# Improving High-Resolution Tropical Cyclone Prediction Using a Unified GSI-based Hybrid Ensemble-Variational Data Assimilation System for HWRF

**Xuguang Wang**

**xuguang.wang@ou.edu**

**University of Oklahoma, Norman, OK**

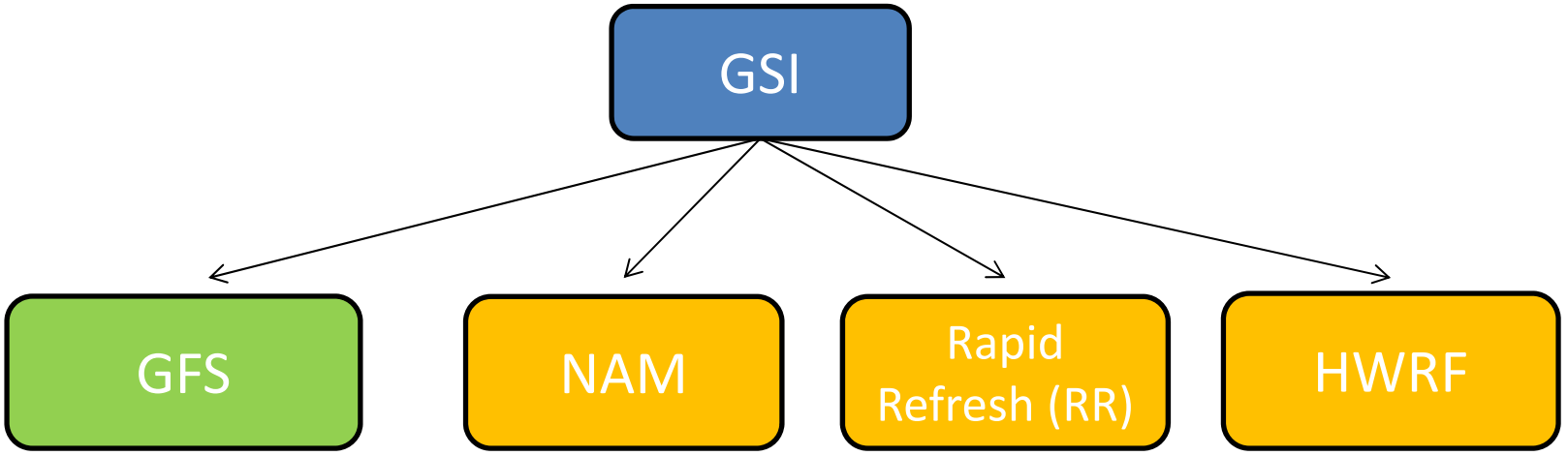
**with**

**Xu Lu (OU), Yongzuo Li (OU), Mingjing Tong (NCEP), Jeff Whitaker (ESRL), Henry Winterbottom (ESRL), Ming Xue (OU) and many other HFIP DA teammates from NCEP, ESRL, HRD, DTC**

HFIP first year review, July 10, 2013

# Background

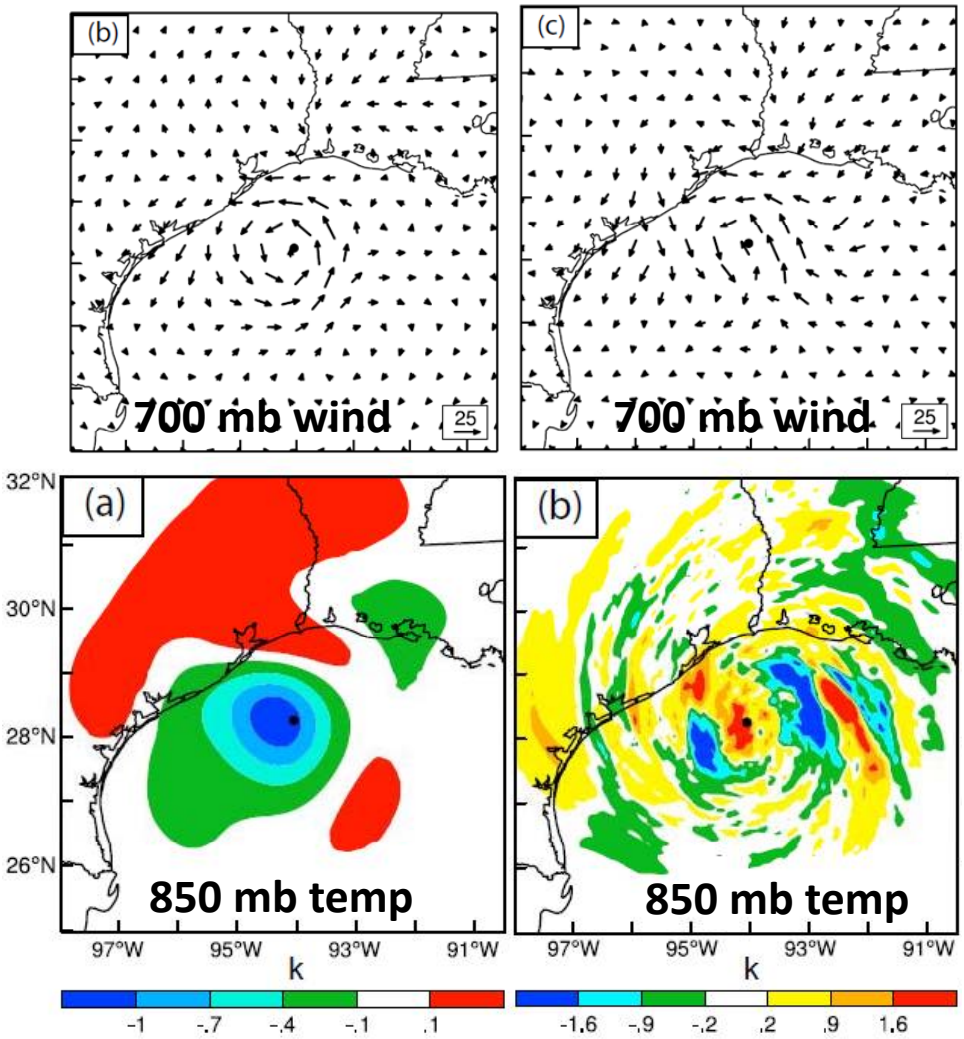
- The GSI-based hybrid DA system showed significant improvement for global forecast compared to GSI 3DVAR and became operational on May 22, 2012 for Global Forecast System (GFS).
- GSI is a unified system which provides data assimilation for all operational global and regional forecast system.



# Background

- Efforts are being conducted to integrate the same GSI-based hybrid DA system with operational regional forecast systems.
- Unifying GSI-based hybrid DA system with operational regional systems facilitates faster transition to operations.
- The focus of the project is the extension, application, testing and research of the GSI-based hybrid data assimilation for the HWRF modeling system at high resolutions.
- Also motivated by encouraging results of ensemble based data assimilation for tropical cyclones.

# Background

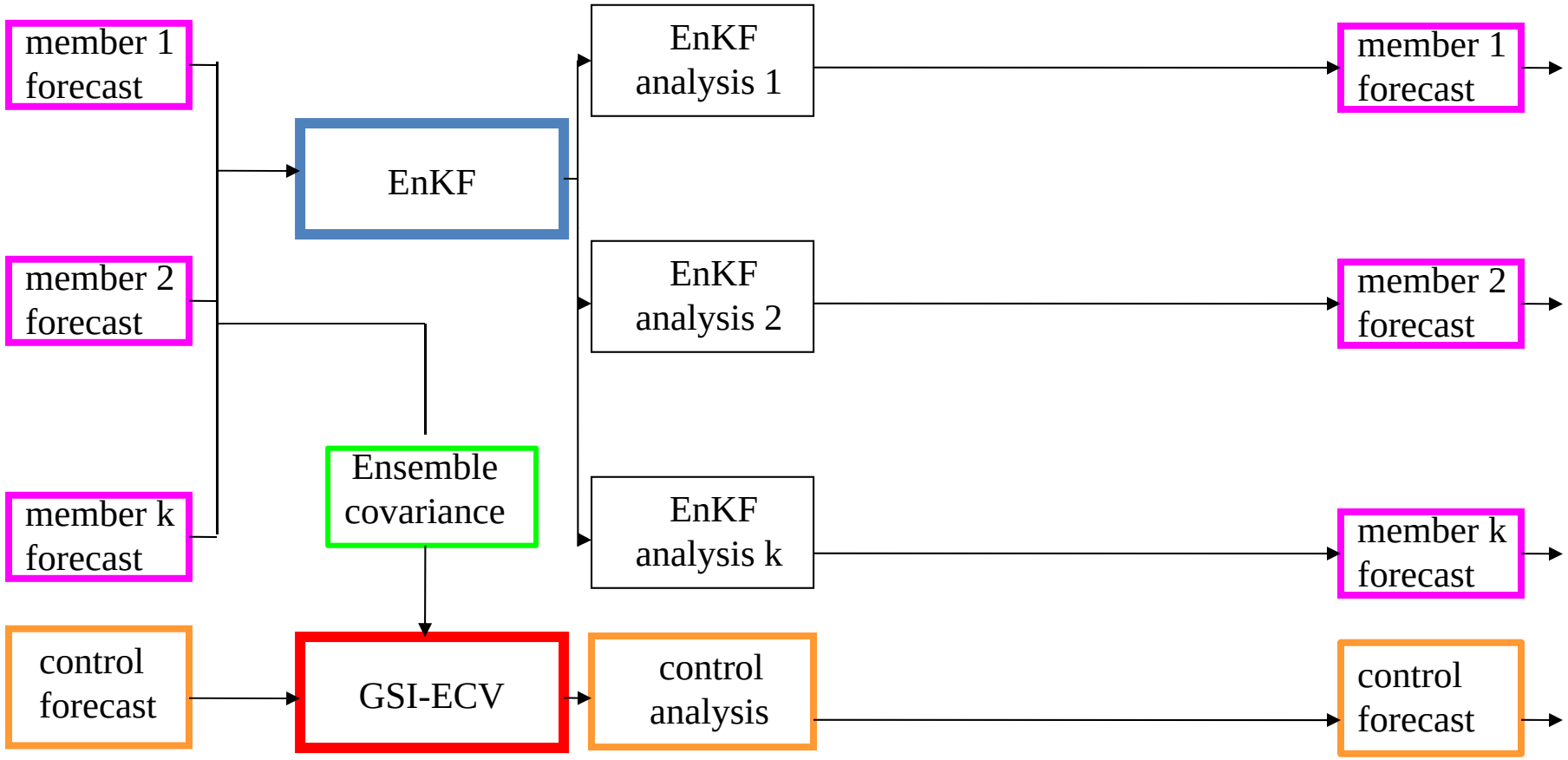



- Hurricane IKE 2008
- WRF ARW: Δx=5km
- Observations: radial velocity from two WSR88D radars (KHGX, KLCH)
- WRFVAR hybrid DA system (Wang et al. 2008ab, MWR)

Li et al., 2012, MWR

# GSI-based Hybrid ensemble-VAR DA system

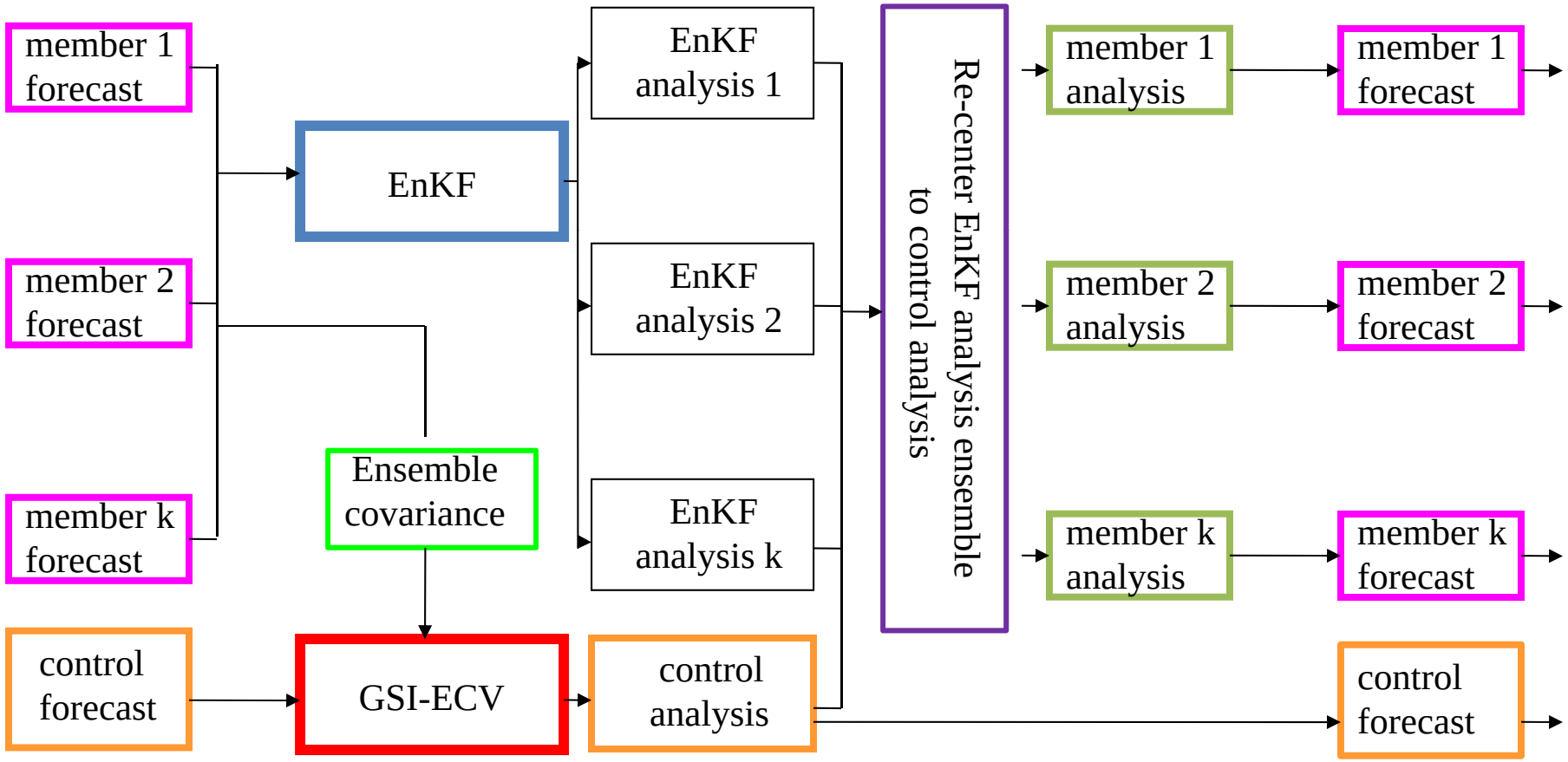
## 1-way coupling




Wang, Parrish, Kleist, Whitaker 2013, MWR

# GSI-based Hybrid ensemble-VAR DA system

## 2-way coupling




Wang, Parrish, Kleist, Whitaker 2013, MWR

# GSI-based hybrid ensemble-variational DA system

- **GSI-ECV**: Extended control variable (ECV) method (Wang 2010, MWR):

$$J\left(\mathbf{x}_1^{'}, \boldsymbol{\alpha}\right) = \beta_1 J_1 + \beta_2 J_e + J_o$$

$$= \beta_1 \frac{1}{2} \mathbf{x}_1^{'T} \mathbf{B}^{-1} \mathbf{x}_1^{'} + \beta_2 \underline{\frac{1}{2} \boldsymbol{\alpha}^T \mathbf{C}^{-1} \boldsymbol{\alpha}} + \frac{1}{2} \left(\mathbf{y}^{o'} - \mathbf{H}\mathbf{x}^{'}\right)^T \mathbf{R}^{-1} \left(\mathbf{y}^{o'} - \mathbf{H}\mathbf{x}^{'}\right)$$

Extra term associated with extended control variable

$$\mathbf{x}^{'} = \mathbf{x}_1^{'} + \underline{\sum_{k=1}^{K} \left(\boldsymbol{\alpha}_k \circ \mathbf{x}_k^e\right)}$$

Extra increment associated with ensemble

- **EnKF**: square root filter interfaced with GSI observation operator (Whitaker et al. 2008, MWR)

