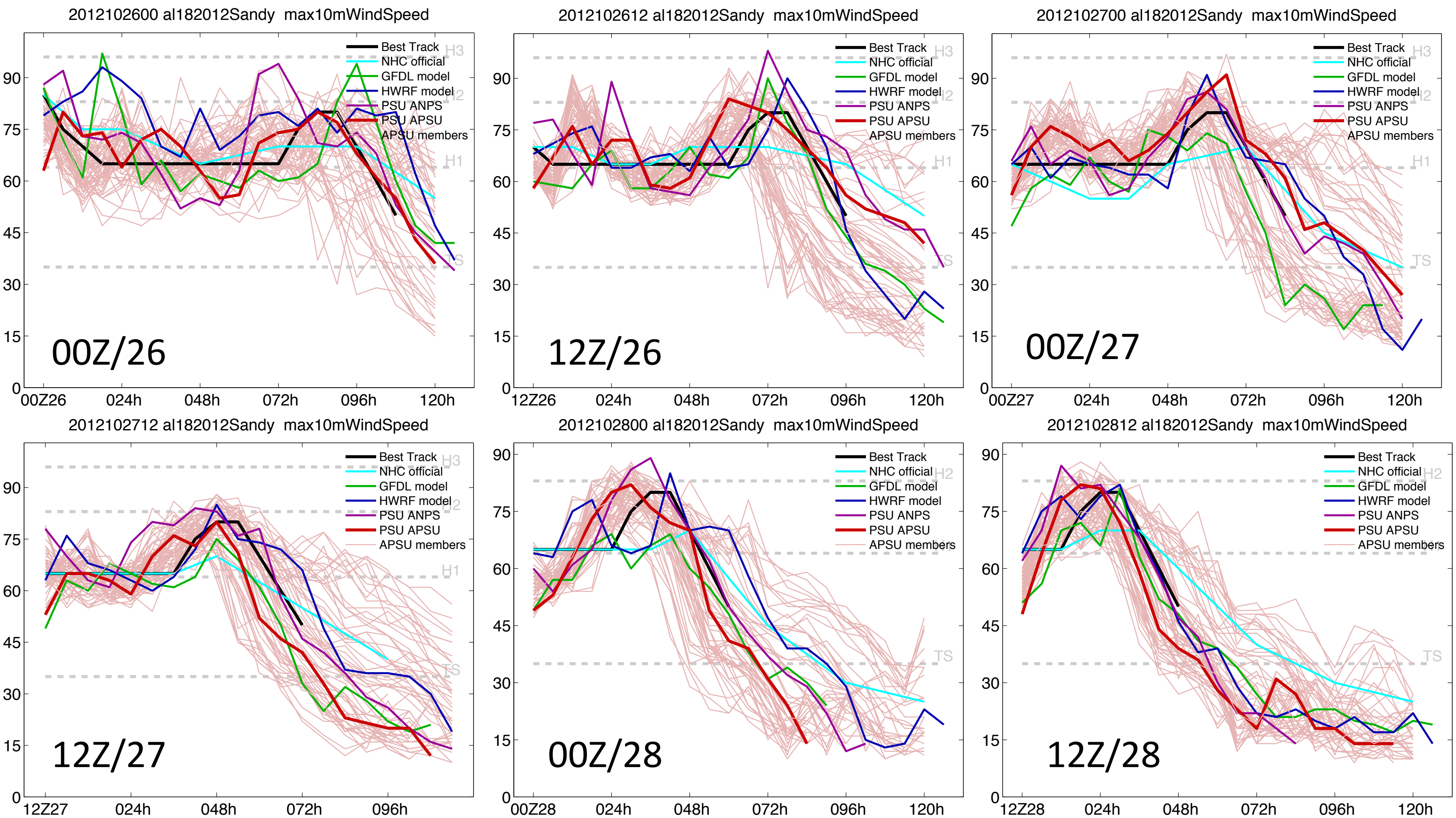
APSU: PSU stream 1.5 with TDR
ANPS: PSU stream 2.0 with GFS analysis
OFCL, HWRF, GFDL and GFS are operational forecasts.

APSU 2012 stream 1.5: ensemble track forecast



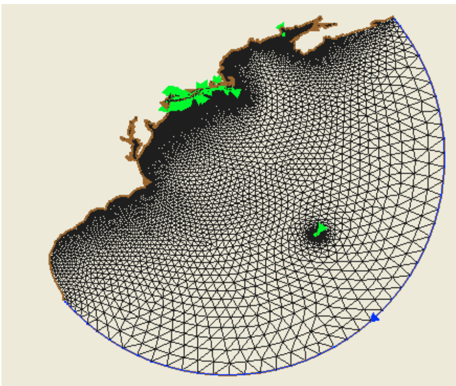
APSU Real-time ensemble track forecasts for hurricane Sandy with TDR assimilation.

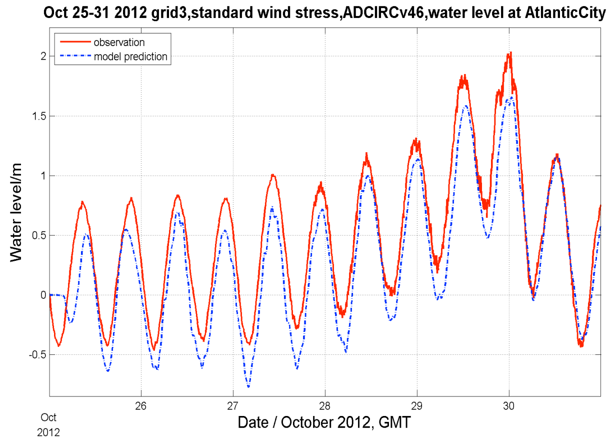
APSU 2012 stream 1.5: ensemble intensity forecast

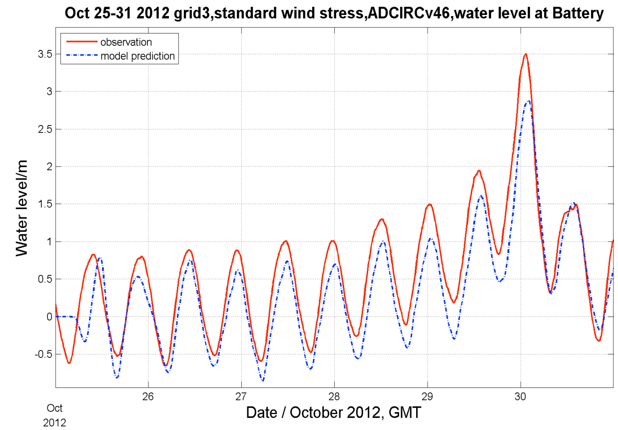


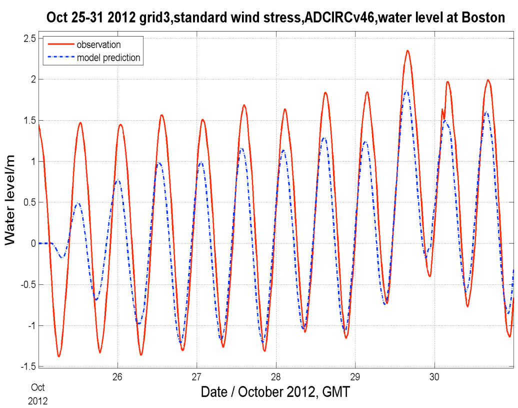
APSU Real-time ensemble intensity forecasts for hurricane Sandy with TDR assimilation.

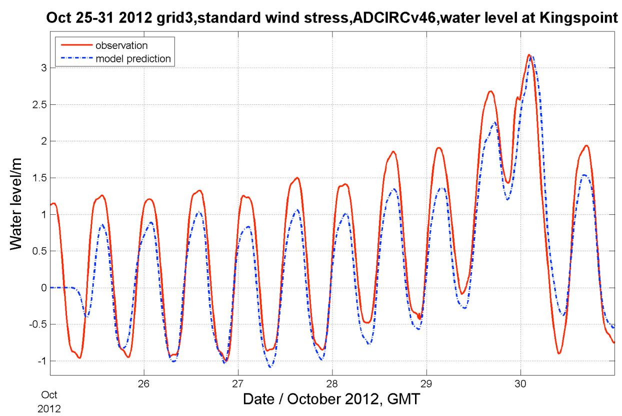
ADCIRC Storm Surge Forecasts for Sandy Driven by the APSU 2012 Stream 1.5 WRF Runs (Brian Colle, SUNYSB)

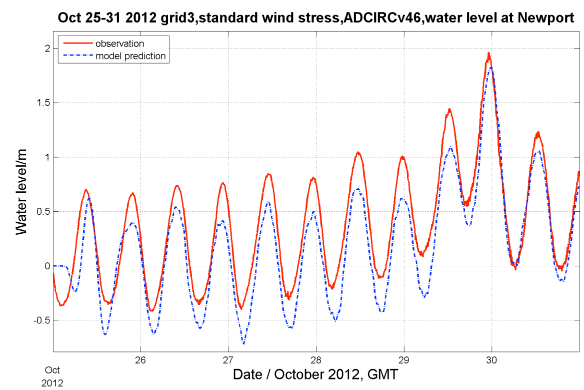










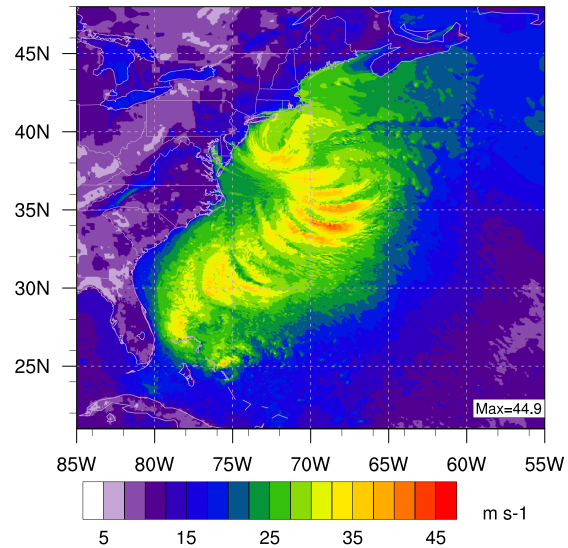


1. **Day 1:** 0000 Oct 24 to 0000 Oct 25. To get tides going, ran ADCIRC from rest with no winds from flat sea surface with tidal ramp only.
2. **Day 2.** 0000 Oct 25 to 0000 Oct 26. Ran ADCIRC with tides and linearly ramped PSU-WRF wind stress from zero to full strength (i.e., as of 0000 Oct 26, keeping wind direction constant).
3. **Days 3 - 8:** Ran ADCIRC with PSU-WRF winds from 0000 Oct 26 to 0000 Oct 31 (using 26/00z and 28/00z runs).

APSU 2012 stream 1.5: wind swatch and probabilities sample

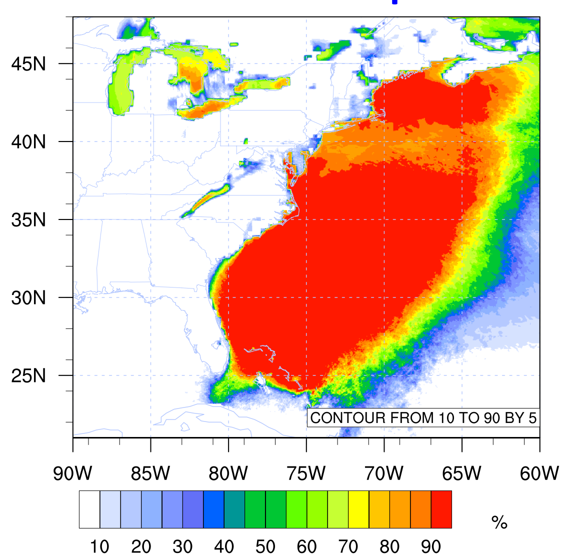
APSU deterministic forecast surface wind swatch and ensemble surface wind forecast probability for hurricane Sandy initialized at 00Z/26 Oct 2012.

APSU surface wind swatch

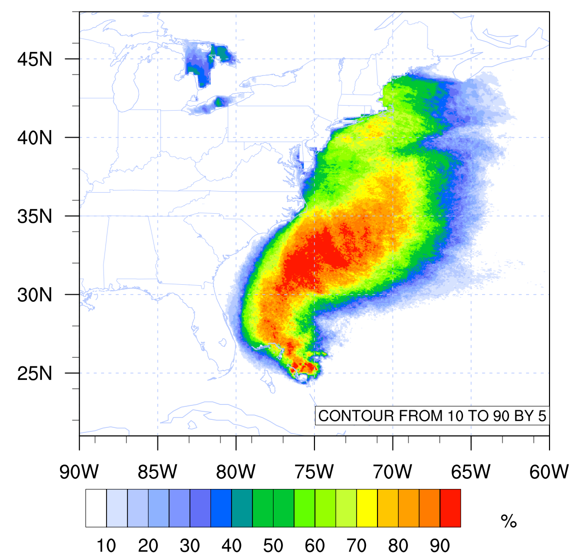


Probability = forecasted members /total members

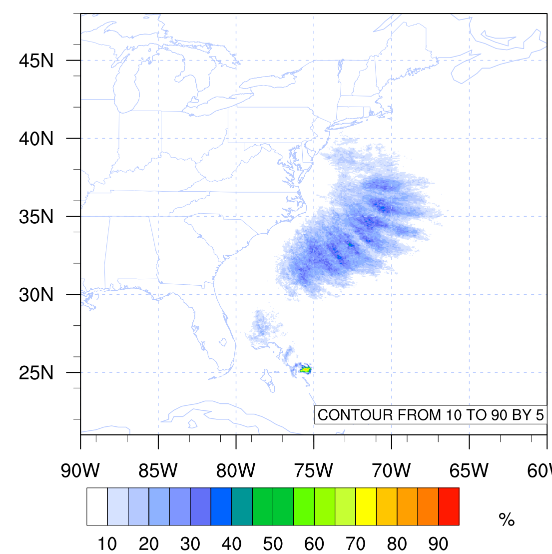
34 kt surface wind probability



50 kt surface wind probability

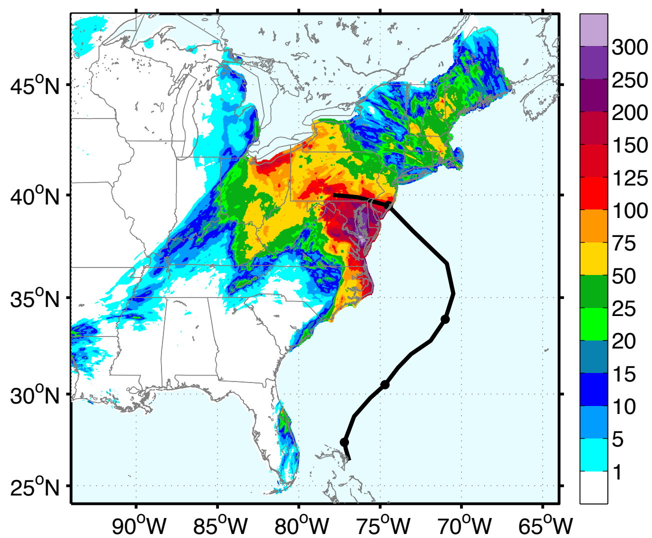


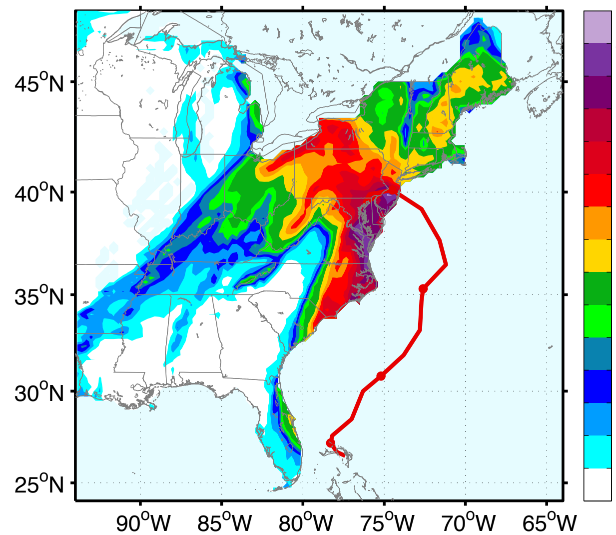
64 kt surface wind probability



APSU 2012 stream 1.5: precipitation forecast sample

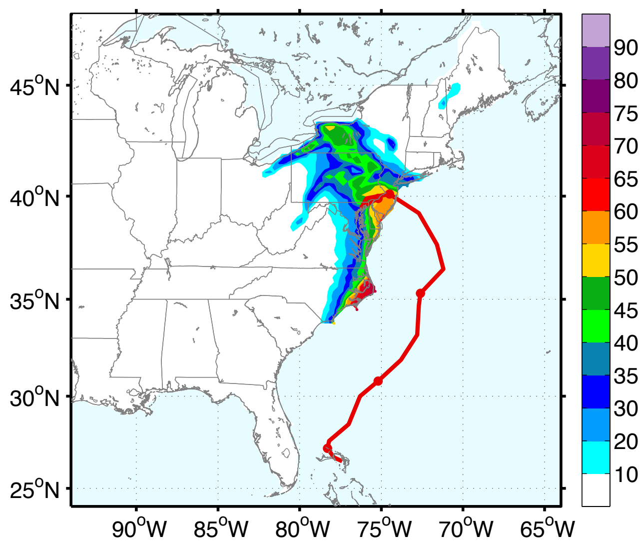
NWS 4km 96-h rainfall





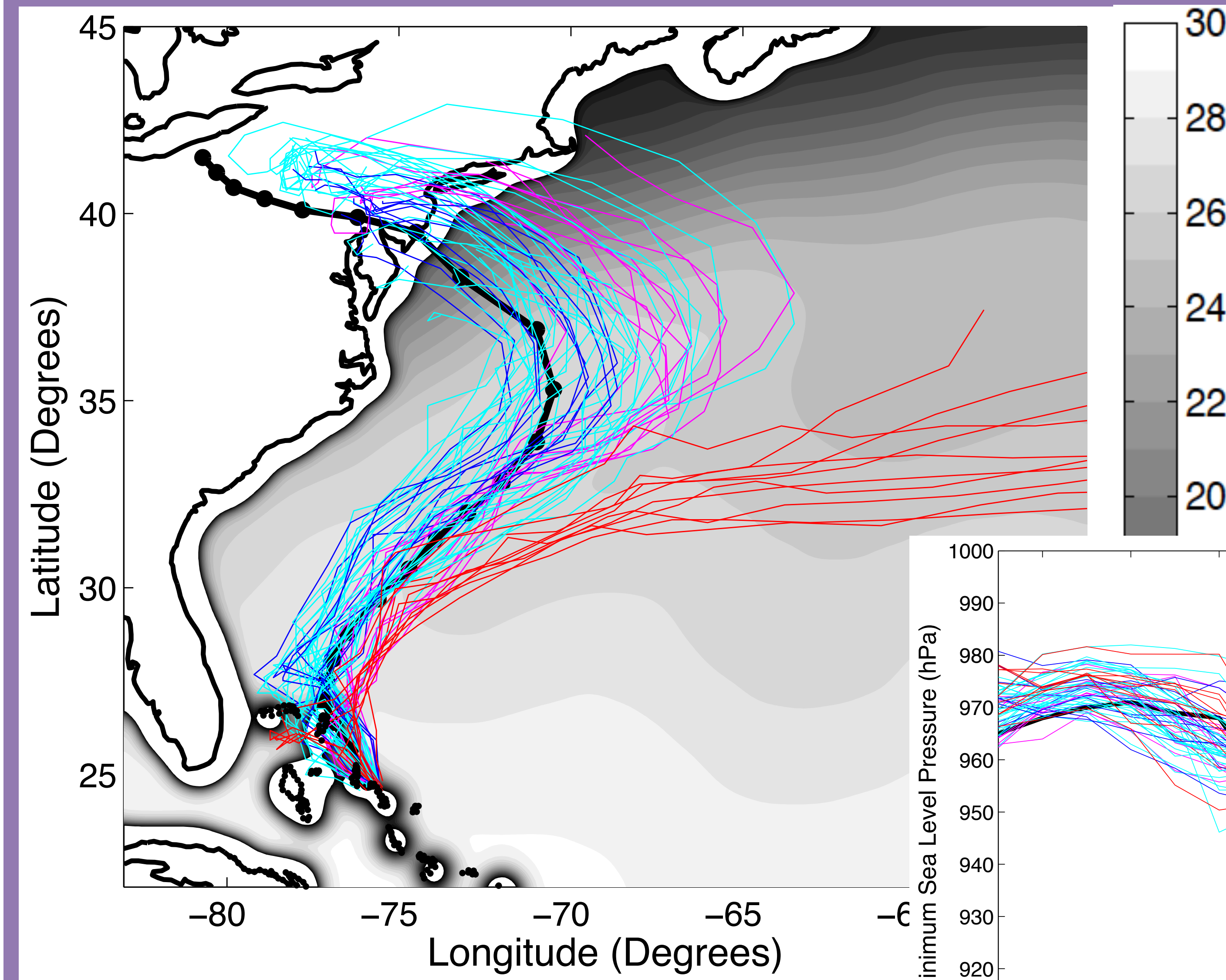
APSU 96-h deterministic rainfall forecast

