NOAA Earth System Research Laboratory

Global Ensemble Predictions of 2009's Tropical Cyclones Initialized with an Ensemble Kalman Filter

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Questions

- Can hurricane ensemble forecasts from a global model be improved substantially by:
  - using an EnKF for data assimilation & ensemble initialization?
  - using a higher-resolution version of global model?
  - using new “TCVitals” sea-level pressure observations in the data assimilation?
- How much of any improvement can be attributed to EnKF vs. higher resolution model vs. new obs?
- How do experimental forecasts compare with operational forecasts from worldwide centers?
- Multi-model ensembles provide improvement?

Testing performed

- Ran a global ensemble square-root filter ("EnKF") data assimilation
  - T382L64 (~40 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, late July to early October 2009.
- Other operational ensembles (next page)
- Also useful: deterministic forecasts from T382 GFS/EnKF, operational GFS/GSI and parallel GFS/GSI with TCVitals
- Compare against "best track" files compiled by NHC and Joint Typhoon Warning Center

Ensemble systems evaluated

- T382L64 "*GFS/EnKF*" (experimental)
- 30-km NOAA "*FIM*" off GFS/EnKF IC's (experimental)

- T126L28 GFS/GSI/ETR (operational "*NCEP*")
- "*CMC*" ensemble, 0.9-degree, L28, EnKF perts around 4D-Var control.
- "*UKMO*" MOGREPS ensemble, 1.25*0.83-degree, L38, ETKF perts around 4D-Var control
- "*ECMWF*" T399L62, v. 35r2 and 35r3 (with stochastic physics upgrade). Singular vector perts around 4D-Var control

- for diagnostic purposes, "*T126L28 GFS/EnKF*" initialized off T382L64 EnKF ICs

What we don't have, and wish we did

- T382L64 GFS/EnKF and subsequent ensembles, *without* TCVitals observations
- T126L28 GFS/EnKF and subsequent ensembles (or T190L64) to examine effect of resolution
- A bigger sample (lackluster Atlantic season, only global-composite statistics likely to be worth interpreting).

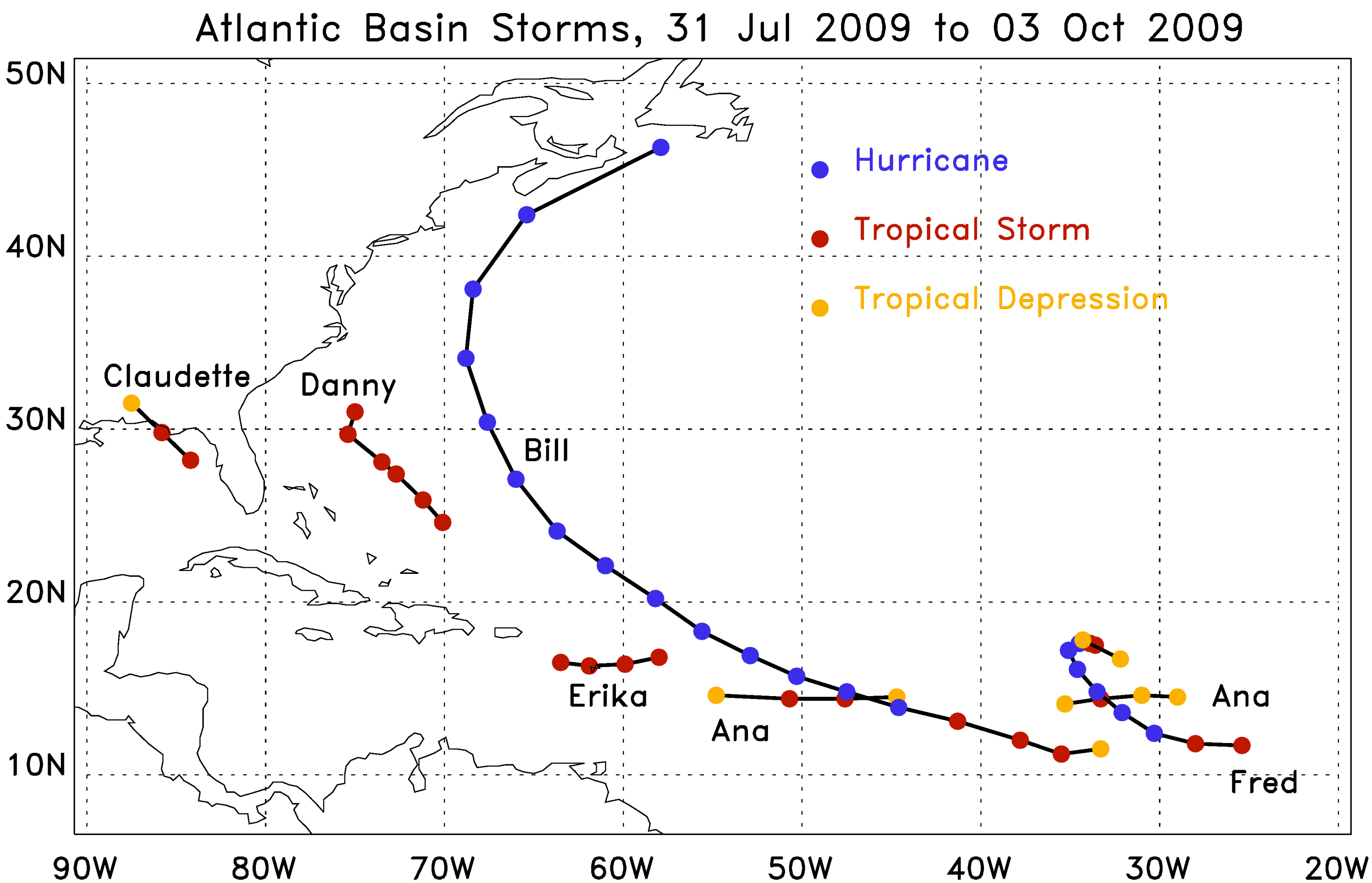
Rules for including a particular storm in "homogeneous" comparisons of models A vs. B

- 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.
- At least 8 members must be tracking the storm to compute statistics; mean error and spread computed from sample of storms tracked.
- When performing "homogeneous" comparison of forecast model A to forecast model B, count a storm as a sample only when both models have forecast available.

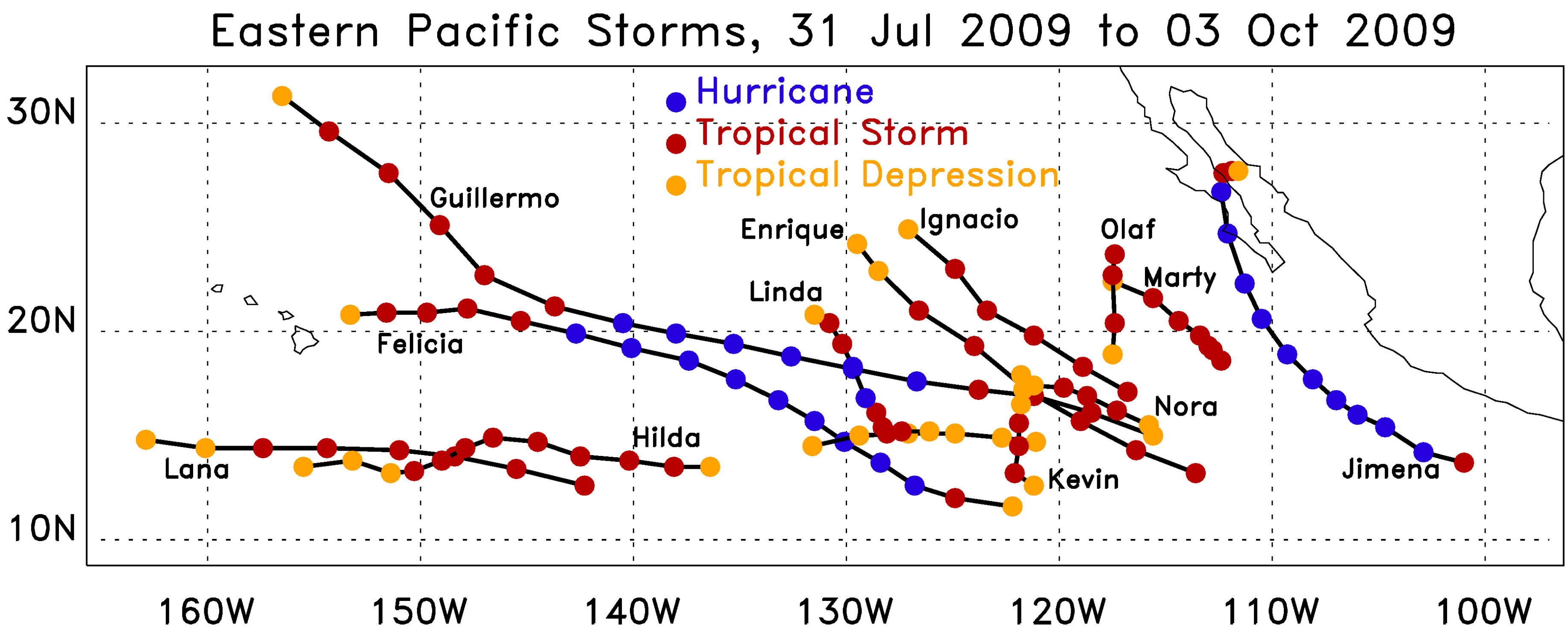
Definitions & metrics

- Absolute error (km) of ens.-mean track forecast for the *i*th of *m* samples $E_i(t)$
- Abs. difference of the *j*th of *n* members from the ens mean: $D_{i,j}$
- Track average error: $\bar{E}(t) = \frac{\sum_{i=1}^{m} E_i(t)}{m}$
- Spread for ith sample .... $S_i(t) = \frac{\sum_{j=1}^{n} D_{i,j}}{n}$
- Average spread : $\bar{S}(t) = \frac{\sum_{i=1}^{m} S_i(t)}{m}$

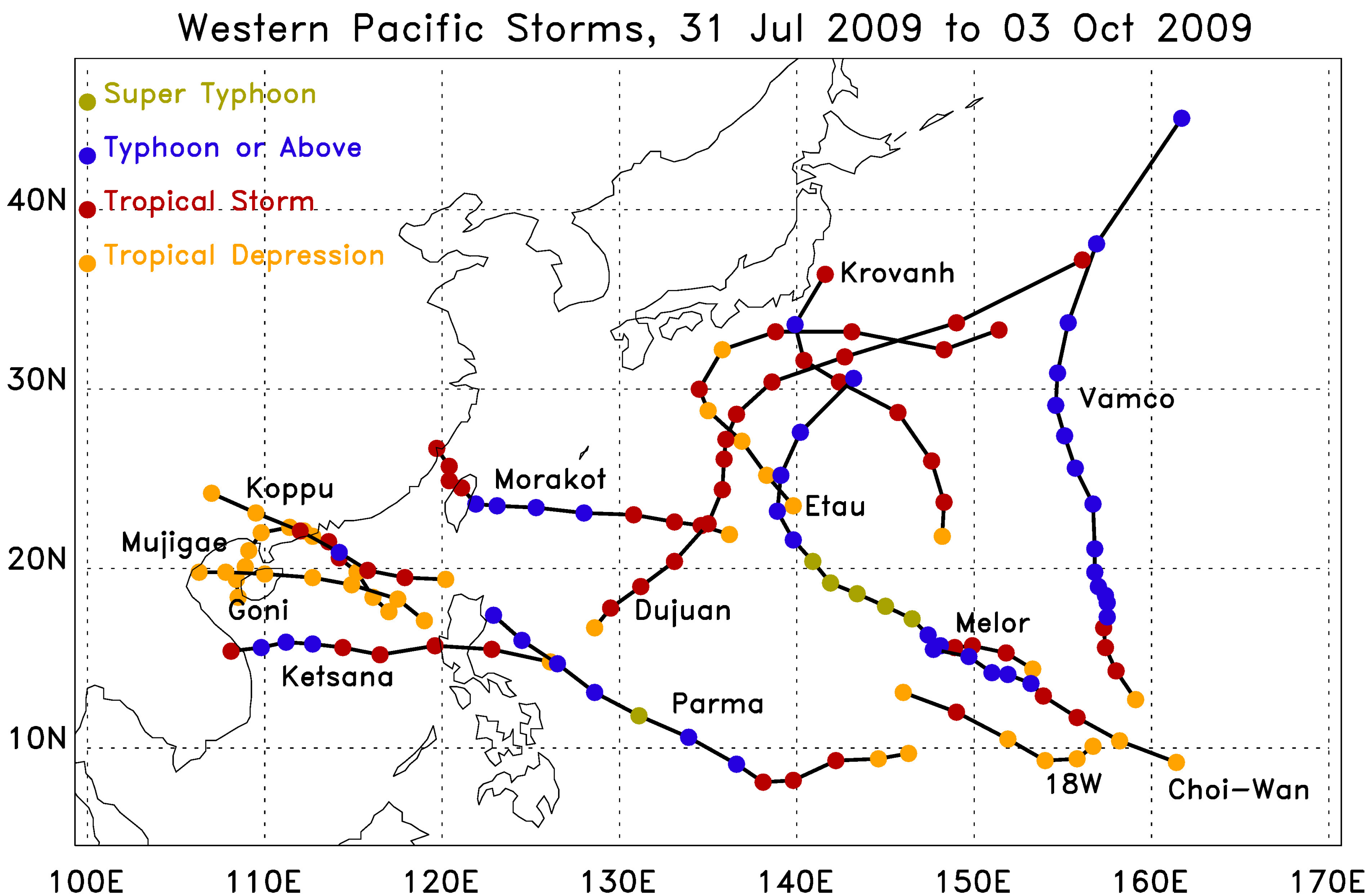
Review of Atlantic Basin activity



Review of Eastern-Pacific activity



Review of Western-Pacific activity



Initialized 00 UTC
5 August 2009.

* indicates observed best-track position.

Bi-variate normal distribution fit to ensemble member positions; contour encloses 90% of fitted probability.

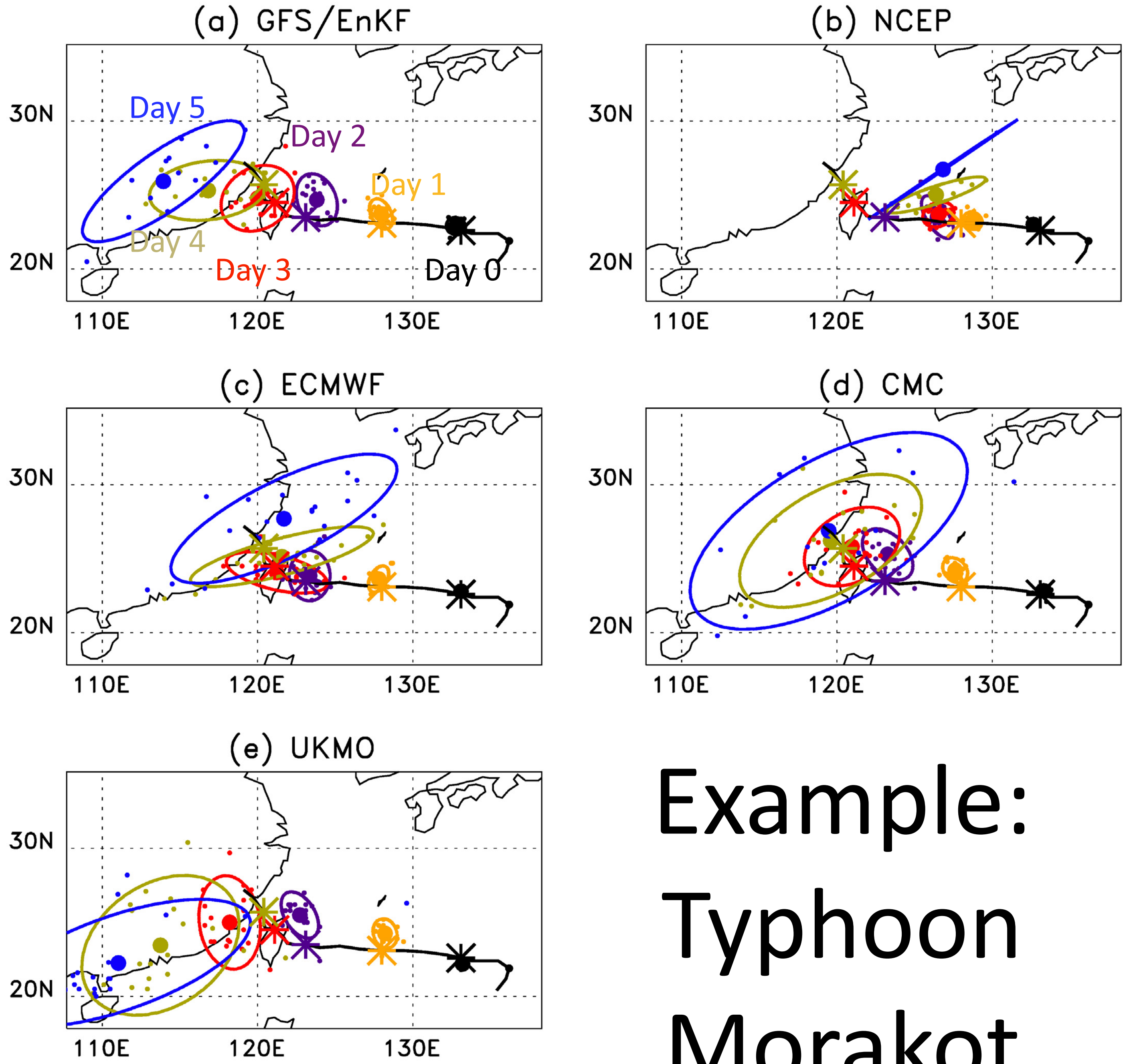
GEFS/EnKF a bit north and too fast.