# System development and enhancement

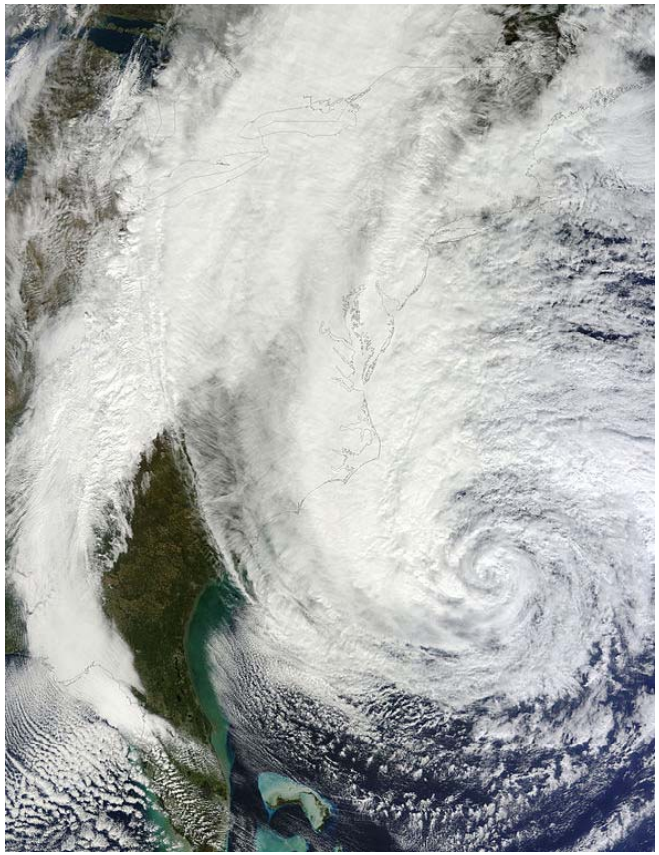
- Develop interface to integrate both EnKF and GSI-ECV components with HWRF; different from H213 where ensemble is provided from GFS ensemble.
- Add/enhance inner core airborne radar data assimilation capability
- Enhance dual resolution assimilation capability
- Development/enhancement for GSI-ECV and airborne radar data have been transitioned into 2013 operational HWRF (H213)

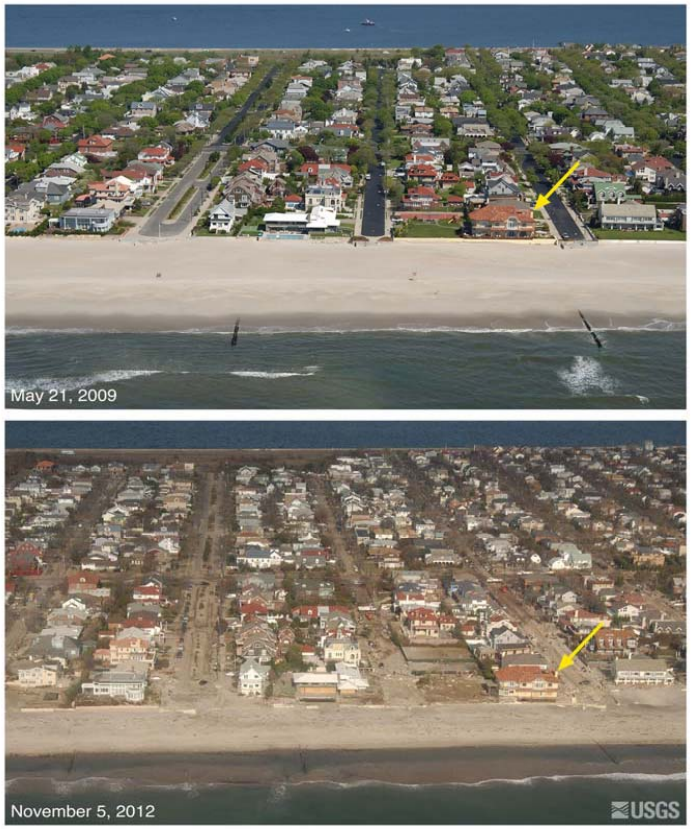
# Why Hybrid? "Best of both worlds"

Summarized in Wang 2010, MWR

| | VAR (3D, 4D) | EnKF | Hybrid | References (e.g.) |
|---|---|---|---|---|
| Benefit from use of flow dependent ensemble covariance instead of static B | | Yes | Yes | Hamill and Snyder 2000; Lorenc 2003; Wang et al. 2007ab,2008ab, 2009; Buehner et al. 2010ab; Wang 2011, Zhang and Zhang 2012, etc. |
| Robust for small ensemble or large model error | | | Yes | Wang et al. 2007b, 2009; Buehner et al. 2010b |
| Better localization for integrated measure, e.g. satellite radiance; radar with attenuation | | | Yes | Campbell et al. 2010 |
| Flexible to add various dynamical/physical constraints | yes | | Yes | Wang et al. 2013 |
| Use of various existing capabilities in VAR (e.g., Outer loops to treat nonlinearity; Variational QC) | yes | | Yes | |

# Test with Hurricane Sandy, Oct. 2012



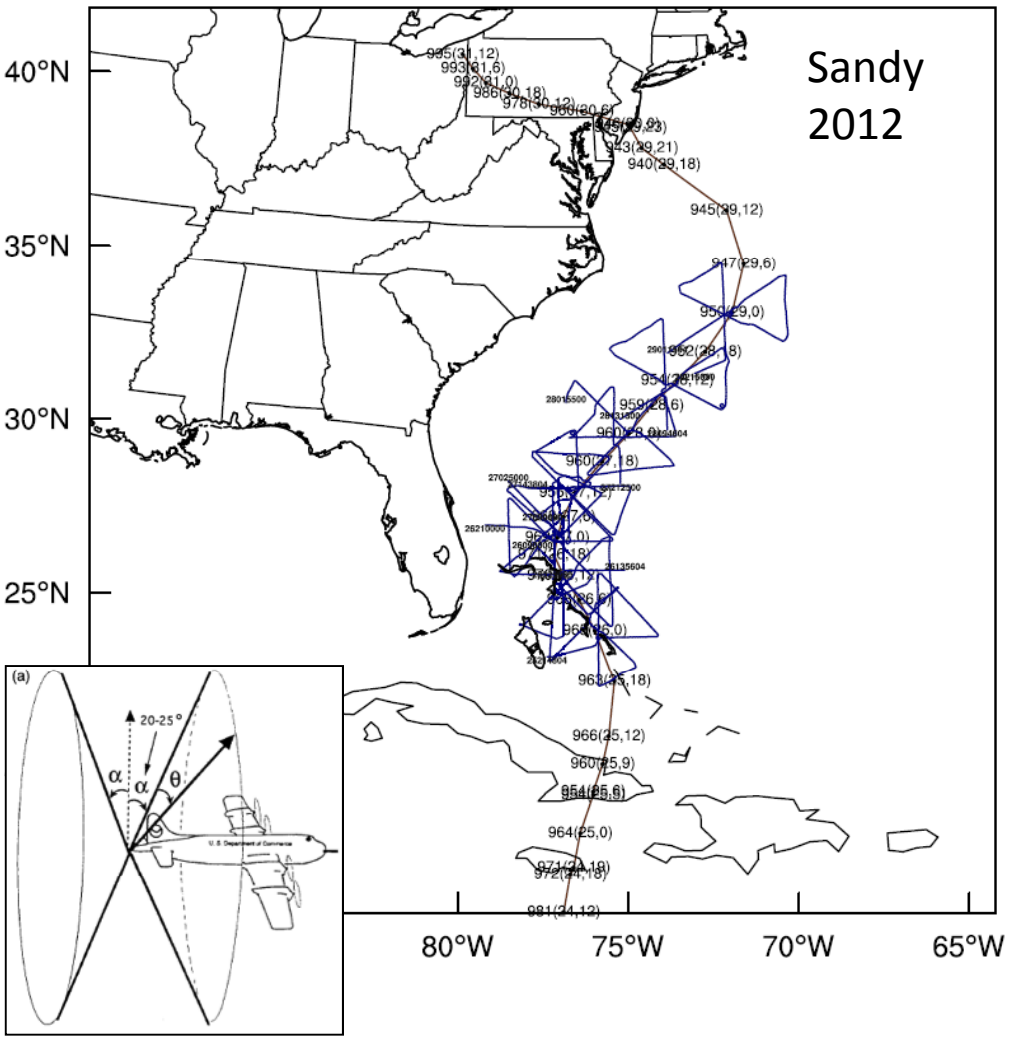



New York State before and after

nhc.noaa.gov

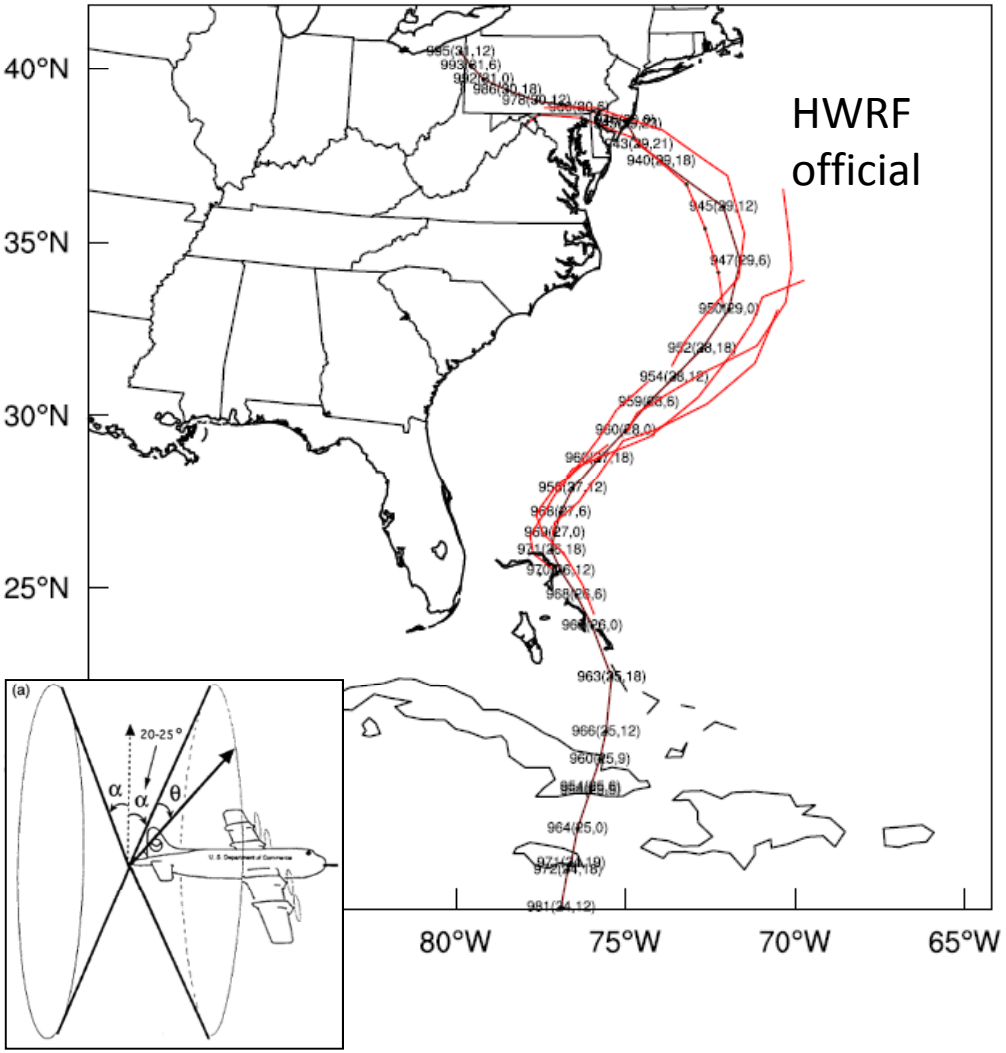
- Complicated evolution
- Tremendous size
- 147 direct deaths across Atlantic Basin
- US damage $50 billion

# Experiment Design



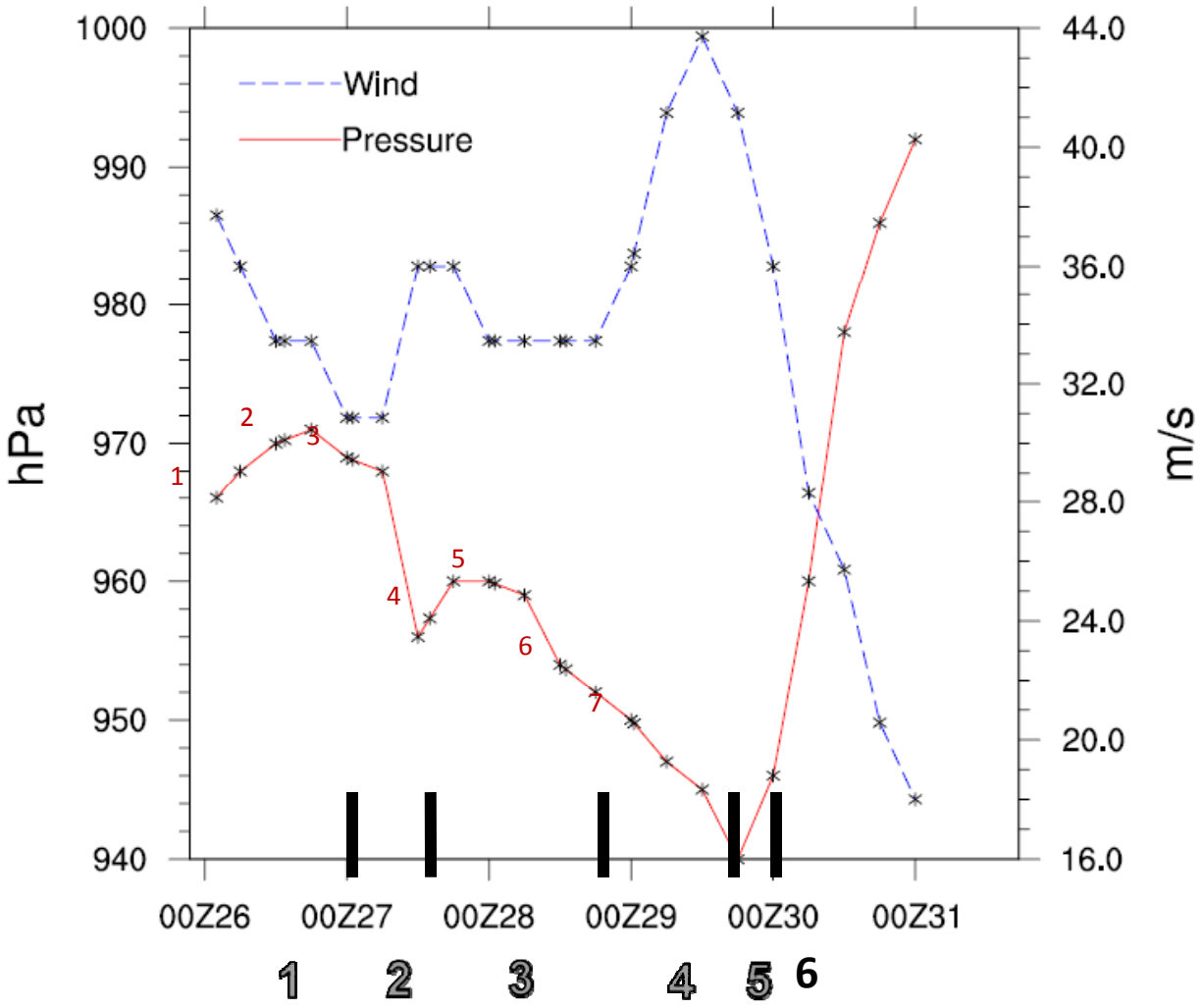

- Model: HWRF
- Observations: radial velocity from Tail Doppler Radar (TDR) onboard NOAA P3 aircraft
- Initial and LBC ensemble: GFS global hybrid DA system
- Ensemble size: 40

# Experiment Design




- Model: HWRF
- Observations: radial velocity from Tail Doppler Radar (TDR) onboard NOAA P3 aircraft
- Initial and LBC ensemble: GFS global hybrid DA system
- Ensemble size: 40

