Improved tropical cyclone initialization for NCEP operations through direct assimilation of storm information

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Background & Motivation

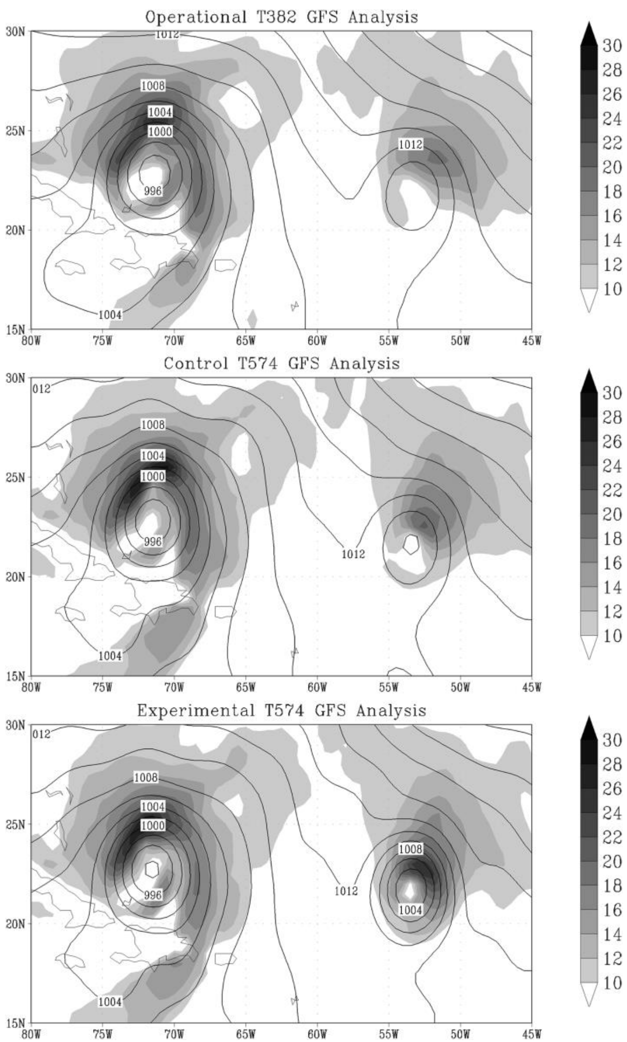
- Continued improvement in TC Track and Intensity guidance important due to high societal impact
- Resolution and complexity of numerical models continues to increase, making vortex initialization ever more important
- Process for initializing TCs in operational NWP suite is complicated and differs by modeling system
  - ***I have been asked about the GFS process many times***

TC Initialization at NCEP

- Almost always contains components outside of DA (before or after):
- GDAS/GFS
  1. First tracker is run on GDAS forecast
     a. If storm found in forecast/background, mechanical relocation of vortex (this code is pretty expensive and quite complicated)
     b. If not found, bogus observations are generated (winds are assimilated)
  2. Advisory minimum sea-level pressure observations are assimilated with other observations (next slide)
- HWRF*
  1. Environment fields from GFS, but HWRF vortex is cycled
  2. Complicated combination of relocation, bogusing, correction (size/intensity/balance), and inner core DA (when possible)

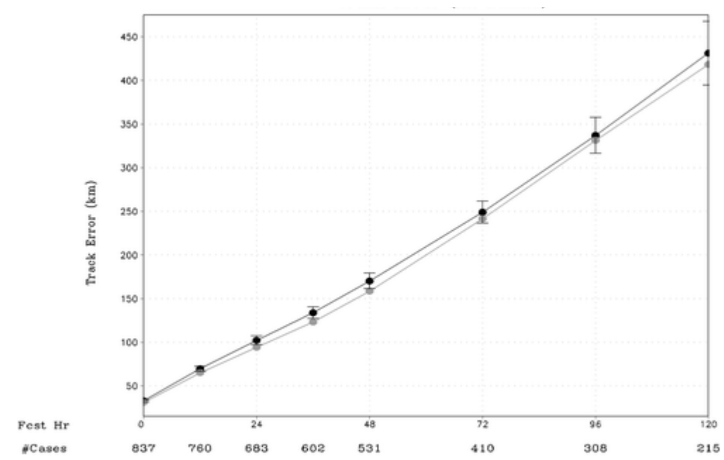
*See pages 18-44 of DTC HWRF Documentation
http://www.dtcenter.org/HurrWRF/users/docs/scientific_documents/HWRFv3.6a_ScientificDoc.pdf

