Performance of hurricane forecasts from global ensemble prediction systems during the 2009 season

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The ensemble Kalman Filter (EnKF)

- A method for the initialization of ensemble forecasts that is conceptually appealing for hurricanes
  - "Flow-dependent" background-error covariances may be useful to achieving quality analyses

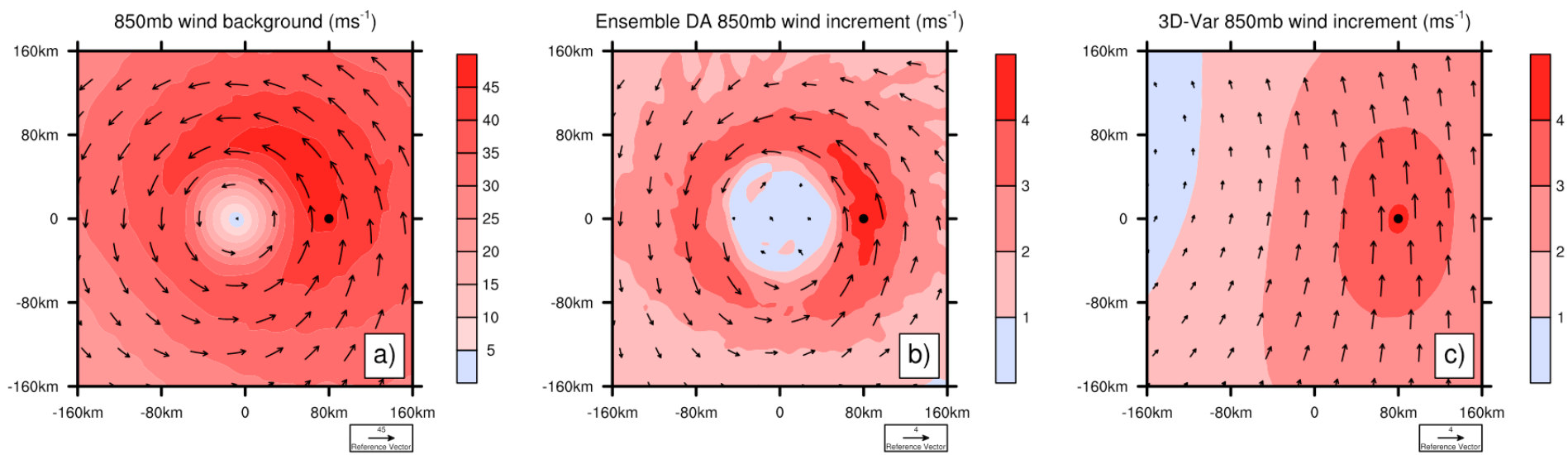


figure c/o Xuguang Wang, University of Oklahoma

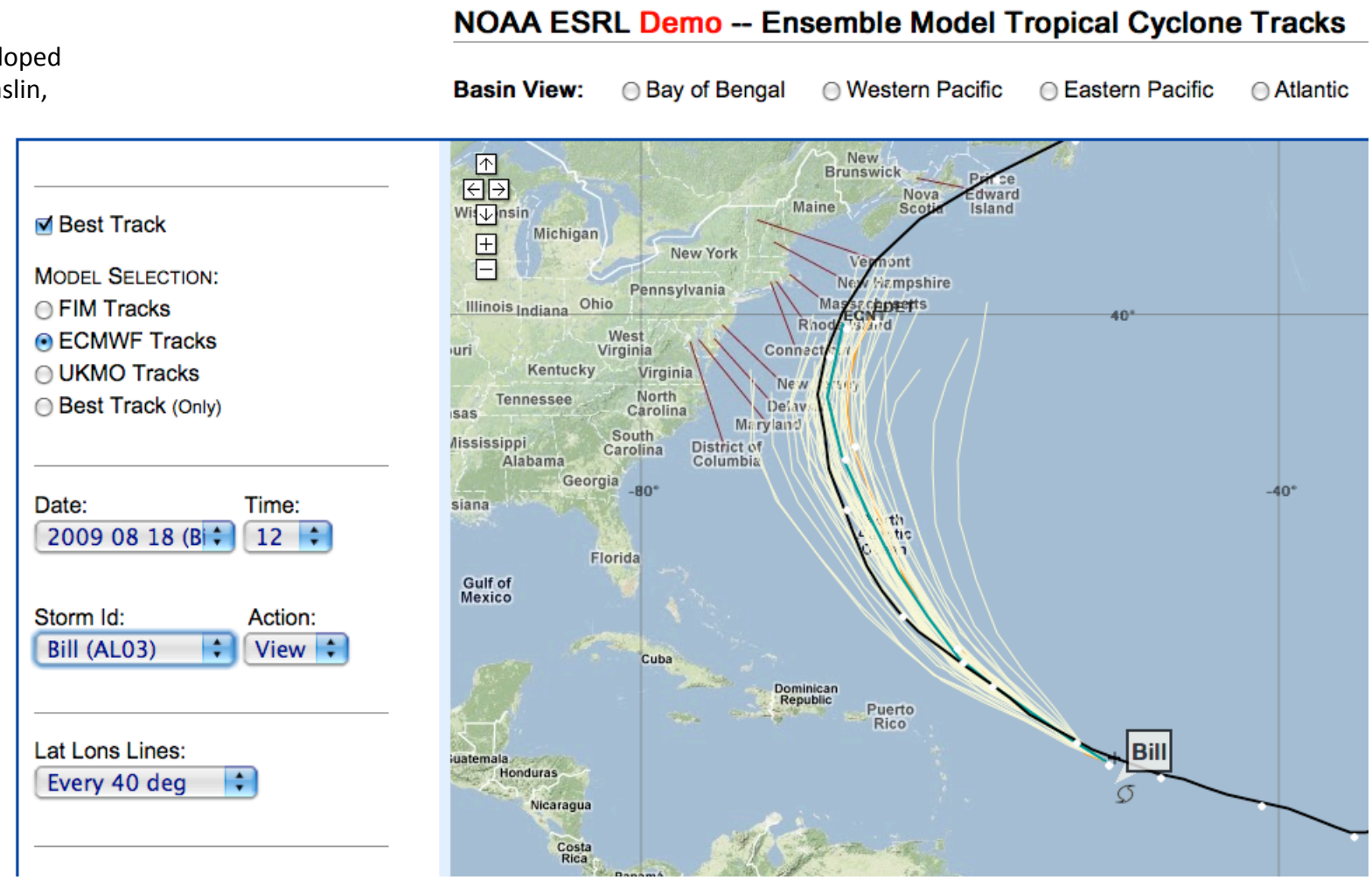
Testing performed

- Ran a global ensemble square-root filter ("EnKF") data assimilation
  - T382L64 (~30 km) version of NCEP GFS, 60 members
  - Full observational data stream + "TCVitals" (min central pressure)
- 20-member ensemble forecasts to 7 days for most active days during hurricane season.
  - T382L64 GFS ensemble (GEFS) from EnKF initial conditions
  - 30-km "FIM" model from GFS EnKF initial conditions
  - ECMWF (T399) and CMC via "TIGGE" database.
- Deterministic forecasts from T382 GFS/GSI and GFS/EnKF
- Compare against "best track" files compiles by NHC and Joint Typhoon Warning Center
- Also: Jeff Whitaker presentation yesterday on global EnKF (IOAS-AOLS 6B.1) for tropical cyclones