# Evolution during TDR missions




1 Tropical to Non-Tropical

2 Non-Tropical back to Tropical

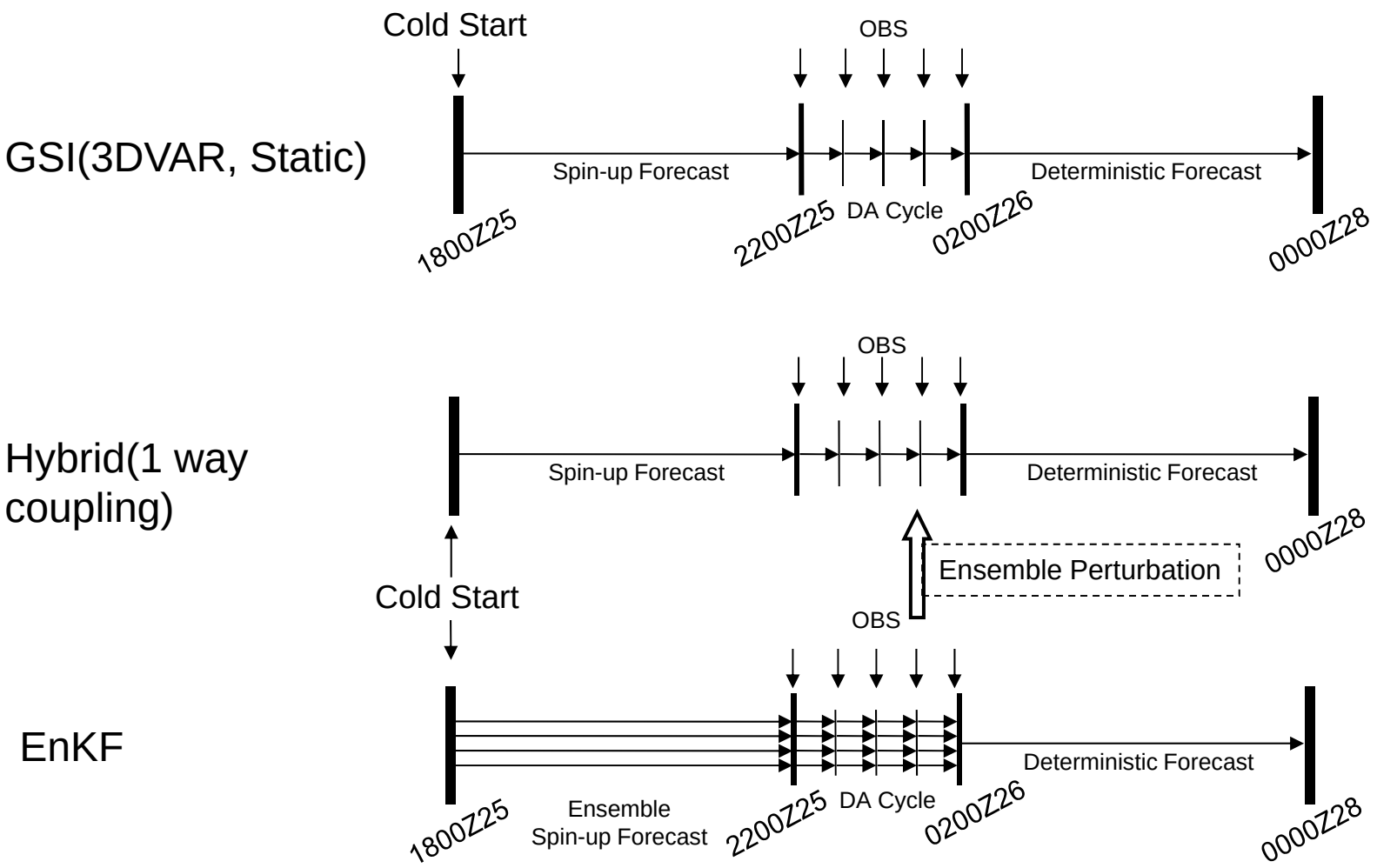
3 Tropical

4 Re-Intensify

5 Extra-Tropical

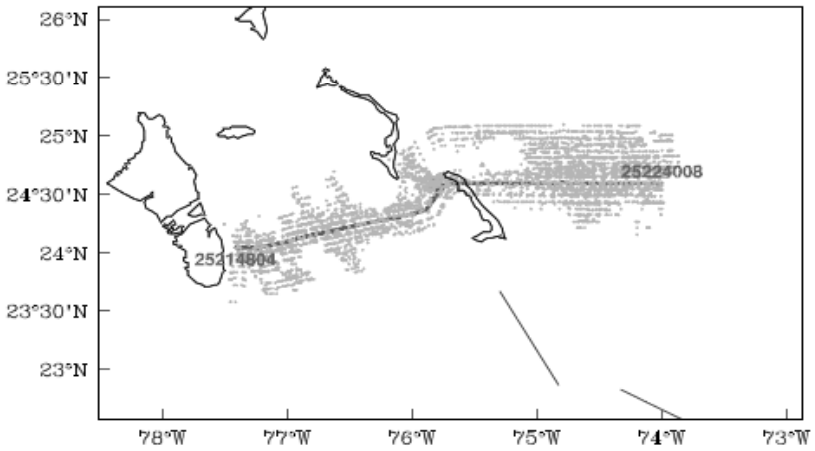
6 Landfall

# DA cycling configuration (mission 1)

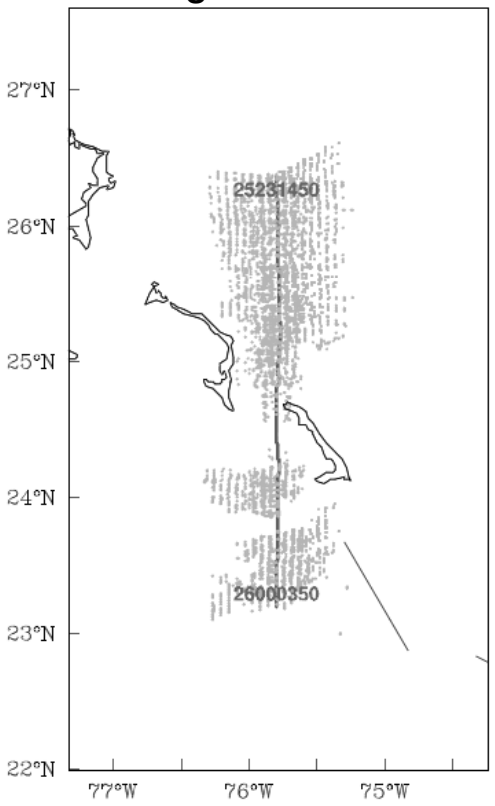


# TDR data distribution (mission 1)

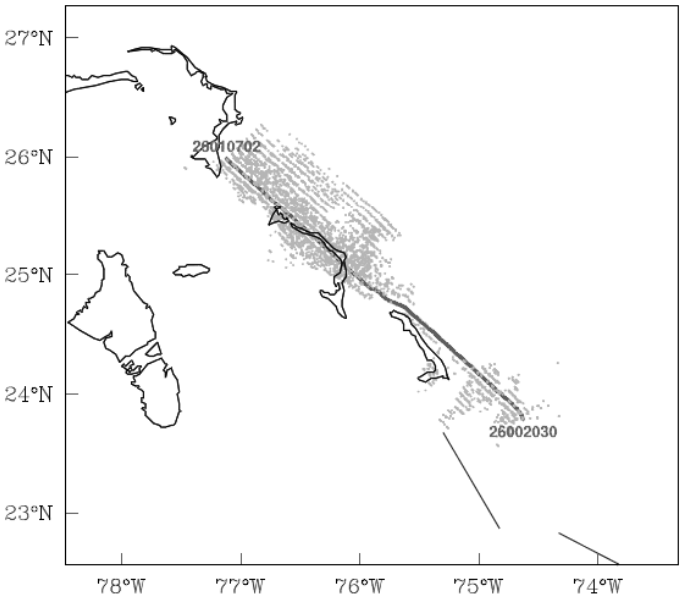
**Vr & flight track 2200Z25**



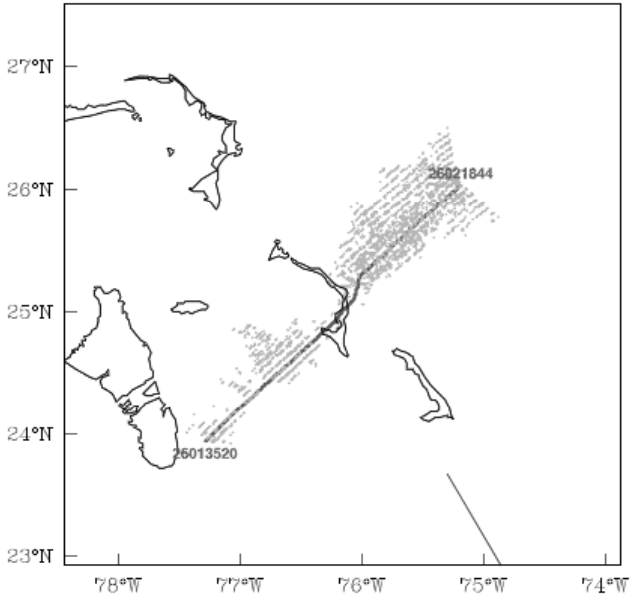

**Vr & flight track 2330Z25**



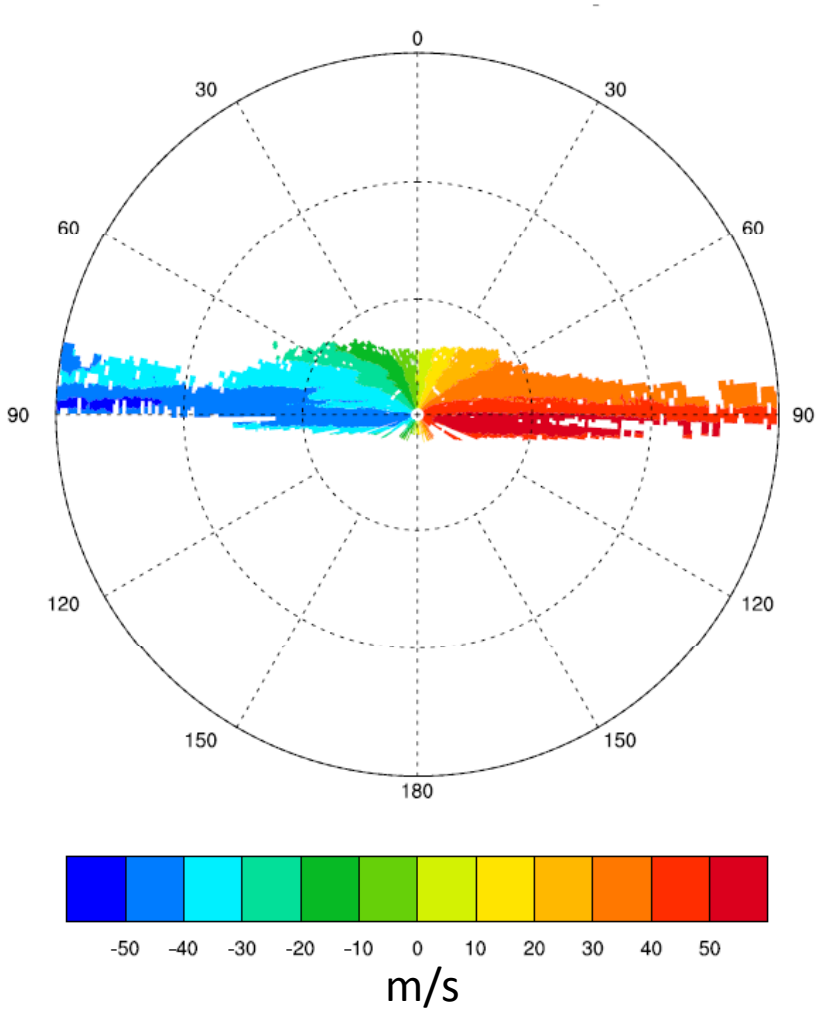

**Vr & flight track 0030Z26**

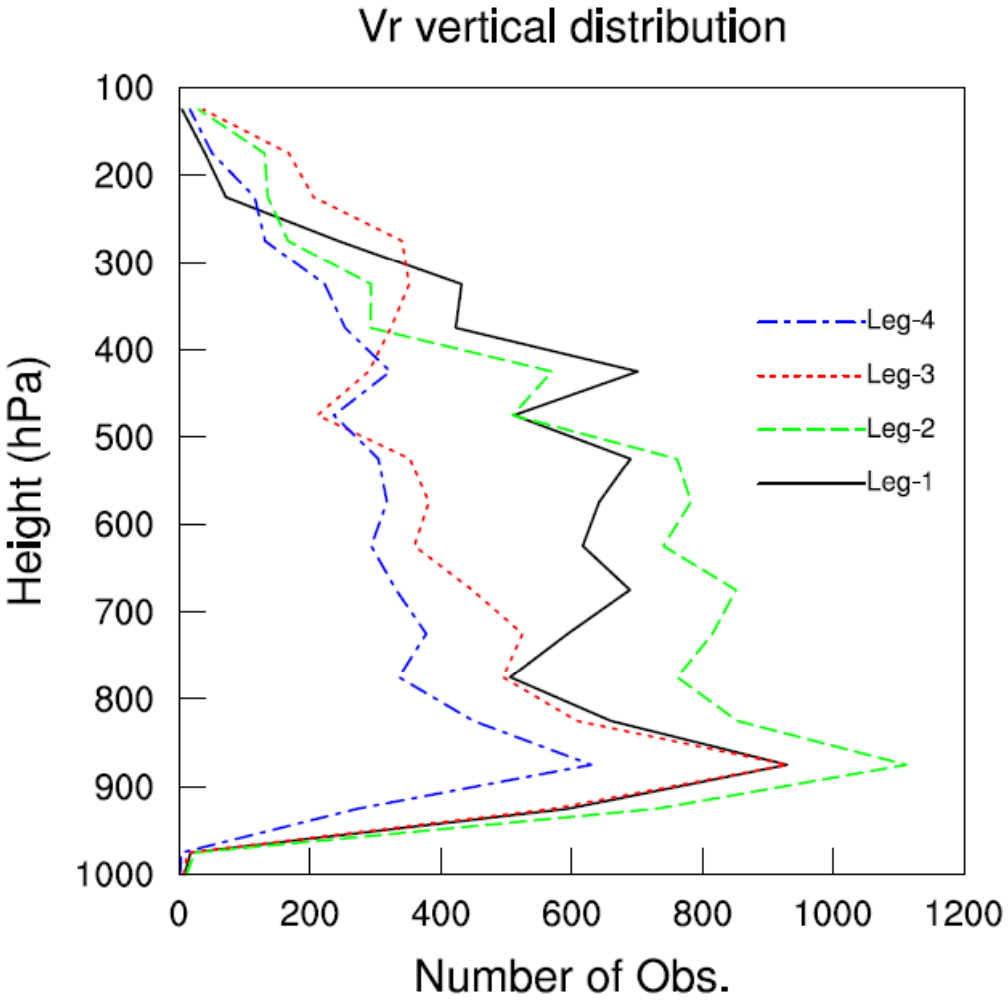



**Vr & flight track 0200Z26**



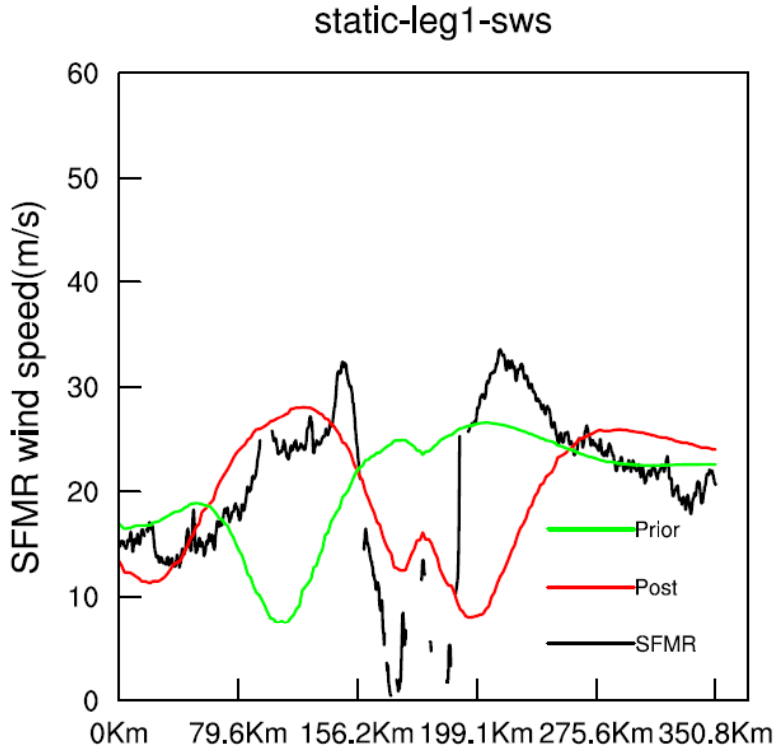
# TDR data distribution (mission 1)