Kleist 2011: Advisory SLP in GDAS/GFS

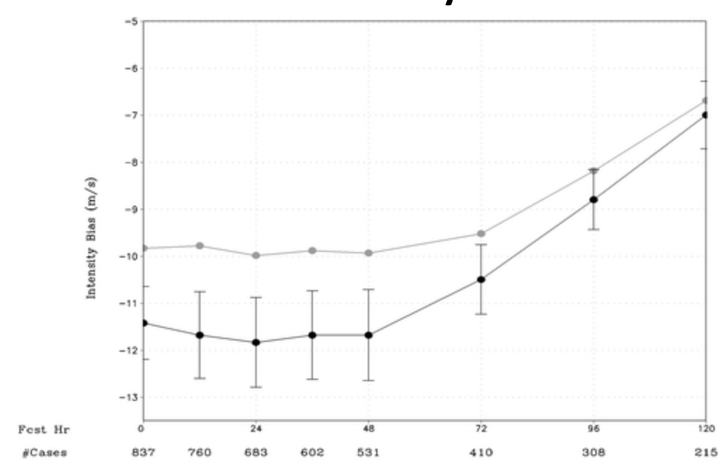


00 UTC 4 September 2008

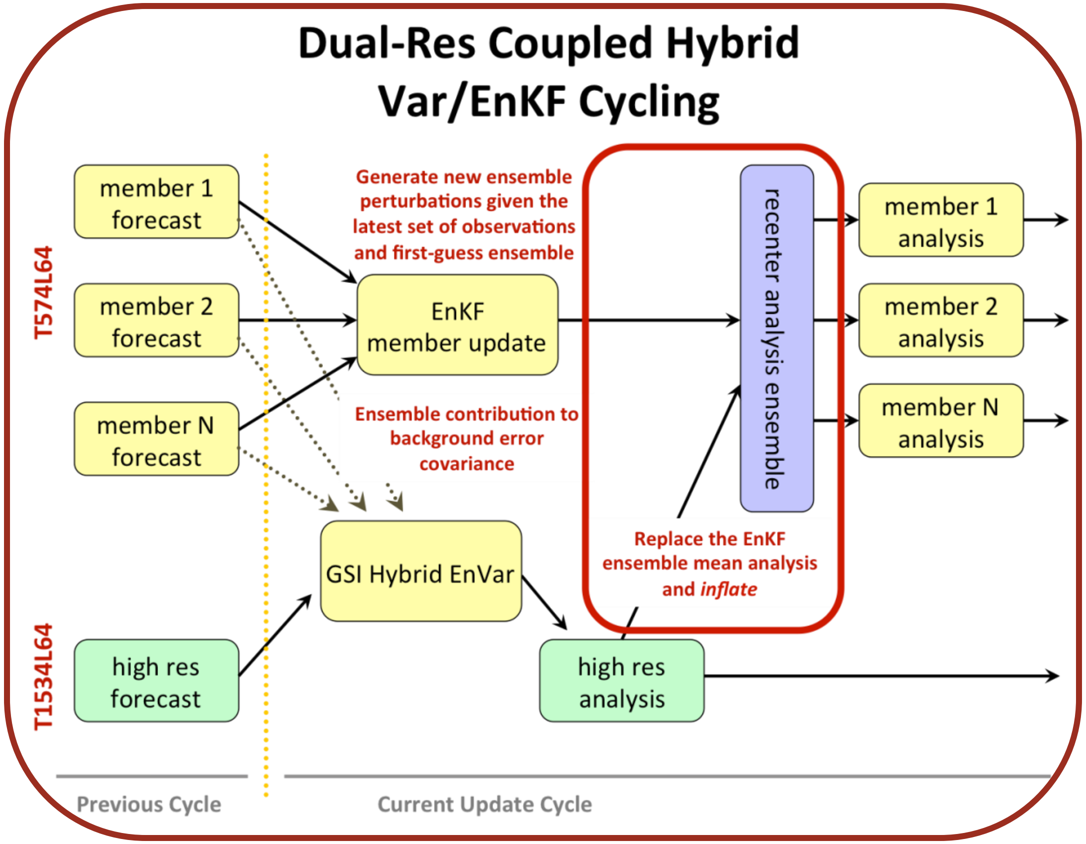
Track Error



Intensity Bias

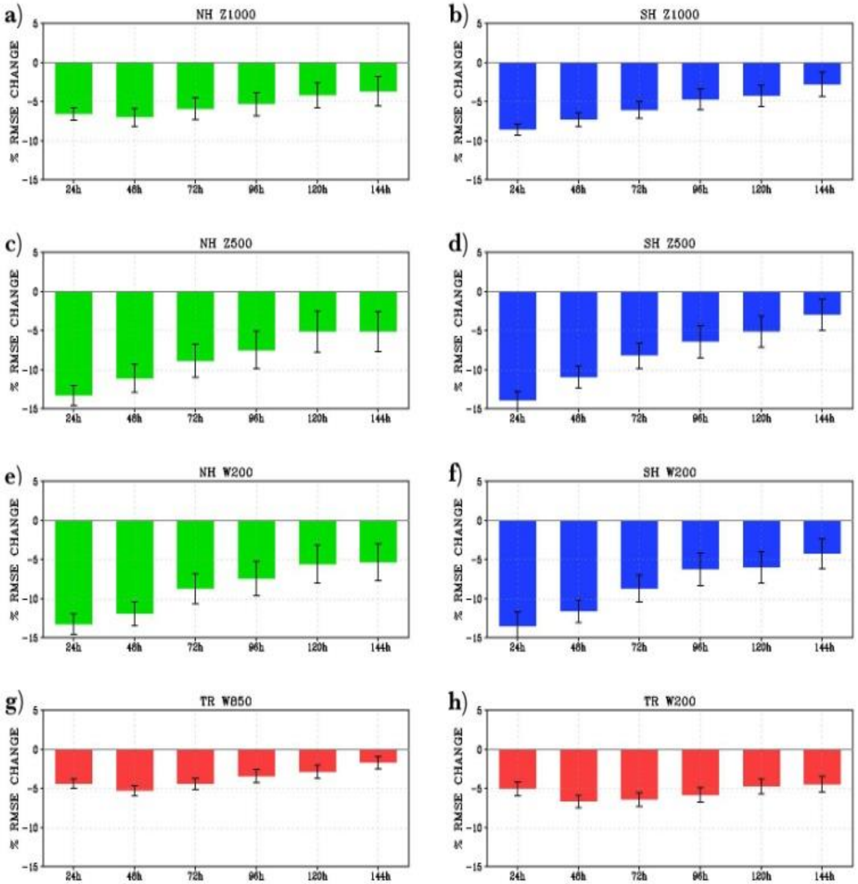


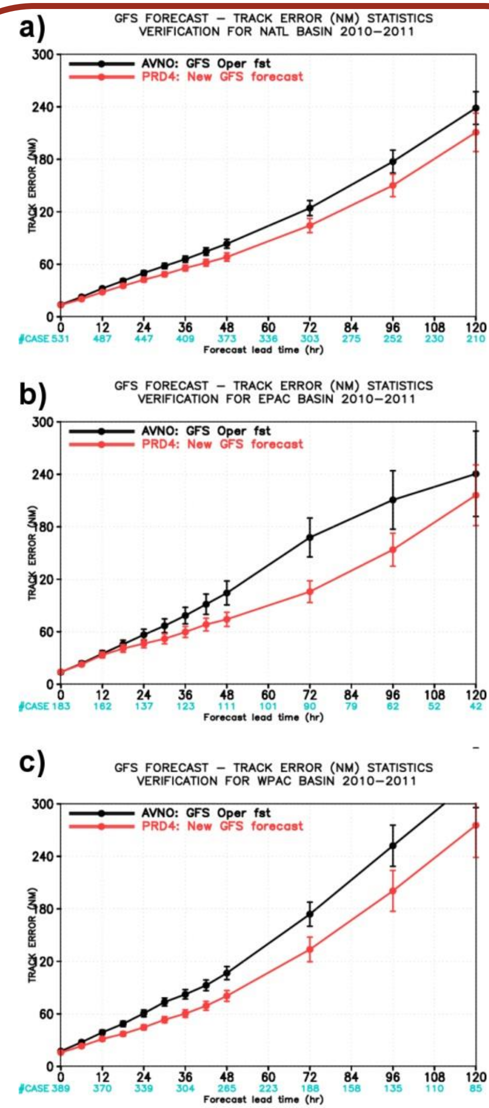
Hybrid Assimilation for GDAS/GFS Implemented May 2012