NCEP has northward & westward bias, few members track.

ECMWF tracks decent up to Taiwan landfall

CMC has very large spread, esp. after landfall.

UKMO too north, too fast.

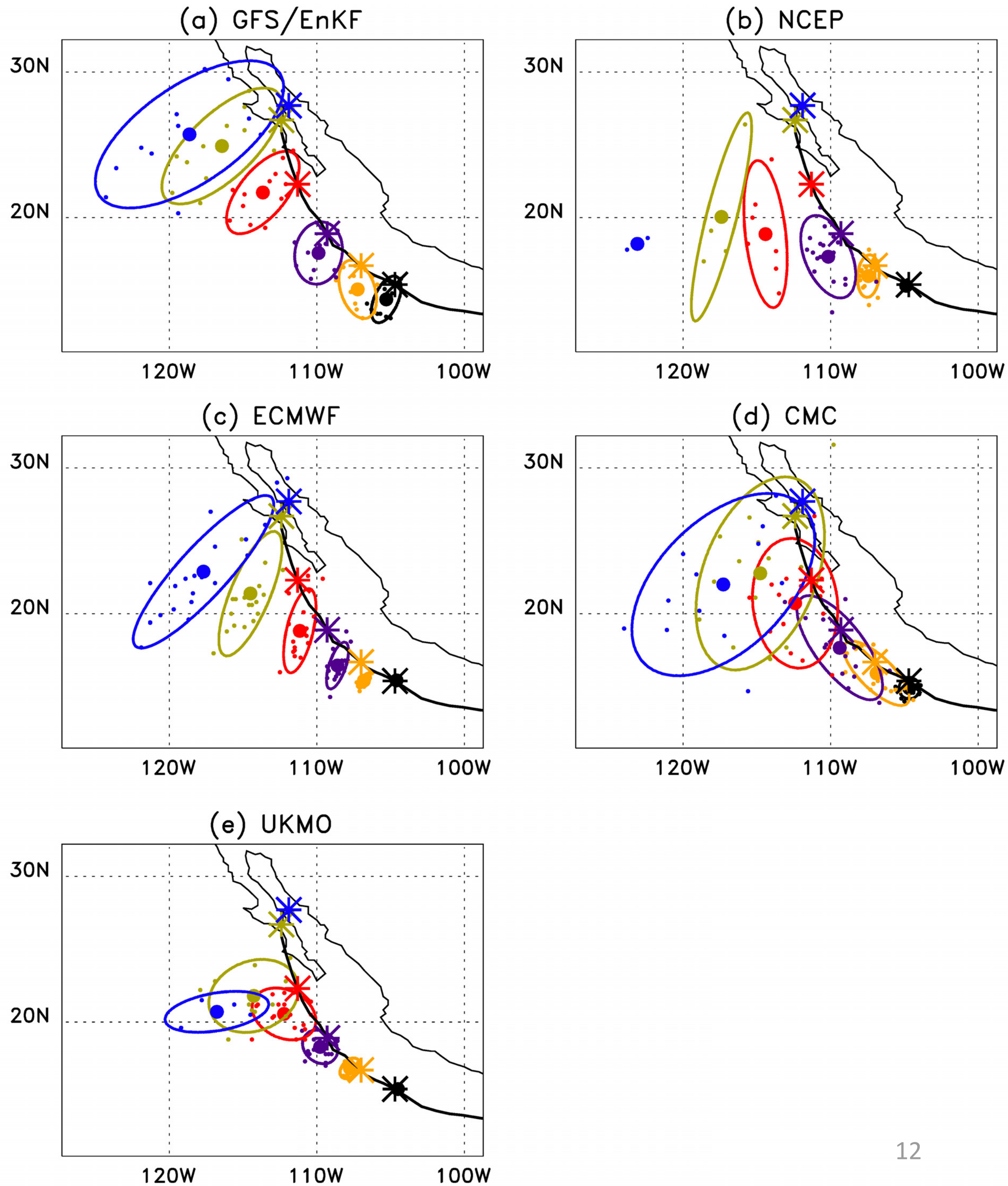


Example: Typhoon Morakot

Example: Hurricane Jimena

Initialized 00 UTC 30 Aug 2009

all models have westward bias; none of the forecasts particularly good.



Example: Hurricane Bill

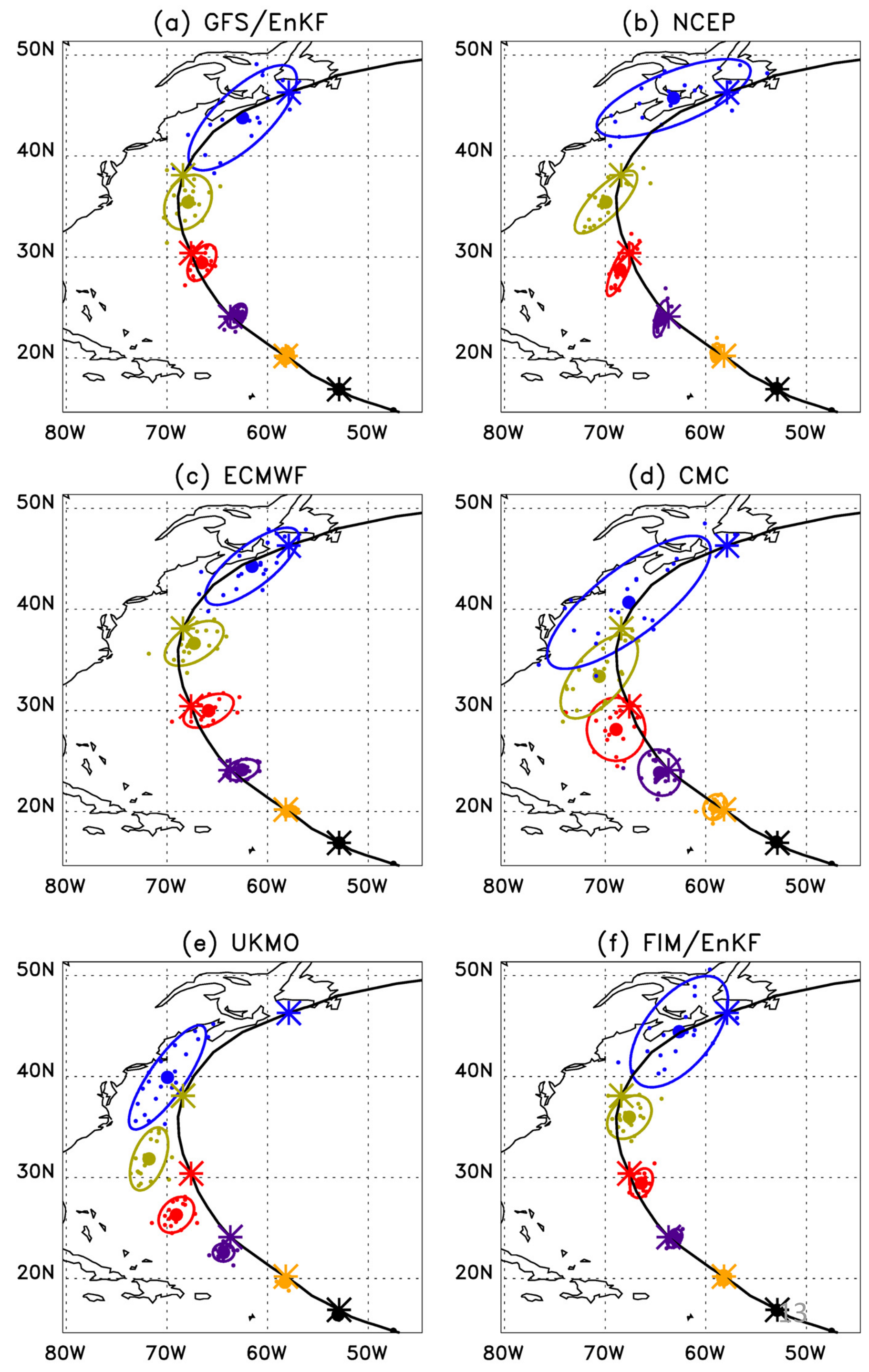
Initialized 00 UTC 19 August 2009.

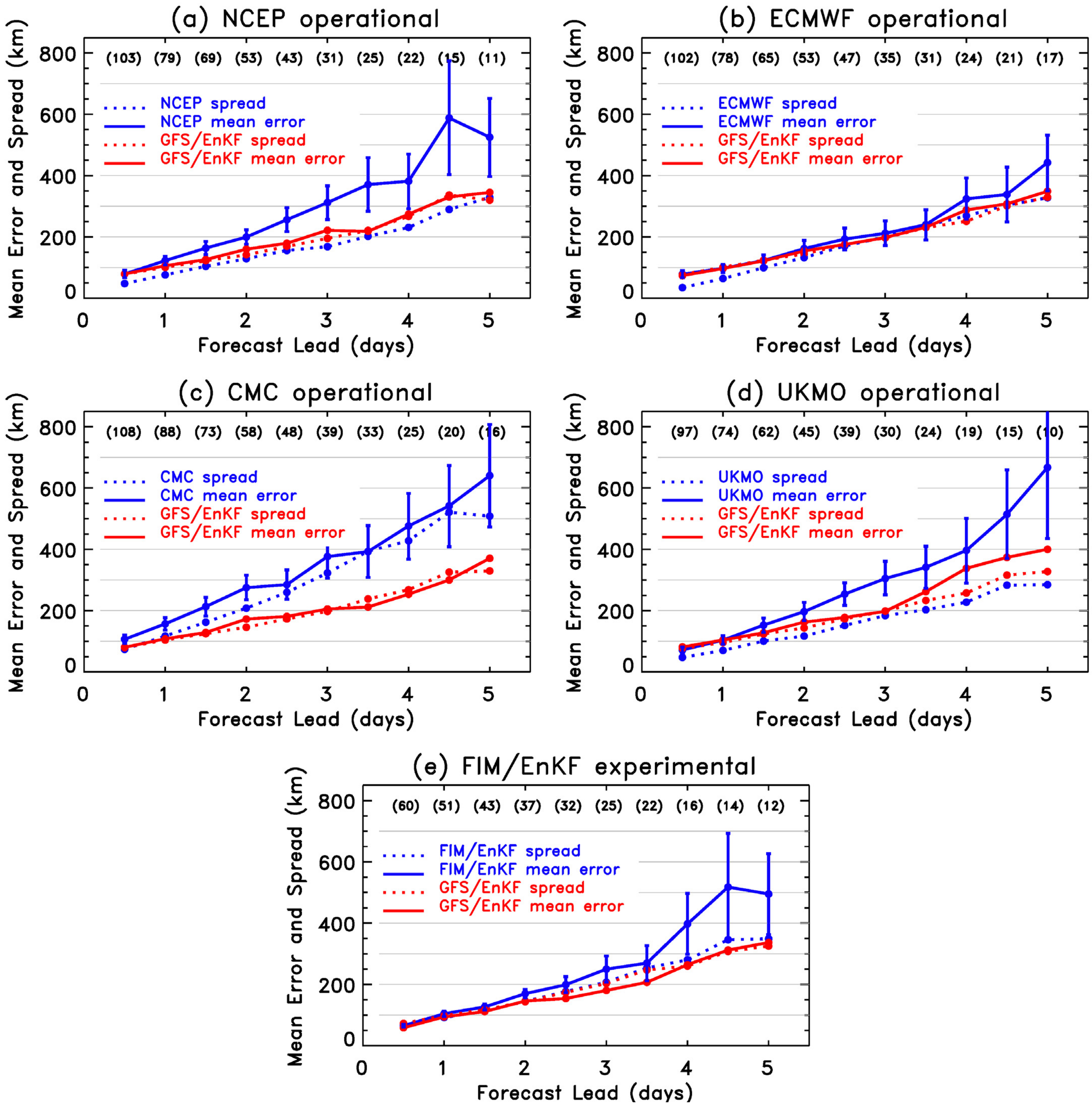
All models slow, to varying extents.

GEFS/EnKF and ECMWF tracks decent.

UKMO, CMC have westward bias.

NCEP, FIM decent.





Track error major findings:

(1) Experimental T382 GFS/EnKF beats NCEP operational handily.
(2) Experimental T382 GFS/EnKF competitive with ECMWF
(3) Experimental T382 GFS/EnKF has overall spread-error calibration.
(4) FIM/EnKF not quite as skillful as GFS/EnKF.
(5) CMC not as skillful, but calibrated.
(6) UKMO not as skillful, under-spread.

Ellipse eccentricity analysis

Question: are errors larger in the direction where the ellipse is stretched out?

$$\mathbf{x}'_{\lambda} = \left(x_{\lambda(1)} - \bar{x}_{\lambda},\ \ldots\ , x_{\lambda(nt)} - \bar{x}_{\lambda}\right) \Big/ (nt-1)^{1/2}$$

$$\mathbf{x}'_{\phi} = \left(x_{\phi(1)} - \bar{x}_{\phi},\ \ldots\ , x_{\phi(nt)} - \bar{x}_{\phi}\right) \Big/ (nt-1)^{1/2}$$

$$\lambda = longitude, \quad \phi = latitude, \quad nt = \#\, tracked$$

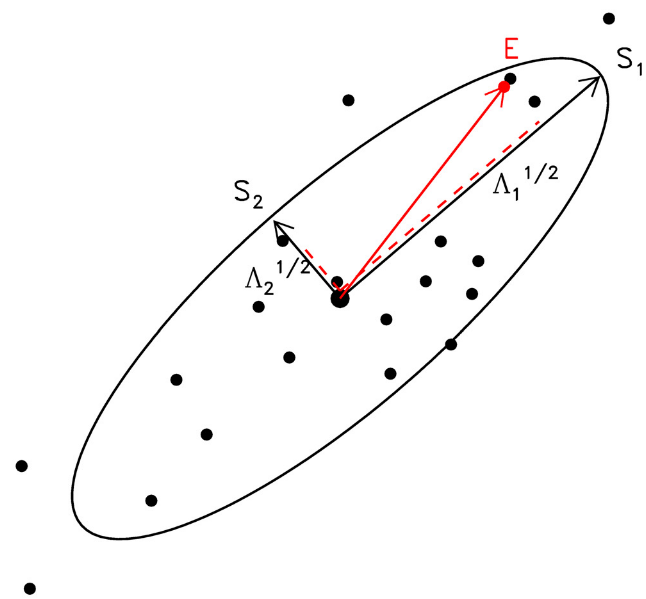
$$\mathbf{X} = \begin{bmatrix} \mathbf{x}'_{\lambda} \\ \mathbf{x}'_{\phi} \end{bmatrix}$$

$$\mathbf{F} = \mathbf{X}\mathbf{X}^{\mathrm{T}} = \mathbf{S}\Lambda\mathbf{S}^{-1} = \mathbf{S}\Lambda\mathbf{S}^{\mathrm{T}} = \left(\mathbf{S}\Lambda^{1/2}\right)\left(\mathbf{S}\Lambda^{1/2}\right)^{\mathrm{T}}$$

$\langle|\mathbf{E} \bullet \mathbf{S}_1|\rangle$ should be consistent with $\langle\langle|\mathbf{X}_{i\bullet} \bullet \mathbf{S}_1|\rangle\rangle$