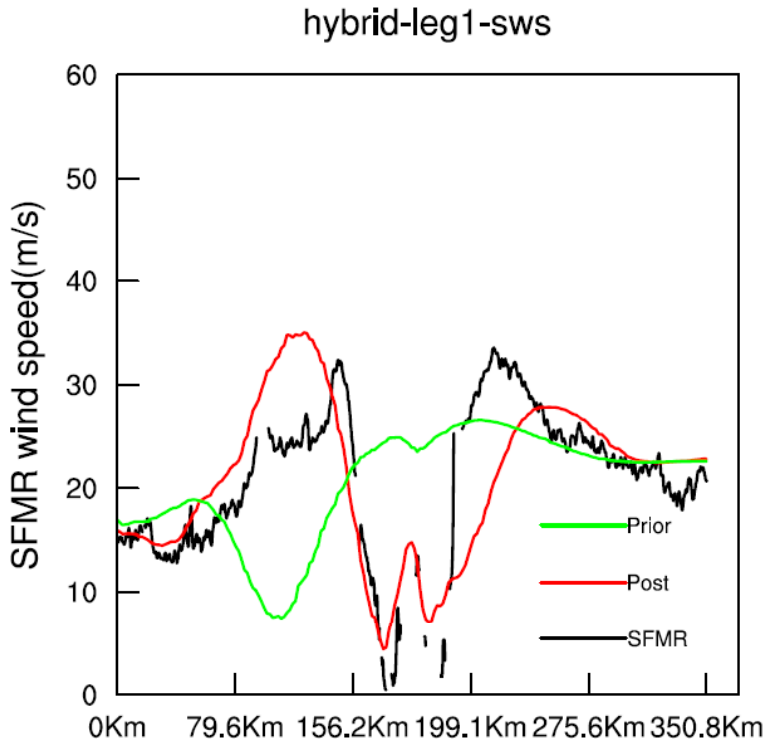


# Verification against SFMR wind speed

First Leg

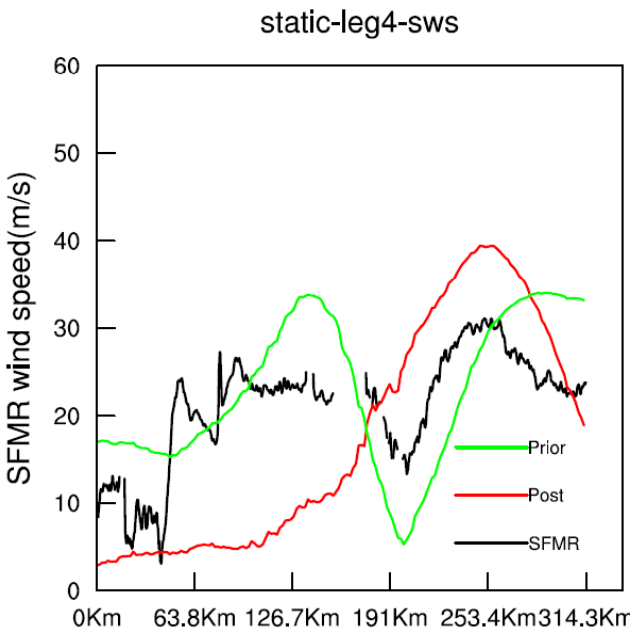


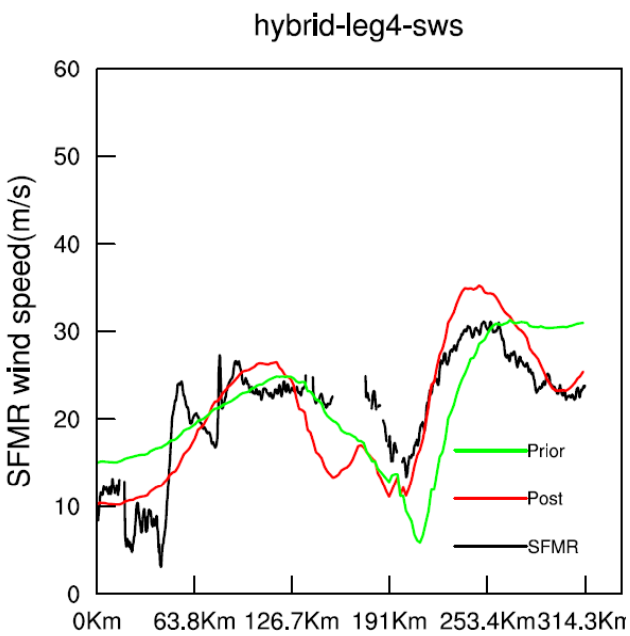



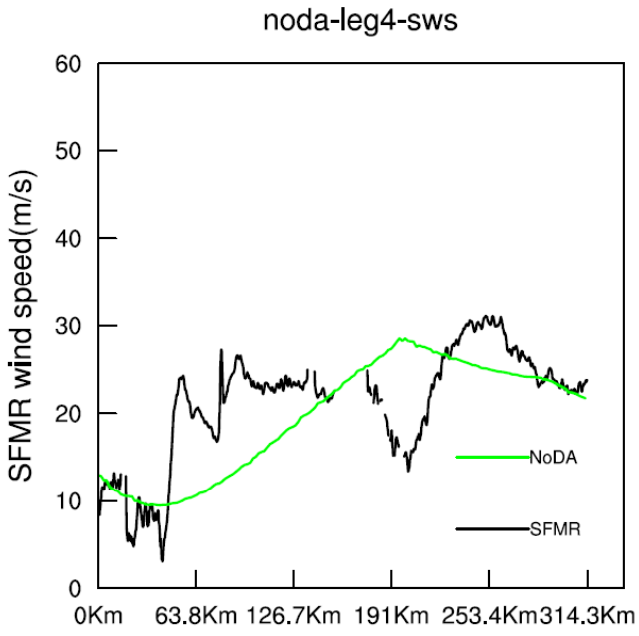

**Acknowledge HRD to make SFMR, flight level data available**

# Verification against SFMR wind speed

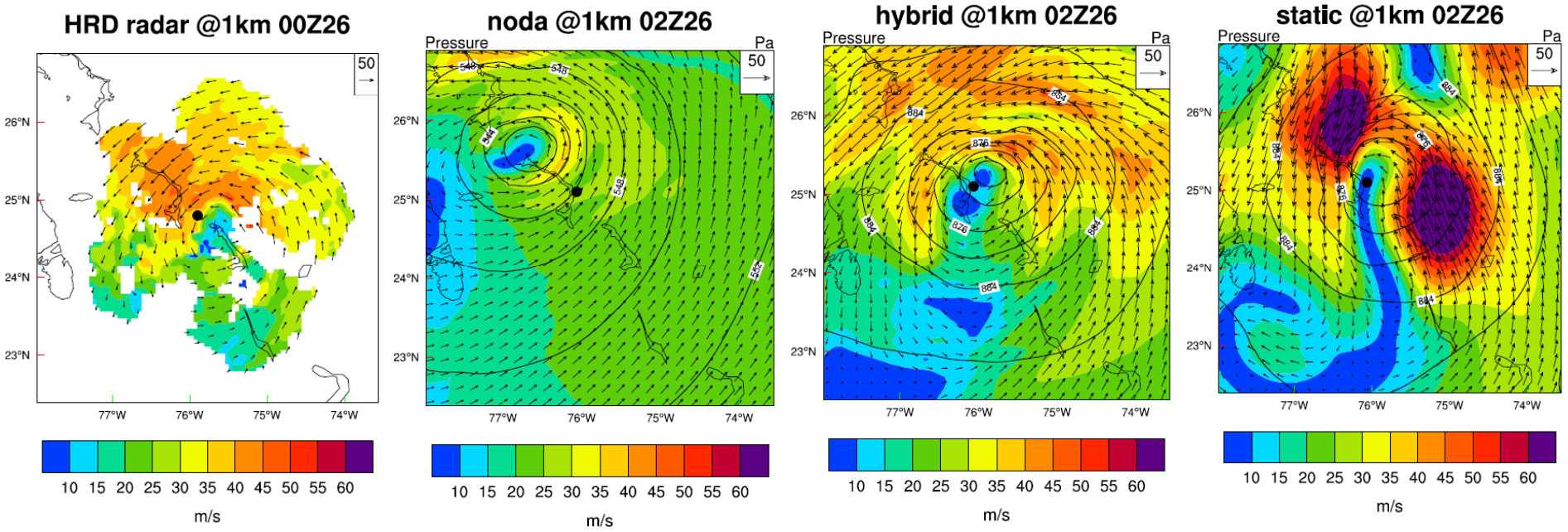
## Last Leg



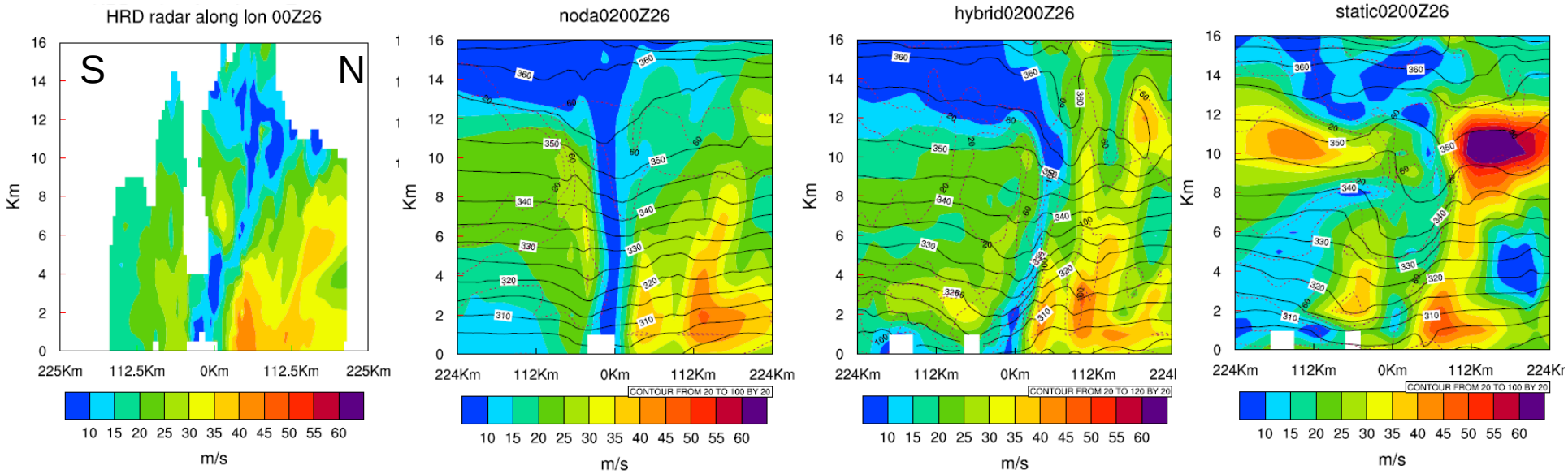



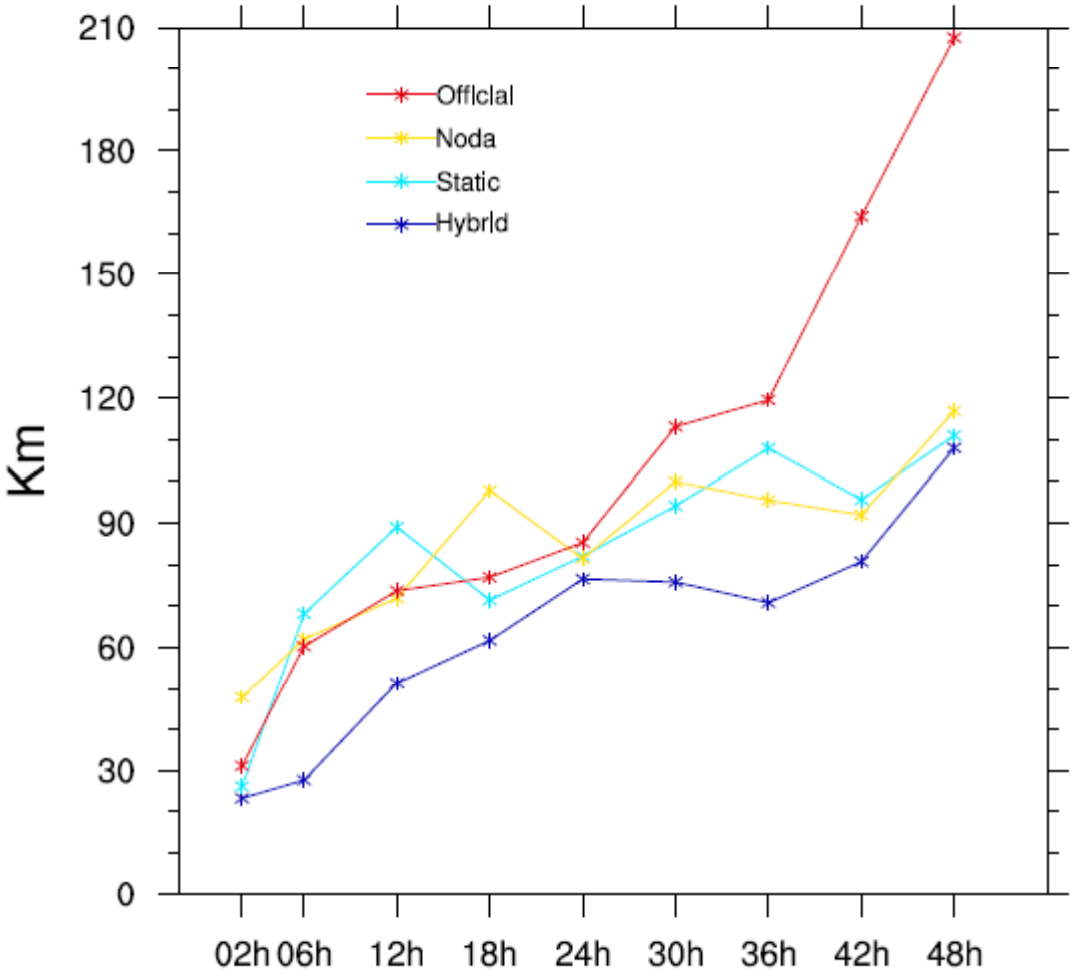
# Comparison with HRD radar wind analysis

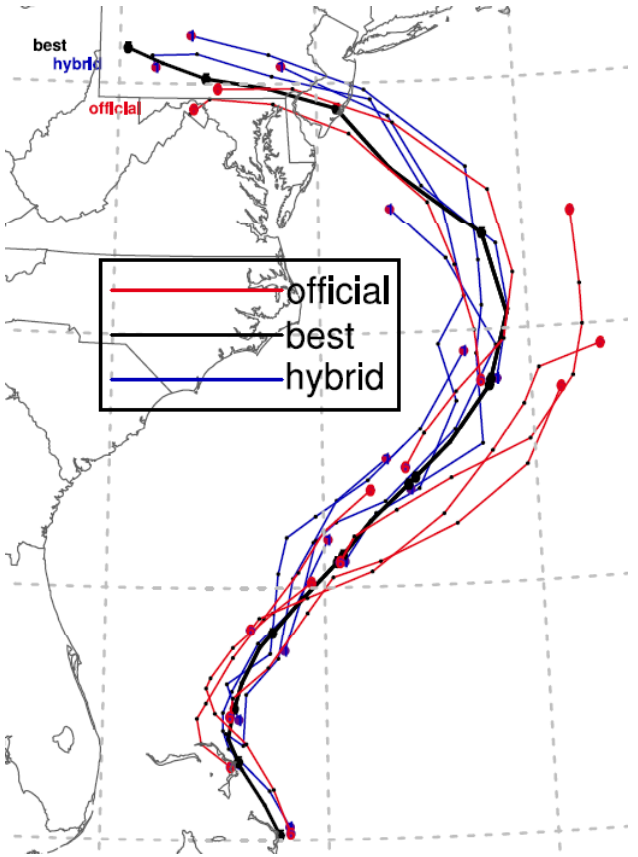


# Comparison with radar wind analysis

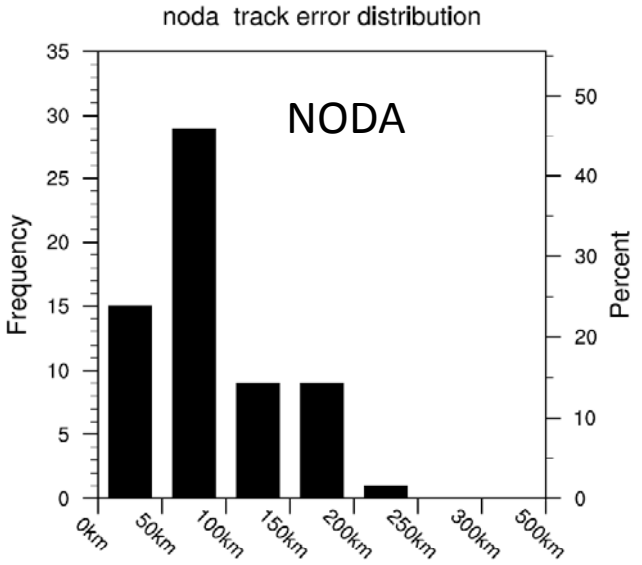


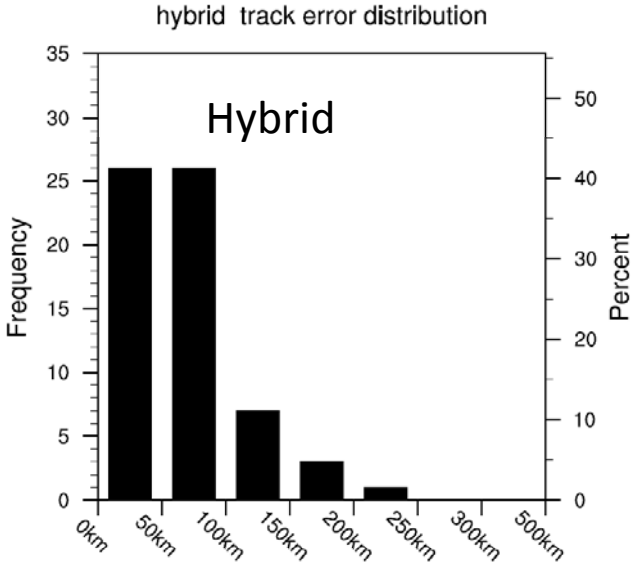
# Track forecast (RMSE for 7 missions)