Track plotting software

http://ruc.noaa.gov/tracks/

software developed
by Paula McCaslin,
ESRL/GSD

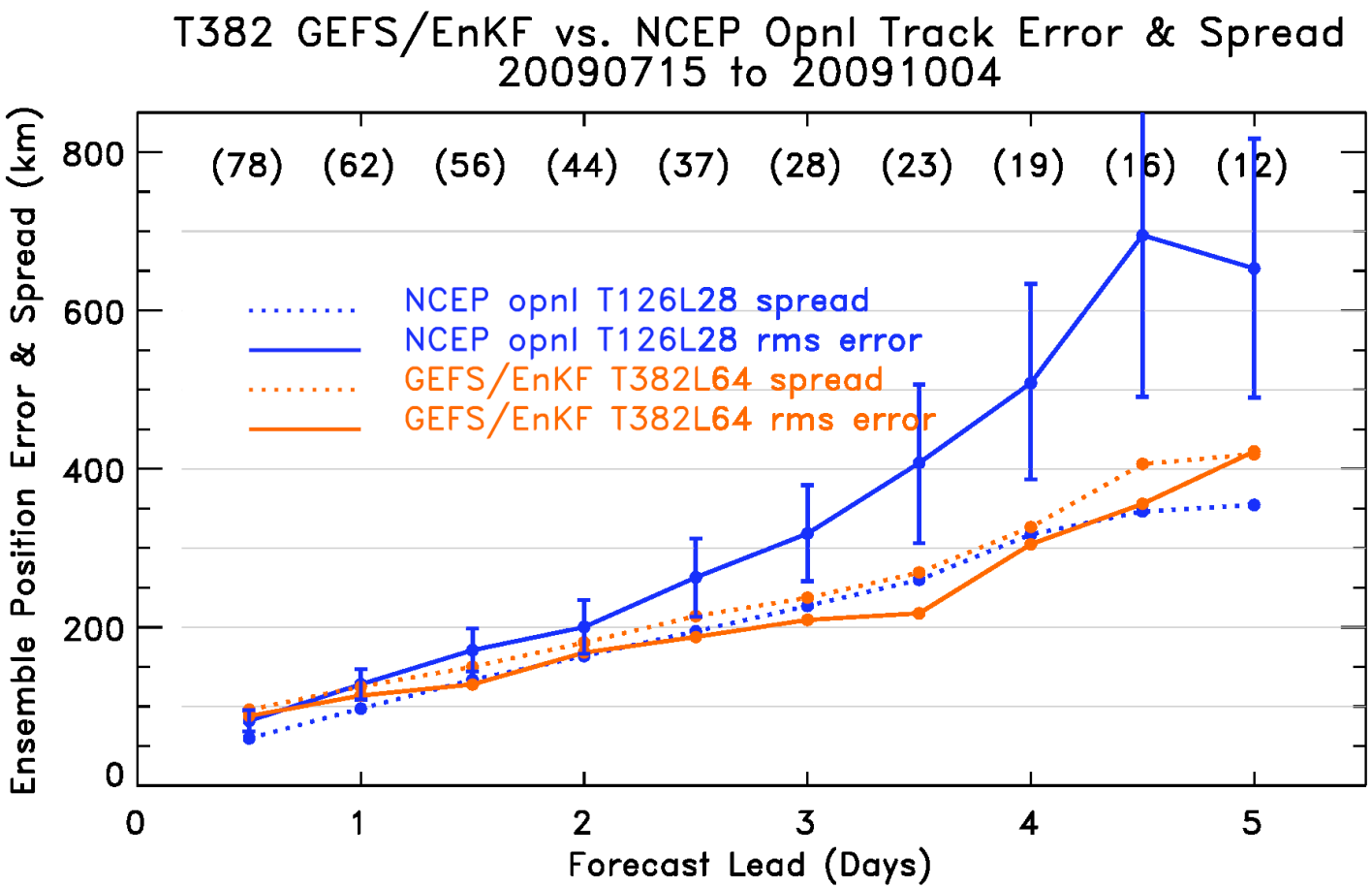


uses Google Maps; black line is observed “best track”;
white lines are forecast members; green is ensemble mean; yellow is control

Rules for including a particular storm in comparisons of models A vs. B

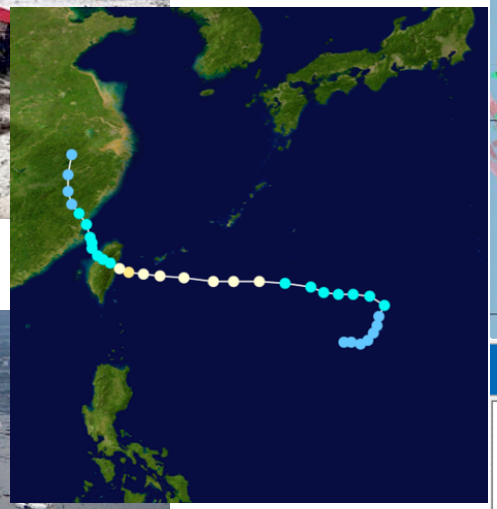
- Storm must be tracked and at least tropical depression strength at initial time of forecast
- Ensemble scores computed only when at least 20 members' forecasts computed
  - but if storm dies out in some members, compute mean error and spread from remaining ones.
- When comparing forecast model A to forecast model B, count a storm as a sample only when both models have forecast available.

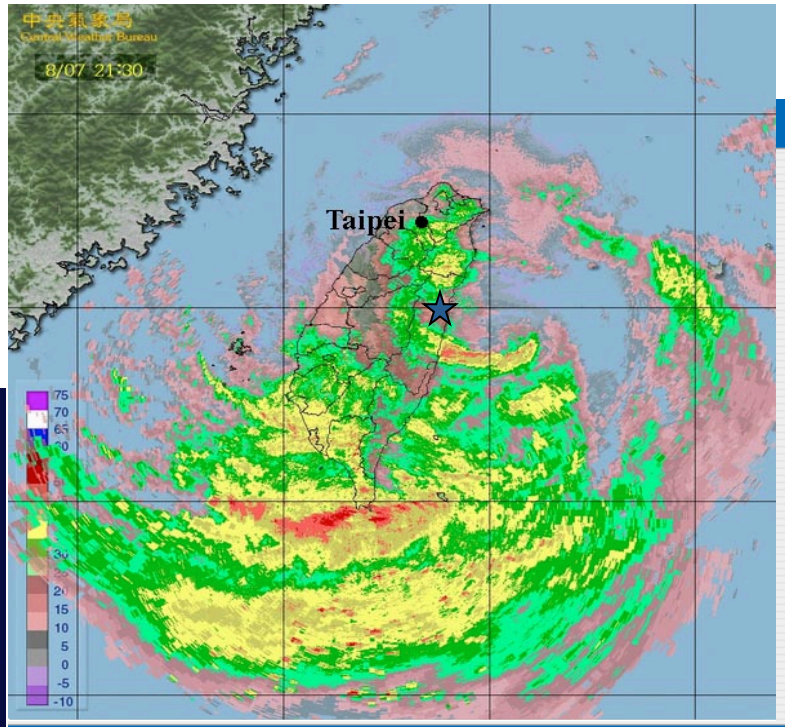
Experimental T382 GEFS/EnKF vs. operational T126 GEFS/ET

