Tropical Cyclone Track Forecast Characteristics in the NOAA/ESRL GEFS Reforecast Dataset

Thomas Galarneau
Regional Climate Section, NCAR Earth System Laboratory, Boulder, CO

Tom Hamill
Physical Sciences Division, NOAA/Earth System Laboratory, Boulder, CO

Gary Bates
CIRES, University of Colorado, Boulder, CO

HFIP Awards First Year Review 2012
10 July 2013

Goals of HFIP Proposal for Year 1

- **Generate TC tracks from GEFS reforecast dataset (1985–2010)**
- **Determine TC track forecast characteristics for North Atlantic basin**
- **Investigate using TC track forecasts statistics from reforecast dataset for bias-correction of real-time forecasts**
- **Examine individual cases to improve understanding of how GEFS reforecast model behaves**

Overview of Year 1

- **Generation of GEFS reforecast dataset completed in Jun 2012**
- **Generation of TC track forecast dataset completed in Jul 2012/updated in Feb 2013**
- **Funded work on proposal began in mid Nov 2012**
- **Analysis of North Atlantic TC track forecast characteristics (Nov 2012-present)**
- **Overview paper accepted to *BAMS* (Hamill et al., 2013, in press)**

Presentation Goals

- What are “reforecasts”?
- Details and availability of data
- TC track forecast characteristics in North Atlantic basin (1985–2010)
- Case study of Hurricane Earl (2010)
  - Illustrative case of slow/early recurvature (characteristic of western/central North Atlantic)
  - Interacting TCs
- Case study of Hurricane Rita (2005)
  - Illustrative case of left-of-track error (characteristic of western Gulf of Mexico)
  - Use of “regional reforecast” with ARW model
- Final comments and plans

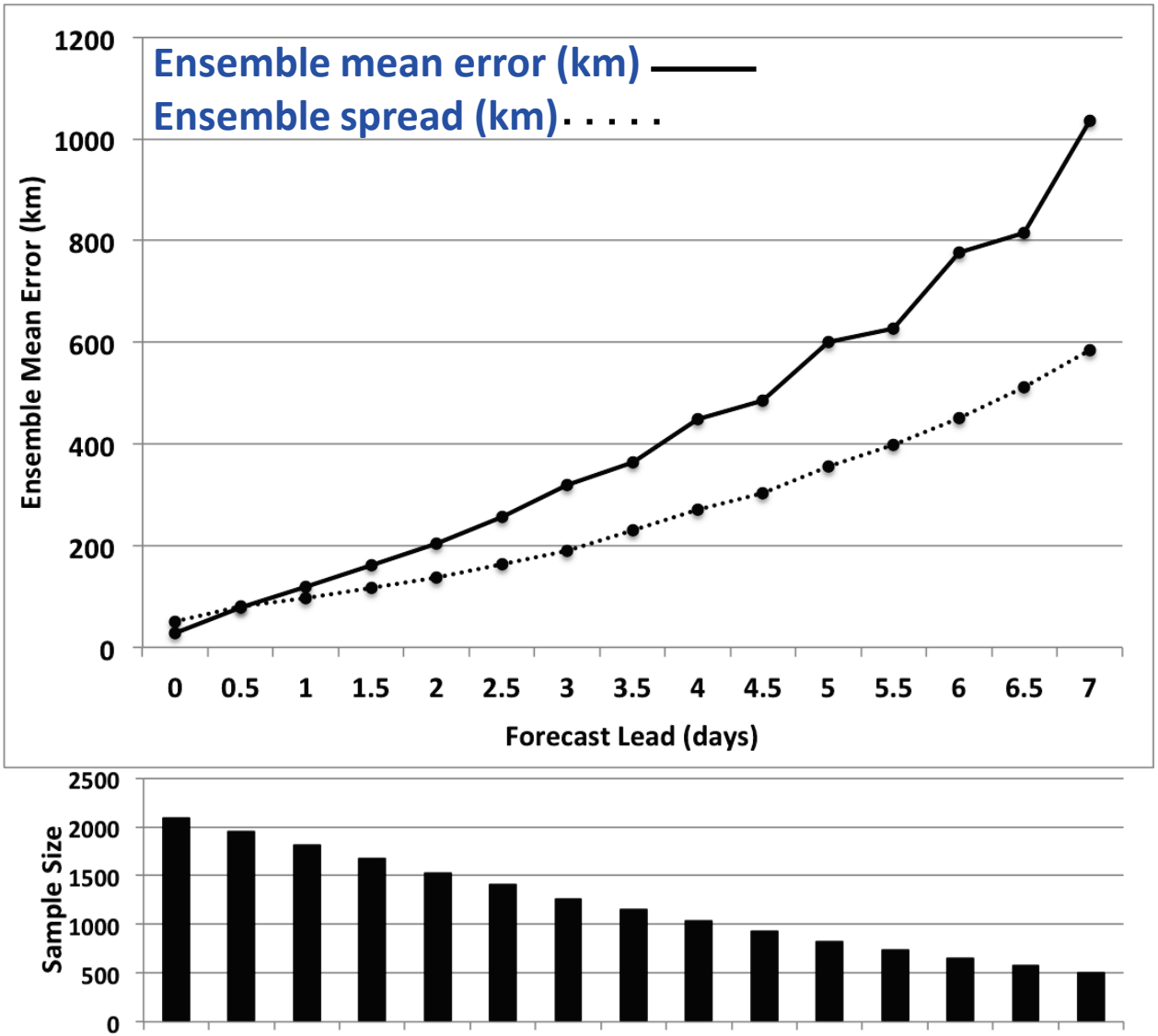
What are “reforecasts”?

- **Numerical simulations of the past weather (or climate) using the same forecast model and assimilation system that (ideally) is used operationally**
- **Long time series of forecasts produces a large training dataset for statistical post-processing of model forecasts of relatively rare events (such as TCs)**

NOAA ESRL's GEFS Reforecast v2

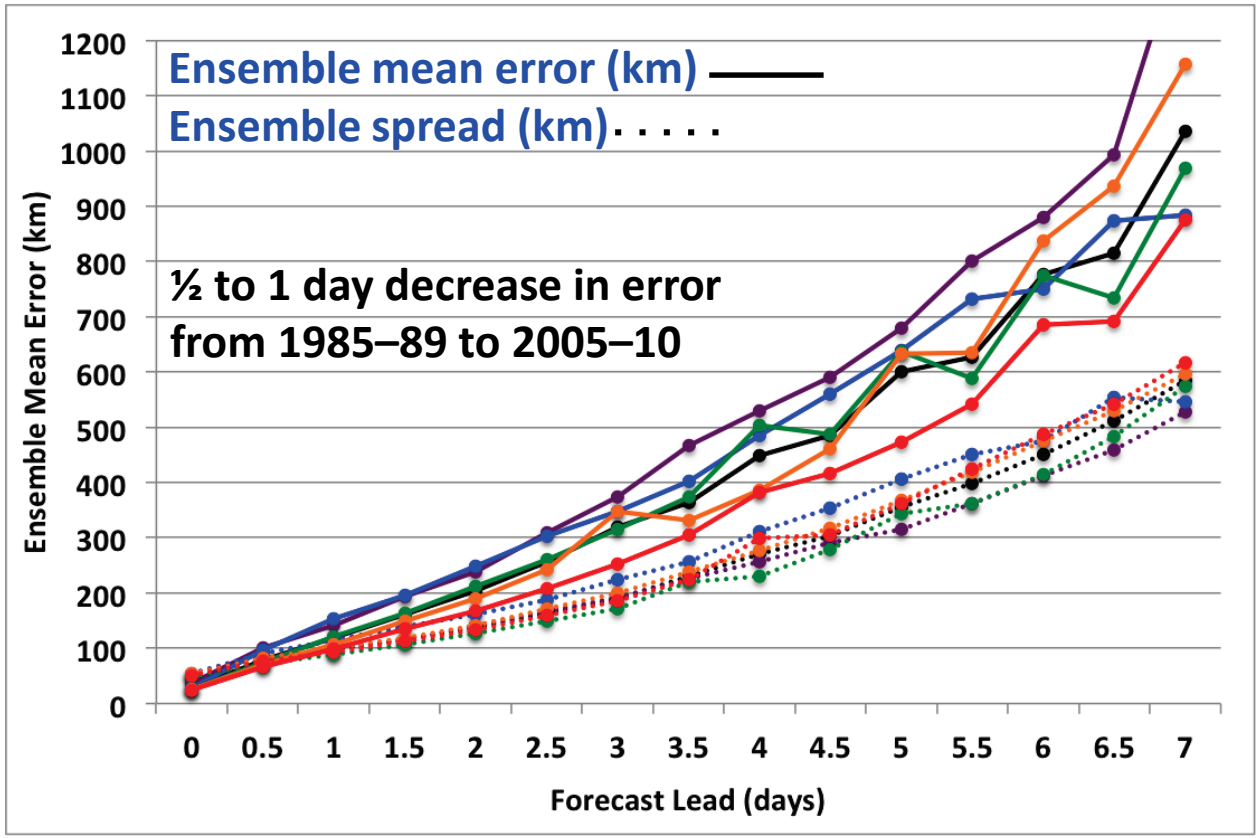
- Uses the February 2012 GEFS (v9.0.1) operational configuration
- 11-member ensemble: 1 control + 10 perturbed
- Reforecasts run once-daily at 00Z from 1 December 1984–present
- Control member initial conditions from NCEP Climate Forecast System Reanalysis (CFSR; Saha et al. 2010); perturbations using ensemble transform with rescaling
- Initial conditions from hybrid EnKF/3D-Var after 22 May 2012
- Horizontal resolution T254L42 (~0.50°) to day 8; T190L42 (~0.75°) to day 16
- Fast data archive at ESRL of 98 variables available at 1.0° resolution (28 of which stored at native ~0.5° resolution during week 1) [http://esrl.noaa.gov/psd/forecasts/reforecast2/]
- Full archive at DOE/Lawrence Berkeley Lab, where data set was created under DOE grant [http://portal.nersc.gov/project/refcst/v2/]
- TC tracks generated by Mike Fiorino (NOAA/ESRL/GSD) using Marchok tracker

