Initializing a Hurricane Vortex with an EnKF

Yongsheng Chen
Chris Snyder

MMM/NCAR

Hurricane Prediction

- Yearly-average 24-h track forecast error ~ 150 km
- Initialization --- Challenge
  - Vortex bogusing and relocation
  - 3DVar, 4DVar
  - Ensemble Kalman filter (EnKF)
- Ensemble hurricane forecast
  - Probabilistic forecast is desirable
  - Implementing EnKF in an ensemble forecast system is simple
  - EnKF also provides initial conditions for ensemble forecast

Hurricane Observation

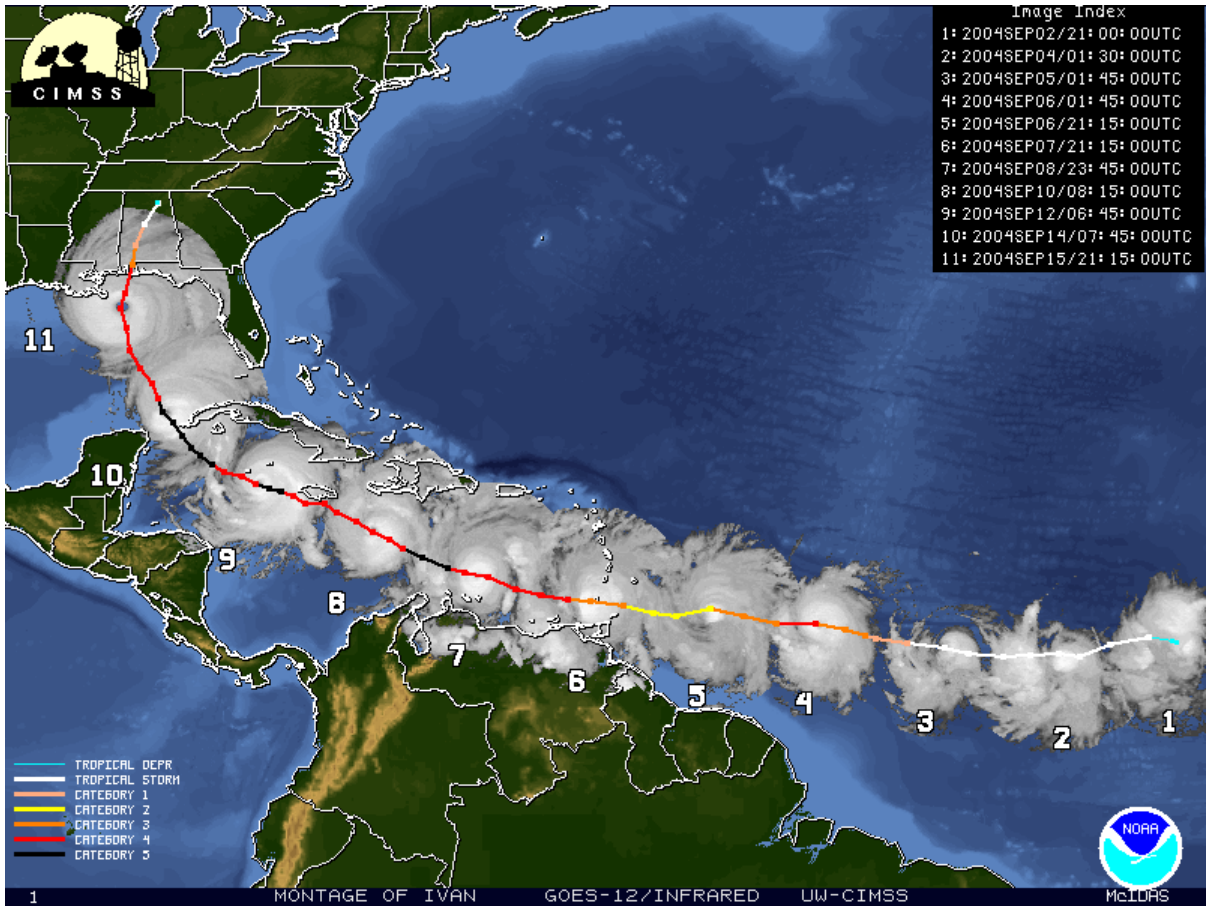


Image courtesy of CIMSS/SSEC/WISC

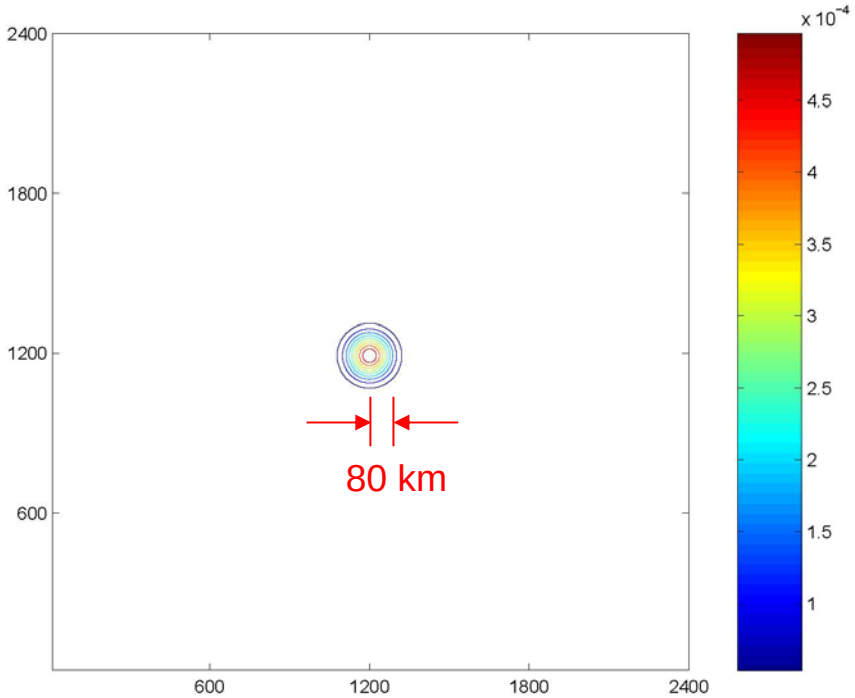
Ensemble Kalman Filter

$$\overline{\mathbf{X}}^{a} = \overline{\mathbf{X}}^{f} + \mathbf{K}(\mathbf{y} - \mathbf{H}\overline{\mathbf{X}}^{f})$$

Analysis Forecast Correction

- Observation operator **H:** find vortex position from model state **X**
- Kalman Gain **K** ~ Cov (X,HX)
  can be computed directly from the ensemble
- Performance
  - Optimal when position errors are small and Gaussian
  - Degrades as position errors increase
  - Other observations such as intensity and shape can extend its effectiveness

A Simple Example



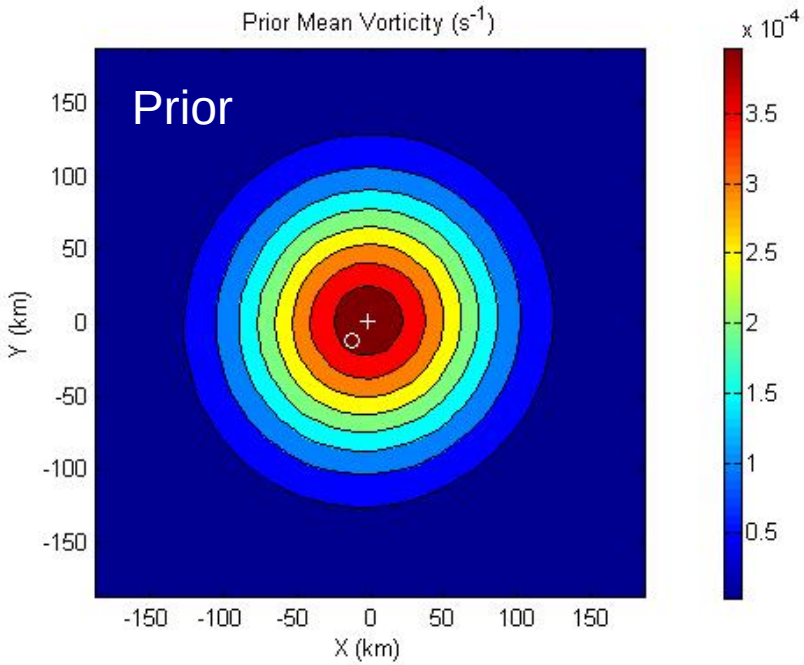
$$\varsigma(\mathbf{x}) = \varsigma_0(\mathbf{x}+\mathbf{d})$$

$$= \varsigma_0(\mathbf{x}) + \mathbf{d}\cdot\frac{\partial\varsigma_0}{\partial\mathbf{x}} + \mathrm{O}(|\mathbf{d}|^2)$$