- No relocation done to ensemble members
- As part of initial development, role of relocation for deterministic component explored

Hybrid EnVar Assimilation for GDAS/GFS (Impact from Trial Runs)





But….
Motivation : Pre-Operational Trials
Small Sample from 2010

Mostly September Cases (AL 07-16, EP 10-12, WP 10-14):
average track errors (NM) FOR HOMOGENEOUS SAMPLE

	00	12	24	36	48	72	96	120
3DVAR(REL)	**18.4**	**33.1**	**50.2**	**70.1**	**83.5**	**124.0**	**171.6**	**195.1**
3DHYB(REL)	**17.5**	**33.0**	**46.9**	**60.3**	**72.4**	**113.7**	**175.1**	**186.5**
3DHYB(NO)	**22.9**	**32.7**	**43.6**	**59.7**	**68.6**	**108.6**	**159.0**	**177.7**
#CASES	73	67	58	49	42	30	24	17

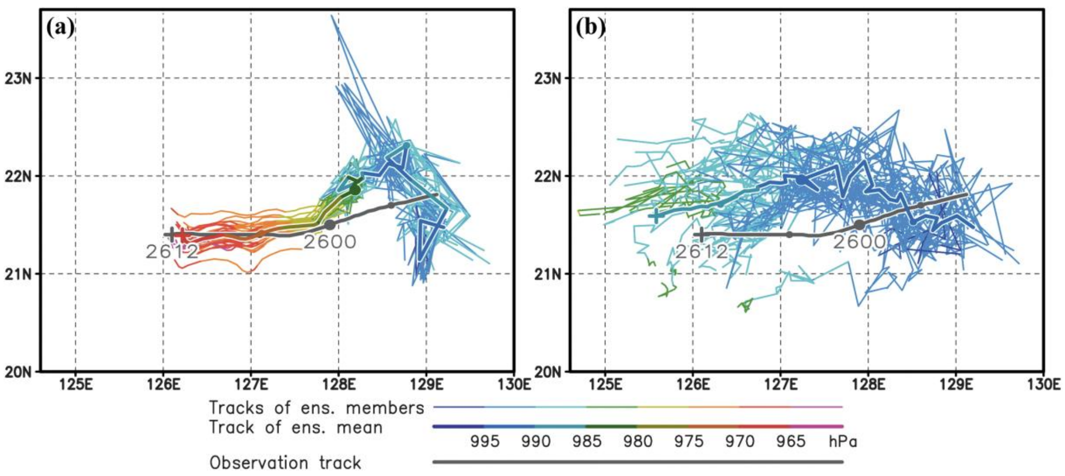
Experiments were initially run ***without* vortex relocation** (eventually turned back on and still operational).

Signs that mechanical vortex relocation in GFS hurts forecast despite seemingly better initial positions (compare red versus green beyond 12h).

New Paradigm: Direct Assimilation of Storm Information

- With experience of advisory min SLP assimilation, work to expand to assimilate more information
- Currently use complicated mix of relocation & bogusing, sometimes done completely outside of the assimilation
  - Bogus observations can have correlated errors and misrepresent storm structure (i.e. asymmetries)

- Experience within ensemble DA community in assimilation of storm position, intensity (Chen and Snyder 2007) and other information (Wu et al. 2010; Kunii 2015)



From Wu et al. (2010)

Finding Storm Center

- Current tracker (part of relocation step and verification) performs an iterative search of various fields (surface pressure, geopotential height, vorticity, etc.)
  - This kind of operator can be used in an EnKF

- However, variational schemes require that the observation operator (map of model to observation space) be quadratic/differentiable
  - Need TL/AD of operator

Finding Storm Center: Parametric Profiles (Kepert)

- TCs can be described parametrically:

$$p_H = p_e - \Delta p\left[1 - exp\left\{-\left(\frac{r_m}{r}\right)^b\right\}\right]$$

p_H: parametric pressure (Holland 1980)