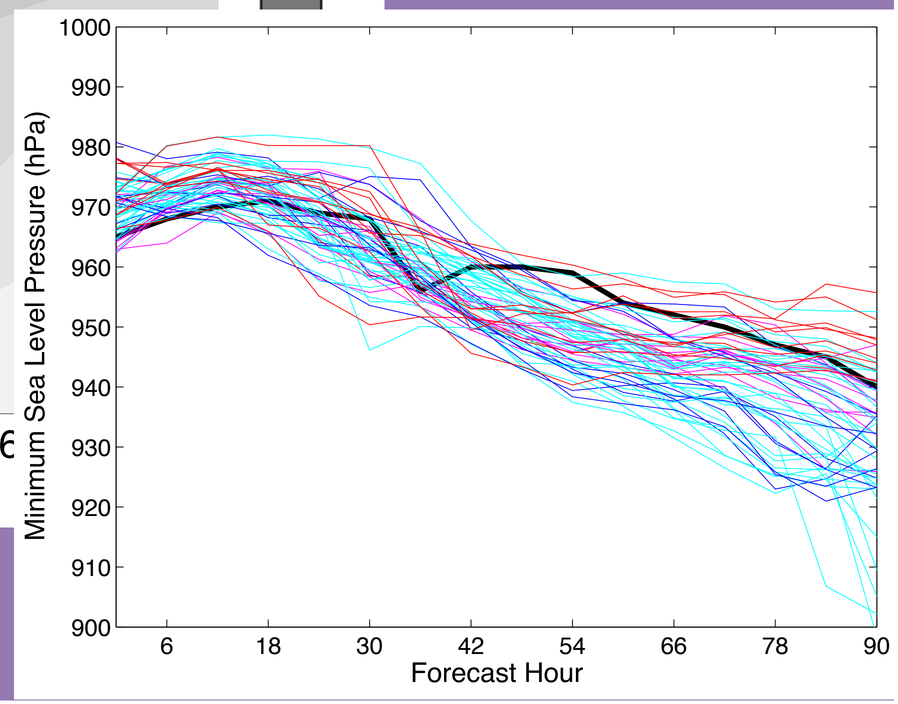
100 mm 96-h rainfall forecast probability derived from APSU ensemble forecast



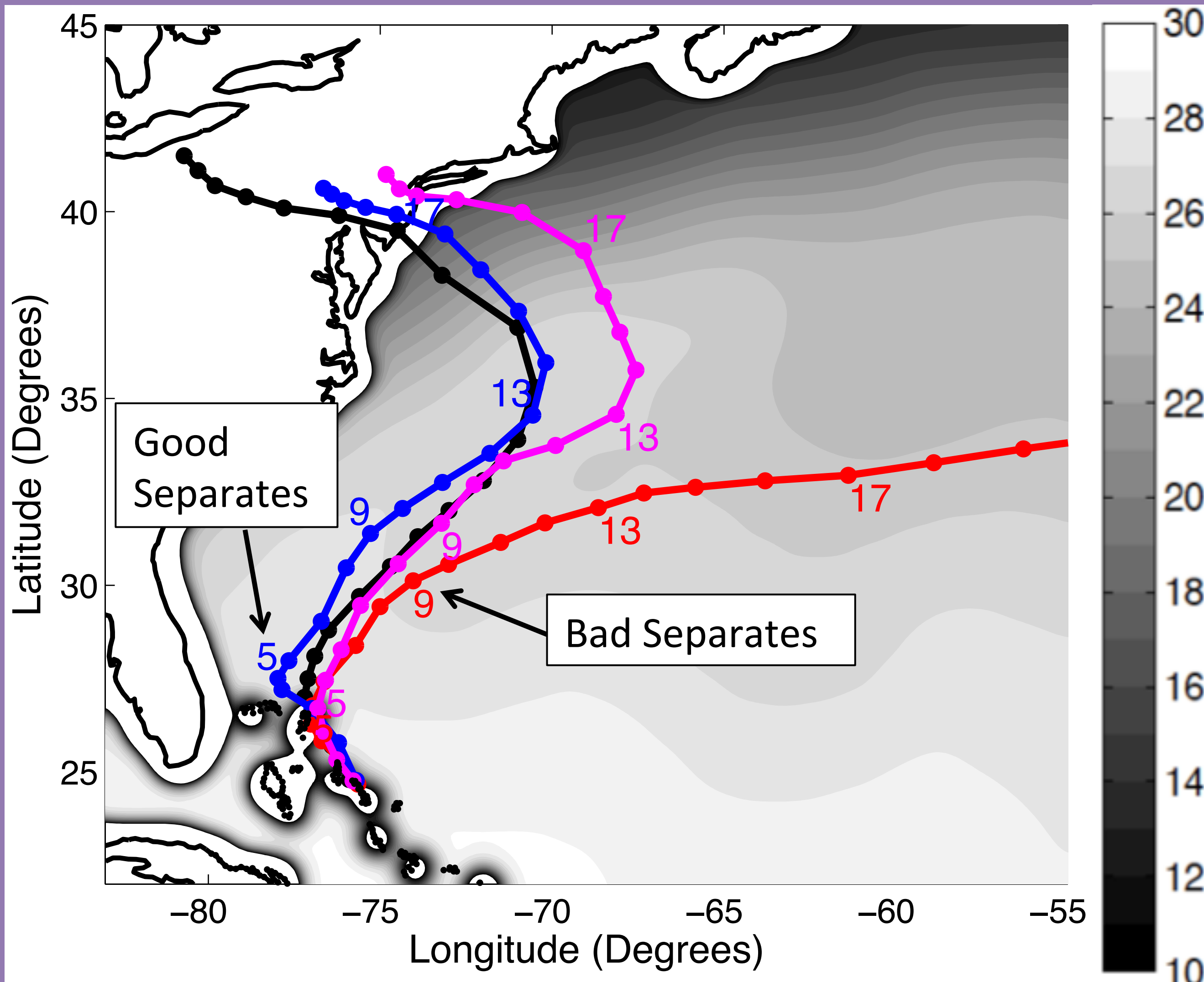
Spatial distribution of the 96-h (12Z26 to 12Z 30) accumulated rainfall (up) and the ensemble-derived probability of accumulated precipitation exceeding 100 mm (left) for hurricane Sandy initialized at 00Z/26 Oct 2012.

Tracks and Intensities of Sandy's 60 Ensemble Members





Composite Analysis: Mean Tracks (by Erin Munsell)



Time 5: 10/27/12 at 00Z

Time 9: 10/28/12 at 00Z

Black: Best Track

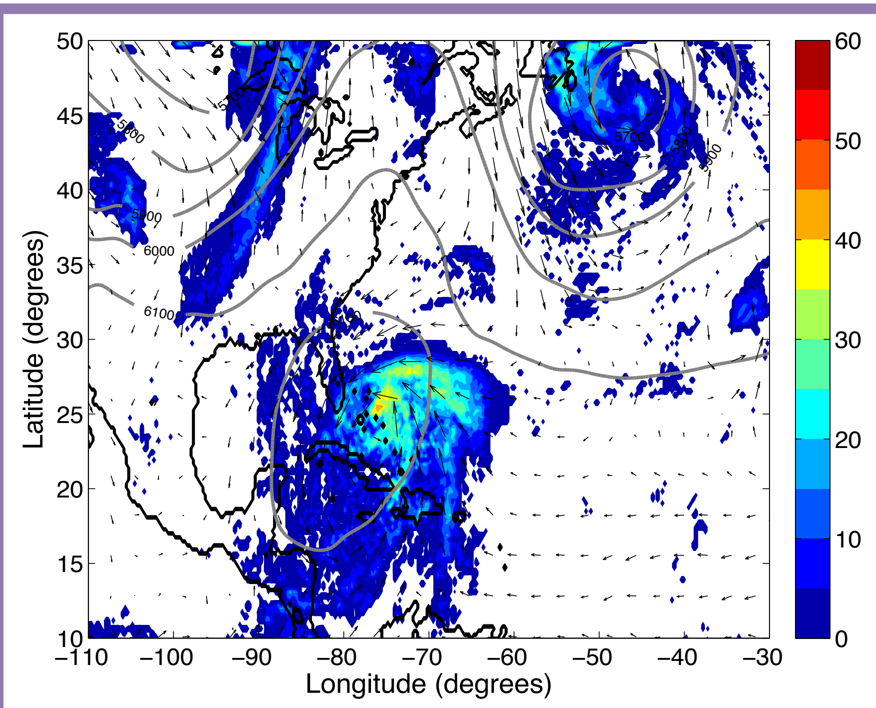
Blue: 10 Best Members (Good)

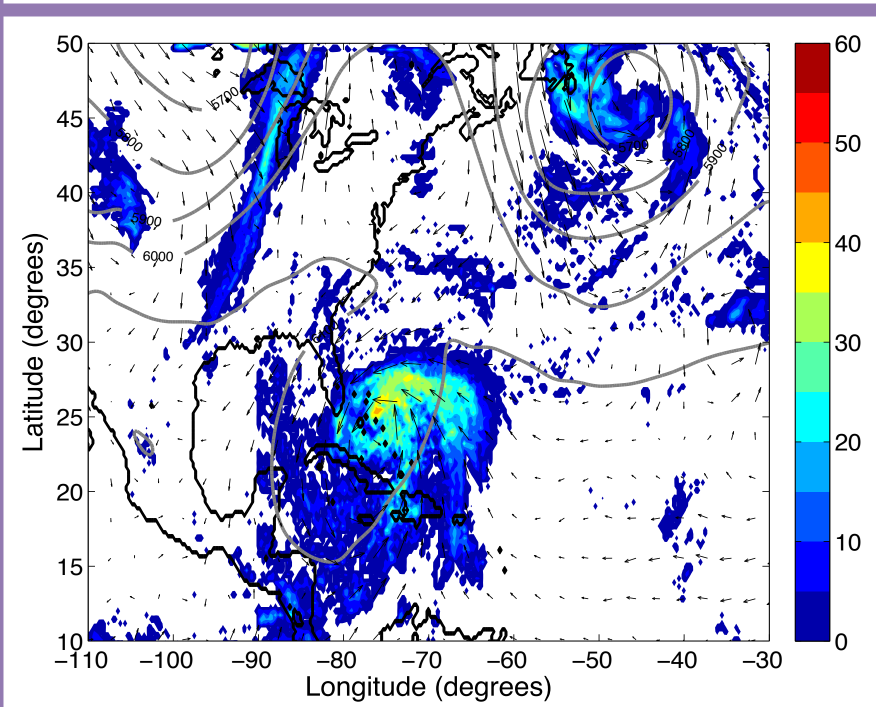
Red: 10 Worst Members (Bad)

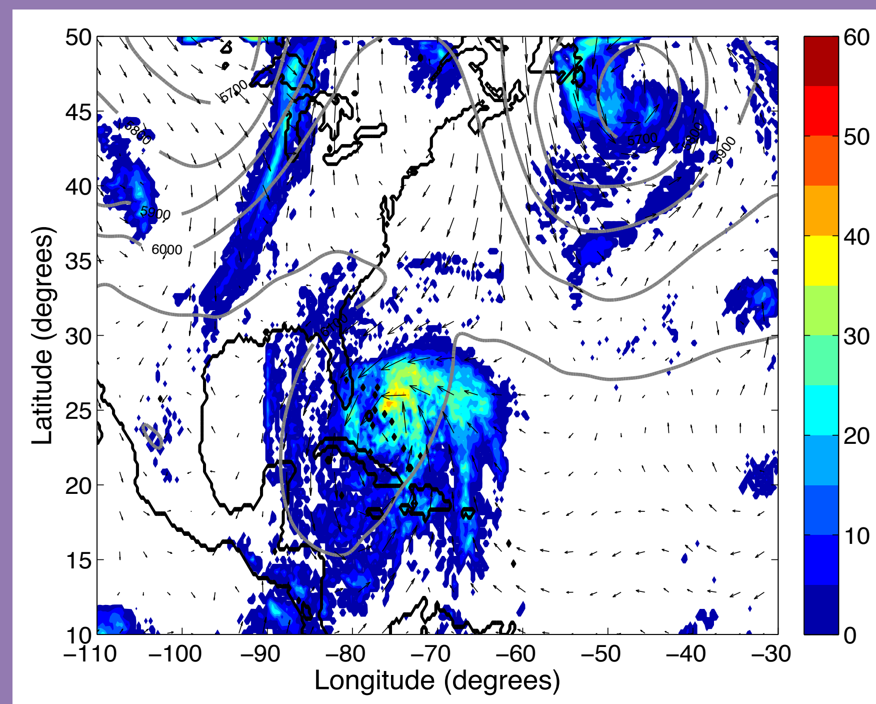
Magenta: 10 Members that were furthest off the coast but still made landfall (Fair)

10/26/12 – 00Z, SLP and dBZ

Top Left: 10 good members
Bottom Left: 10 fair members whose tracks were furthest off shore before curving back towards land
Bottom Right: 10 bad members

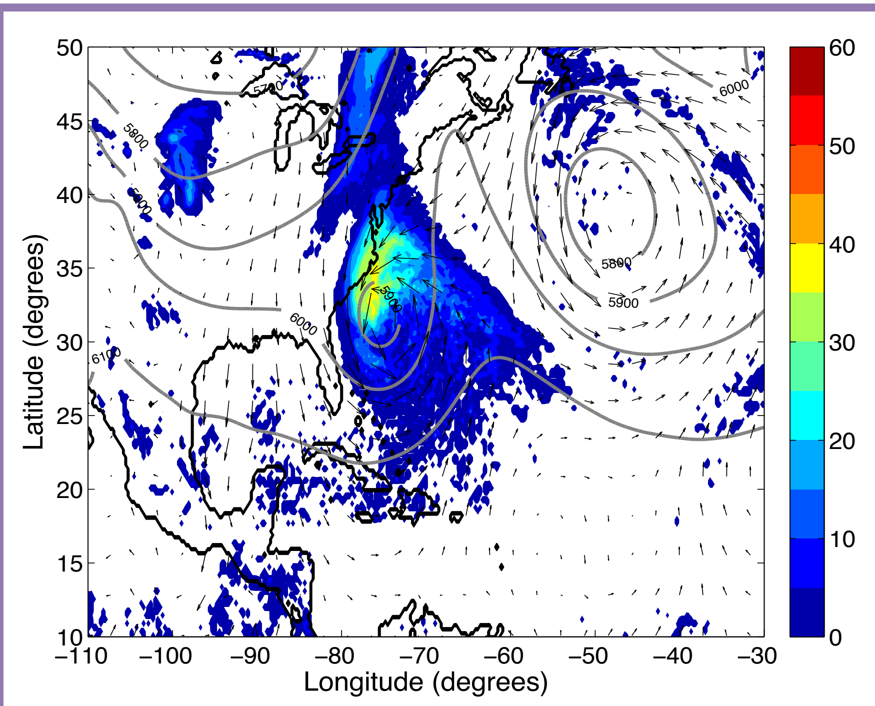


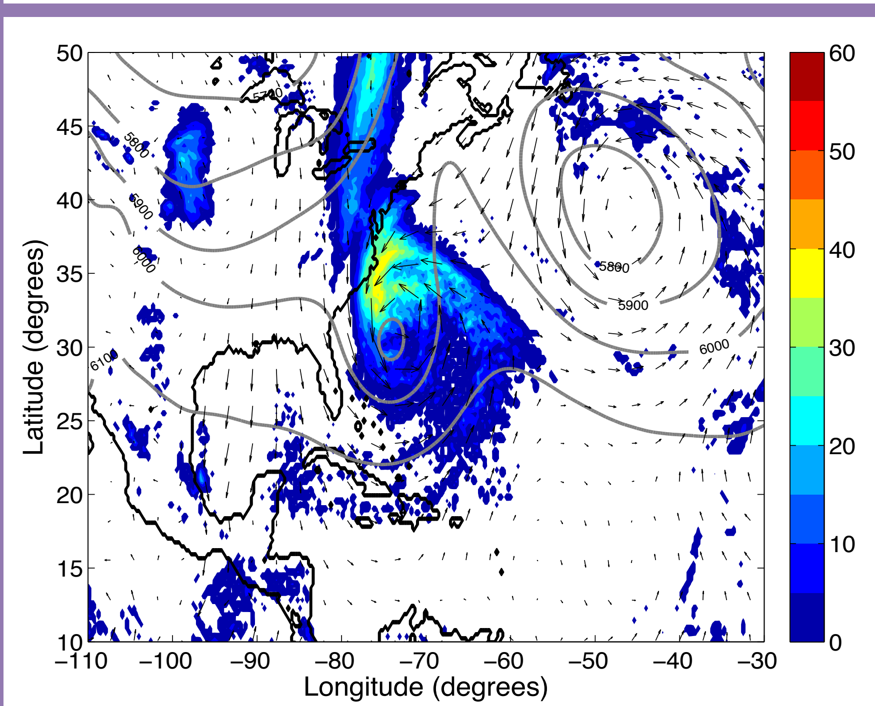


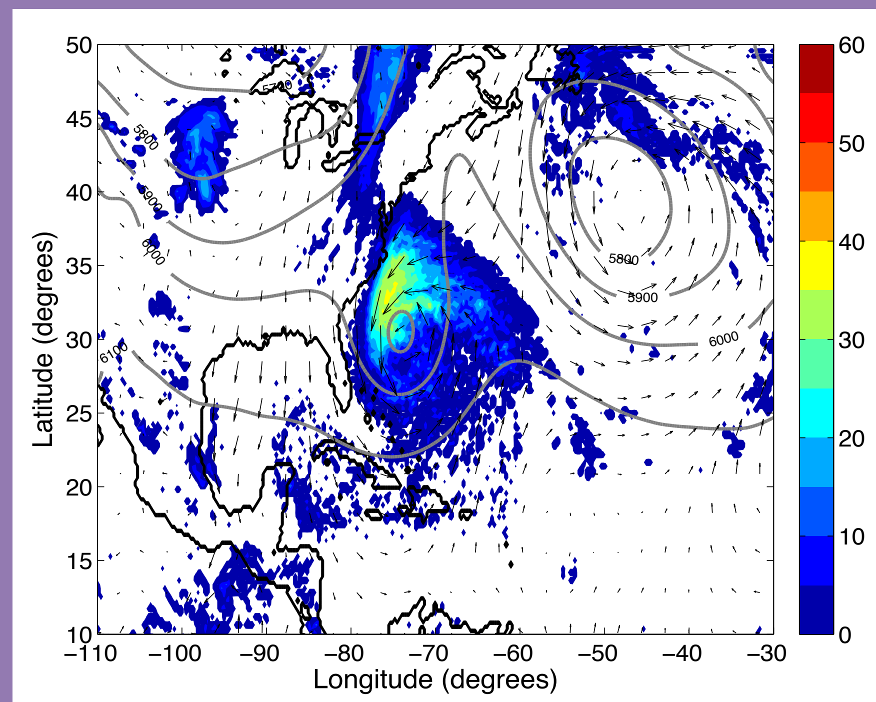


10/28/12 – 00Z, SLP and dBZ

Top Left: 10 good members
Bottom Left: 10 fair members whose tracks were furthest off shore before curving back towards land
Bottom Right: 10 bad members