For small $\mathbf{d} \sim \mathrm{N}(\mathbf{0}, \sigma_f^2\mathbf{I})$,

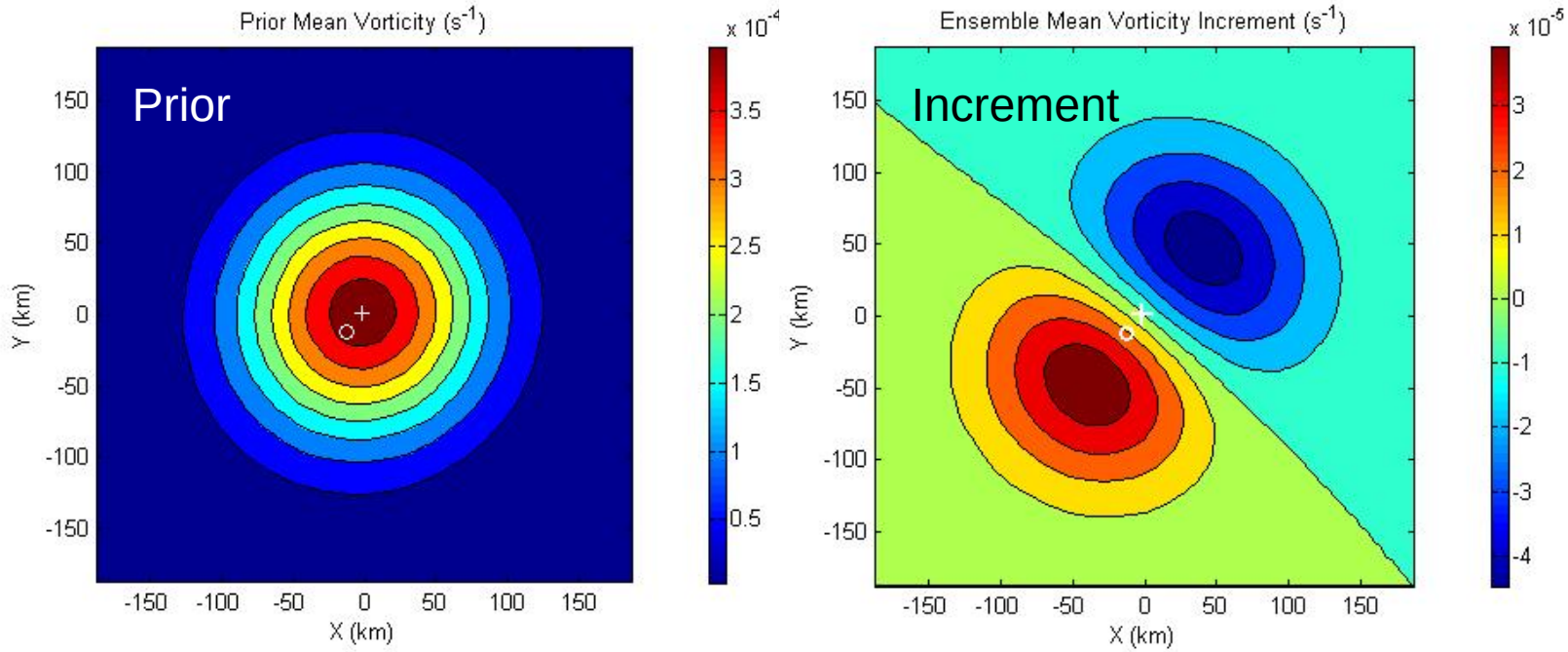
$$\varsigma \sim \mathrm{N}(\varsigma_0, \sigma_f^2(\frac{\partial\varsigma_0}{\partial\mathbf{x}})(\frac{\partial\varsigma_0}{\partial\mathbf{x}})^T)$$

Assimilating center position



+ prior mean center
o observed center
dot posterior mean center

Assimilating center position



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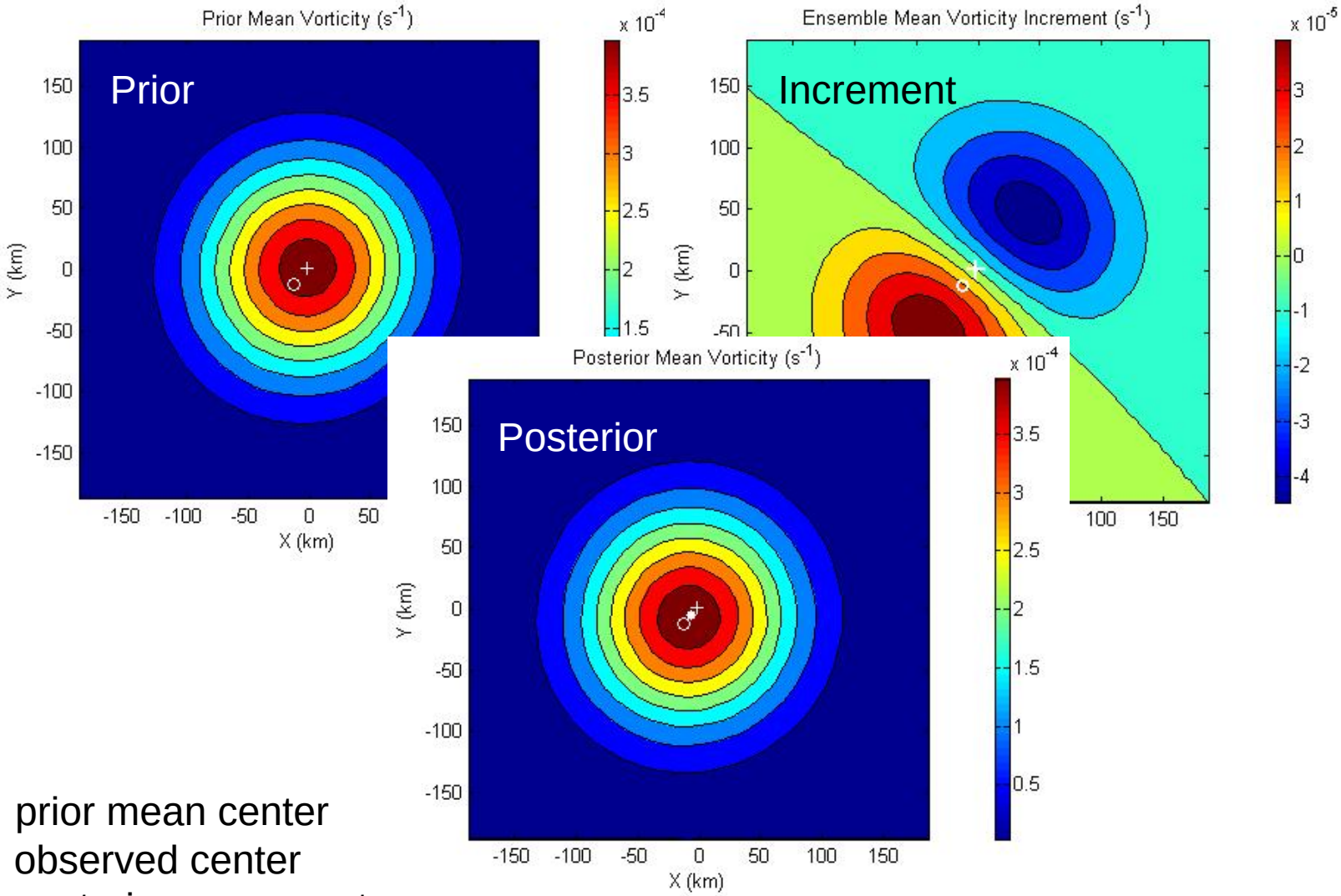

