Assimilation of Inner-Core Observations in Convection-Permitting NWP Models

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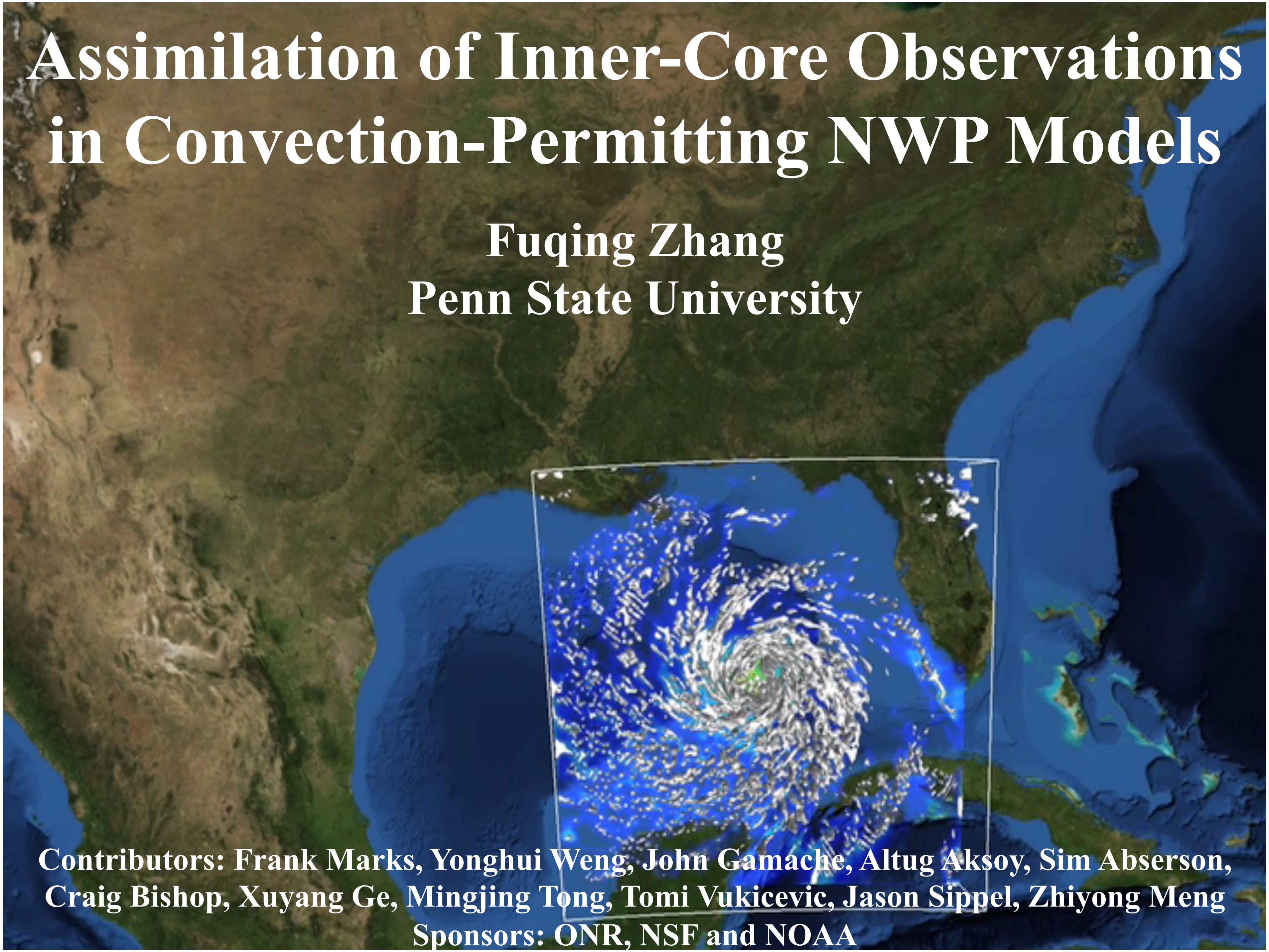
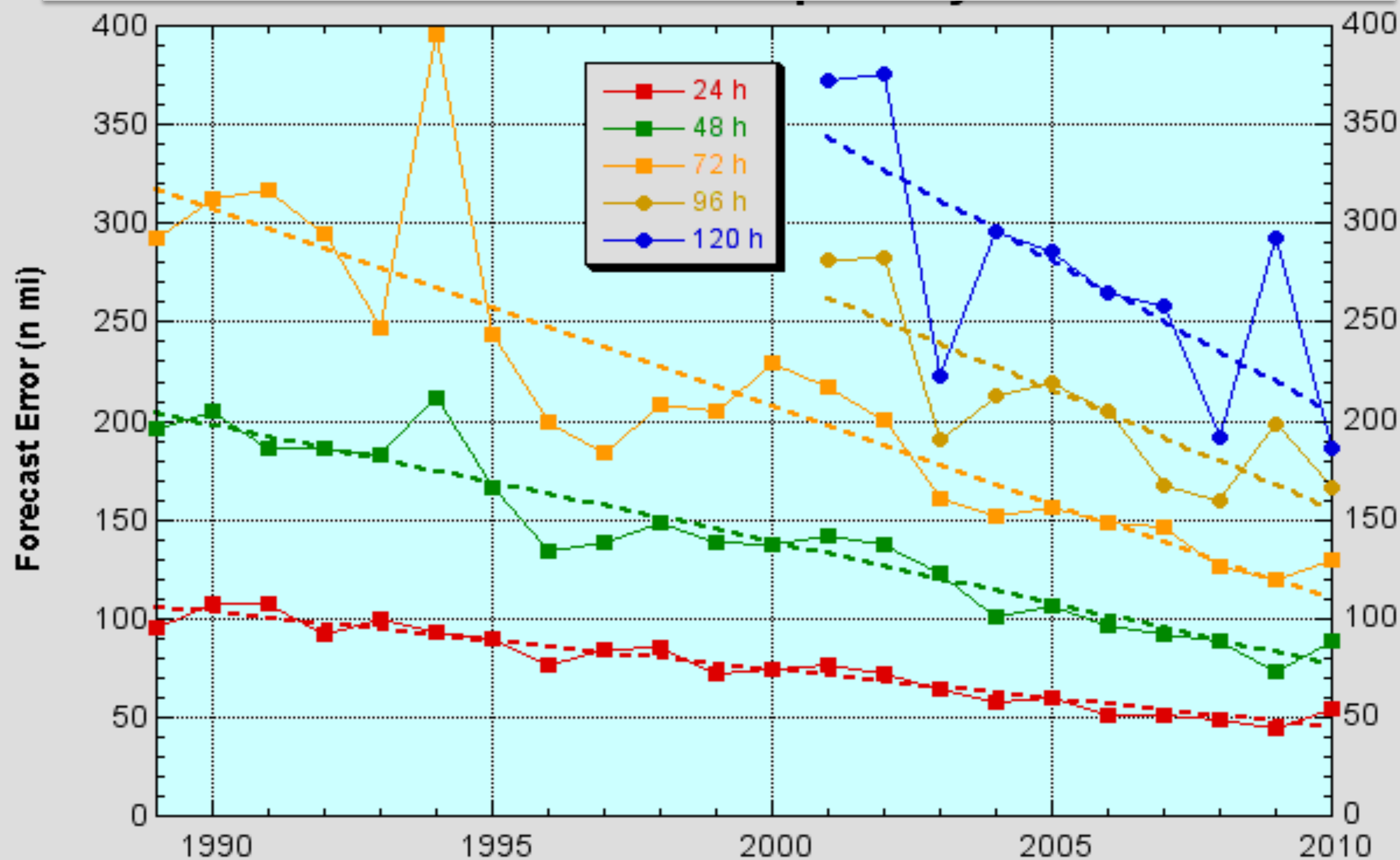


Contributors: Frank Marks, Yonghui Weng, John Gamache, Altug Aksoy, Sim Aberson, Craig Bishop, Xuyang Ge, Mingjing Tong, Tomi Vukicevic, Jason Sippel, Zhiyong Meng
Sponsors: ONR, NSF and NOAA

How did I start the game – serendipity?

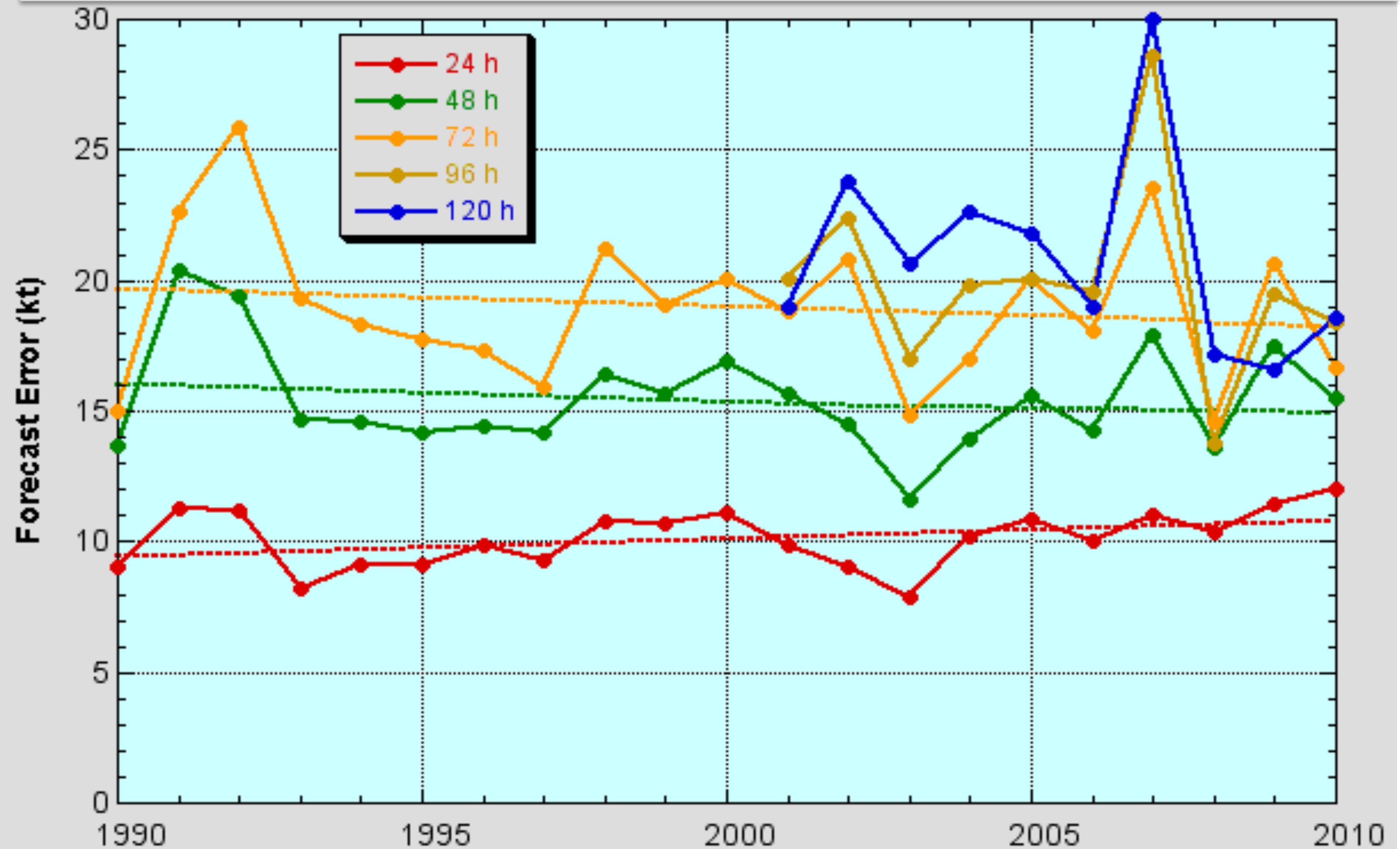
- HiFi Science Strategy Workshop on October 11-13, 2006 in Houston
  - Organized by Greg Holland and Gary Barnes hosted by Chevron
  - Suggested by Worth Nolin to represent Texas A&M as TC expert
  - Encouraged by Frank Marks during the workshop to use Doppler radar
  - First promising results for Katrina with 88D, then Humberto (2007)
- Interactions with Frank during 1st HFIP workshop at HRD in March 2008 and the AMS Hurricane Conference in April 2008 in Orlando
  - Dealt Altug Aksoy from NCAR to AOML to start the DA effort at HRD
  - Commit myself to work with Altug and others at HRD in the summer 2008
  - Altug started at HRD on July 14, and I arrived there the same week
- 30-million CPUs from NSF/TACC through HFIP for proof-of-concept 2008
  - Super-obbing the TDR velocity by John Gamache and Yonghui Weng
  - Near realtime for Dolly, first end-to-end realtime test for Ike w/ 16k cores

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, less understood, under-observed, under-resolved, and/or intrinsically less predictable?

Overview of TC Inner-Core Observations

- **Standard surface and sounding observations: very limited coverage**
- **Ground based radars: good volume but limited to coastal areas**
- **Satellite data:**

    Derived products: winds, moisture and temperature, …

    Radiance: abundant but hard to assimilate, especially cloudy area

    Space borne radars: TRMM, CloudSat, …; infrequent

- **Airborne platform: operational only in Atlantic basin**

    Flight-level measurements

    Dropsondes

    Airborne radars

  Unmanned aircraft: UAV, Global Hawk

Overview of DA for TC Initialization

1. Vortex bogussing through insertion of a balanced TC-type vortex (GFDL, COAMPS)

2. Vortex relocation or surgery (GFS)

3. Combination of vortex bogussing with variational data assimilation:

   - HWRF (Liu et al. 2008); BDA (Xiao and Zou 2001); UKMO

4. Balance inversion often with high-resolution radar/sat observations:

   - Vorticity method (Lee et al. 2003); 3.5-DVAR (Zhao and Jin 2008)

5. Vortex initialization with advanced data assimilation methods: EnKF and 4DVAR

   - EnKF assimilation of TC location/intensity (Chen&Snyder 2006; Torn&Hakim 2010)

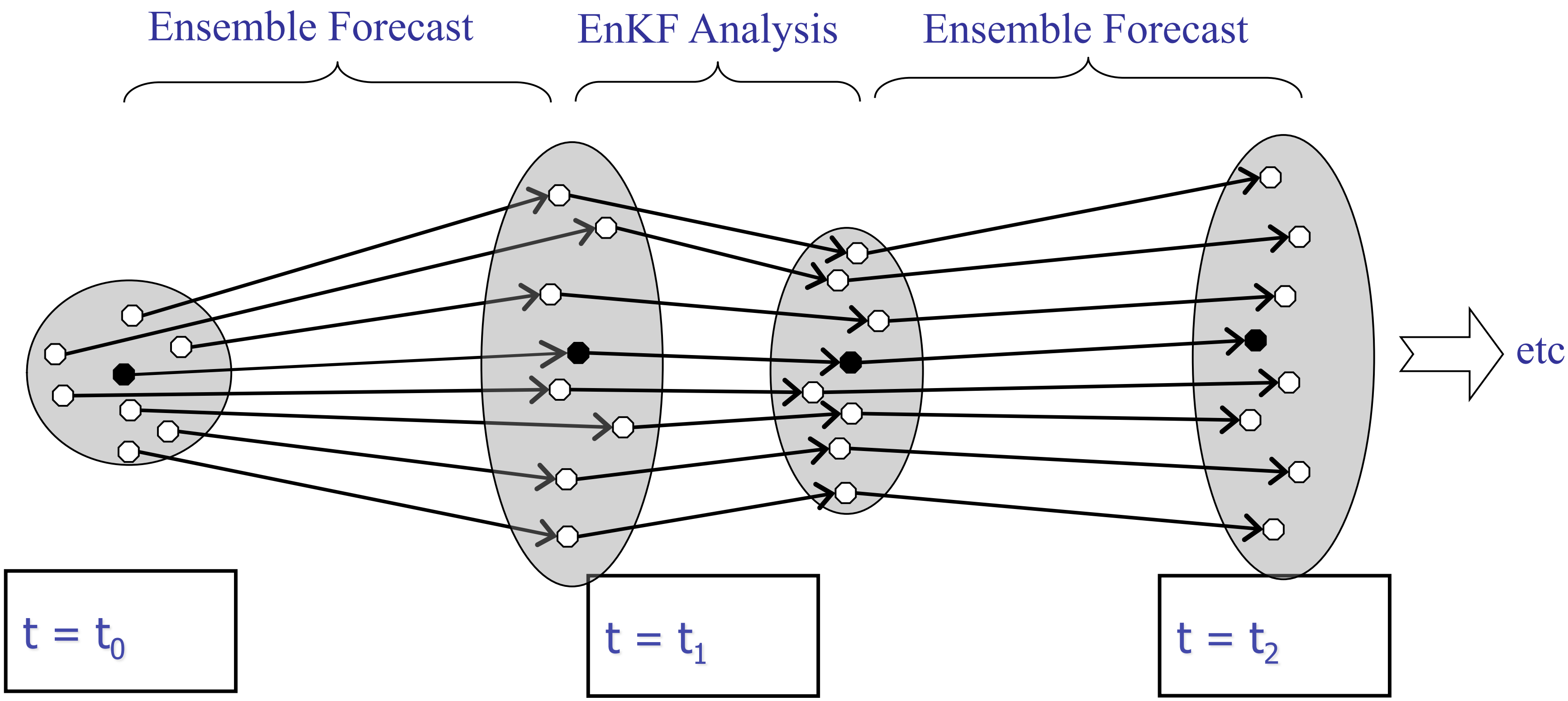
   - EnKF assimilation of inner-core Doppler radar observations (this talk)

EnKF: flow-dependent sample covariance from ensemble

(Evensen 1994; Snyder and Zhang 2003)

$x^a = x^f + BH^T(HBH^T+R)^{-1}(y-Hx^f)$

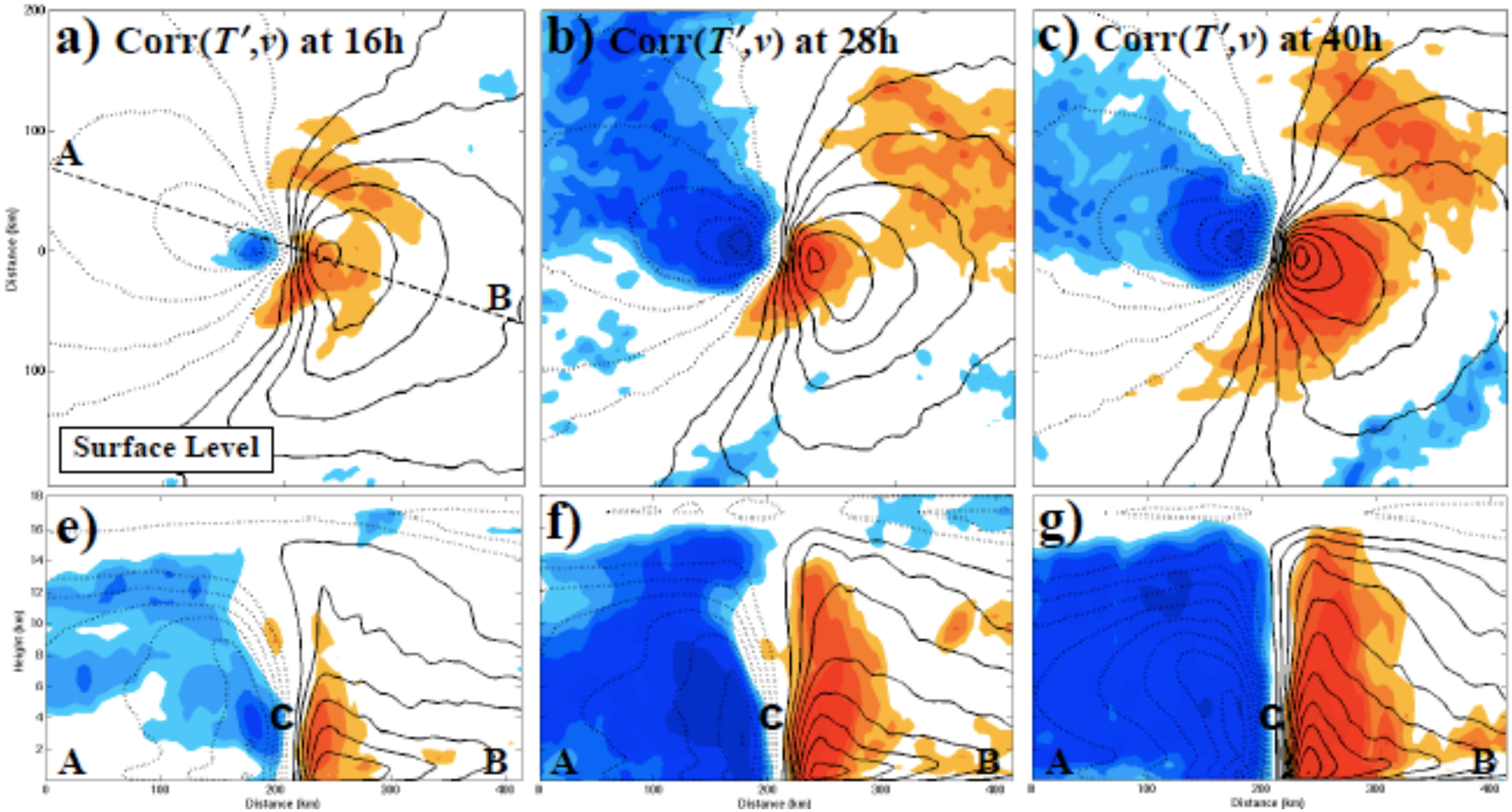
$B = N_e^{-1}\Sigma\,(x_i^f-\underline{x})(x_i^f-\underline{x})^T$



Equivalence to 4Dvar in linear systems; no adjoint or TLM; fully coupled with ensemble forecast; nonlinear dynamics included; adaptable to be coupled/hybrid with 3D/4DVar

Dynamics and Structure of Error Covariances

Cross-spatioal correlation of 4-km T at point C with v

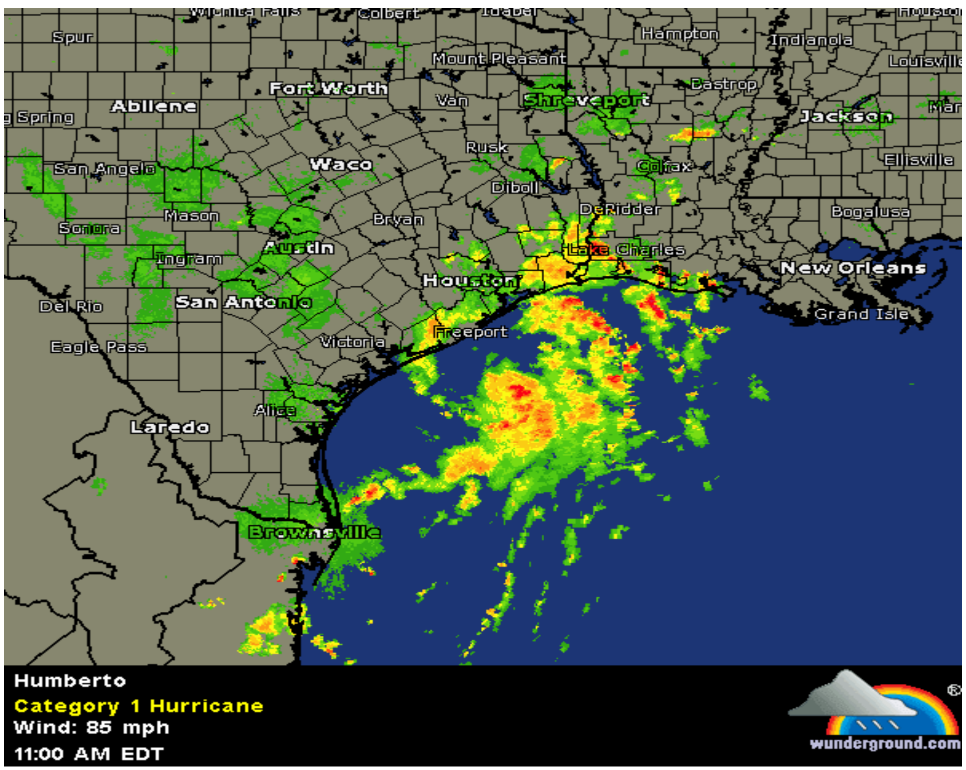


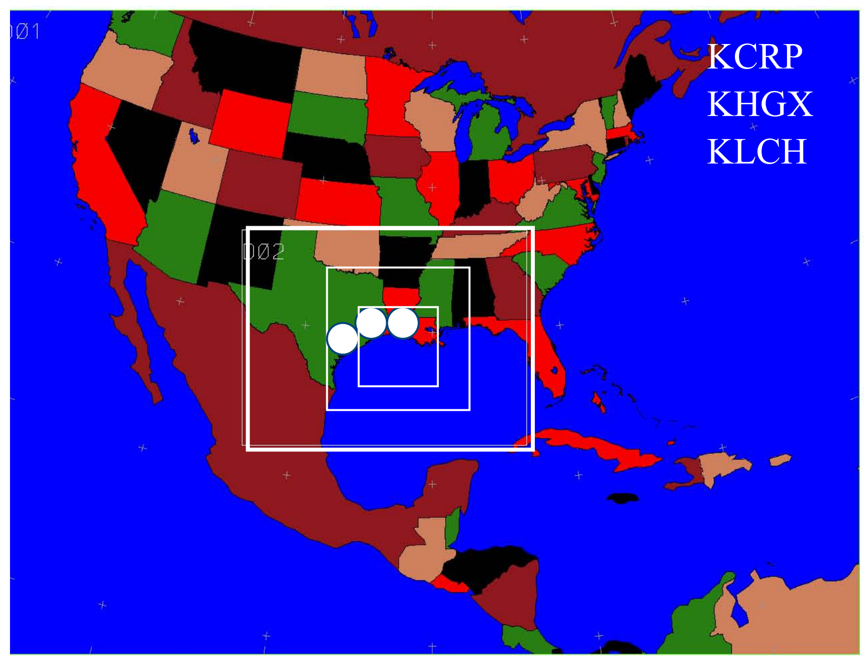
(Poterjoy and Zhang 2011 JAS)