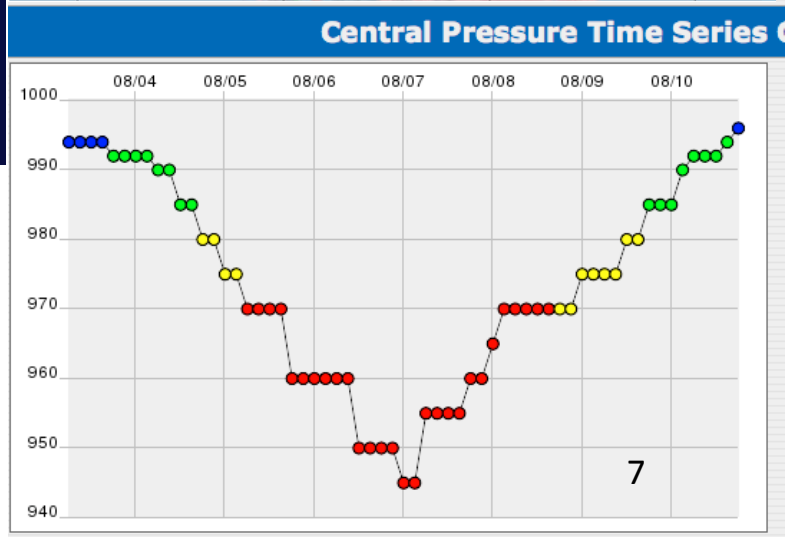


higher resolution + EnKF = clear improvement
but how much from resolution vs. EnKF?

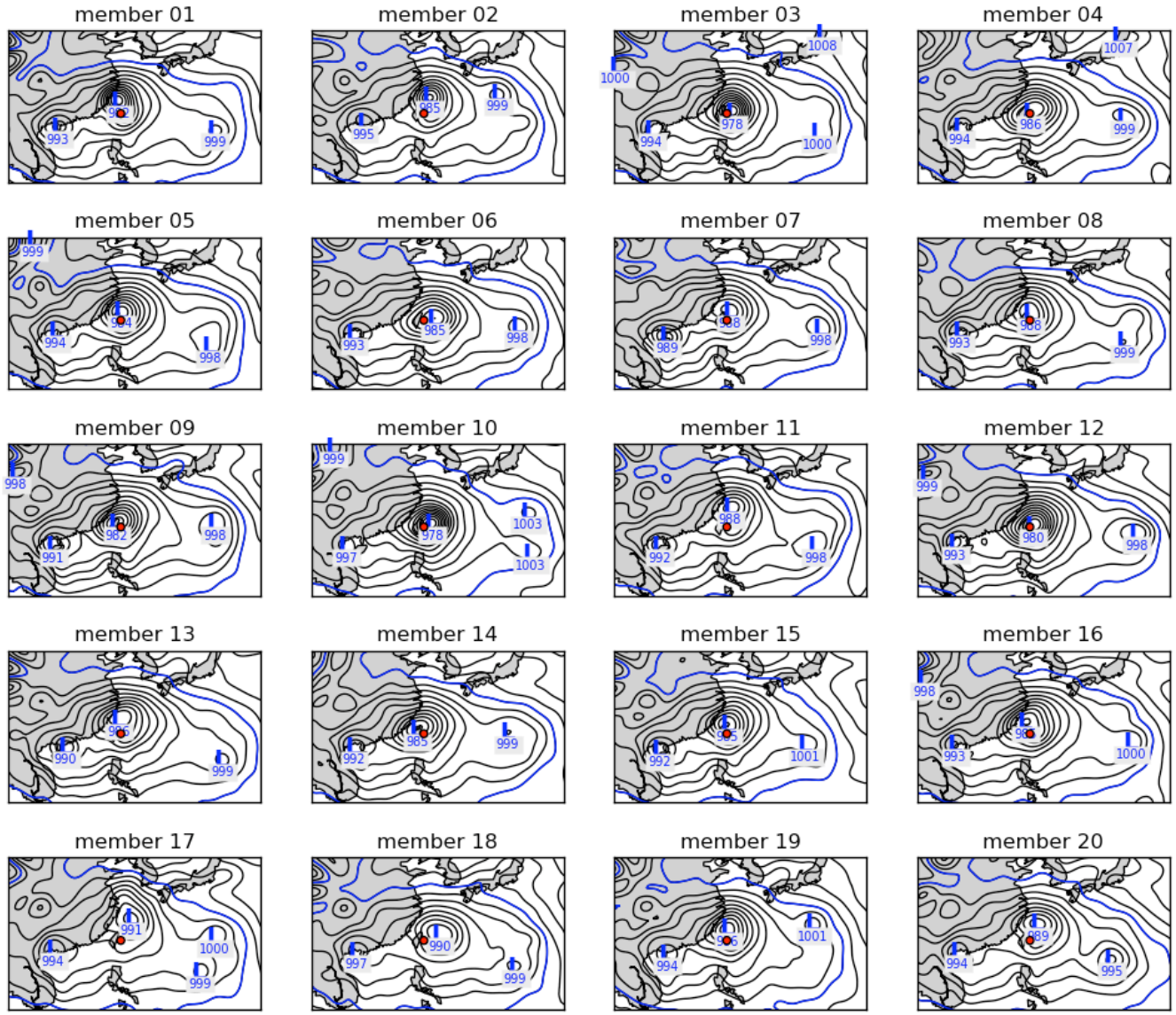
EnKF performance with 2009 typhoon Morakot (Taiwan floods)







54-h ensembles from T382 GFS & EnKF initial conditions.



Intense vortices in forecasts, with ensembles of forecast positions relatively close to the observed position (red dot).