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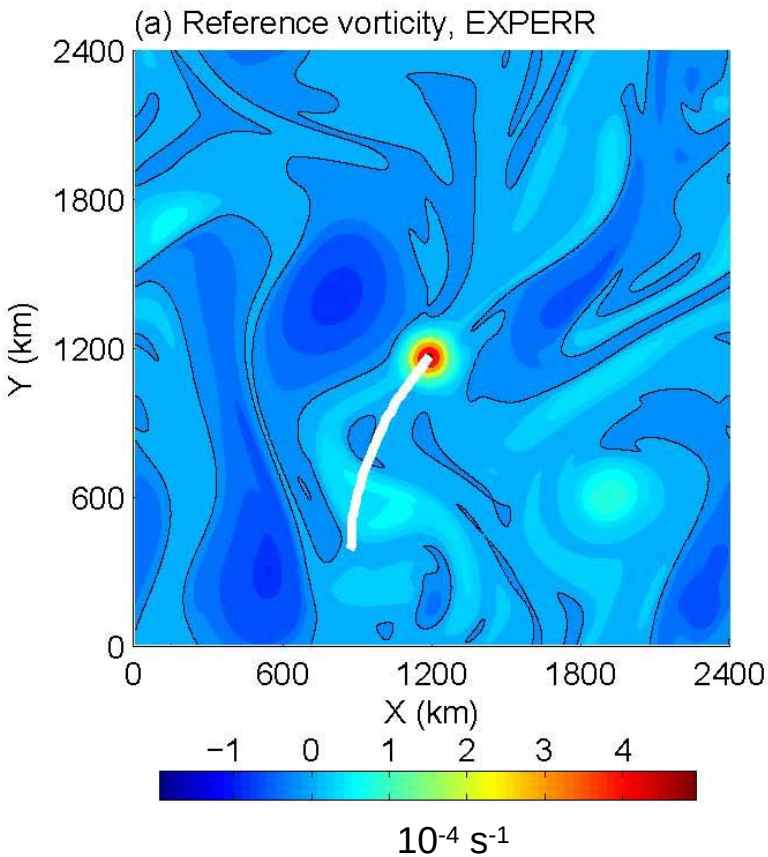
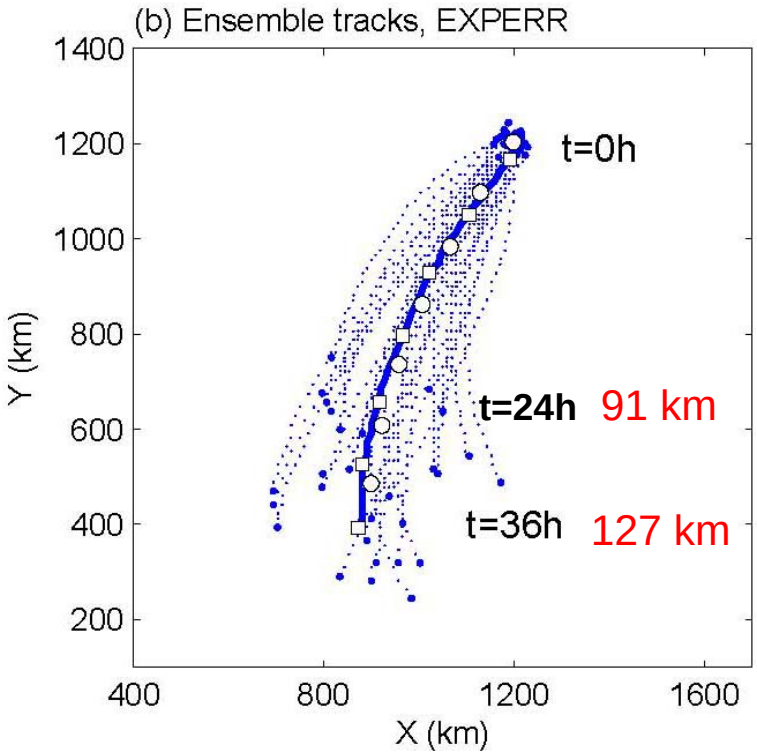
A simple experiment with a barotropic model



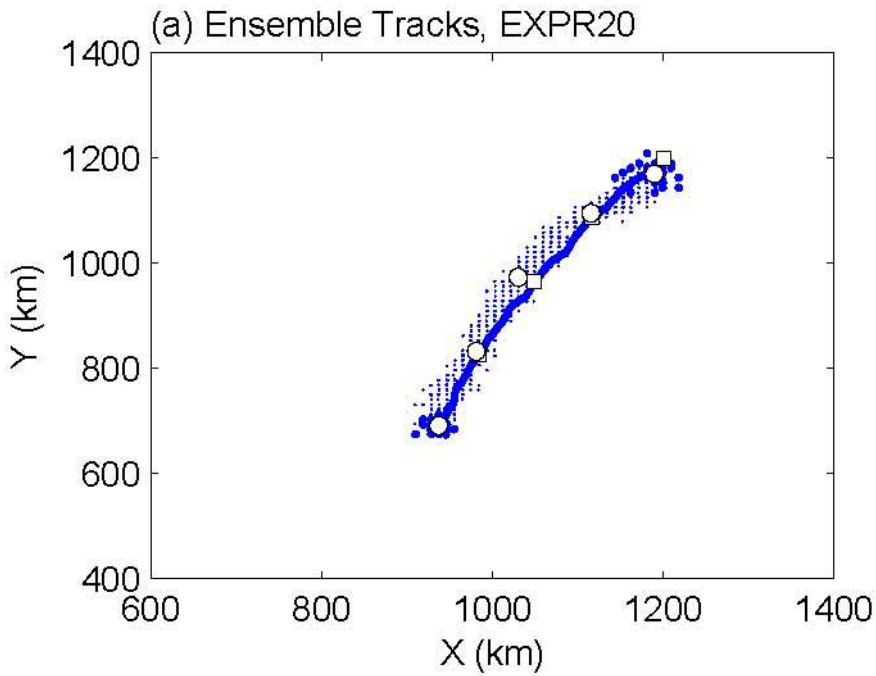
- Barotropic vorticity equation
- 2400 km x 2400 km, doubly periodic domain
- True state is strong 80-km vortex embedded in large-scale turbulent flow
- Simulate obs of vortex position with random error
- Assimilate obs into forecast with initial errors in vortex position and large-scale flow
- 30 ensemble members + 1 true/reference

Ensemble tracks

Without assimilation



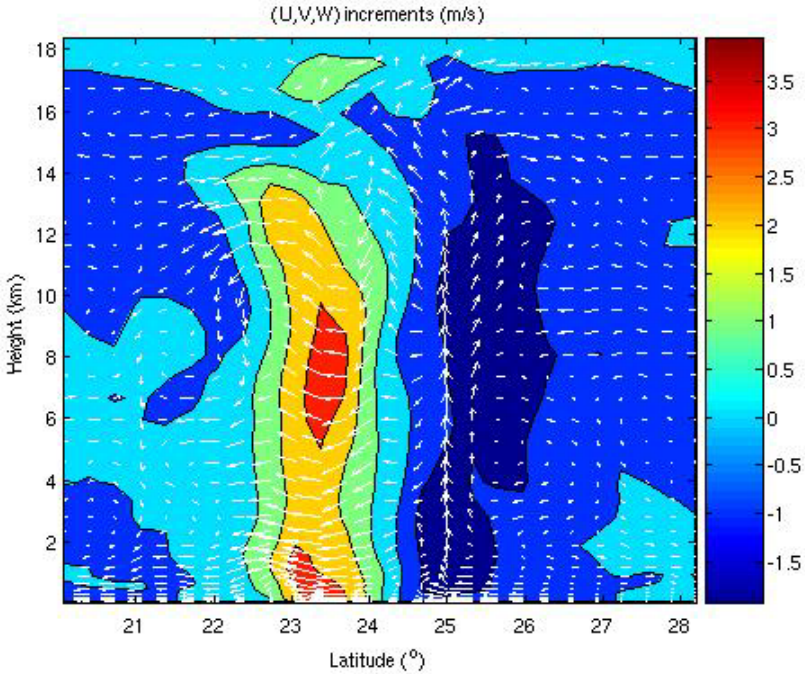
With assimilation

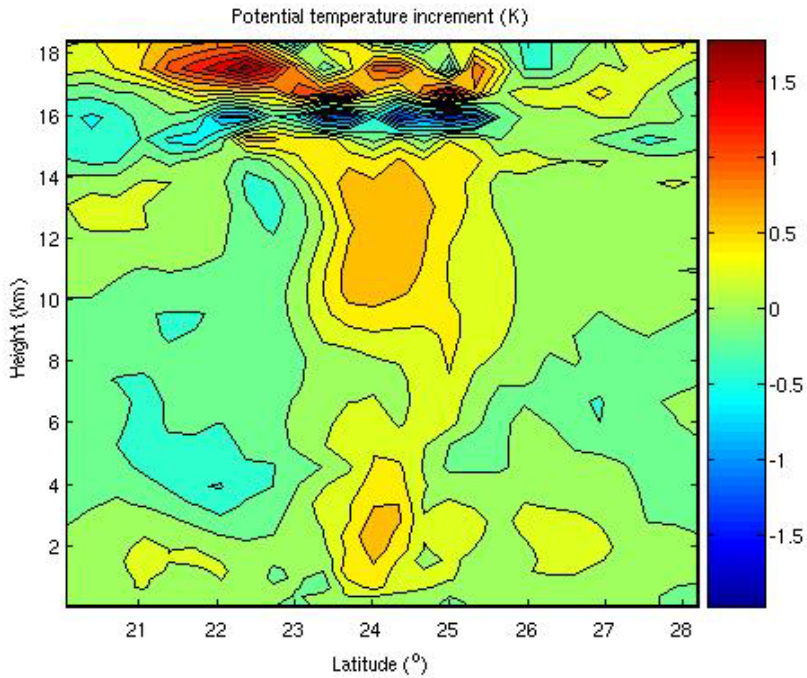


Experiments with WRF/DART

- WRF -- Weather Research and Forecasting model
- DART -- Data Assimilation Research Testbed
- 36 km horizontal resolution, 35 vertical levels
- 26/28 ensemble members
- Ensemble initial and boundary conditions are generated by perturbing GFS(AVN) analysis/forecast with WRF-VAR error statistics
- Assimilated observations:
  - hurricane track (center position and minimum sea level pressure from NHC advisories)
  - Satellite winds (3% available observations)
- Compare forecasts initialized from the EnKF mean analysis and from the GFS analysis