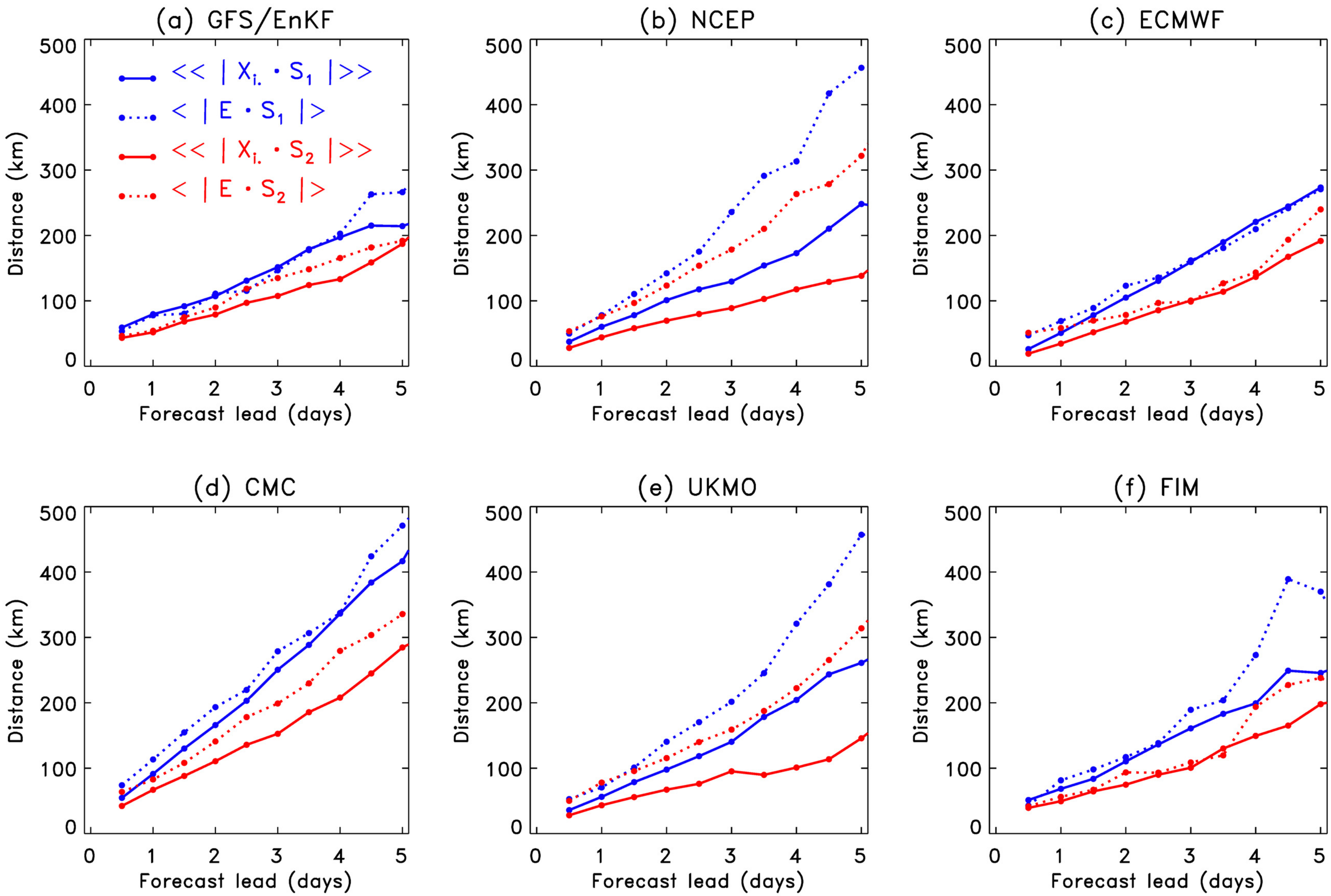
$\langle|\mathbf{E} \bullet \mathbf{S}_2|\rangle$ should be consistent with $\langle\langle|\mathbf{X}_{i\bullet} \bullet \mathbf{S}_2|\rangle\rangle$

$\langle\bullet\rangle$ = average over cases; $\langle\langle\bullet\rangle\rangle$ = average over cases, members

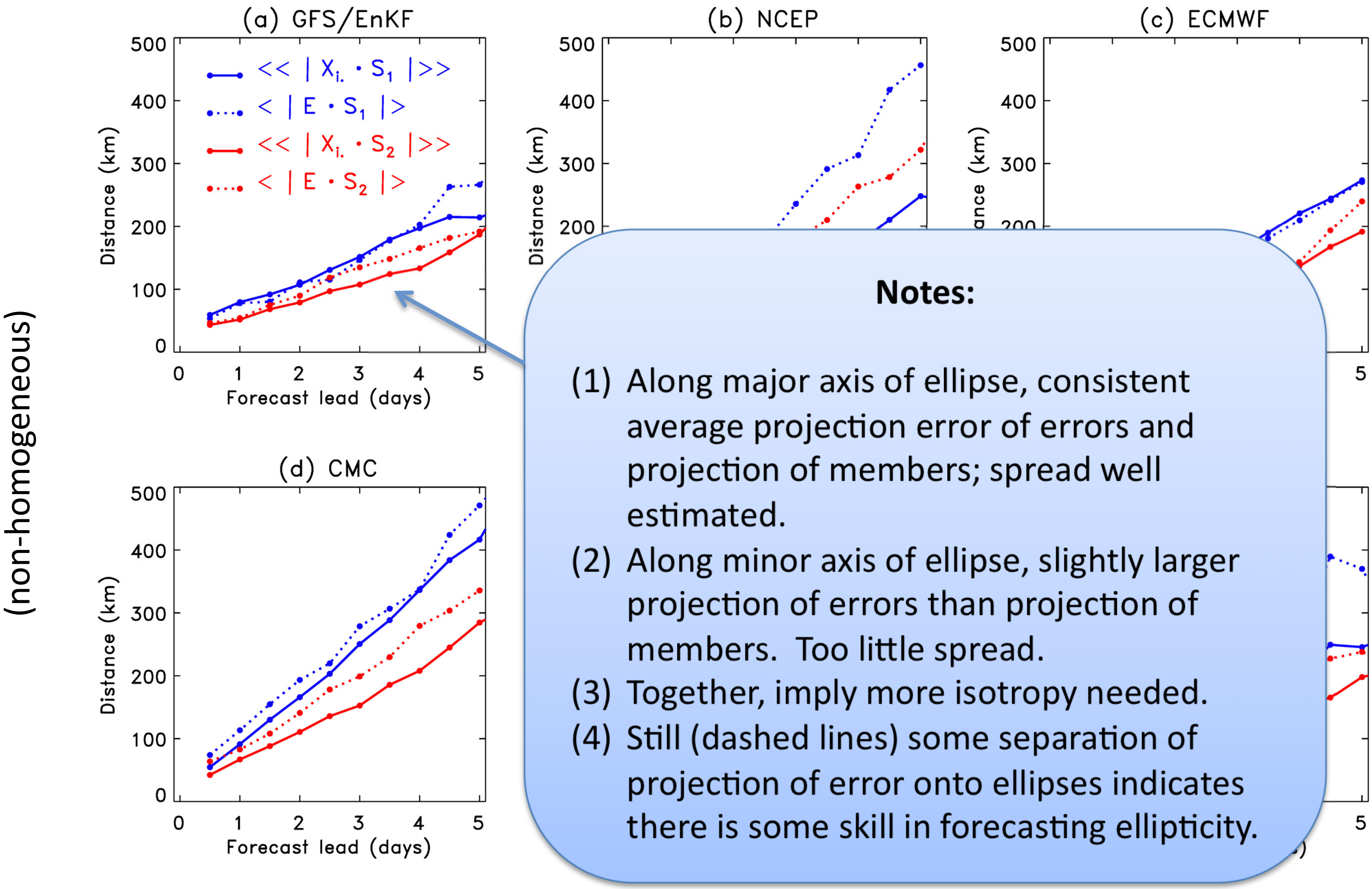


Ellipse eccentricity analysis

(non-homogeneous)



Ellipse eccentricity analysis



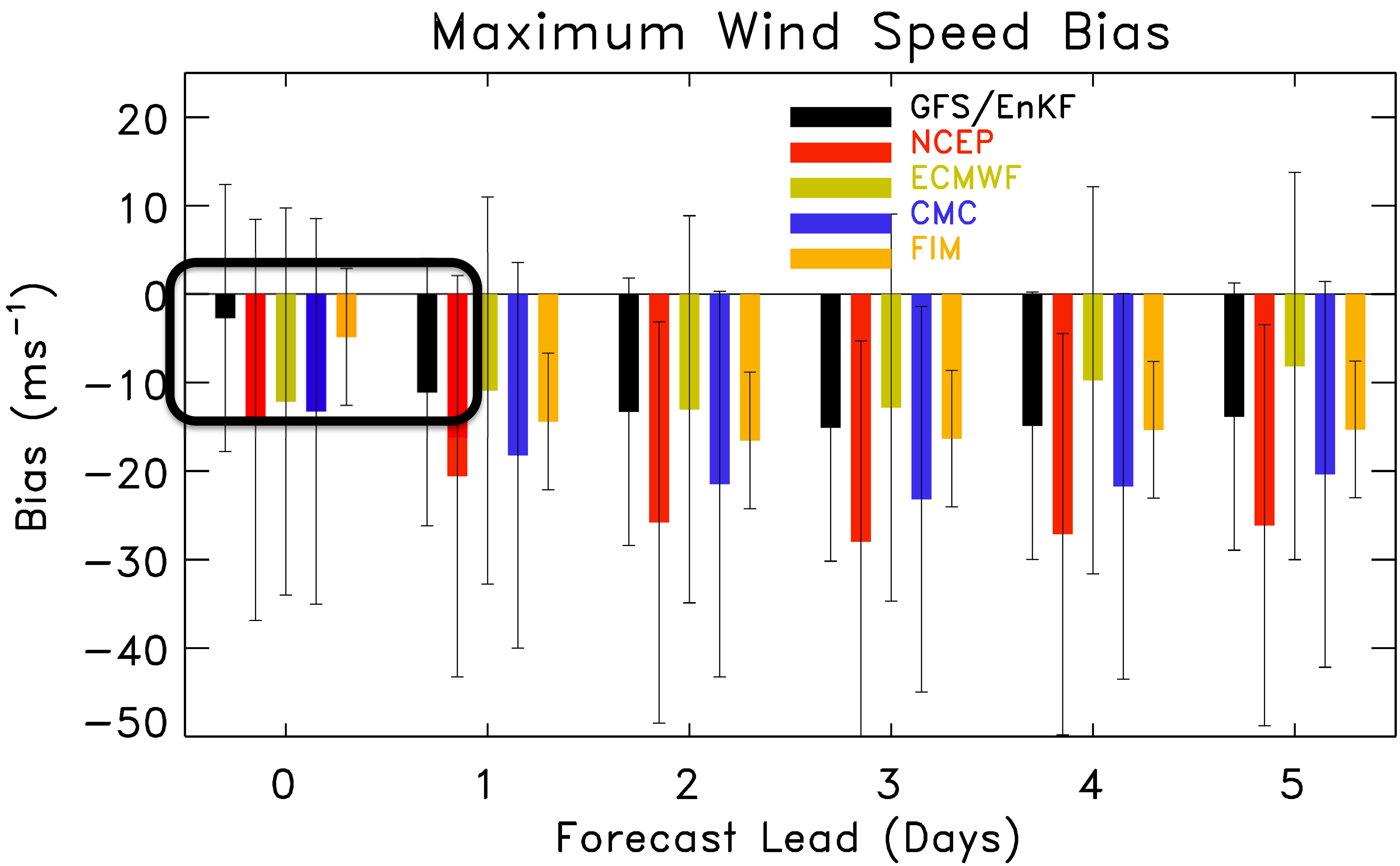
Notes:

(1) Along major axis of ellipse, consistent average projection error of errors and projection of members; spread well estimated.

(2) Along minor axis of ellipse, slightly larger projection of errors than projection of members. Too little spread.

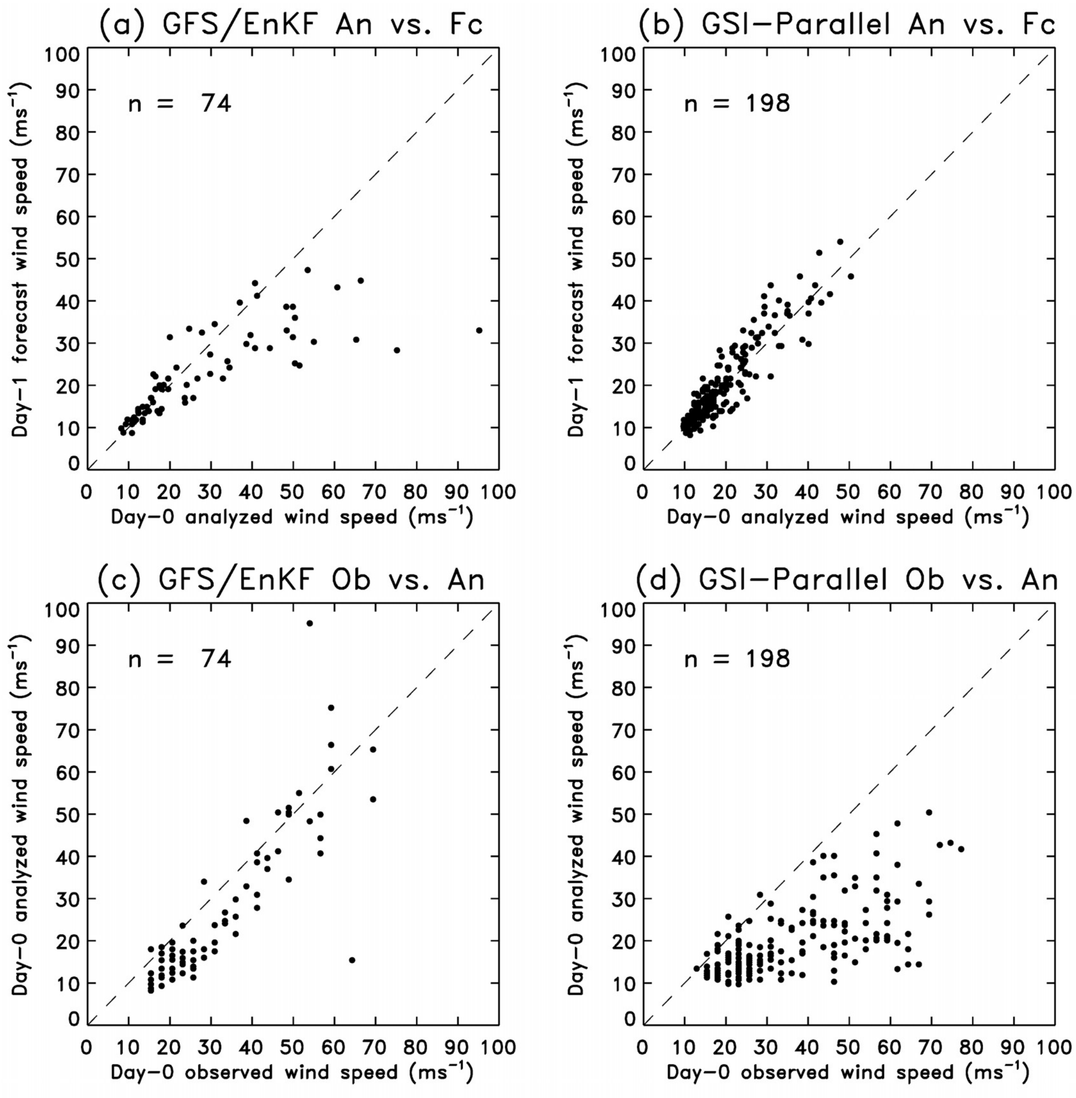
(3) Together, imply more isotropy needed.

(4) Still (dashed lines) some separation of projection of error onto ellipses indicates there is some skill in forecasting ellipticity.



non-homogeneous; error bars are 5th, 95th percentiles of normal distribution fit to data.

Source of rapid decrease of GFS/EnKF wind speeds between day 0 and day 1?

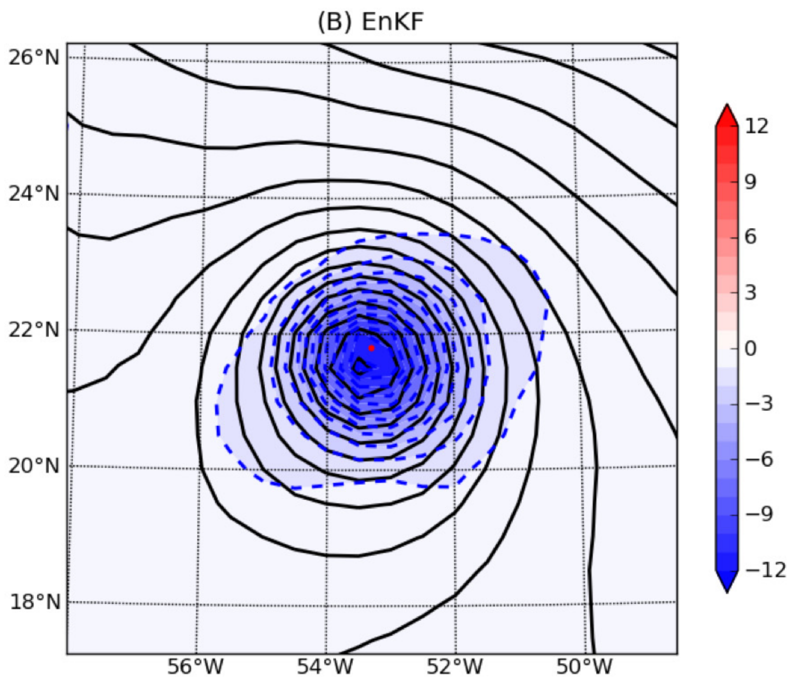


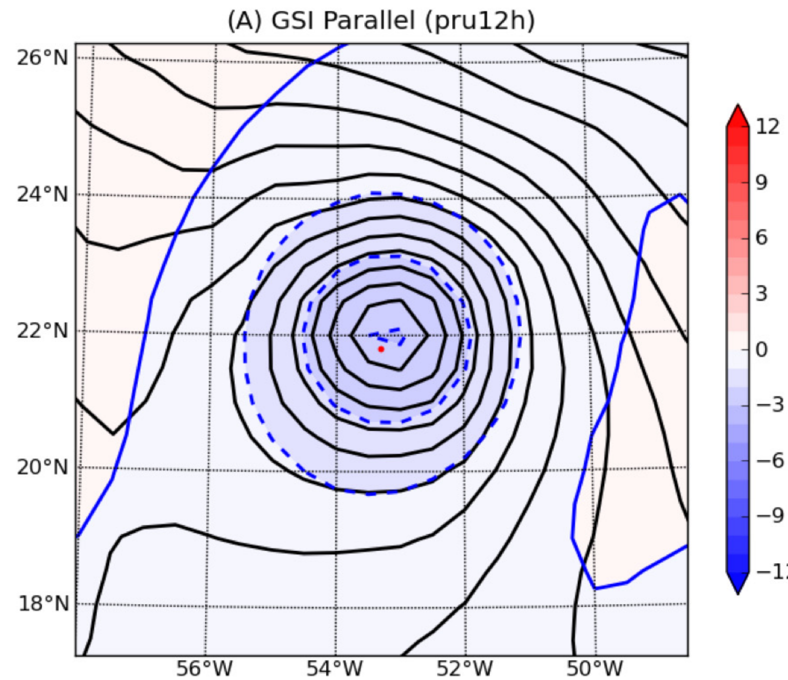
Rapid decrease in speed of GFS/EnKF forecasts; not so for GSI initialized

But looking at analyzed wind speeds, GFS/EnKF produces appropriately strong vortex, GSI does not.