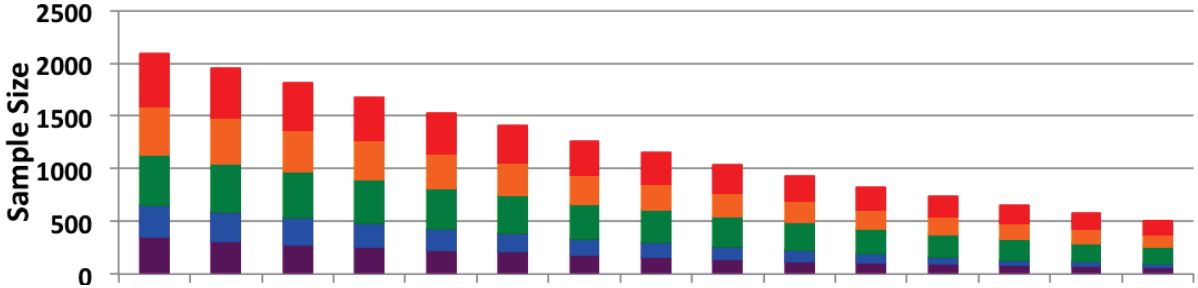
GEFS Reforecast North Atlantic TC Track Error Statistics (1985–2010)



GEFS Reforecast North Atlantic TC Track Error Statistics by ½ Decade

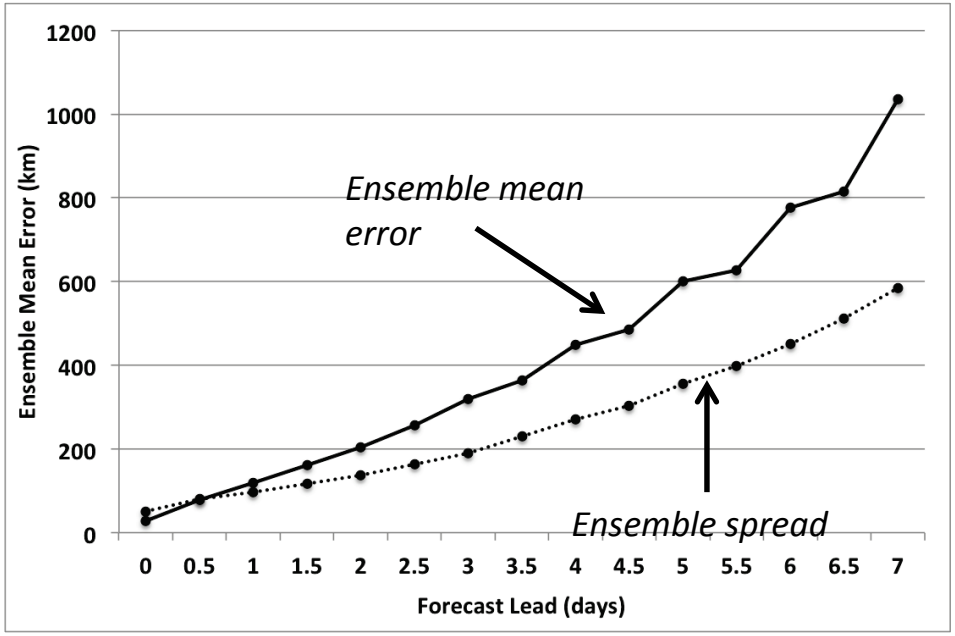
1985–2010
1985–1989
1990–1994
1995–1999
2000–2004
2005–2010

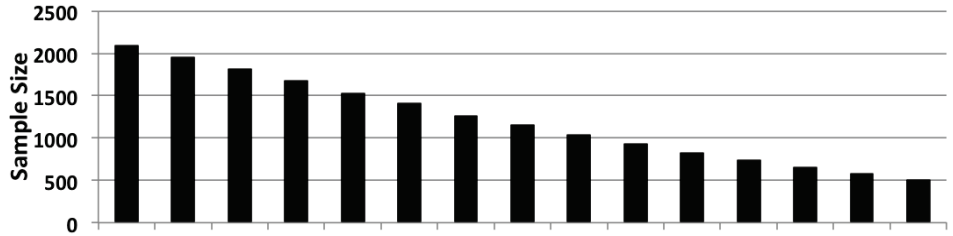




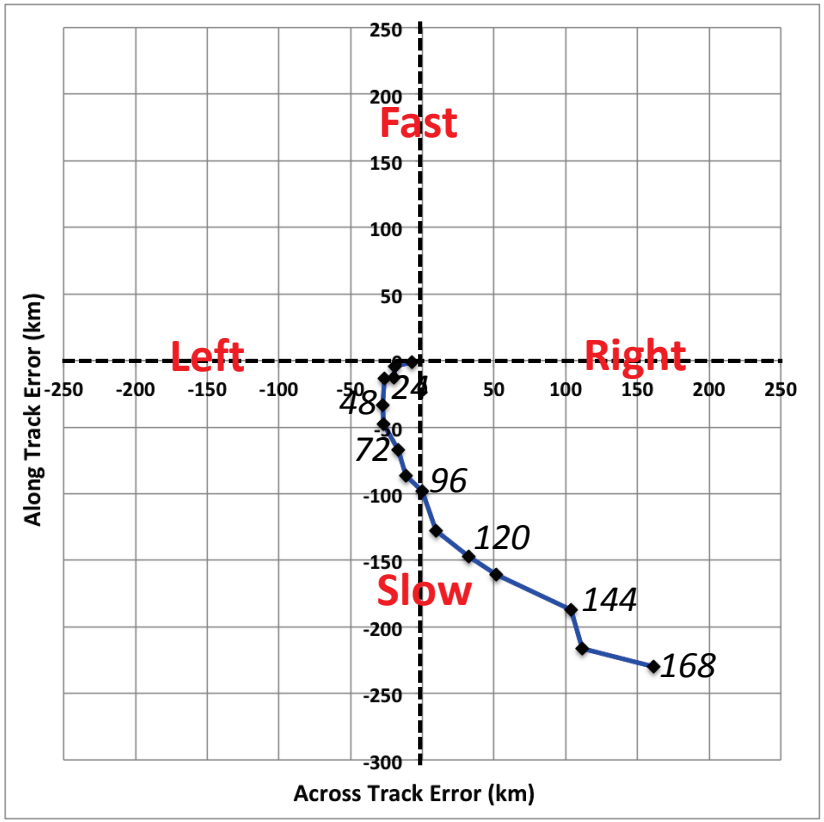
GEFS Reforecast North Atlantic TC Track Error and Bias