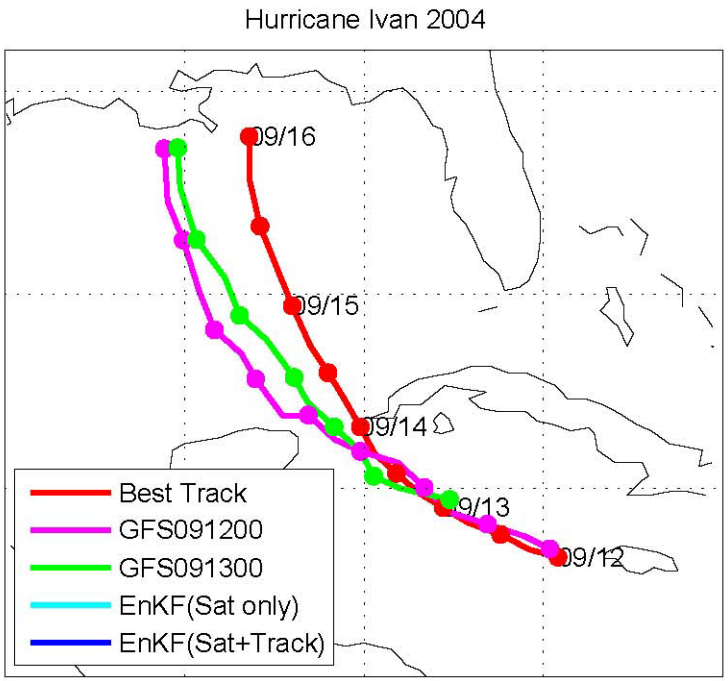
Position and intensity Correction

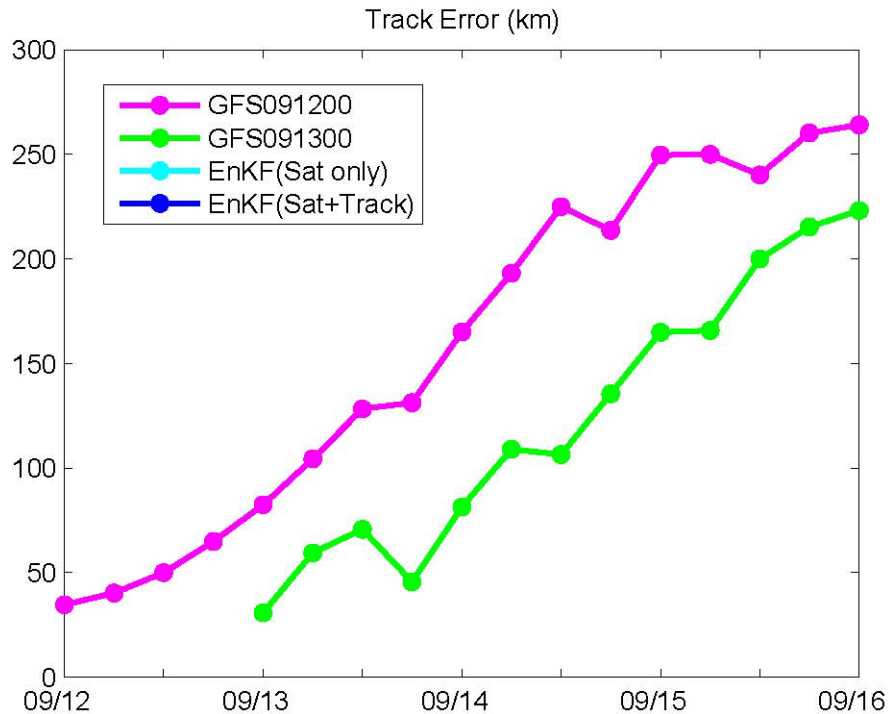




RITA 2005-09-20-23Z	Center Lat. (°N)	Center Lon. (°W)	Mini. SLP(mb)
Observation (error)	24.00 (0.3)	-82.20 (0.3)	973.0 (5.0)
Prior mean (spread)	23.85 (0.24)	-82.33 (0.23)	988.6 (2.0)
Posterior mean (spread)	23.89 (0.15)	-82.29 (0.18)	986.5 (2.0)

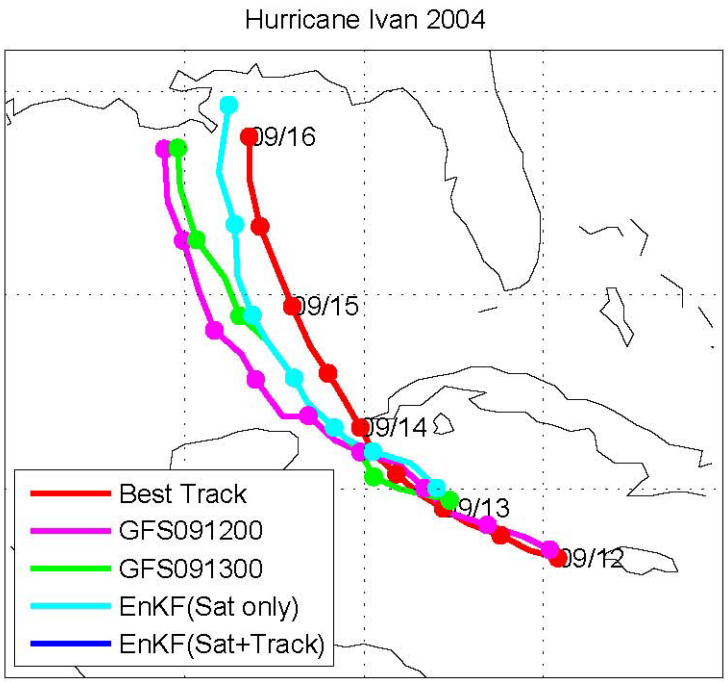
Hurricane Ivan 2004

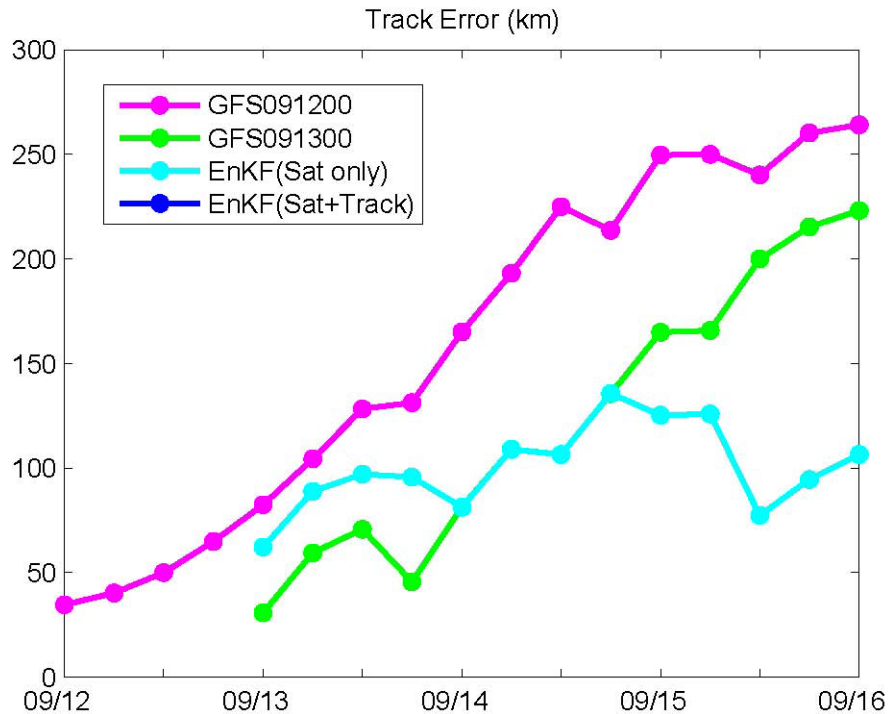




- 36-km horizontal resolution, 28 ensemble members
- Assimilate position, intensity and satellite winds every 3h for a total of 24h
- Compare forecasts initialized from the EnKF analysis and from the GFS analysis