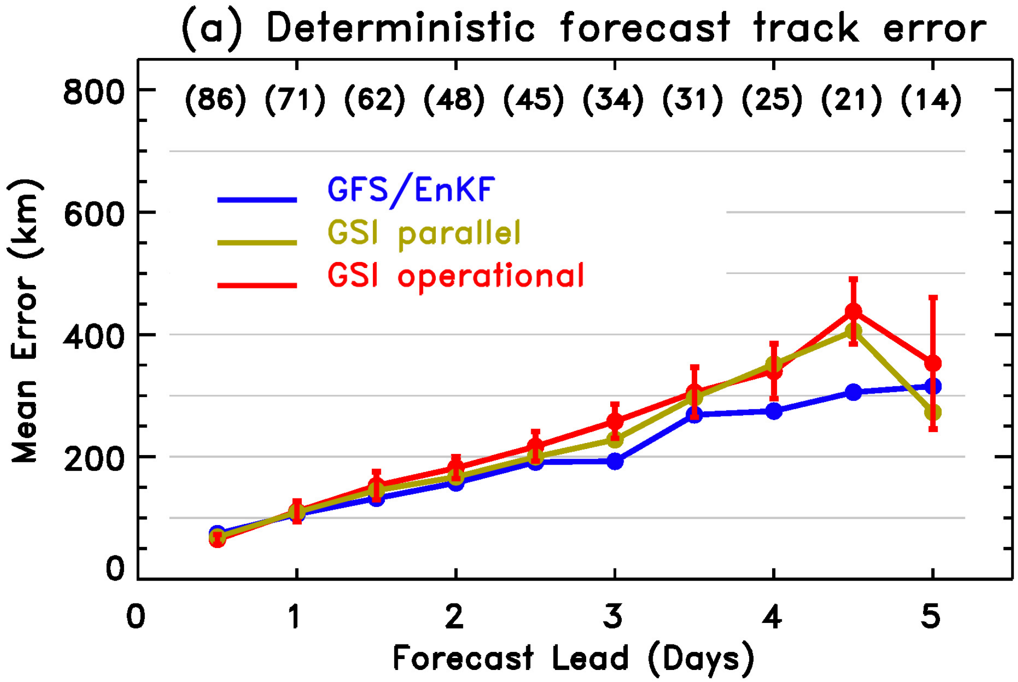
Increments in GFS/EnKF and GSI-parallel to TCVitals SLP

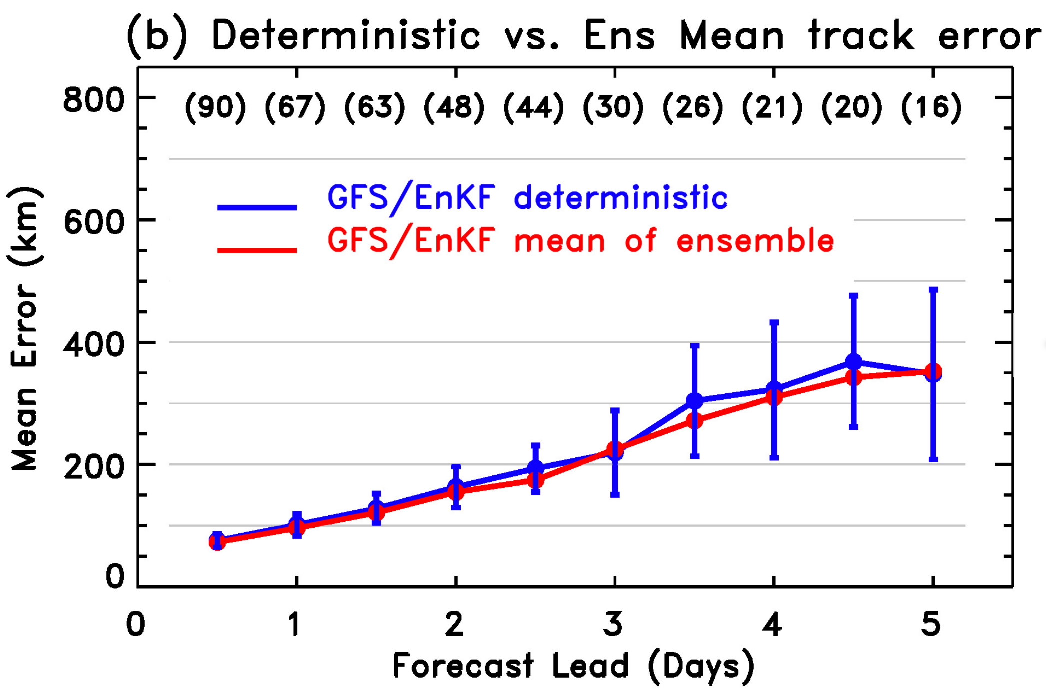
Hurricane Ike, 00 UTC 4 September 2008





Change to EnKF initializes much deeper, tighter vortex; contours every 1 hPa.
But, model cannot support the analyzed storm at this resolution.

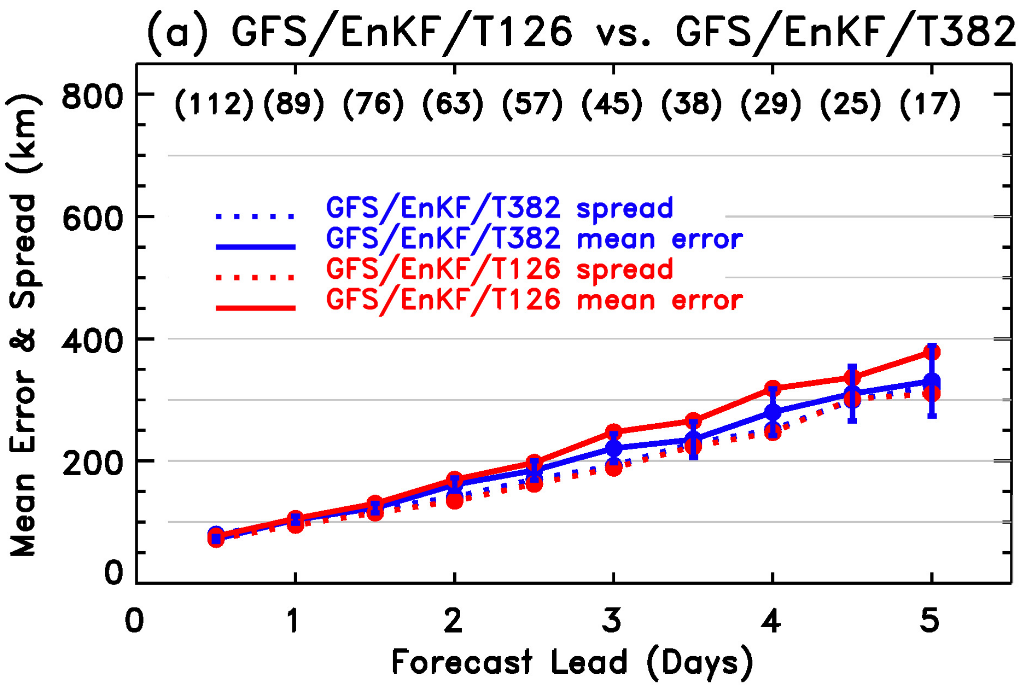


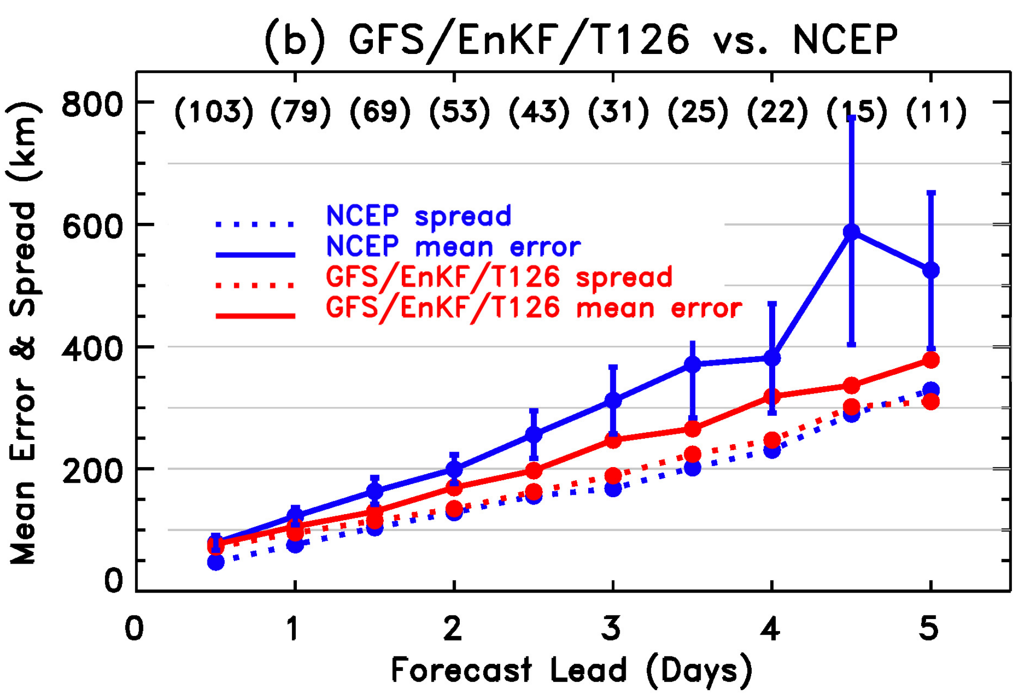


Trying to understand effects of TCVitals, EnKF, resolution, ensemble averaging

GFS parallel with TCVitals had slightlylower errors than GSI operational. Maybe different effect with EnKF/flow dependent B?

Ensemble averaging did not appear to have a large effect on track forecast performance.



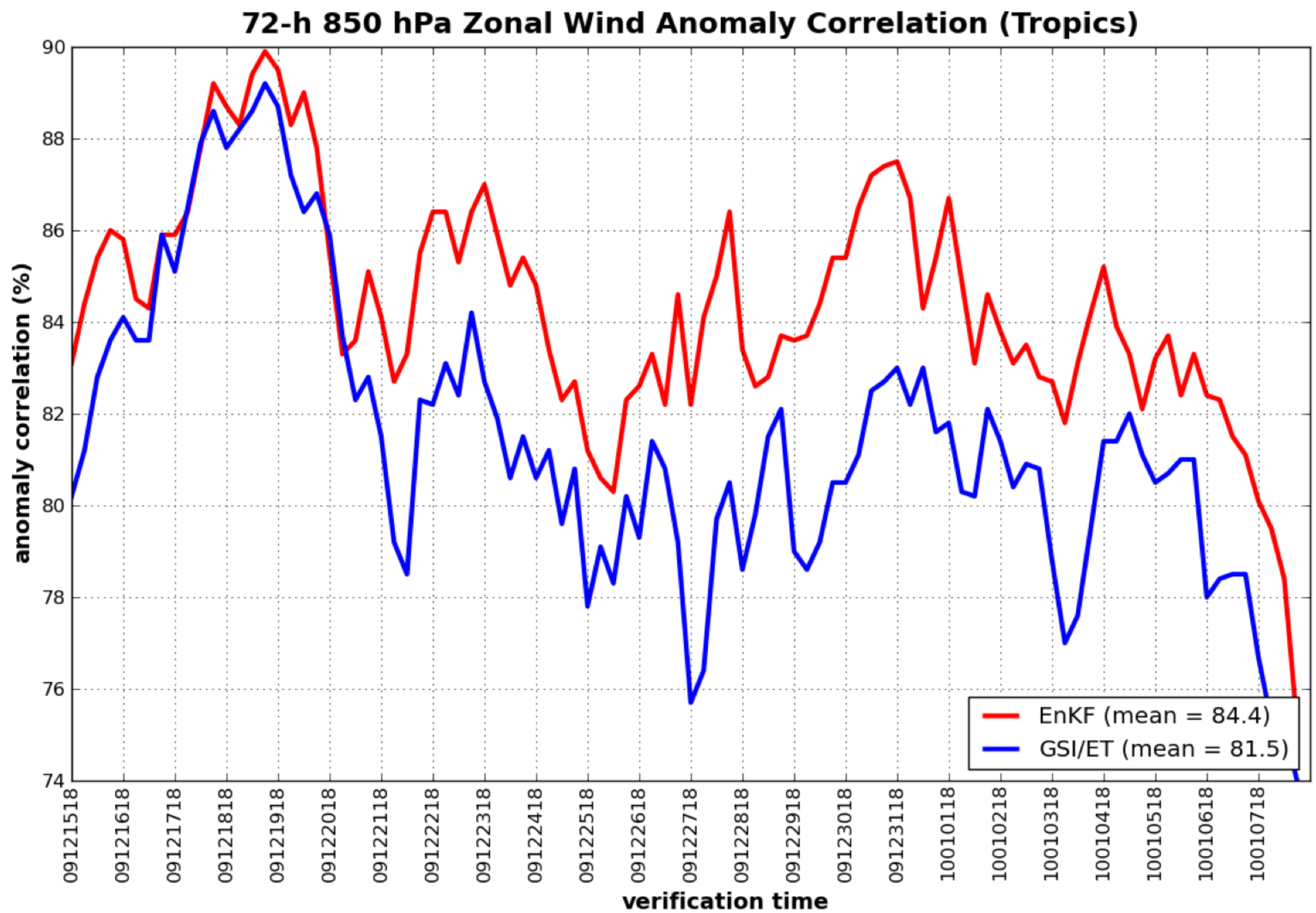


Trying to understand effects of TCVitals, EnKF, resolution, ensemble averaging

modest impact on track forecast from degrading the resolution of the forecast (still T382 during the data assimilation).

larger impact of GFS/EnKF at T126 vs. operational. However, 2009 operational version had more diffusion, so that complicates analysis.

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



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

Improvements next summer

- T574, new GFS physics.
- Assimilation of pos/intensity separately?
- Vortex relocation when 6-h forecast too far off?
- TCVitals error estimates incorporated into data assimilation?

	Dvorak	vs.	in-situ	error	(mb)	
TD	TS	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5
3.3	6.1	9.5	11.7	13.9	16.1	19.1

* table c/o Ryan Torn, U Albany

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.
  - information on ellipticity of track positions useful
- Improvement in TC forecasts likely due to increased model resolution, EnKF, and TCVitals.
  - however, forecast resolution had smaller impact when data assimilation with hi-res EnKF
  - TCVitals had small positive impact in GSI; parallel tests with/without in EnKF not conducted. Presumed effect larger.