p_e: environmental pressure

Δp: drop in pressure to center of storm

r_m: radius of maximum winds

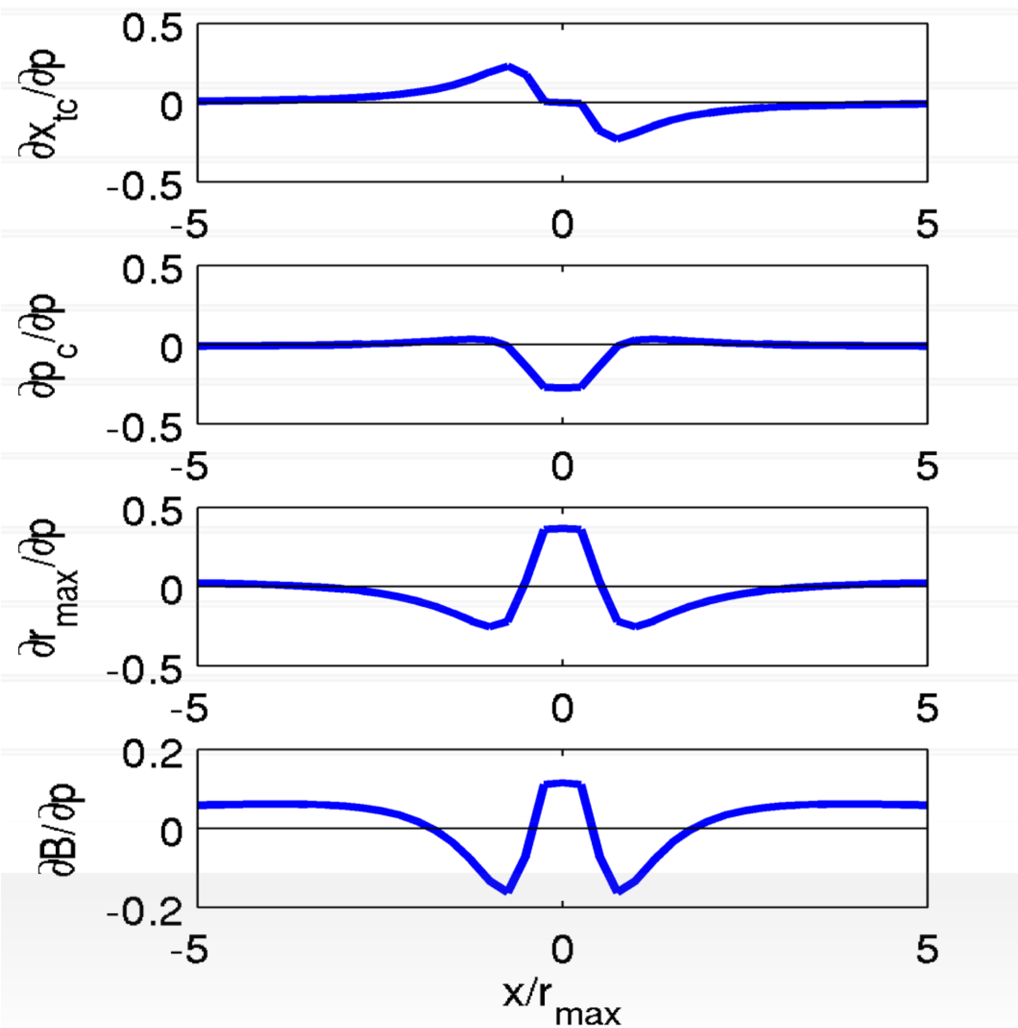
r: radius

b: extent of outer circulation (1 < b < 2.5)

- Kepert (2005): Can then find center through optimization (least squares fit). Originally designed for observations. The control vector is a function of storm position, motion, delta pressure, radius of maximum winds, and circulation extent).

$$J(\mathbf{a}) = \sum_{i=1}^{n} \frac{(p_i - p_H)^2}{\sigma_{pi}^2} \qquad \mathbf{a} = [x_t, y_t, u_t, v_t, \Delta p, r_m, b]$$

Sensitivity (adjoint of center finder)



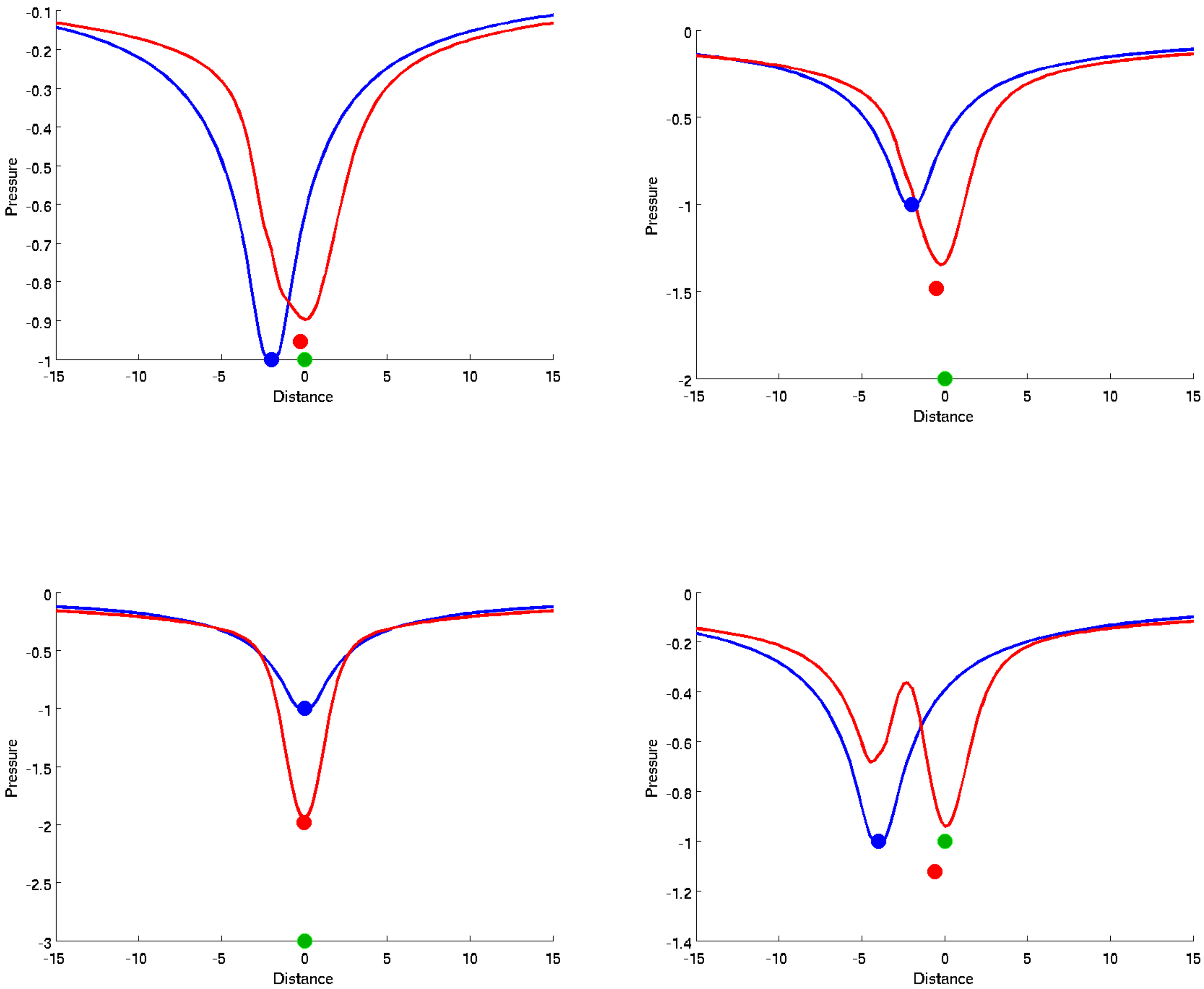
From Kepert (2009): Sensitivity to pressure of position, intensity, radius of maximum winds, and circulation size.