Assimilate WSR88D Doppler Winds for Hurricanes

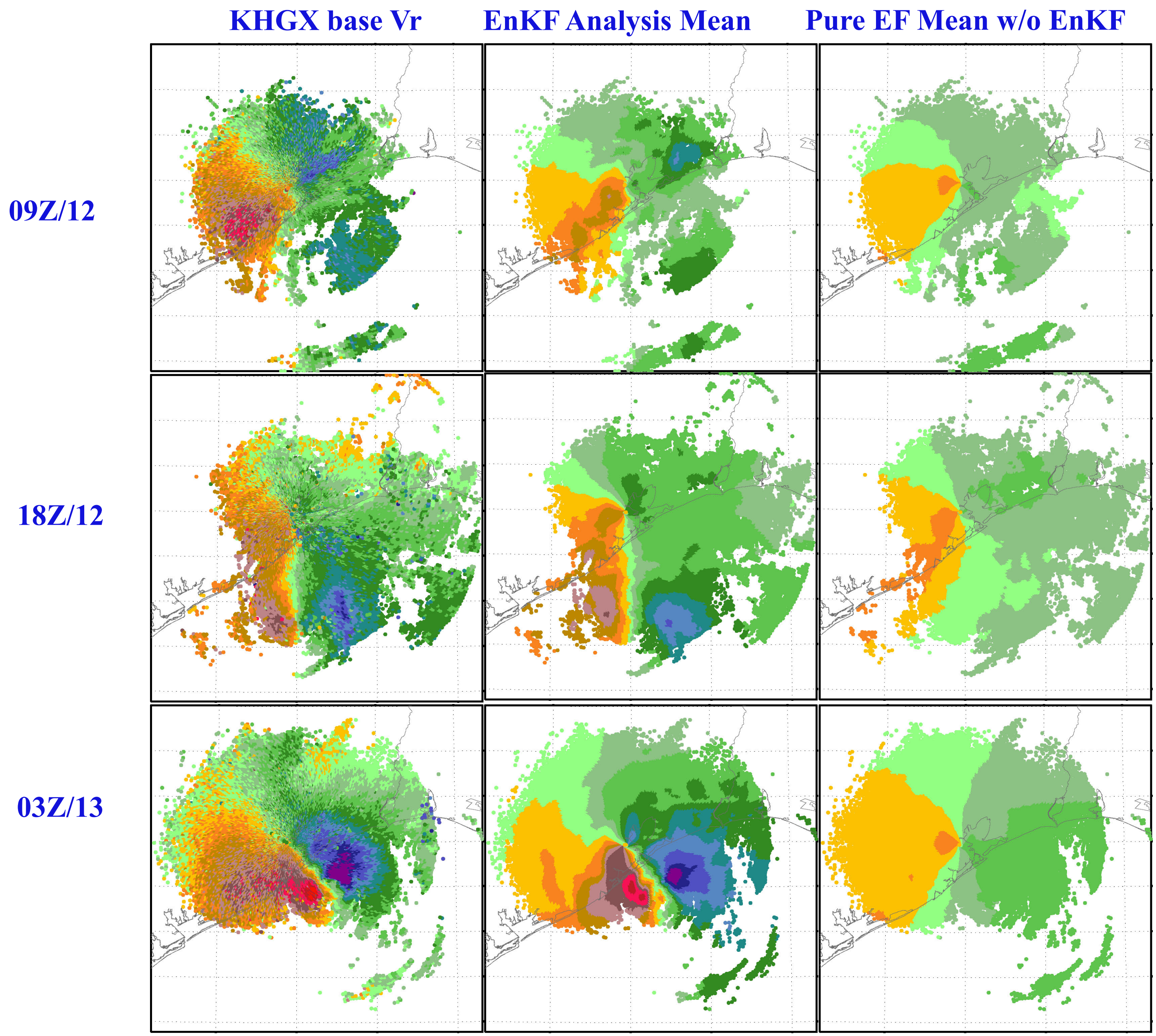
- **Model:** Weather Research and Forecast Model (WRF) with 4 domains two-way nested and grid sizes of 40.5, 13.5, 4.5, and 1.5km [NOAA HWRF: model 9km]
- **Data:** Doppler winds from three coastal weather surveillance radars [available routinely for more than 20 years but never used in any NOAA operational models]
- **Data assimilation method**: Ensemble Kalman Filter (Meng and Zhang 2008a,b) [as we will show, the current scheme in NOAA operational models is insufficient]

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



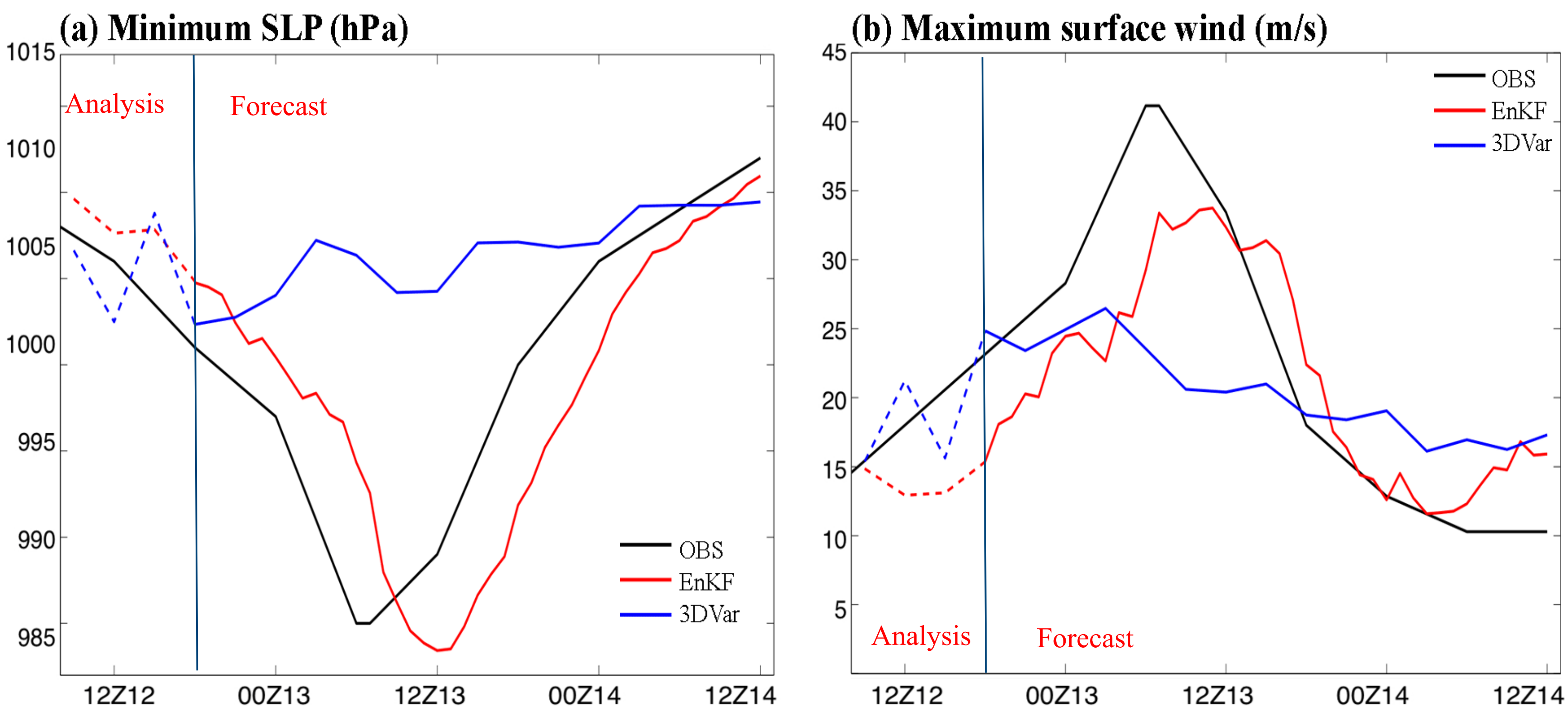


WRF/EnKF Analysis vs. Observations vs. NoDA



Assimilate W88D Doppler Vr for Humberto'05

WRF/EnKF Forecast vs. Observations vs. 3DVAR

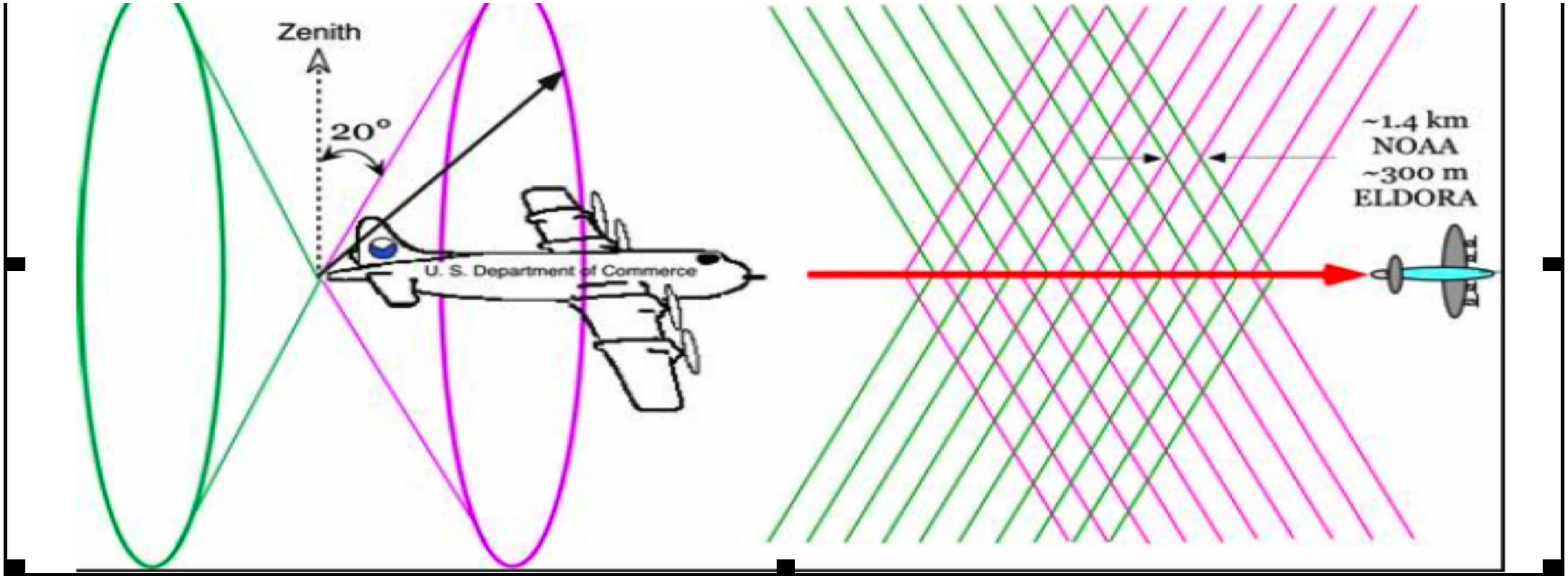


The WRF/3DVAR (as a surrogate of operational algorithm) assimilates the same radar data but without flow-dependent background error covariance, its forecast failed to develop the storm despite fit to the best-track observation better initially

(Zhang et al. 2009 MWR)

Assimilate Airborne Doppler Winds with WRF-EnKF

Available for 20+ years but never used in operational models due to the lack of resolution and/or the lack of efficient data assimilation methods



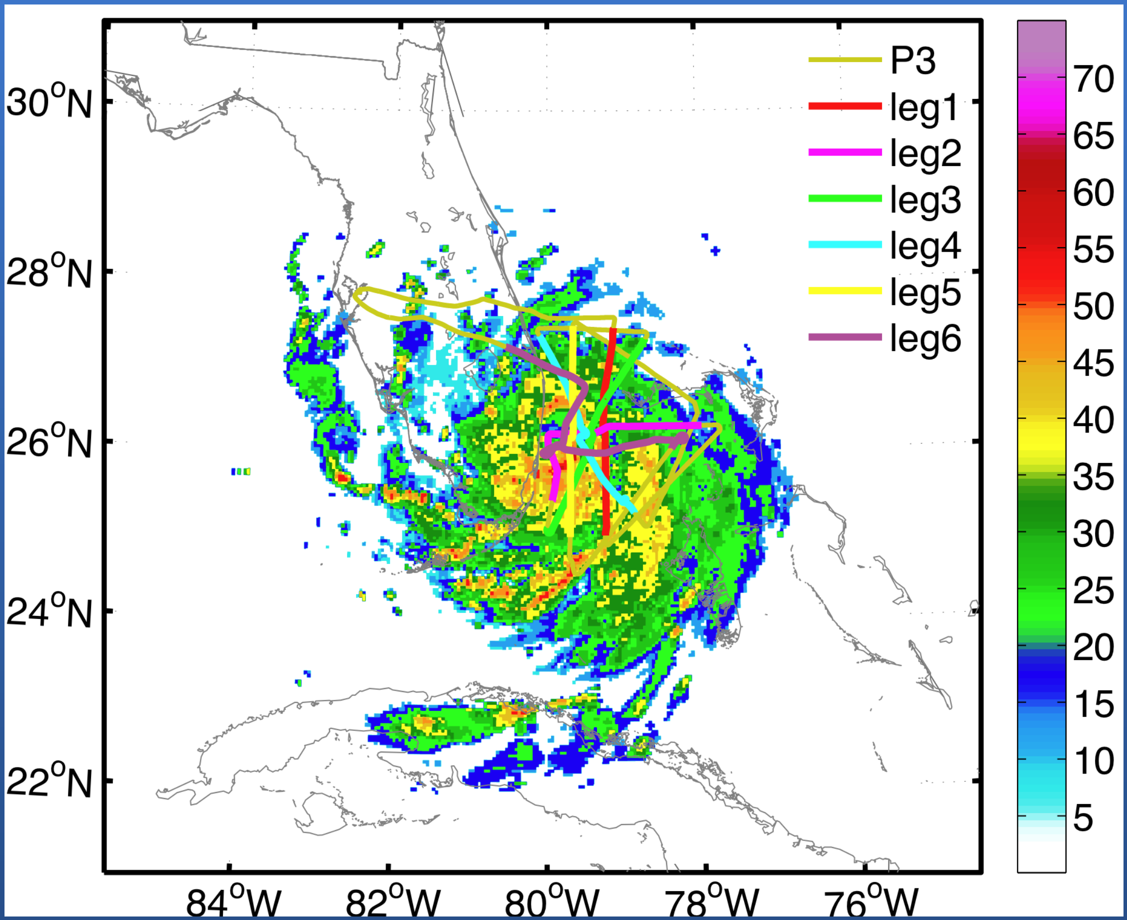
Superobservations: 1. Separate forward and backward scans; 2. treat every 3 adjacent full scans as one fixed-space radar (translation<5km); 3. thinning ---one bin for 2 km in radial distance and 3 degree in scanning angle; 4. use medium as SO after additional QC checking

These SOs are generated onboard of NOAA P3 flights; transmitted to ground in real-time

WRF-EnKF: 3 domains (40.5, 13.5&4.5km), 60-member ensemble

(Weng and Zhang 2011 MWR; Zhang, Weng, Gamache and Marks, 2011 GRL)

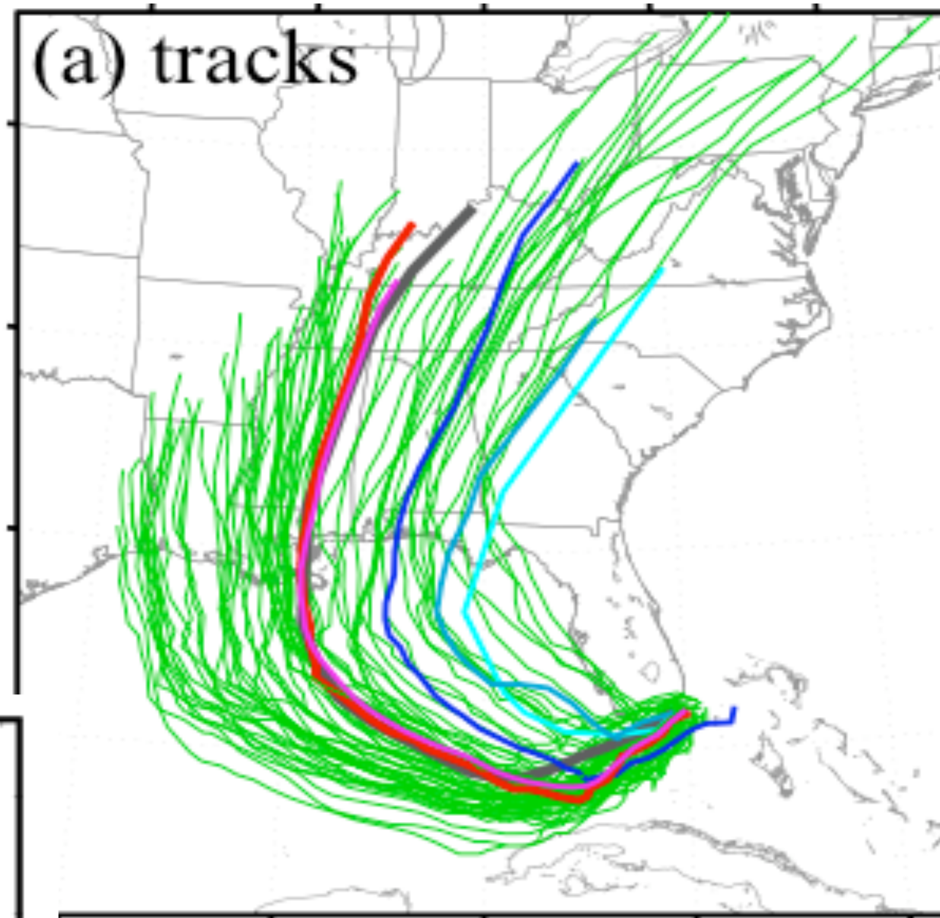
Katrina: Airborne Radar Observations

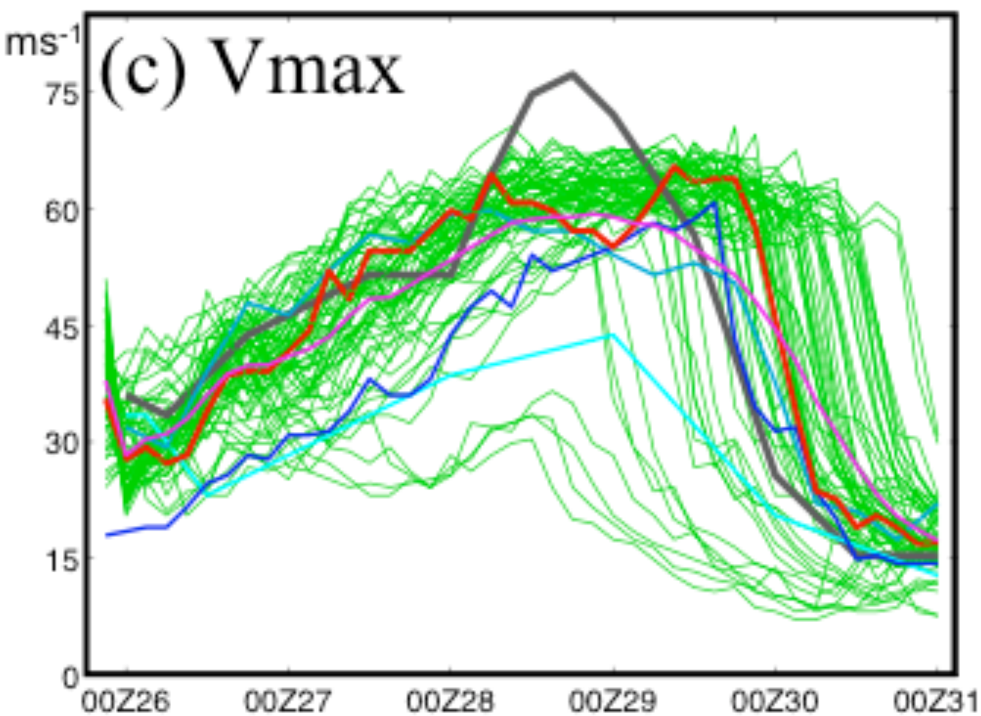


KAMX composite reflectivity at 2000 UTC 25 Aug 2005 (the center time of the last leg of P3 050825I1 mission) and P3 flight track for the 050825I1 mission over the 4.5 km horizontal resolution model domain.

WRF/EnKF Performance With airborne Vr obs

60-member ensemble forecast from EnKF posterior uncertainty



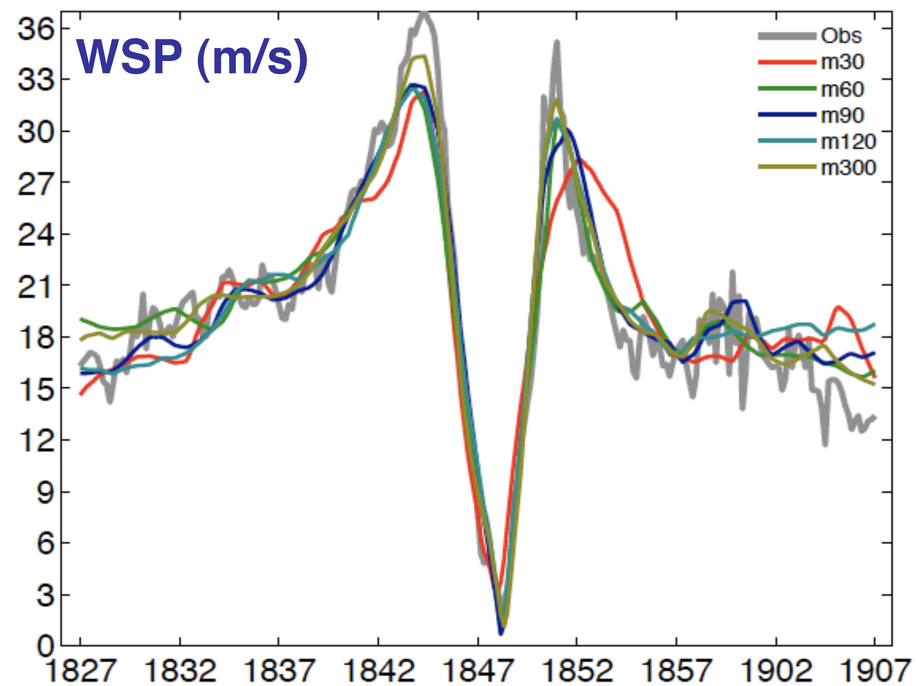


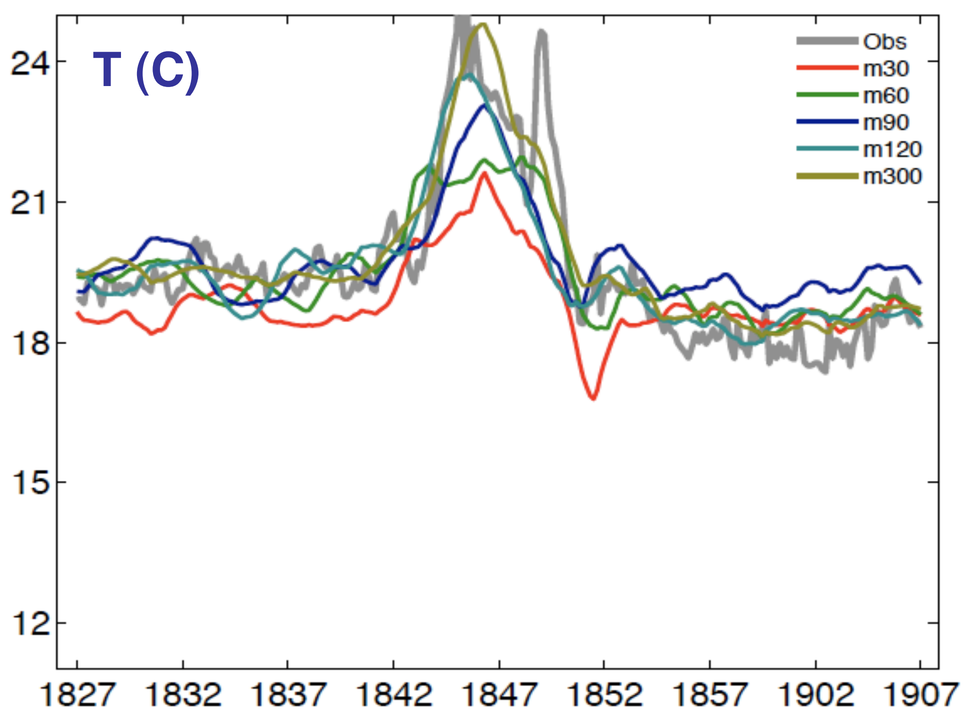
(Weng and Zhang 2011, MWR)

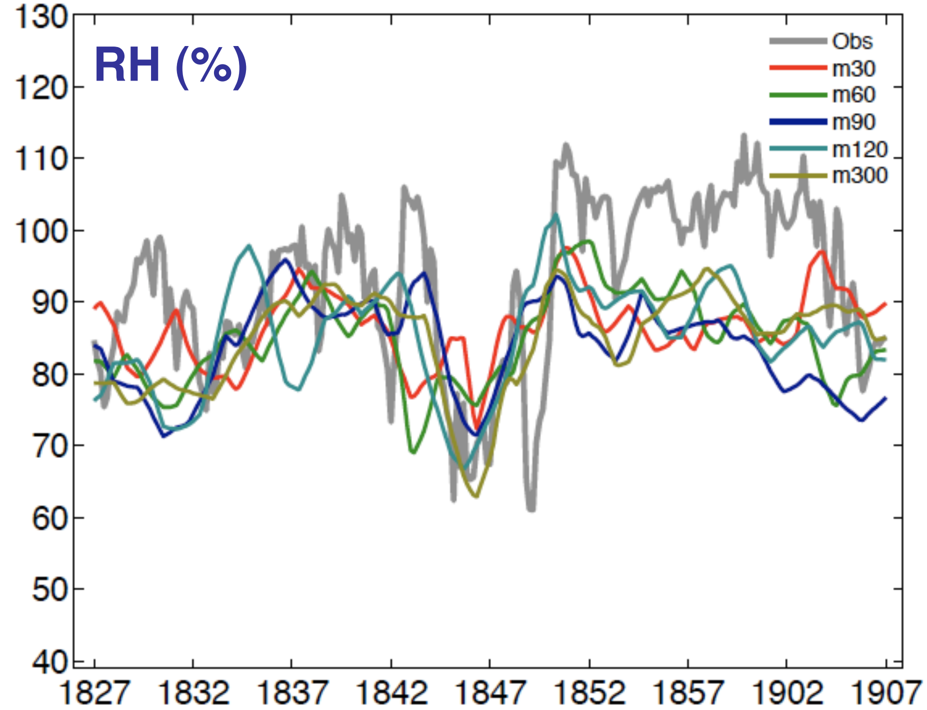
Verification of flight-level wind, T and RH (leg 5)

Sensitivity to ensemble size:
30 good, >=60 even better

(Weng and Zhang 2011, MWR)