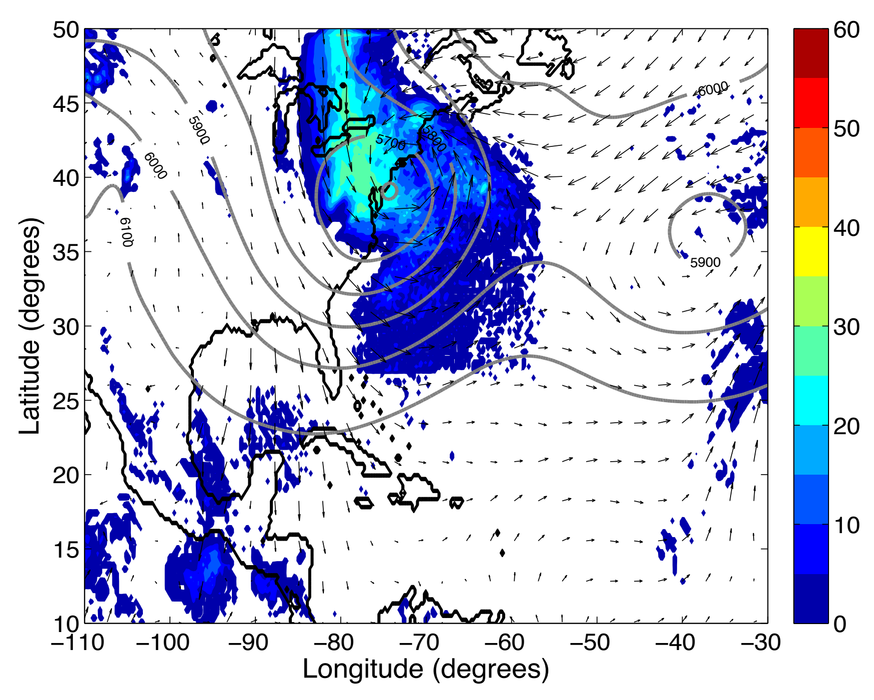


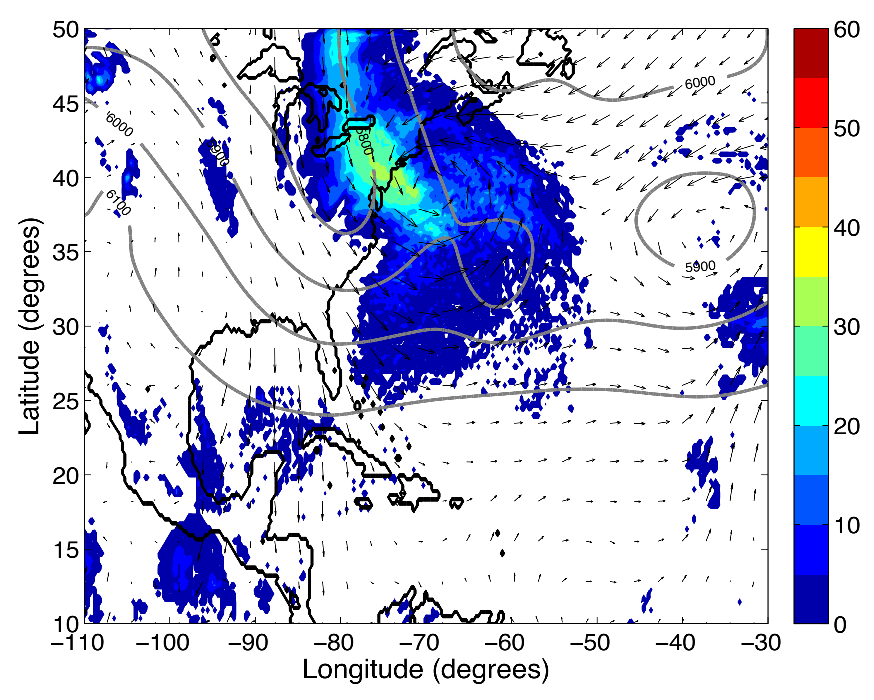


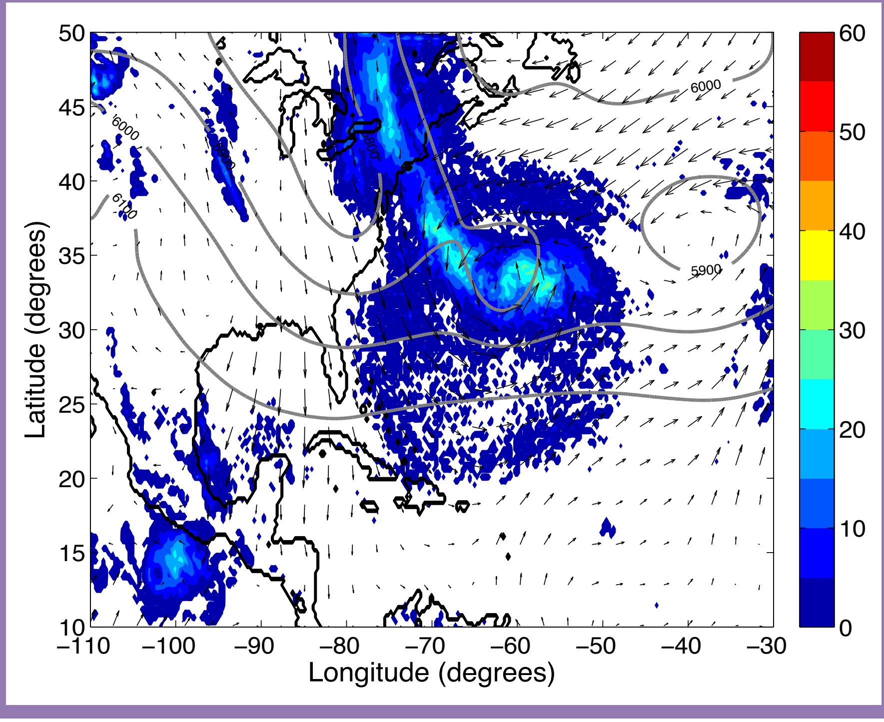


10/30/12 – 00Z, SLP and dBZ

Top Left: 10 good members
Bottom Left: 10 fair members whose tracks were furthest off shore before curving back towards land
Bottom Right: 10 bad members



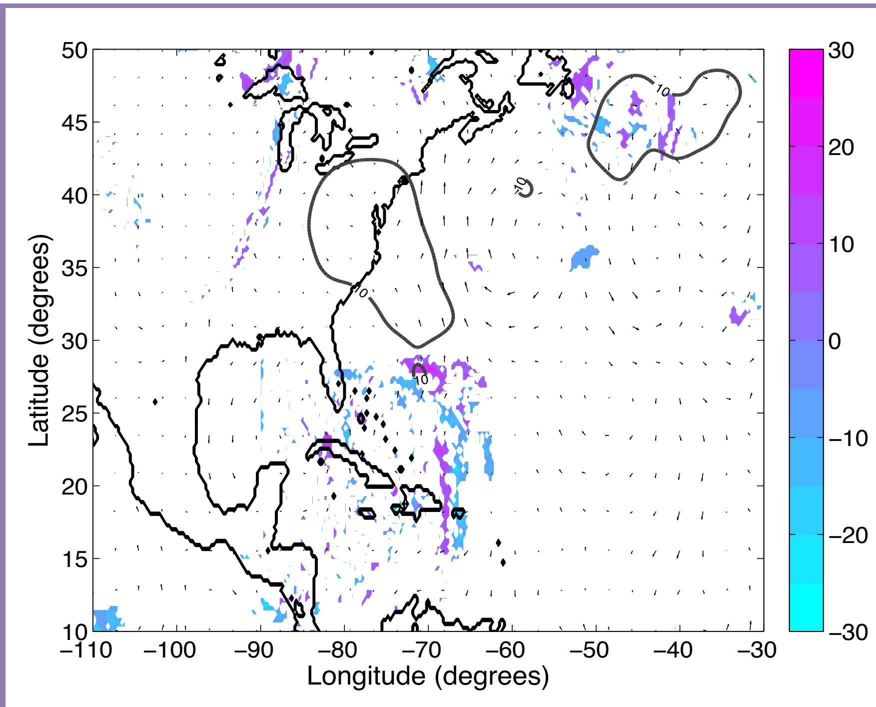


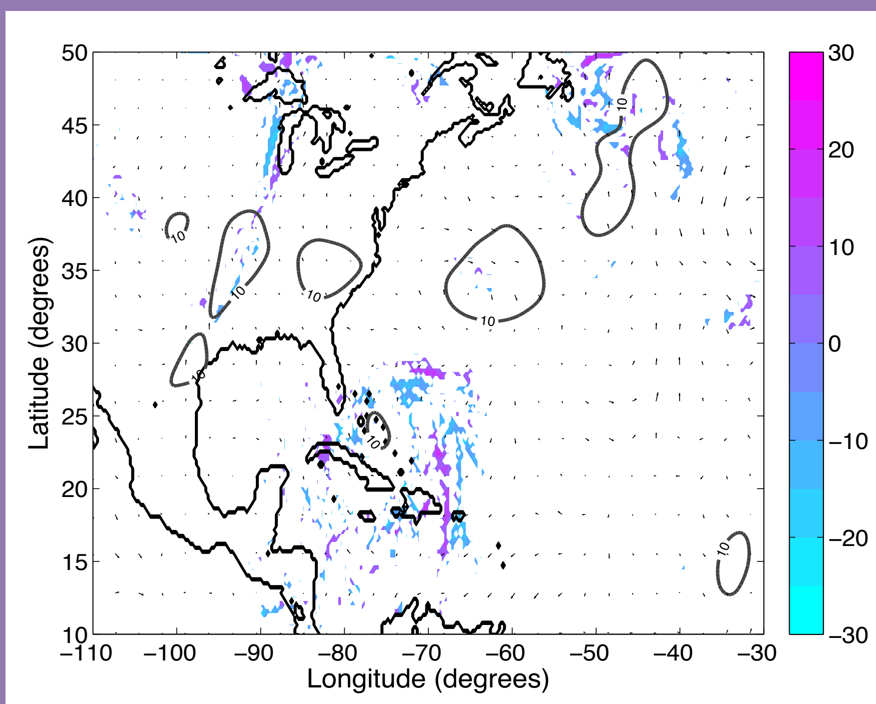


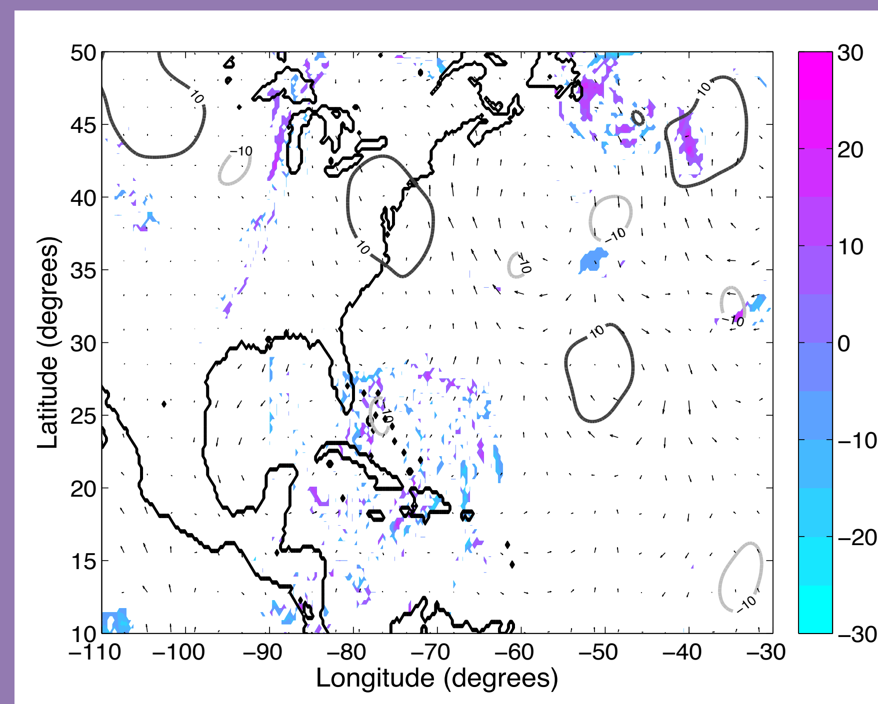
Time 1: 10/26/12 – 00Z

dBZ, 500 mb Geopotential Height and Surface Winds differences

Top Left: Good – Bad
Bottom Left: Good – Fair
Bottom Right: Fair – Bad



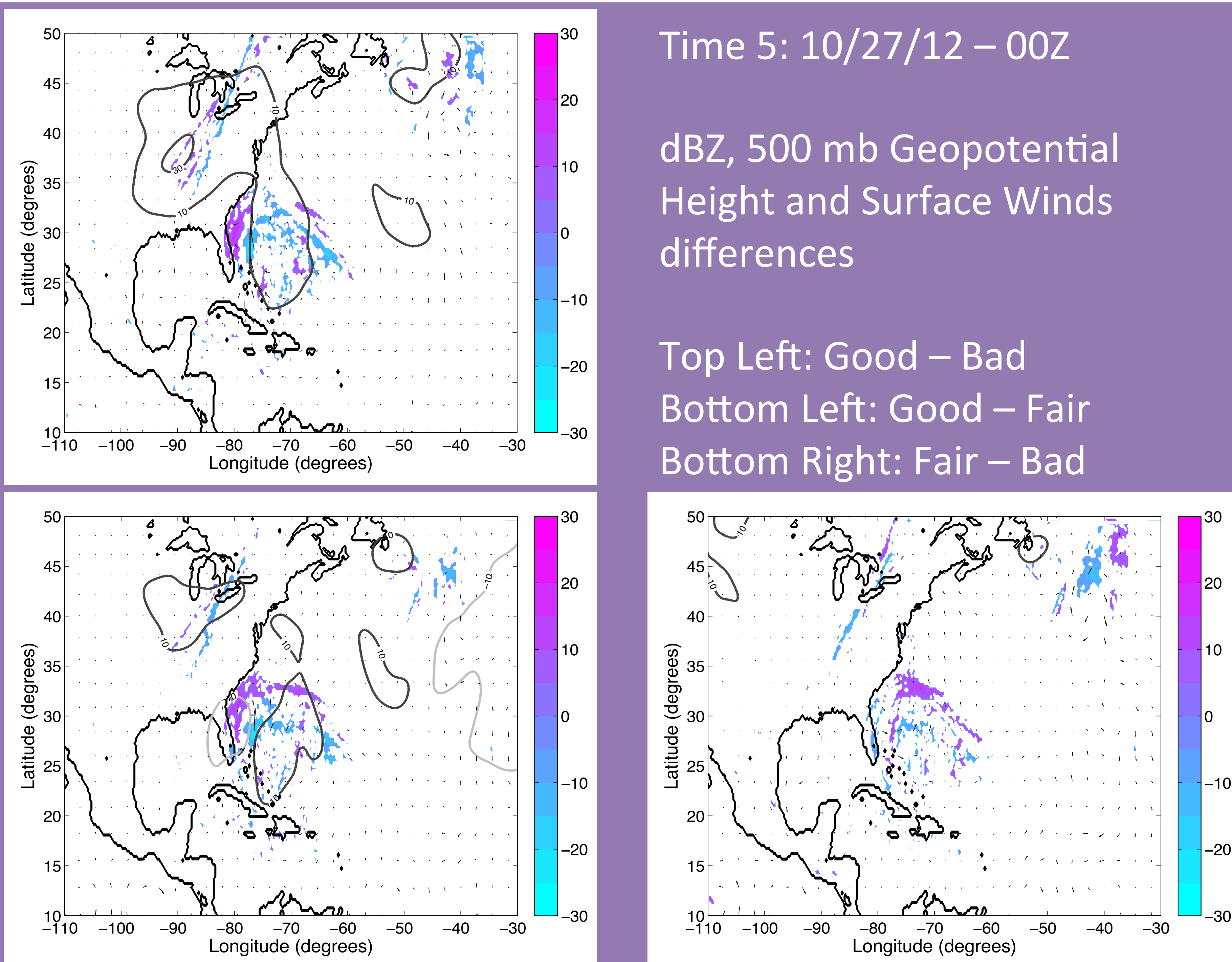




Time 5: 10/27/12 – 00Z

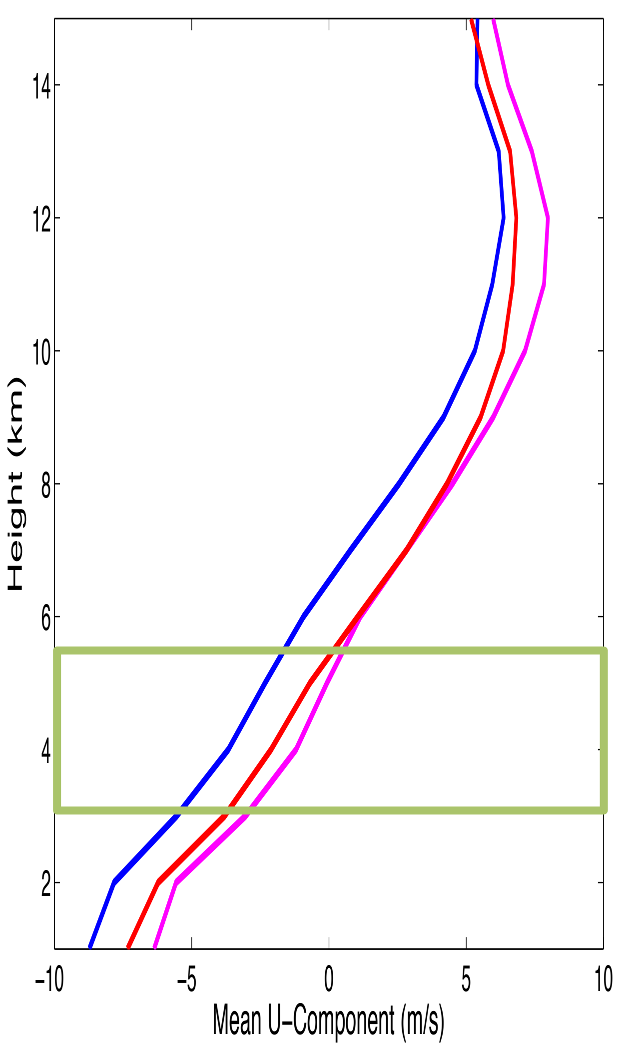
dBZ, 500 mb Geopotential Height and Surface Winds differences

Top Left: Good – Bad
Bottom Left: Good – Fair
Bottom Right: Fair – Bad

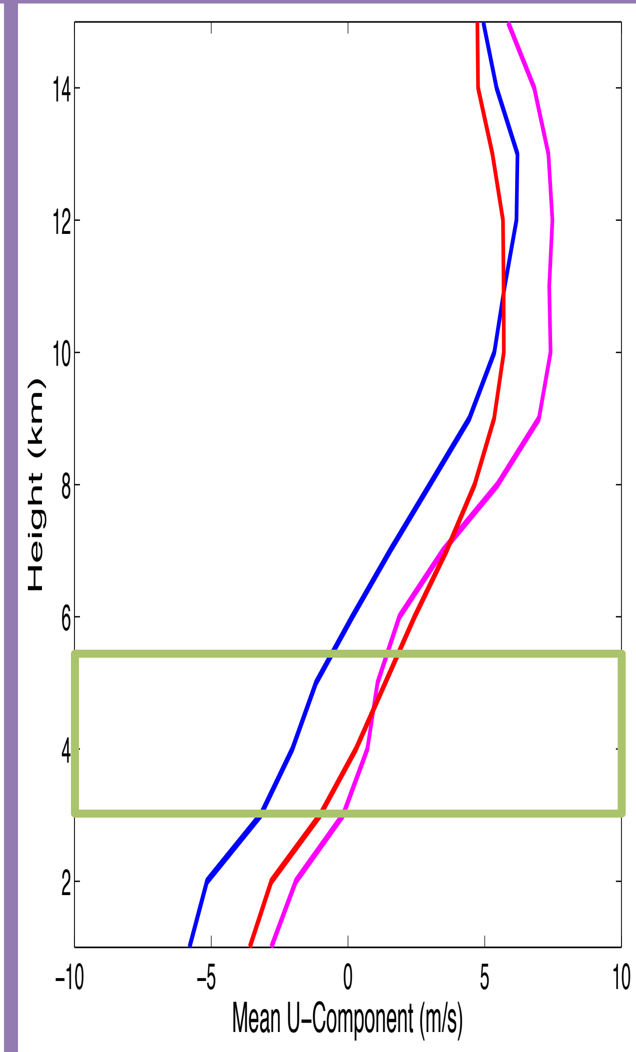


Differences in Environmental Steering Flow – Zonal

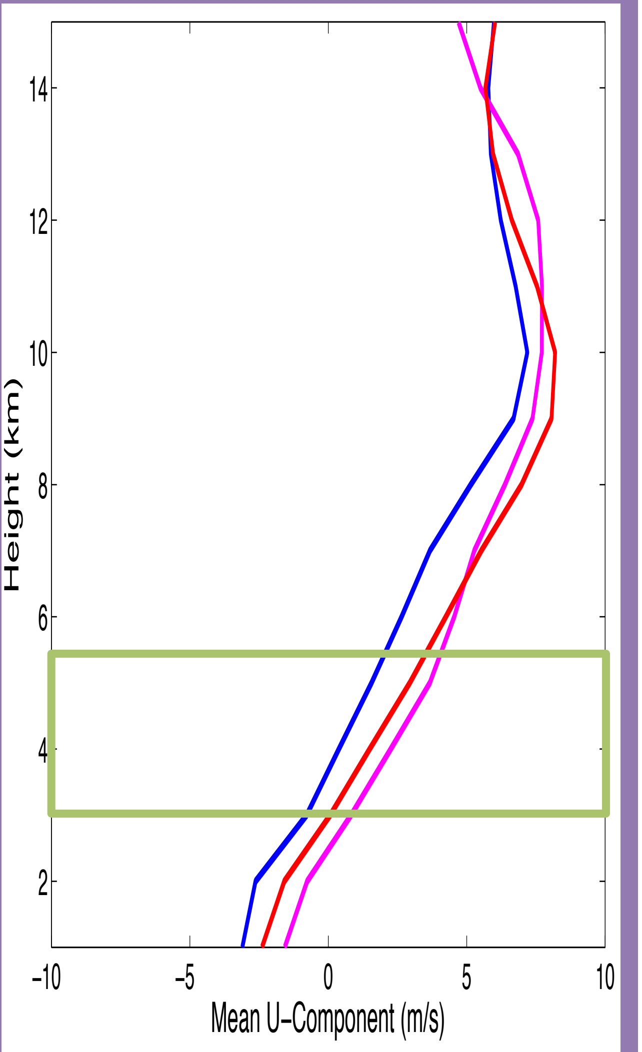
- Good composite track separates by Time 5