Mean Absolute Track Error



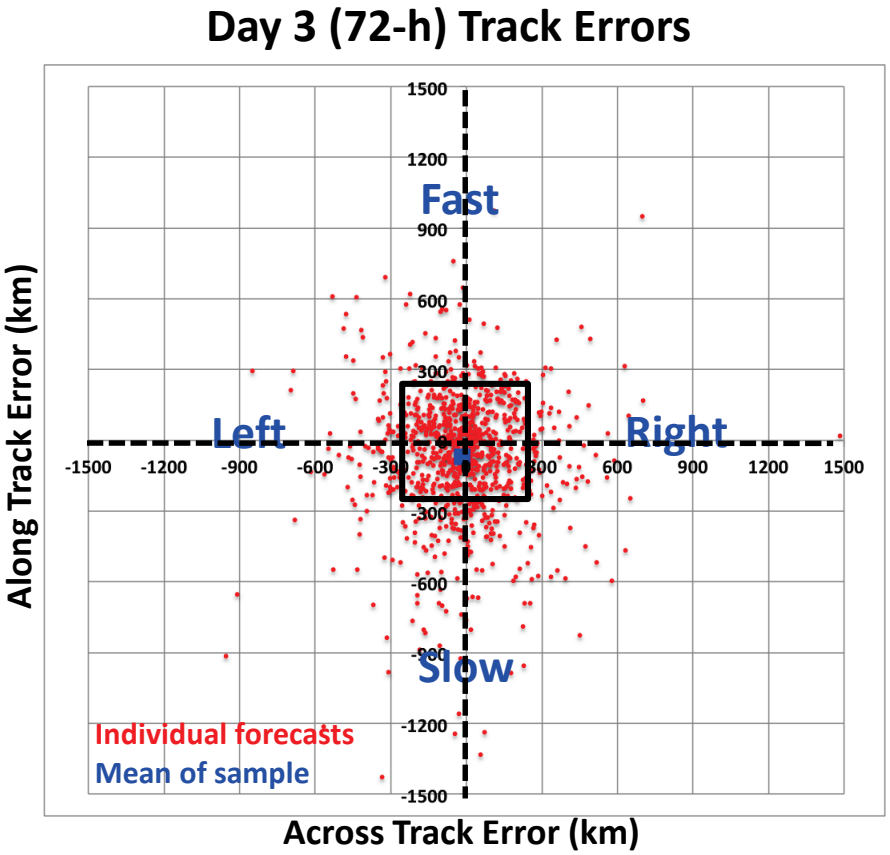


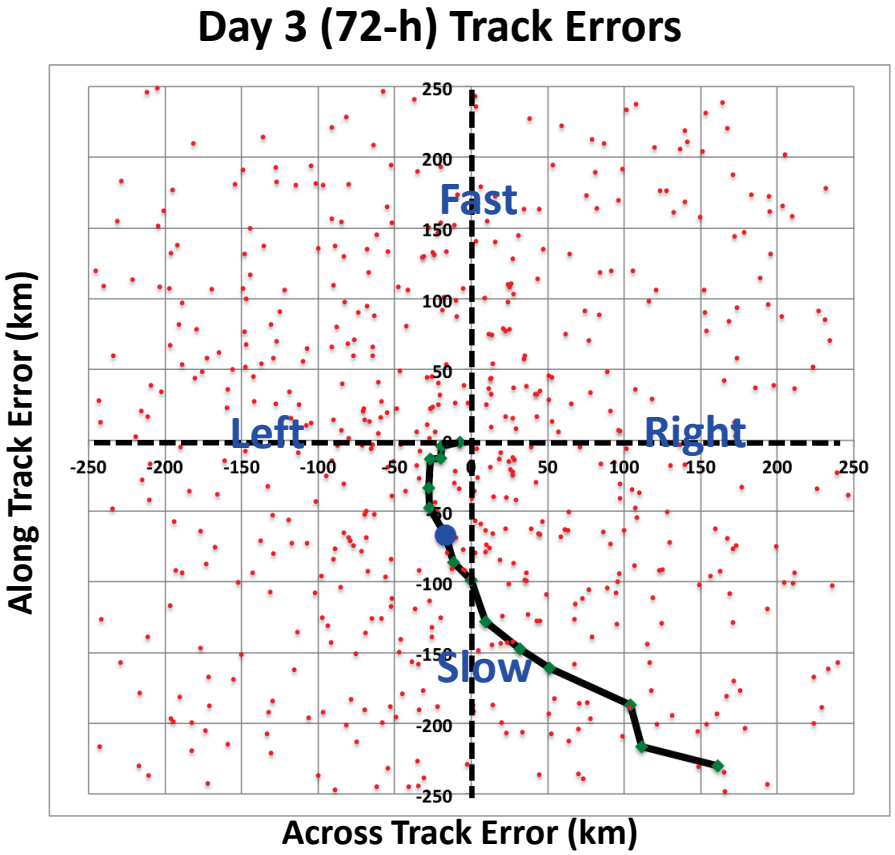
Track Bias



- GEFS reforecast track bias suggests:
- Slow error at all times
- Left-of-track error before 96-h
- Right-of-track error after 96-h

GEFS Reforecast TC Track "Bias"



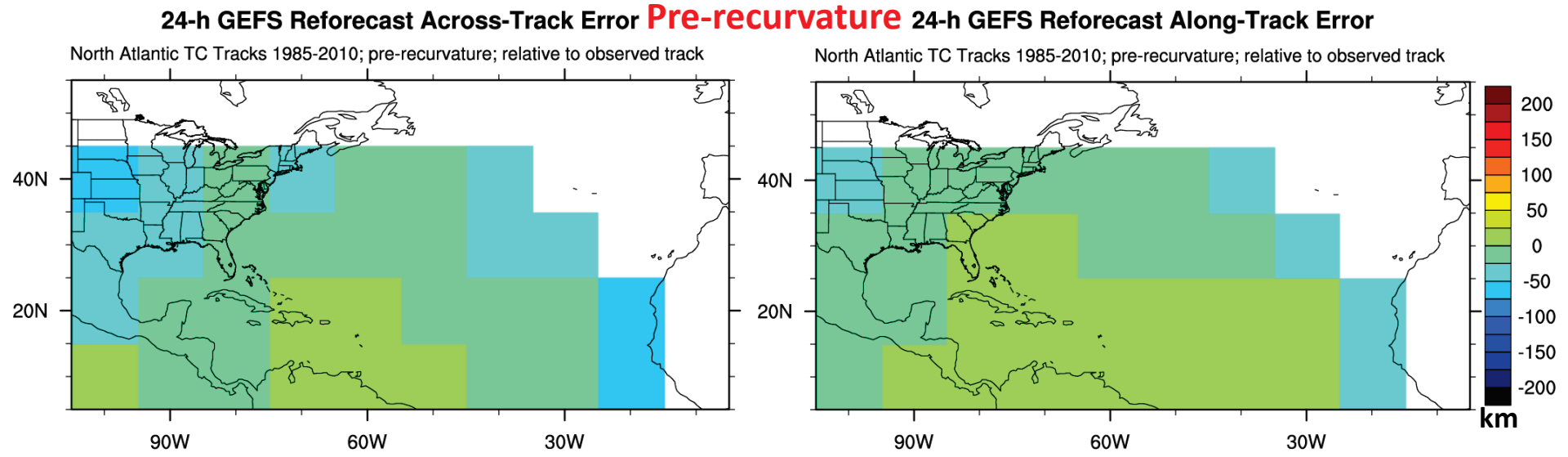


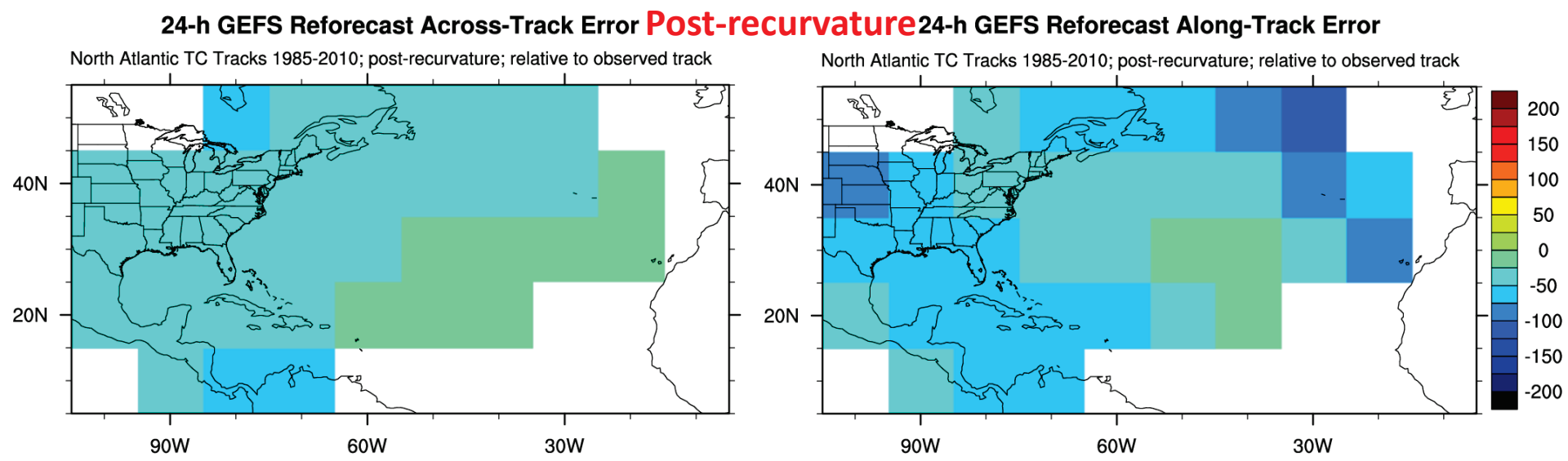
- Note large degree of scatter despite seemingly "physical" track bias

Geographical Characteristics of TC Track Forecasts

- For each lead time, identify forecast positions of TCs (1985–2010) within a 20°×20° latitude-longitude box centered on a pre-determined set of grid points
  - 10–50°N and 100–20°W every 10°
- Determine whether forecasted TC is in pre- or post-recurvature stage
  - Pre-recurvature TC has westward motion
  - Post-recurvature TC has eastward motion
- Compute MAE, bias, sample size for each location