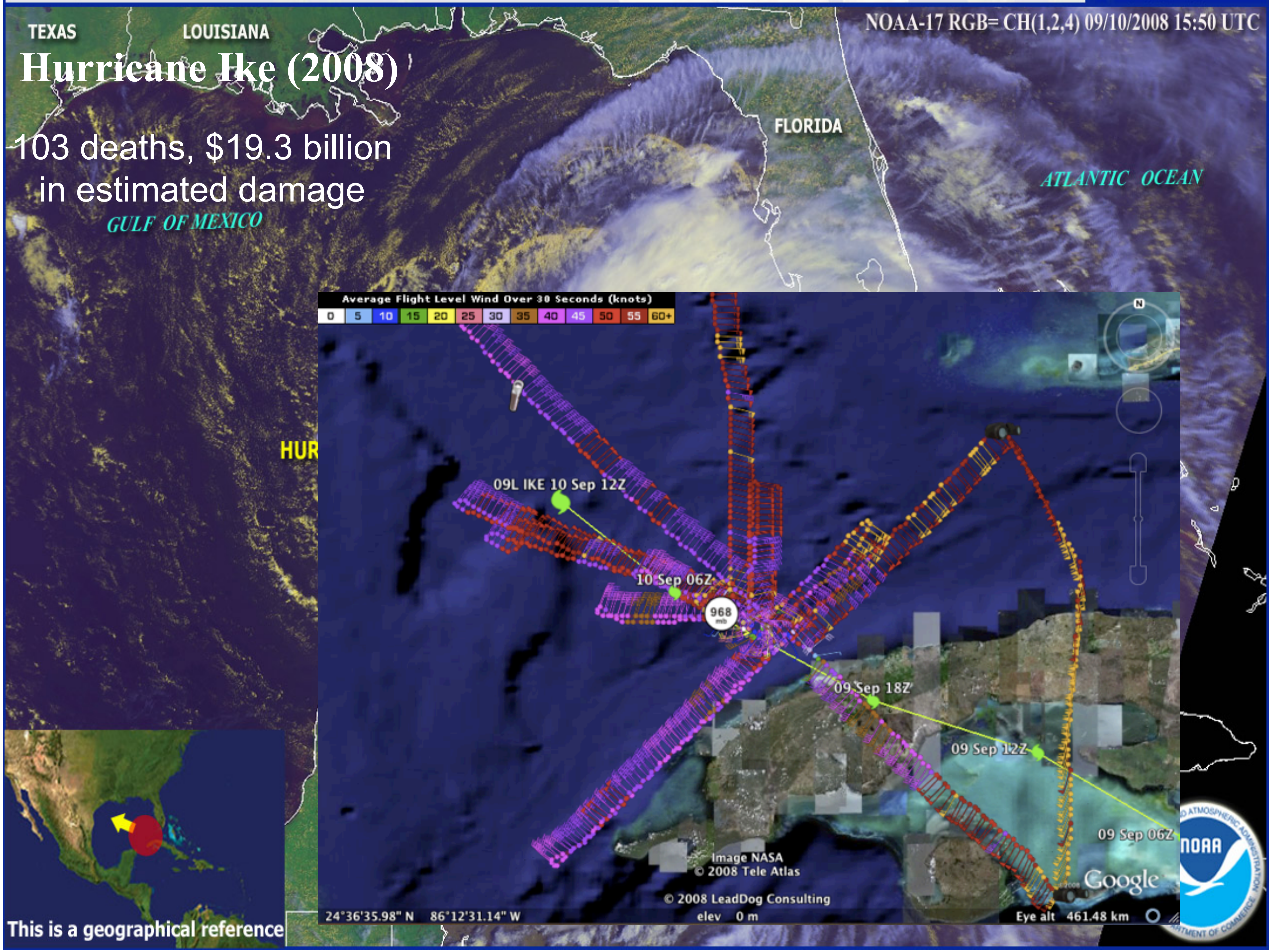






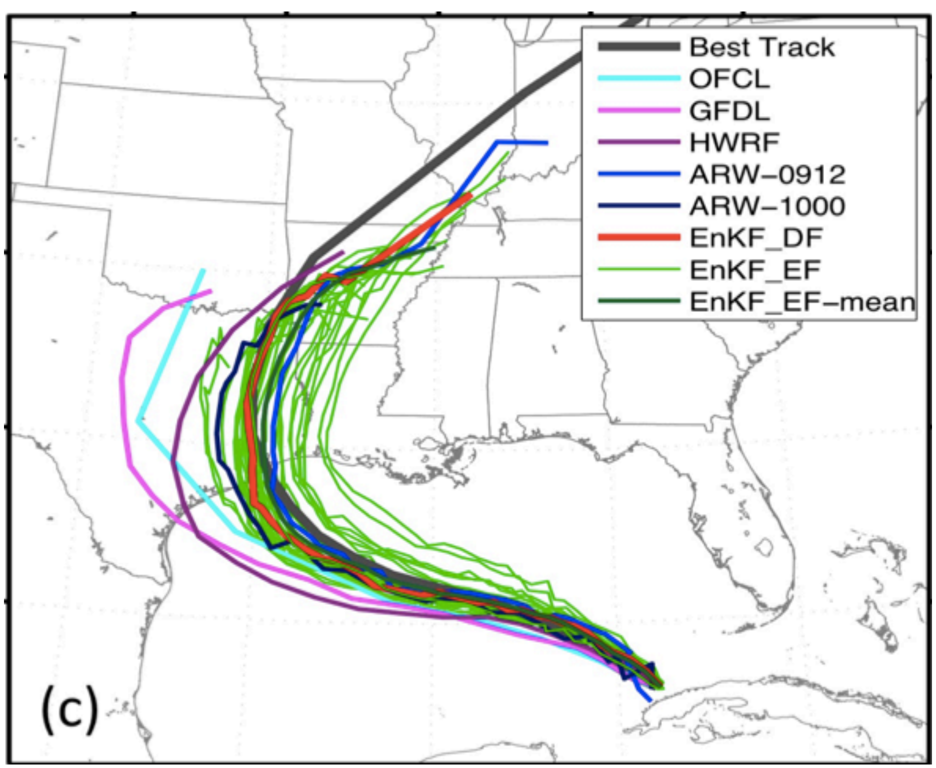
at 8 mph with maximum sustained winds of 90 mph.

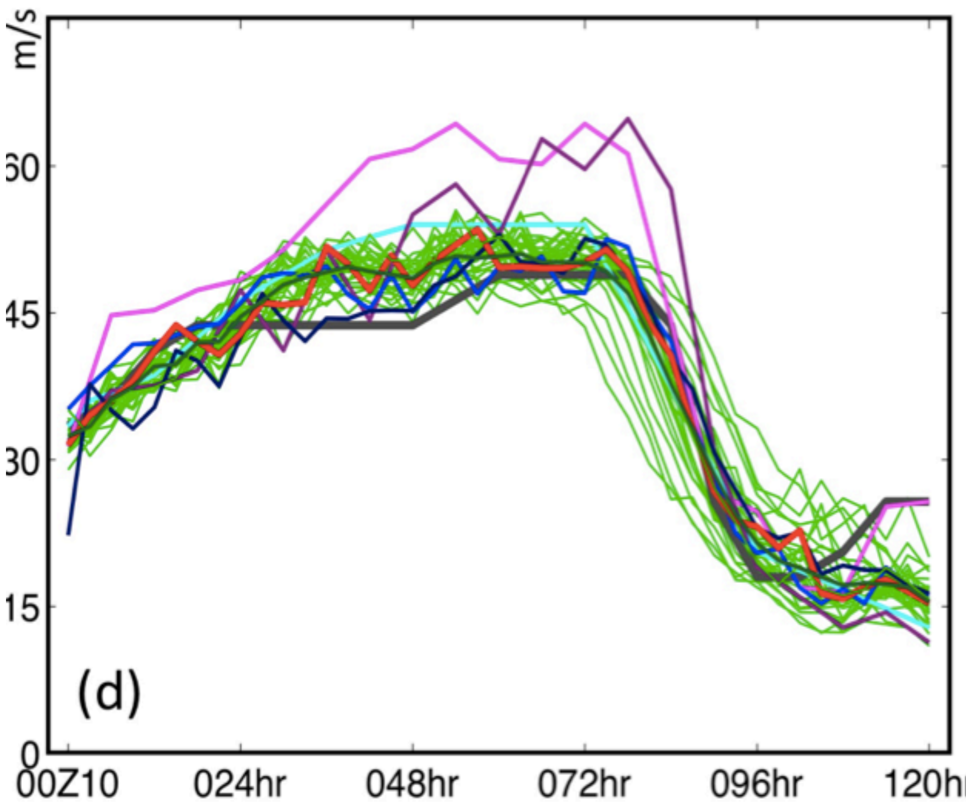
Credit: NOAA



WRF-EnKF Performance: Hurricane IKE (2008)

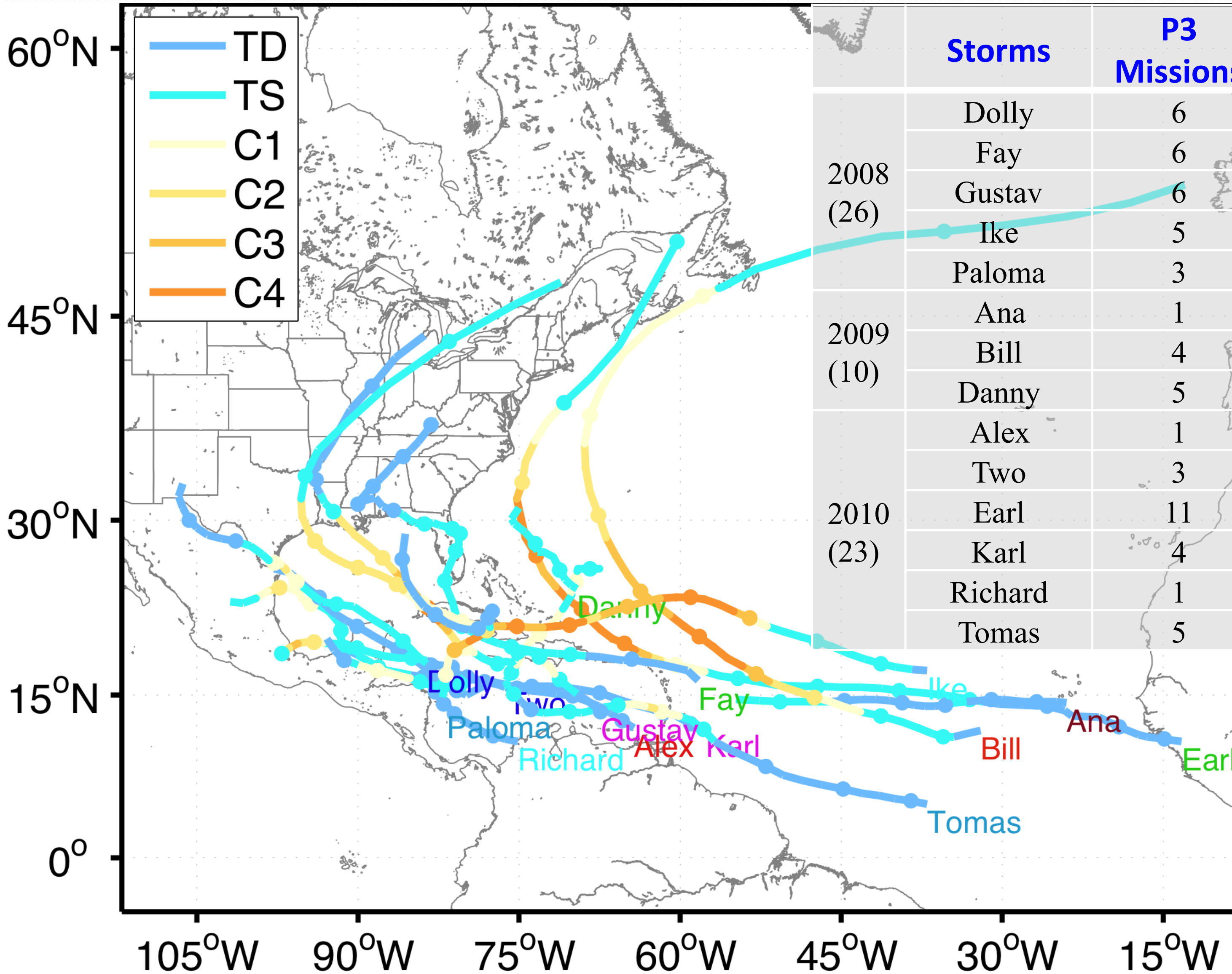
- *1st end-to-end realtime convection-permitting ensemble forecast with EnKF assimilation of Vr SOs from P3; available 3.5h after obs*
- *16,000 TACC cluster cores used simultaneously; 60-member ensemble*





(Zhang 2011 CiSE)

WRF-EnKF Performance with Airborne Vr for 2008-2010

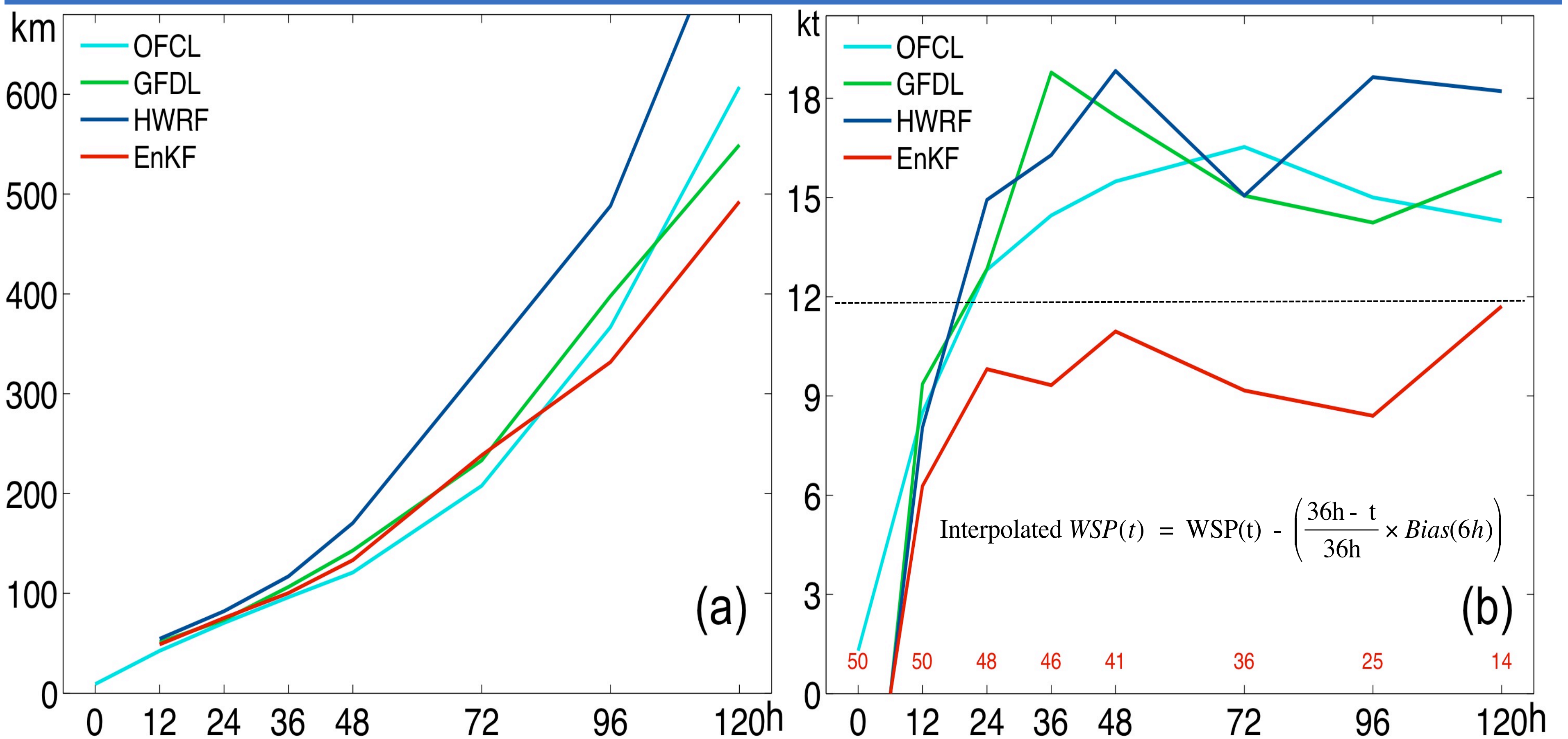


	Storms	P3 Missions
2008 (26)	Dolly	6
	Fay	6
	Gustav	6
	Ike	5
	Paloma	3
2009 (10)	Ana	1
	Bill	4
	Danny	5
2010 (23)	Alex	1
	Two	3
	Earl	11
	Karl	4
	Richard	1
	Tomas	5

(Zhang et al. 2011 GRL)

WRF-EnKF Performance Assimilating Airborne Vr

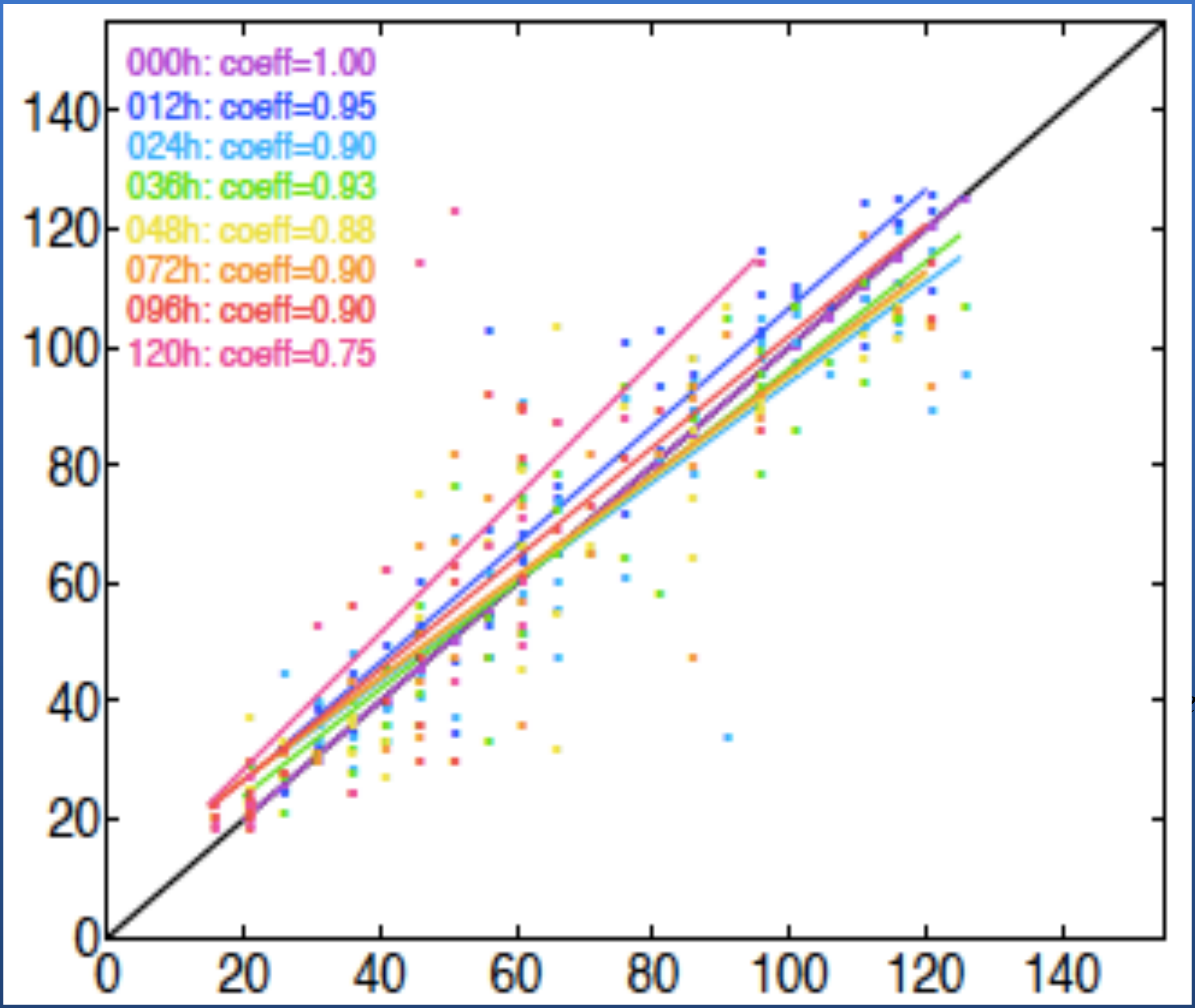
Mean absolute track & intensity error for all 61 TDR missions 2008-2010



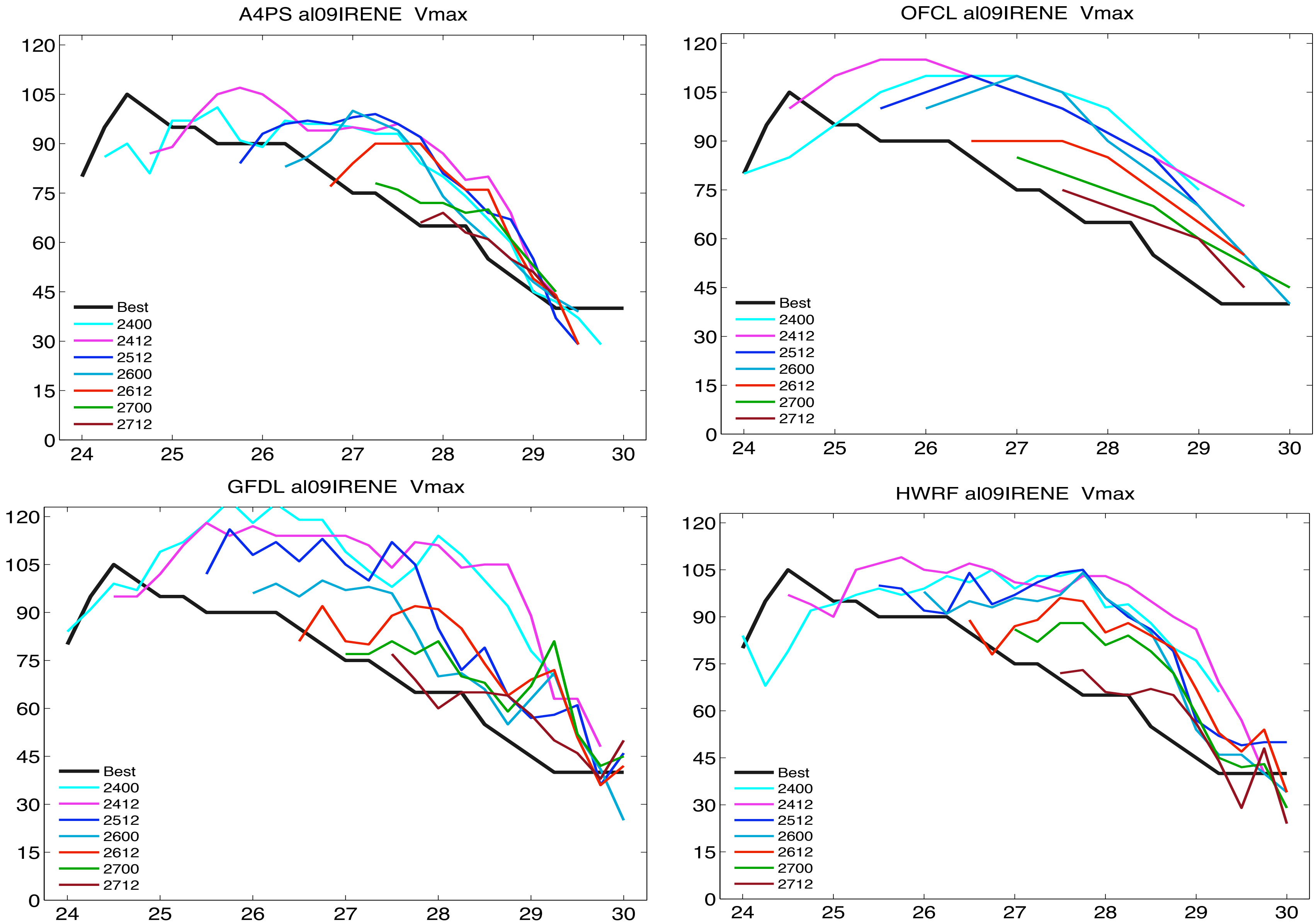
(Zhang et al. 2011 GRL)

WRF-EnKF Performance Airborne Vr for 2008-2010

1.5-km EnKF Predicted versus Best-track Maximum Wind Speed Error (kts)