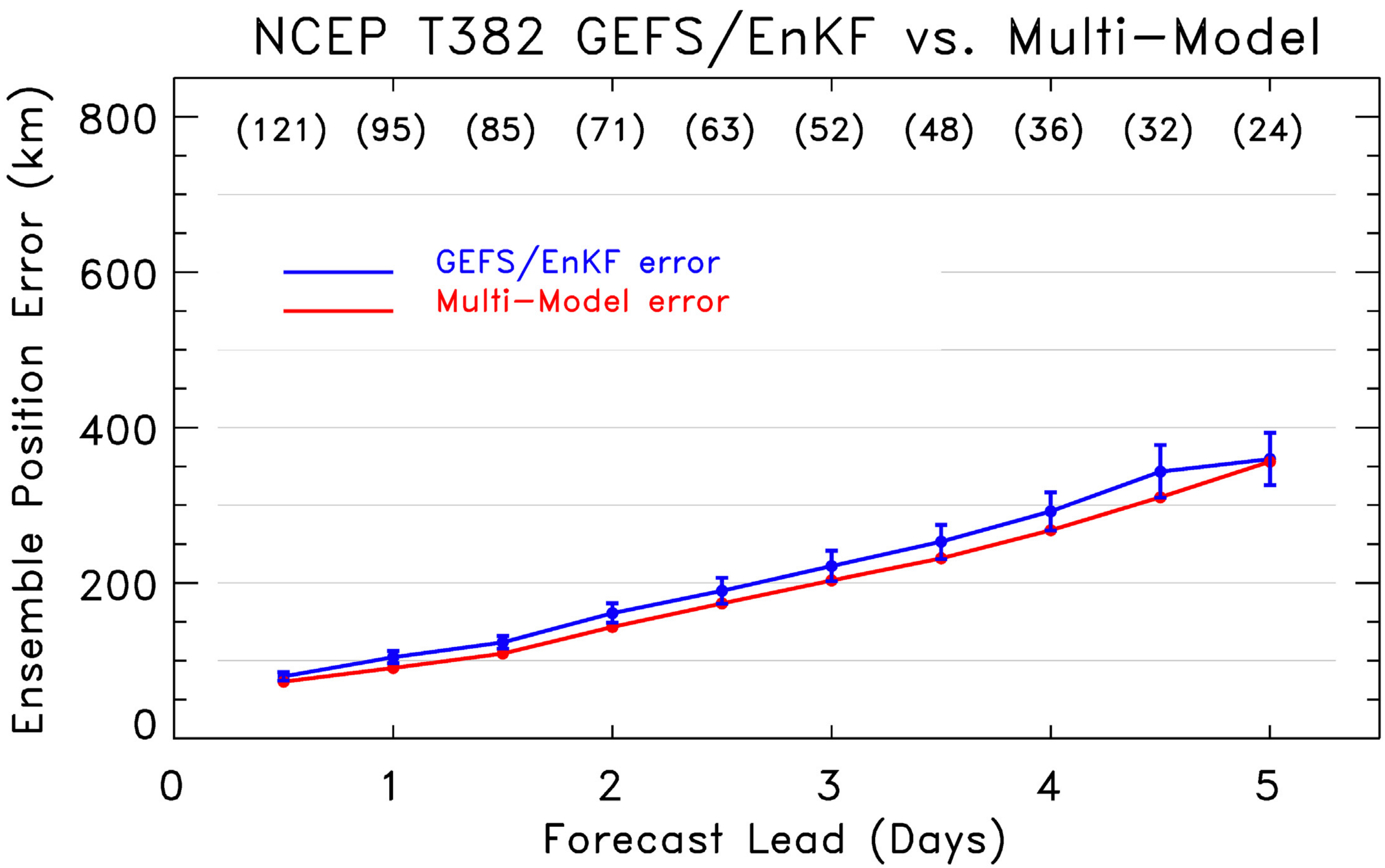
Some Questions

- improve methods for vortex initialization in EnKF. Incorporate relocation in some cases?
- 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 2009 summer test support
- NOAA THORPEX, ESRL base for EnKF development
- U. Texas NSF supercomputer for CPU cycles
- Phil Pegion for programming support, analysis.
- Mike Fiorino (tracker files, software sanity check)
- Other ESRLites, e.g., Chris Harrop for scripting, Stan Benjamin for management
- Tim Marchok (tracker files)
- Daryl Kleist (GFS parallel runs)
- Chris Snyder, Jeff Anderson for ensemble bull sessions
- and you, for your constructive feedback

Multi-model error (GEFS/EnKF, ECMWF only)

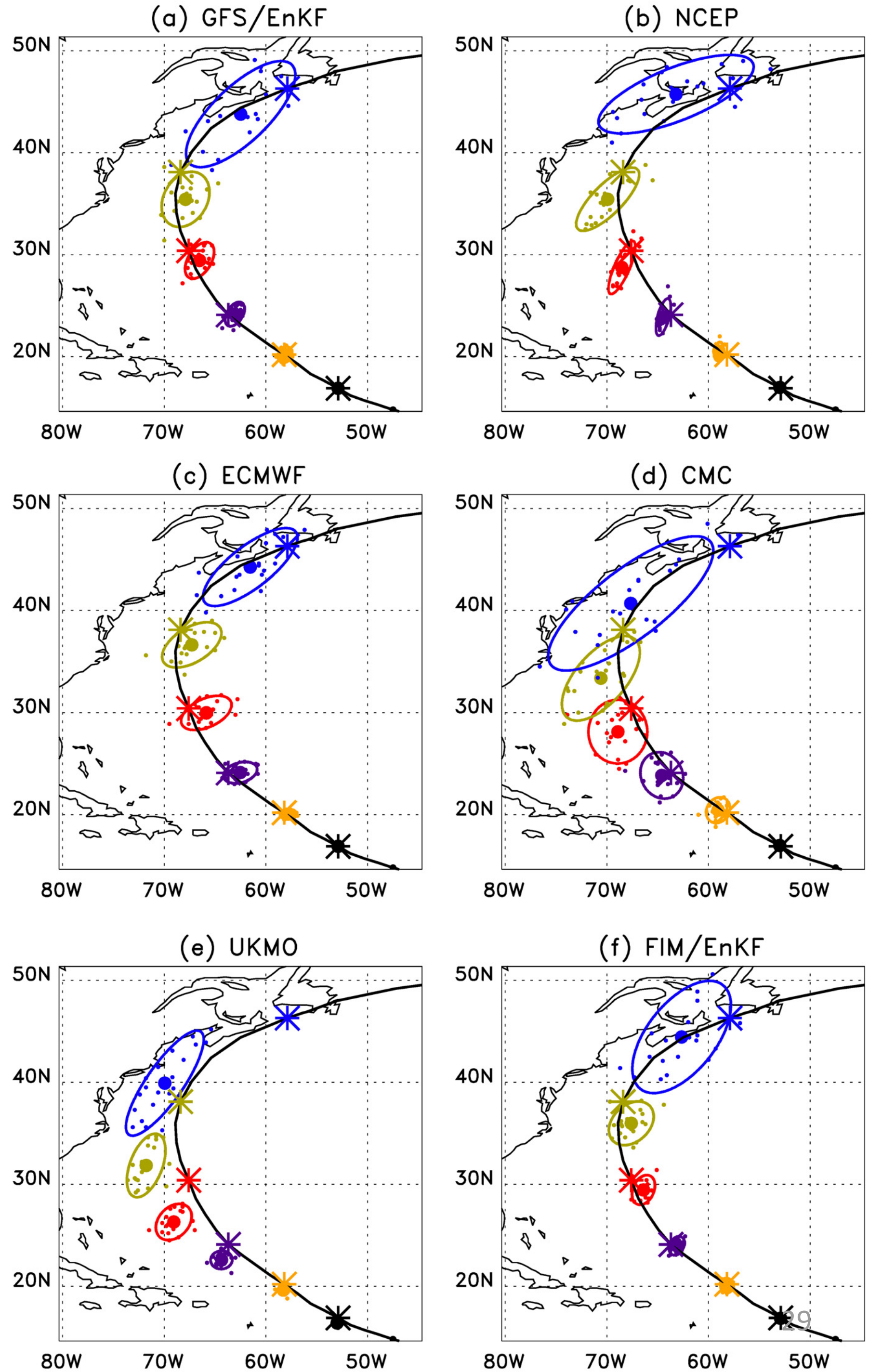


Now some improvement, ~ 6 - 9 hours lead.

Multi-model forecast? Hurricane Bill

Initialized 00 UTC 19 August 2009.

What if we combine the forecasts in some fashion, using their error statistics?



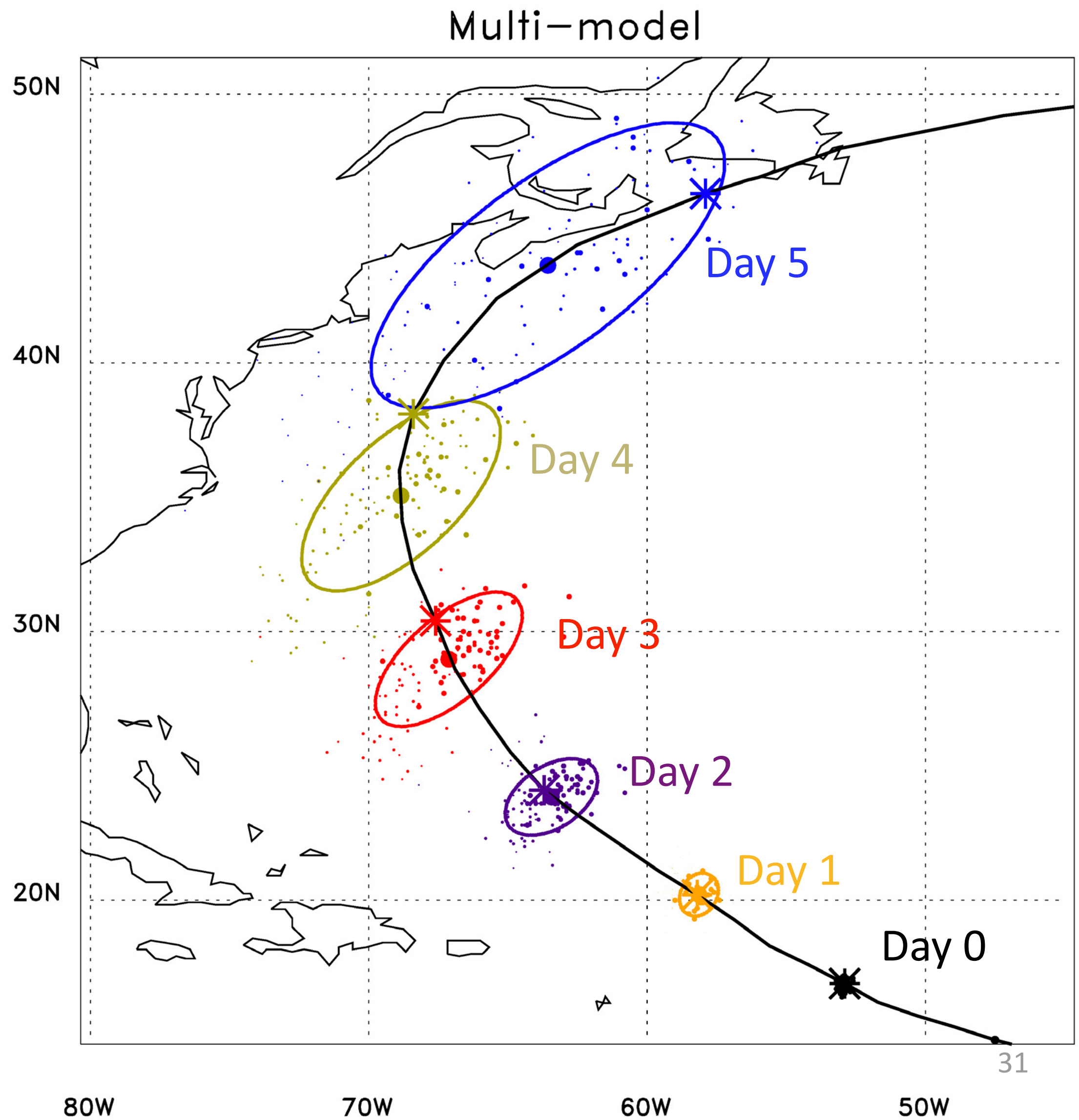
Proposed multi-model technique

- Estimate average absolute error $\sigma_{m,t}$ of the ensemble-mean forecast for a given lead time *t* and forecast model *m*, quasi-cross validated (e.g., when estimating error for Bill, don't use Bill data, but ok to use every other storm).
- Set weights for every available member forecast to be $1/\sigma^2_{m,t}$
- Estimate weighted ensemble mean and weighted ensemble covariance matrix.

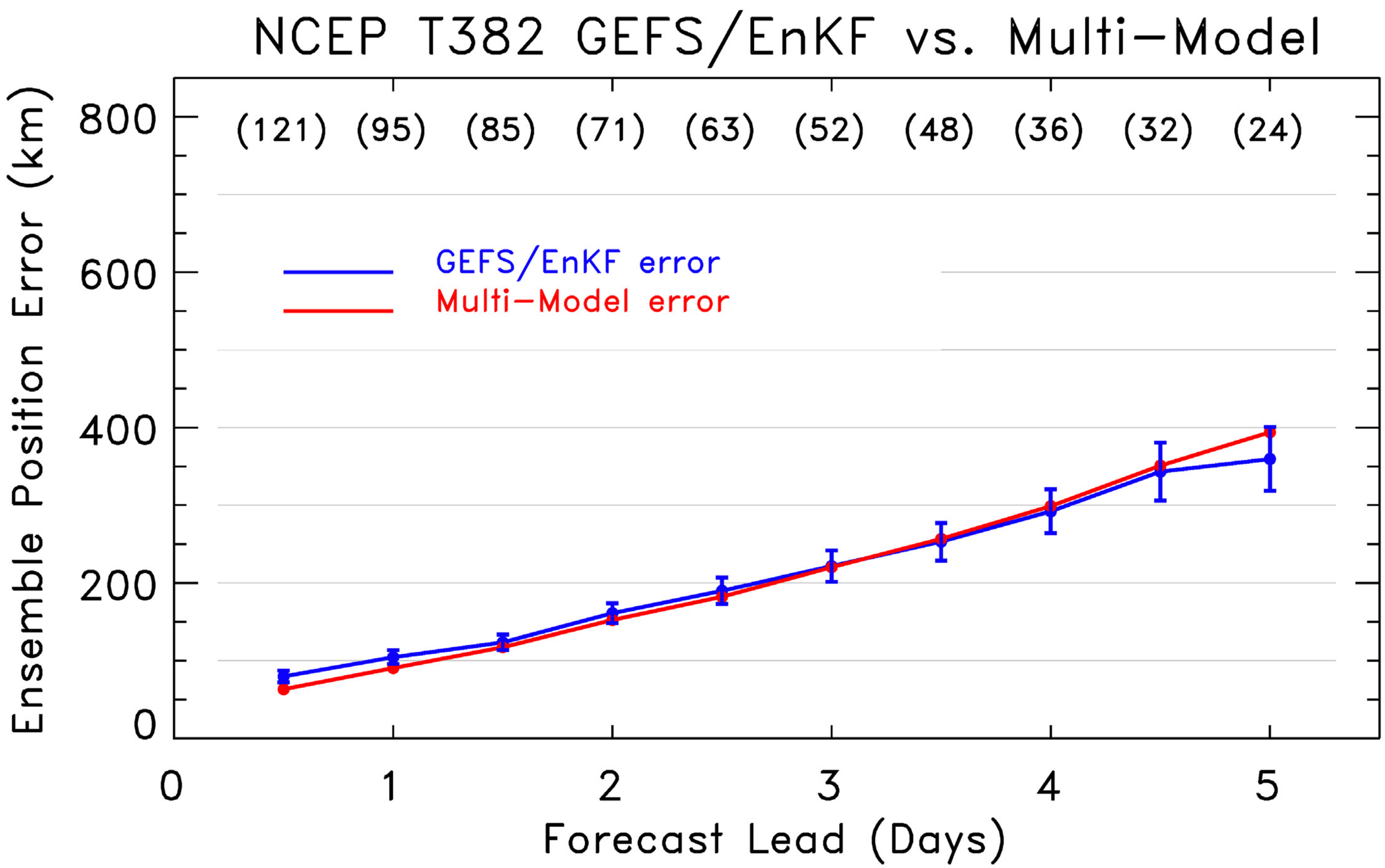
An experimental multi-model product

Dot area is proportional to the weighting applied to that member

• = ens. mean position
* = observed position



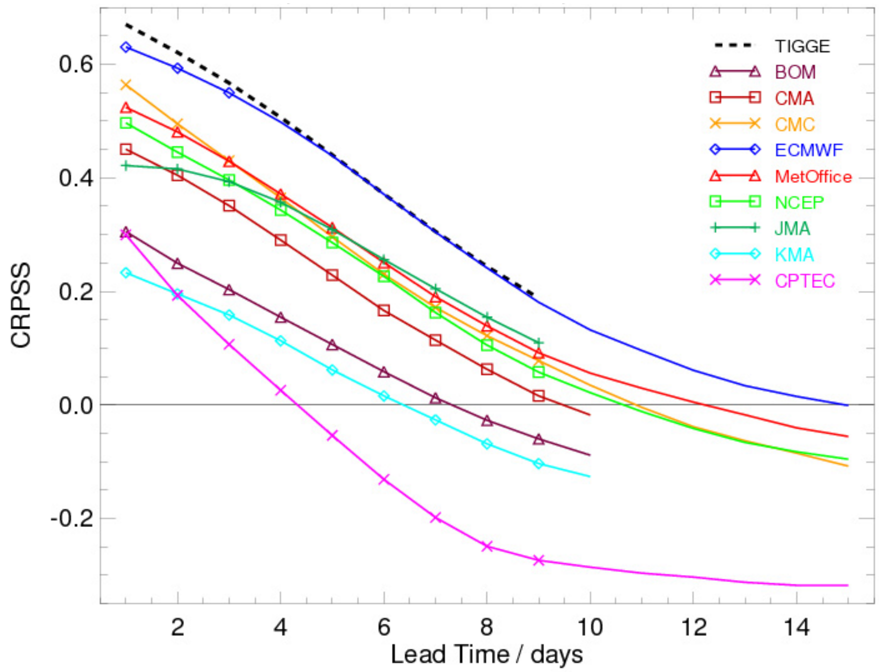
Multi-model error (GEFS/EnKF, ECMWF, FIM, UKMO, CMC, NCEP)



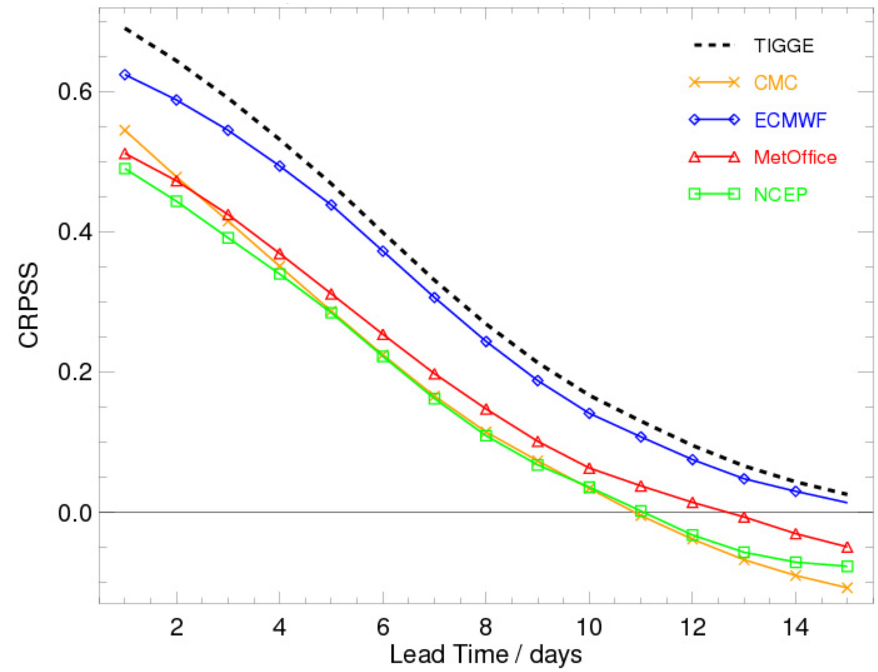
Not much improvement from multi-model. Why?