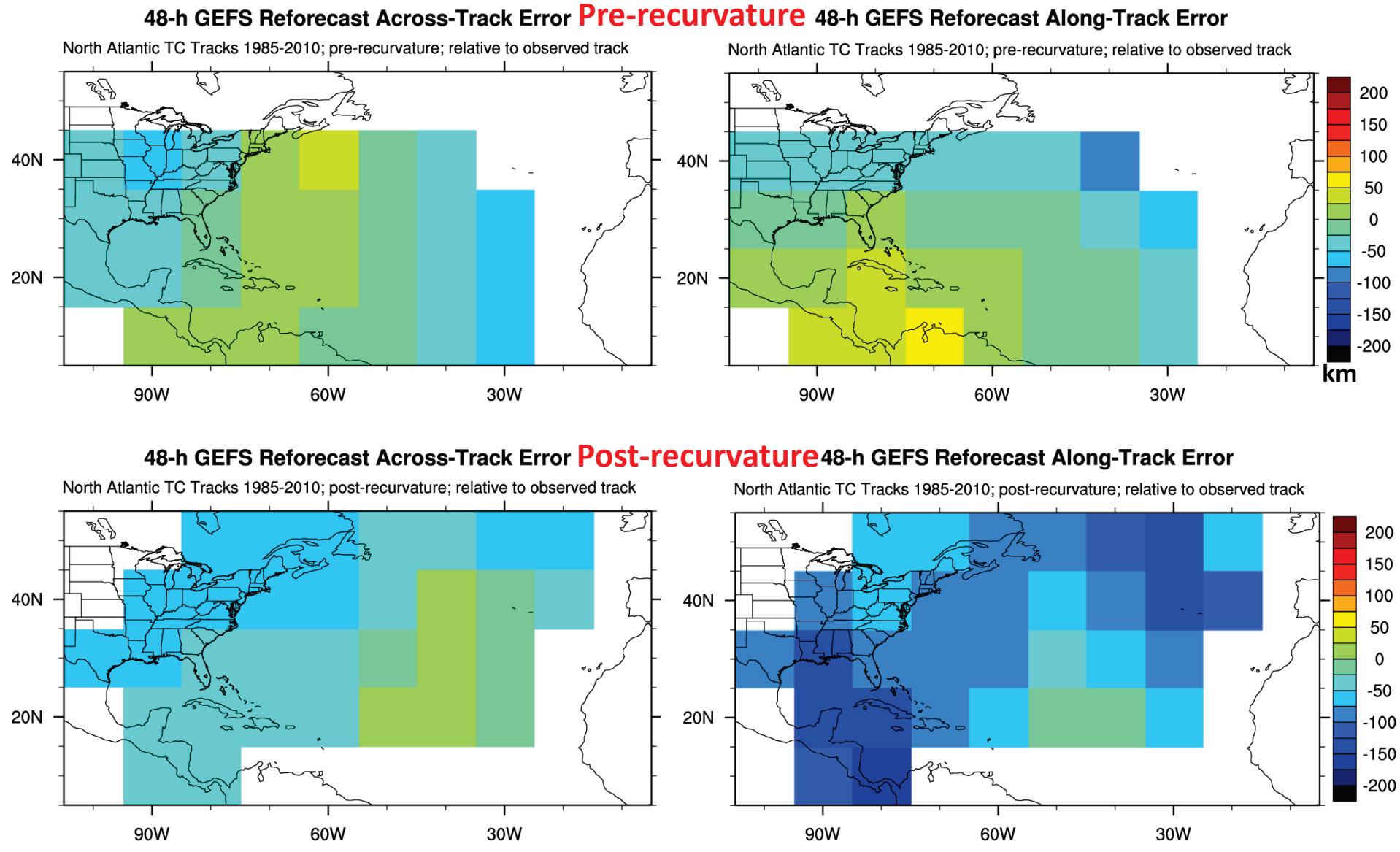
GEFS Reforecast Track-Relative Error





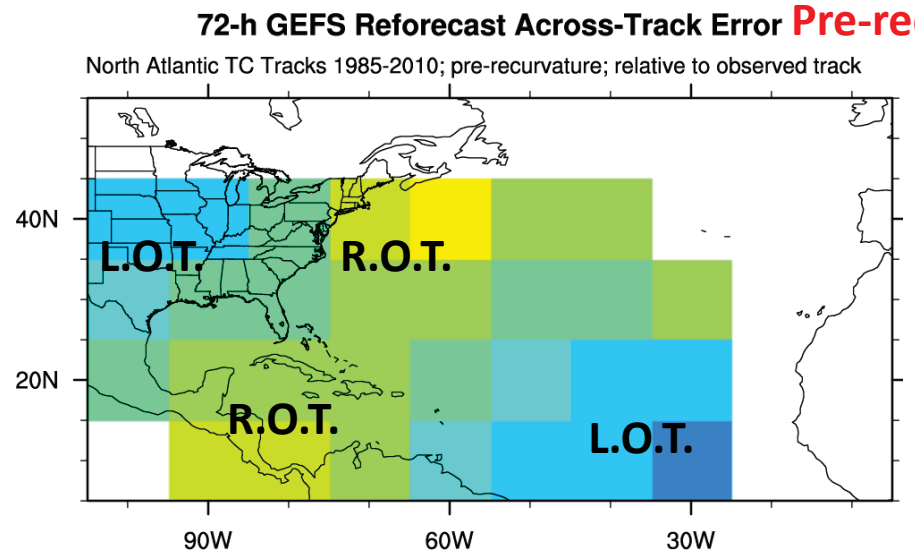
Recall that recurvature stage is defined for the forecasted TC

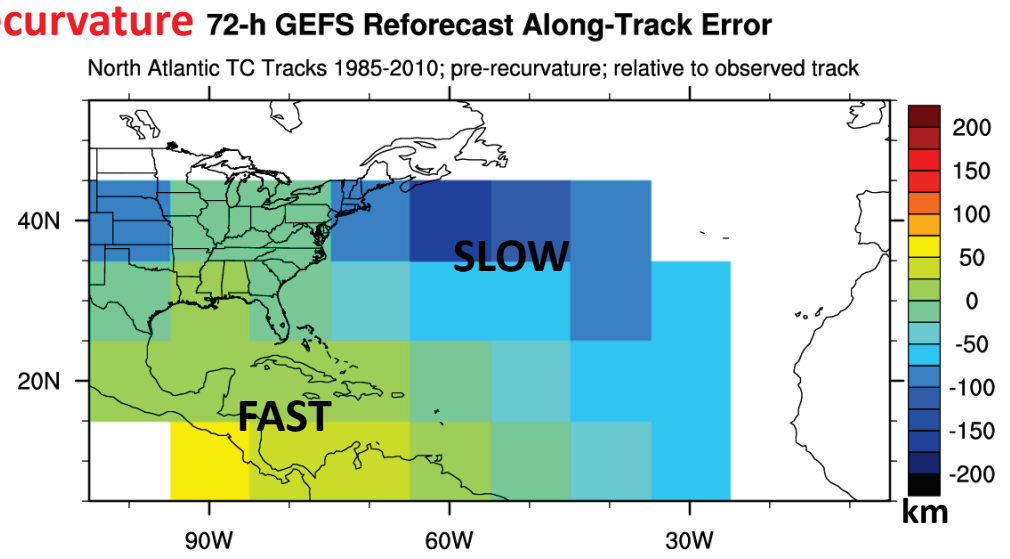
GEFS Reforecast Track-Relative Error

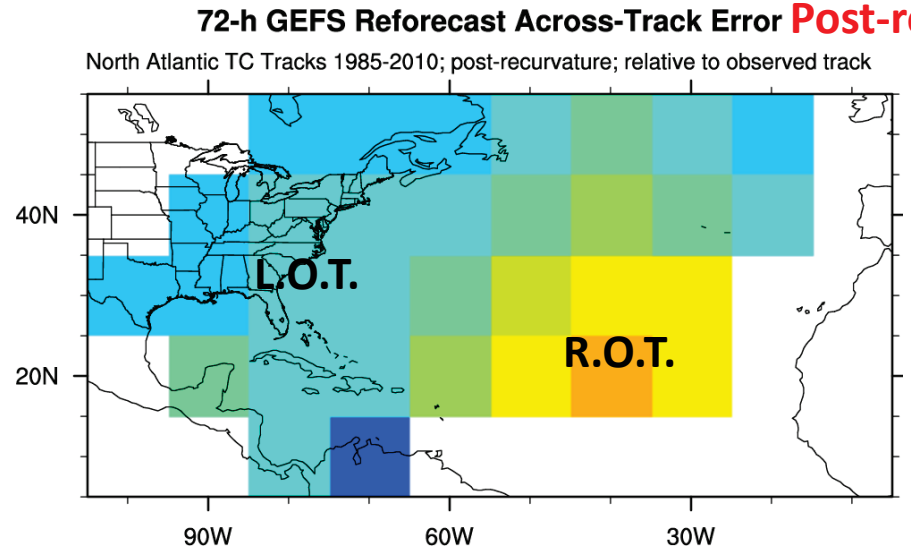


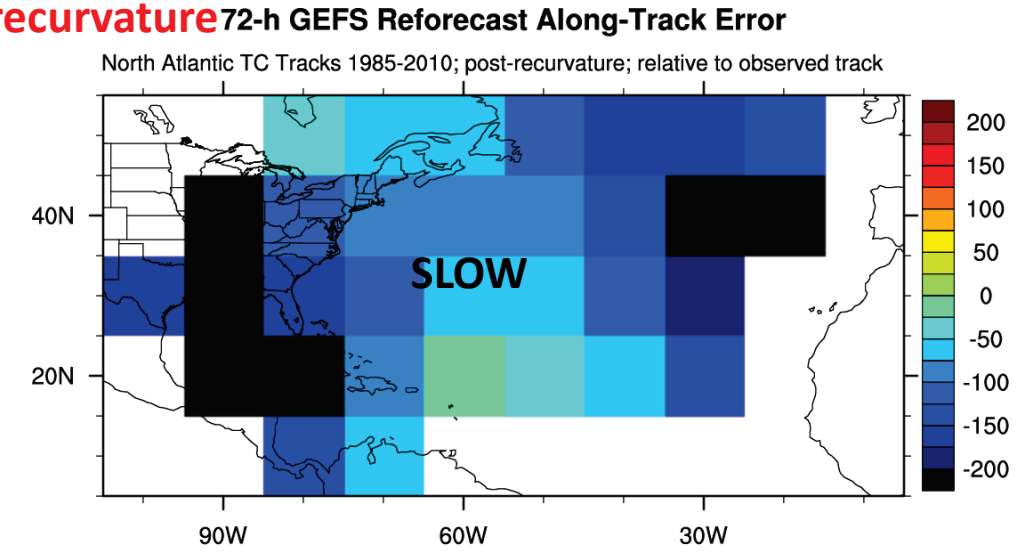
Recall that recurvature stage is defined for the forecasted TC