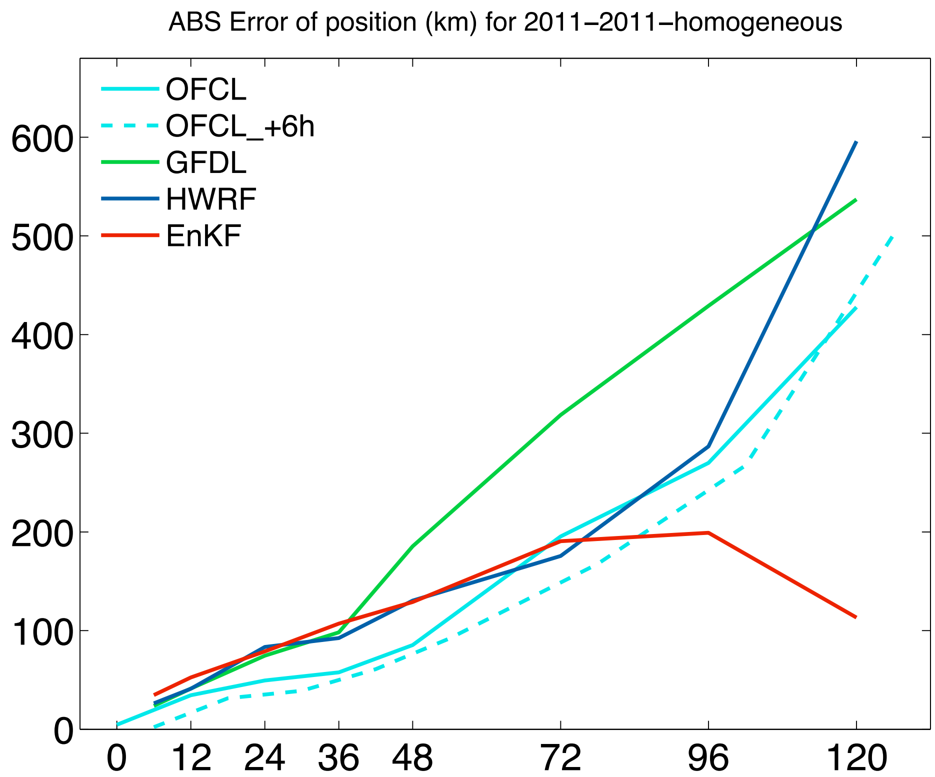


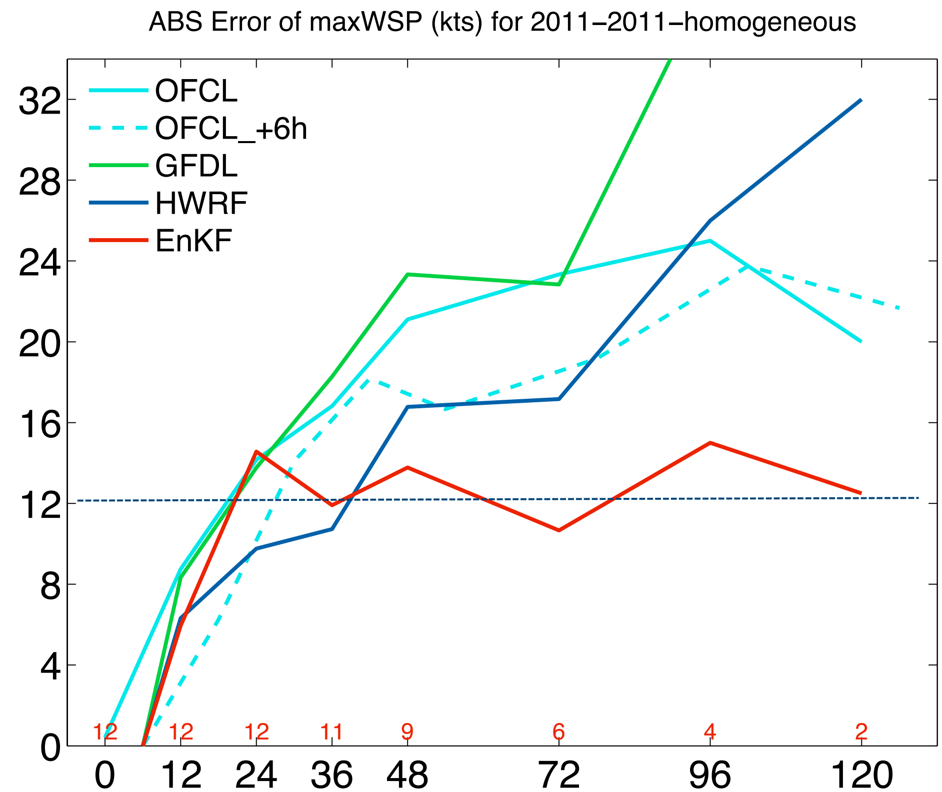
Irene (2011): HFIP Stream1.5 with WRF/EnKF
Realtime assimilation of airborne Vr obs (7 missions)



EnKF Performance Assimilating Airborne Radar OBS

Mean Absolute Error for 12 missions of 2011 (7 Irene + 5 Rina)

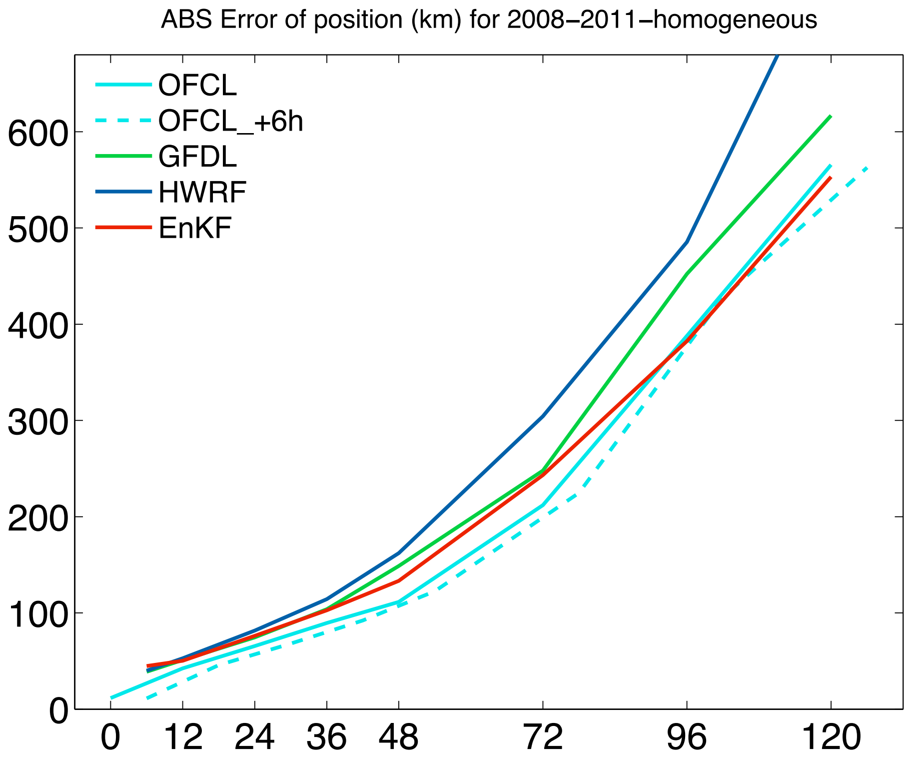


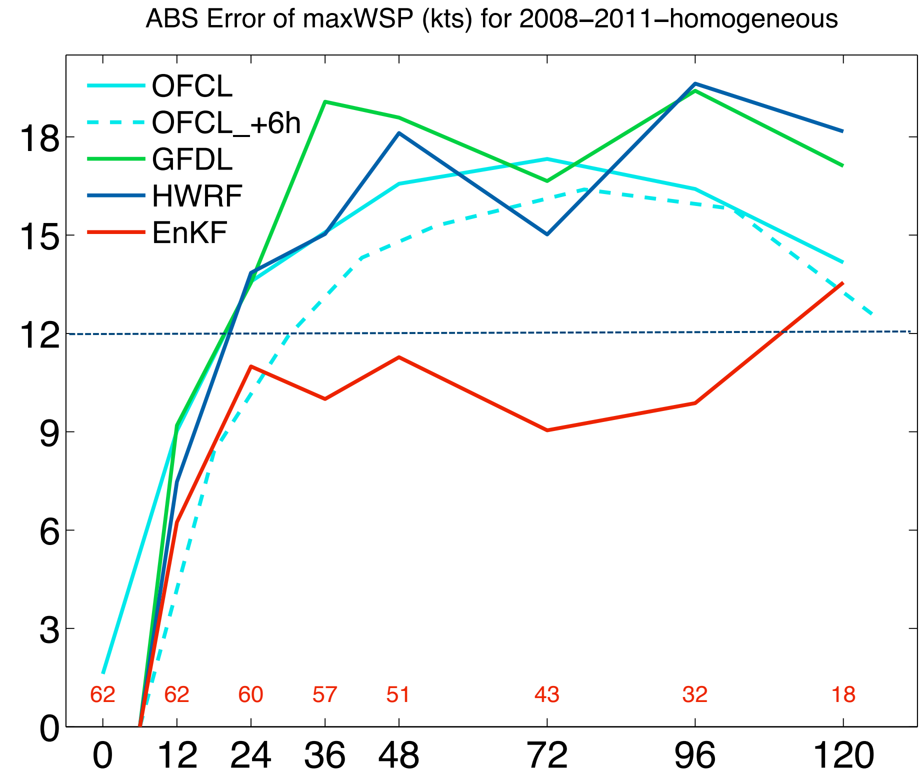


A4PS: PSU 4.5km single forecast initialized with EnKF analyses

EnKF Performance Assimilating Airborne Radar OBS

Mean Absolute Error and Ensemble Spread for 73 missions during 2008-2011

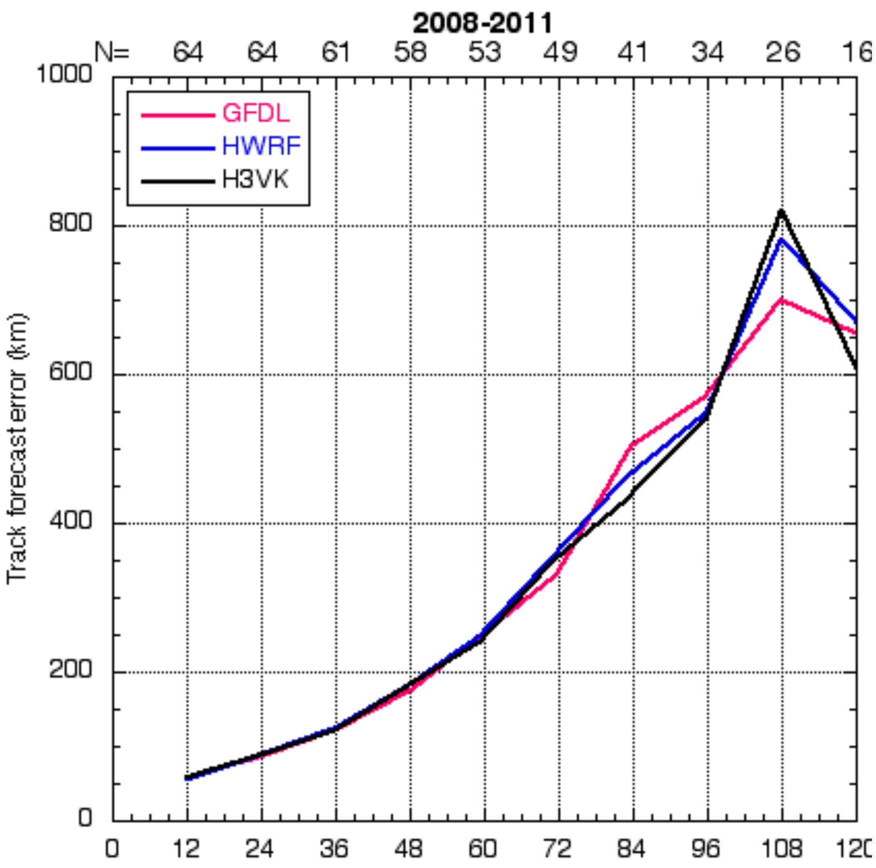


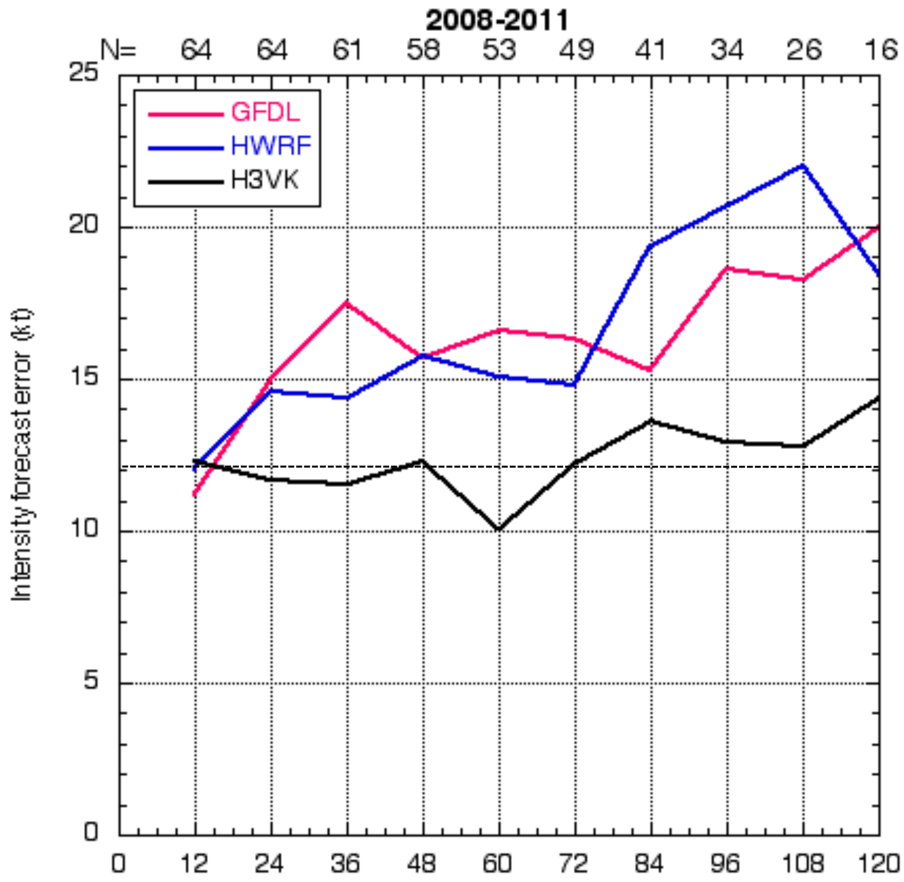


With bias correction of intensity error

$$Corrected\ WSP = \mathrm{WSP} - \left(\frac{\mathrm{30h} - \mathrm{t}}{\mathrm{30h}} \times Bias\_at\_initial\_time \right)$$

VORTEX-SCALE DA WITH NOAA/AOML/HRD's HEDAS 2008-2011 REAL-TIME & RETRO RUNS

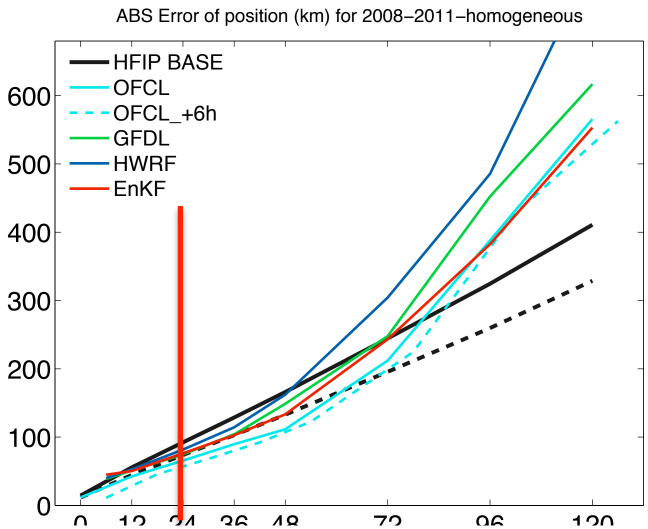


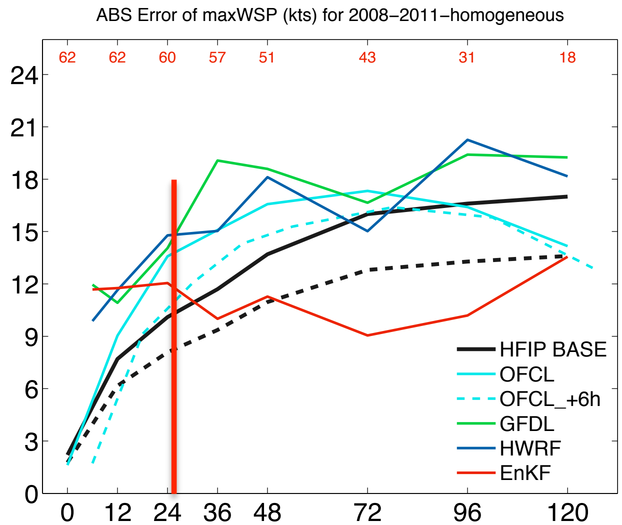


Courtesy of Altug Aksoy and Sim Aberson at NOAA/AOML Hurricane Research Division

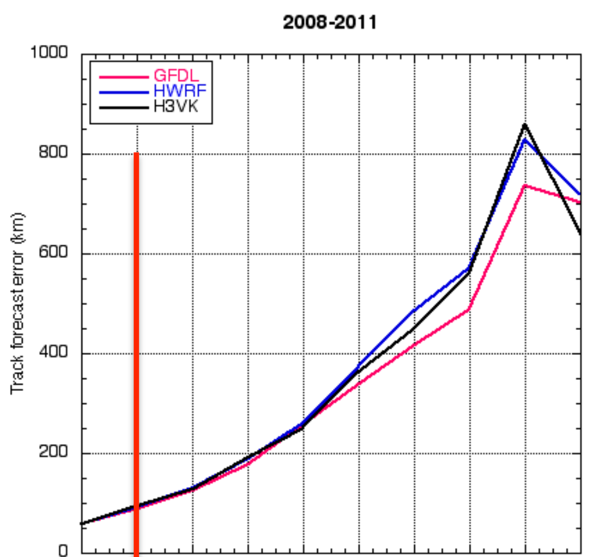
0-24h forecast bias from PSU and HRD's vortex scale EnKF DA (2008-2011)

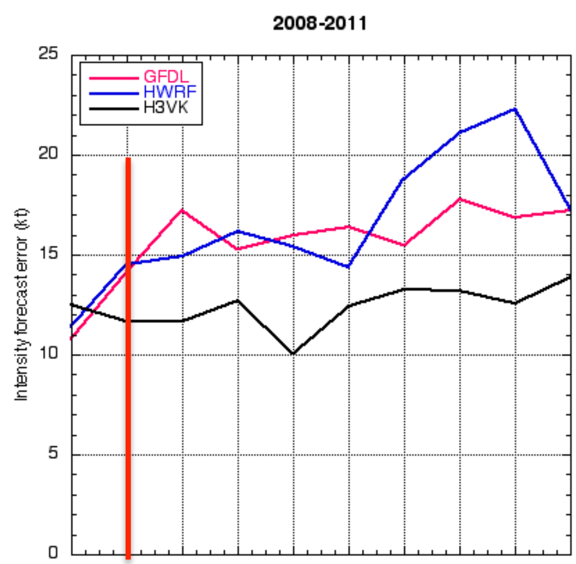
PSU WRF-ARW





HRD HWRF HEDAS





Slide from Tomi Vukicevic, NOAA/AOML Hurricane Research Division

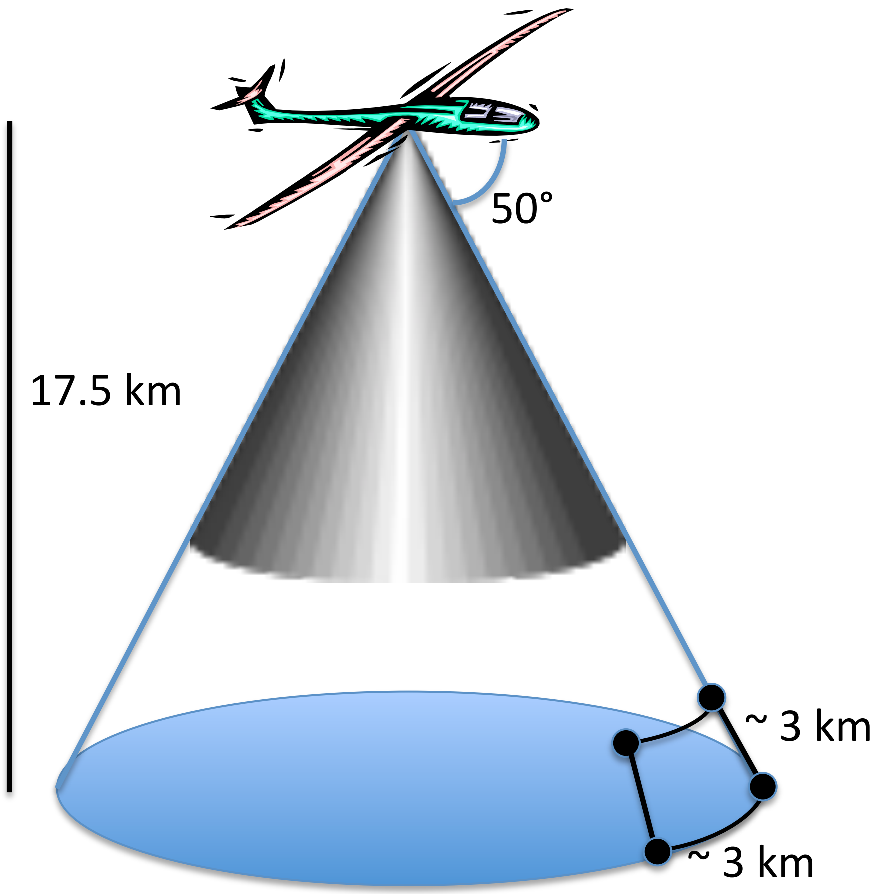
Lecture learned and research challenges

- Negative intensity bias in short-term forecasts is common among high-resolution systems and causes significant errors in the forecast at 6-24 h range
- HWRF experience suggests that the negative bias is related to spin-down for cases with hurricane initial intensity
- The short-term forecast bias affects the data assimilation results and the impact of data assimilation on the forecast
- **Would be good to have more diagnostics about the short-range forecast bias from different groups working on the vortex-scale systems. Where is the bias coming from ?**
- **Need new research to understand vortex adjustment in short-range forecast**
- **What is the impact of short-range bias on longer-range skill?**

Slide from Tomi Vukicevic, NOAA/AOML Hurricane Research Division

HIWRAP Doppler Radar Vr from Global Hawk

NASA Hurricane and Severe Storm Sentinel (HS3)

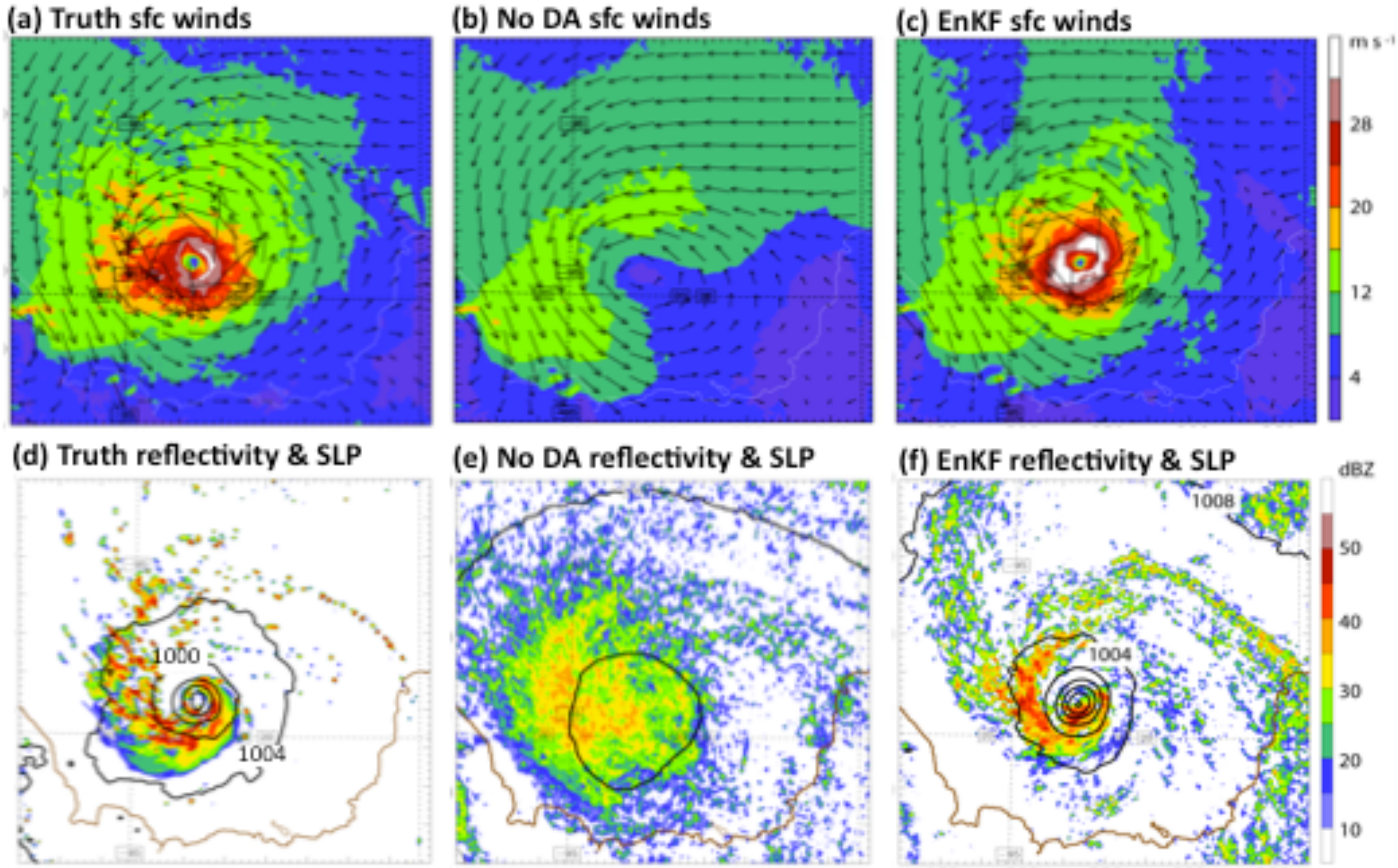


- Assuming instantaneous scan
- Using one scan every ~28 km (~0.25° lat)
- Approximately constant ~3-km spacing between obs on surface of cone
- Only assimilate when dBZ > 10

In collaboration with Jason Sippel and Scott Braun at NASA

Assimilating HIWRAP Vr from GH: OSSE

NASA Hurricane and Severe Storm Sentinel (HS3)