Hurricane Ivan 2004





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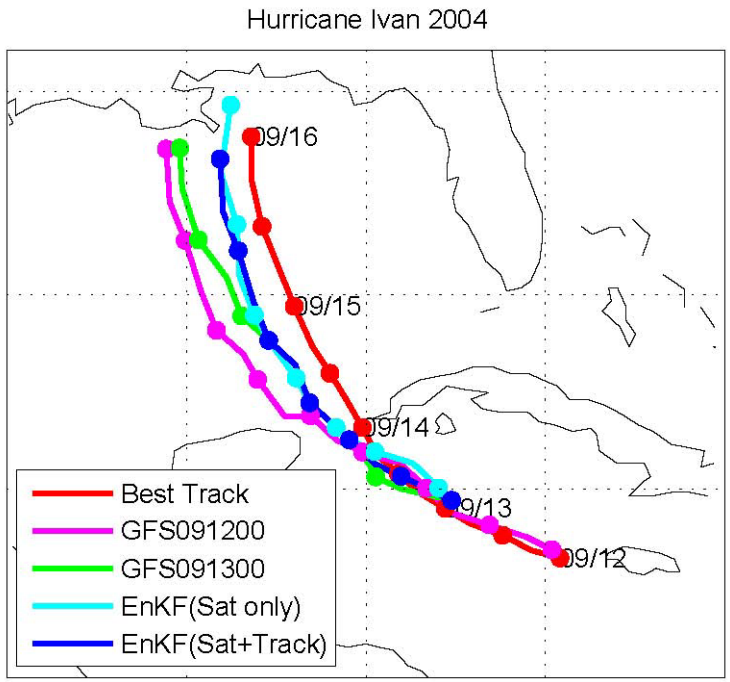

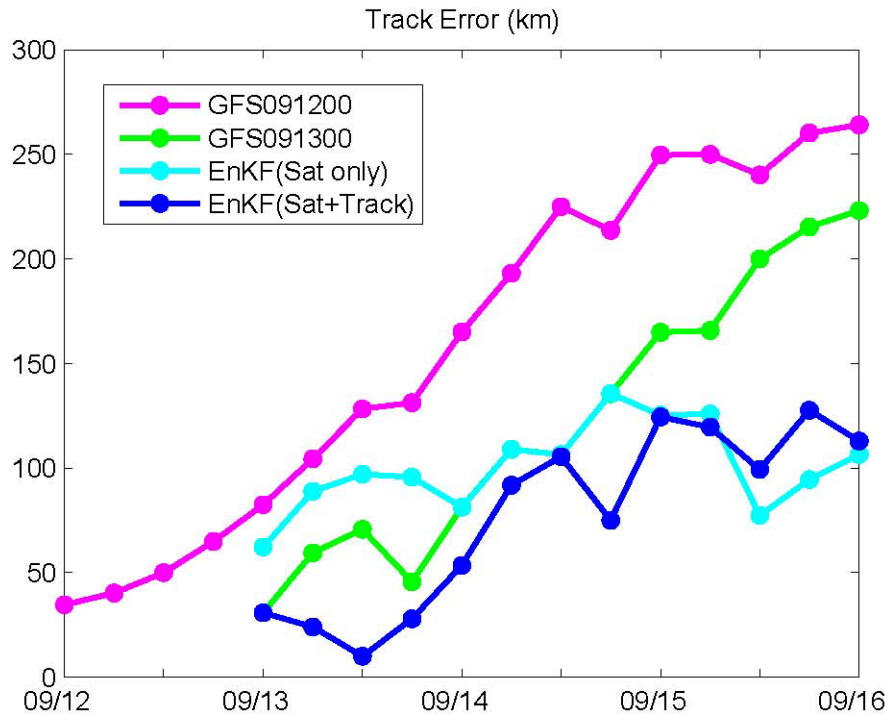

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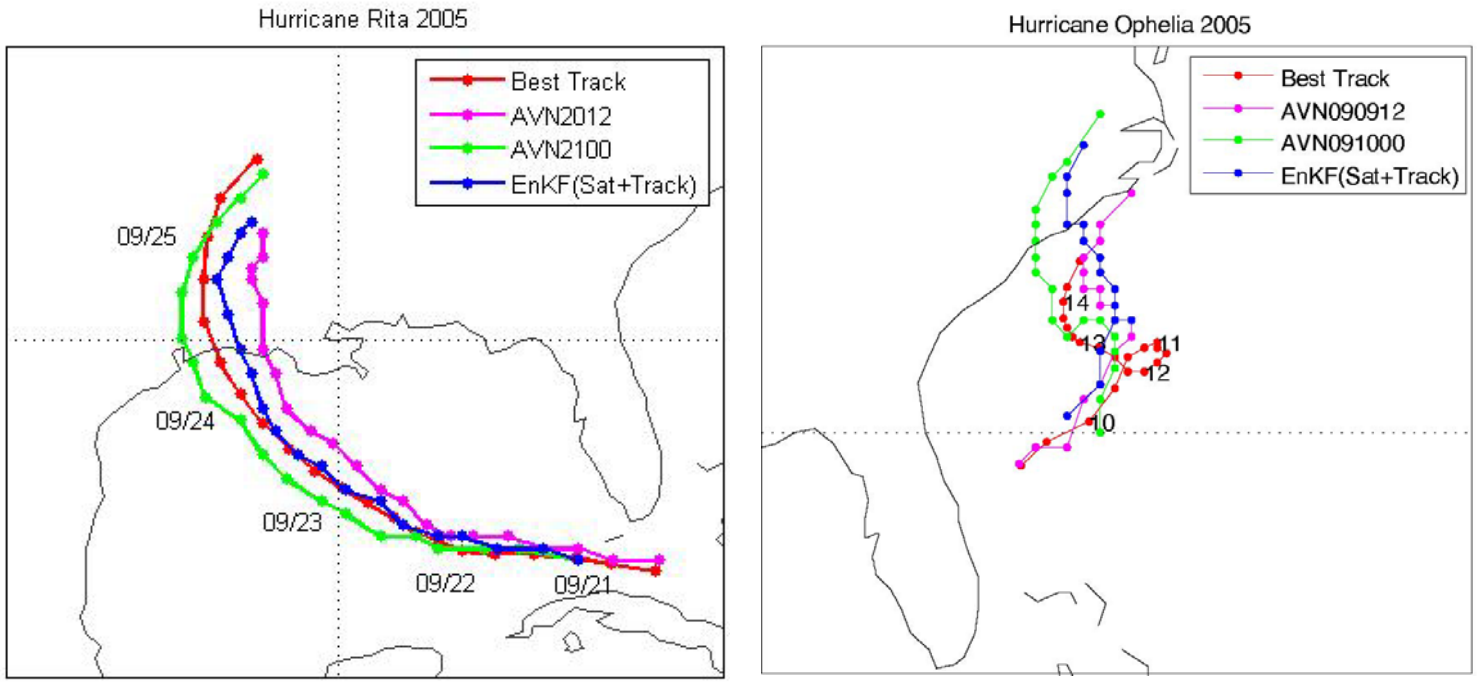
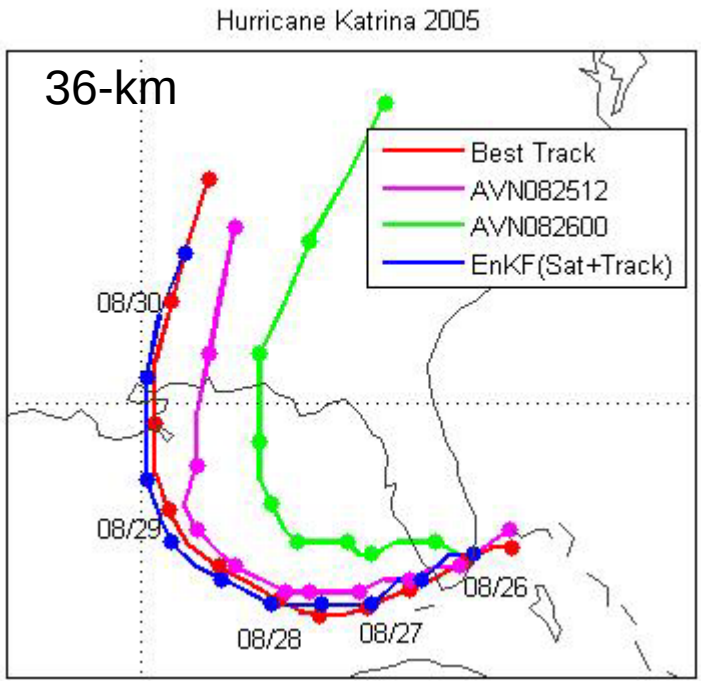
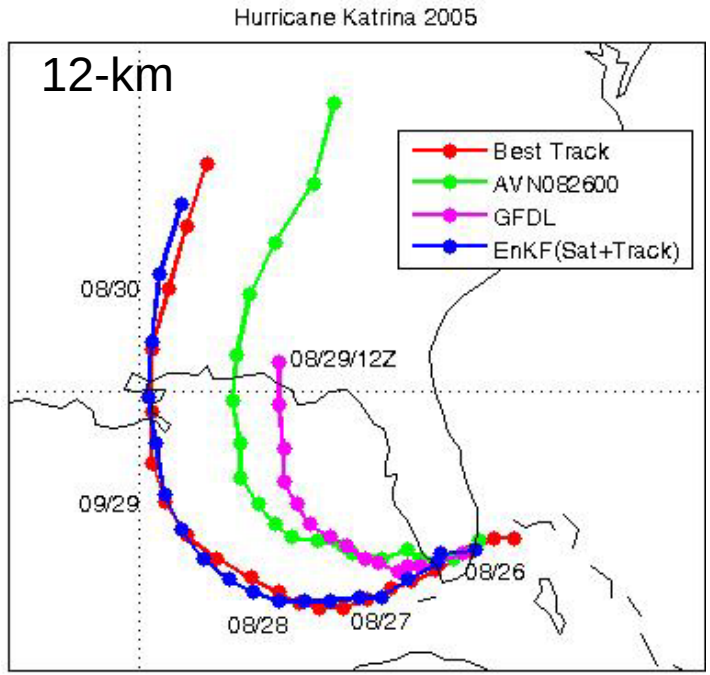
Hurricane Rita and Ophelia 2005