Time 3



Time 4

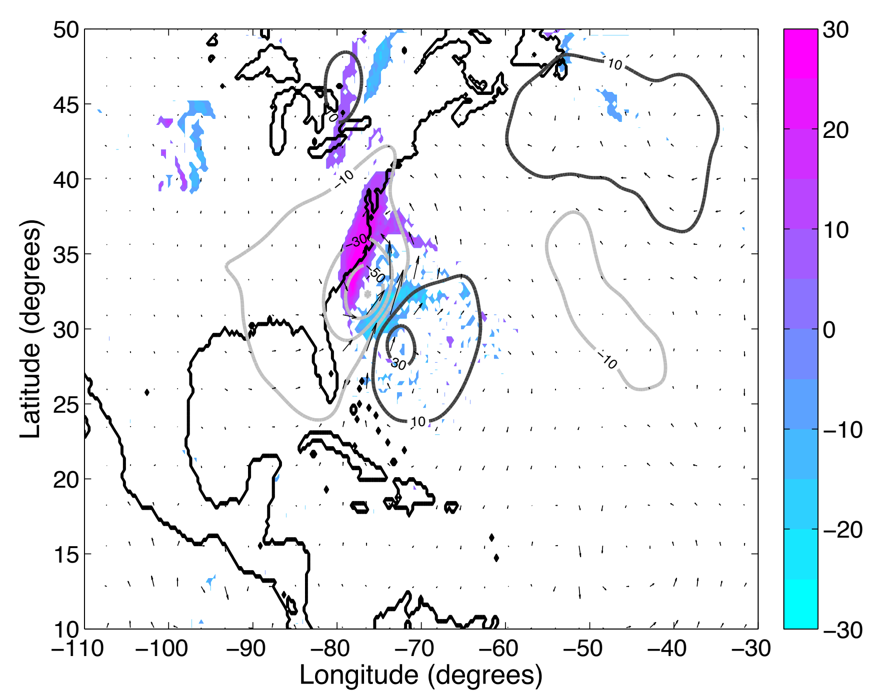


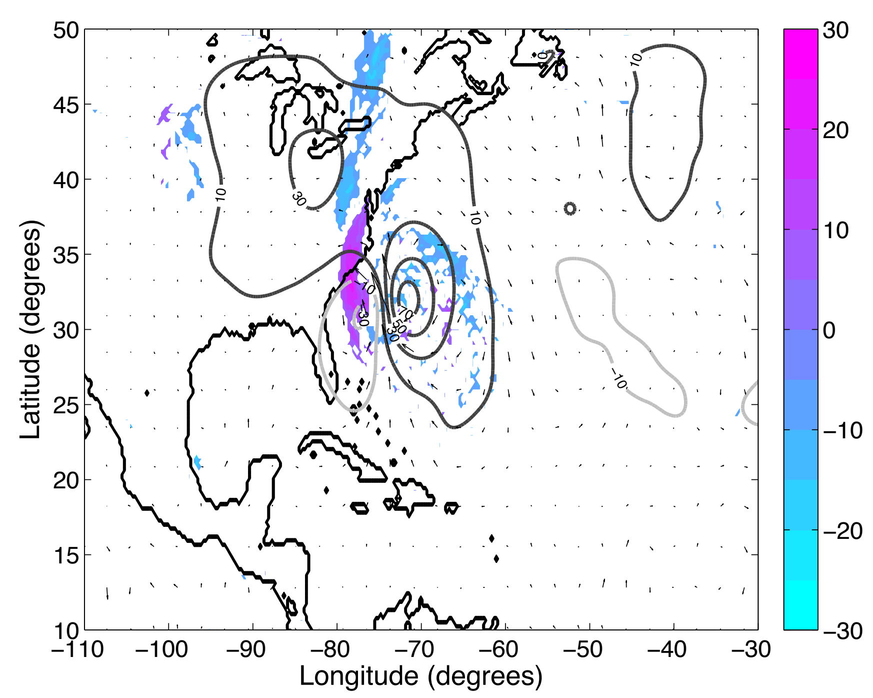
Time 5

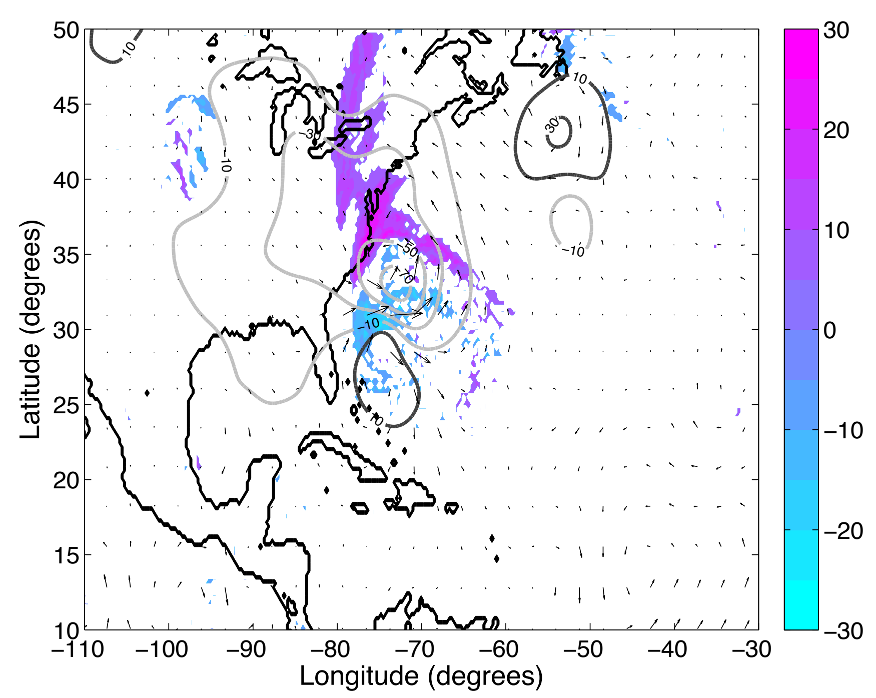
Time 9: 10/28/12 – 00Z

dBZ, 500 mb Geopotential Height and Surface Winds differences

Top Left: Good – Bad
Bottom Left: Good – Fair
Bottom Right: Fair – Bad

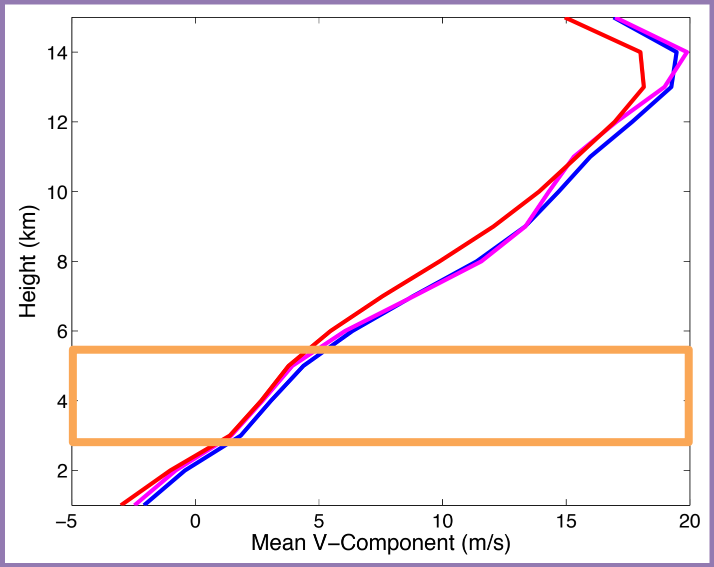




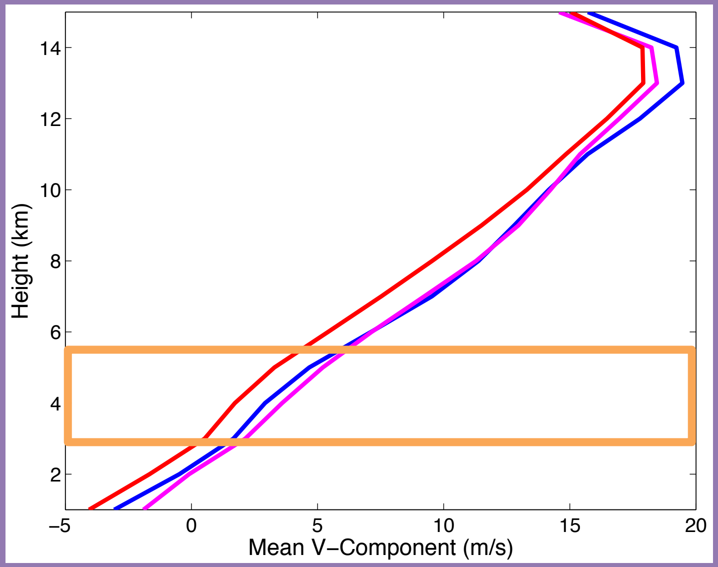


Differences in Environmental Steering Flow – Meridional

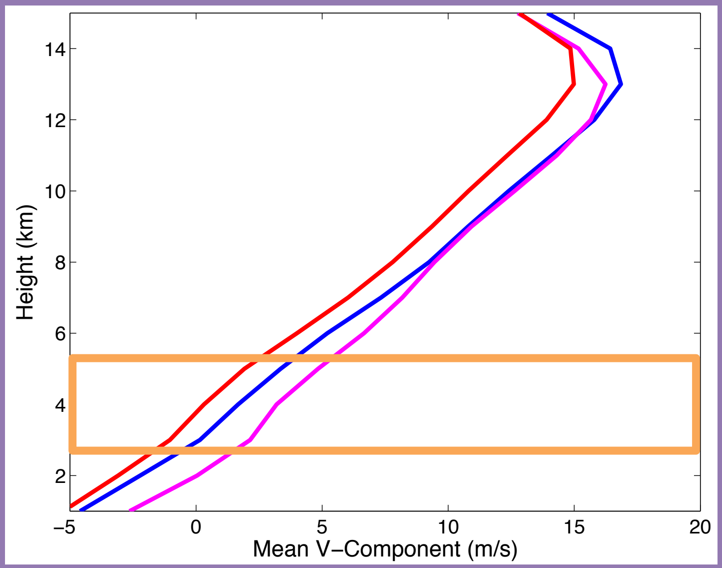
- Bad composite track separates by Time 9



Time 7



Time 8

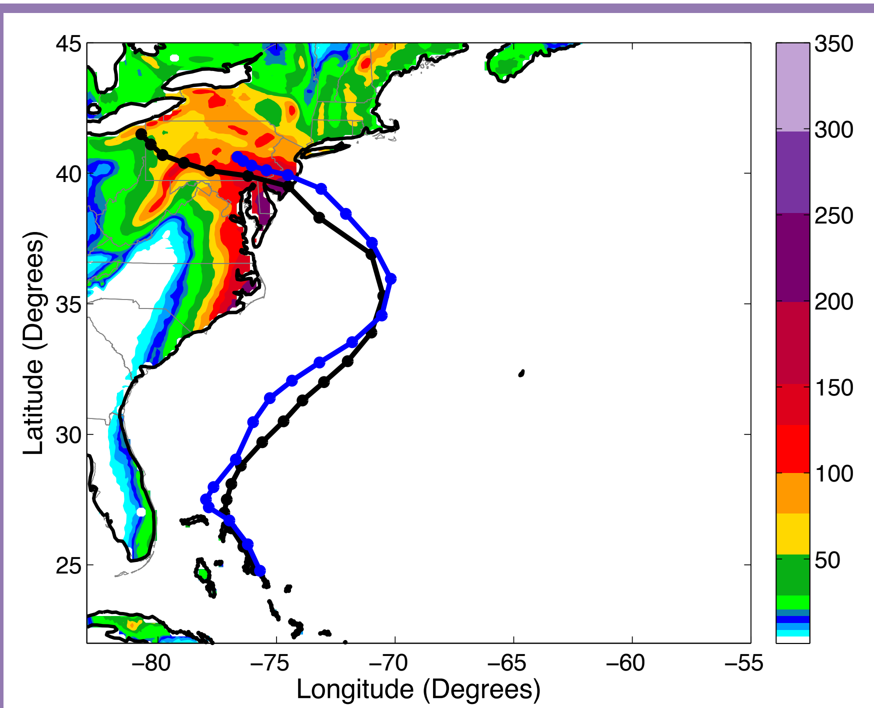


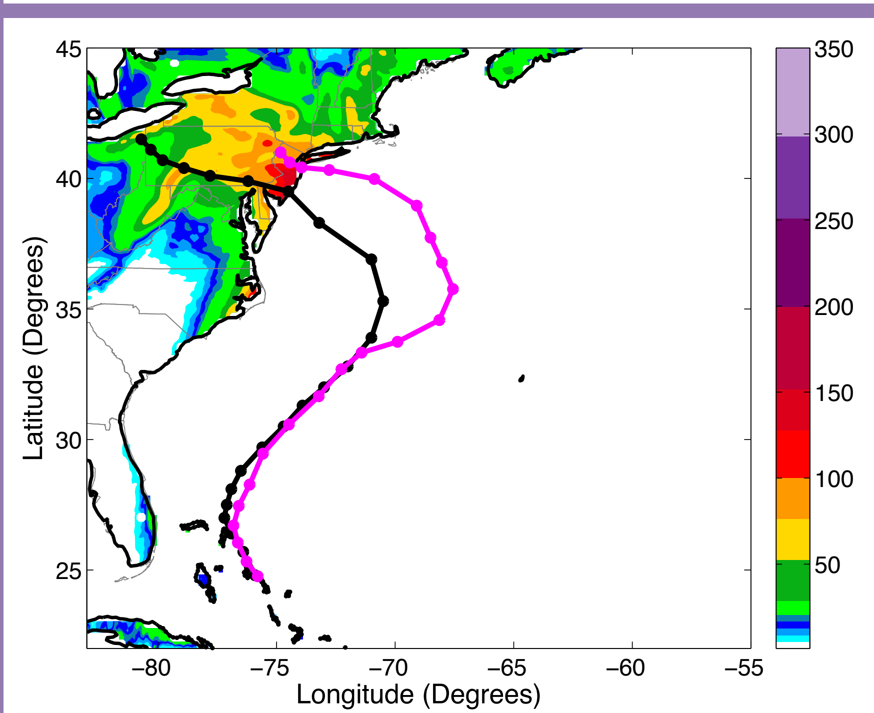
Time 9

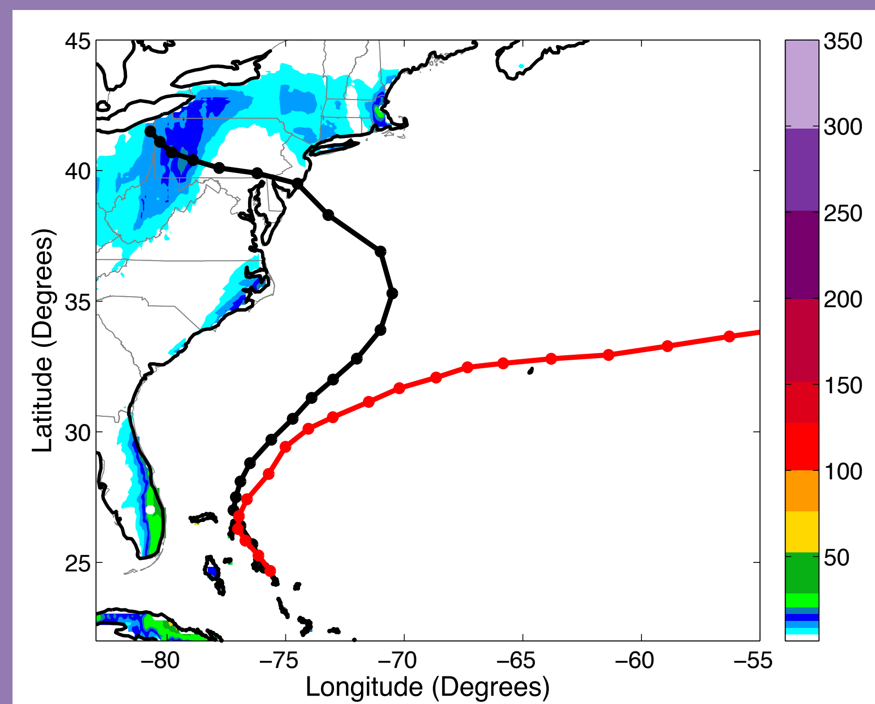
Composite Cumulative Rainfall between 10/26/12 at 00Z – 10/31/12 at 06Z

Domain 2 – Mask over Ocean

Top Left: Good
Bottom Left: Fair
Bottom Right: Bad



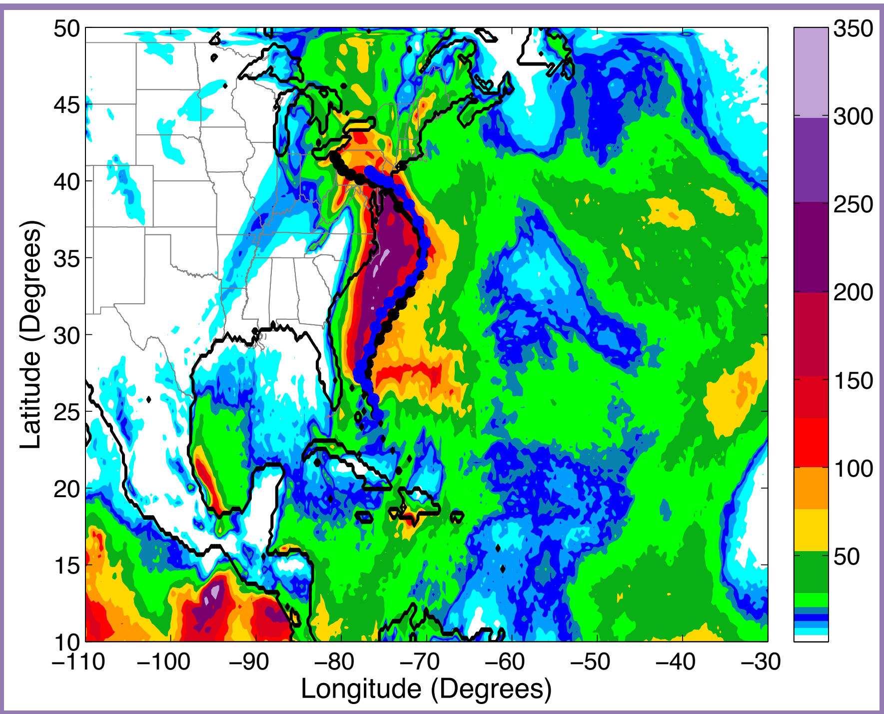


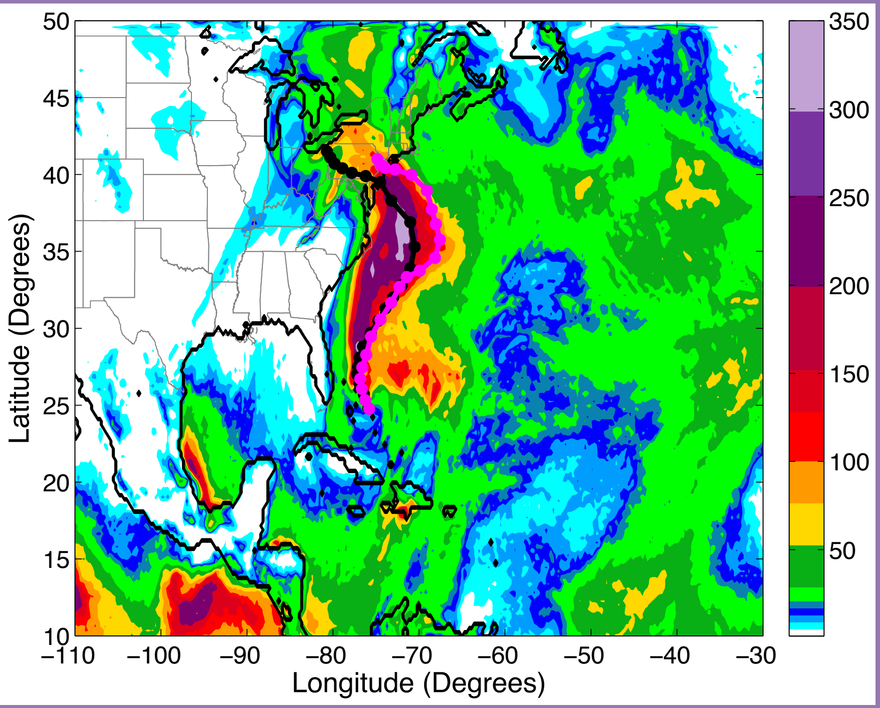


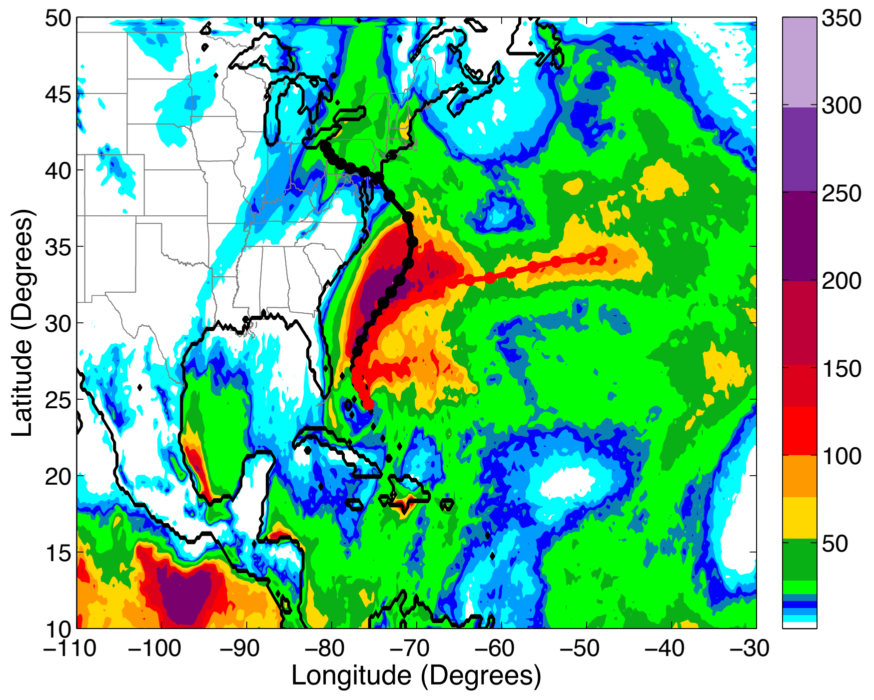
Composite Cumulative Rainfall between 10/26/12 at 00Z – 10/31/12 at 06Z