In collaboration with Jason Sippel and Scott Braun at NASA

Assimilation of Satellite Winds from John Knaff

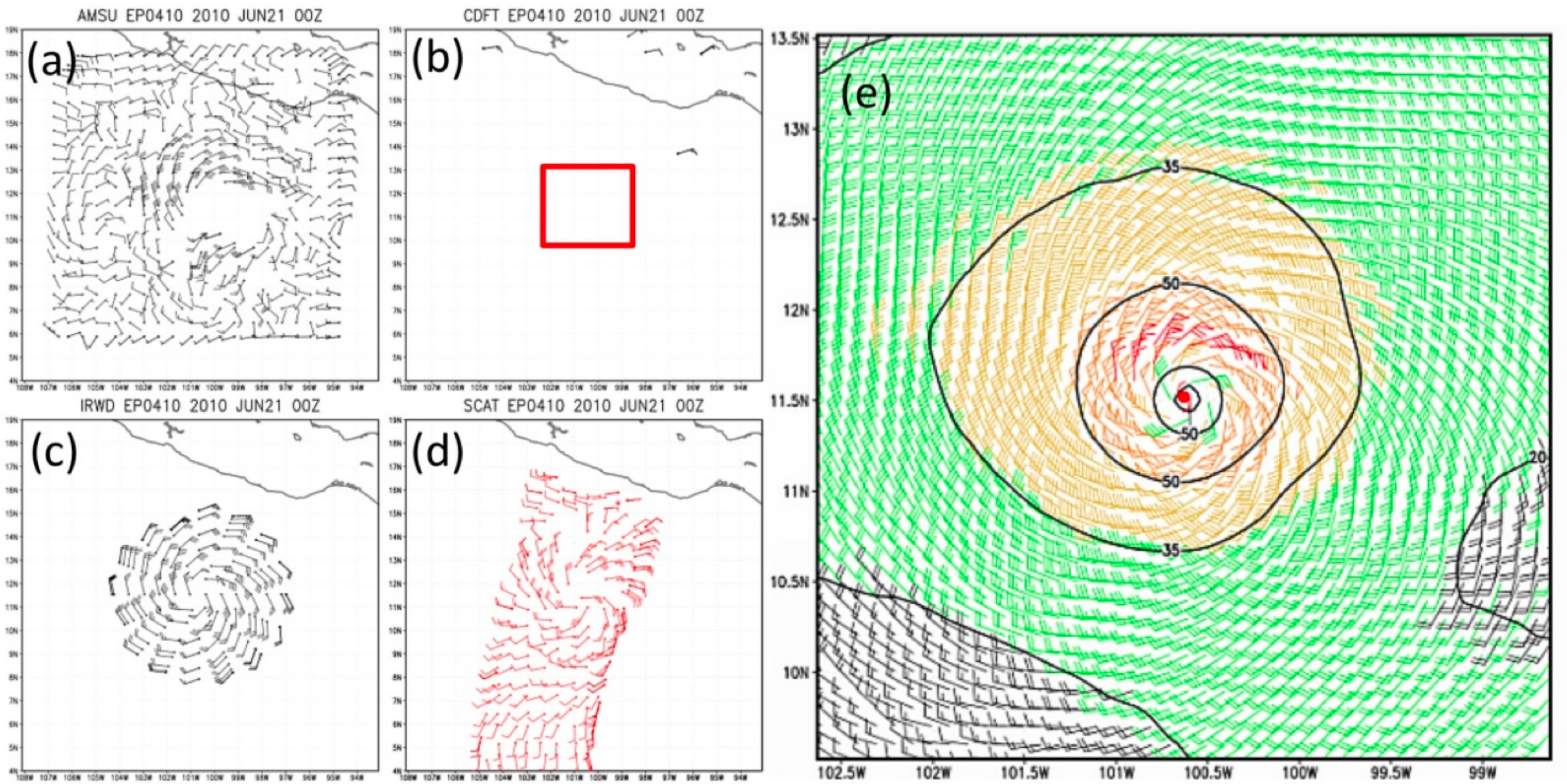
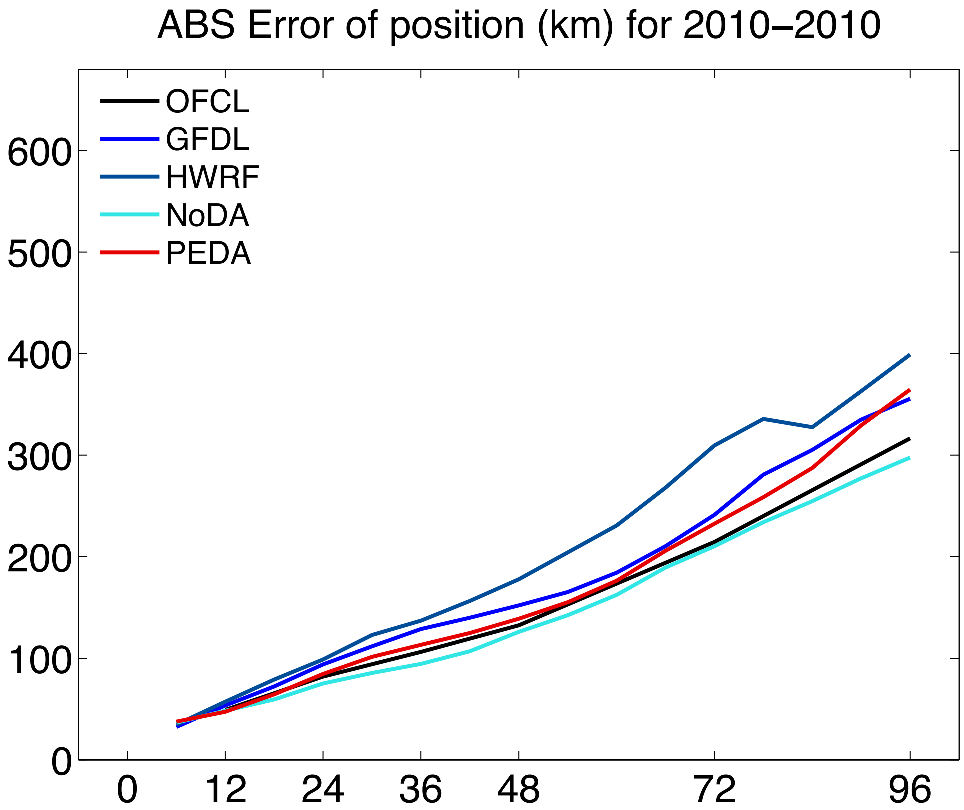
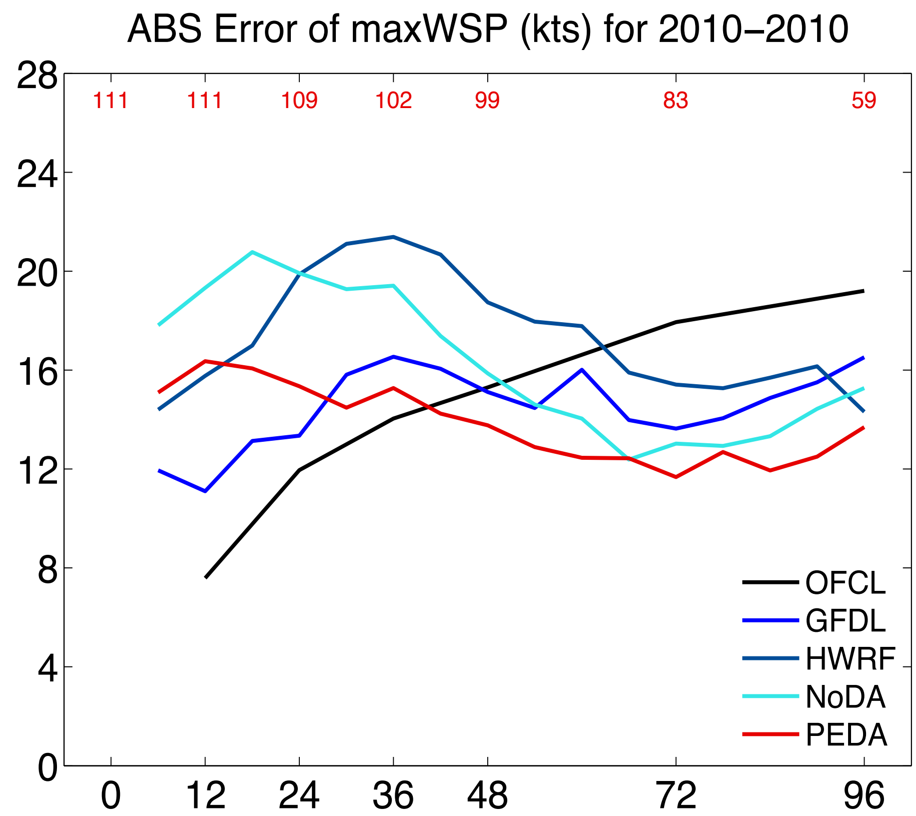


Figure 9. Examples of wind products generated for Hurricane Celia (EP0410) on 21 June 2010 at 00UTC. (a) AMSU, (b) CDFT, (c) IRWD, (d) ASCT and (e) MTCSWA. The red frame shown in (b) is the plotted area of MTCSWA wind in (e). (J. Knaff, 2011)

Performance with MTCSWA winds from John Knaff for all 2010 Atlantic hurricanes (>=Cat 1) every 6 hr

Mean Absolute error without bias correction

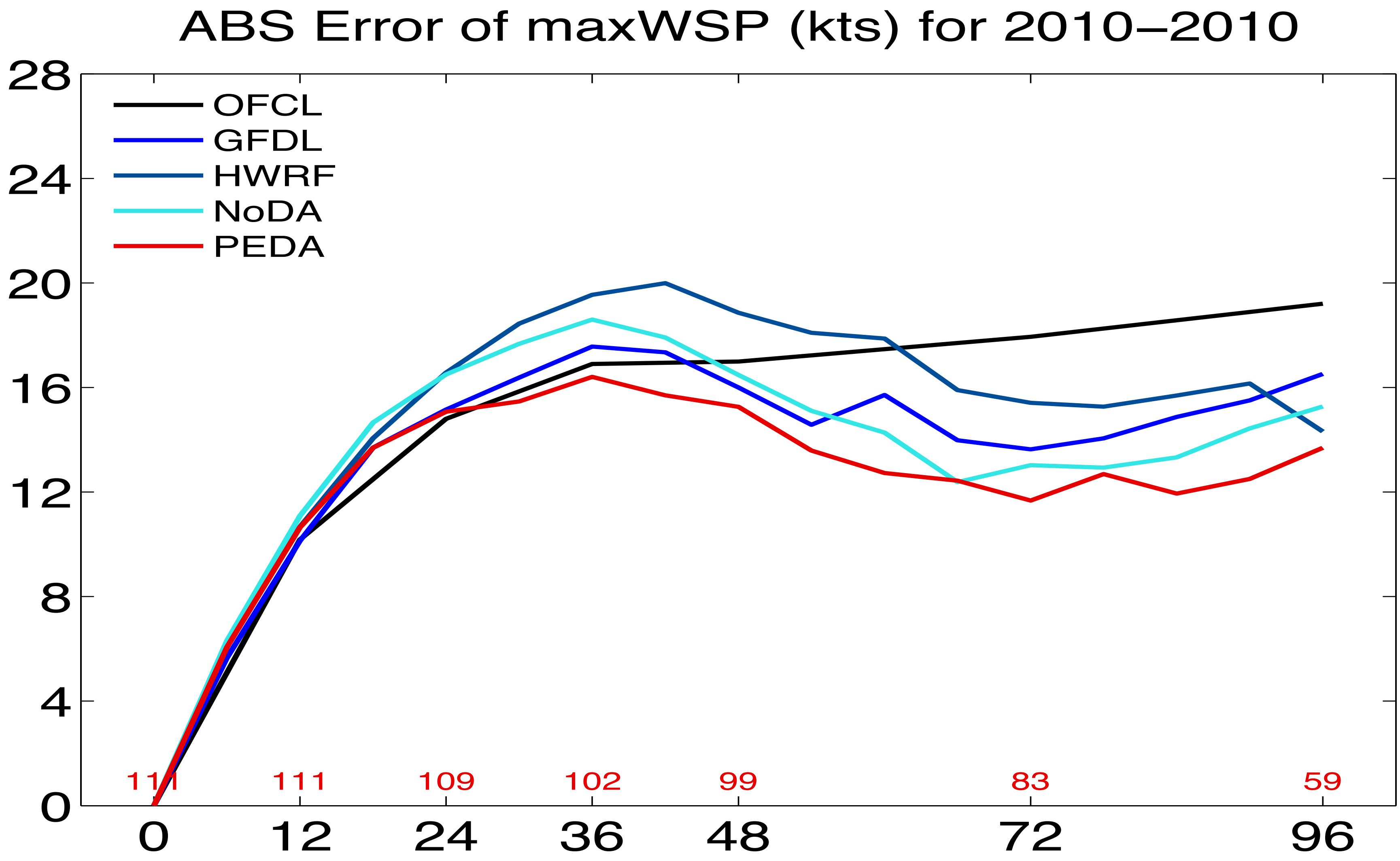




The psedo-ensemble hybrid data assimilation (PEDA) based on WRF-Var using a tape library of TC vortices is used to derived vortex-dependent error covariance instead of full flow-dependent error covariance in the EnKF

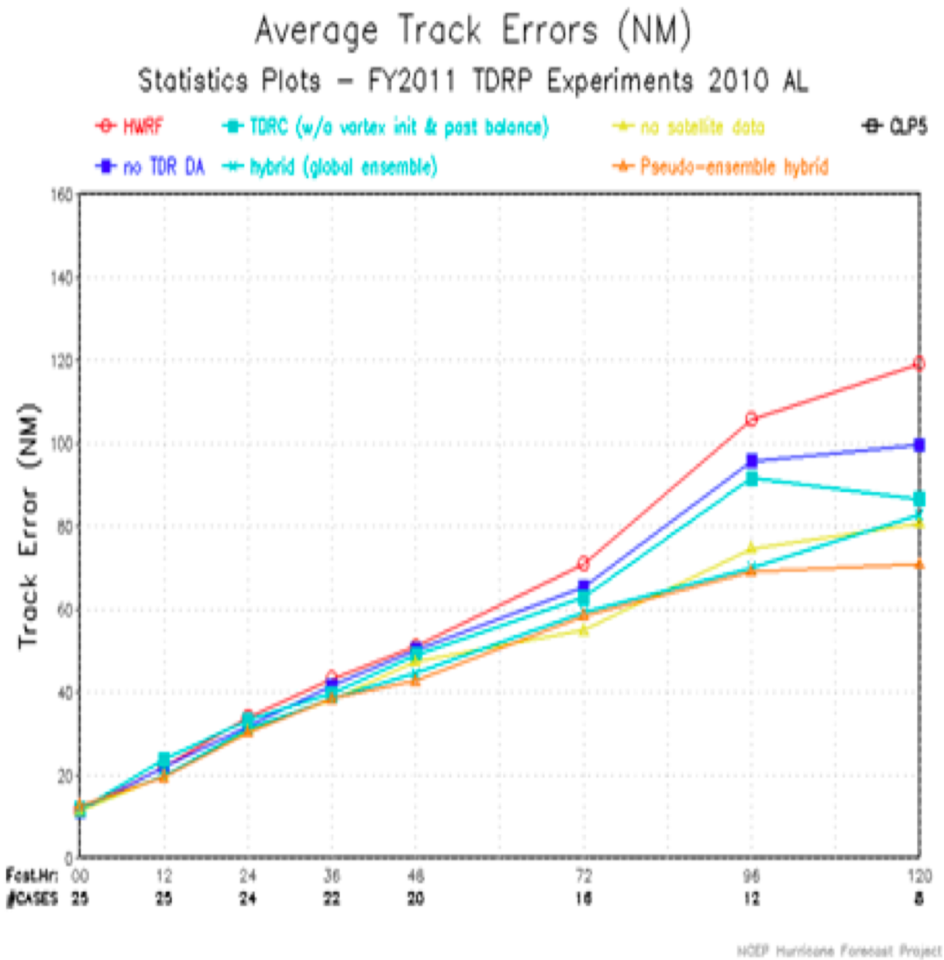
Performance with MTCSWA winds from John Knaff for all 2010 Atlantic hurricanes (>=Cat 1) every 6 hr

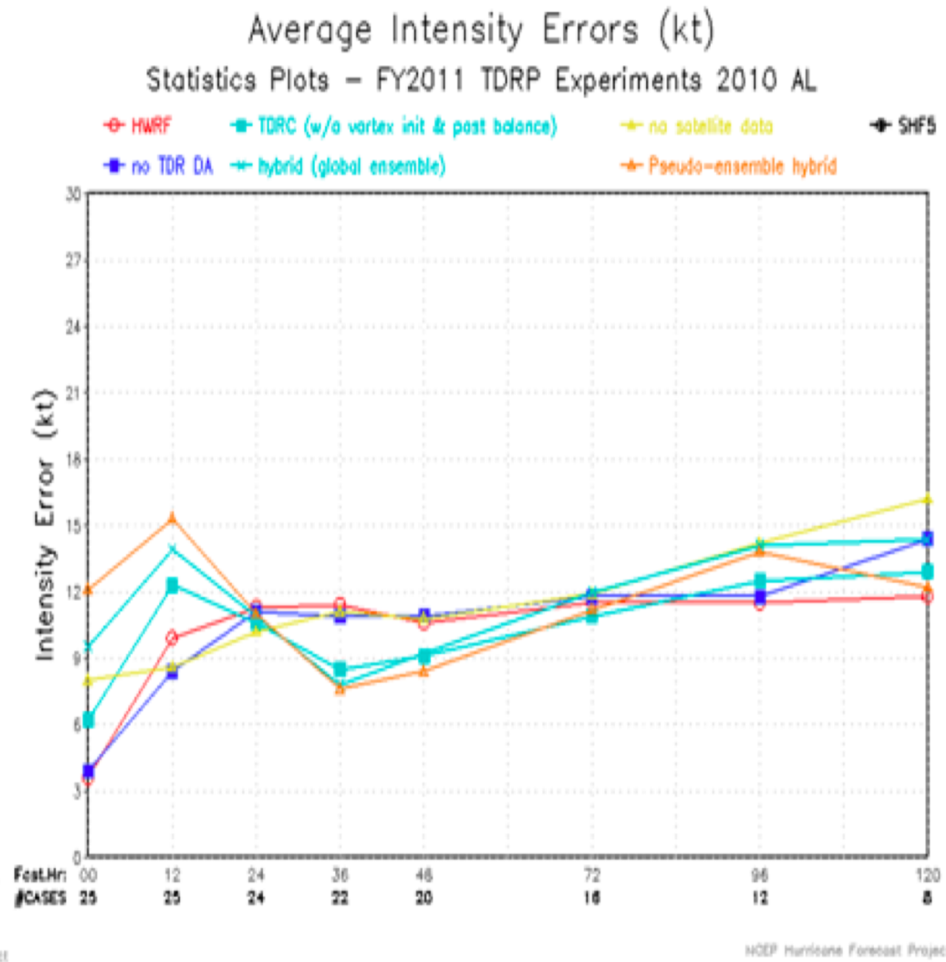
Mean Absolute intensity error with 60-h bias correction



Initial Tests of PEDA in HWRF using GSI-hybrid

Mean track and intensity error for 25 initializations during Hurricane Earl (2010)





In collaborations with Mingjing Tong (EMC) and Xuyang Ge (PSU/EMC)

Concluding Remarks

- **It is clear that inner-core observations, such as from ground-based or airborne Doppler radar observations, if assimilated with advanced data assimilation using flow/vortex-dependent background error covariance, can significantly improve the hurricane intensity forecasts**

- **More work needs to be done in the initial adjustment of the TC initialization using the current ensemble-based data assimilation systems such as EnKF**

- **Satellite observations, and measurements from unmanned aircrafts such as Global Hawk may be natural alternatives beyond the current TDR observations for the future hurricane intensity forecasts**

- **It has been a very rewarding personal experience for me as an university professor to work directly with researchers and forecasters at NOAA on the hurricane intensity forecasts; all this started with Frank Marks**

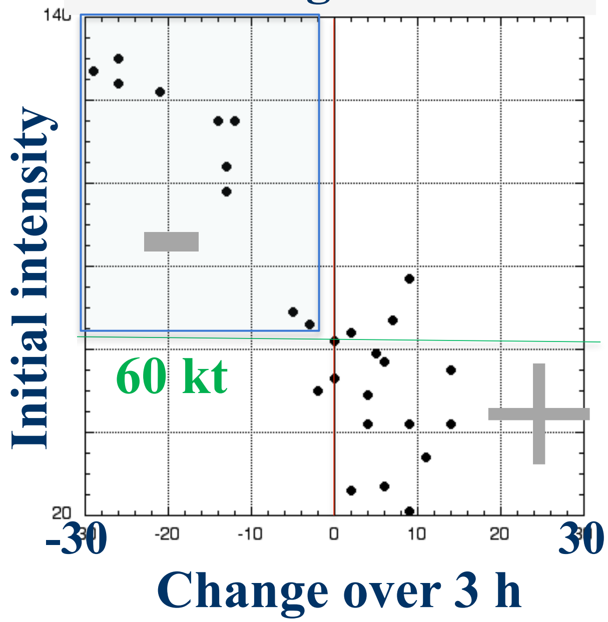
Short-term forecast bias and relationship to data assimilation

- The high-resolution forecasts from different model and data assimilation systems show a significant negative intensity bias at forecast range up to 36-48 hours
  - Maximum bias occurs at 6-24 hour forecast range, depending on the system and initialization method (and frequency of output)
  - The bias seems to account for a large portion of the forecast error at the short-range
- Improved mesoscale initial conditions should have most impact on forecast skill at 1-24 hour range
  - **Did improved ICs reduce the bias?**
  - The results from different mesoscale systems are mixed, for example
    - COAMPS shows consistent improvement, but bias remains
    - PSU and HRD EnKF experimental systems show large positive impact at forecast range longer than 36-48 hours, but seem to be increasing the negative intensity bias at short-range: 6-12 hours

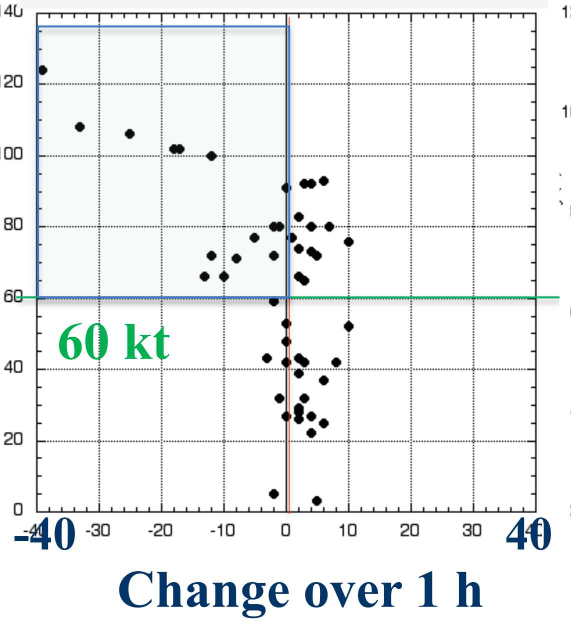
Slide from Tomi Vukicevic, NOAA/AOML Hurricane Research Division

Identifying the source of bias: HWRF examples

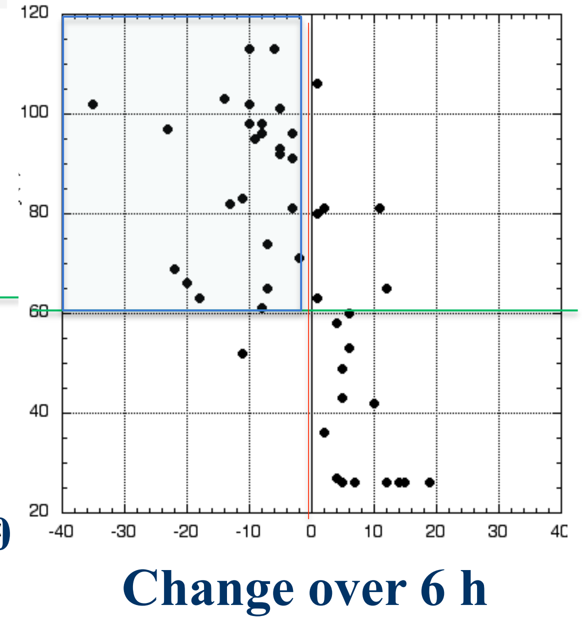
HWRFx forecasts with bogus vortex



HWRFx forecasts with HEDAS IC



HWRF_3.2 forecasts with bogus vortex

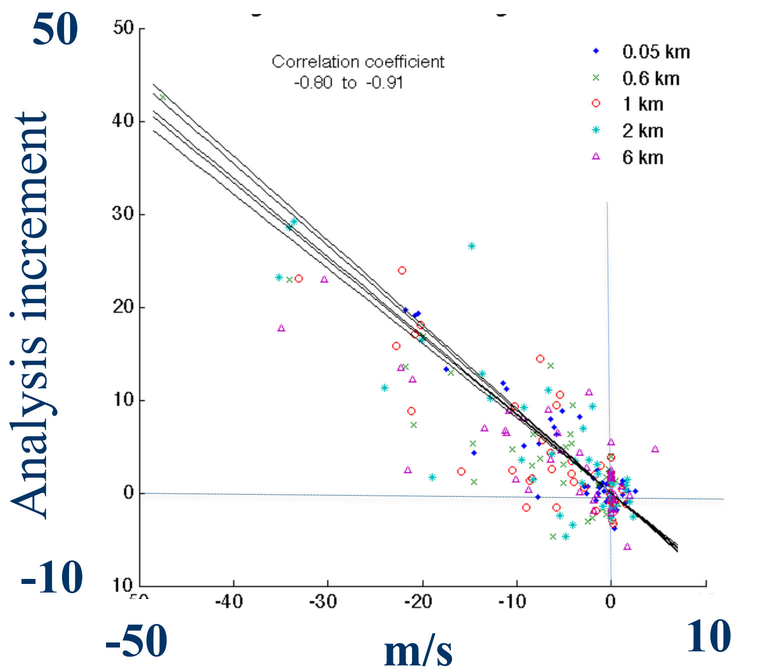


- **Vortex spin-down at hourly time scales for cases with hurricane initial intensity**
- **High tendency for initial spin-down is present regardless of the method of initialization or model version**

Slide from Tomi Vukicevic, NOAA/AOML Hurricane Research Division

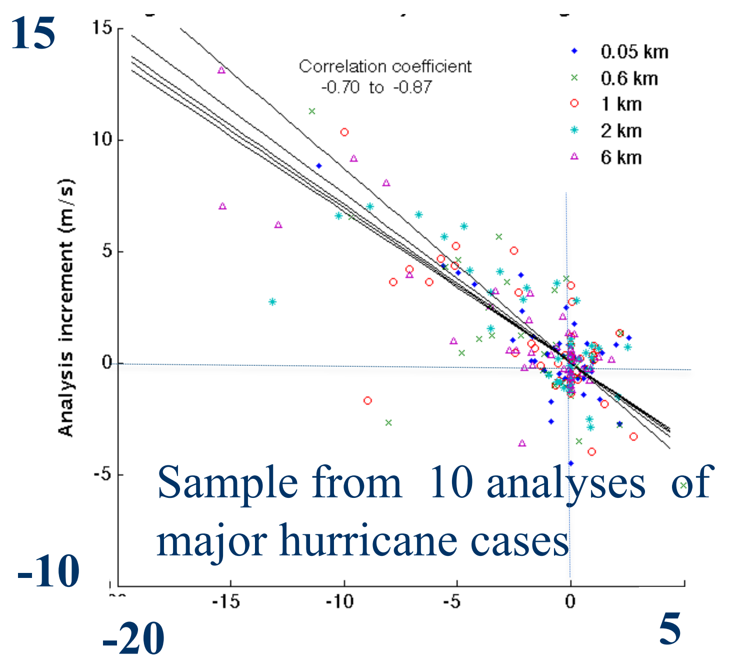
Impact of short-term forecast bias on data assimilation: HEDAS experience