Multi-model 2-m temperature forecasts

All models (with 30-day bias correction) & multi-model "TIGGE"



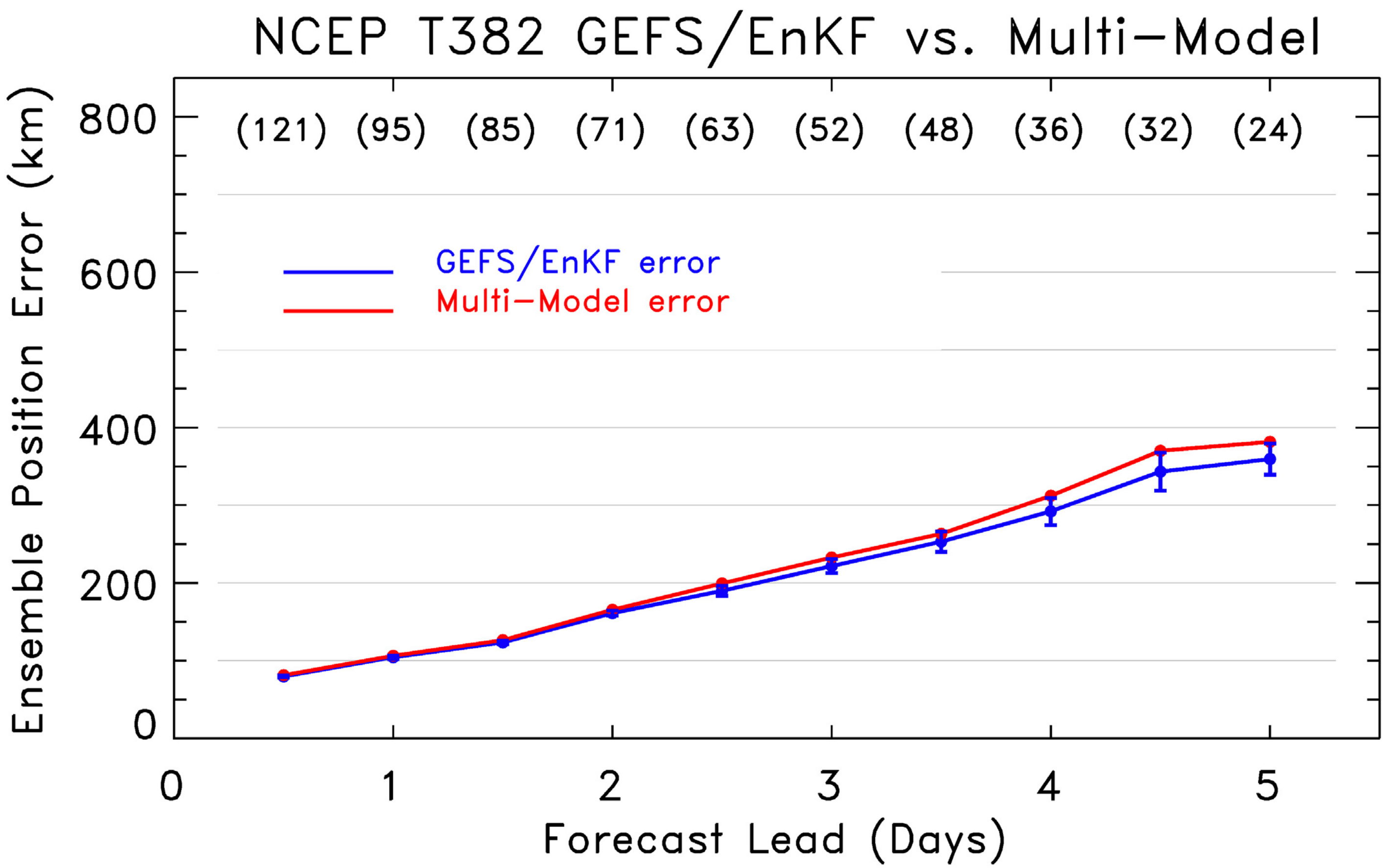
Best 4 models (with 30-day bias correction) & multi-model "TIGGE"



collaborative work led by Renate Hagedorn, ECMWF; conditionally accepted, MWR

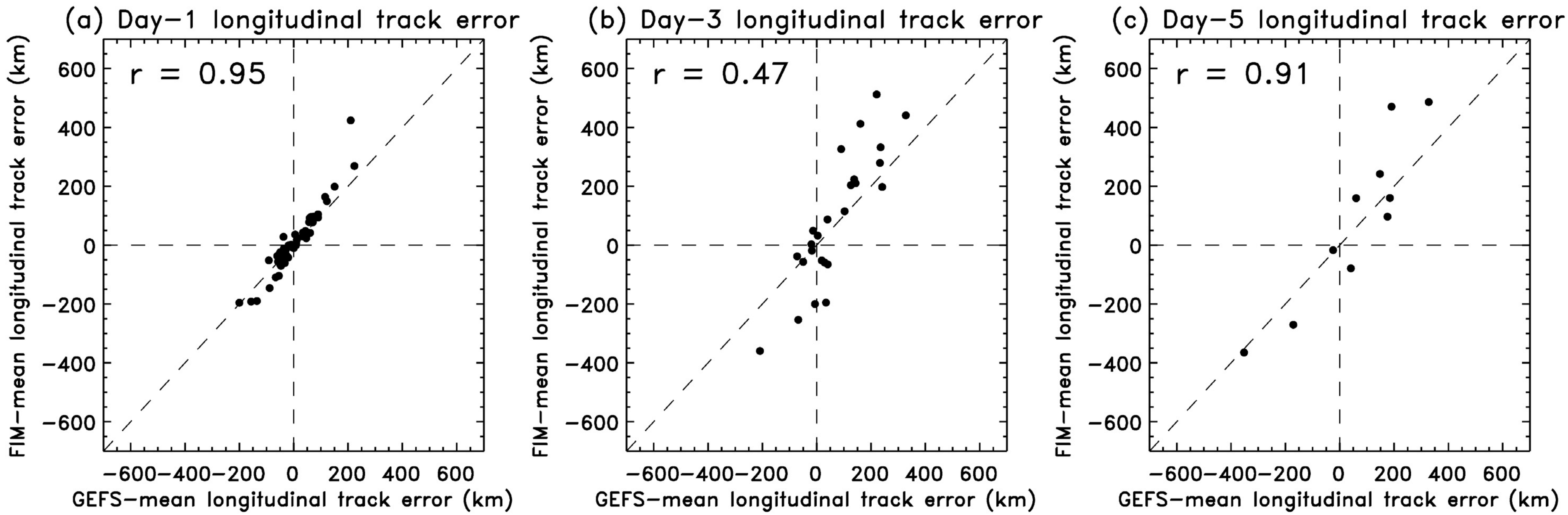
Lesson: discard less skillful models?

Multi-model error (GEFS/EnKF, FIM only)



Degradation relative to GFS/EnKF alone. Why?

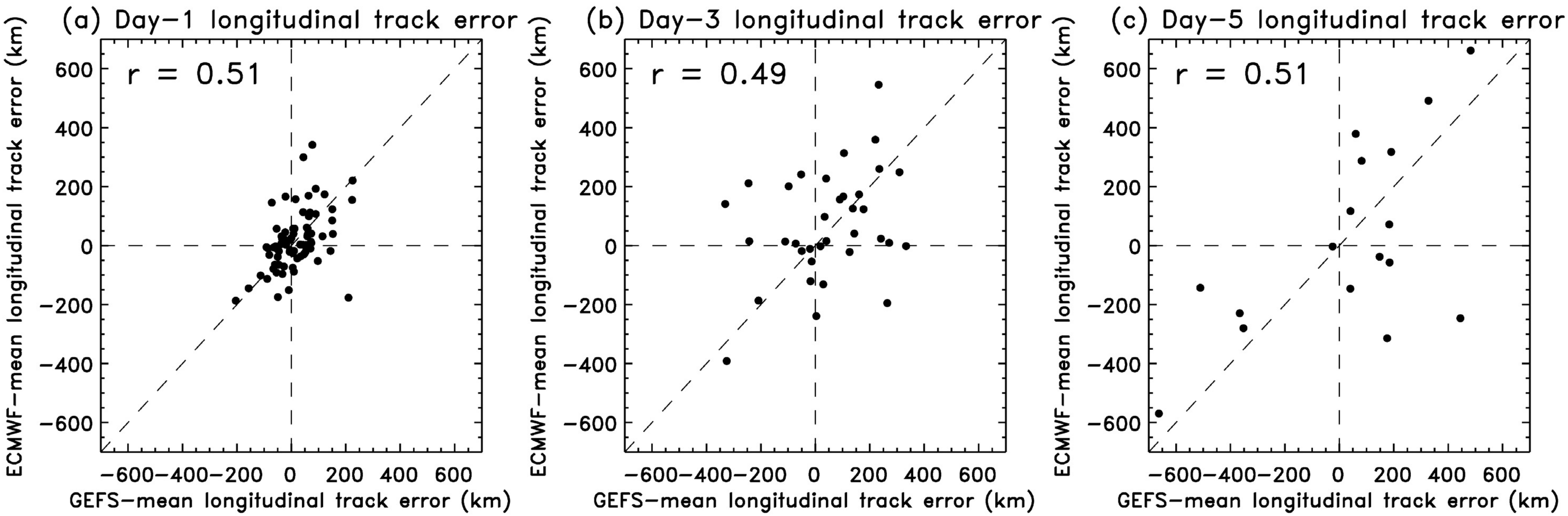
Correlation of errors, GFS/EnKF & FIM



r is the Spearman rank correlation.

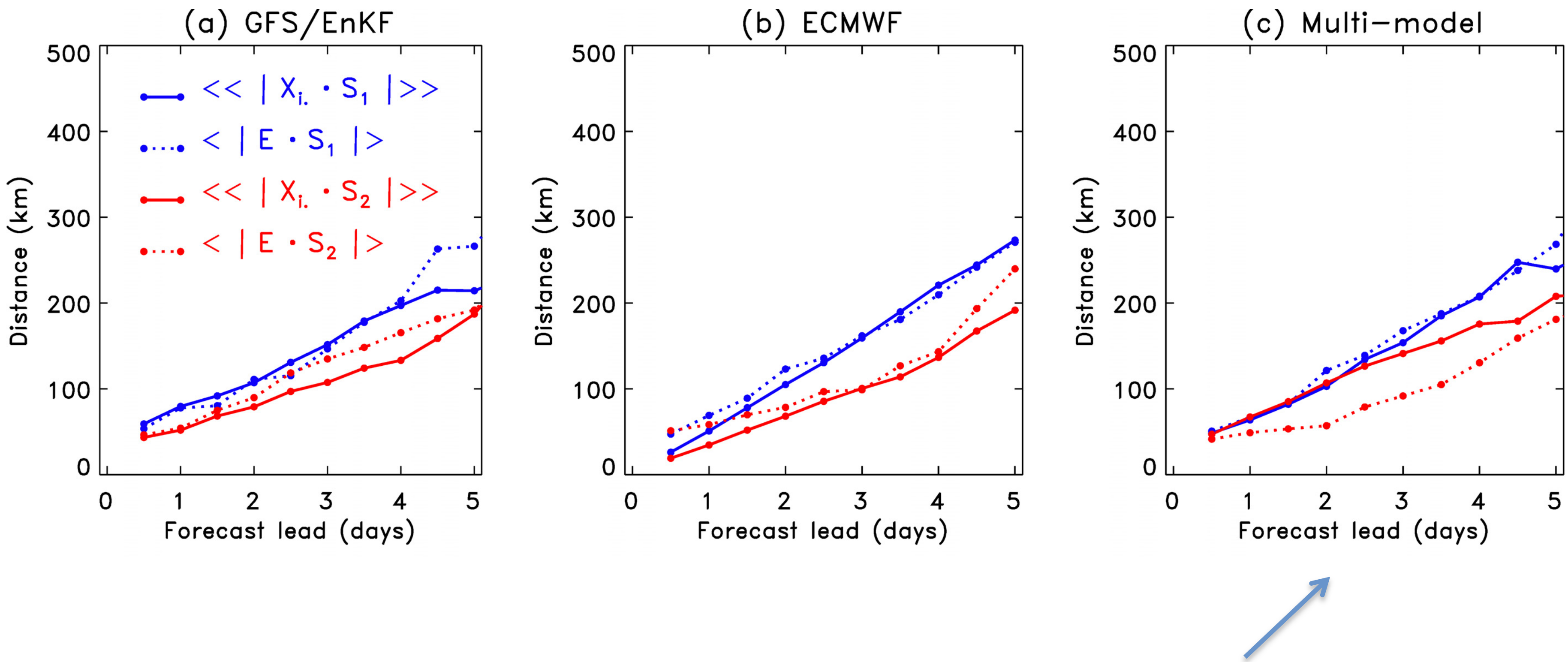
Multi-model forecasts generally predicated on the assumption that models provide independent information. In this case, FIM errors are highly co-linear with GFS/EnKF errors.

Correlation of errors, GFS/EnKF & ECMWF



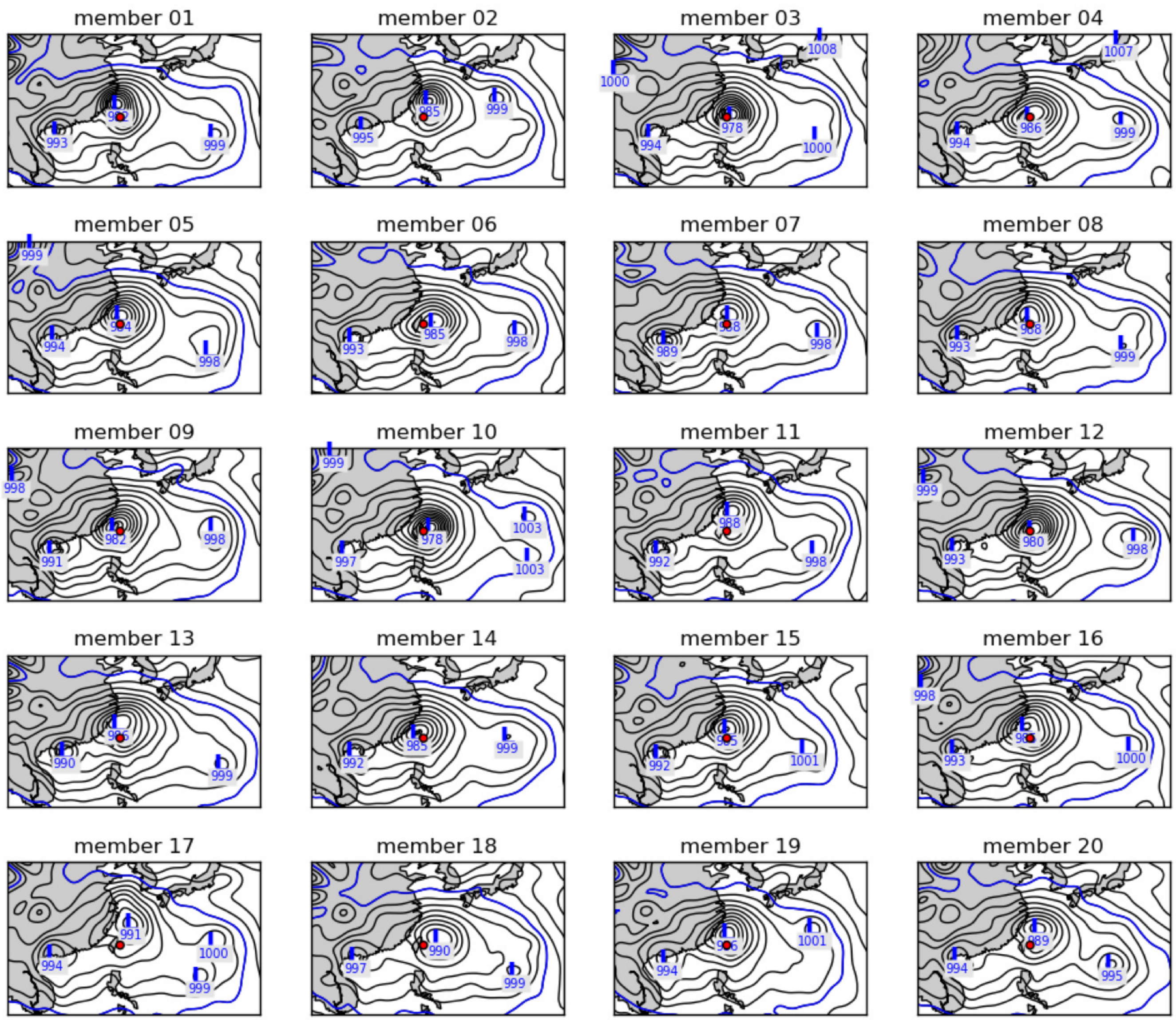
Less co-linearity of forecast errors between GFS/EnKF & ECMWF systems; the greater independence of their forecast errors permits a multi-model improvement.