Domain 1 – No Mask

Top Left: Good
Bottom Left: Fair
Bottom Right: Bad

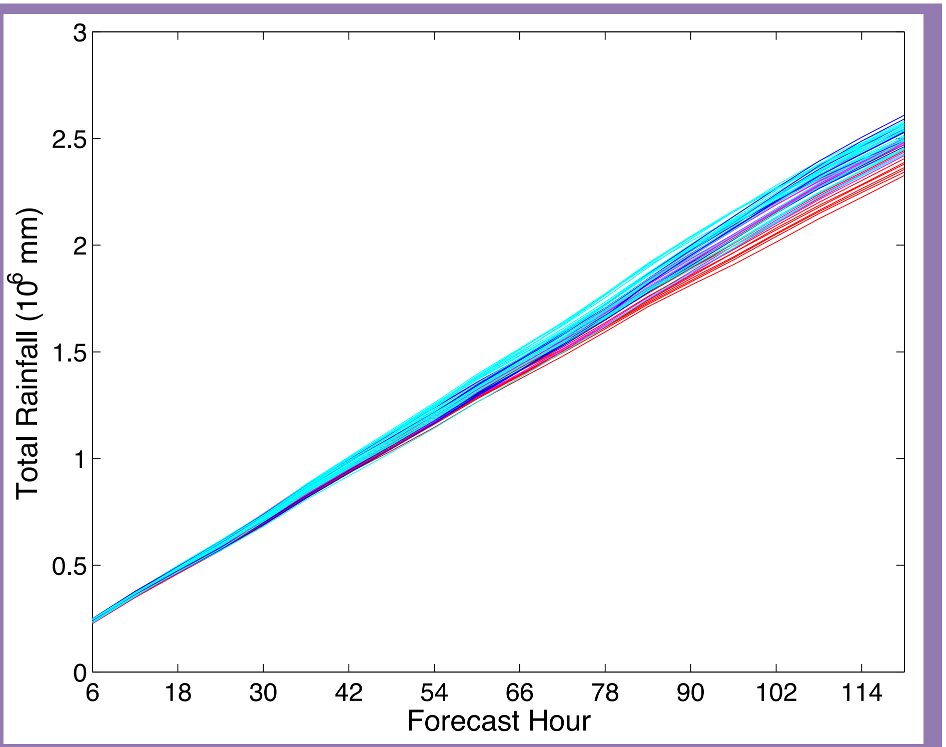


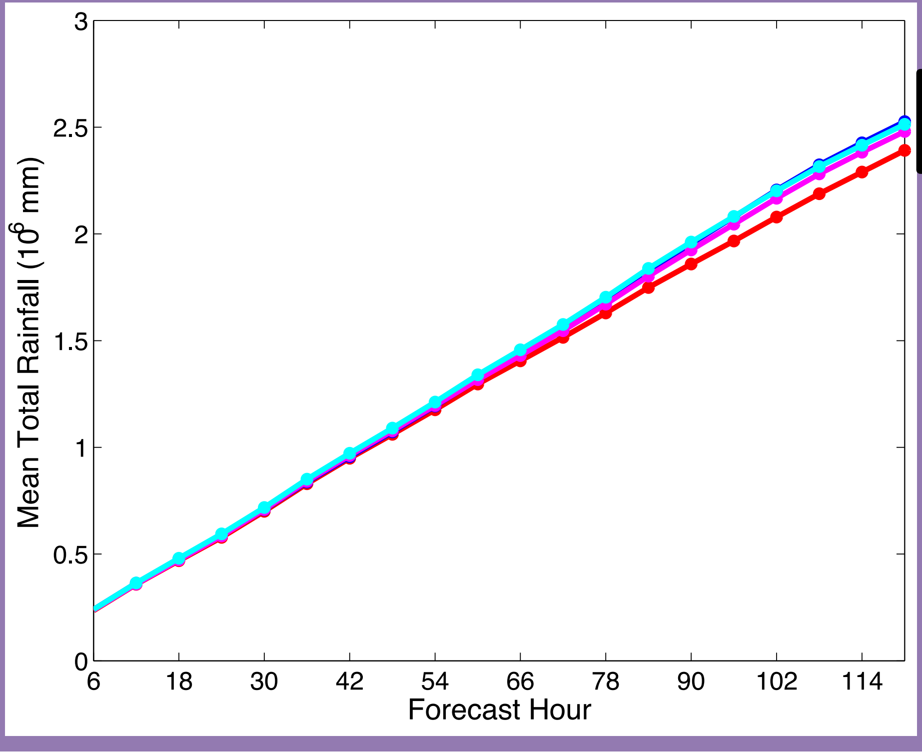




Evolution of Total Rainfall Across Domain 1

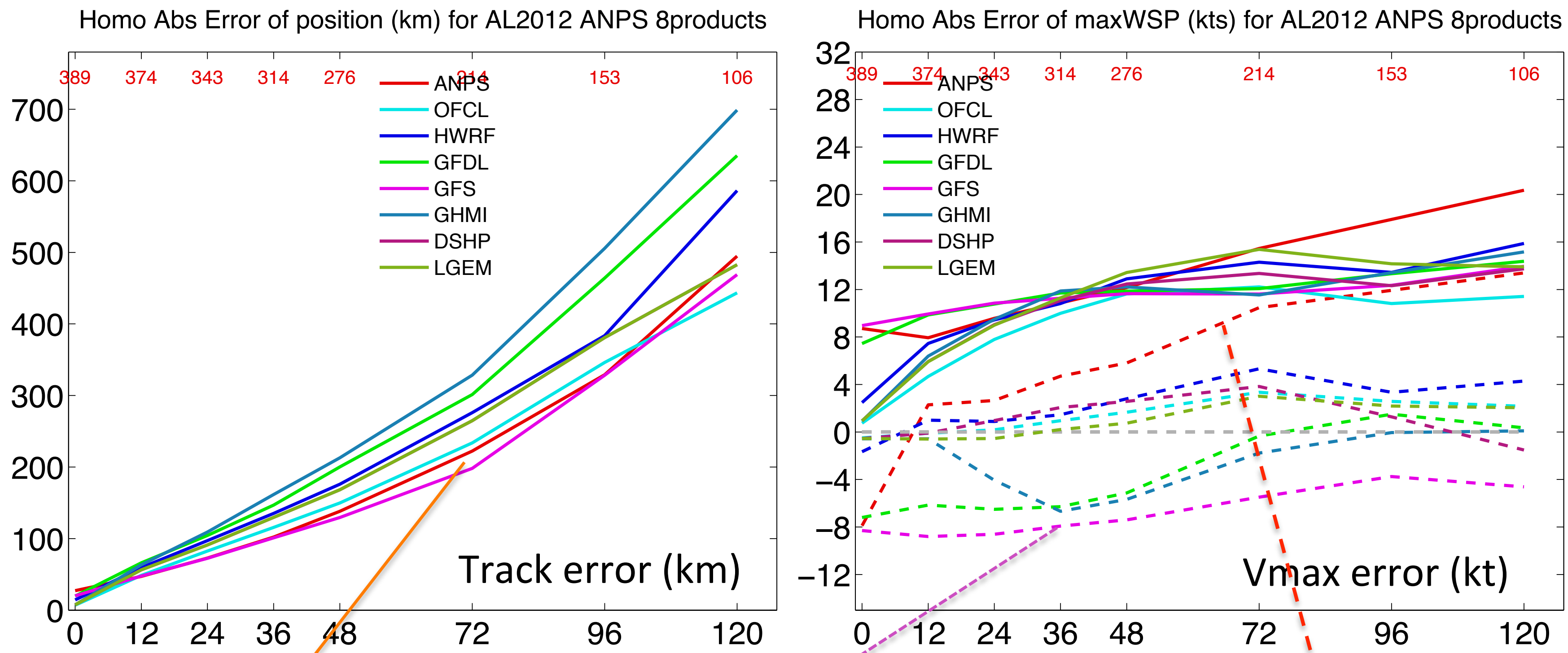
Blue: Good
Magenta: Fair
Red: Bad
Cyan: Other





} 5% Difference in Total Rainfall

ANPS 2012 stream 2.0 performance



GFS and ANPS

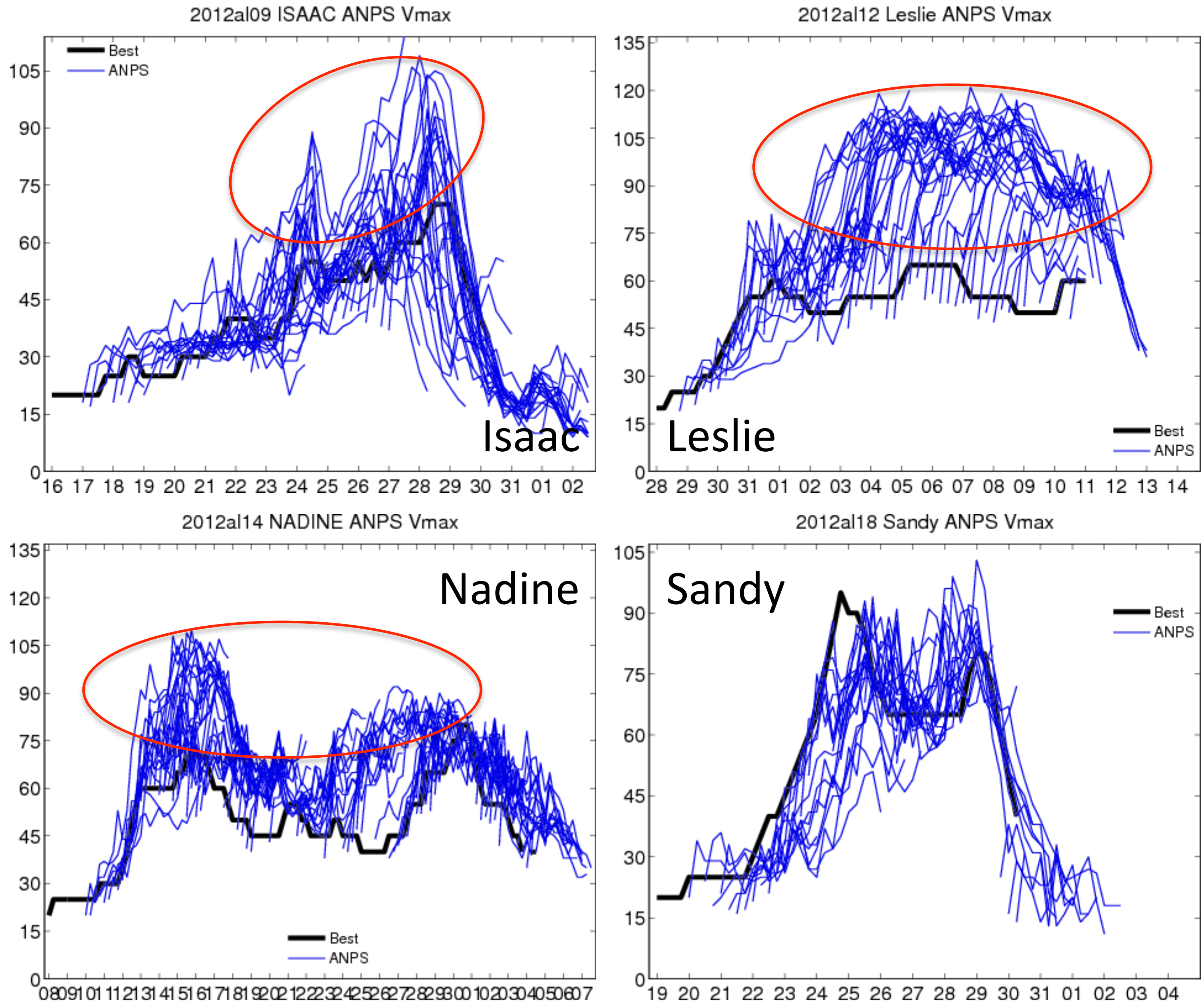
Negative bias – GFS forecast is weaker than the Best track

ANPS forecast is much stronger than the Best track

ANPS 2012 stream 2.0 system real-time forecasts for Atlantic storms.

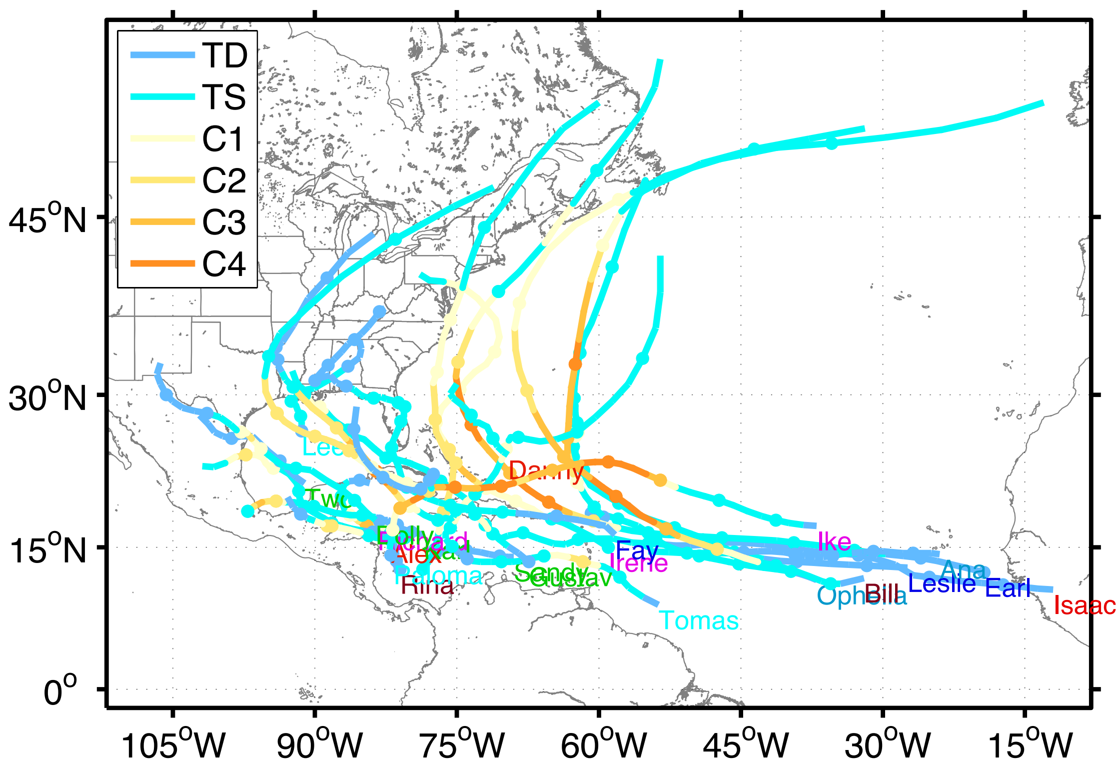
Total 762 forecasts were made in 2012 for storms and invests.