GEFS Reforecast Track-Relative Error





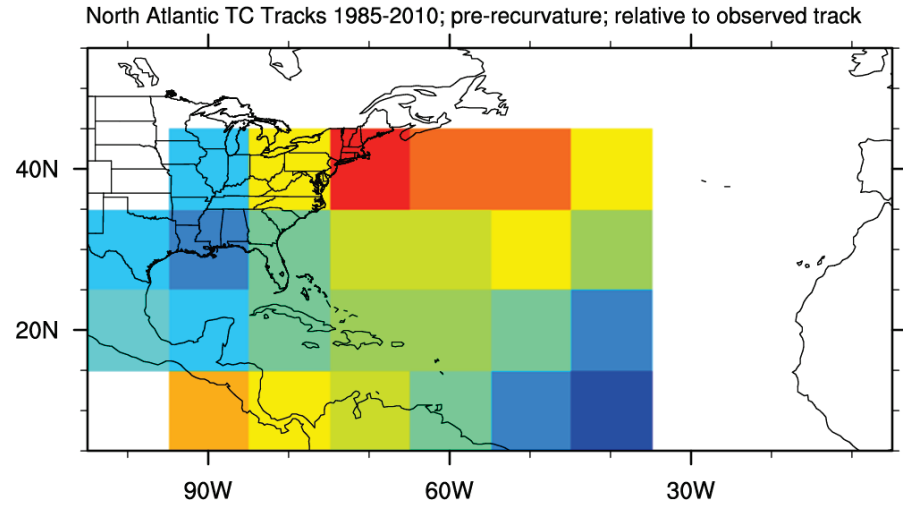




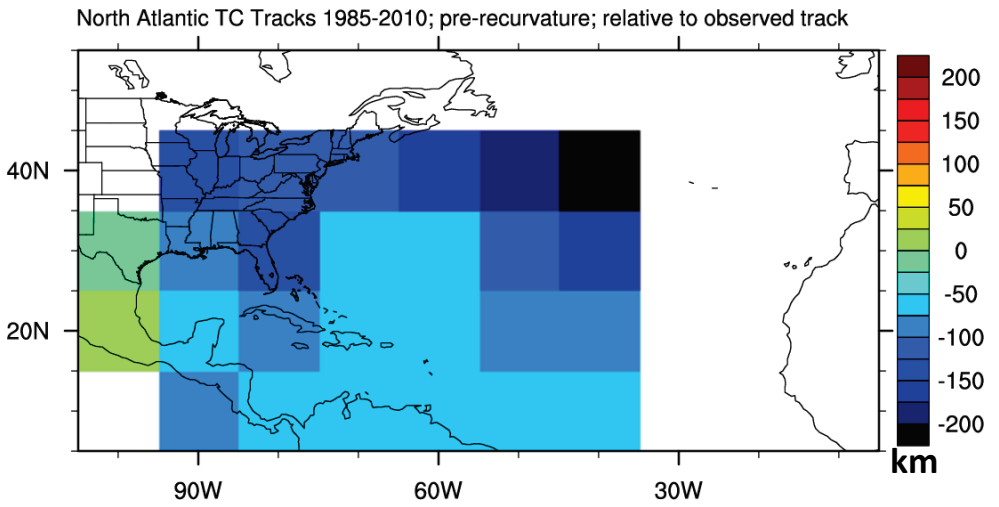
Recall that recurvature stage is defined for the forecasted TC

GEFS Reforecast Track-Relative Error

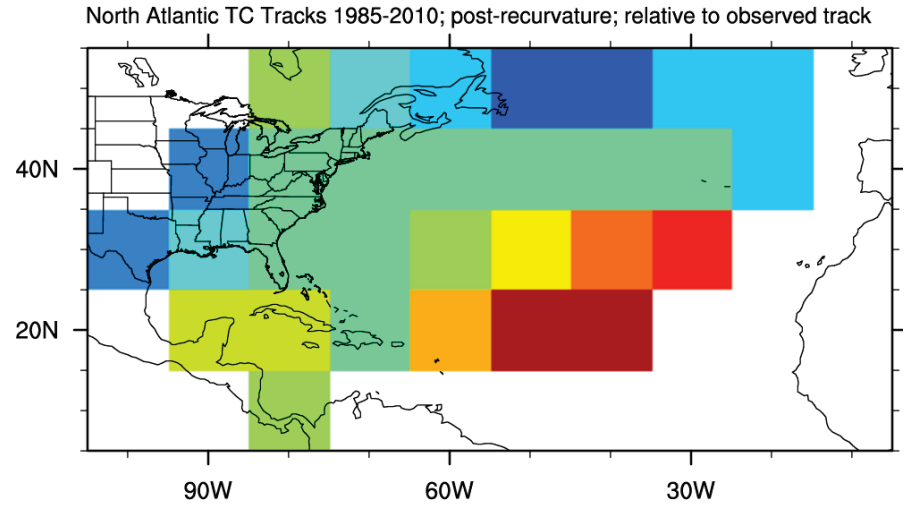
96-h GEFS Reforecast Across-Track Error Pre-recurvature