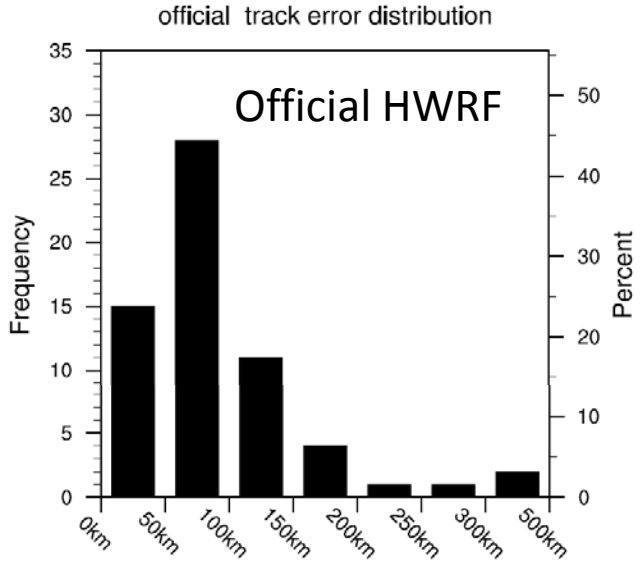


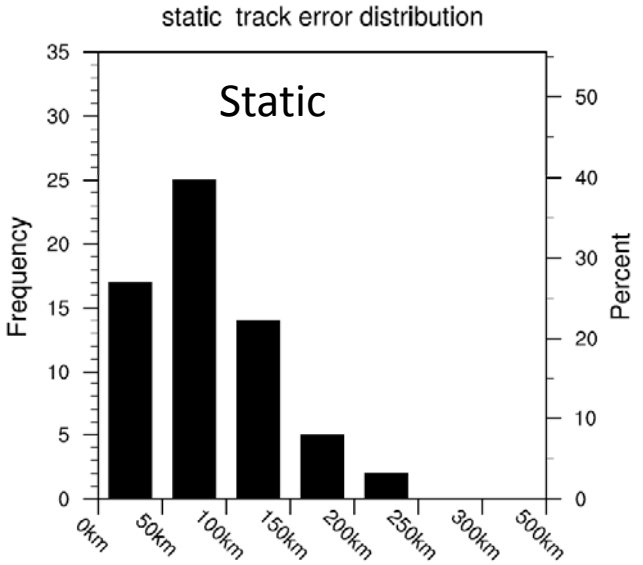



# Track forecast (error distribution)

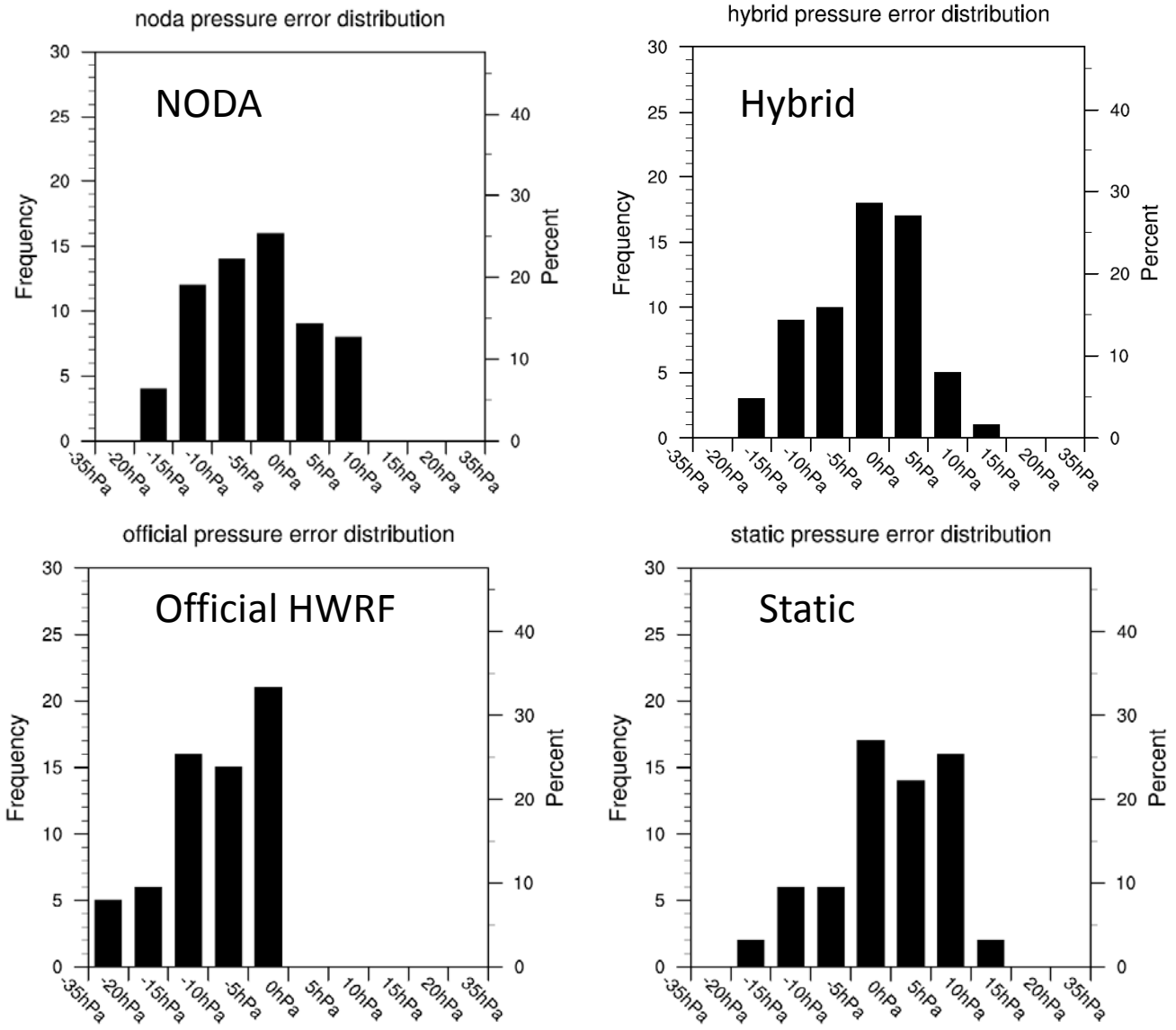


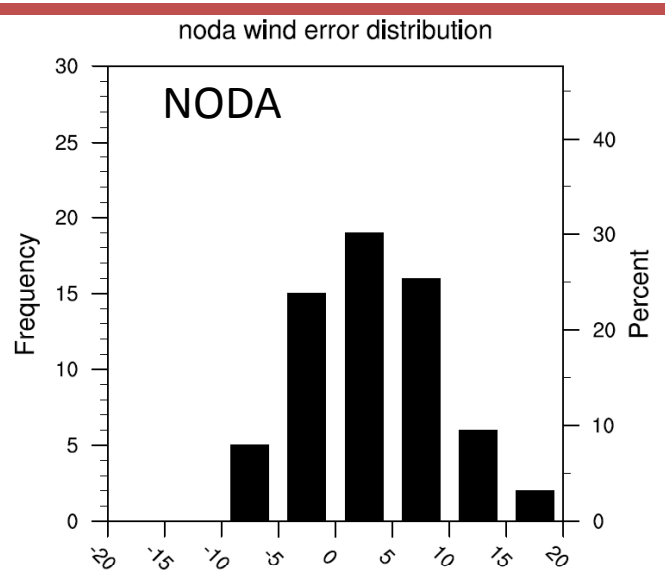



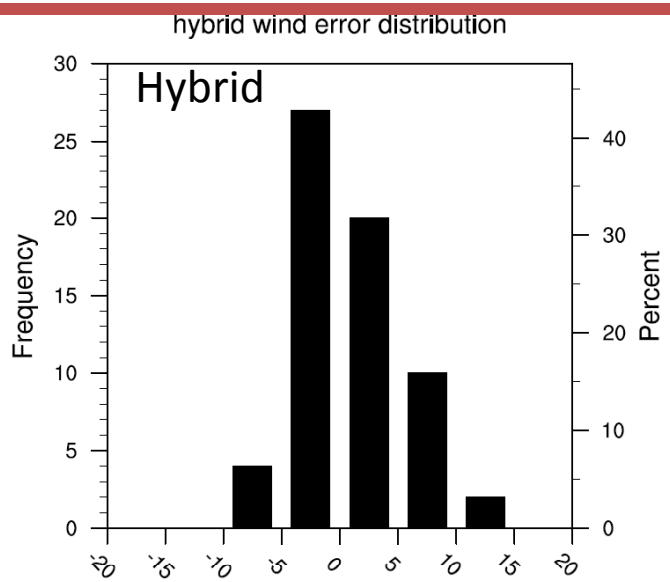



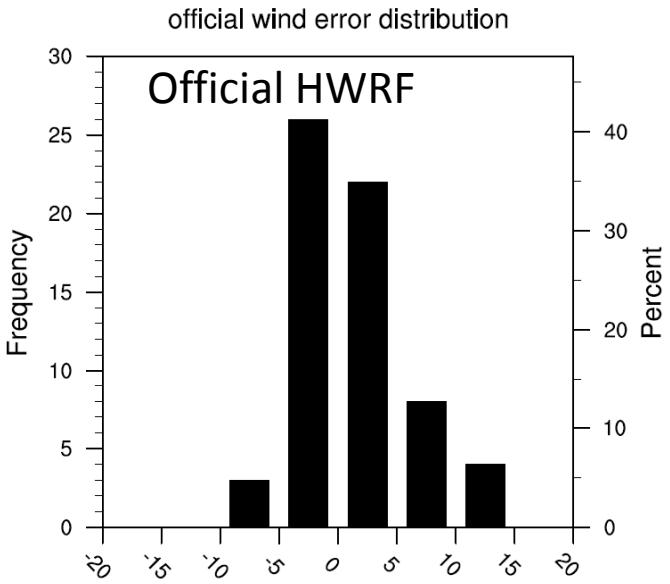
# MSLP forecast (error distribution)