- 36-km horizontal resolution, 26 ensemble members
- Assimilate position, intensity, and satellite winds every hour for a total of 12 hours
- Compare forecasts initialized from the EnKF analysis and from the GFS/AVN forecasts.

Hurricane Katrina 2005

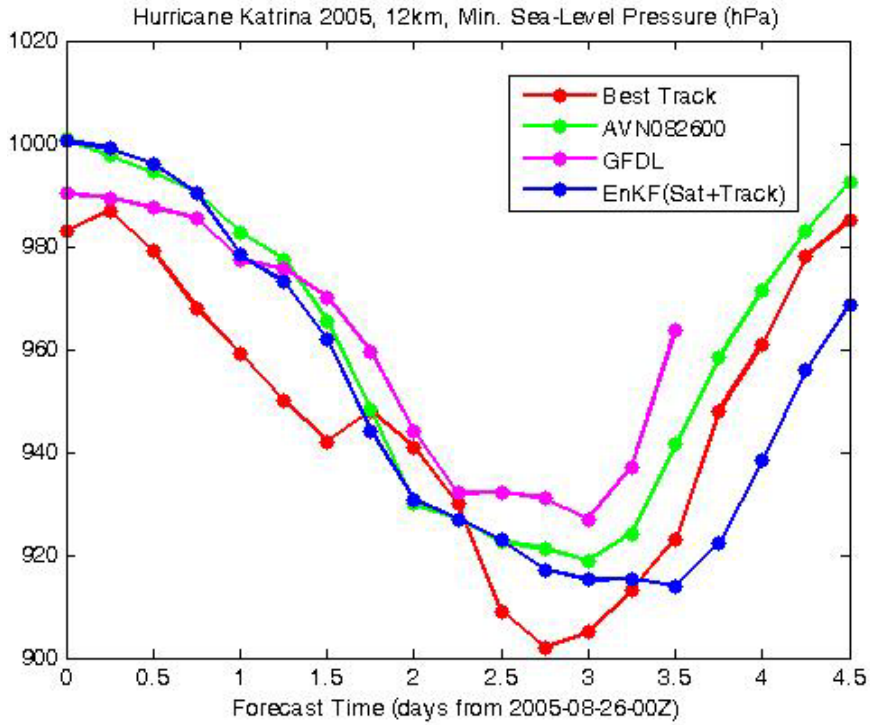


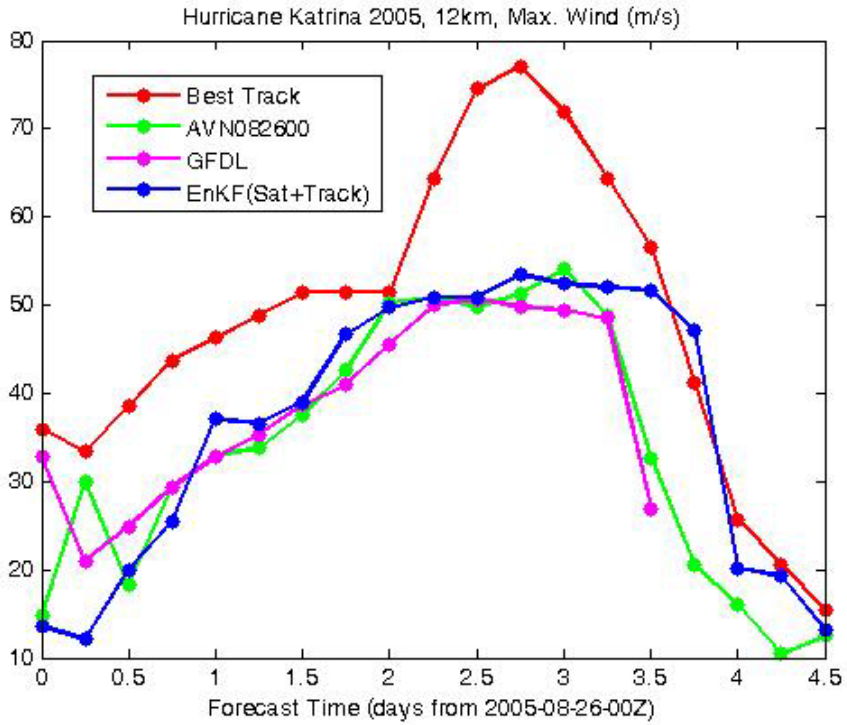


- Analysis:
  - 36-km horizontal resolution, 26 ensemble members
  - Assimilate position, intensity, and satellite winds every hour for a total of 12 hours
- Forecasts:
  - Compare forecasts initialized from the EnKF analysis, from the GFS/AVN forecasts and from GFDL analysis at 36-km and 12-km resolutions