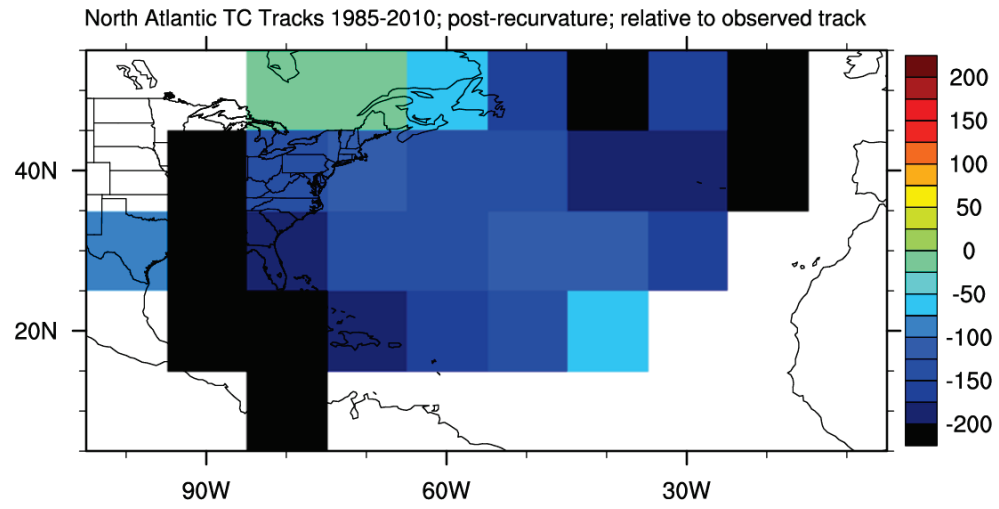
96-h GEFS Reforecast Along-Track Error



96-h GEFS Reforecast Across-Track Error Post-recurvature



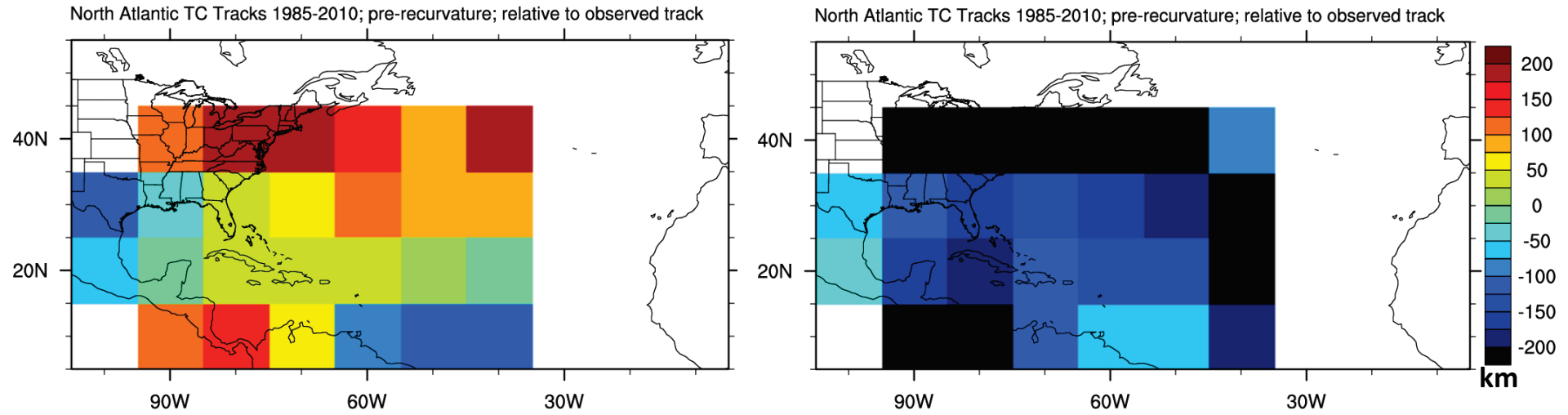
96-h GEFS Reforecast Along-Track Error



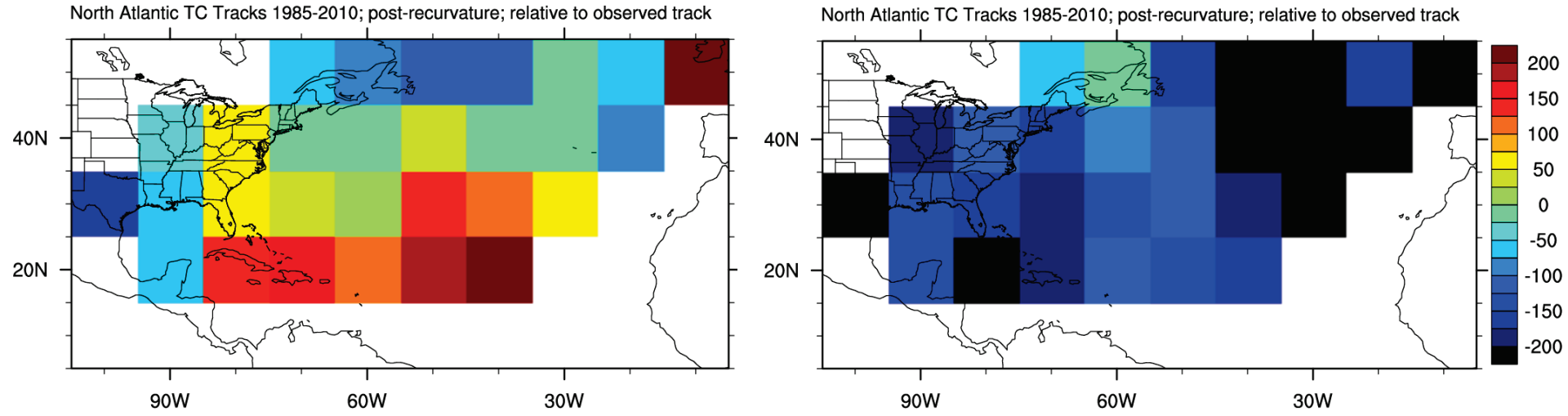
Recall that recurvature stage is defined for the forecasted TC

GEFS Reforecast Track-Relative Error

120-h GEFS Reforecast Across-Track Error **Pre-recurvature** **120-h GEFS Reforecast Along-Track Error**

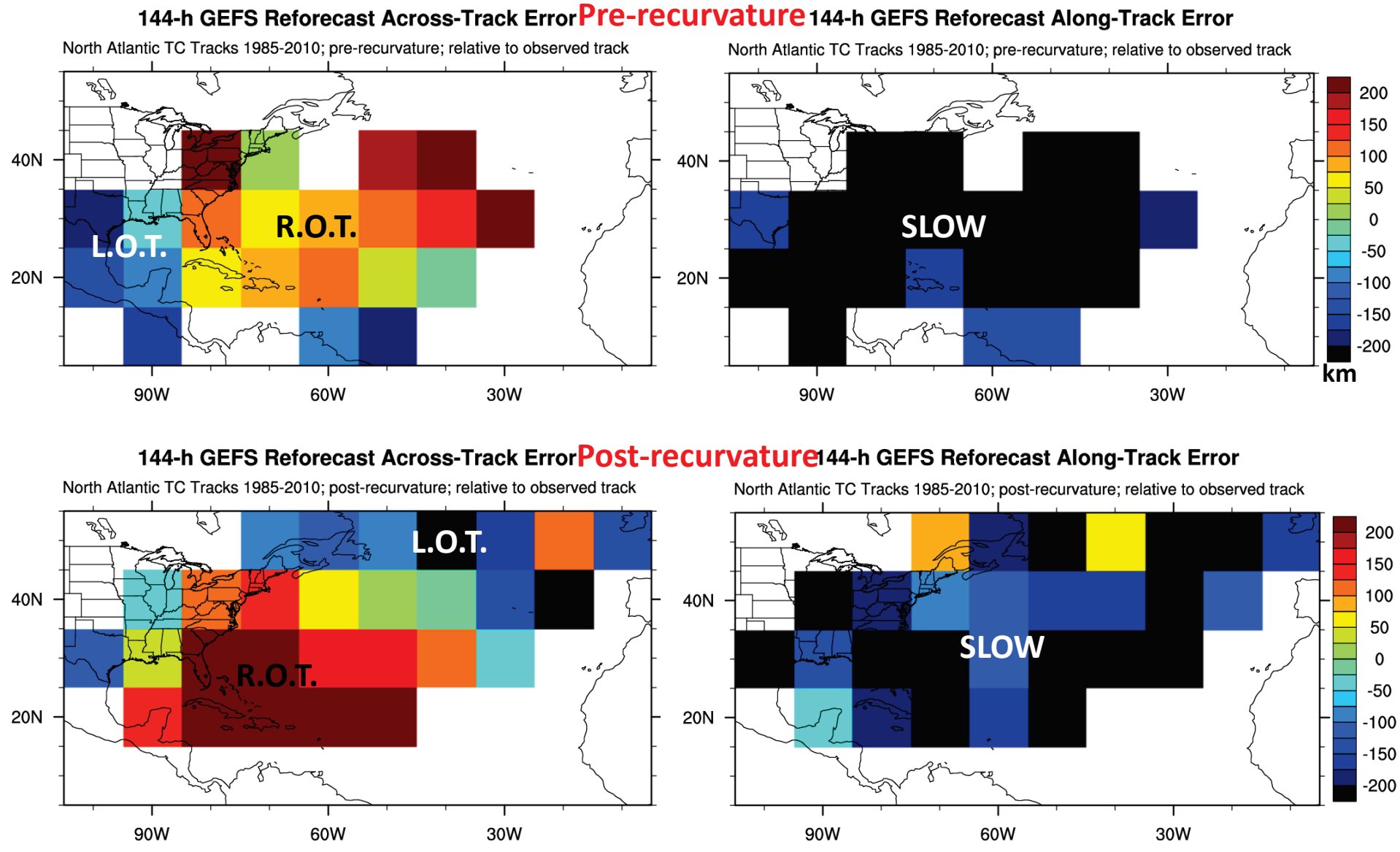


120-h GEFS Reforecast Across-Track Error **Post-recurvature** **120-h GEFS Reforecast Along-Track Error**