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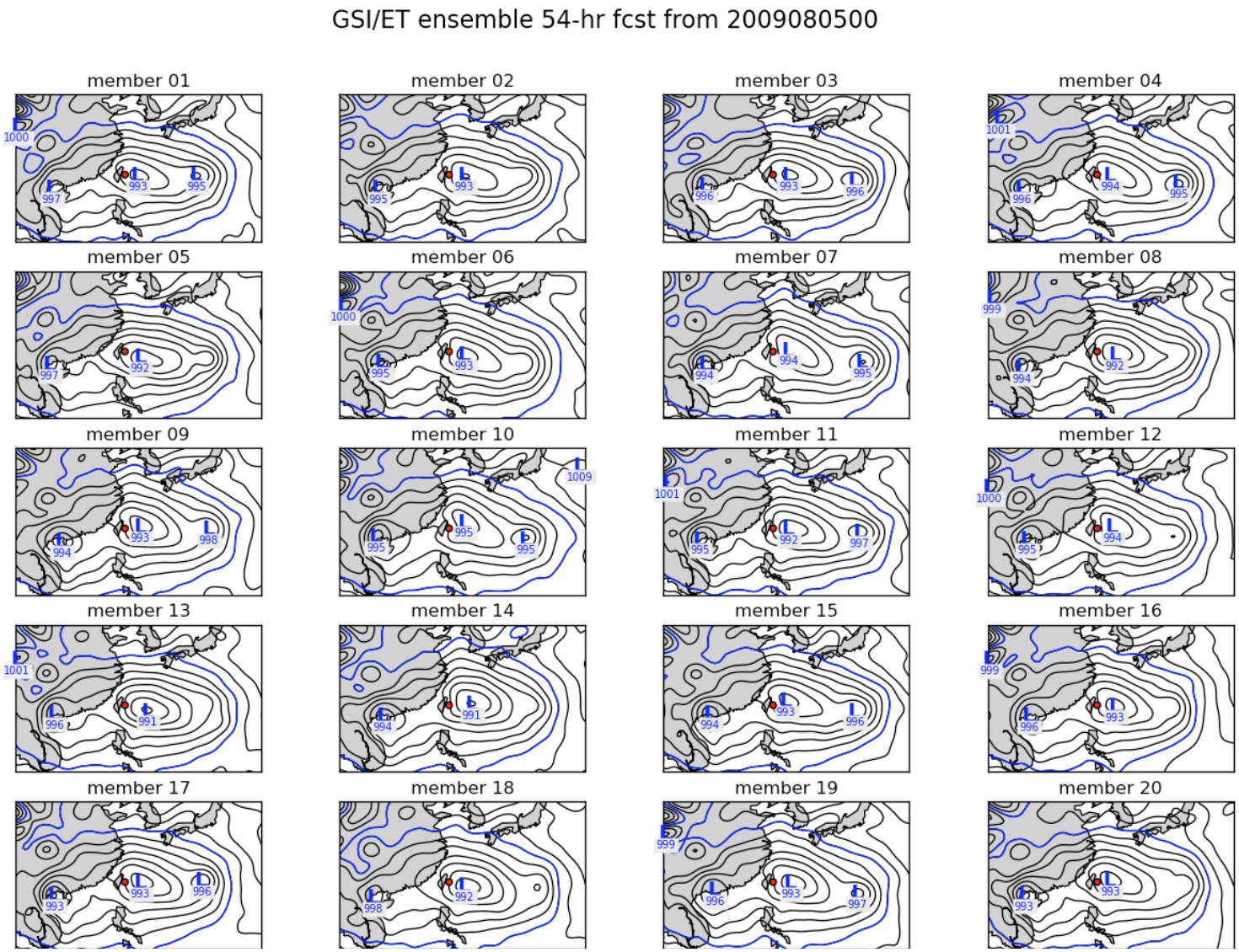
54-h ensembles from experimental T382 GFS & GSI / ET perturbations (operational).

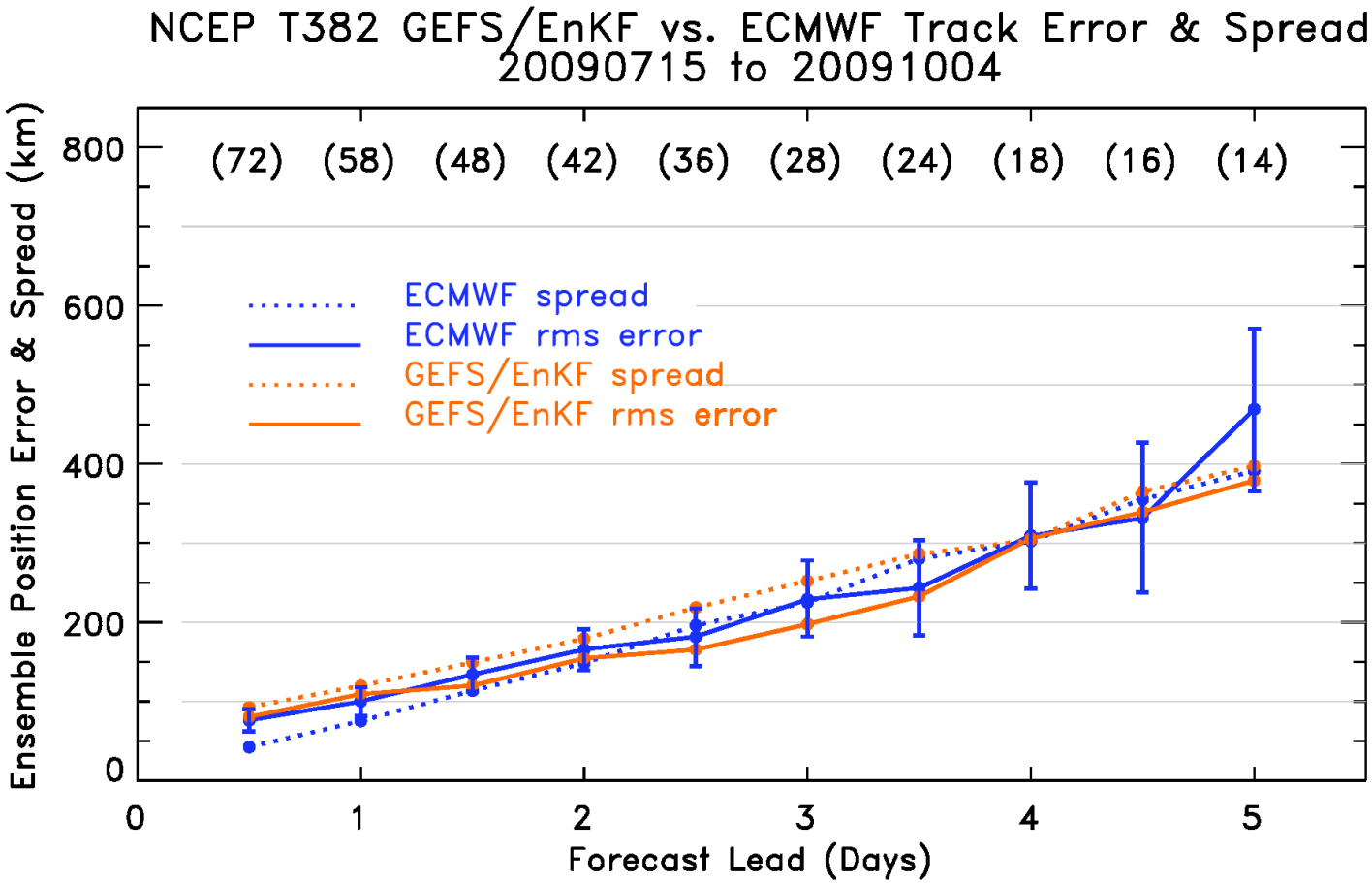


Note that GFS model resolution is much greater than current operational, T126

GSI-ET initialized ensemble produces less intense vortices, and forecasts are slow in moving typhoon west.