Maximum tangential velocity



Change in subsequent forecast

Max axisymmetric velocity



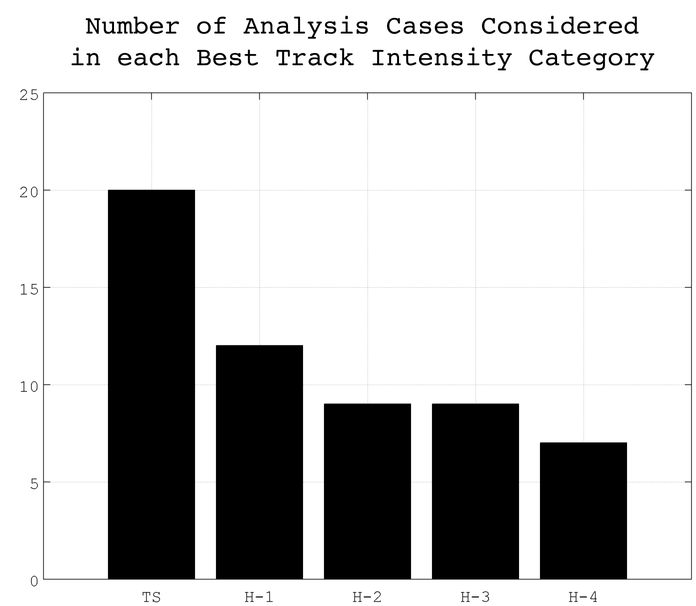
Change in subsequent forecast

- **In DA cycling the entire vortex core spins-down during 1 h forecast after spin-up by the observations for hurricane intensity cases**

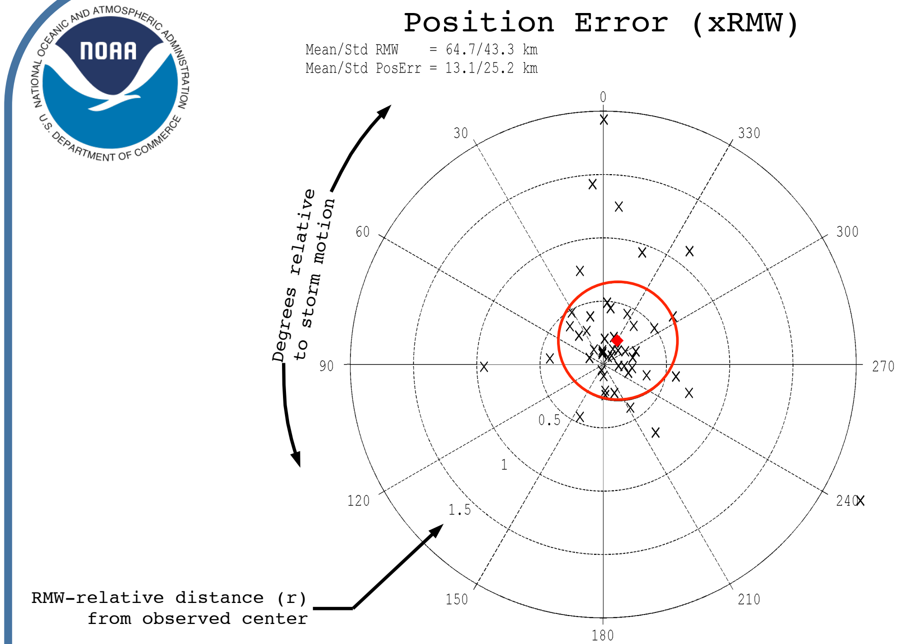
Slide from Tomi Vukicevic, NOAA/AOML Hurricane Research Division

VORTEX-SCALE DA WITH NOAA/AOML/HRD's HEDAS: 2008-2011 REAL-TIME & RETRO RUNS

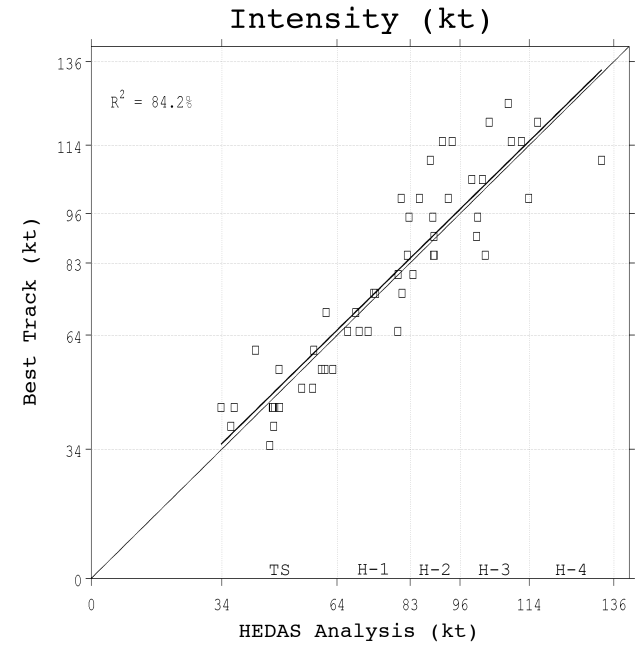
- HEDAS = HWRF Ensemble Data Assimilation System:
  - EnKF-based DA system to assimilate airborne hurricane inner-core observations
  - Assimilates Doppler wind speed, flight-level, SFMR, and dropsonde data
  - 30 ensemble members
  - HWRF 3.1 at 9/3-km resolution
  - Ensemble mean vortex analysis is used as the initial condition for deterministic HWRFx
- Retrospective (2008 & 2009) and real-time (2010 & 2011) analyses have been performed
- Diagnosis of **analyses**: Only cases that were Tropical Storm intensity or greater in the Best Track database are considered: ***52 cases***
- Diagnosis of **forecasts**: All tropical cyclone cases considered: ***71 cases***



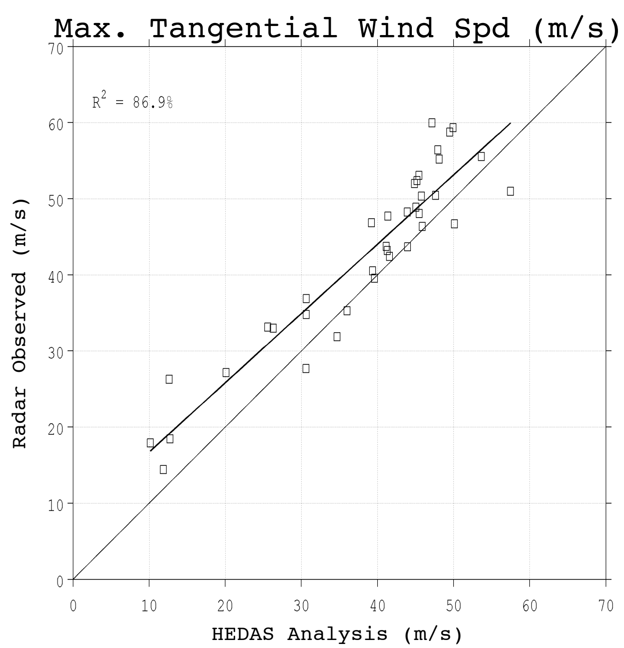
Slide courtesy of Altug Aksoy and Sim Aberson at NOAA/AOML Hurricane Research Division



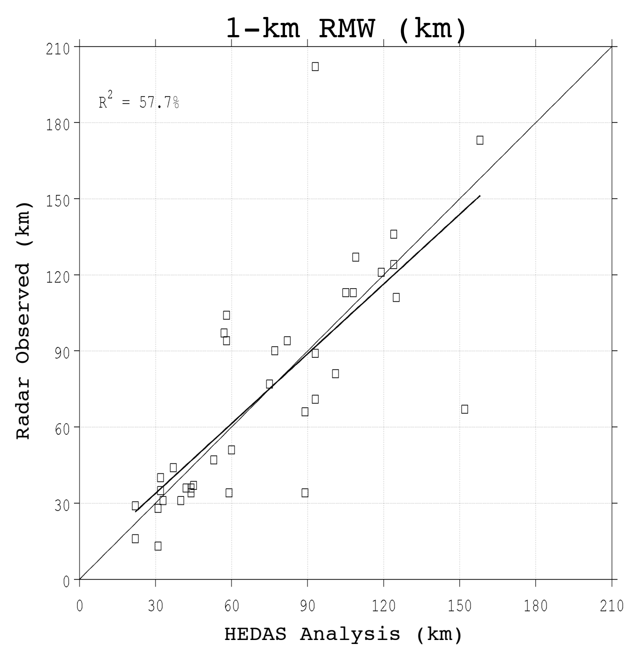
Position Error (xRMW)
Mean/Std RMW = 64.7/43.3 km
Mean/Std PosErr = 13.1/25.2 km
Degrees relative to storm motion
RMW-relative distance (r) from observed center



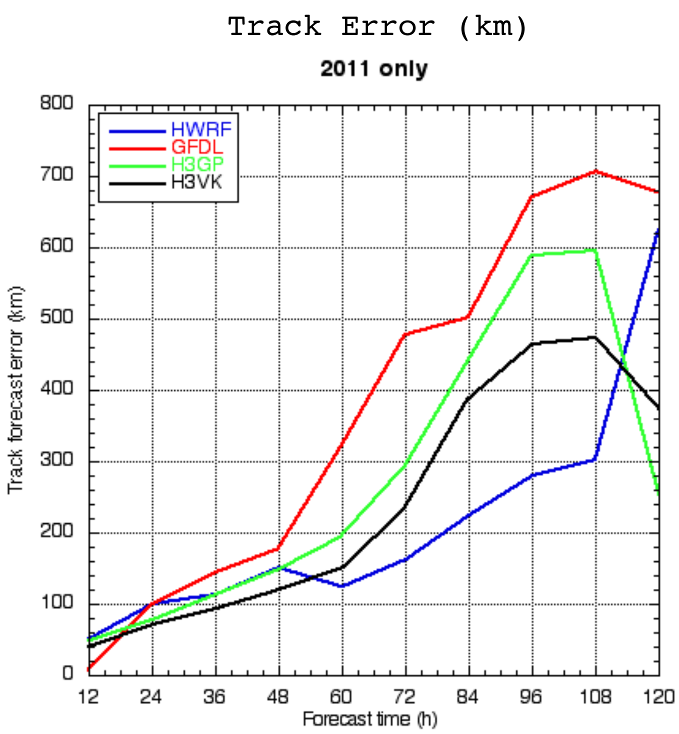
Intensity (kt)
R² = 84.2%
Best Track (kt)
HEDAS Analysis (kt)
TS H-1 H-2 H-3 H-4

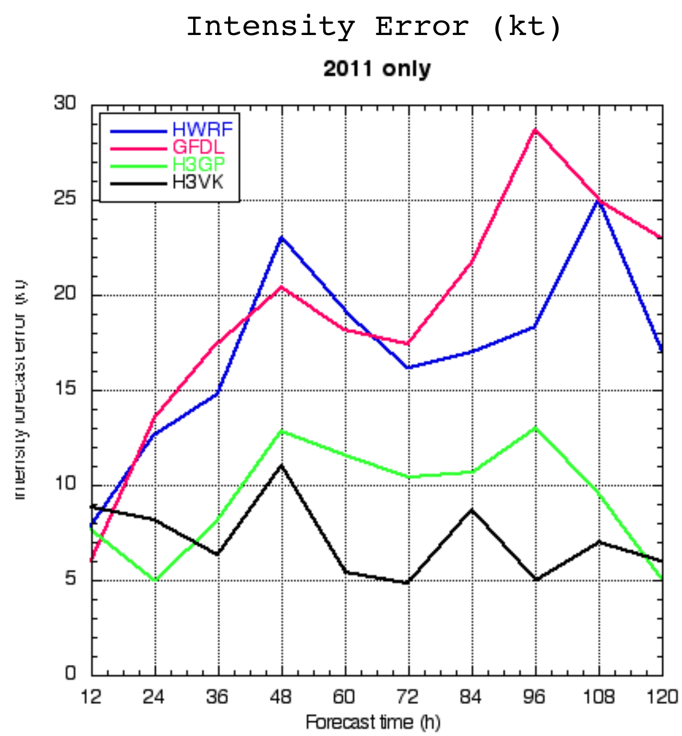


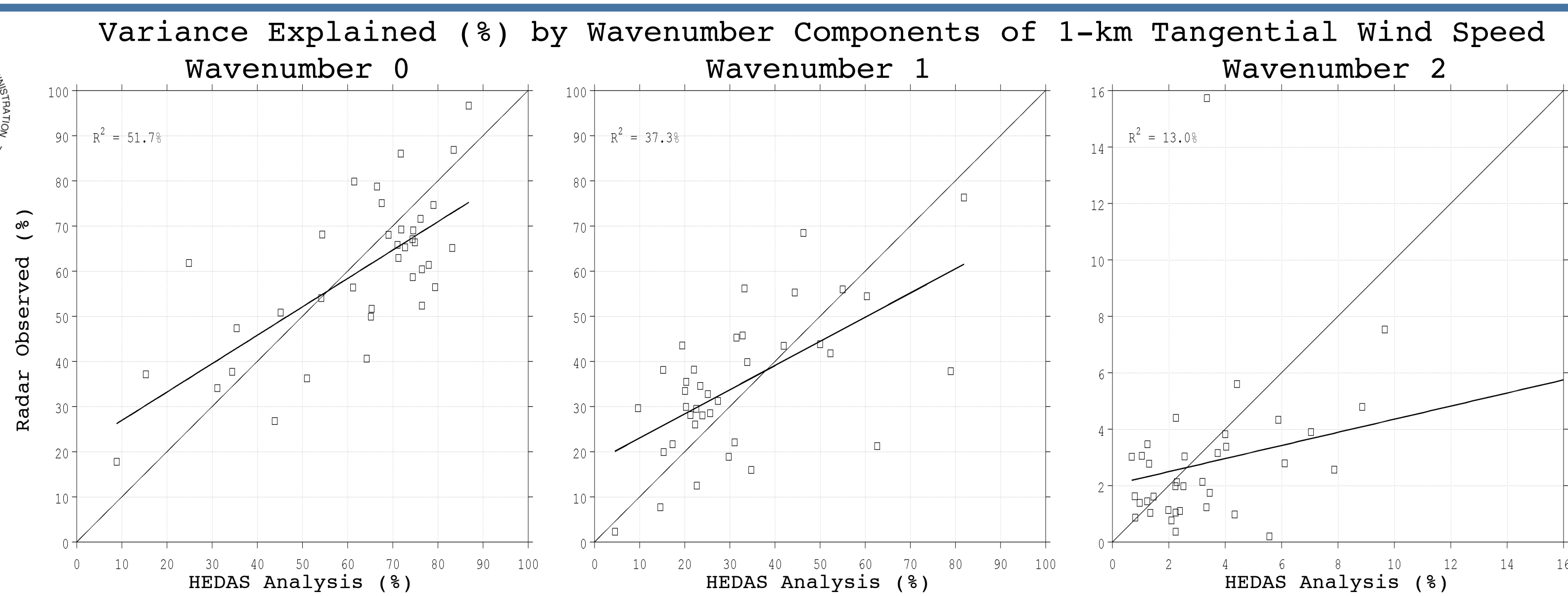
Max. Tangential Wind Spd (m/s)
R² = 86.9%
Radar Observed (m/s)
HEDAS Analysis (m/s)

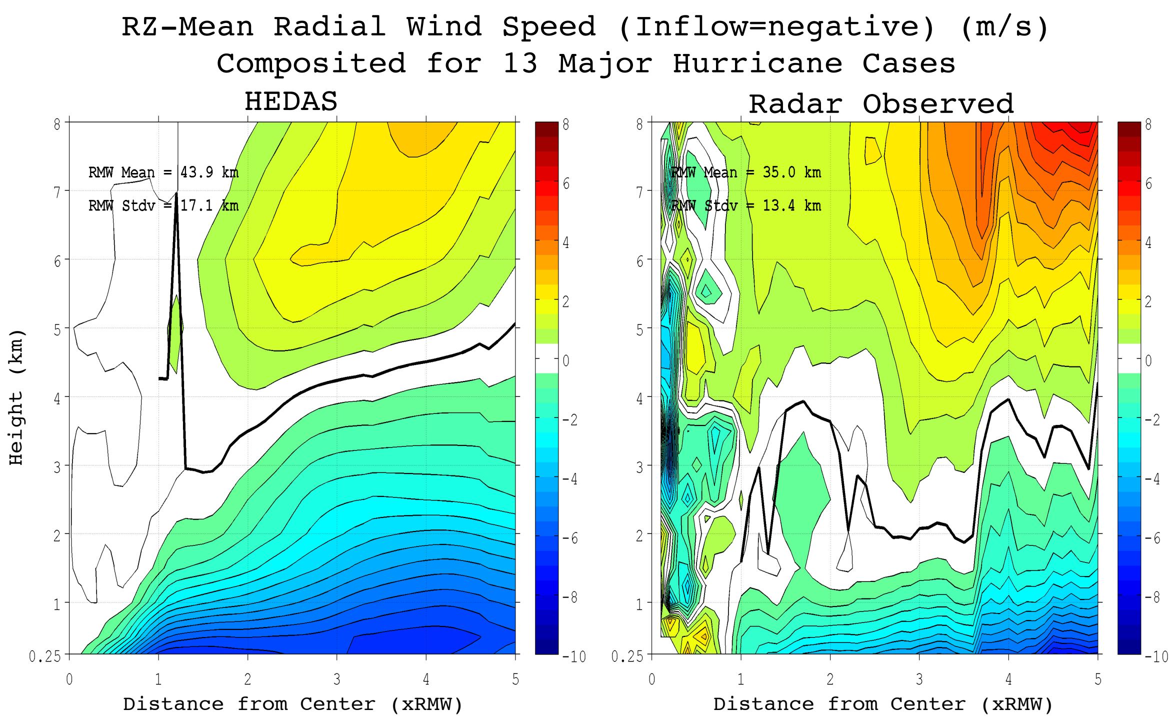


1-km RMW (km)
R² = 57.7%
Radar Observed (km)
HEDAS Analysis (km)


Track Error (km)
2011 only
HWRF
GFDL
H3GP
H3VK
Track forecast error (km)
Forecast time (h)
0
100
200
300
400
500
600
700
800
12
24
36
48
60
72
84
96
108
120


Intensity Error (kt)
2011 only
HWRF
GFDL
H3GP
H3VK
Forecast time (h)
0
5
10
15
20
25
30
12
24
36
48
60
72
84
96
108
120





- The good:
  - Position error to within 0.2 RMW
  - Good fit of analysis intensity to best track intensity
  - RMW captured to within 10 km
  - Wavenumbers 0 and 1 captured well
- Where research is needed:
  - Importance of higher-wavenumber structure
  - Boundary layer structure
  - Vertical correlations and localization
  - How well does the radar sample the radial wind?

Vortex Initialization in Operational Models

NOGAPS: (1) Vortex generation based on balanced hurricane vortex of Kurihara; (2) Fully-developed vortex is inserted in HPC-analyzed position

GFS: (1) Vortex removal is made using multiple filter passes; (2) Hurricane component moved to HPC-analyzed position

UKMO: (1) Manual intervention when satellite or in-situ data is significantly different from first guess field; (2) Synthetic wind observations are added; (3) Analysis cycle balances mass field to produce a realistic vortex

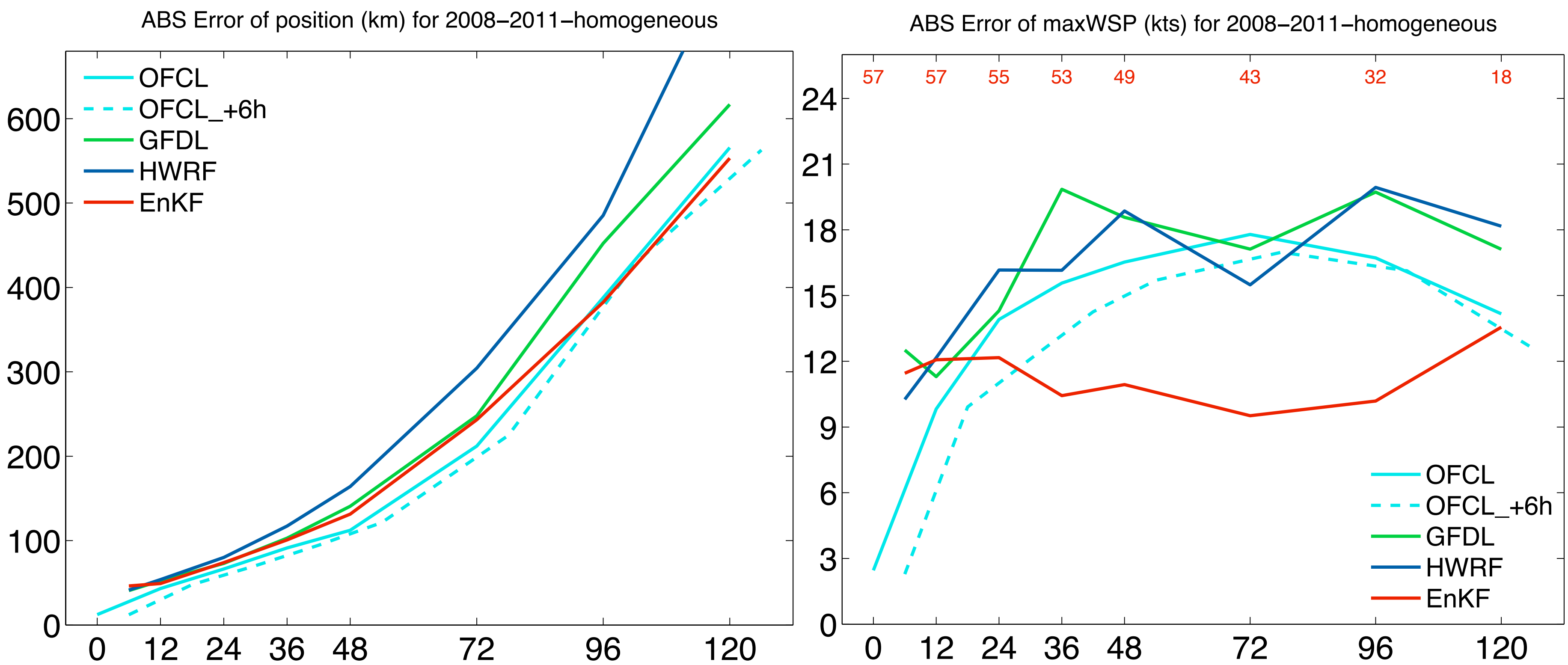
ECMWF: Regular 4DVAR global analysis, no bogussing or relocation

GFDL: (1) Vortex in GFS initial fields is removed using filters and optimal interpolation; (2) New vortex is grown in model; (3) Full treatment of SST evolution and interaction; (4) Strong, well-balanced vortex in initial fields

HWRF: (1) GFS analysis + modified 6-h HWRF forecasted TC vortex (merged through GSI); (2) Adjustment of the initial HWRF forecasted TC vortex: RMW, Vmax, Psfc and 3D T, moisture (hydrometeor), and storm depth

EnKF Performance Assimilating Airborne Radar OBS

Mean Absolute Error and Ensemble Spread for 66 missions during 2008-2011



A4PS: PSU 4.5km single forecast initialized with EnKF analyses

Coupling EnKF with WRF 3DVar/4DVar

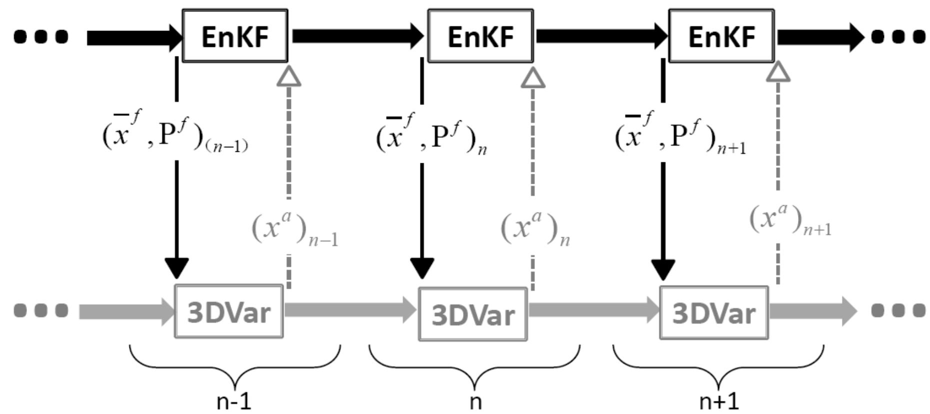
Necessary Variable Changes:

i) EnKF provides ensemble-based background error covariance (P^f) for 3D/4DVar

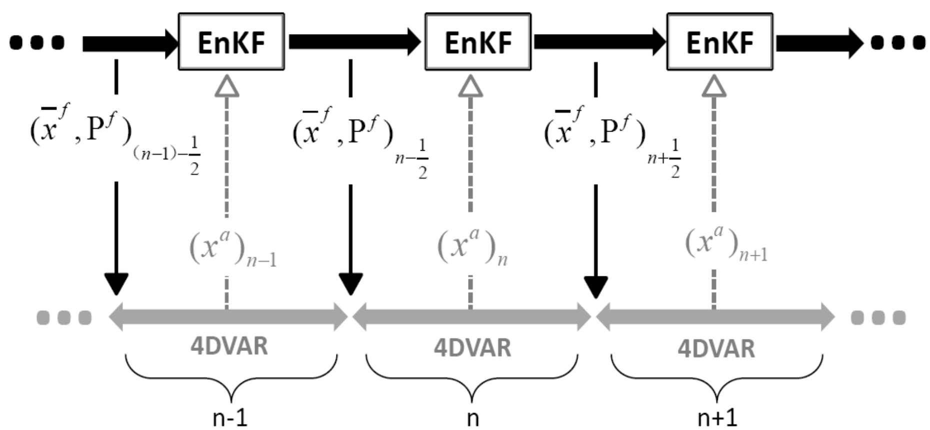
ii) EnKF provides the prior ensemble mean ($\overline{x}^f$) as the first guess for 3D/4DVar

iii) 3D/4DVar provides deterministic analysis ($\overline{x}^a$) to replace the posterior ensemble mean for the next ensemble forecast

Coupler of EnKF-3DVar Hybrid (E3DVar):