1D Examples (Kepert 2009)

Background

Analysis

Observation



Summary of Kepert Work
Next Steps

- Observations of location, intensity, and scale can be used to alter entire state estimate
  - Analysis can update location and intensity, or both simultaneously
  - Tends to underestimate intensity (tunable)?
  - For large distance relocation, can still have double vortex problem (as in most bogusing schemes)

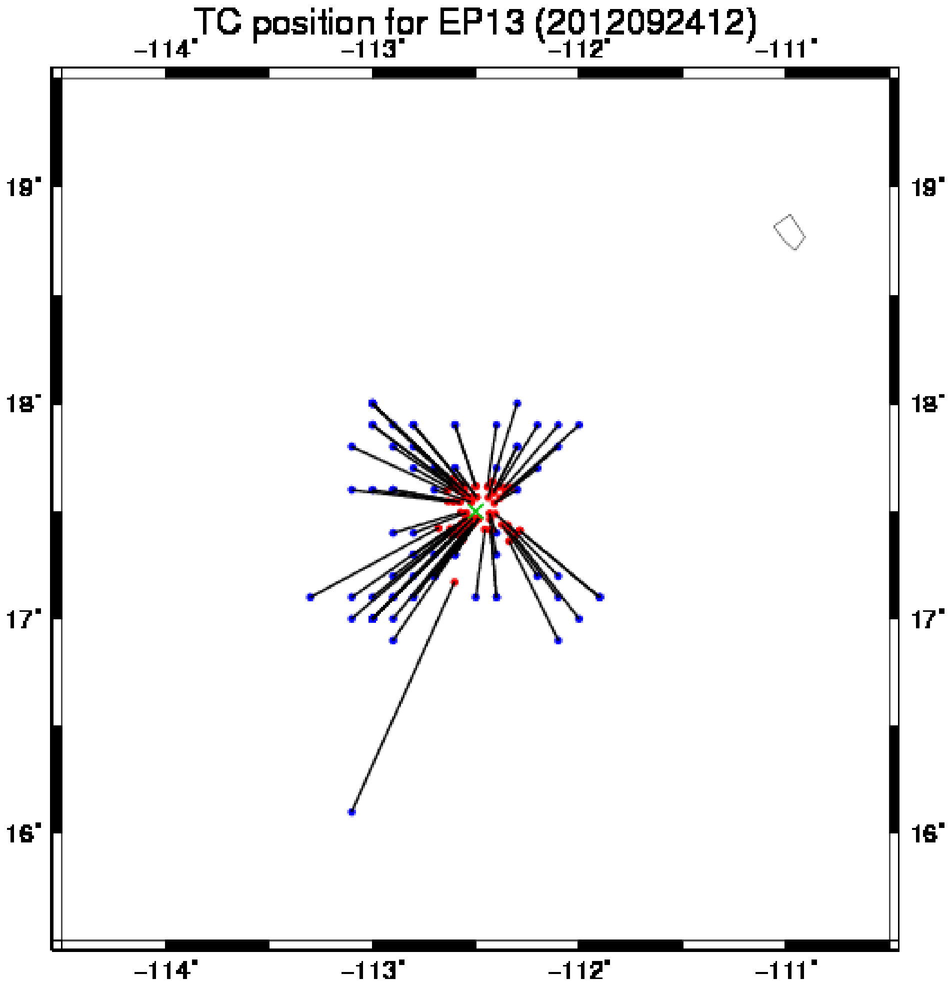
- For this project:
  - Design and implement observation operator for GSI
  - Test assimilation for single observation/storm using GSI hybrid EnVar
  - Test as a replacement for vortex relocation
  - Extend to hurricane modeling application
  - Incorporate higher temporal advisory information within context of 4D EnVar
    - Get 4D increment (tendency) to fix model trajectory through 4D IAU

Continuation of Work by Ota Application of "Relocation" to EnKF

- TCs in EnKF ensemble used as part of EnVar solver can sometimes have issues do to lack of TC relocation
  - MinSLP assimilated in EnKF and EnVar, but relocation only in EnVar
- TC relocation of EnKF first guess ensemble has been proposed by Ota
  - Compromise of methods of position assimilation and mechanical relocation
- Algorithm already developed with preliminary tests completed.
  - Not yet implemented for technical reasons
- As part of R2O project, will resurrect and continue this development path
  - Has significant potential for position assimilation in EnVar through improved TC covariances
  - Implications for use of EnKF ensemble in GEFS as well

TC relocation to the EnKF ensembles (From Ota)

Apply TC relocation used in deterministic analysis to each ensemble member, but allowing TC structure perturbations and some TC position spread.