Recall that recurvature stage is defined for the forecasted TC

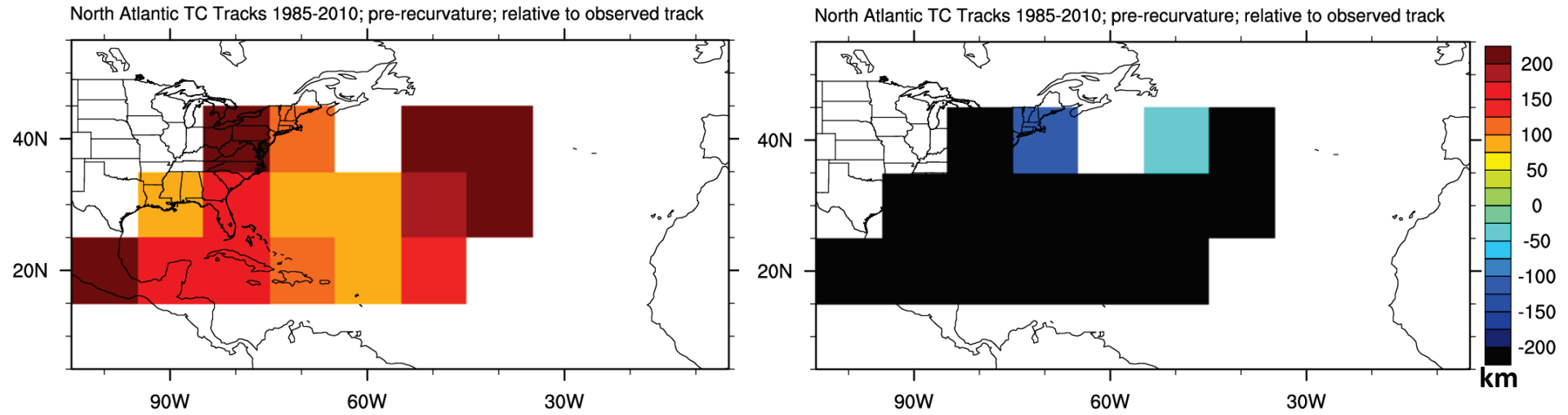
GEFS Reforecast Track-Relative Error



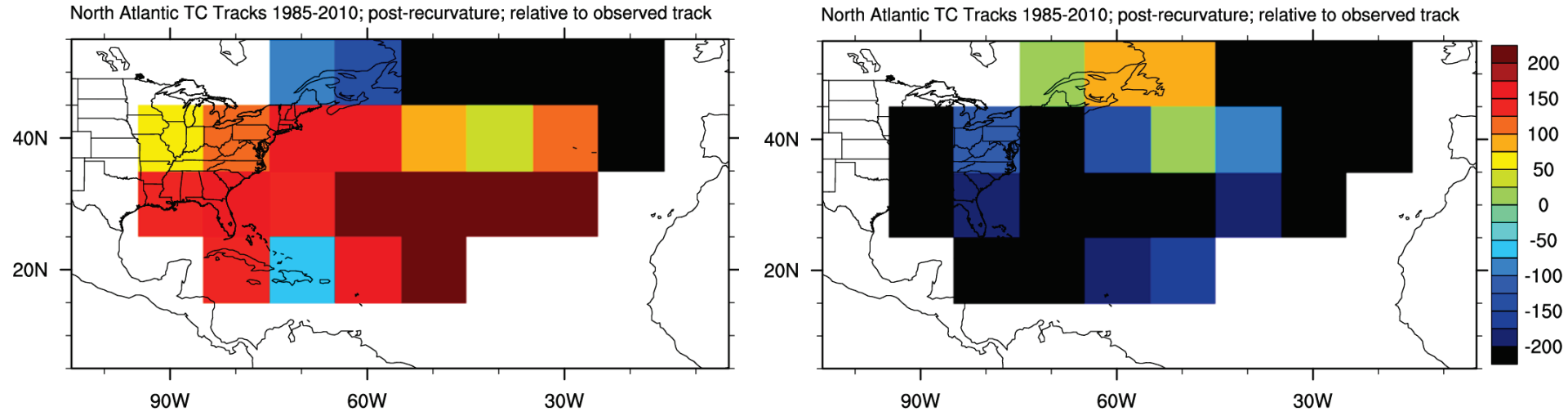
Recall that recurvature stage is defined for the forecasted TC

GEFS Reforecast Track-Relative Error

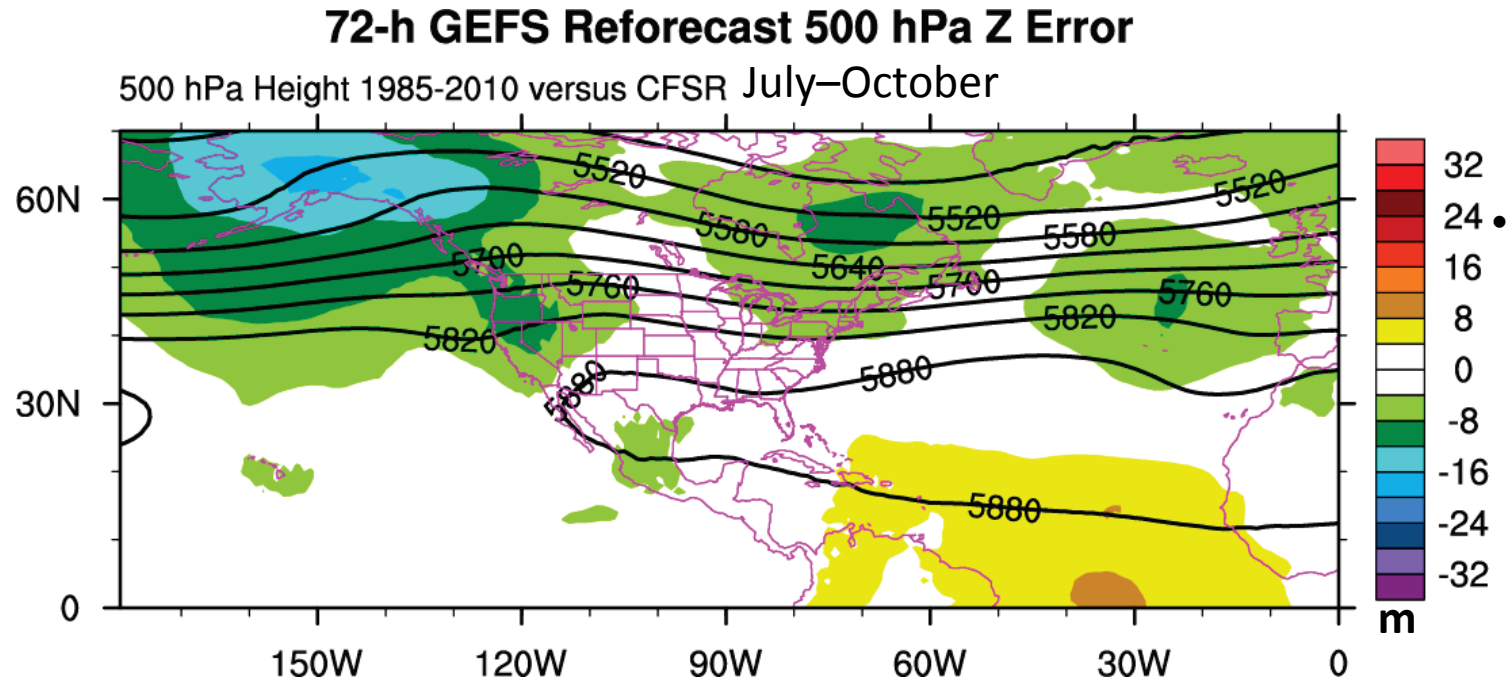
168-h GEFS Reforecast Across-Track Error Pre-recurvature **168-h GEFS Reforecast Along-Track Error**



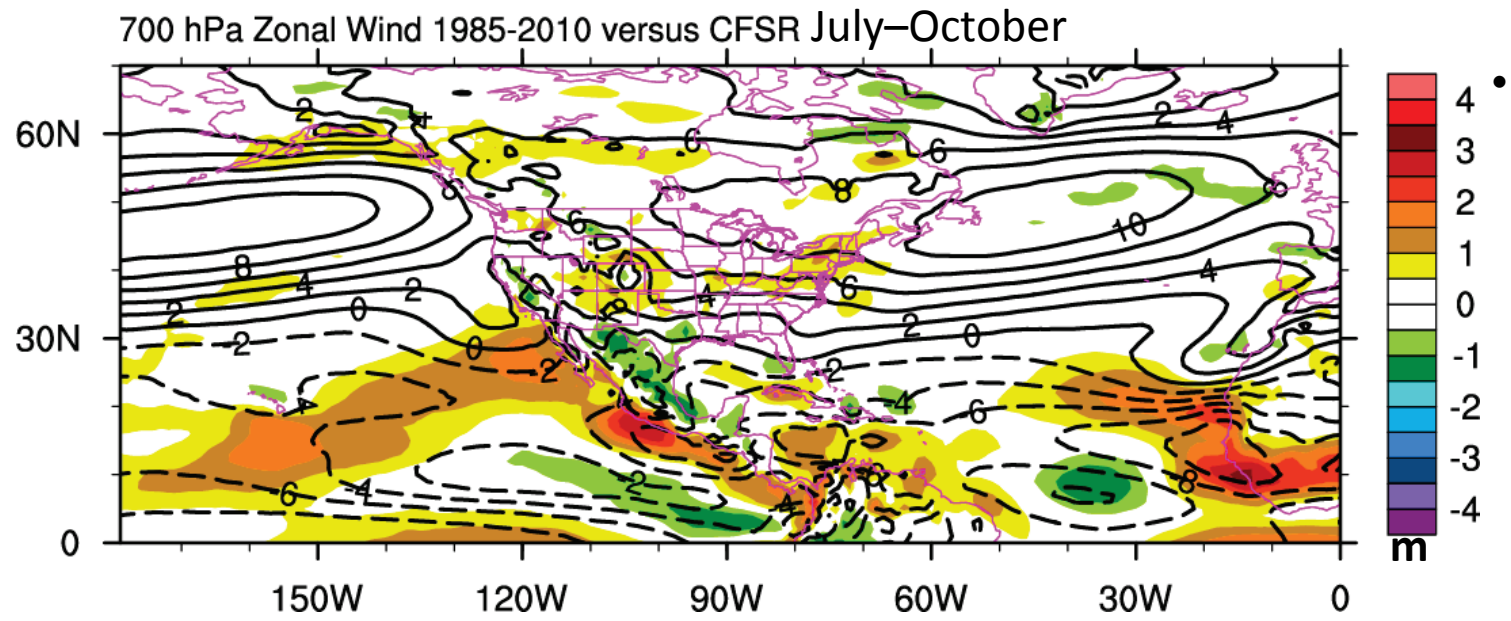
168-h GEFS Reforecast Across-Track Error Post-recurvature **168-h GEFS Reforecast Along-Track Error**