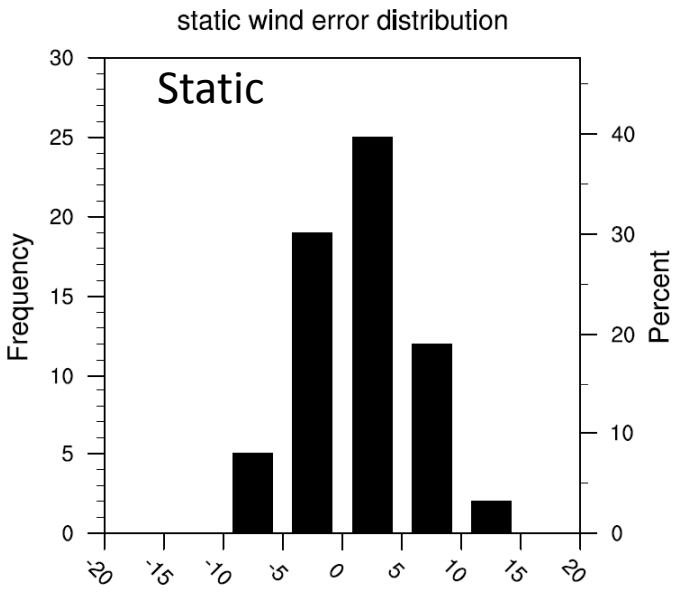


# Max wind forecast (error distribution)

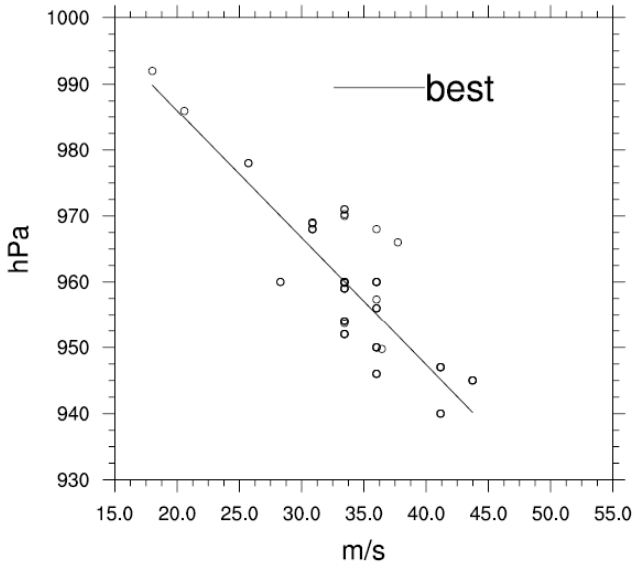


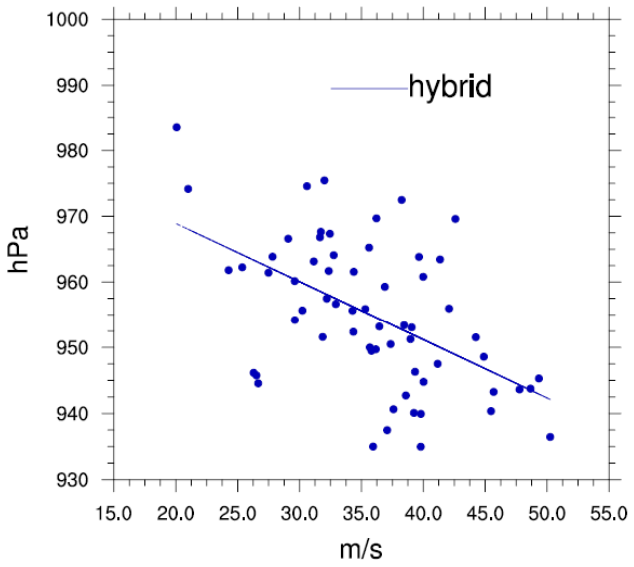



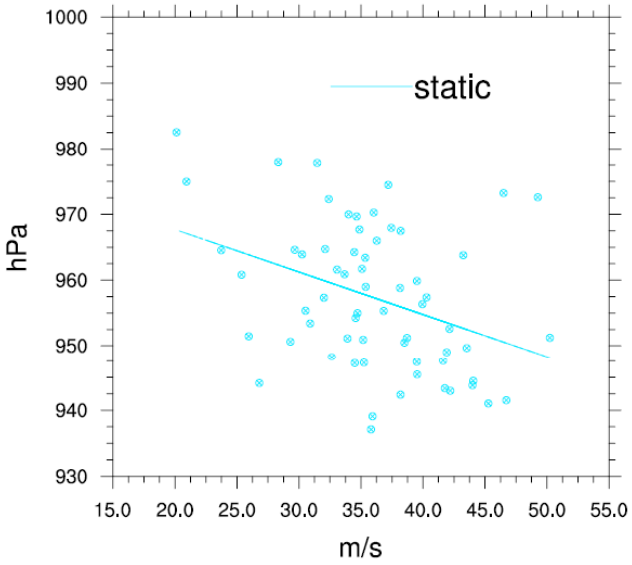



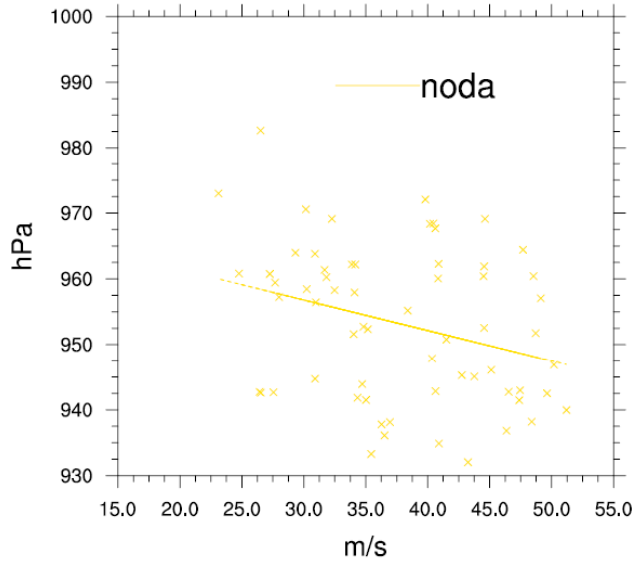



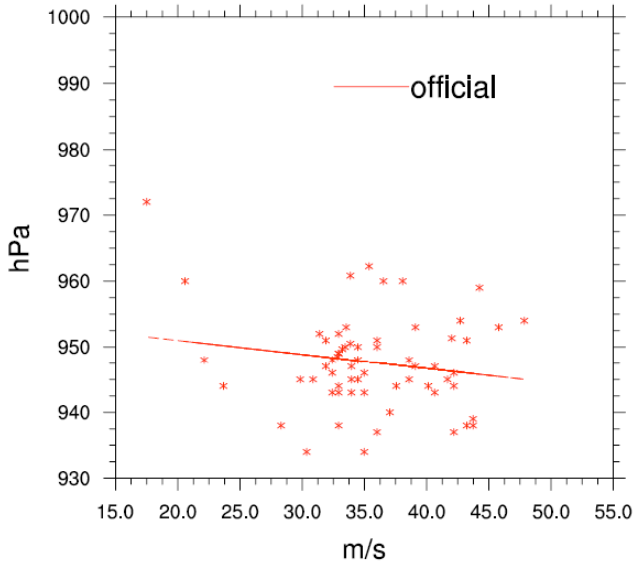
# Max wind and MSLP relationship



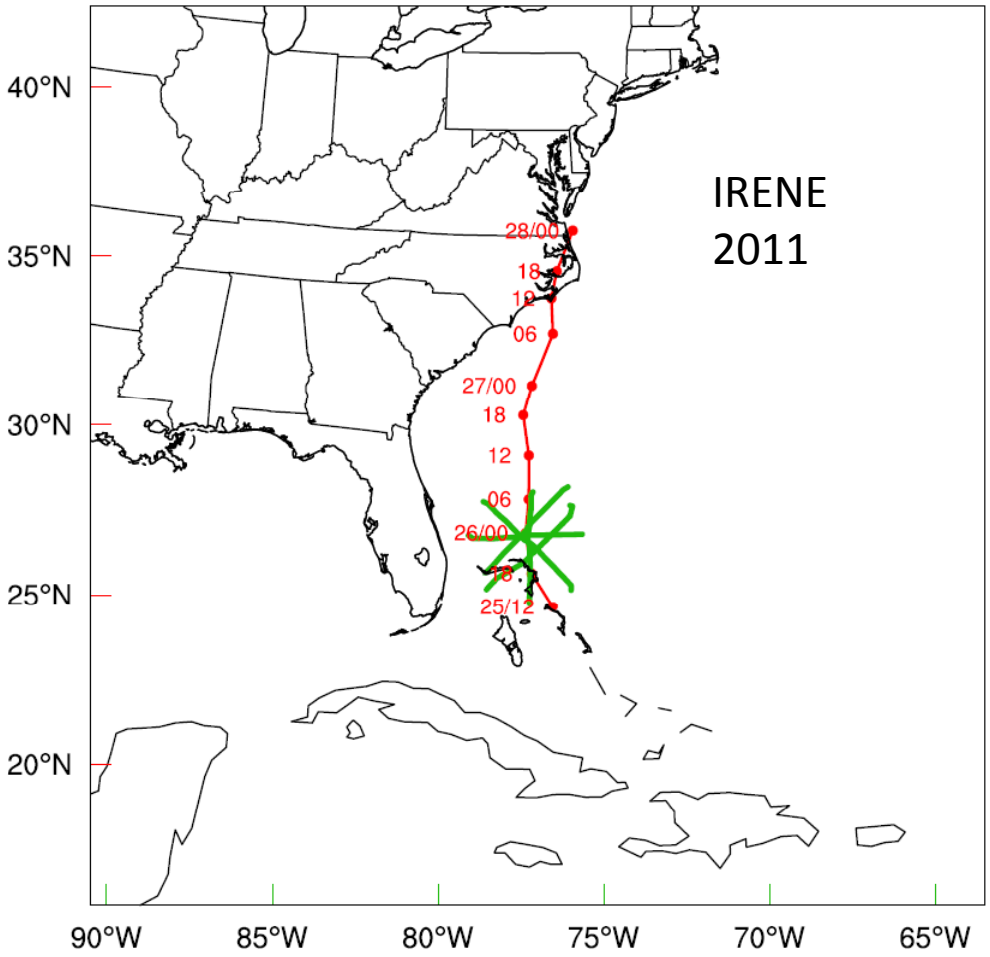



# Test with IRENE 2011

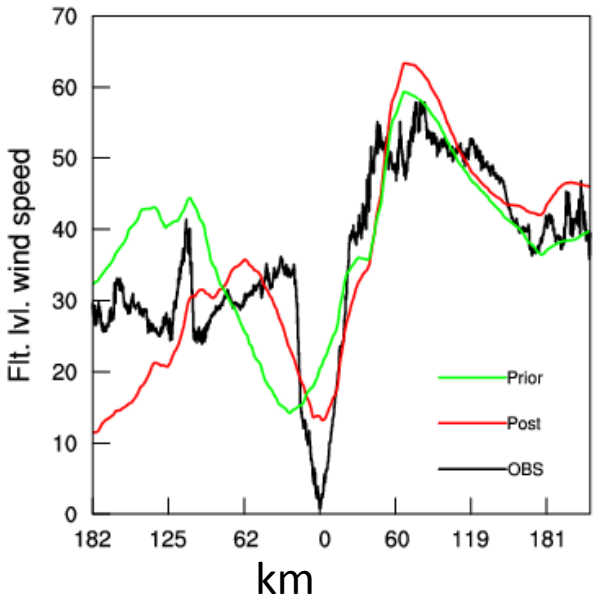



- Model: HWRF
- Observations: radial velocity from Tail Doppler Radar (TDR)
- Initial and LBC ensemble: GFS global hybrid DA system
- Ensemble size: 40

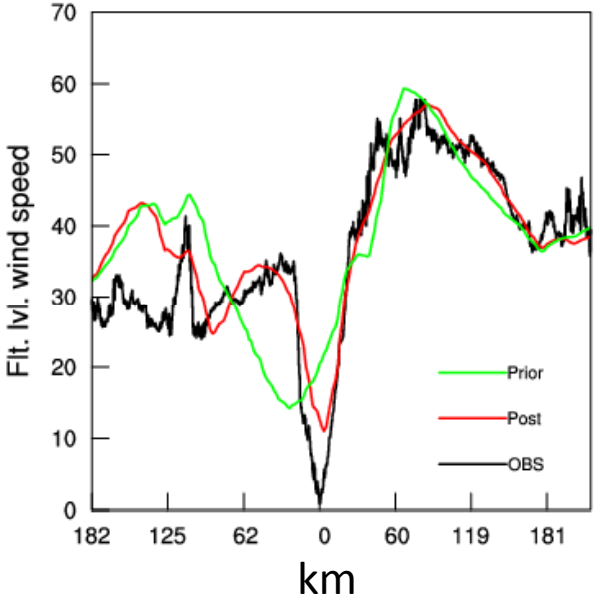
# Verification against independent flight level wind speed

First Leg

Static




hybrid



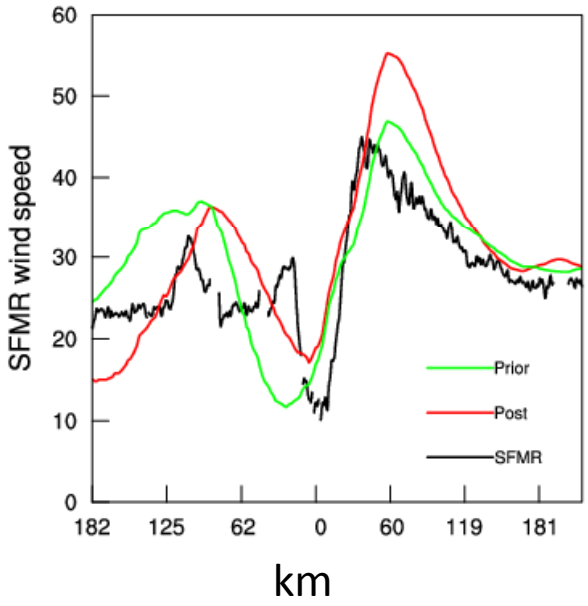


27

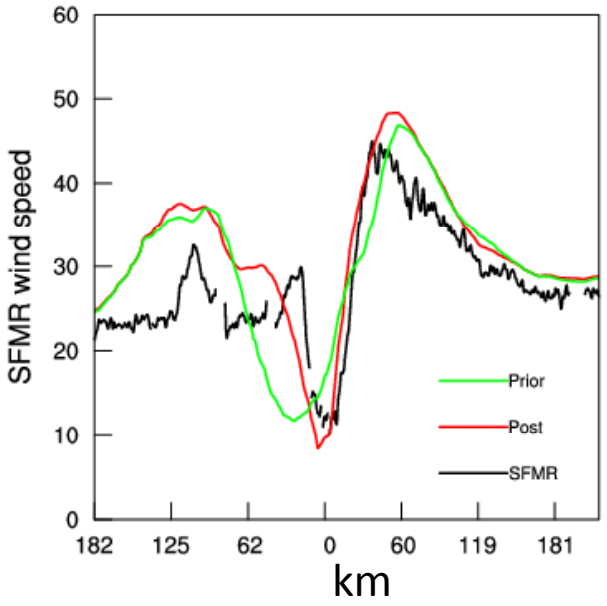
# Verification against SFMR wind speed

First Leg

Static




hybrid



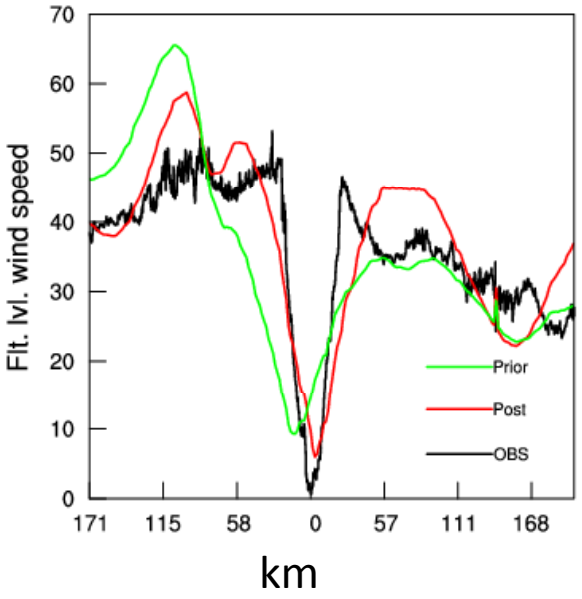


28

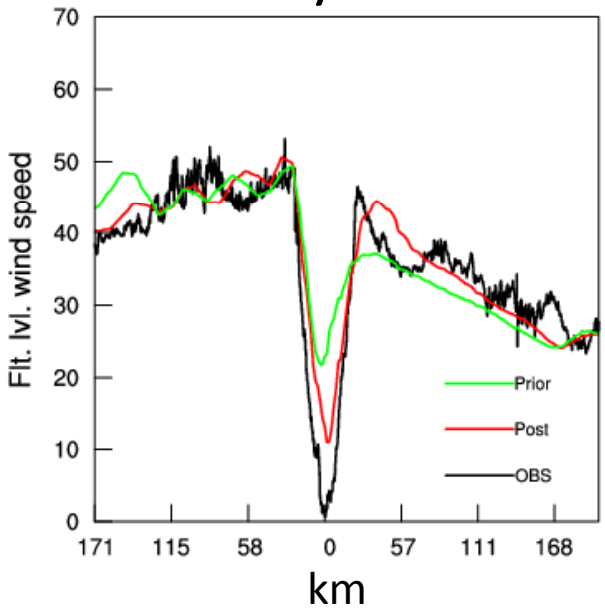
# Verification against independent flight level wind speed