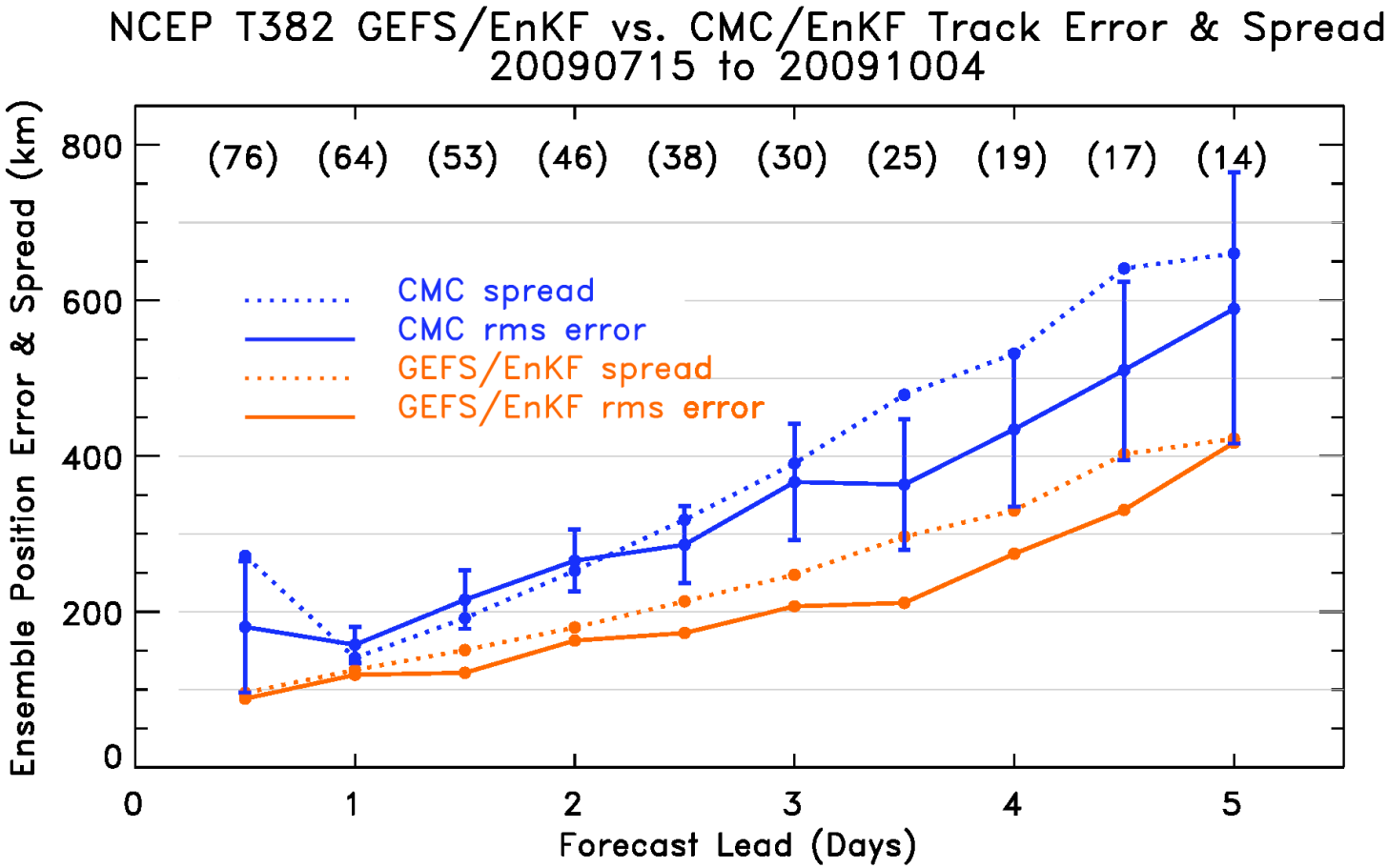
This operational version of GSI did not include TCVitals central pressure obs.

T382 GEFS/EnKF vs. operational T399 ECMWF



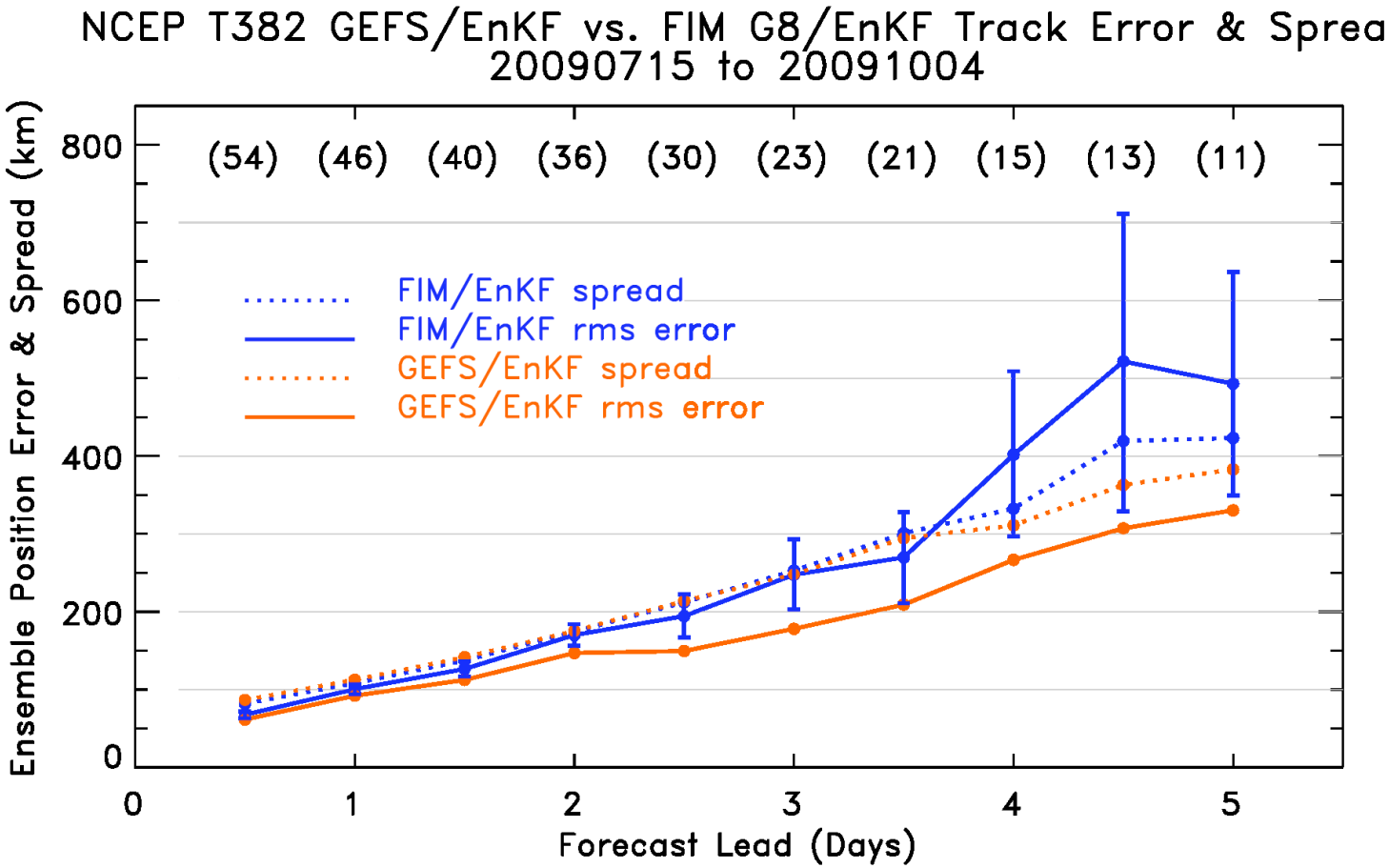
competitive with ECMWF in position error

T382 GEFS/EnKF vs. operational Canadian Centre EnKF



lower in error than CMC; they run EnKF at lower resolution and do no assimilate TCVitals