ANPS cases: intensity forecast

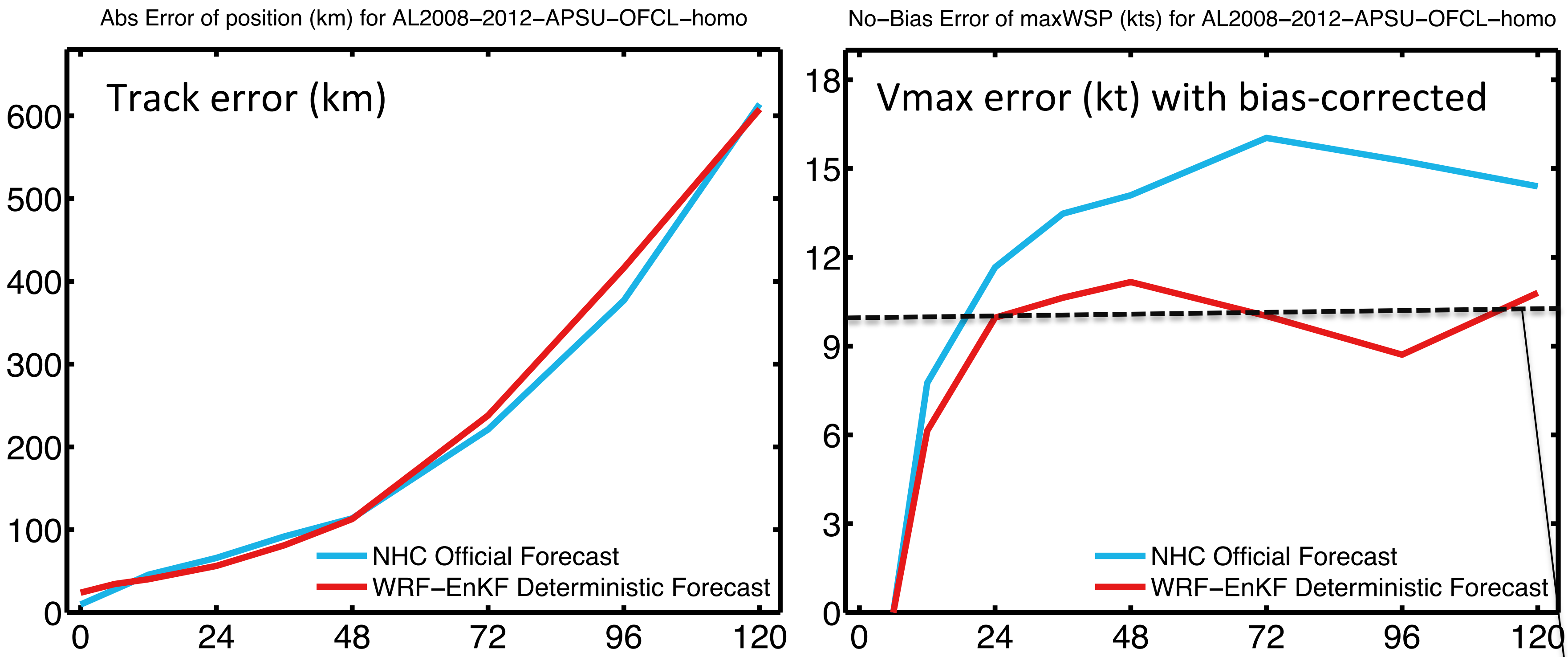


APSU for 2008-2012 TDR cases

Year	Cases	Storm (cases)
2008	35	Dolly (6), Fay (6), Gustav (6), Ike (6), Kyle(8), Paloma(3)
2009	10	Ana (1), Claudette (4), Danny (5)
2010	25	Alex (1), Two (3), Earl (11), Karl (4), Gaston (1), Tomas (5)
2011	13	Irene (7), Lee (1), Ophelia (1), Rina (4)
2012	19	Isaac (9), Leslie (3), Sandy (7)
Total	**102**	**22 storms**



2008-2012 APSU Errors

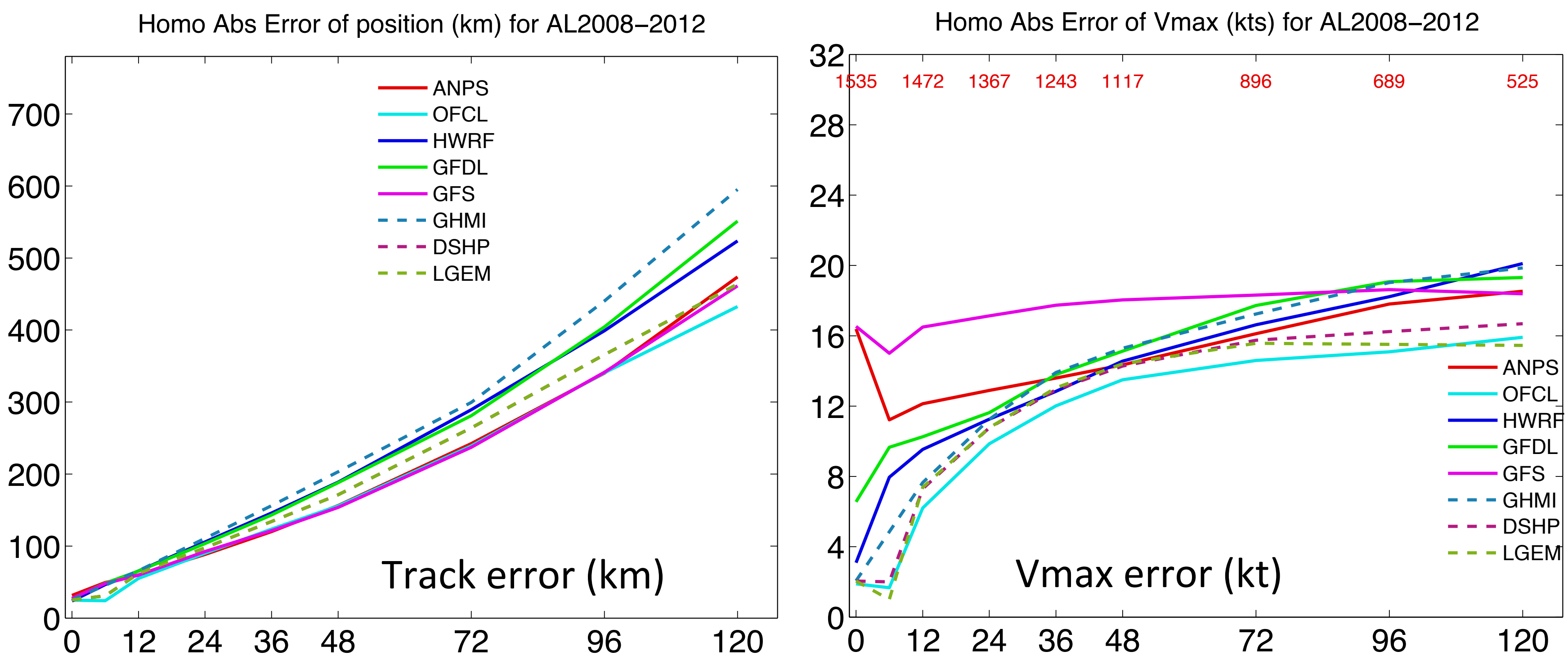


APSU forecast error for 102 TDR cases during 2008-2012.

Average uncertainty in Best track:
Landsea, C., and J. Franklin, 2013

$$Bias\_corrected = \left(Best - Forecast\right)_{t=06h} \frac{\left(30 - t_{t<30h}\right)}{30} + Forecast$$

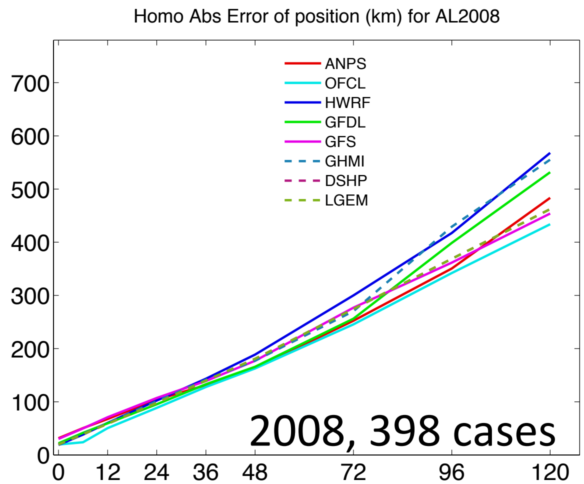
ANPS for 2008-2012 Atlantic Storms

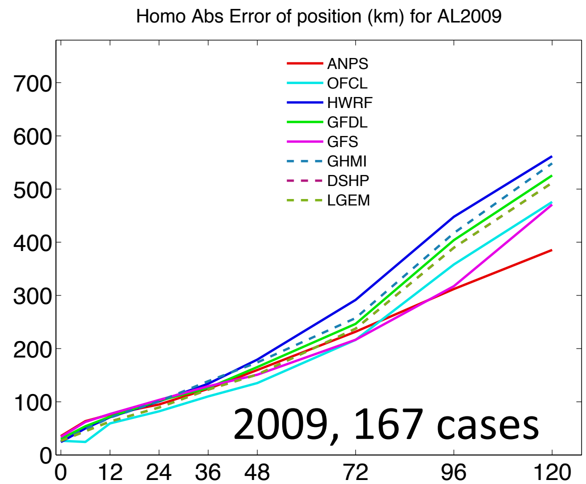


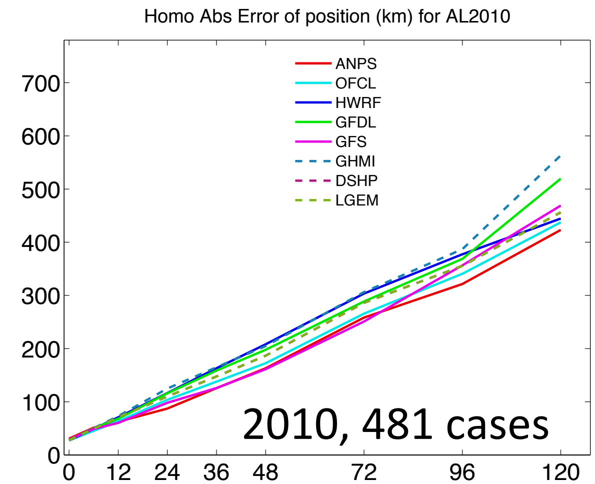
ANPS forecast error homogeneously averaged over 2140 cases of 2008-2012 Atlantic storms.

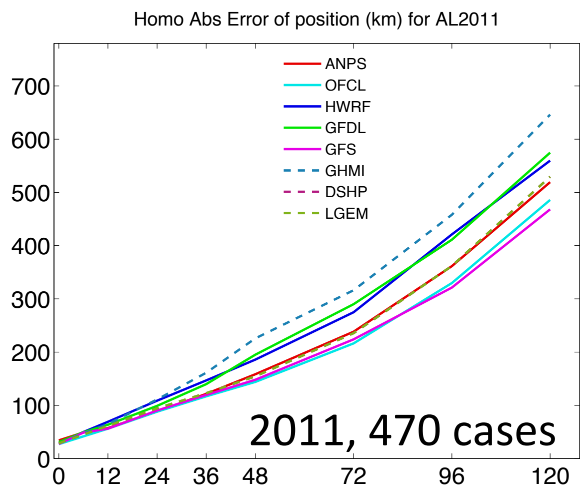
- OFCL has the smallest track and intensity error;
- ANPS has the same track error as GFS, but has smaller intensity error;
- Initial intensity bias for ANPS and GFS are very large;
- ANPS is 2012 system, others are operational systems. (the comparison for other forecasts are unfair.)

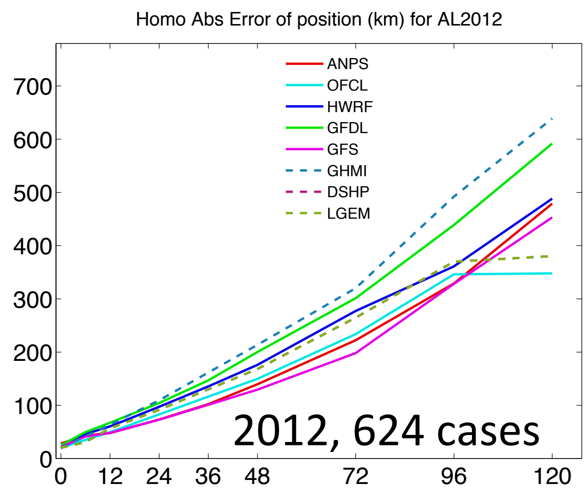
ANPS track errors each year during 2008-2012



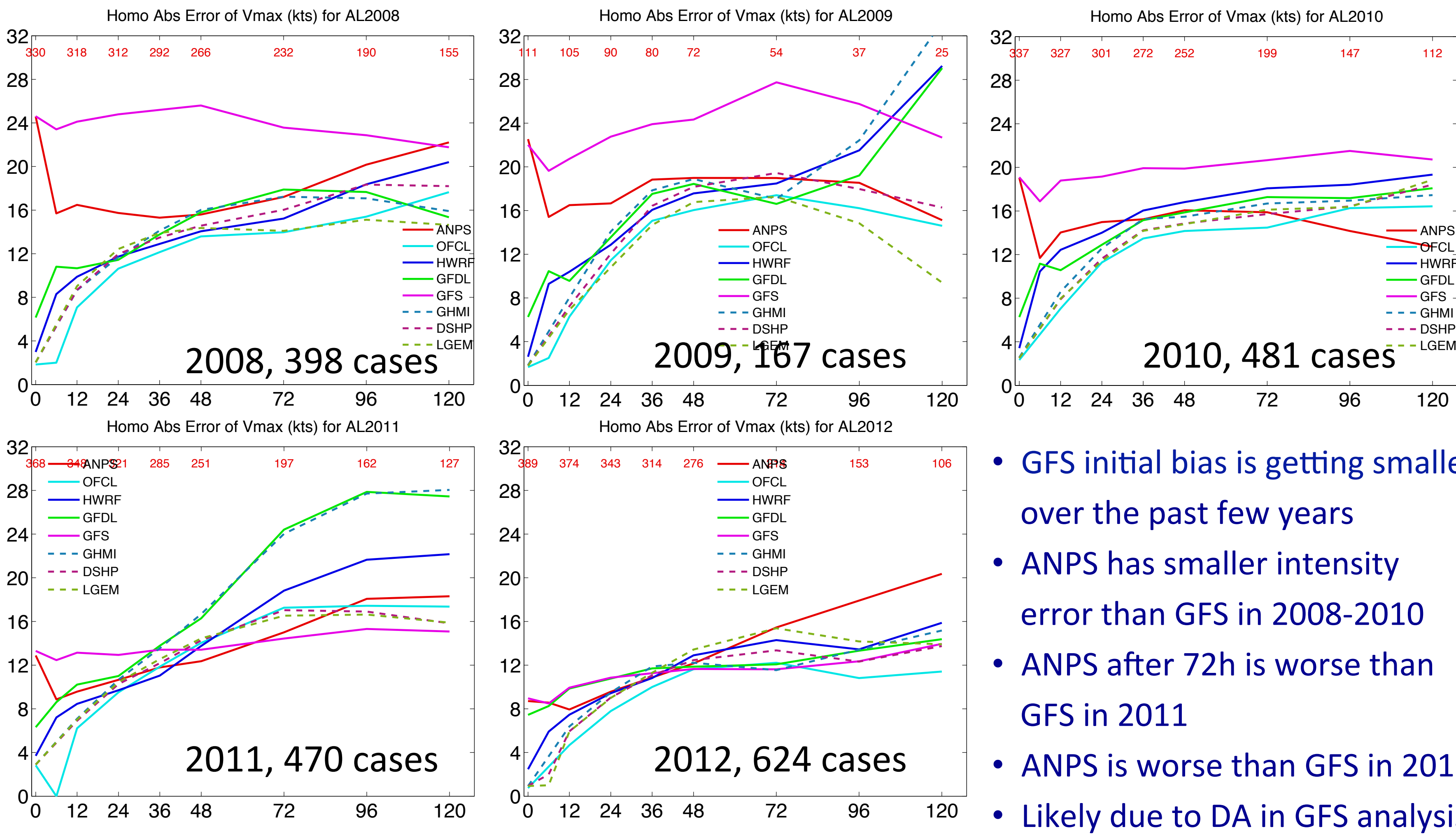






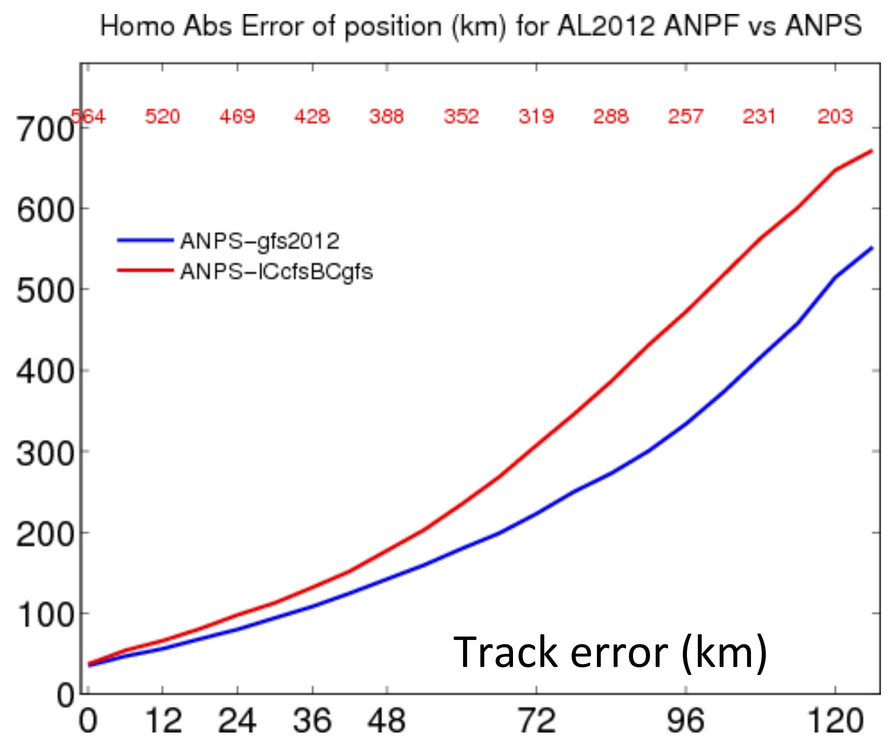


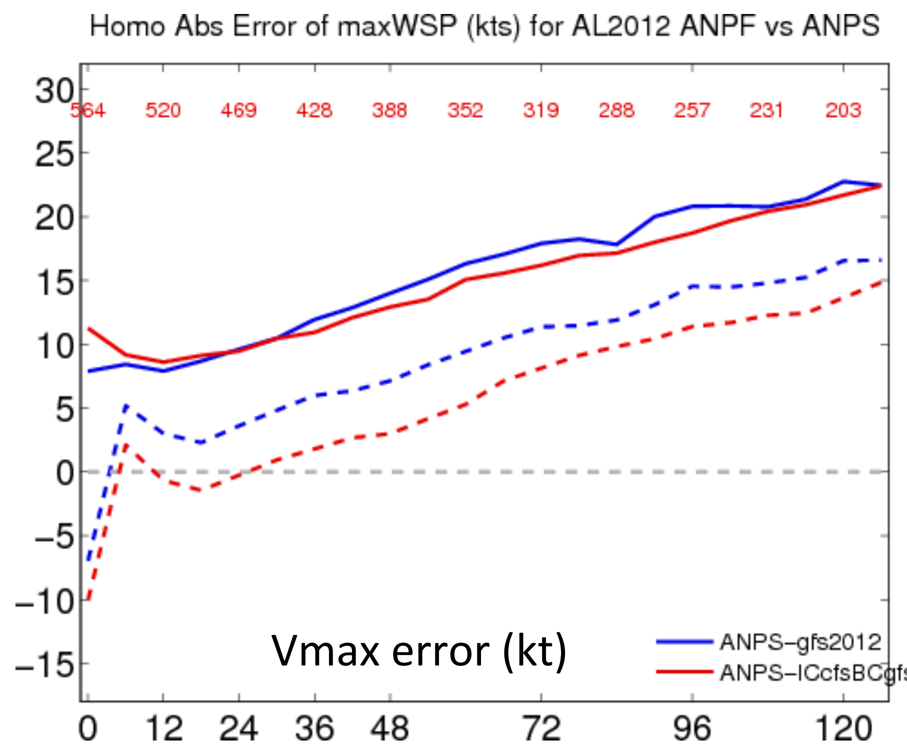
ANPS intensity errors each year during 2008-2012



- GFS initial bias is getting smaller over the past few years
- ANPS has smaller intensity error than GFS in 2008-2010
- ANPS after 72h is worse than GFS in 2011
- ANPS is worse than GFS in 2012
- Likely due to DA in GFS analysis

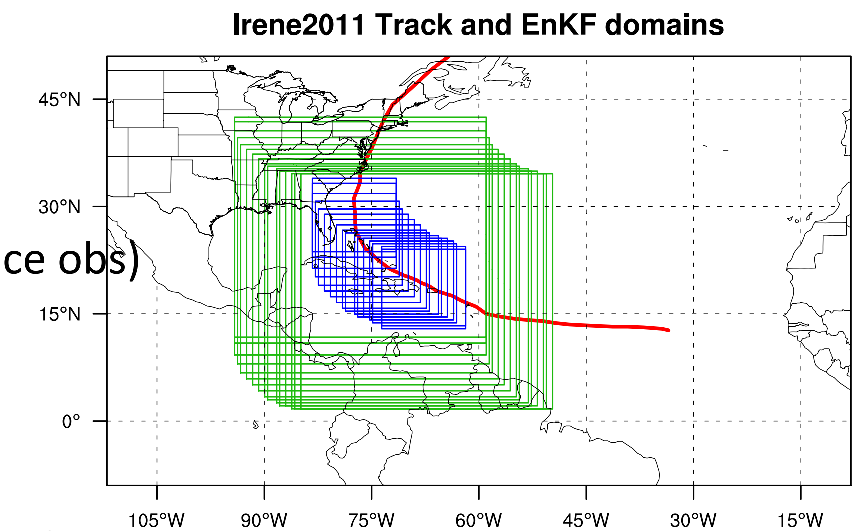
Different Global Analyses/Forecasts for ANPS: GFS vs. CFSRv2 for 2012 Atlantic Storms





- GFS upgrades lead to better ARW track forecasts but higher intensity bias and error

Recon Impact Tiger Team Recon : FL/drops vs. TDR



ATCF ID:

APCT (APCI): ConTrol (regular GTS non-radiance obs)

APRC (APRI): ReCon (FL + drops)

APAR (APAI): All Recon (Doppler + FL + drops)

Experiment design:

- The system configurations are the same as APSU;
- The system is initialized with operational GFS, and cycled every 3 hours till the end of the storm or the storm moves to the north of 45N or the east of 30W ;
- The inner domains follow TCvitals;
- Assimilating obs. within the area of 1200kmx1200km around the storm every 3 hours;
- Environment fields (out of the 1200kmx1200km area) will be replaced by GFS operational analysis every 6 hours;
- Deterministic forecasts are conducted every 6 hours.