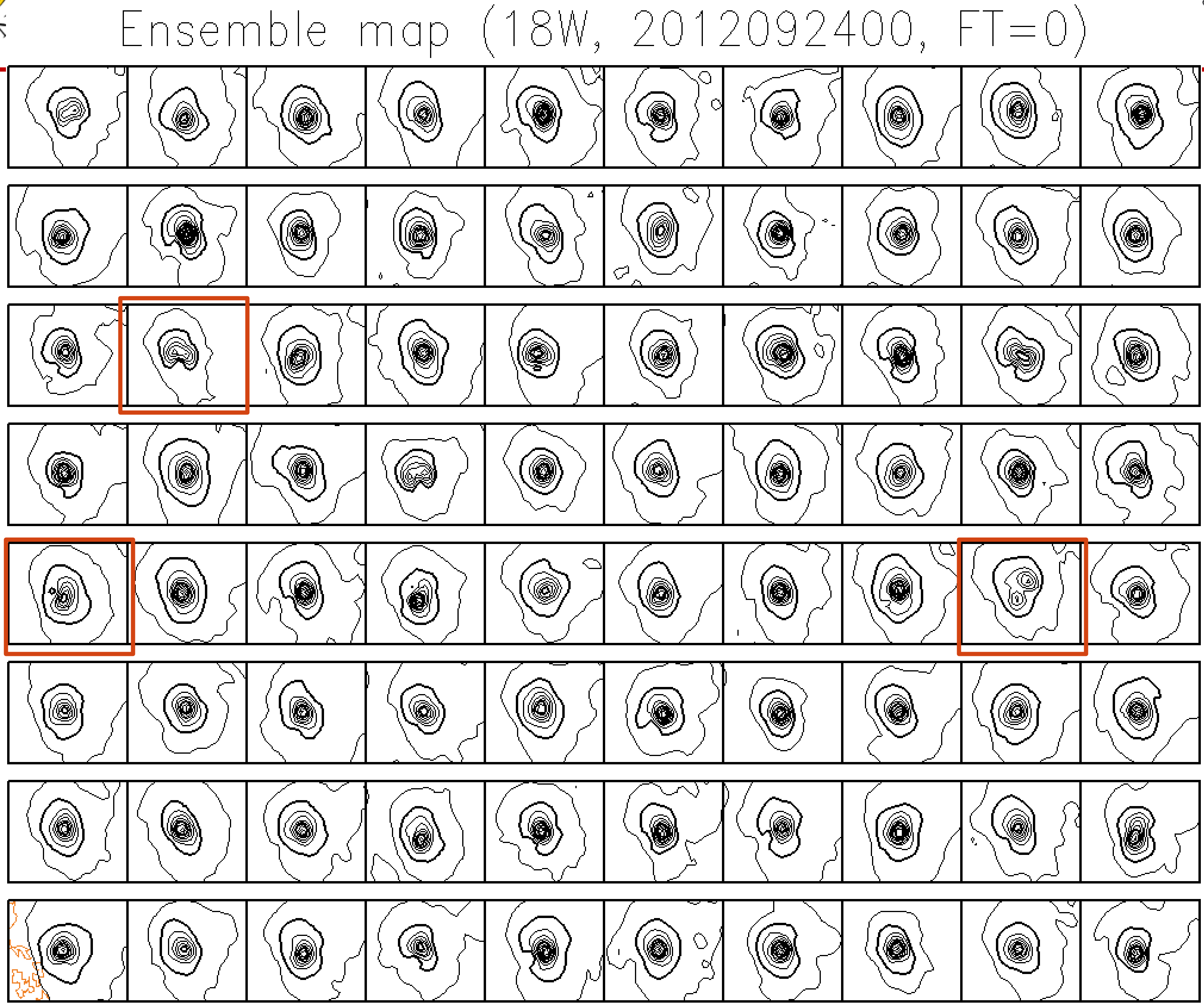


1. Update TC center position (latitude and longitude) by the EnKF
2. Use updated positions as inputs to the TC relocation
3. Apply this procedure before the EnKF analysis and GDAS analysis

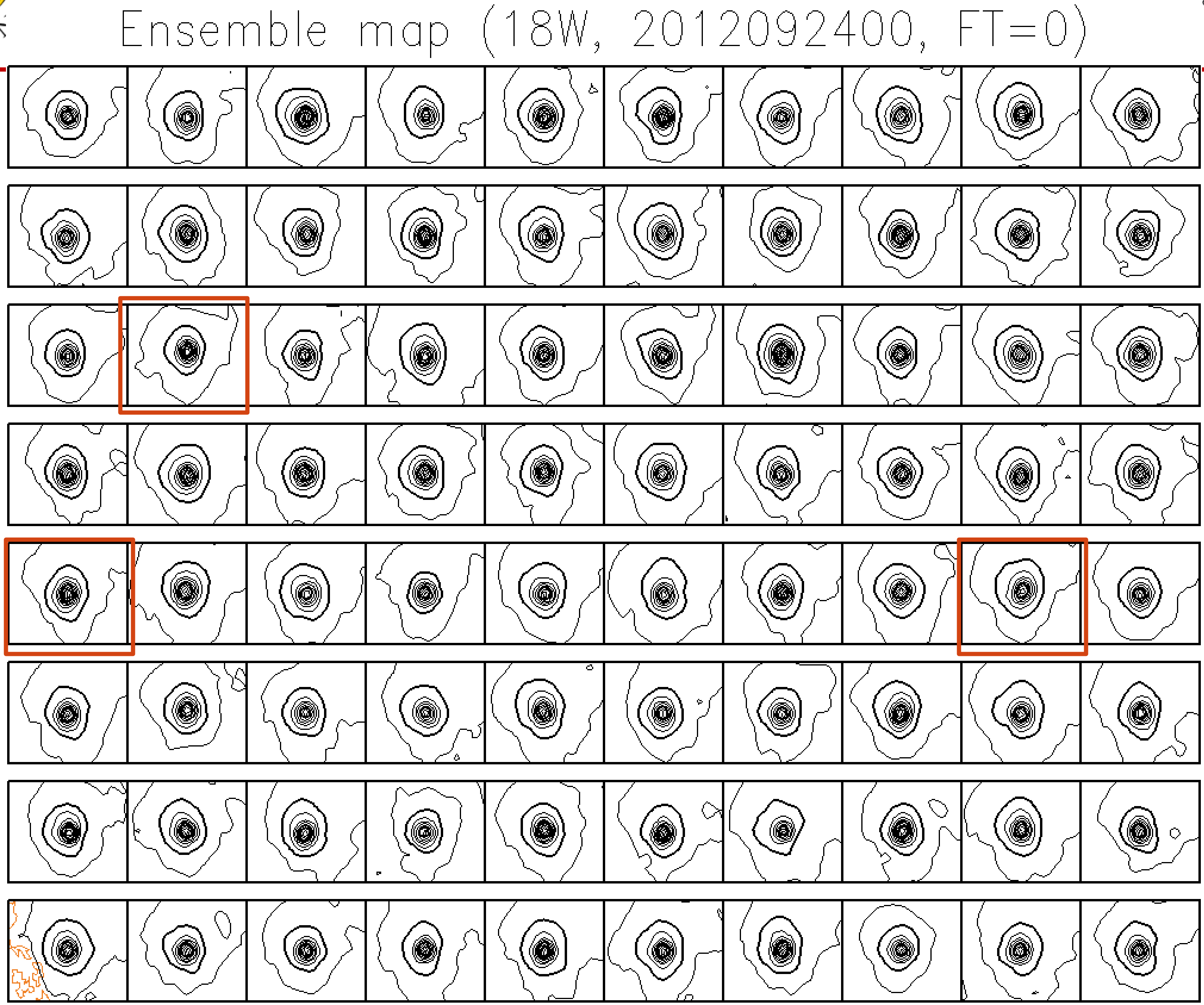
The idea is to separate linear problem (TC location space) and nonlinear problem (actual relocation of fields).