Last Leg

static




hybrid



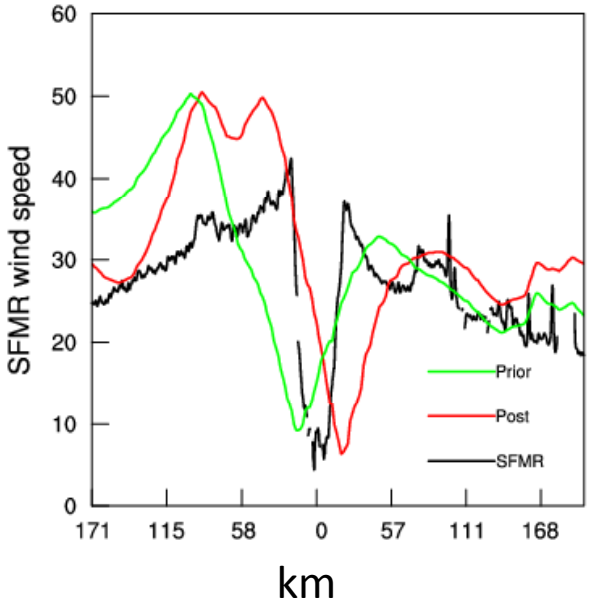


29

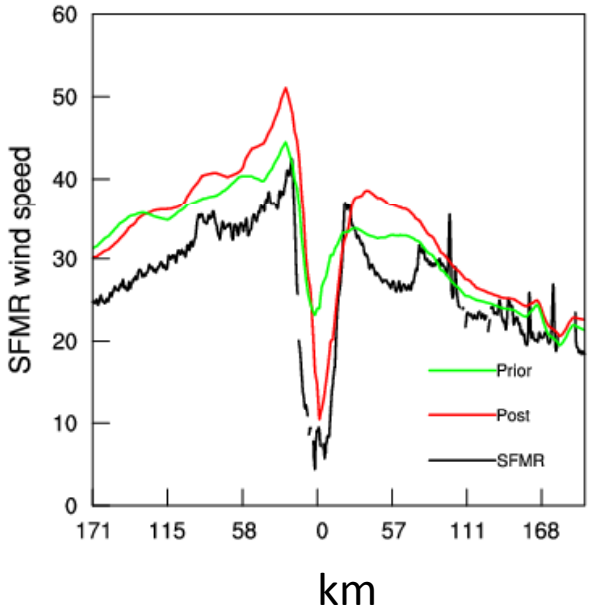
# Verification against SFMR wind speed

Last Leg

static




hybrid

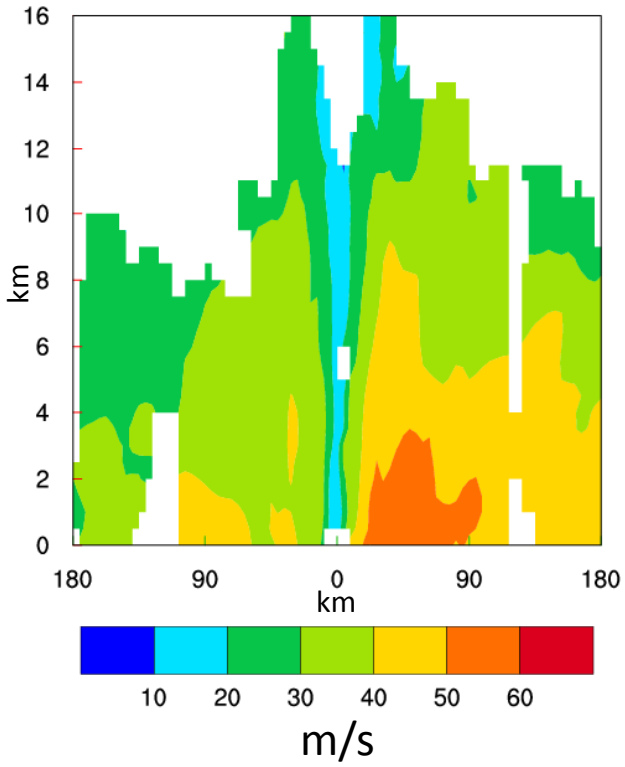




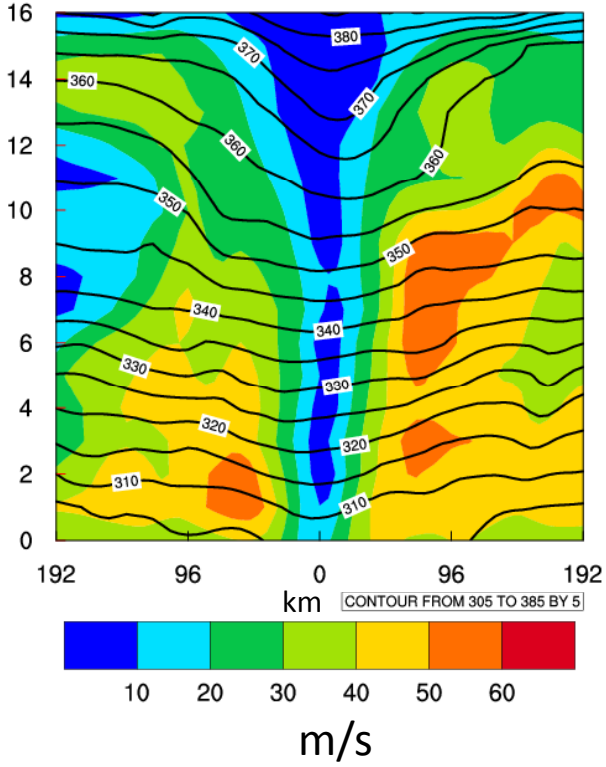
30

# Comparison with HRD radar wind analysis

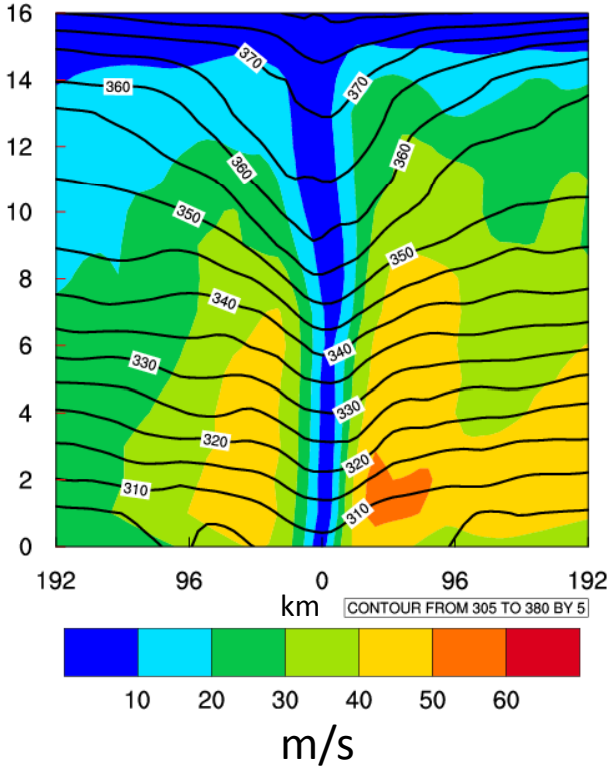
HRD radar wind analysis




static




Hybrid

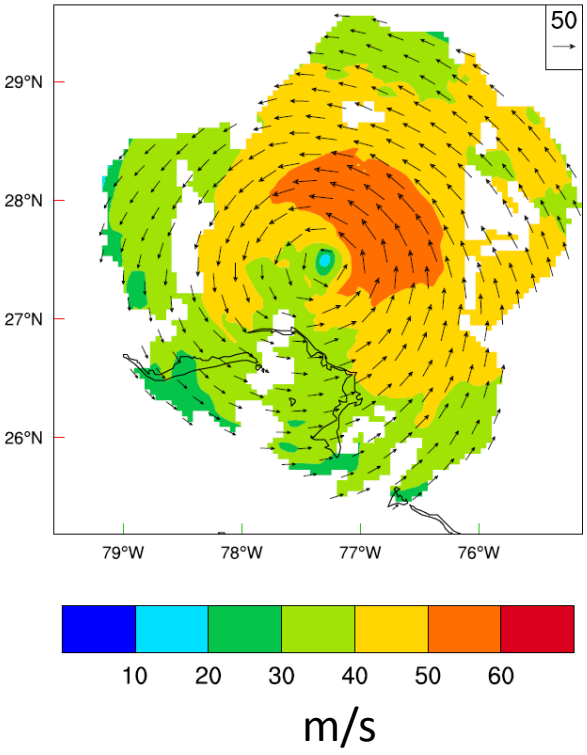




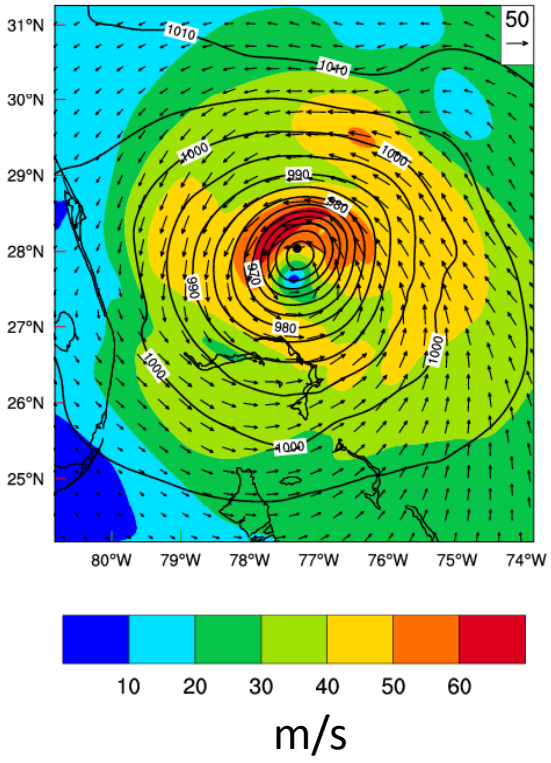
31

# Comparison with radar wind analysis

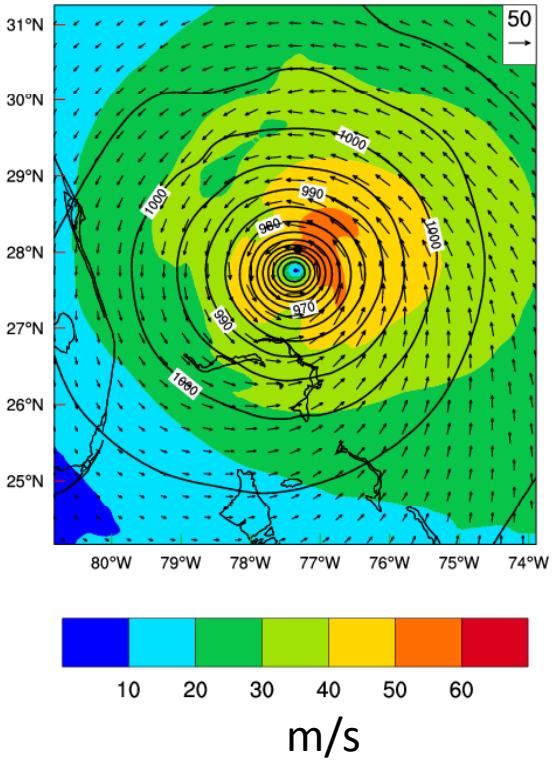
HRD radar wind analysis @ 1km




static @ 1km




Hybrid @ 1km

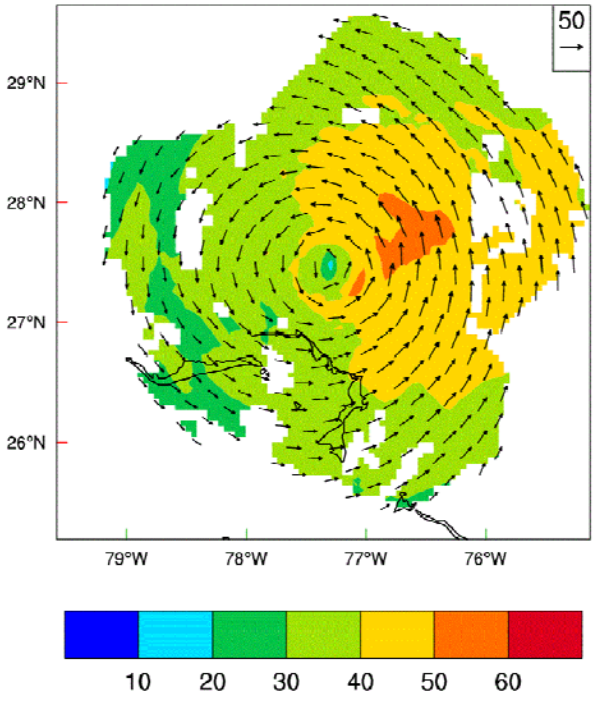




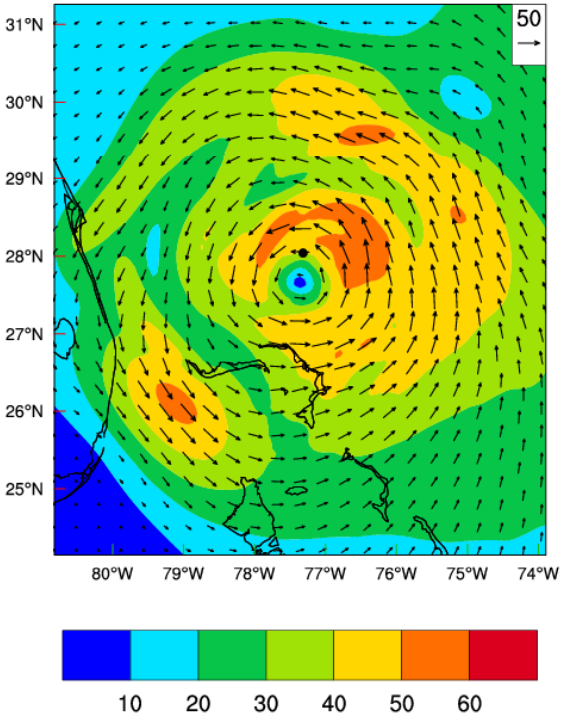
32

# Comparison with radar wind analysis

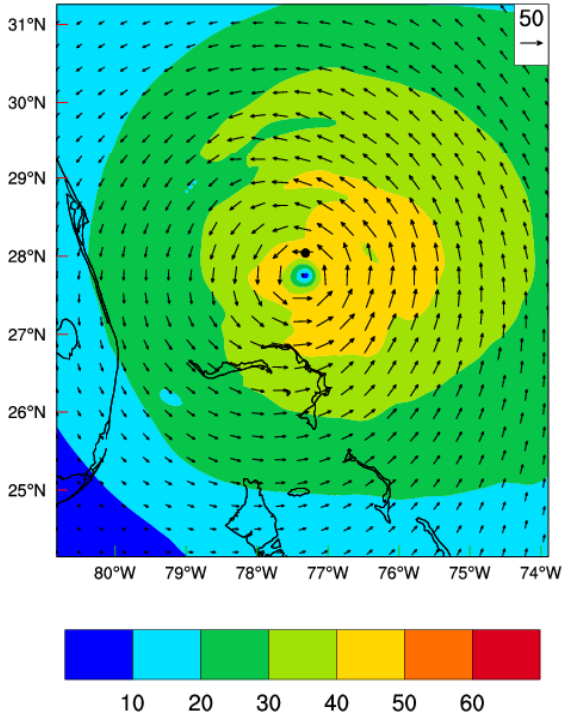
HRD radar wind analysis @ 3km




static @ 3km

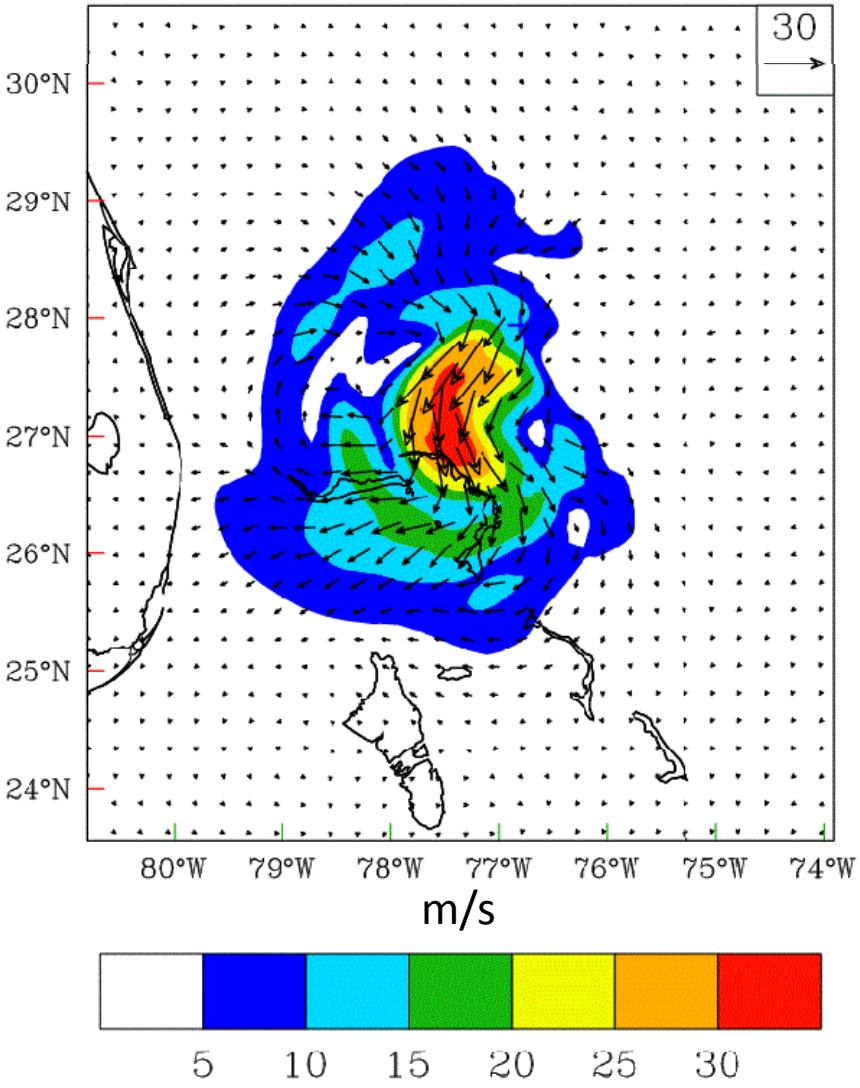



Hybrid @ 3km

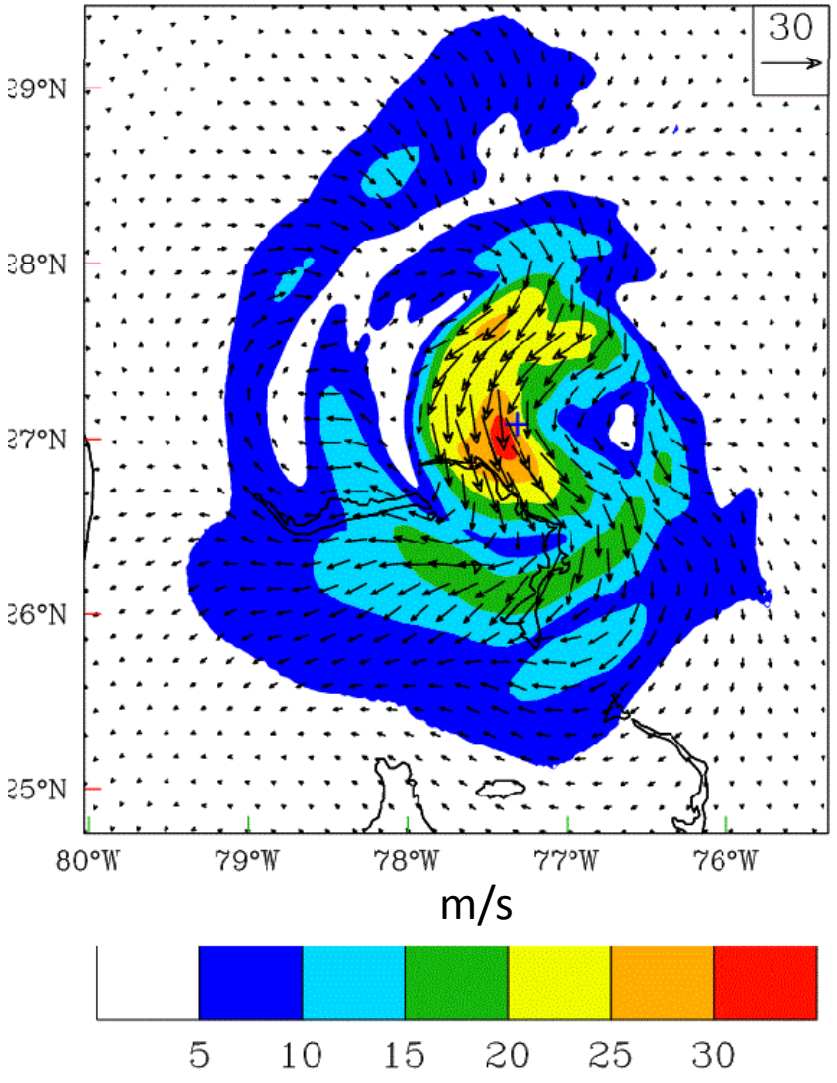


# 3km-9km dual resolution hybrid DA with moving nest

9 km grid 700mb wind increment

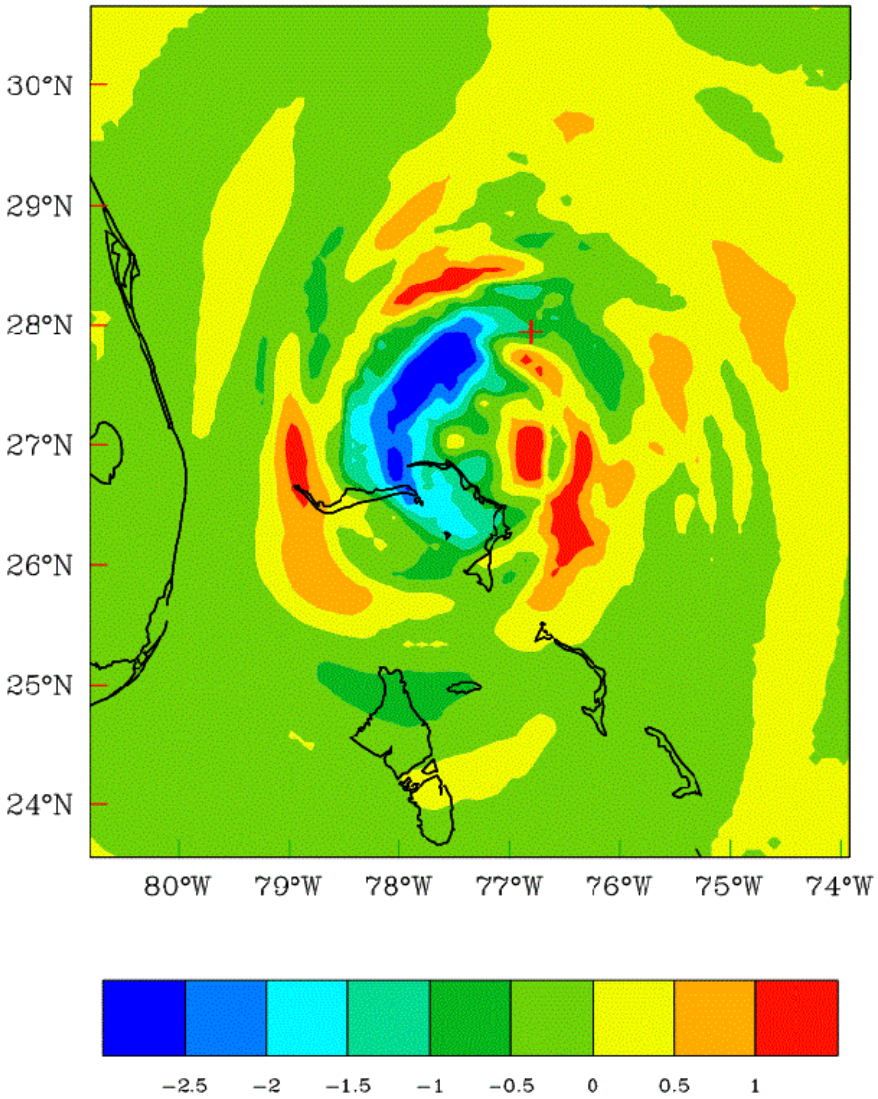



3 km grid 700mb wind increment

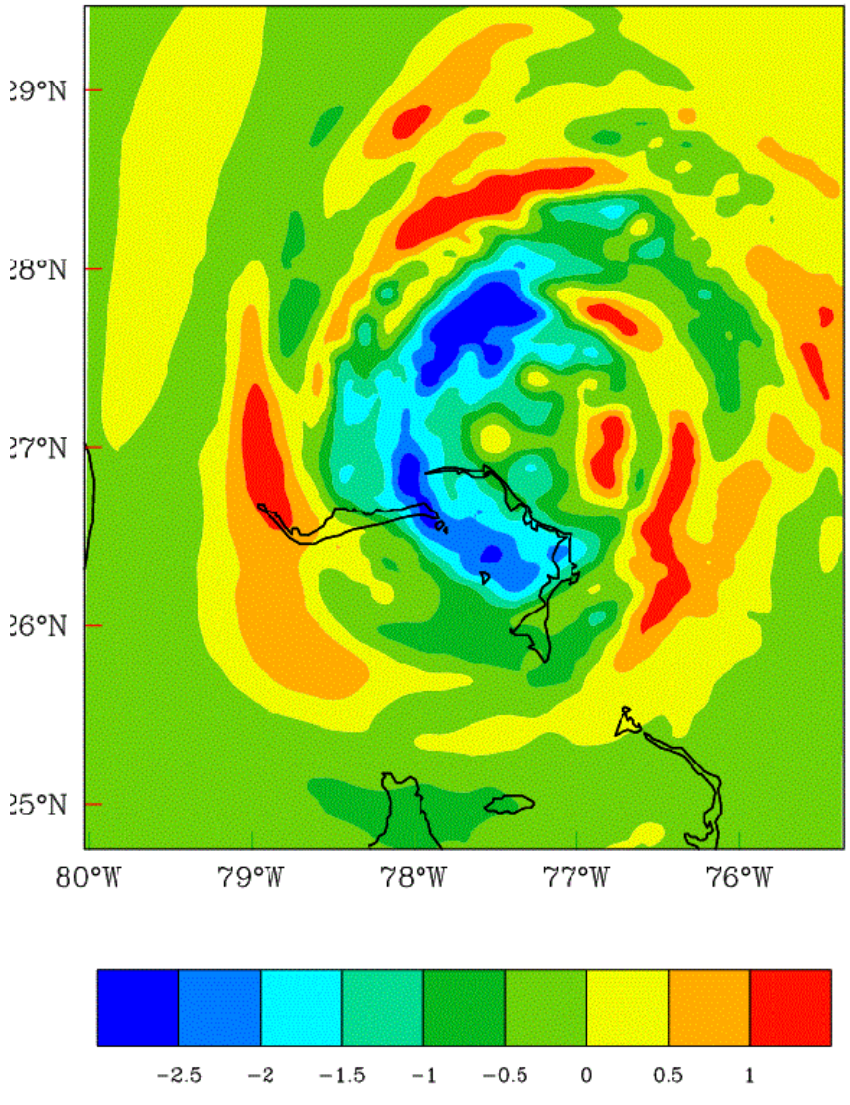


# 3km-9km dual resolution hybrid DA with moving nest

9 km grid 700mb temp increment



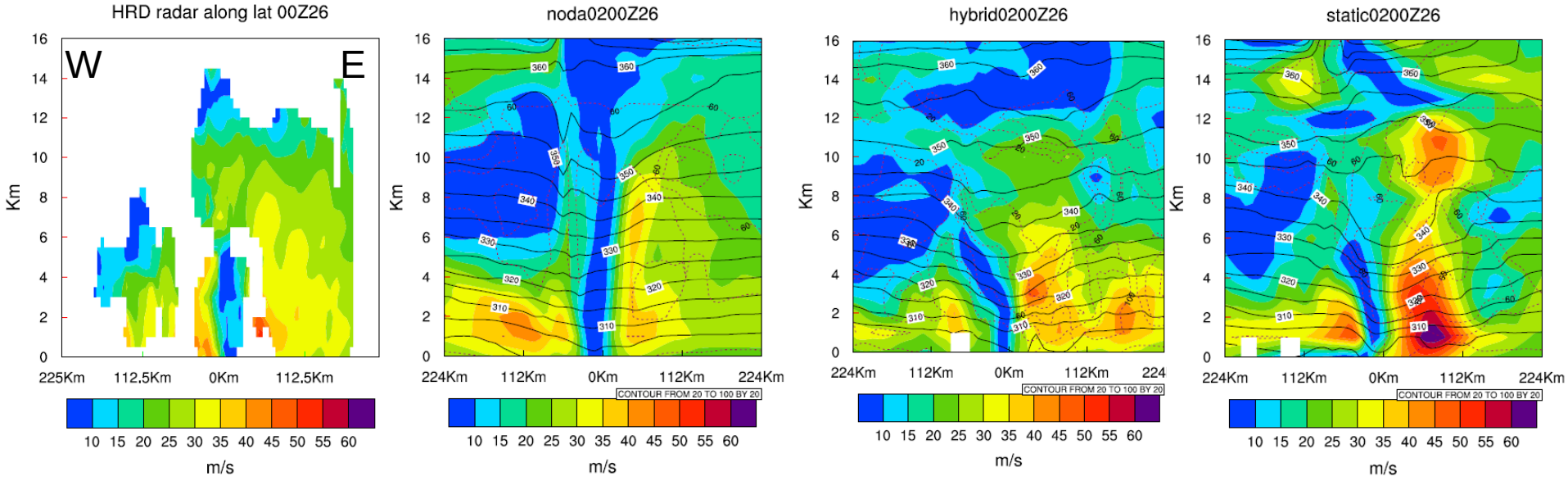

3 km grid 700mb temp increment