Multi-model ellipse eccentricity



suggests that multi-model forecast now has a bit too much spread in directions of trailing eigenvectors. Also, the projection of error onto the trailing eigenvector has decreased.

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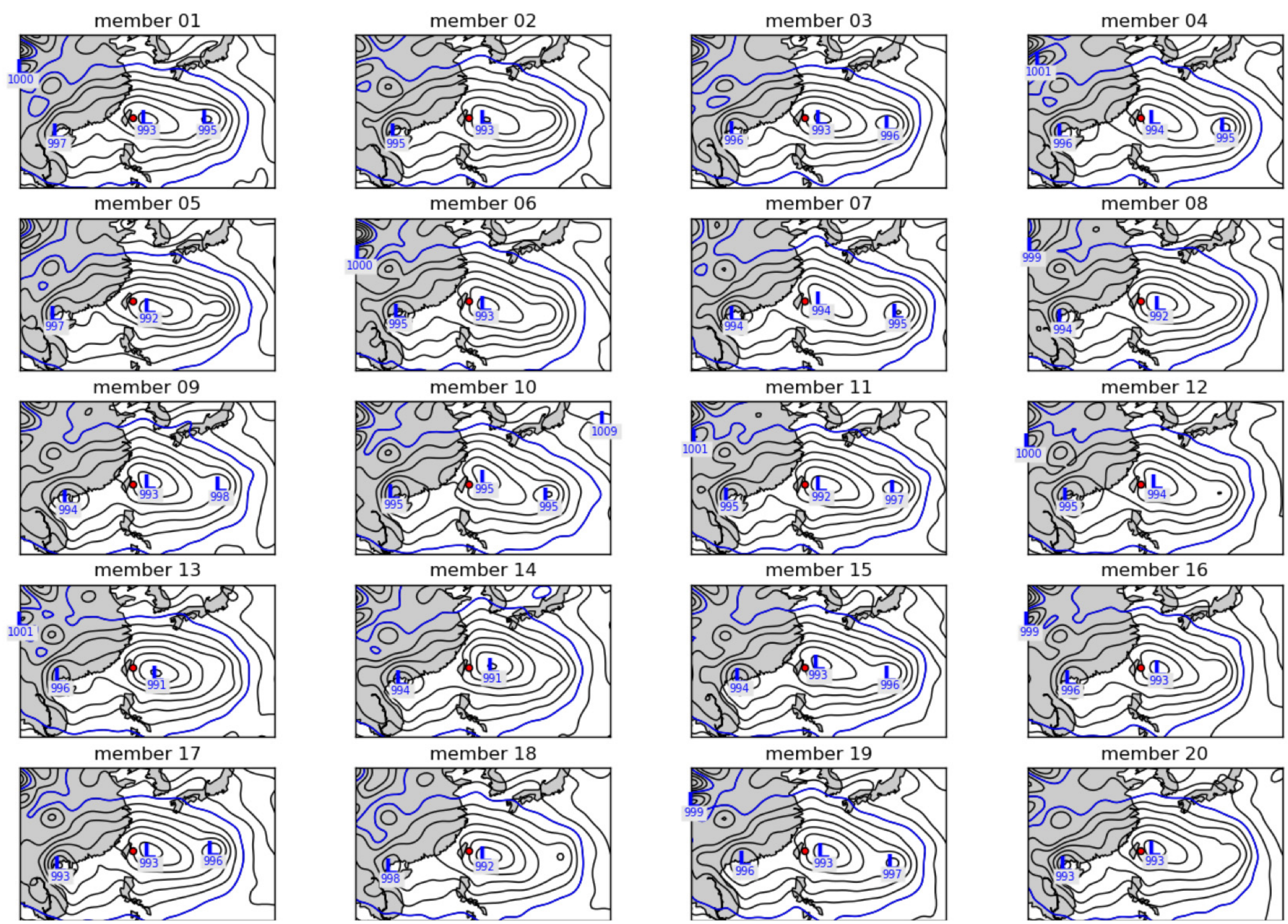
54-h ensembles from experimental T382 GFS & GSI / operational ET perturbations

GSI/ET ensemble 54-hr fcst from 2009080500



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.

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Canonical EnKF update equations (for time *t*)

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

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

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

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

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

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

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

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

(**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

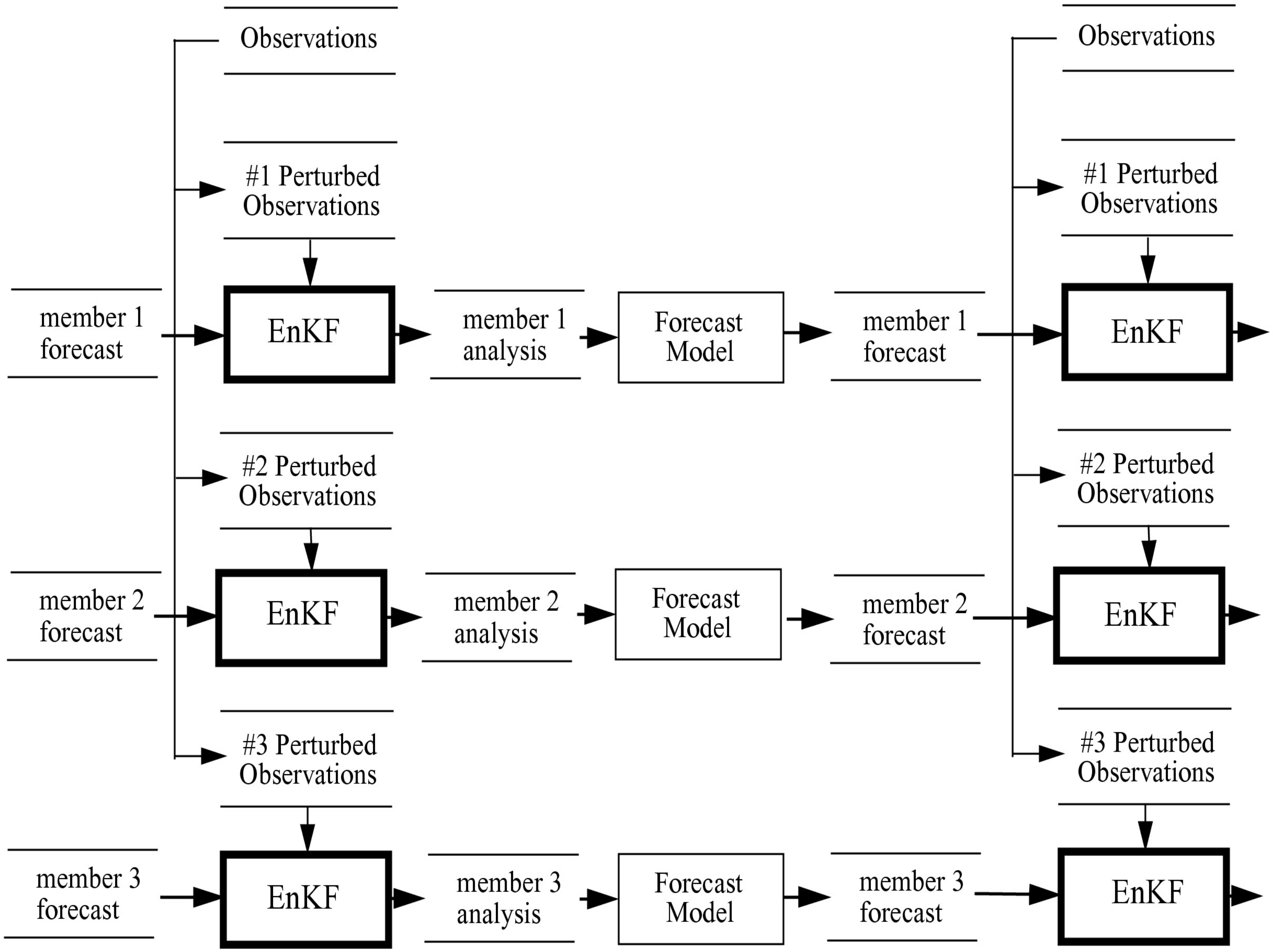
- or -

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

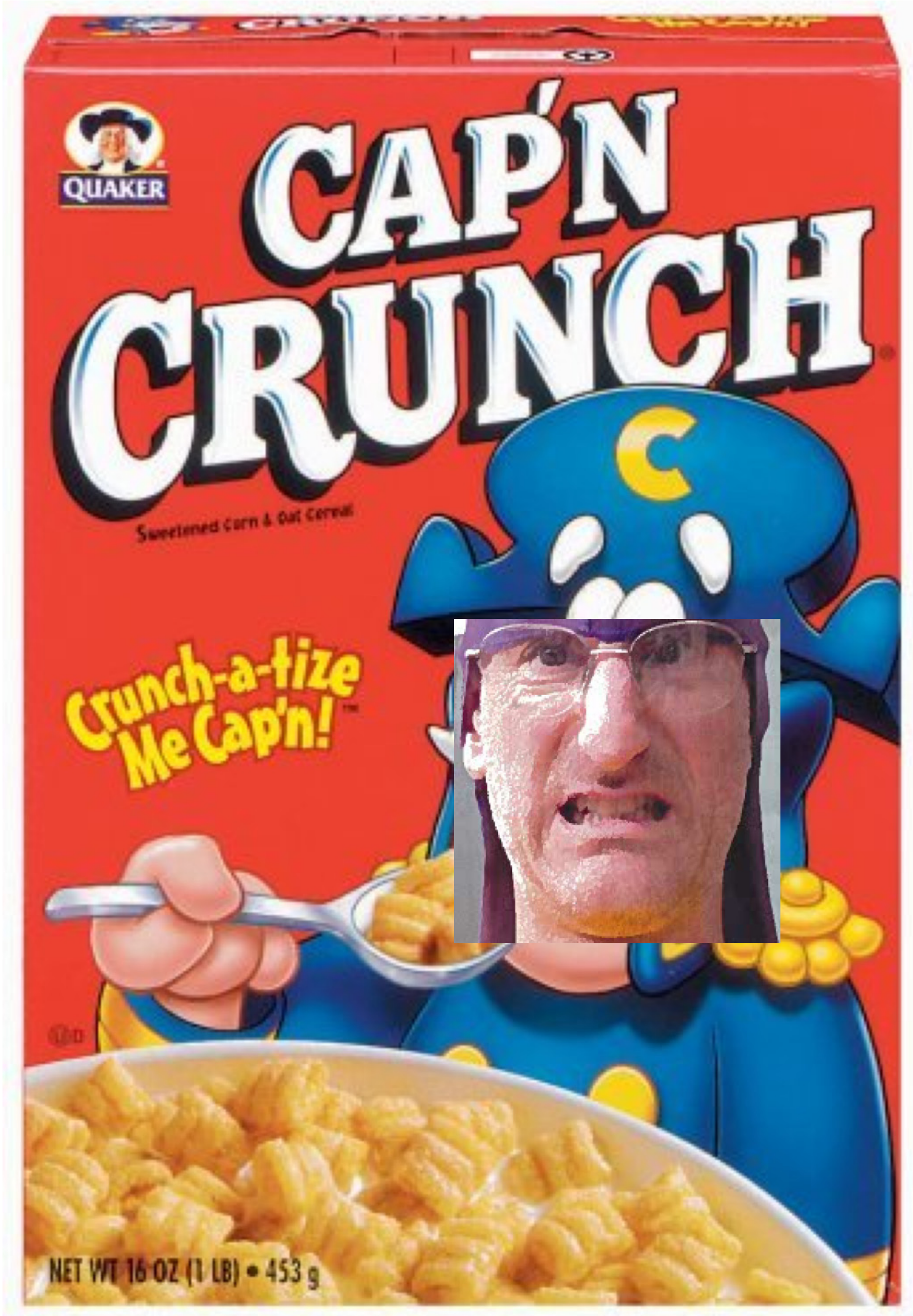
$$\langle \eta_i \eta_i^T \rangle = \mathbf{Q}$$

…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)



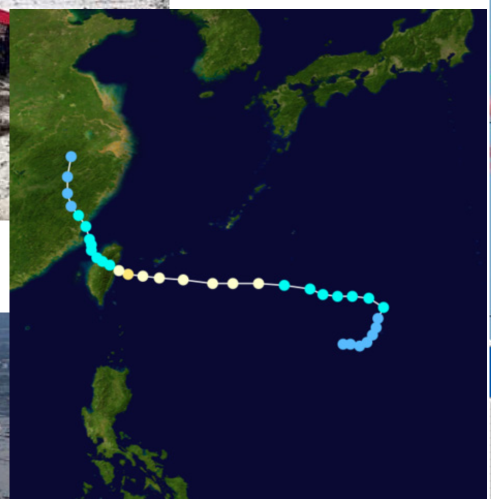
All due credit
to Jeff Whitaker,
chief number
cruncher,
EnKF innovator

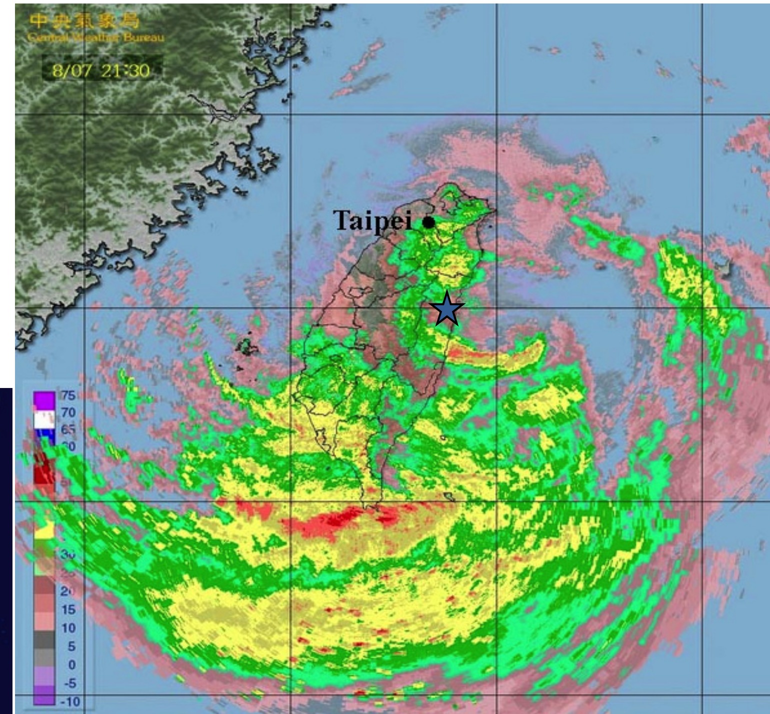
Example: RMS error and AC, Z500

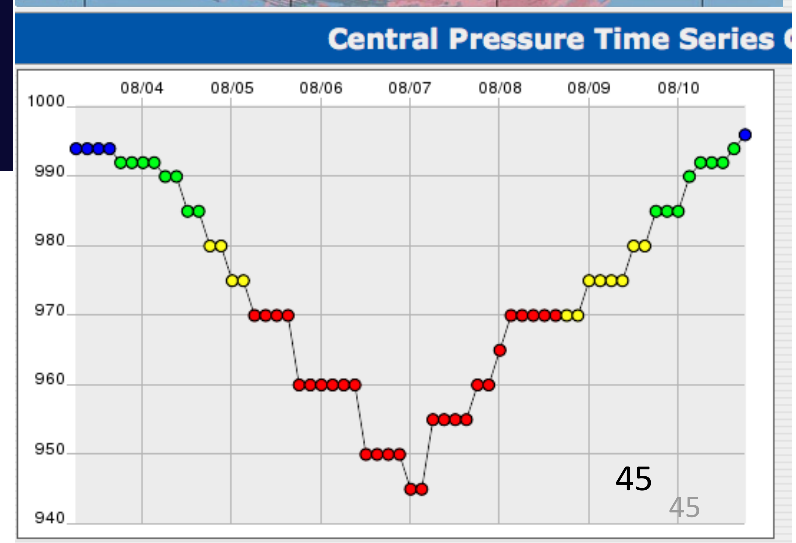
	ECMWF T399	GFS/GSI-ET T126	GFS/EnKF T382
RMSE 500-mb height, N. Hem.	32.35	39.98	36.22
RMSE 500-mb height, N. Hem.	51.14	63.12	56.72
AC 500-mb height, N. Hem.	0.888	0.832	0.854
AC 500-mb height, N. Hem.	0.891	0.829	0.856

Table 1: Errors and anomaly correlations of forecasts from the 2009 operational ECMWF T399 ensemble-mean forecasts, the operational GFS-based ensemble at NCEP (GSI initial condition, T126 forecast model), and the experimental T382 GFS ensemble initialized with the EnKF. All errors are measured with respect to the own products's analysis, and all verifications are performed on a 2.5-degree lat-lon grid. RMSE indicated the root-mean square error, AC the anomaly correlation.