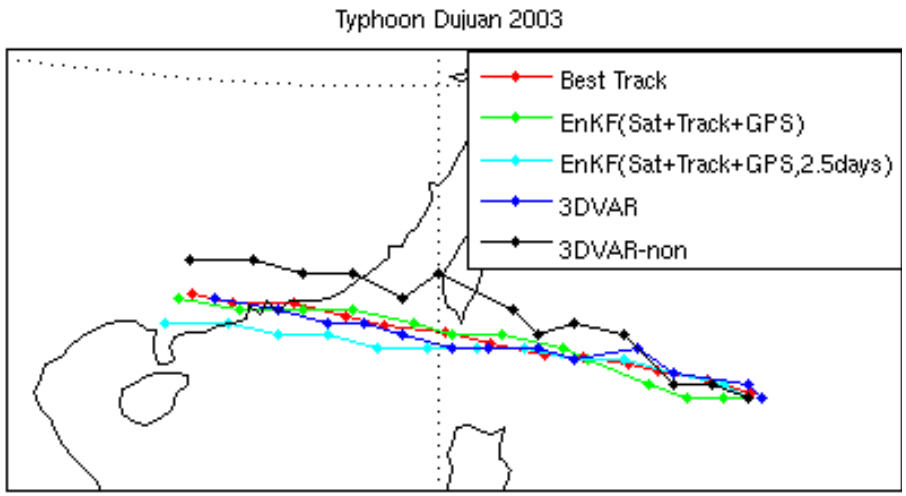
Hurricane Katrina 2005

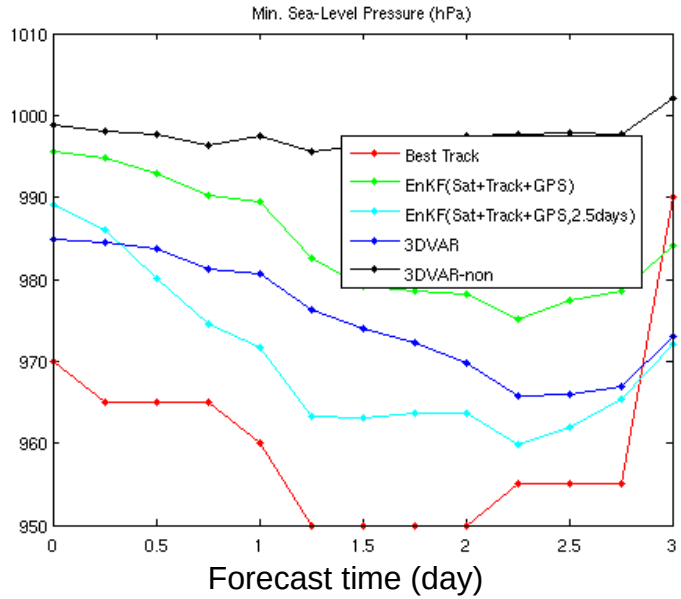
12-km forecast





Typhoon Dujuan 2003



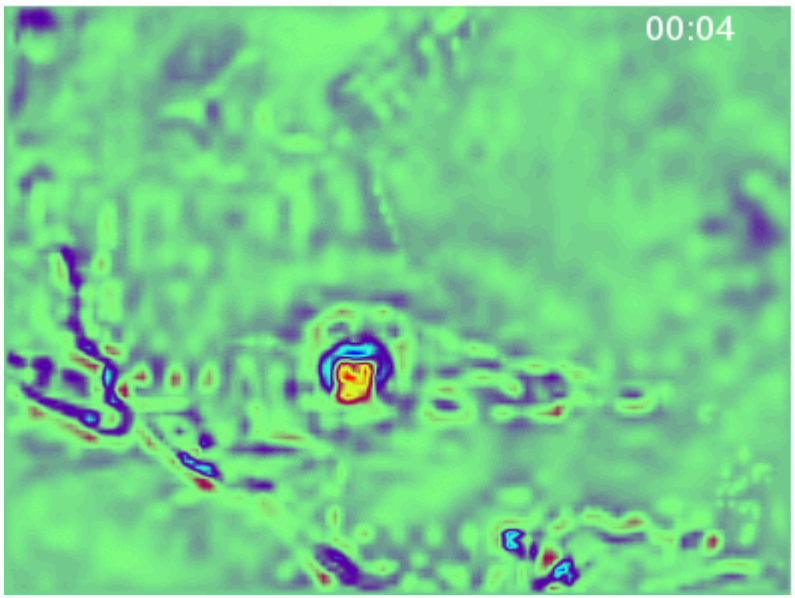


- 45-km horizontal resolution, 28 ensemble members
- Assimilate position, intensity, satellite winds, and GPS refractivity for 1 day or 2.5 days
- Compare forecasts initialized from
  - EnKF analysis
  - WRF 3DVAR analysis (3DVAR, cycling for 2.5 days)
  - GFS analysis (3DVAR-non)