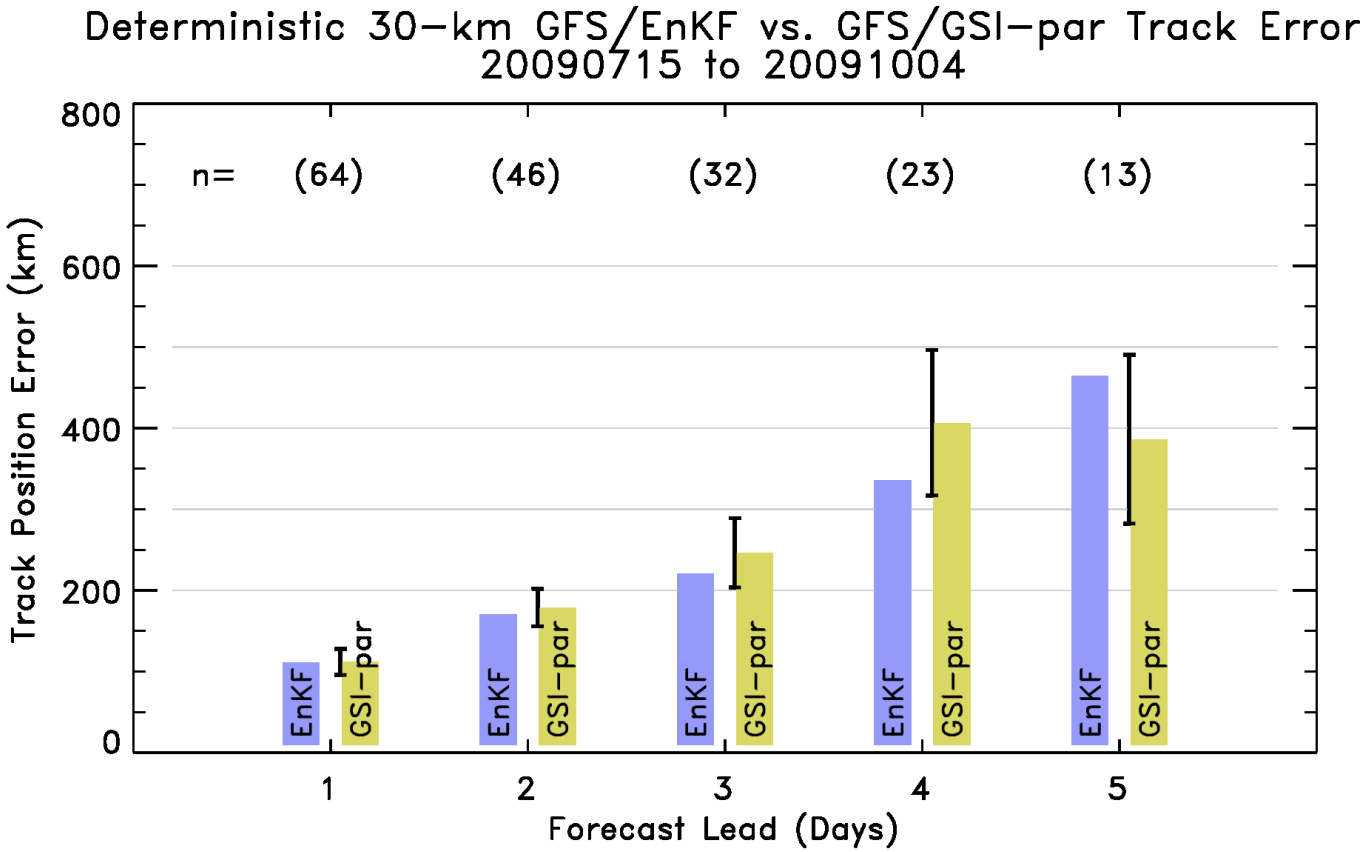
T382 GEFS/EnKF vs. experimental FIM/EnKF



FIM ensemble with somewhat higher errors than GEFS

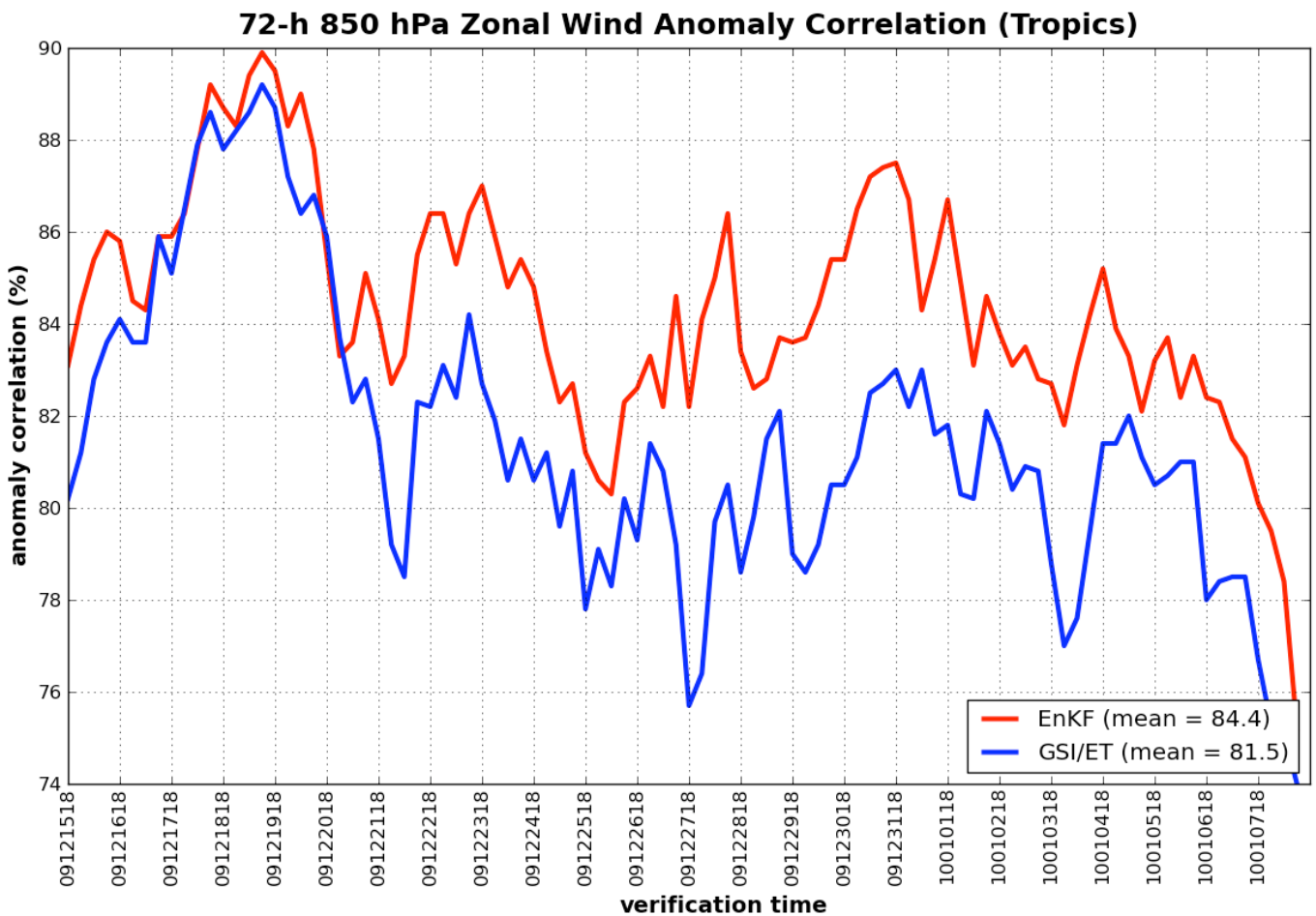
Deterministic track forecasts from parallel T382 GFS/GSI vs. T382 GFS/EnKF