Typhoon Morakot (Taiwan floods)







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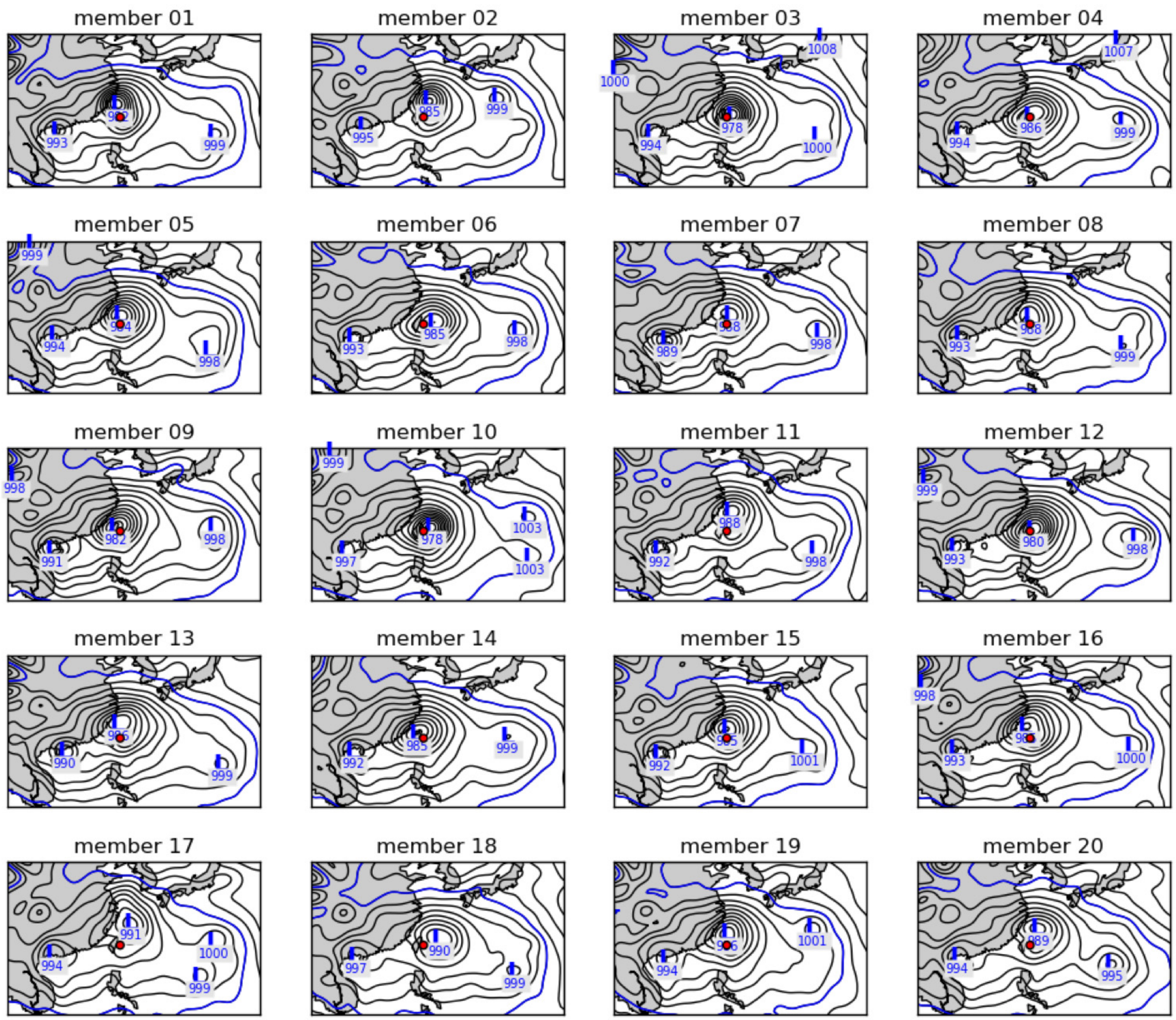
Data availability

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
					Jul 31: F	Aug 1: F
2: F,E	3: F	4: F	5: F	6: F,U	7: F	8: F
9: F	10: F,G	11: F	12: F	13	14	15
16	17	18	19	20	21	22
23: U	24: F	25	26: G	27: F	28: F	29: F
30	31	Sep 1: G	2	3	4: F	5
6	7: F	8	9	10	11	12
13	14	15: C	16	17	18	19
20	21	22	23: F,E	24: F	25	26: E
27: E,U	28: U					

Table 1: Availability of 0000 UTC global ensemble forecast data between 31 July 2009 and 28 September 2009. For a particular date, "F" indicates that FIM ensemble data was unavailable for this initial time; E indicates that ECMWF ensemble was unavailable; U indicates UKMO; C indicates CMC; N indicates NCEP, and G indicates experimental GEFS/EnKF.

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

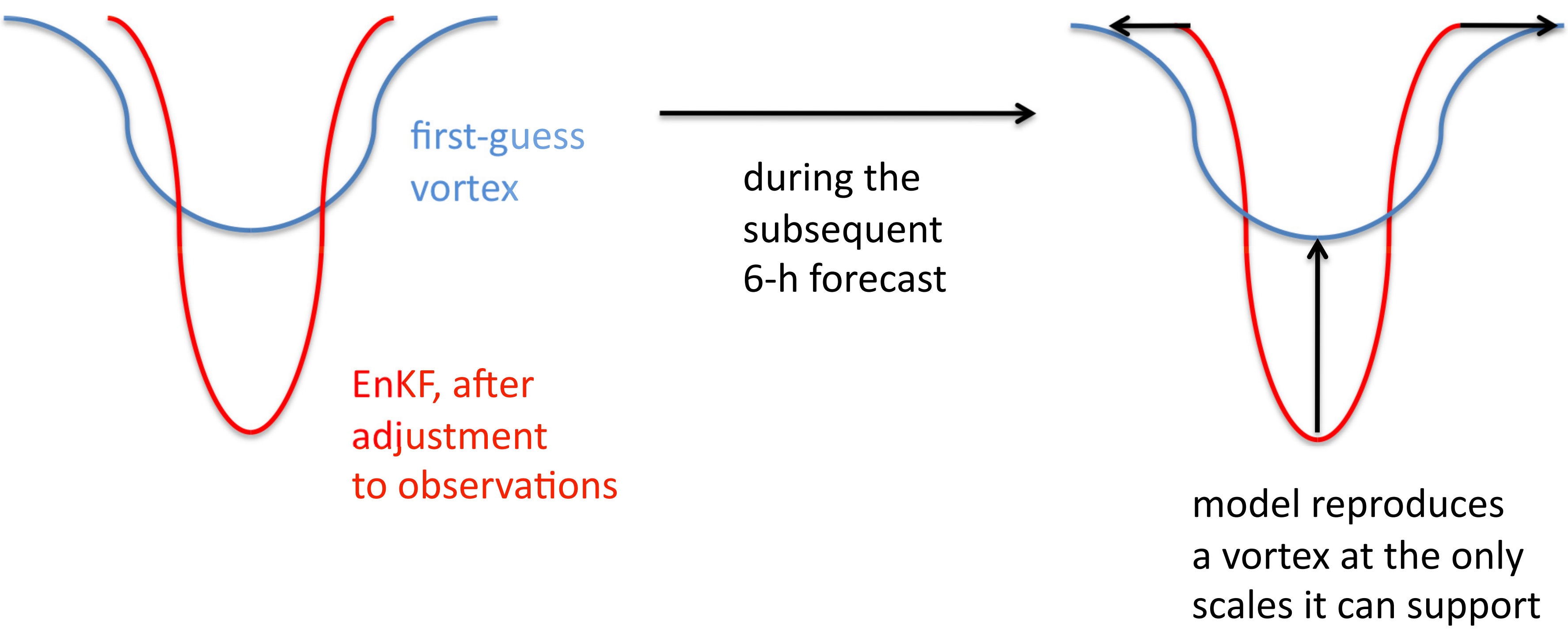


Intense vortices in forecasts, with ensembles of forecast positions relatively close to the observed position (red dot).

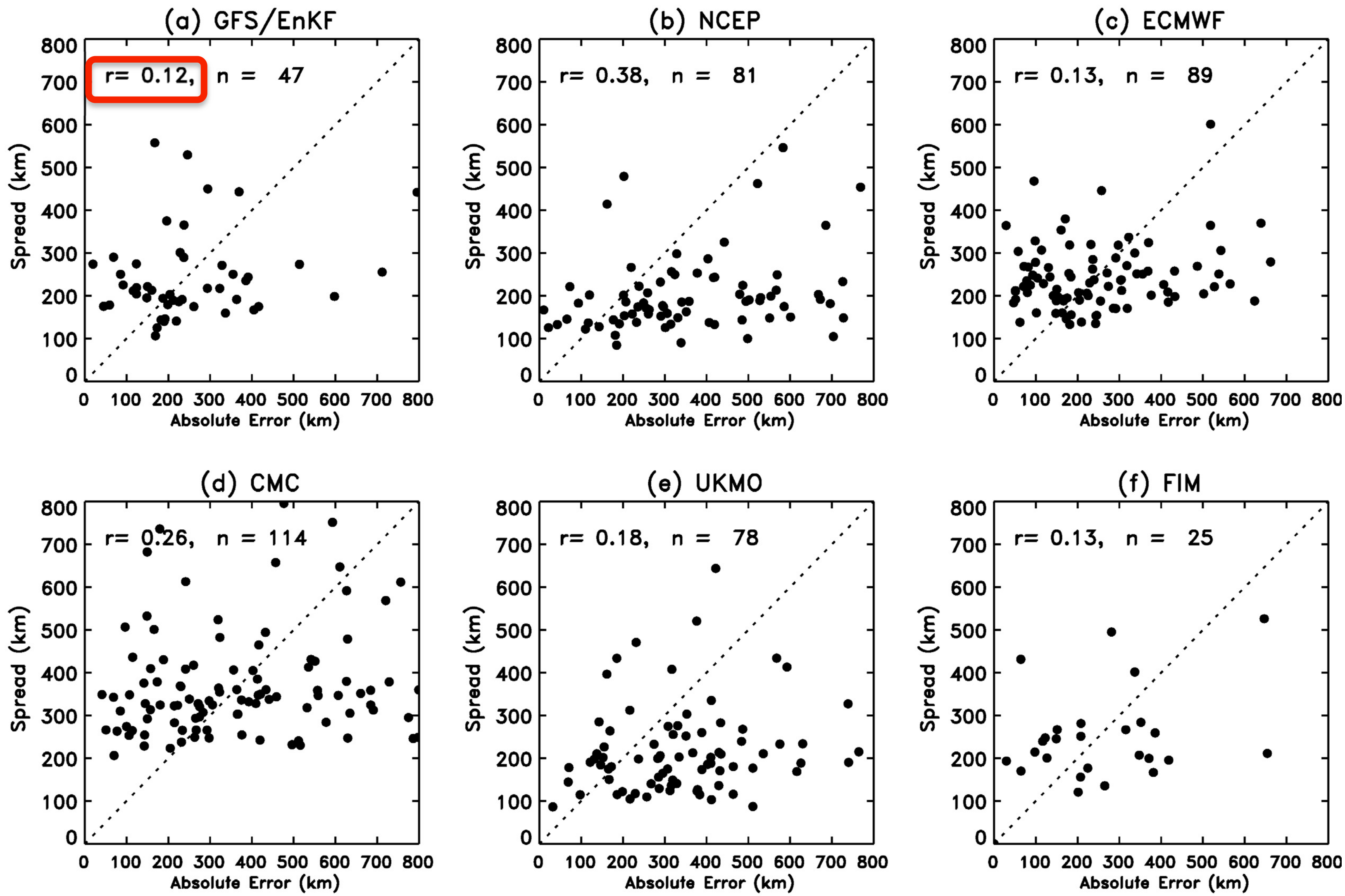
47

Why the persistent under-forecast of the strength of vortices?

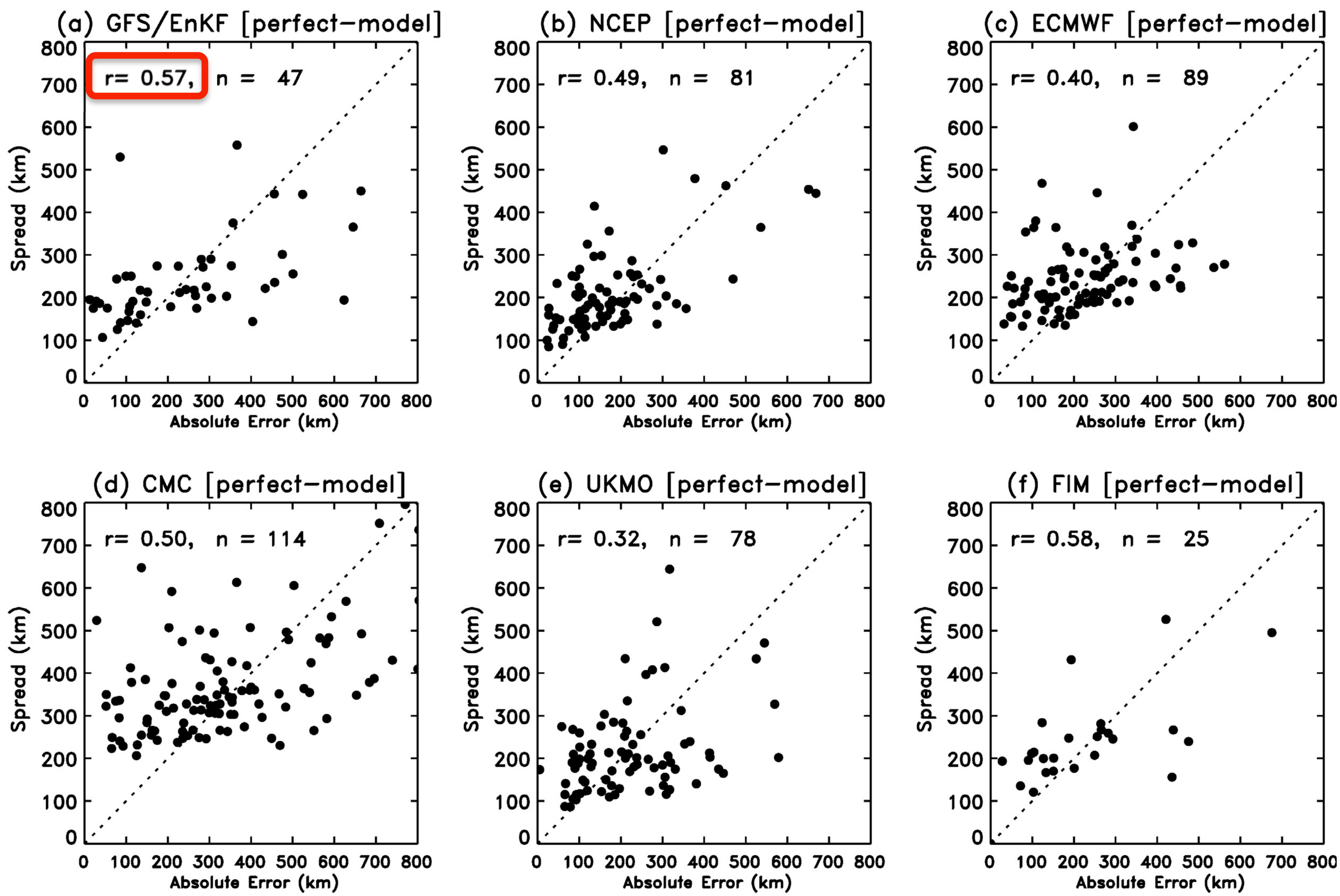
AT COARSE RESOLUTION THE MODEL SIMPLY CANNOT SUPPORT INTENSE VORTICES, EVEN IF PROPERLY ANALYZED



Spread-error relations? (Day-3)



Spread-error relations, perfect-model assumption



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

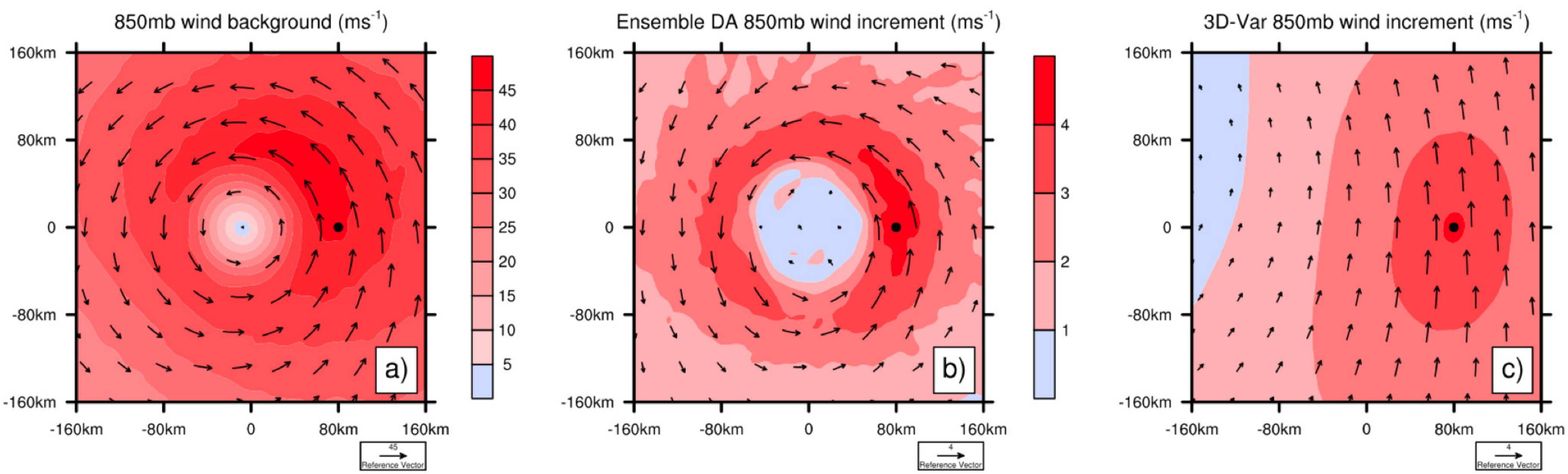


figure c/o Xuguang Wang, University of Oklahoma