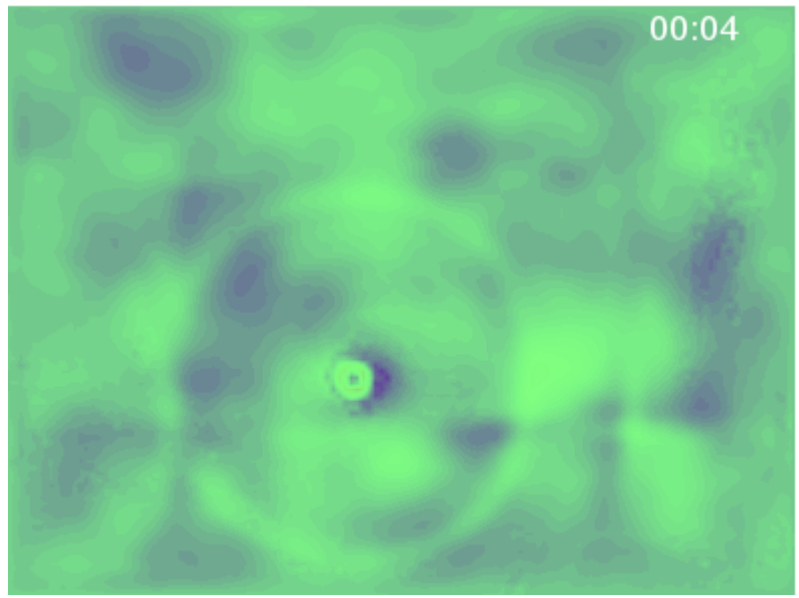
Vortex Spin-up

Hurricane Ivan 2004
Surface Pressure Tendency

GFS0913



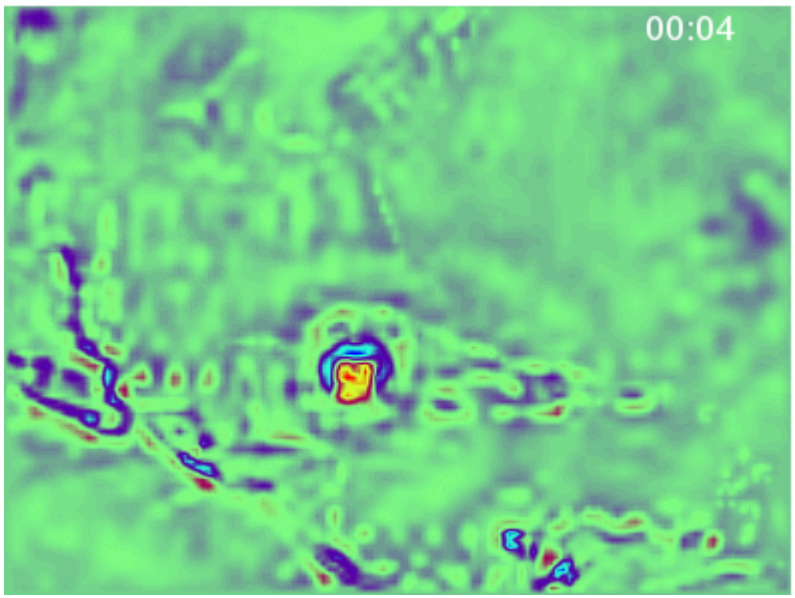
EnKF



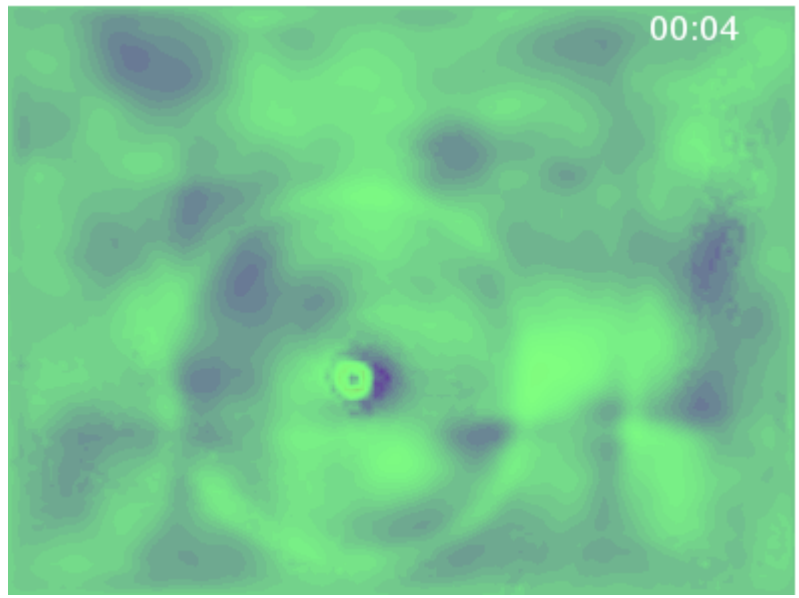
Vortex Spin-up

Hurricane Ivan 2004
Surface Pressure Tendency

GFS0913

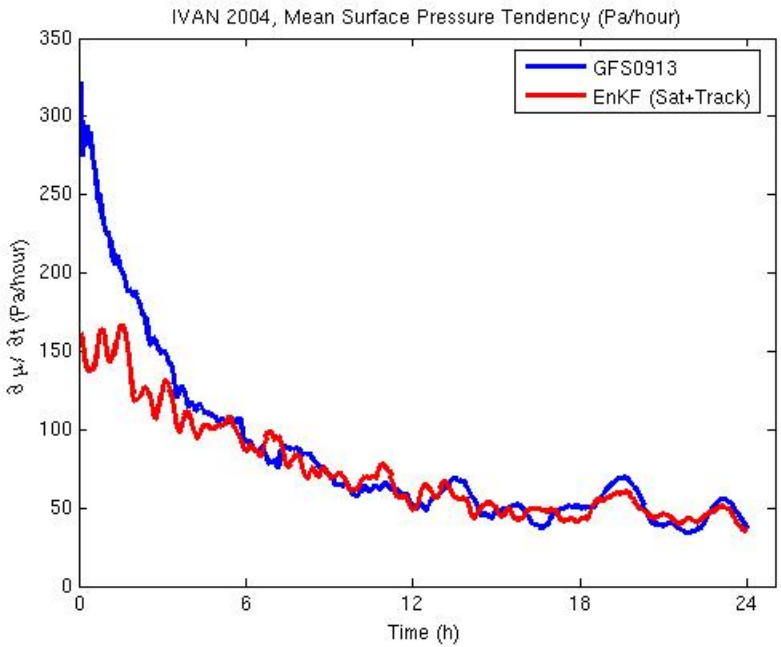


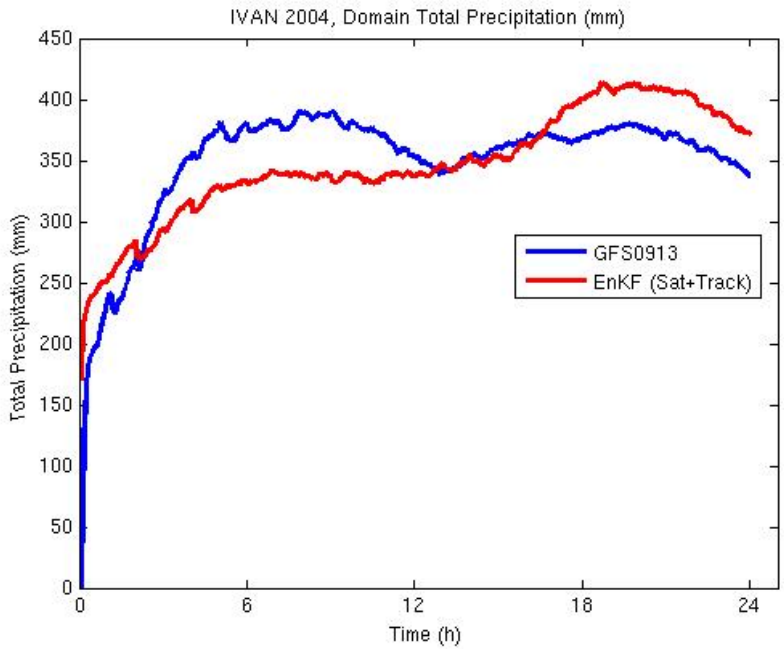
EnKF



Vortex Spin-up

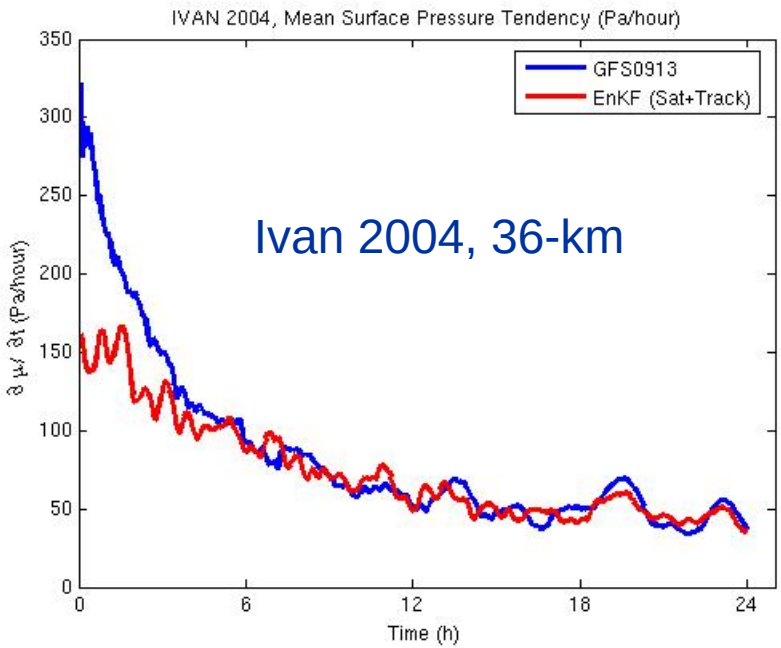
Hurricane Ivan 2004

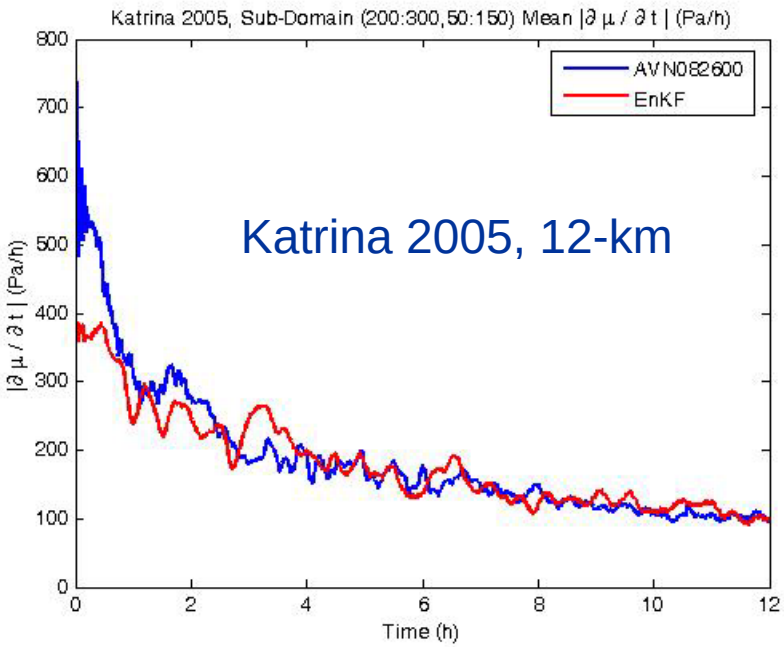




Vortex Spin-up

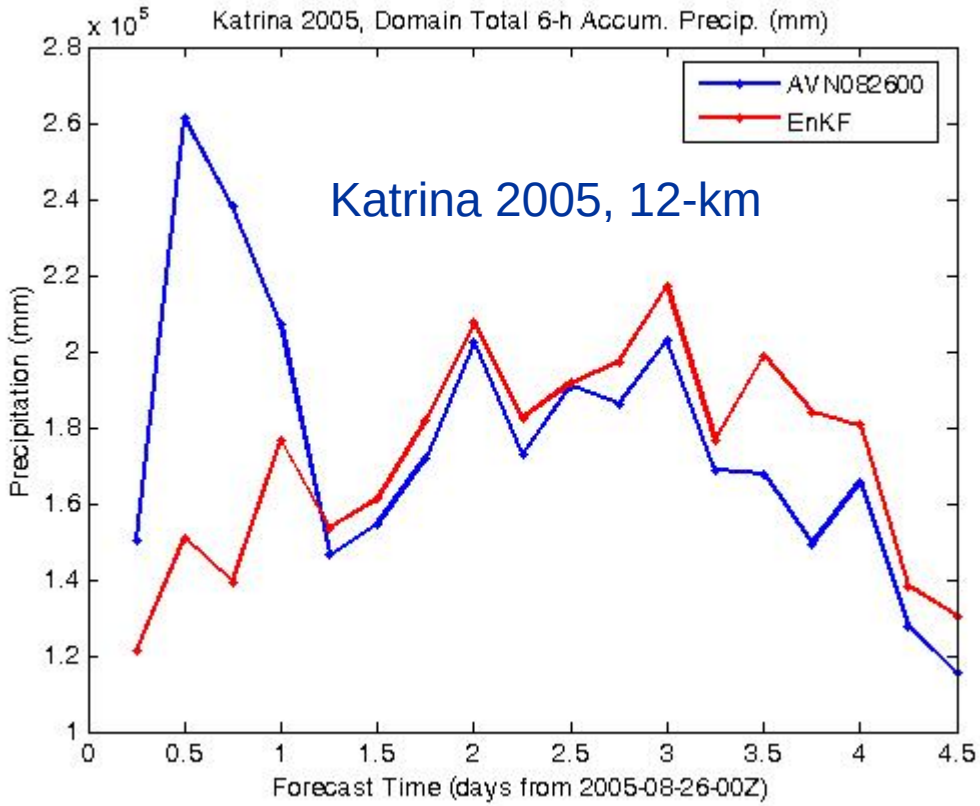
Mean Surface Pressure Tendency





Vortex Spin-up

6-h Accumulated Precipitation



Summary

- Hurricane track observations can be easily assimilated with an EnKF
- Track forecasts initialized from the EnKF analysis are significantly improved
- EnKF analysis produces dynamically consistent increments, and reduces spurious transient evolution of initial vortex