This "parallel" version of GSI now uses TCVitals min pressure pseudo-obs



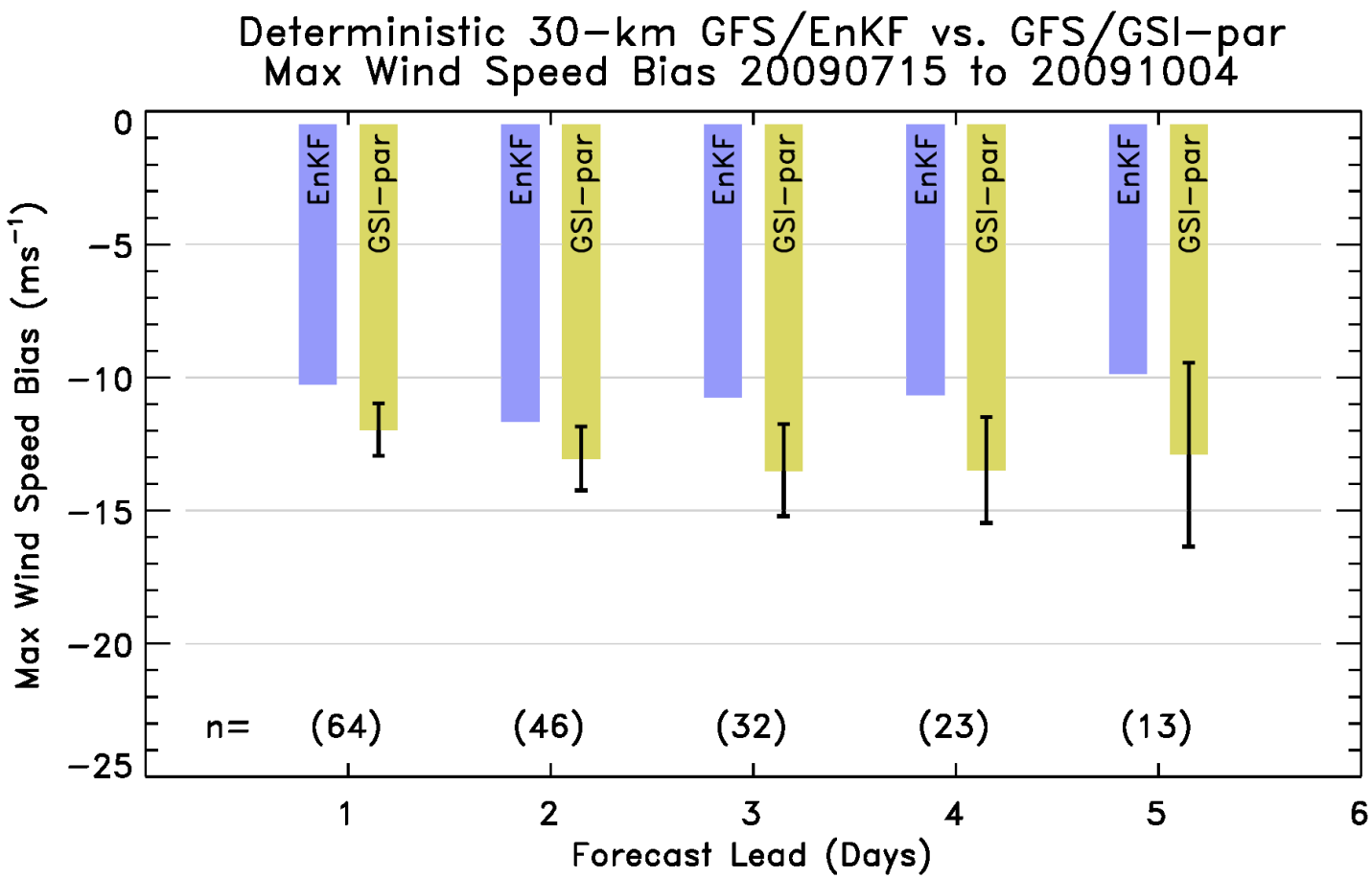
General slight improvement of EnKF except at longest lead (small sample).

Tropical winds from parallel tests of T190 GFS/GSI & GFS/EnKF



EnKF provides better wind forecasts; better steering of tropical cyclones?

Deterministic max wind speed forecast bias from parallel T382 GFS/GSI vs. T382 GFS/EnKF



EnKF appears to have improved max wind speed bias relative to GSI.

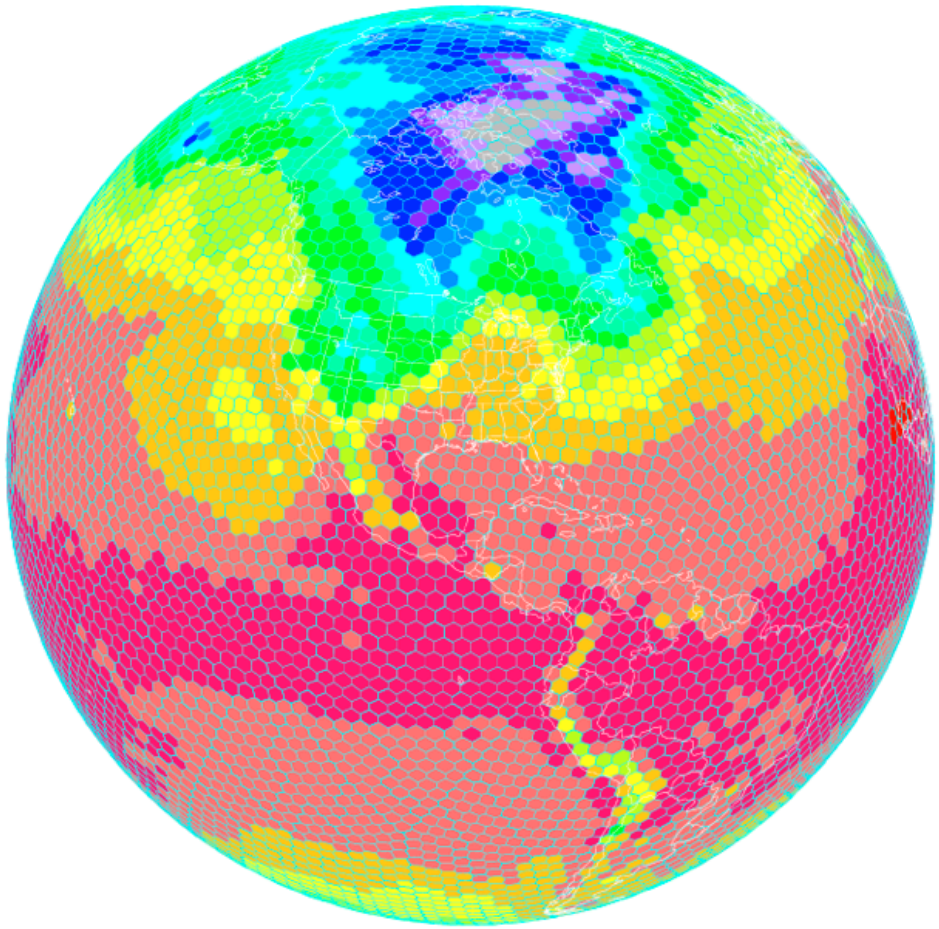
Conclusions

- EnKF + high-resolution global model showed remarkable success in 2009 season
  - track forecasts competitive with state-of-the art ECMWF forecast ensemble.
  - track forecasts clearly better than NCEP, CMC operational, FIM.
  - good consistency between ensemble spread and error.
  - generally better tropical wind analyses.
  - user-friendly, real-time tracker software.
- Improvement in TC forecasts likely due to both to increased model resolution and EnKF
- Some questions
  - improve methods for vortex initialization in EnKF. Incorporate relocation?
  - methods for treating hurricane-related model error?
  - resolution impacts of global model in EnKF?
  - effect of assimilating position and intensity of TCVitals separately?
  - will nesting of high-resolution regional EnKF and SREF forecasts provide even better results?