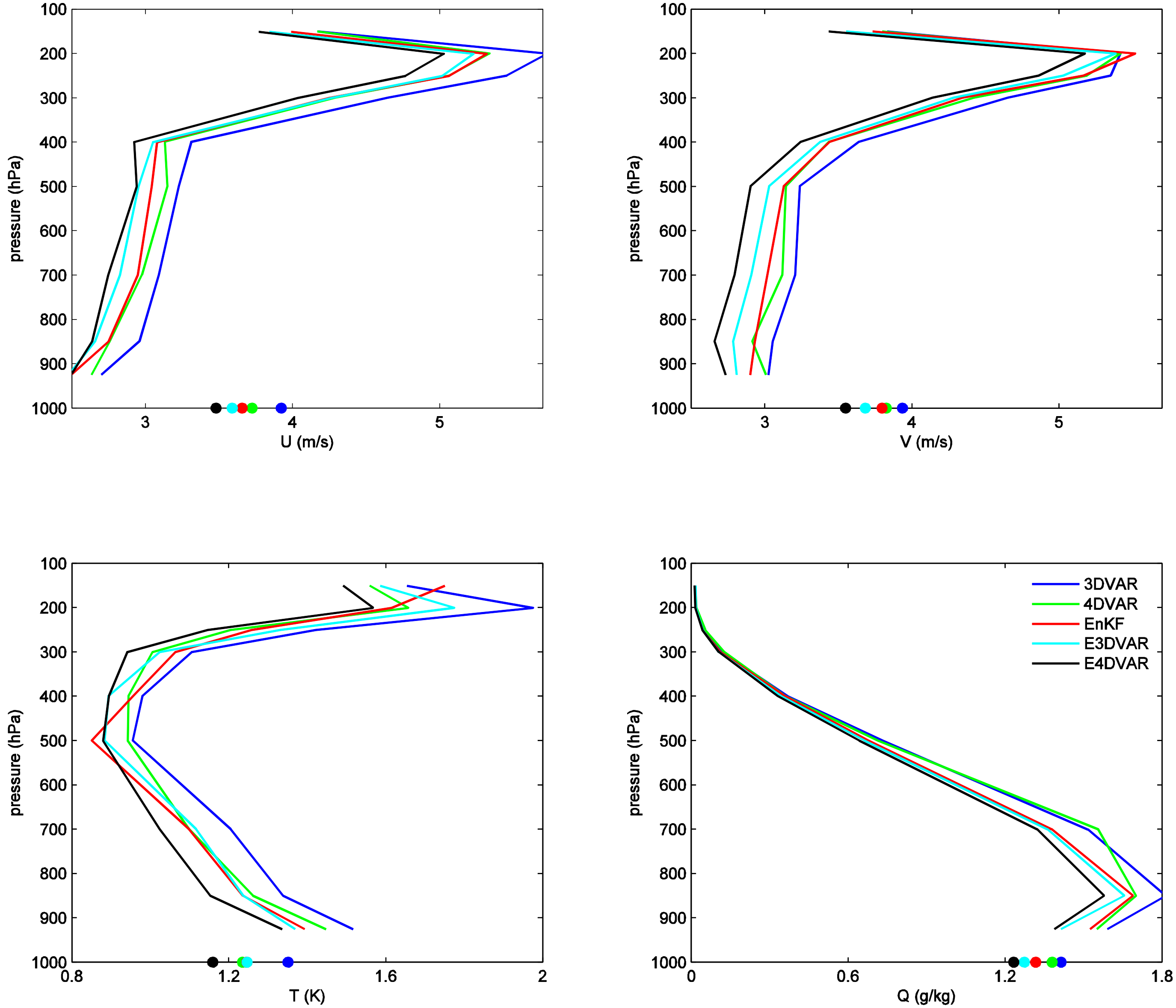
Coupler of EnKF-4DVar Hybrid (E4DVar):



(Zhang and Zhang 2011; Zhang et al. 2009)

Comparison of 3DVar, 4DVar, EnKF, E3DVar & E4DVar

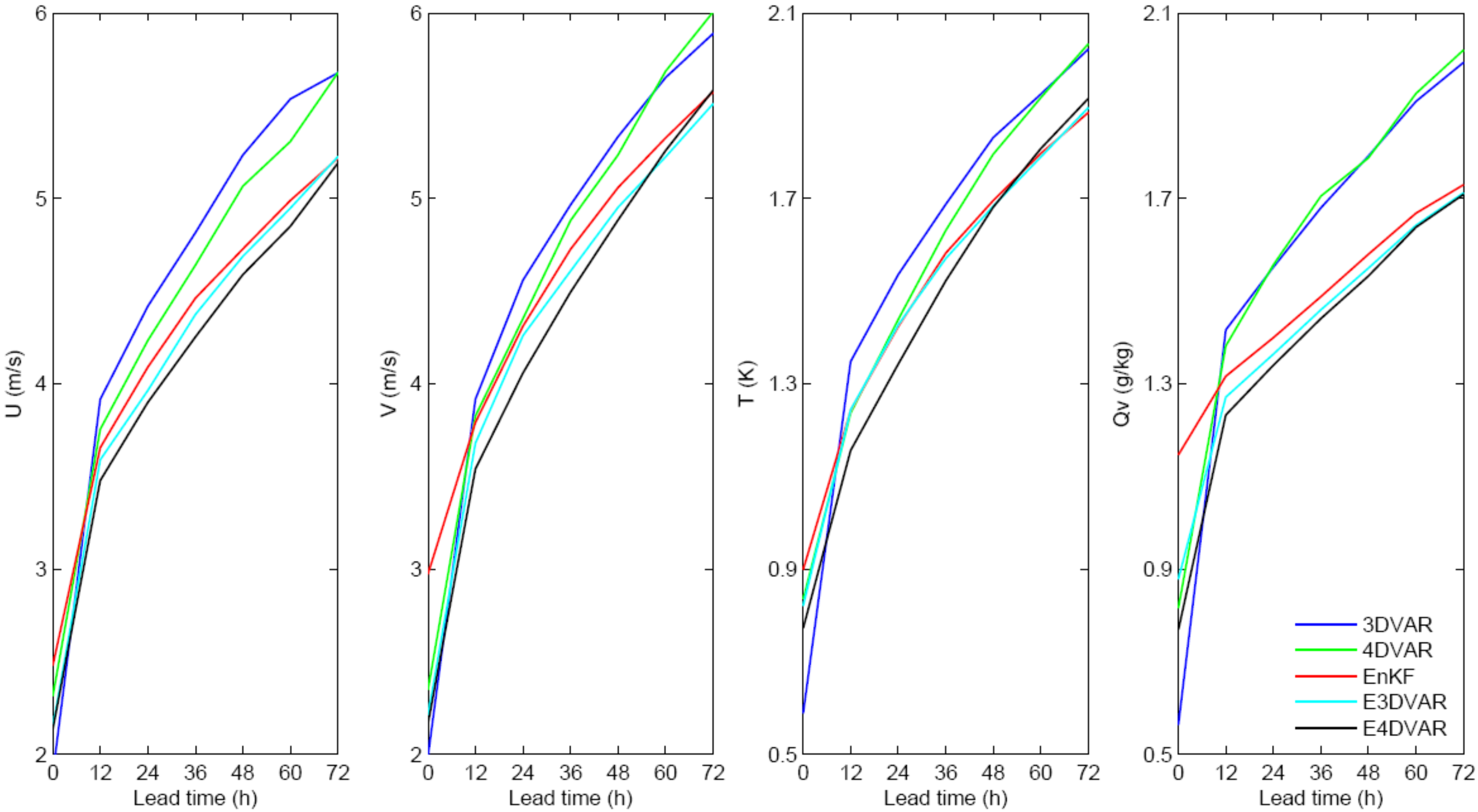
Mean vertical profiles of month-averaged 12-h forecast RMSE



(Zhang et al. 2010; Zhang and Zhang 2011)

Comparison of 3DVar, 4DVar, EnKF, E3DVar & E4DVar

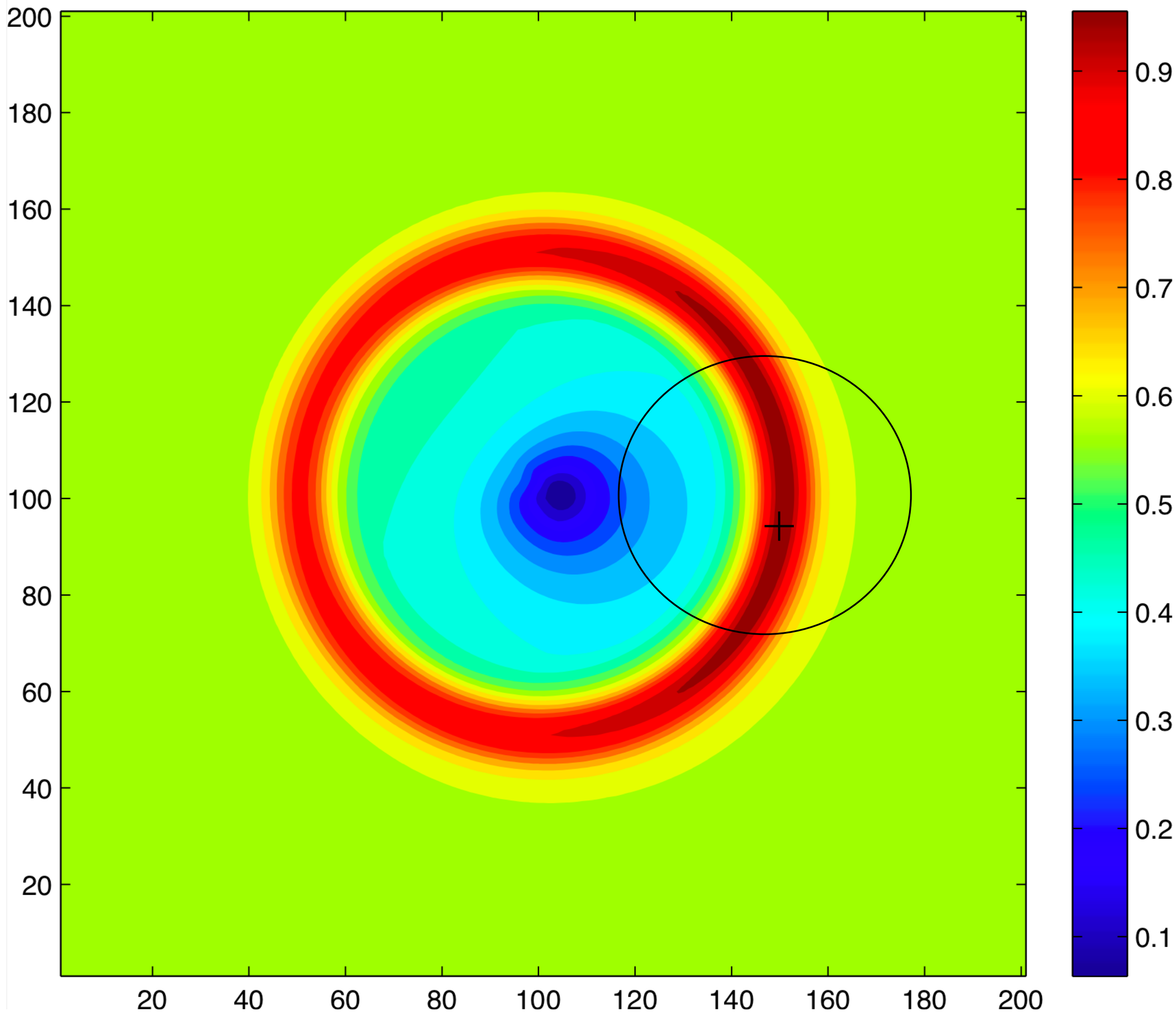
0-72hr U, V, T & Q RMS forecast error over CONUS Jun 2003 (60 runs)



(Zhang et al. 2010; Zhang and Zhang 2011)

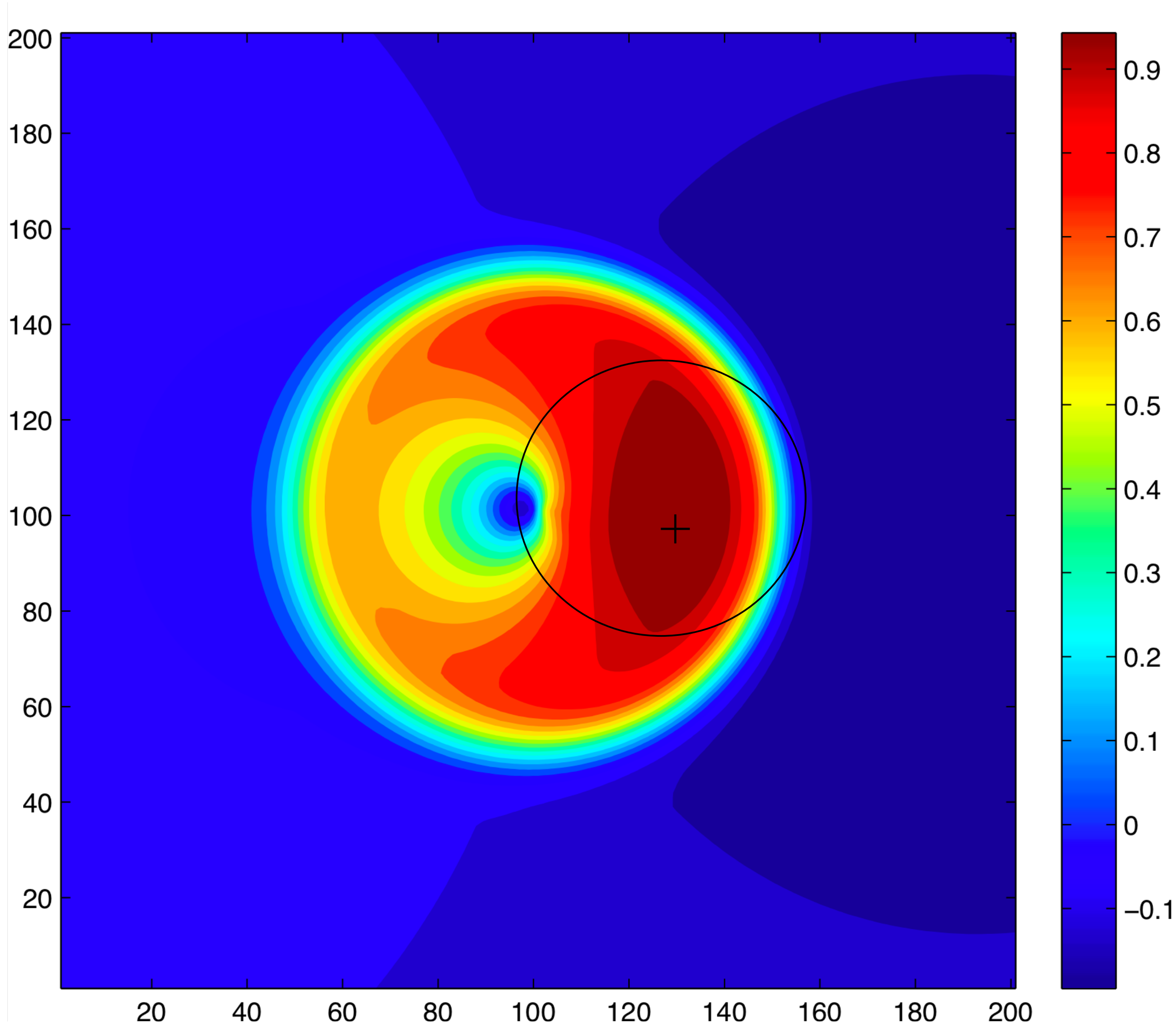
Flow-Dependent Error Covariances in Hurricanes

Correlation to Velocity observations on radius of Maximum Wind



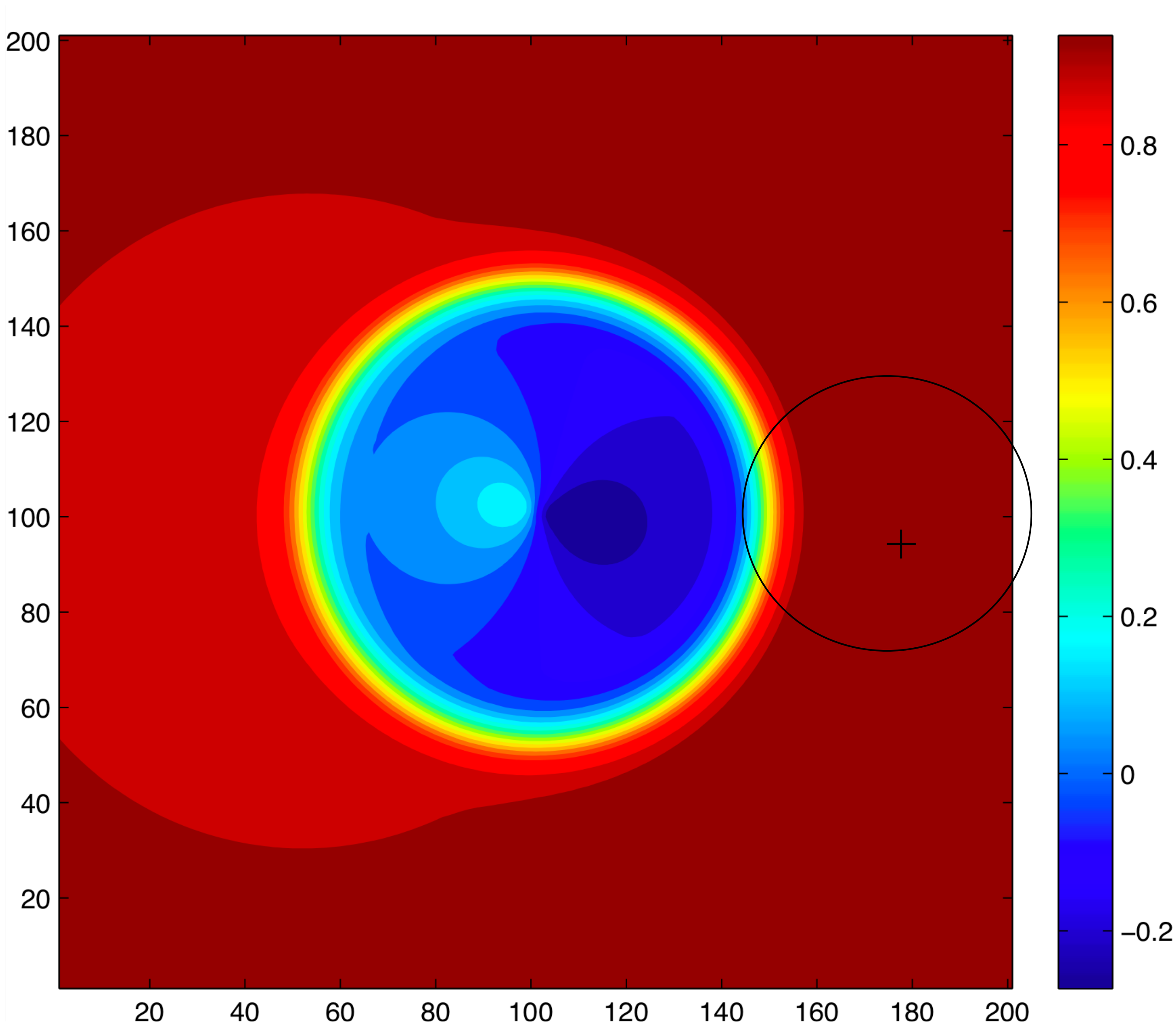
Flow-Dependent Error Correlations in Hurricanes

Correlation to Velocity observations inside radius of Maximum Wind



Flow-Dependent Error Correlations in Hurricanes

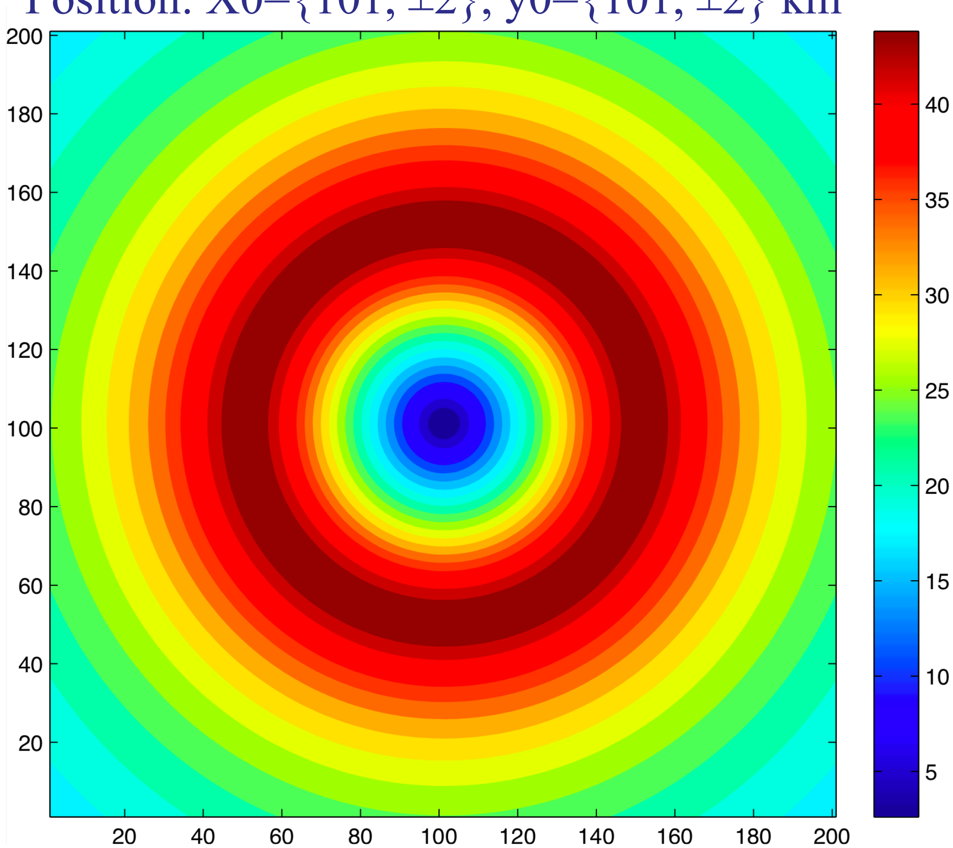
Correlation to Velocity observations outside of radius of Maximum Wind

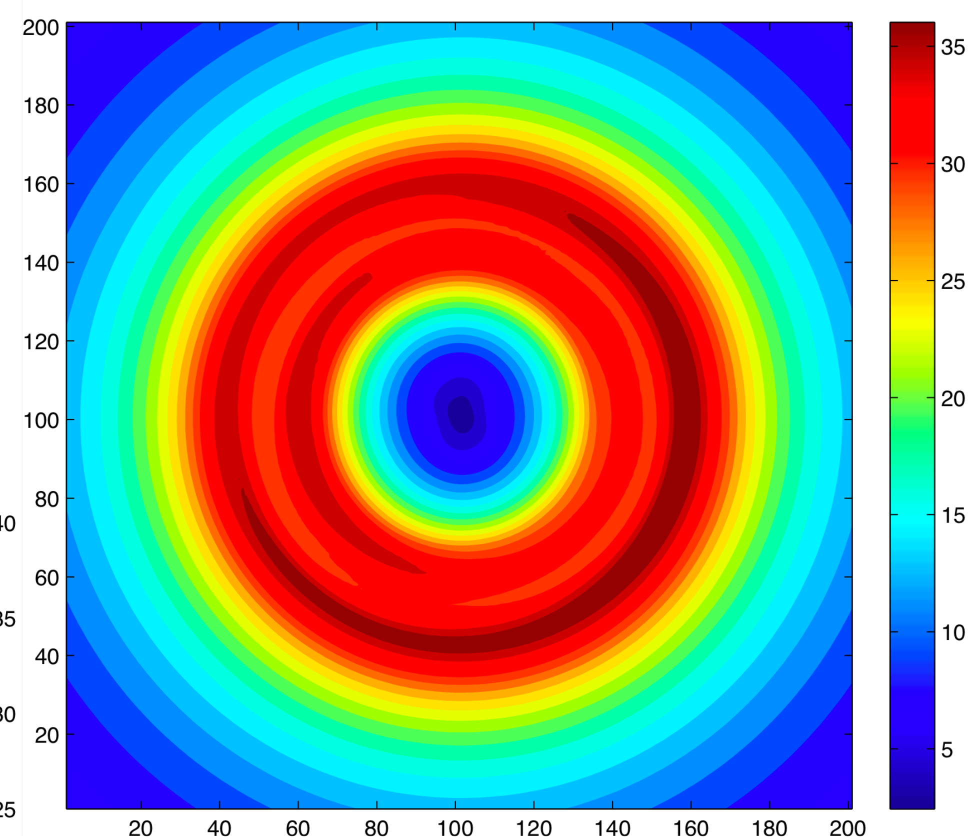


Flow-Dependent Error Covariance in Hurricanes

Rankine Vortex: V(r)=(V0/R0)*r for r<R0
V(r)=(V0*R0)/r for r>R0

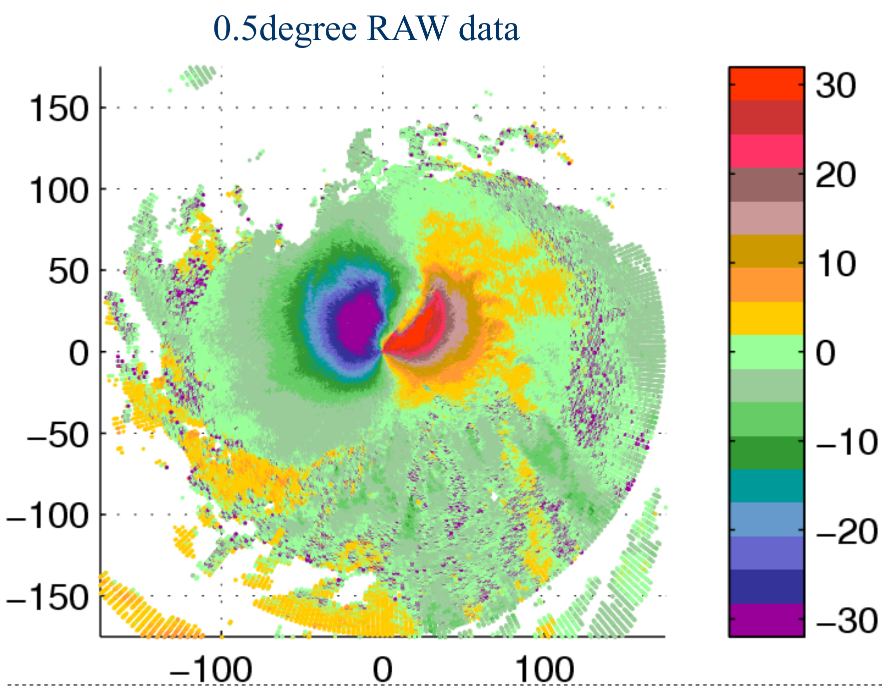
Intensity: V0={50m/s, ±5m/s},
Radius: R0={50km, ±5km},
Position: X0={101, ±2}, y0={101, ±2} km