Blue: first guess position
Red: Updated position
Green: TC vital position

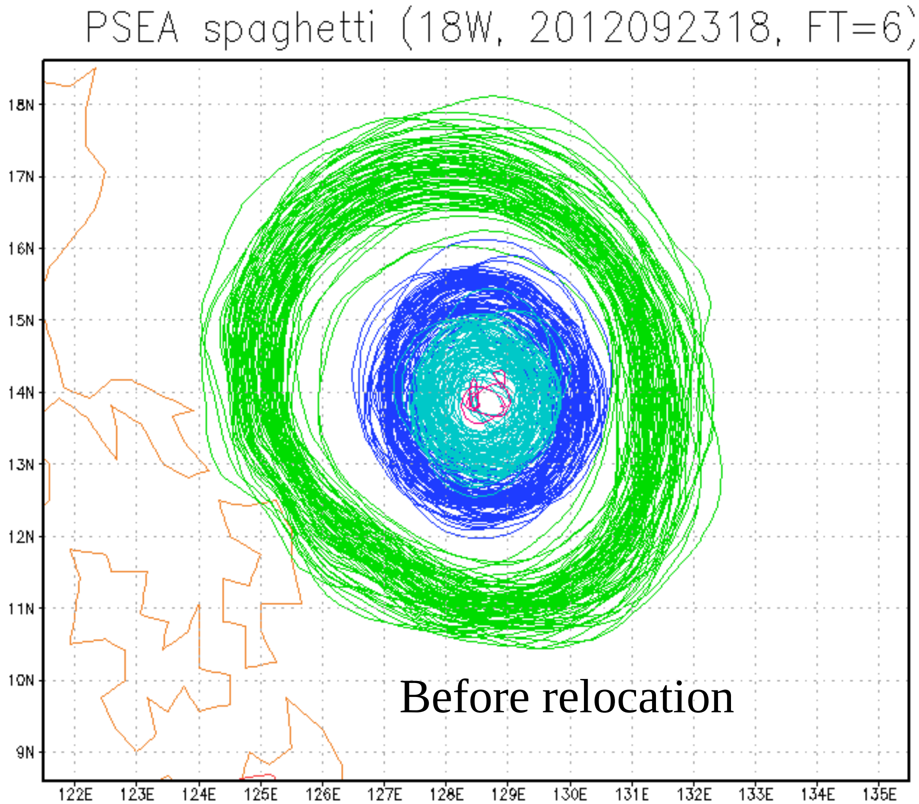
18W: 00UTC Sep. 24 EnKF analysis (no relocation)

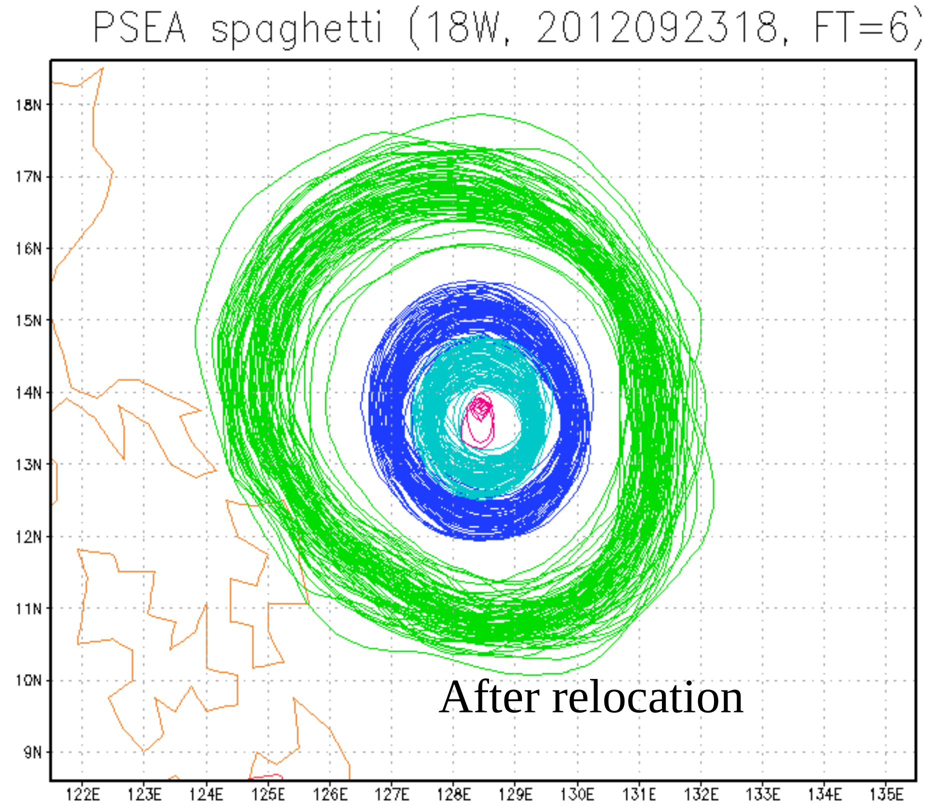


18W: 00UTC Sep. 24 EnKF analysis (with relocation)