Acknowledgments: NOAA HFIP program for support, U. Texas NSF supercomputer for CPU cycles to make real-time ensemble forecasts; Tim Marchok (tracker files); Darryl Kleist (GFS parallel runs).

FIM model (fim.noaa.gov)

- icosahedral grid; nearly uniform resolution
- hybrid sigma/theta or sigma/pressure vertical coordinate.
- physics ported from GFS
- being developed & tested at NOAA ESRL as a candidate for future operational global forecast model.



Canonical EnKF update equations (for time *t*)

$$\mathbf{x}_i^a = \mathbf{x}_i^b + \mathbf{K}\left(\mathbf{y}_i - H\mathbf{x}_i^b\right)$$

$$\mathbf{K} = \mathbf{P}^b H^{\mathbf{T}}\left(H\mathbf{P}^b H^{\mathbf{T}} + \mathbf{R}\right)^{-1}$$

$$\mathbf{P}^b = \mathbf{X}\mathbf{X}^{\mathbf{T}}$$

$$\mathbf{X} = \left(\mathbf{x}_1^b - \overline{\mathbf{x}^b}, \ldots, \mathbf{x}_n^b - \overline{\mathbf{x}^b}\right)$$

$$\mathbf{y}_i = \mathbf{y} + \mathbf{y}_i^{'}$$

$$\mathbf{y}_i^{'} \sim N(0, \mathbf{R})$$

Notes:

(1) An ensemble of *n* parallel data assimilation cycles is conducted, assimilating *perturbed observations* .

(2) Background-error covariances are estimated using the ensemble.

Propagation of state and error covariances in EnKF

$$\mathbf{P}^a(t) = \left\langle \left[\mathbf{x}_i^a(t) - \overline{\mathbf{x}}_i^a(t) \right] \left[\mathbf{x}_i^a(t) - \overline{\mathbf{x}}_i^a(t) \right]^T \right\rangle$$

($\mathbf{P}^a$ never explicitly formed)

$$\mathbf{x}_i^b(t+1) = M\mathbf{x}_i^a(t)$$

if forecast model is "perfect"; *M* is forward model operator

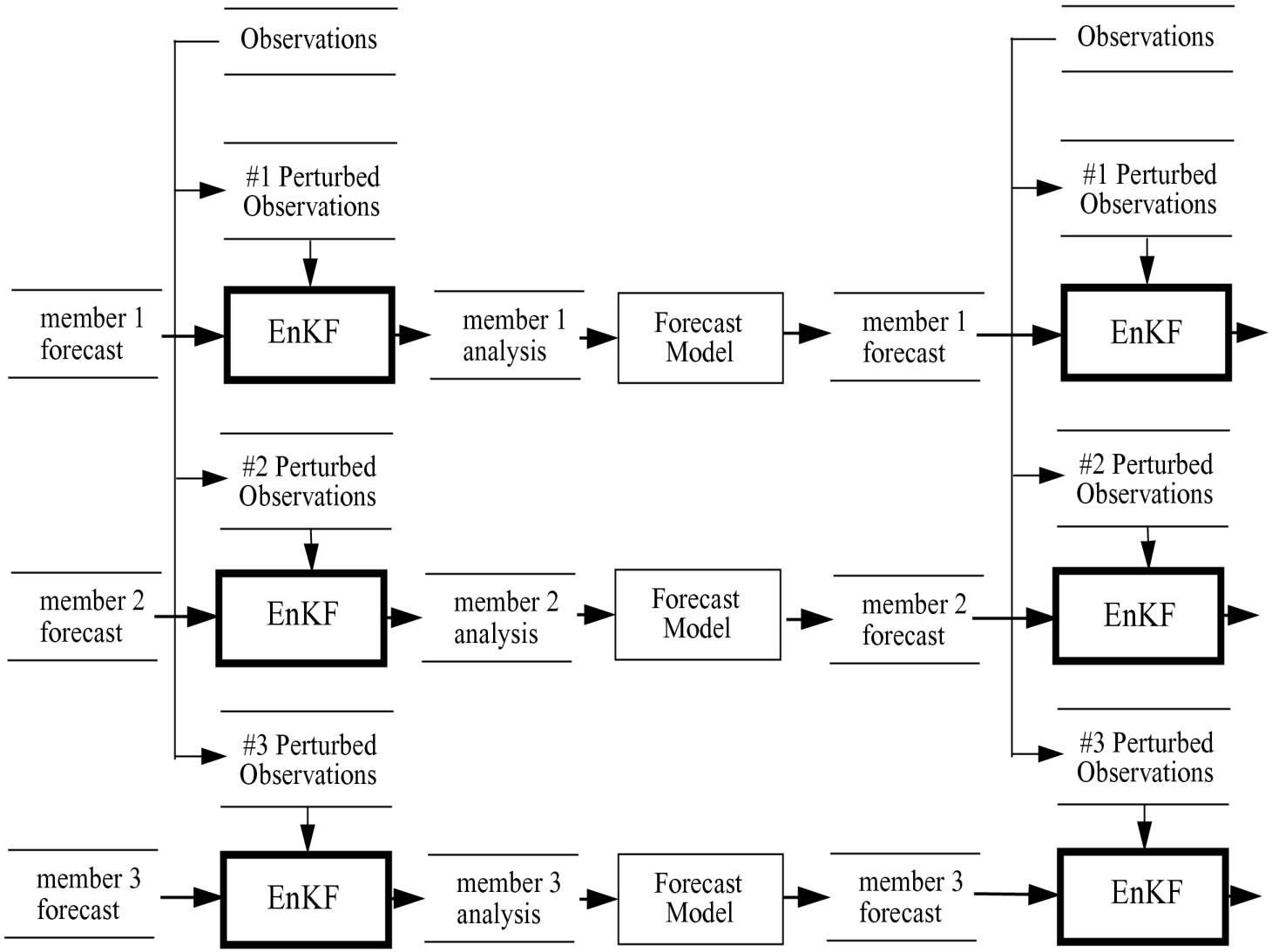
- or -

$$\mathbf{x}_i^b(t+1) = M\mathbf{x}_i^a(t) + \eta_i$$

$$\left\langle \eta_i \eta_i^T \right\rangle = \mathbf{Q}$$

…or something similar,
if forecast model imperfect.

Perfect-model EnKF schematic



(This schematic is a bit of an inappropriate simplification, for EnKF uses every member to estimate background-error covariances)