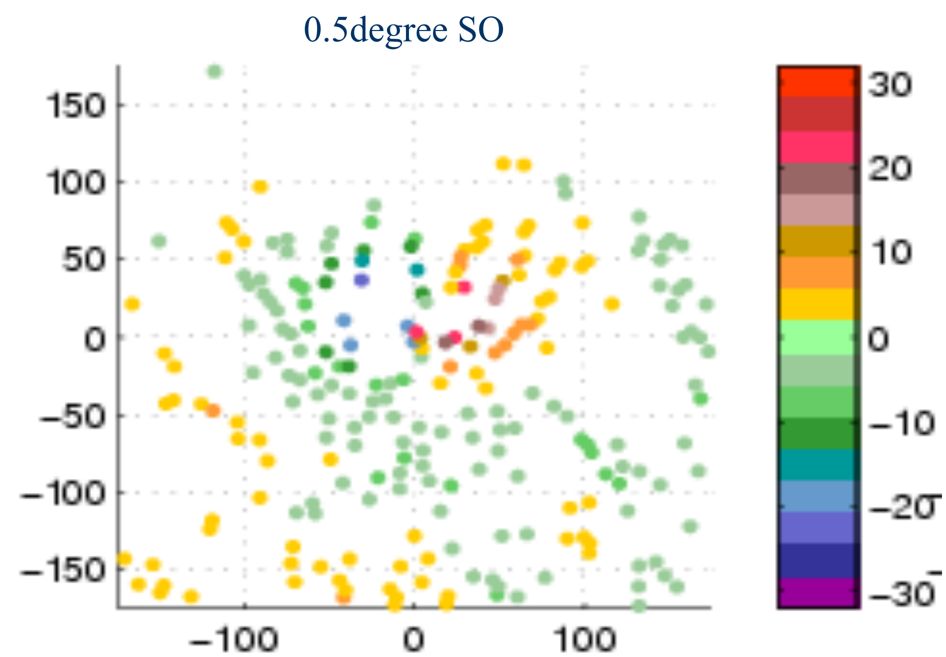




Ensemble mean (left) and Variance (top) estimated from 300 ensemble members

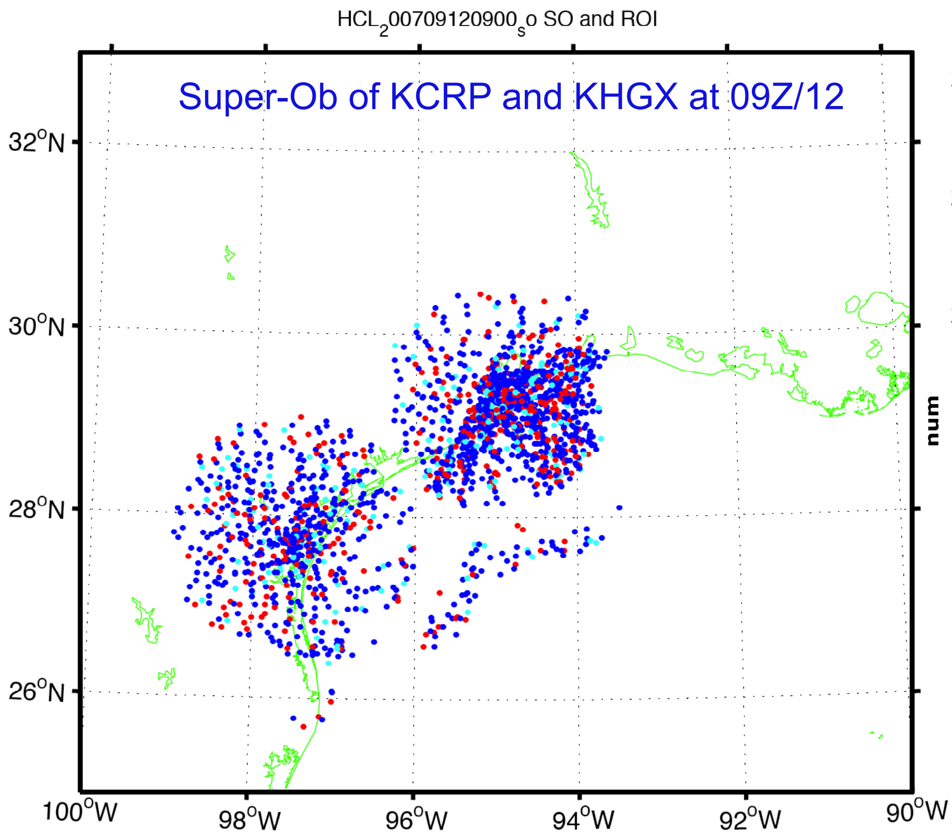
Super-Obs: QC and thinning of WSR-88D Vr Obs

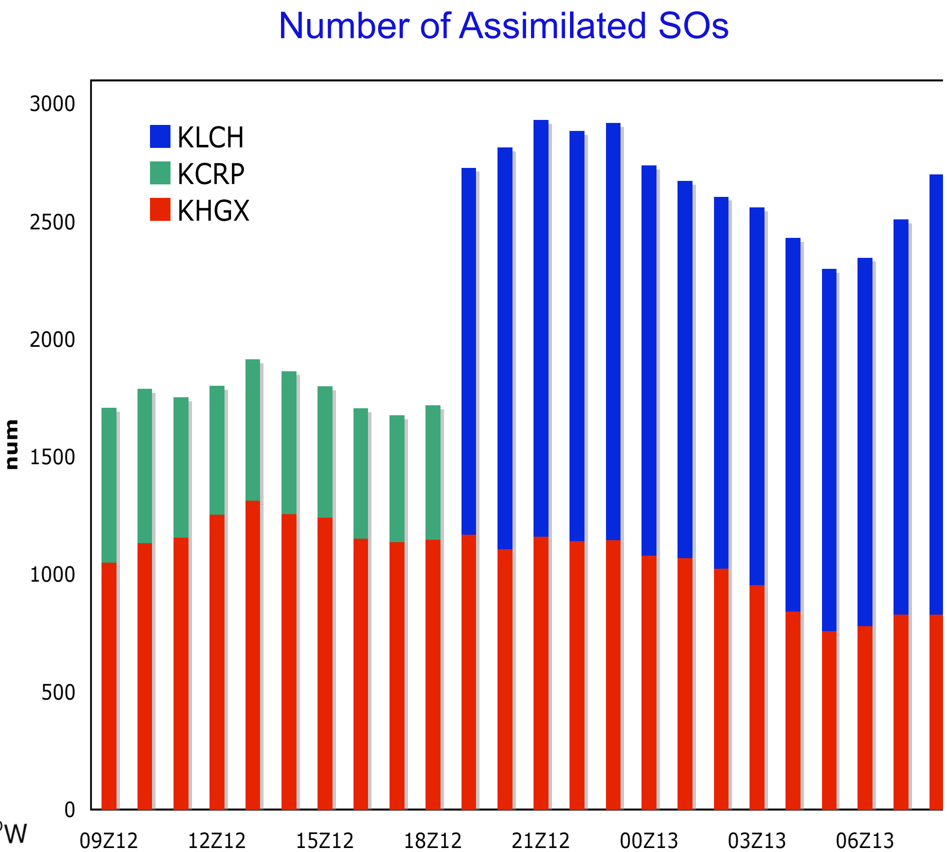




- Define SO position depended on the radial distance
- Average10 nearest data points in the raw polar scan to create a SO
- Averaging bin is 5km max radial range and 5° max azimuthally resolution
- There are at least 4 valid velocity data within an averaging bin.
- The standard deviation checking of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

Assimilate WSR88D Vr Obs: Number of SOs

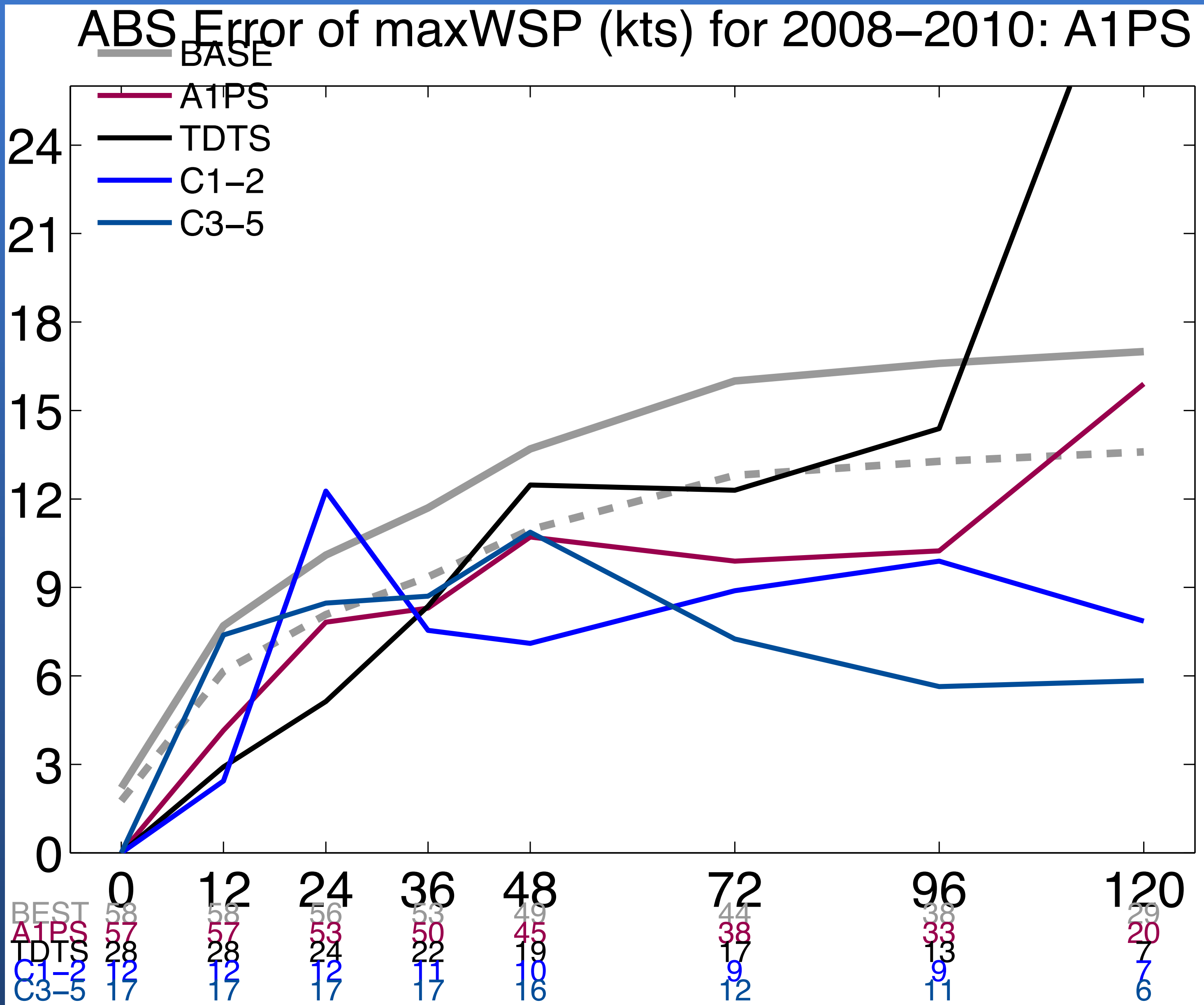




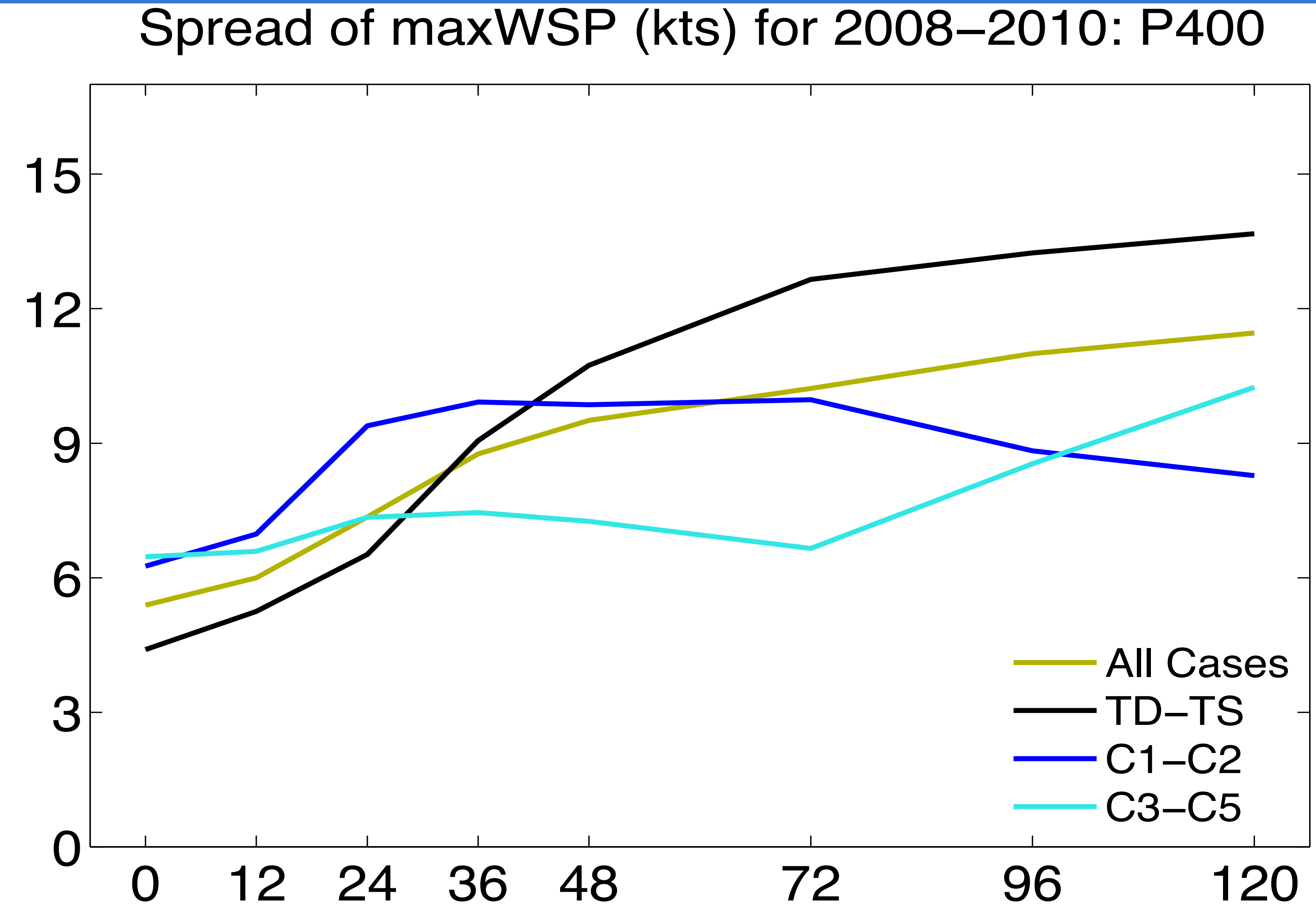
-WRF/EnKF starts assimilating hourly Vr obs of CRP, HGX and LCH WSR88D radars from 09Z/12 to 21Z/12 after a 9-h ensemble forecast from GFS/FNL analysis

-Successive covariance localization with different ROIs for different subset of SOs

Forecast Error as a Function of Initial Intensity

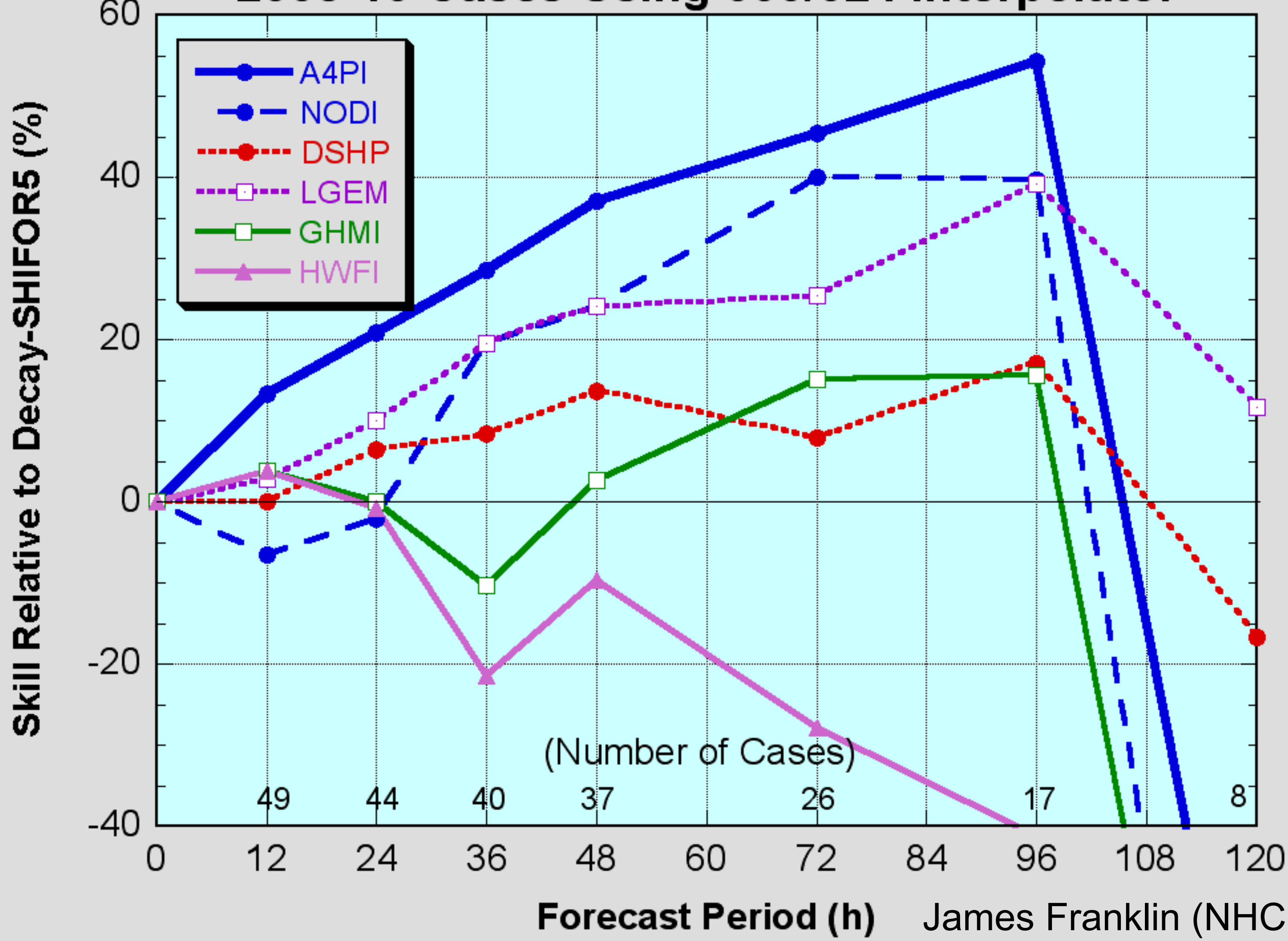


Ensemble Spread As a Function of Initial Intensity



	0	12	24	36	48	72	96	120
All Cases	58	58	56	53	49	44	38	28
TD–TS	29	29	27	24	22	20	16	11
C1–C2	12	12	12	12	10	10	10	7
C3–C5	17	17	17	17	17	14	12	10

Intensity Forecast Skill
Penn State WRF-EnKF Realtime System
2008-10 Cases Using 000/024 Interpolator



James Franklin (NHC)

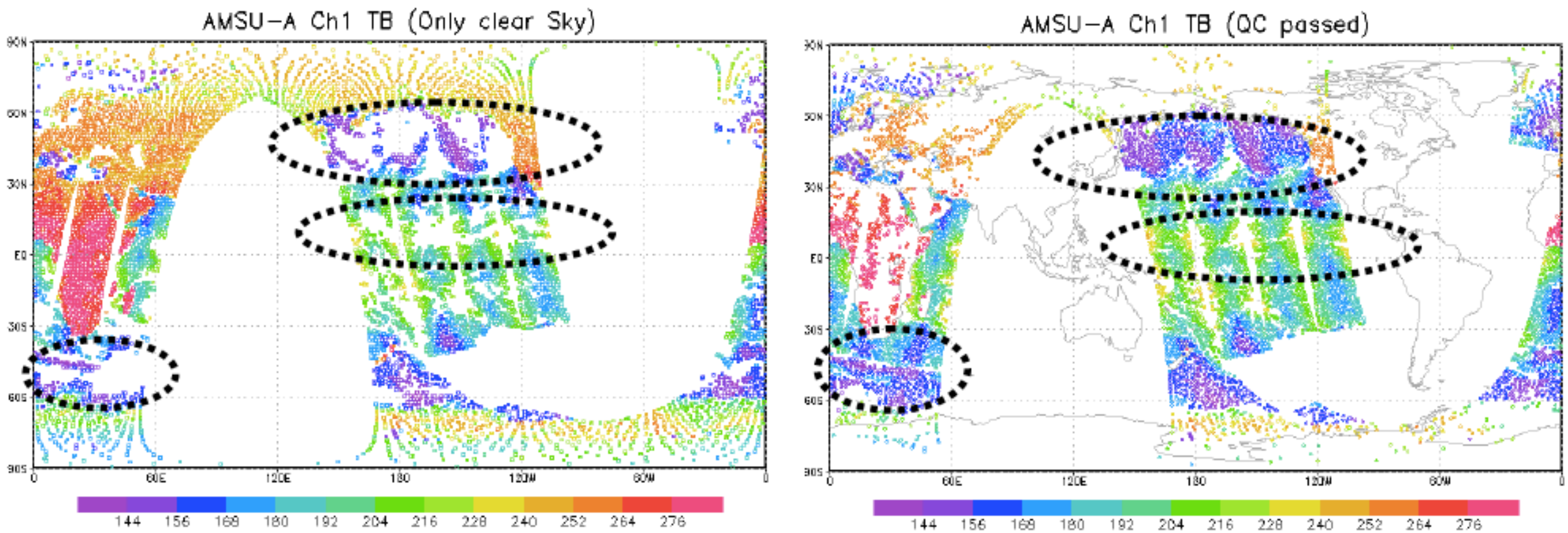
What have we learned from the research on data assimilation at vortex scales and what are the outstanding challenges ?

Tomislava Vukicevic
NOAA/AOML Hurricane Research Division

Cloudy Radiance Assimilation:

Importance and Challenges

Slide taken from Min-Jeong Kim's talk on the NCEP GSI analysis posted online

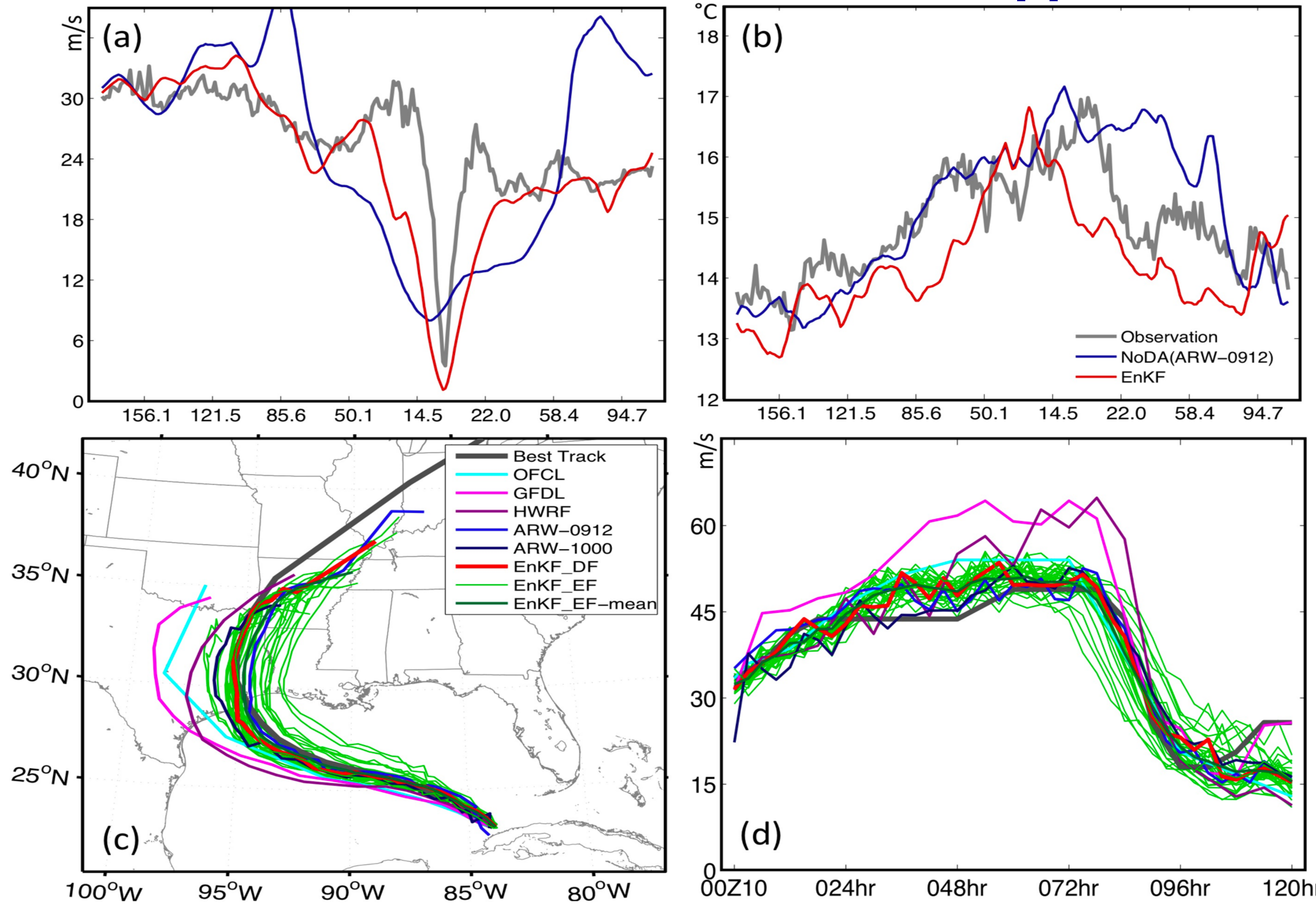


1.Thin cloudy area have been assimilated without including cloudy radiance computation.

2. Thick cloudy area screened out. Can we extract useful information on cloud out of observations by cloudy radiance assimilation?

- Cloud or precipitation indicates that some dynamically important weather is occurring. Subsequent forecasts are often sensitive to initial conditions in regions with cloud and precipitation occurrence.

Hurricane IKE (2008): Forecast from 00Z 10 Sept
Realtime EnKF assimilation of airborne Doppler winds



(Zhang 2011 CiSE)