# Summary and ongoing work

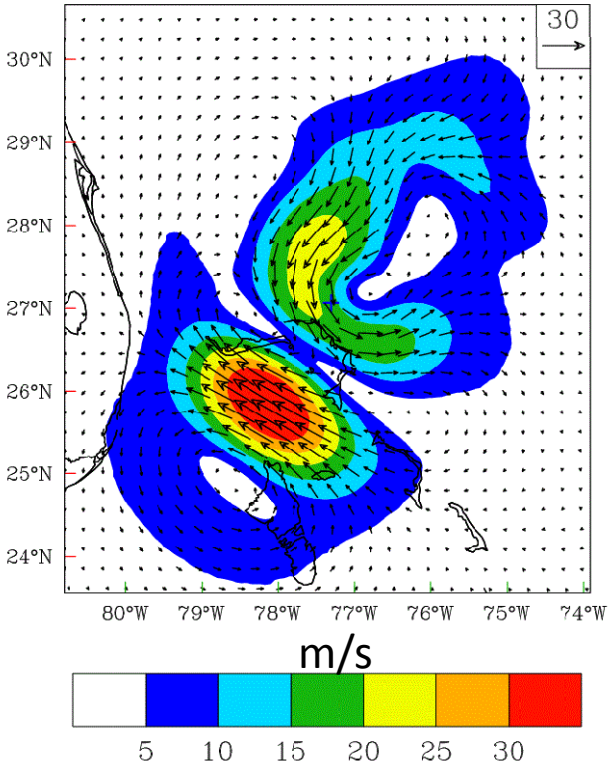
a. The GSI-based hybrid EnKF-Var data assimilation system including both the Var and EnKF components were expanded to HWRF.
b. TDR data assimilation capability was added/enhanced for the HWRF hybrid DA.
c. Some of the development/enhancement is transitioned in 2013 HWRF operational DA system.
d. TDR data improved TC structure analysis and forecast, TC track and MSLP forecasts.
e. Various diagnostics and verifications suggested incorporating ensemble in GSI hybrid provided more skillful TC analysis and forecasts than the GSI 3DVar.
f. Testing more missions/cases.
g. Develop and research on various new capabilities for HWRF hybrid (dual resolution hybrid, etc.).

# Comparison with radar wind analysis

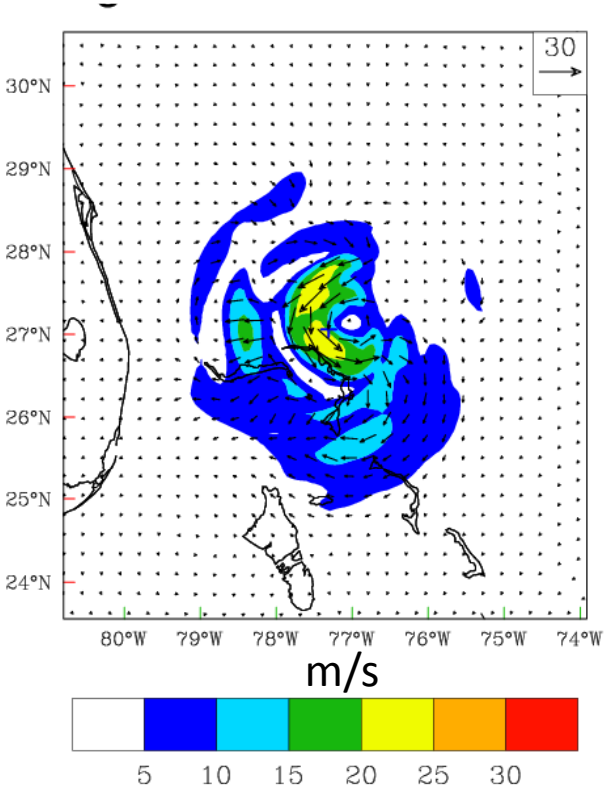


# 700 mb wind increment

GSI 3DVar



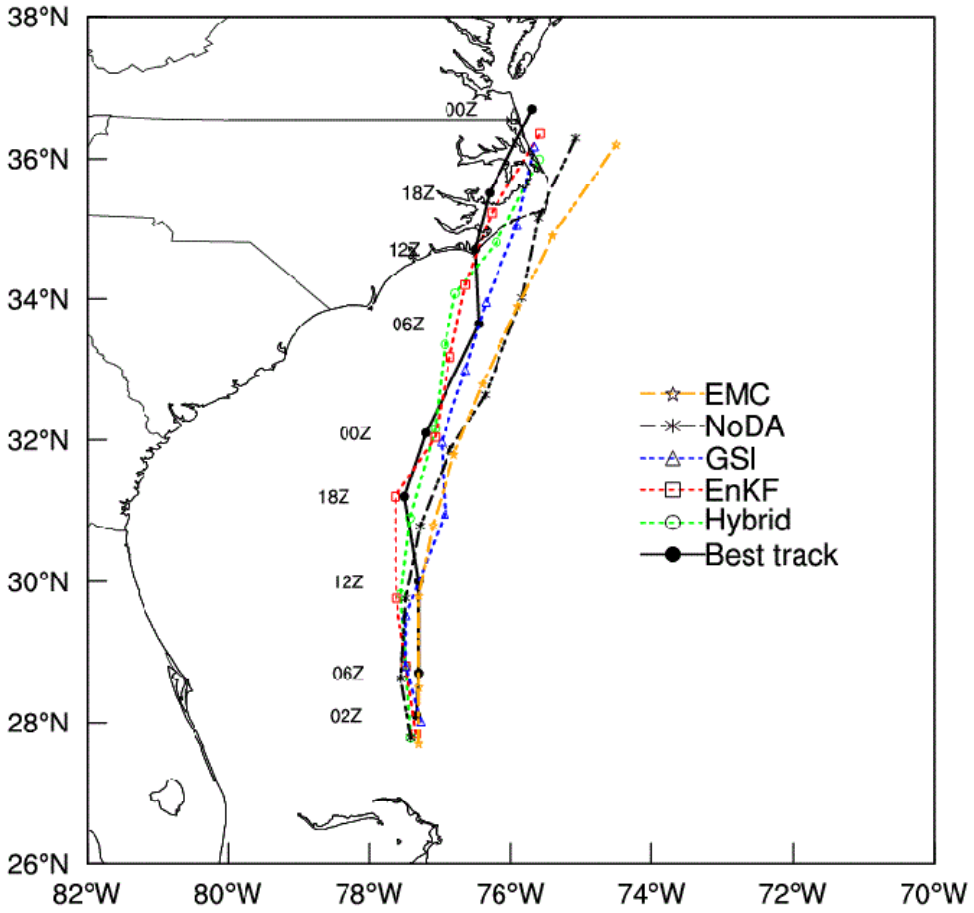

3DEnsVar





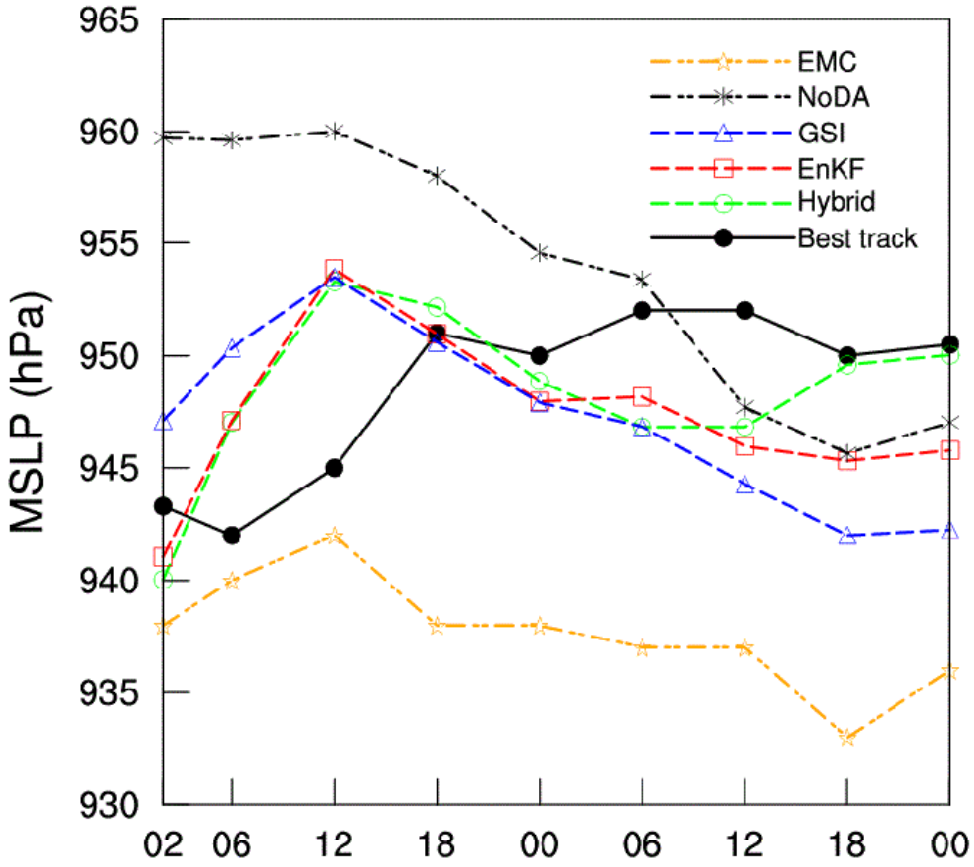
38

# Track forecast




EMC: HWRF official forecast
NoDA: no TDR assimilation
GSI: assimilating TDR using GSI 3DVar
EnKF: assimilating TDR using EnKF
Hybrid: assimilating TDR using hybrid

# MSLP forecast




EMC: HWRF official forecast
NoDA: no TDR assimilation
GSI: assimilating TDR using GSI 3DVar
EnKF: assimilating TDR using EnKF
Hybrid: assimilating TDR using hybrid