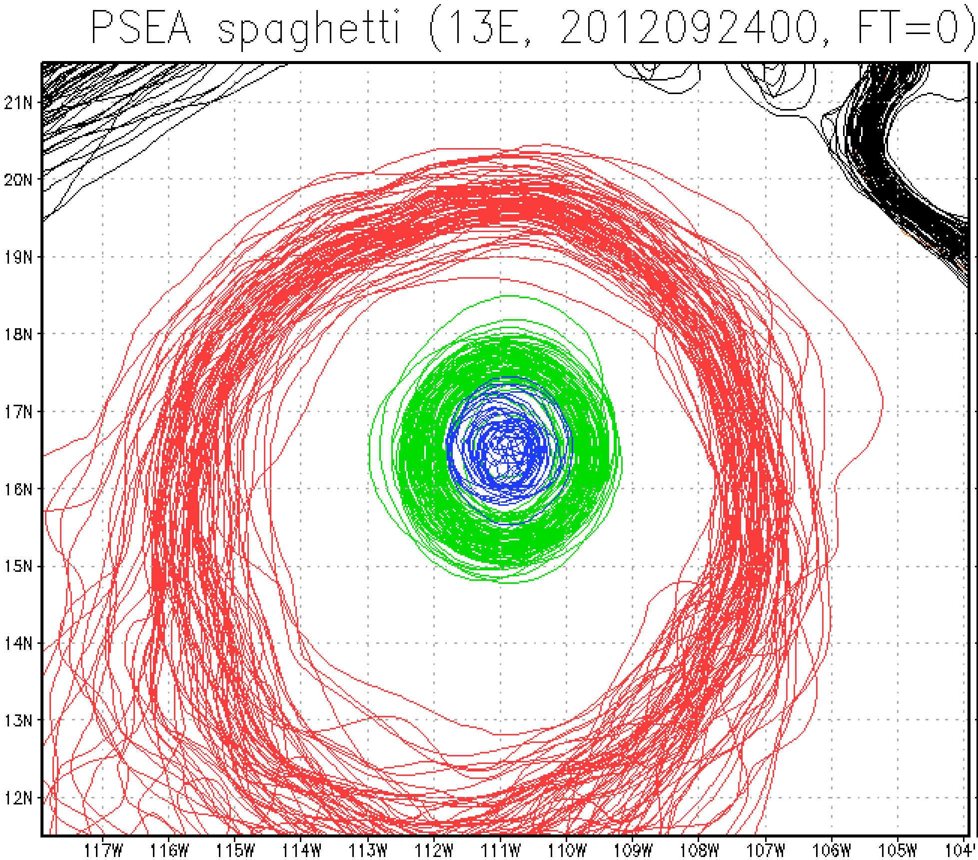
Example: spaghetti diagram
From Ota



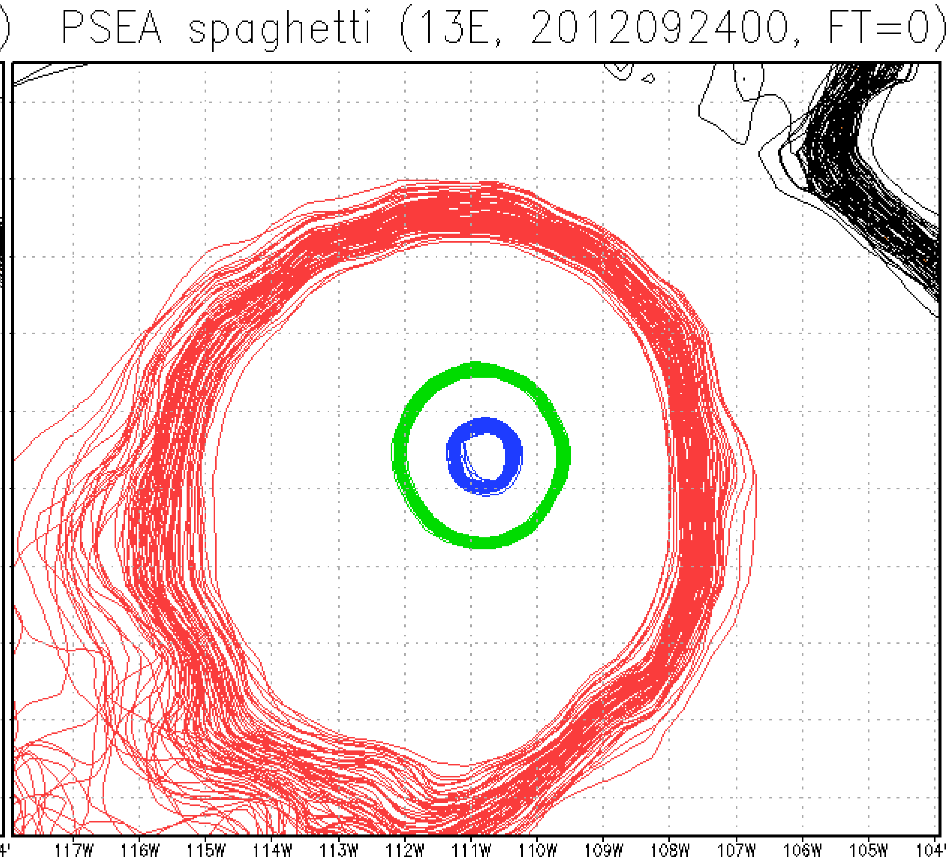


TC relocation of this method can reduce the uncertainty on the TC position, maintaining the TC structure perturbations and some of the position uncertainty.

Comparison with GEFS TC relocation (from Ota)



EnKF analysis with TC relocation



EnKF 6 hour forecast perturbation + GEFS TC relocation

GEFS operational TC relocation scheme destroyed almost all initial position uncertainty and create very small spread around TC.

Project Status

- Award period began short time ago, not much progress to report
  - Have started looking at Mr. Ota’s ensemble-relocation software
- PhD student will start on project next month
- Familiarity with GSI (hybrid EnVar), MinSLP assimilation, GFS, and related codes as a core developer and former EMC employee
- Access to begin work immediately on NOAA R&D, WCOSS, and other assets. Will need to work on getting access to R&D computing for PhD student (can leverage UMD assets in the meantime)

Plan/Direction

- Finishing work on TC relocation in EnKF has started. Will work directly with EMC global and DA teams on testing and eventual implementation
- PhD student will work on reproducing Kepert simple model results, and work toward developing observation operator for EnVar
  - Will be validated through a variety of single test cases before cycling
- Baseline test with new method (to replace current relocation scheme) will be done with GFS
  - Would like to coordinate with D-WRF testing
- Plan to leverage collaborators at EMC for pieces that the UMD team is less familiar with (HWRF)

Relation to NGGPS

- This project strives to directly address the stated goal of the R2O initiative of providing improved weather prediction accuracy for high impact events (tropical cyclones) through (2) advanced data assimilation
- Having been a part of several significant implementations (GDAS/GSI 2007, GDAS/3D EnVar 2012, GDAS/4D EnVar 2016), well positioned to transition research to operations rapidly
- Will assist in unification, by coming up with a process that should be applicable to many models/applications
- Should yield improvements in assimilation of near-storm observations through improved error covariances (relocation) and simultaneous assimilation of storm information (instead of off-line, ad-hoc methods)

Thank you