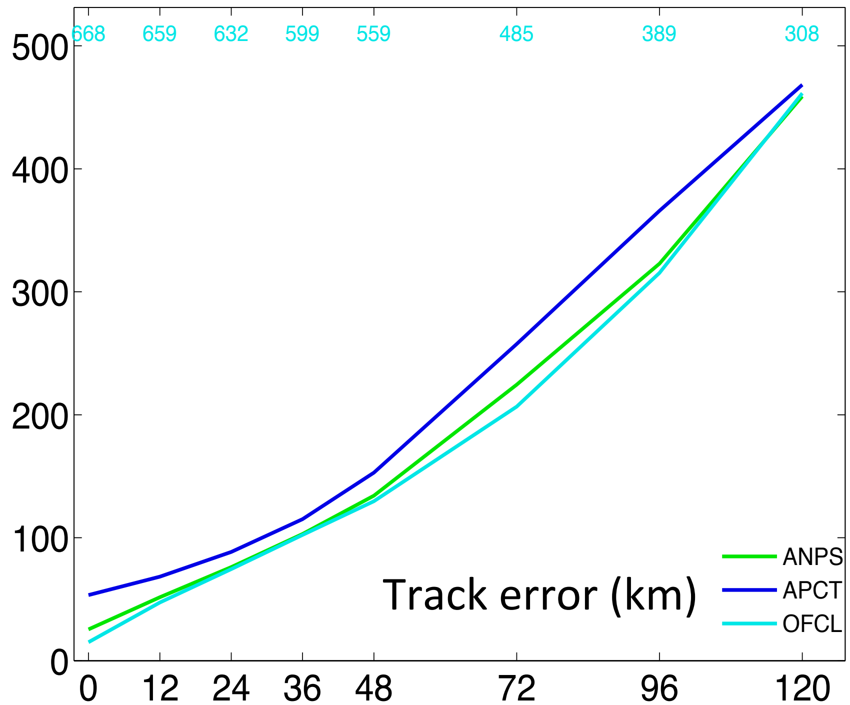
DA Tiger Team: selected cases 2008-2012

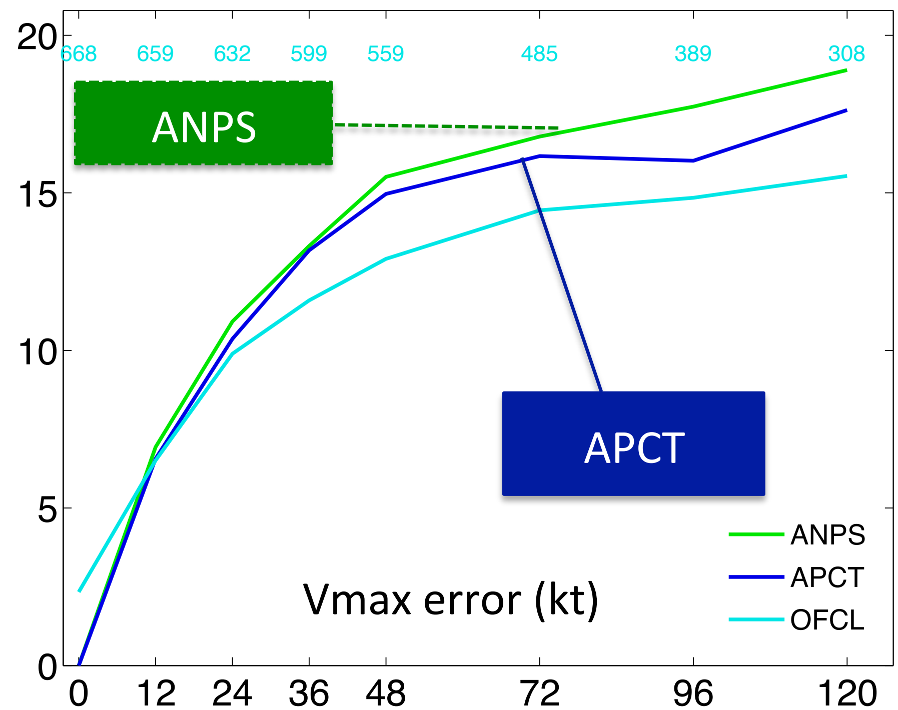
Year	Storm	APCT	APRC	APAR
2008	04-Dolly	072012-072418	072012-072418	072012-072300
	06-Fay	081400-082400	081400-082400	081400-081906
	07-GUSTAV	082512-090200	082512-090200	082918-090118
	09-Ike	090200-091312	090512-091312	090918-091218
	11-Kyle	092300-092812	092318-092812	092318-092718
	17-Paloma	110600-111000	110600-111000	110706-110900
2009	02-Ana	081200-081700	081612-081700	081618-081700
	03-Bill	081600-082312	081812-082312	081818-082012
	05-Danny	082612-082900	082612-082900	082612-082812
2010	01-Alex	062512-070112	062512-070112	062900
	07-Earl	082600-090400	082712-090400	082900-090400
	13-Karl	091412-091800	091412-091800	091300-091700
	19-Richard	102012-102600	102012-102600	102306-102312
	21-Tomas	102912-110806	102912-110806	110400-110700
2011	09-Irene	082000-082900	082012-082900	082400-082712
	13-Lee	090200-090612	090200-090612	090200
	16-Ophelia	092100-100218	092312-092900	092418
	18-Rina	102212-102818	102312-102800	102600-102718
2012	09-Isaac	082000-083018	082112-082906	082300-082900
	12-Leslie	083000-091100	090712-090812	090712-090812
	14-Nadine	091000- 100318	091118- 100318 (GH dropsondes)	
	17-Rafael	101300-101718	101300-101718	101600-101700
	18-Sandy	102100-103018	102212-102918	102600-102900
Total	23	758	636	240

Data source

- GFS: Jet HSMS: /mss/fdr/YYYY/MM/DD/grib/ftp/7/0/96/0_259920_0, grib2.
- Flight level data: ftp://ftp.aoml.noaa.gov/hrd/pub/data/flightlevel, netcdf and ascii formats.
- Dropsonde data: /mss/fdr/2012/10/25/data/dropsonde/netcdf, netcdf.
- TDR: JET: /lfs2/projects/hfip-psu/yweng/Data/Airborne/SO/YYYY.

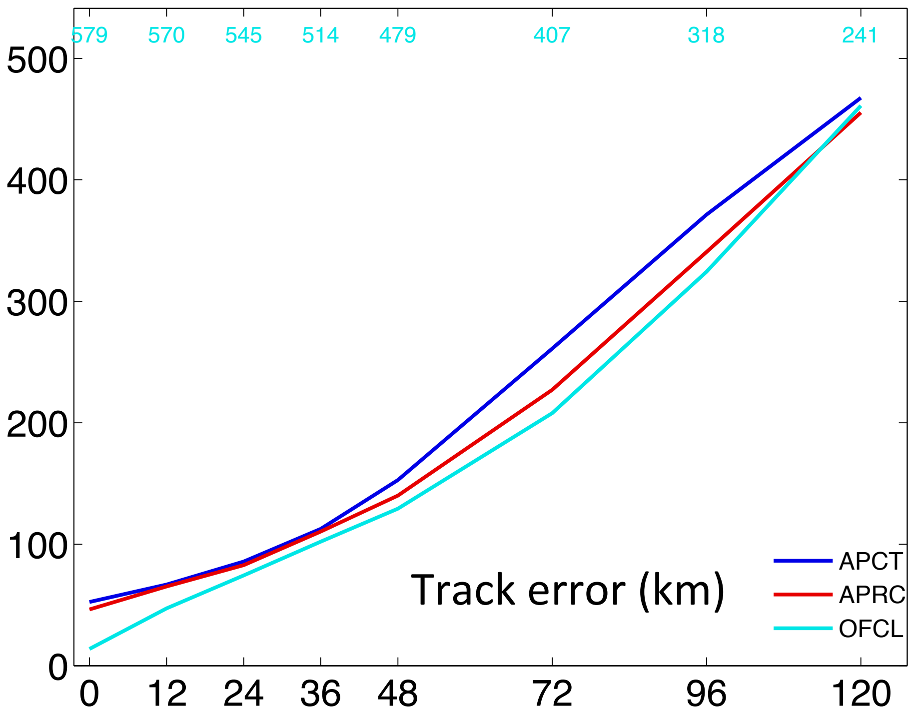
DA Tiger Team:
APCT vs. ANPS errors for 2008-2012

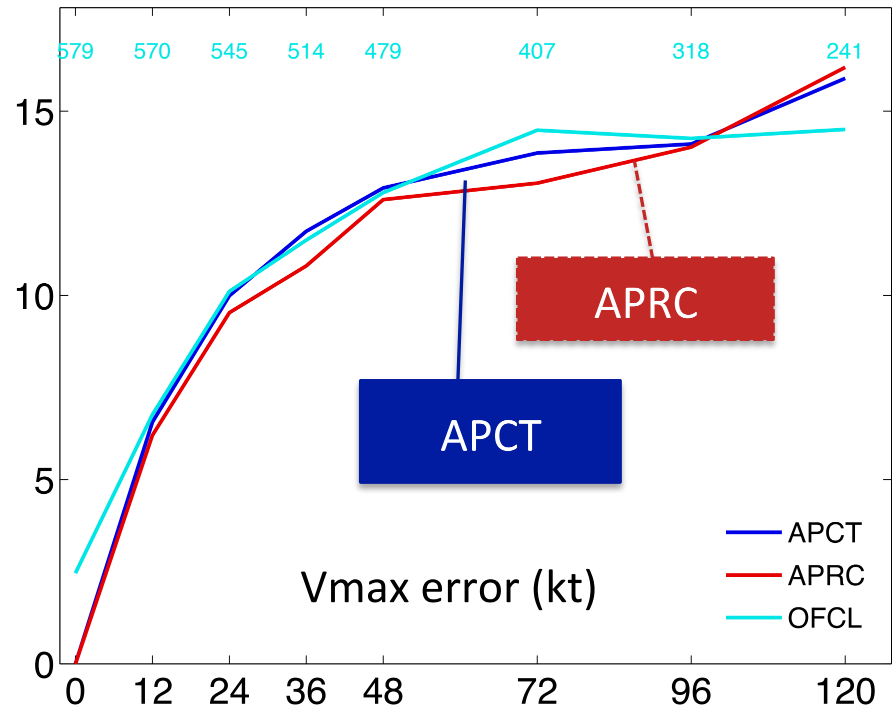




- PSU cycling ARW-EnKF system assimilating non-radiance GTS obs only performs comparable to ANPS initialized from GFS

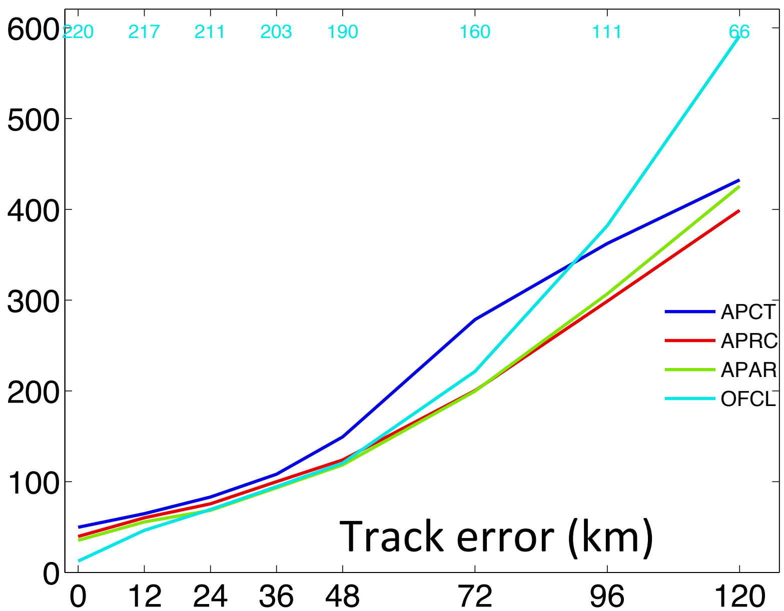
DA Tiger Team:
APRC vs. APCT errors for 2008-2012

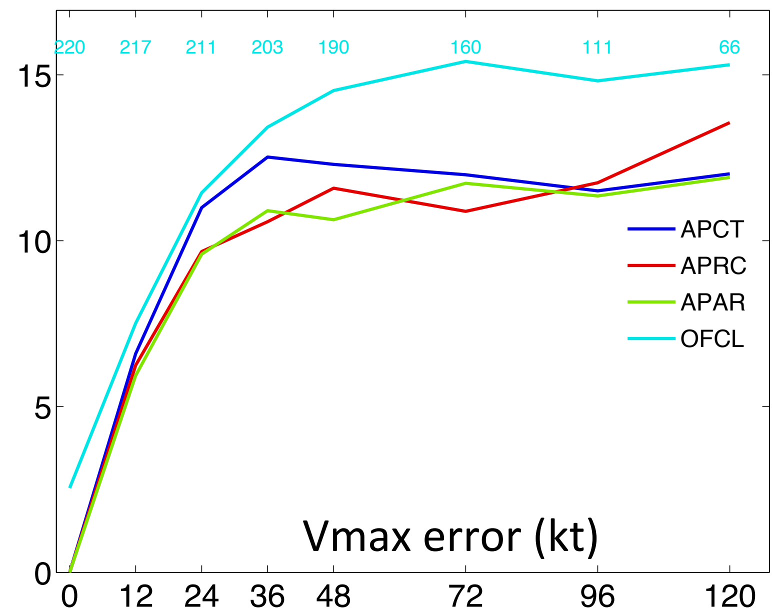




- Assimilation of additional recon flight-level plus dropsondes improves both track and intensity forecasts

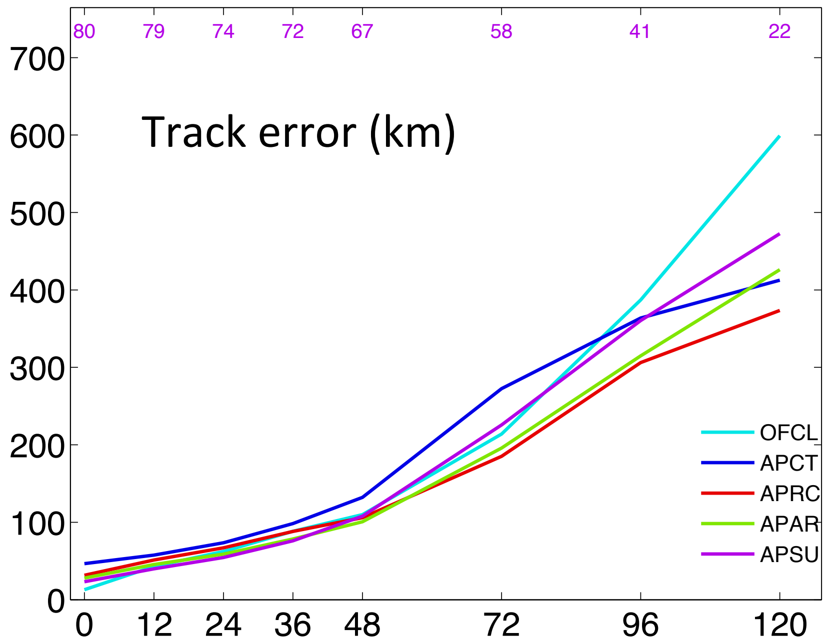
DA Tiger Team:
APRC, APCT & APAR errors for 2008-2012

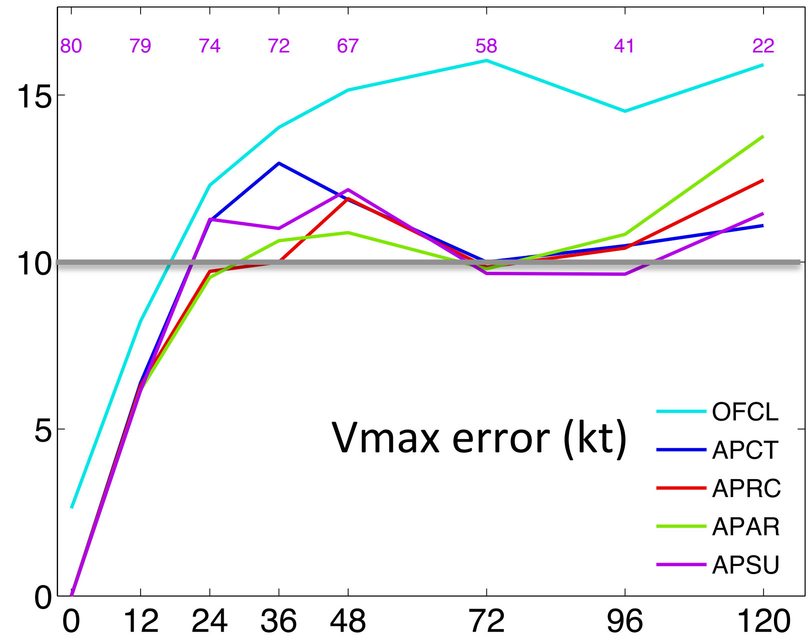




- Somewhat surprisingly, addition of TDR does not further improve beyond FL +drops

DA Tiger Team:
APAR vs. APSU (2012 system) errors for 2008-2012



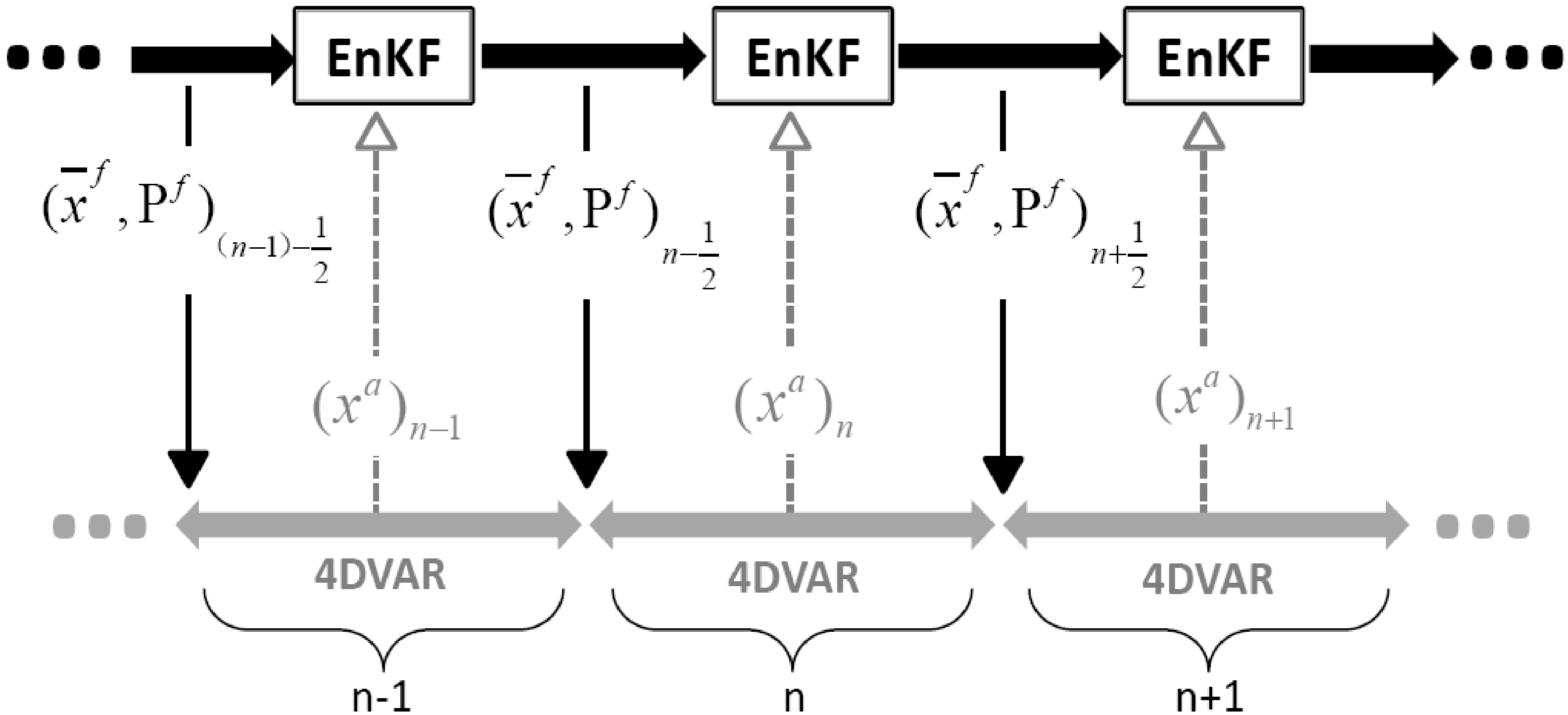


- For all the TDR cases, no significant performance difference between experiments
- More tests needed

Looking Forward

- 2013 stream 2.0:
  - APSU: ARW deterministic forecast initialized by cycling PSU WRF-EnKF system with GTS non-radiance data, Recon data, NOAA TDR and satellite derived winds assimilation. Four times per day
  - AP01-AP10: ensemble forecast with 10 members twice per day initialized with APSU EnKF perturbations
- Continue the Recon Data Impact Experiment by adding an ocean model, and improving EnKF configurations
- Development and implementation of a WRF/AHW-based coupled EnKF and 4DVar system (E4DVar) for convection-permitting hurricane analysis and prediction (2014?)

E4DVAR: 2-way Coupling of EnKF with 4DVar



Necessary Variable Changes:

EnKF provides ensemble-based background error covariance (P^f) for 4DVar

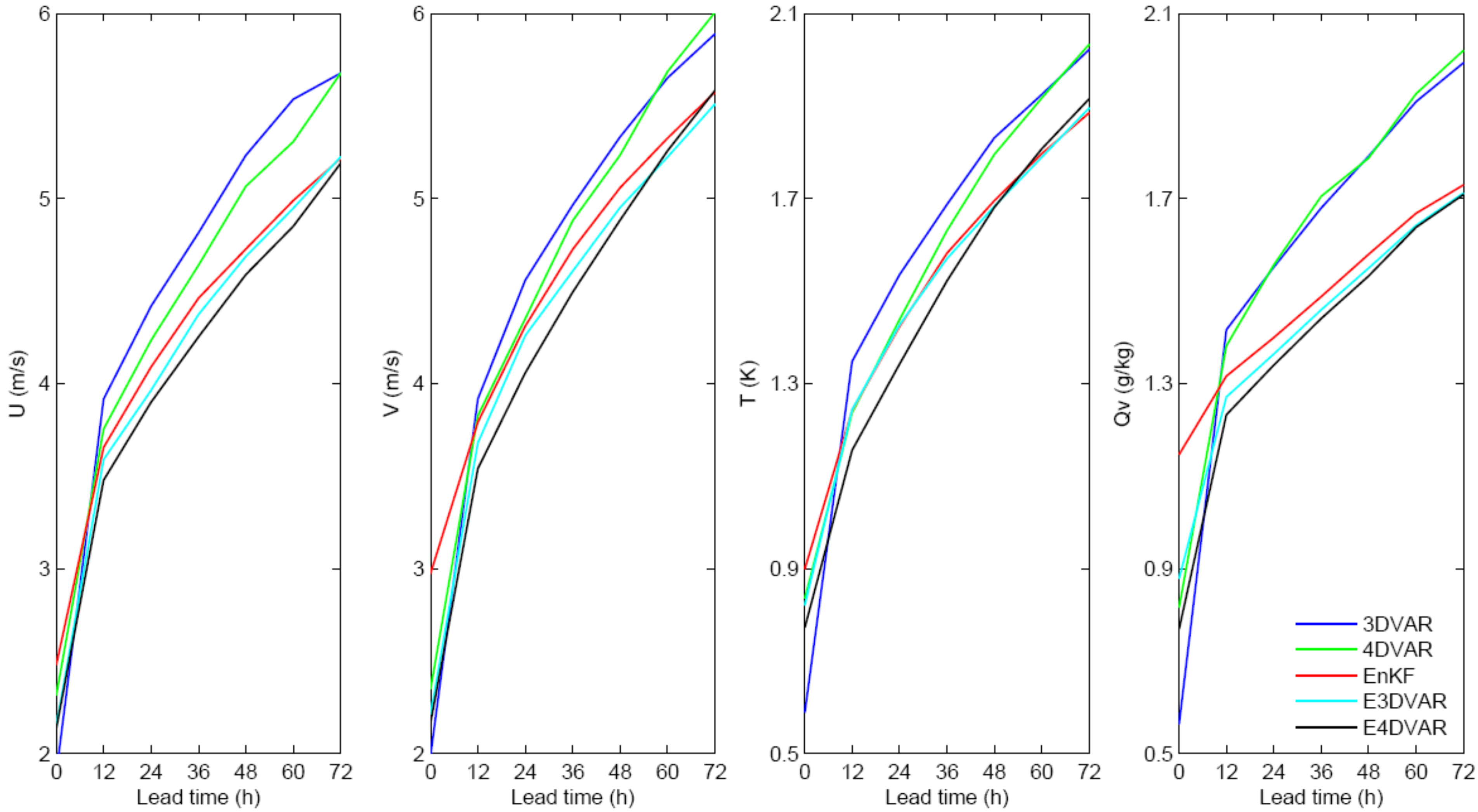
EnKF provides the prior ensemble mean ($\overline{x}^f$) as the first guess for 4DVar

4DVar provides deterministic analysis ($\overline{x}^a$) to replace the posterior ensemble mean for the next ensemble forecast

Proof-of-concept in Zhang, Zhang and Hansen (2009 AAS), real-data expts in Zhang and Zhang (2012 MWR)

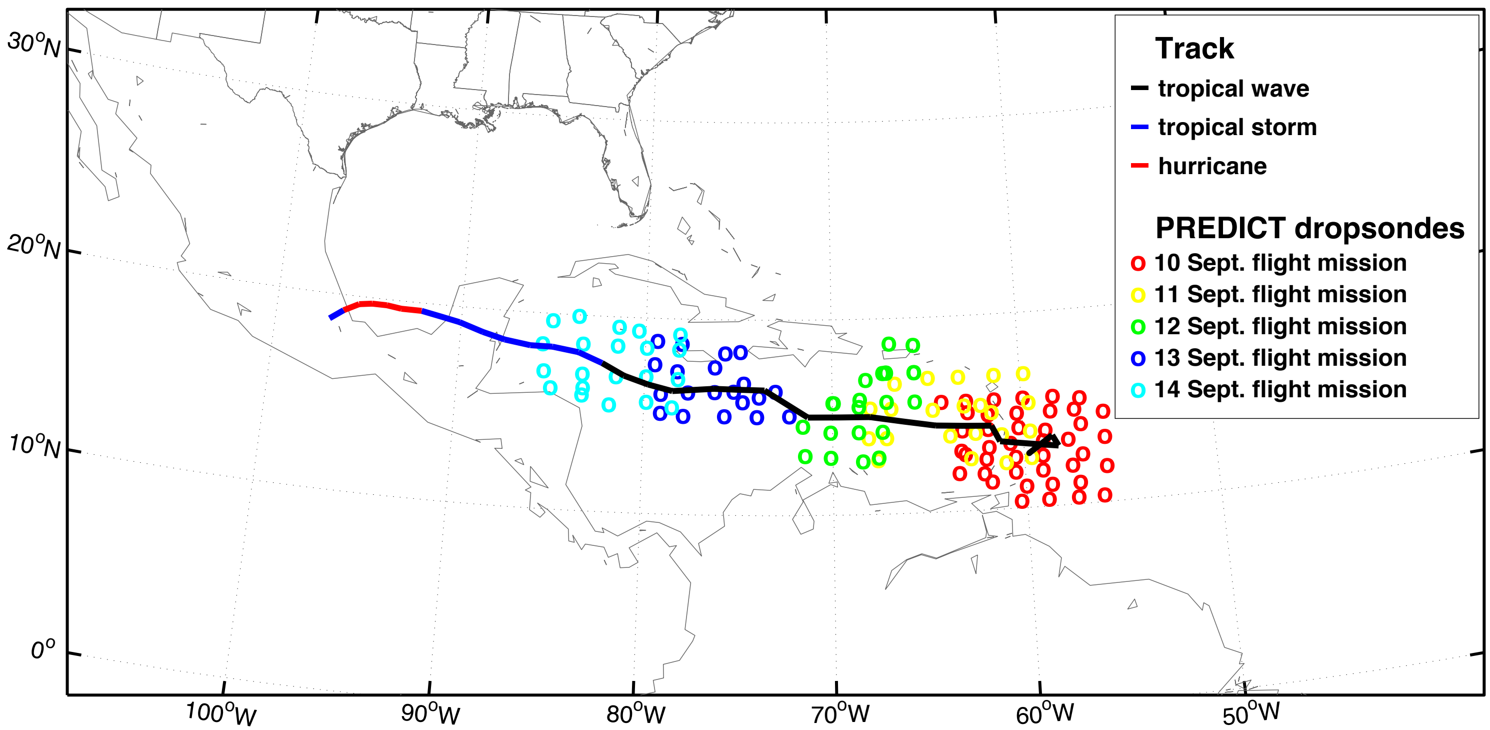
E4DVar, E3DVar vs. EnKF, 3DVar, 4DVar

RMSE of 12~72h forecast for BAMEX domain, June 1-30 2013



(Zhang and Zhang 2012; Zhang et al. 2013 MWR)

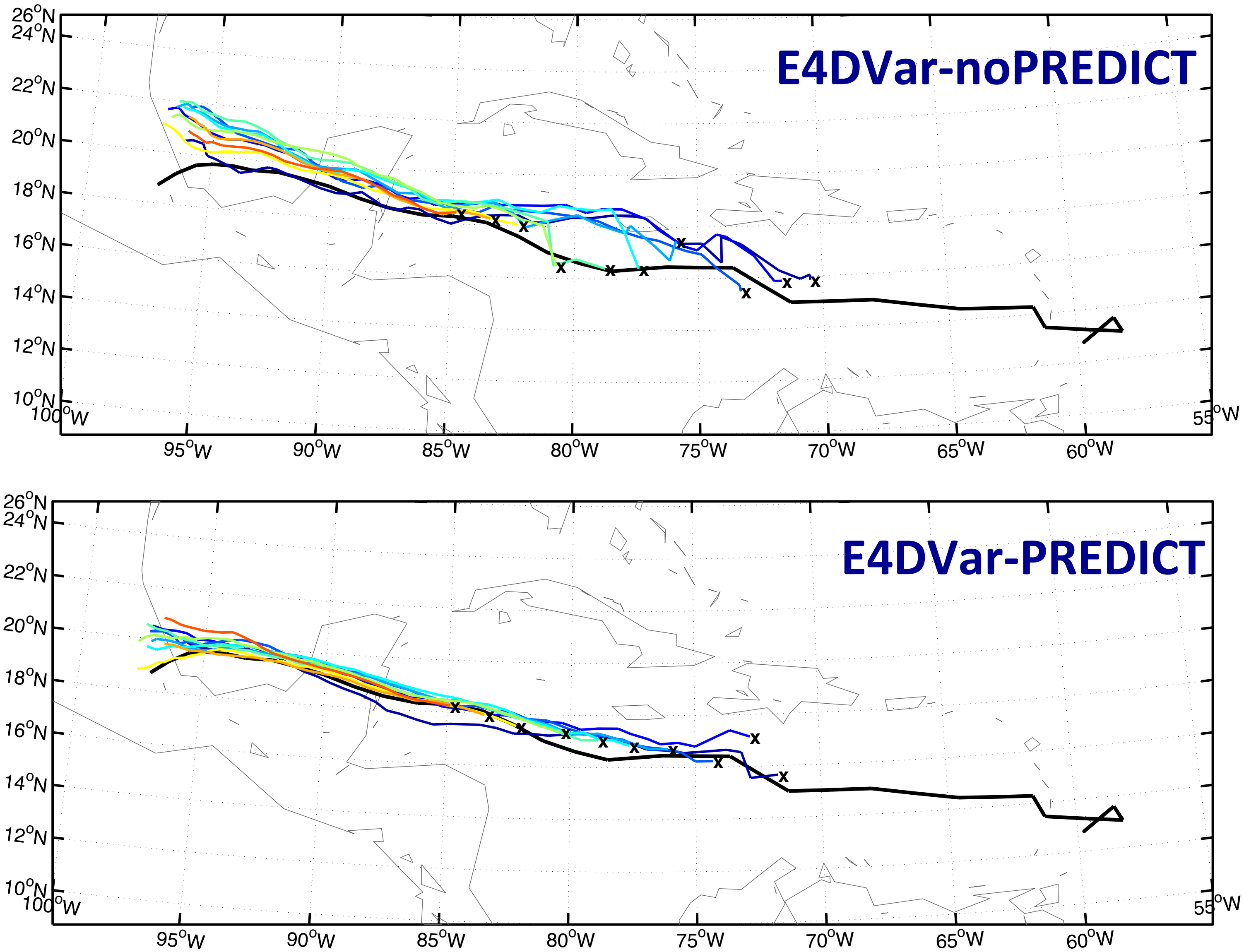
Assimilation of PREDICT Dropsondes for Hurricane Karl (2010) with Coupled EnKF-4DVar (E4DVar)



- **WRF-ARW V3.4; 451 x 226 x 35 domain**
- **13.5 km grid spacing; 30-/60-member ensembles for WRF-EnKF; new WRF-4DVar**
- **Data assimilated (EnKF, 4DVar and E4DVar) every 6 h from 06 UTC 08 Sept. to 00 UTC 15 Sept. 2012 (9 days); GFS analysis and forecast as ICs and BCs**
- **Observations include all MADIS data (except radiance) and dropsondes from the NASA Genesis and Rapid Intensification Processes (GRIP) experiment**

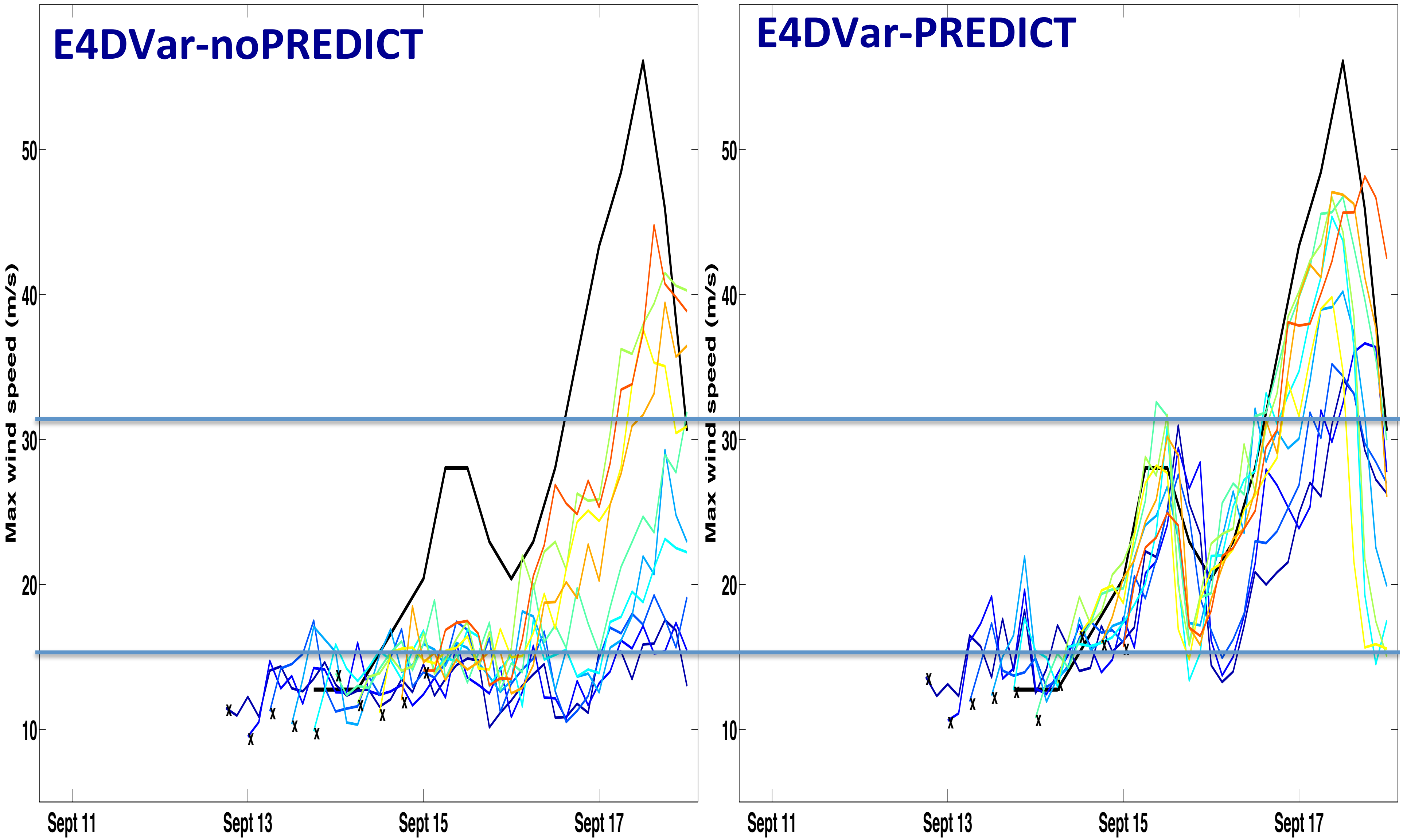
Ongoing research of Jon Poterjoy

Forecasts Sensitivity to PREDICT Dropsondes: Tracks



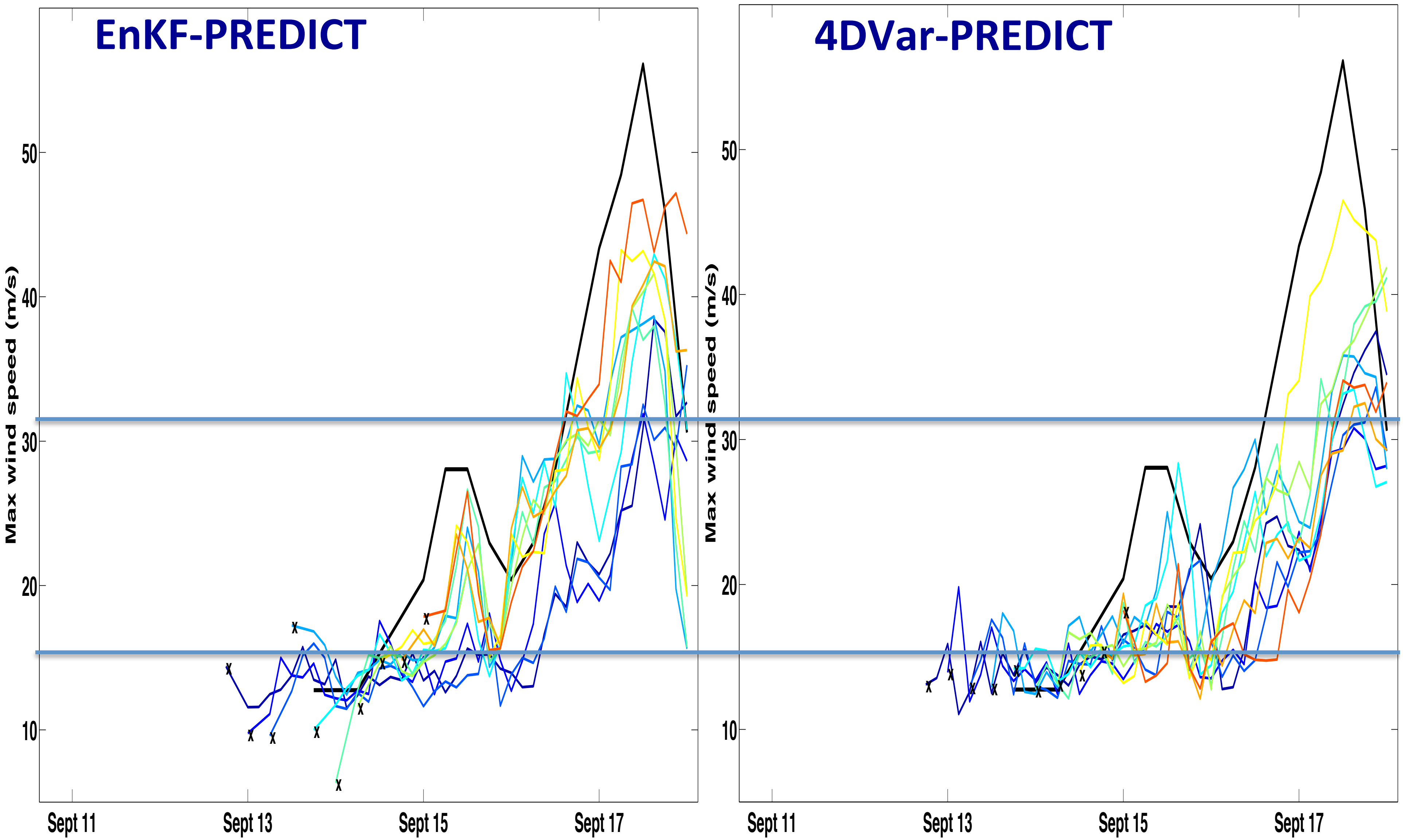
- Forecasts are plotted starting from 18 UTC Sept 12

Forecasts Sensitivity to PREDICT Dropondes: Intensity



Ongoing research of Jon Poterjoy

Forecasts Sensitivity to Data Assimilation Methods



Computational Considerations

With a 40.5-km WRF setup of Karl, the time for each DA:

Average number of 4DVar iterations: 37.4
Average number of E4DVar iterations: 25.6

Average TLM time: 37 s
Average ADM time: 78 s
Average NLM time: 22 s

Average 4DVar analysis time: 82 minutes

Estimated EnKF time: 46 minutes + (22 minutes)

Average E4DVar analysis time: 59 m + 46 m + (22 m)