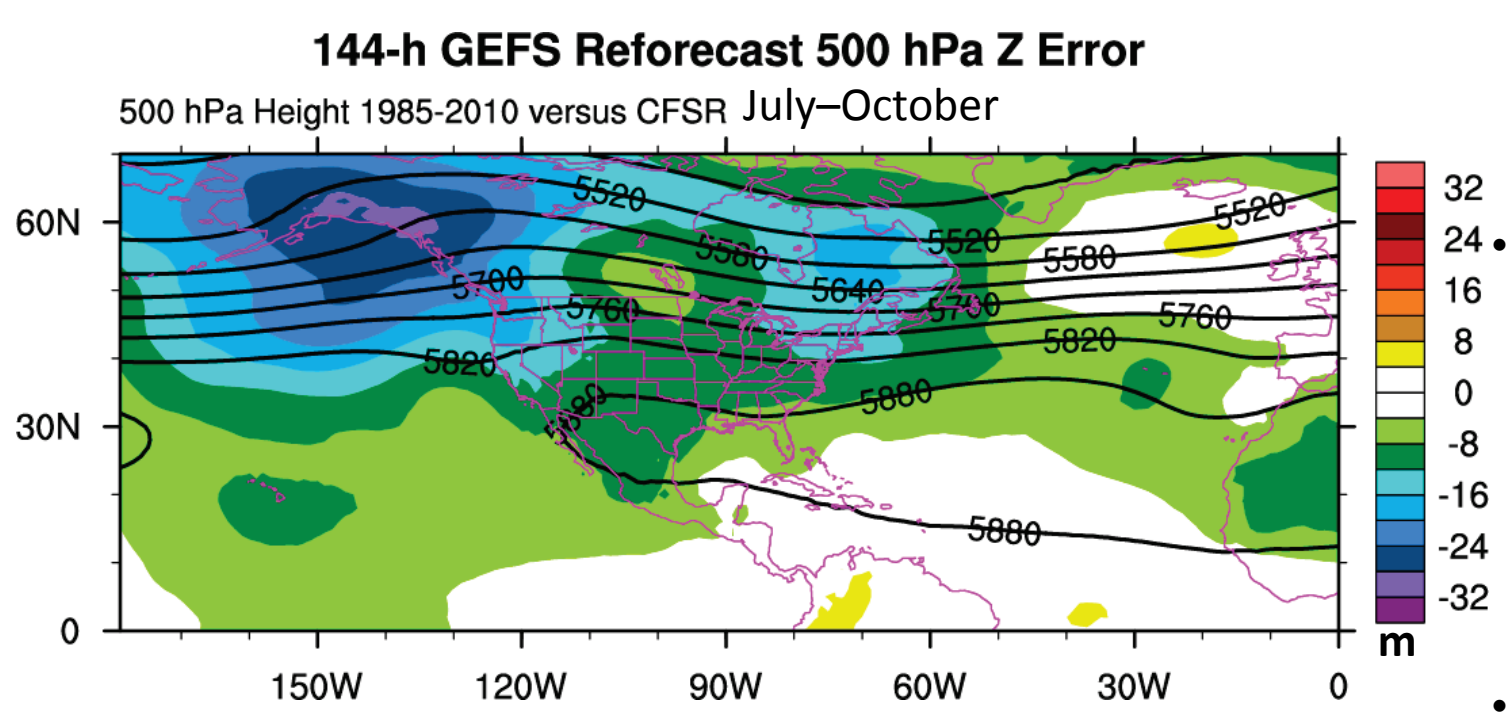
Recall that recurvature stage is defined for the forecasted TC

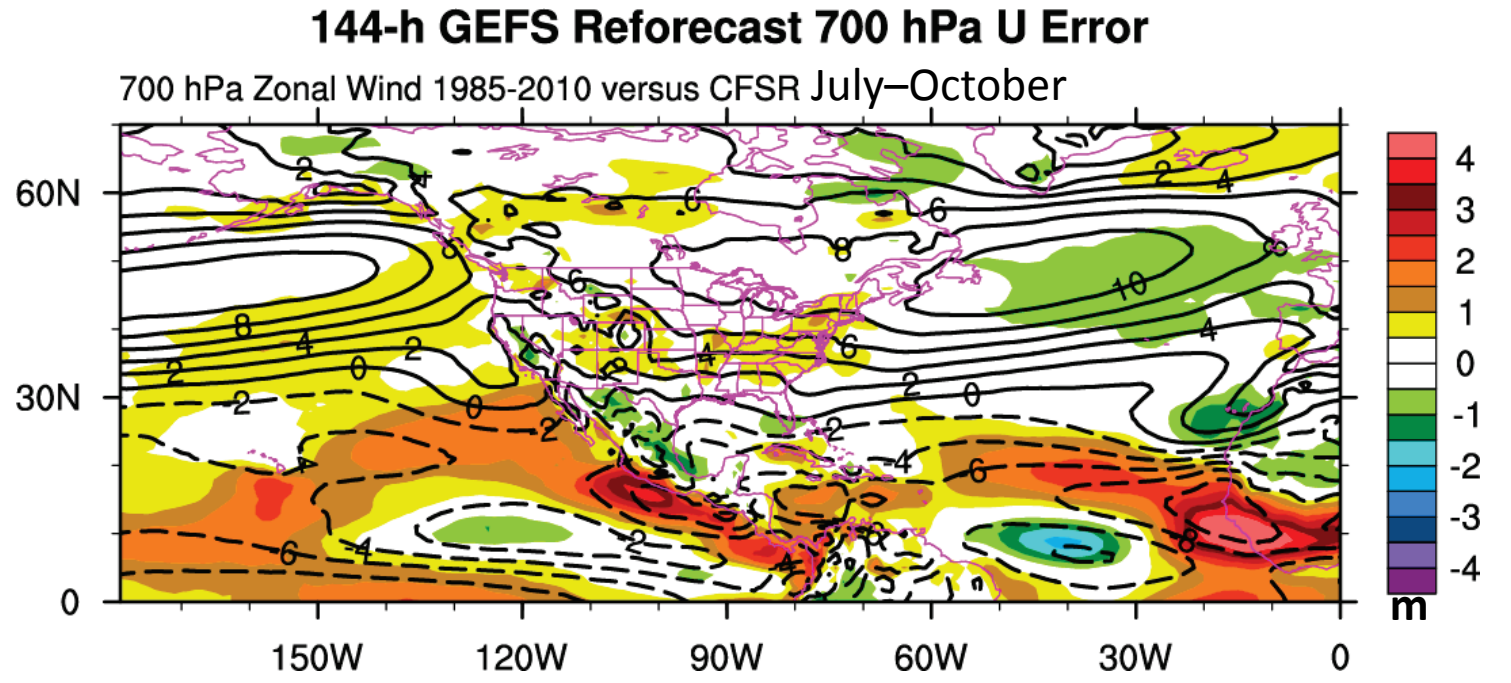


- **Negative height errors in midlatitudes and positive height errors in tropics is consistent with weaker easterly subtropical flow by 72 h**



- **Weaker easterly steering flow likely contributes to slow error for pre-recurvature systems**





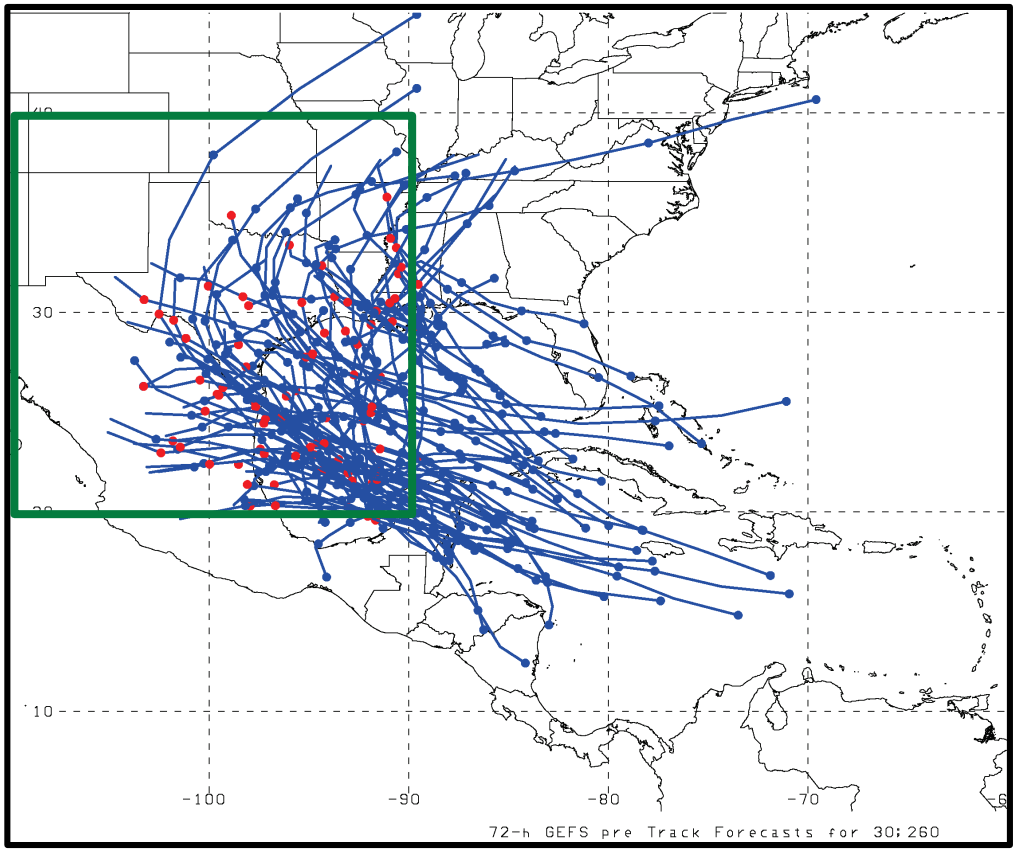
- **Enhanced troughing over eastern North America consistent with early recurvature**
- **Enhanced troughing in Gulf of Alaska suggests slower eastward progression of transients; related to L.O.T. error in western Gulf?**

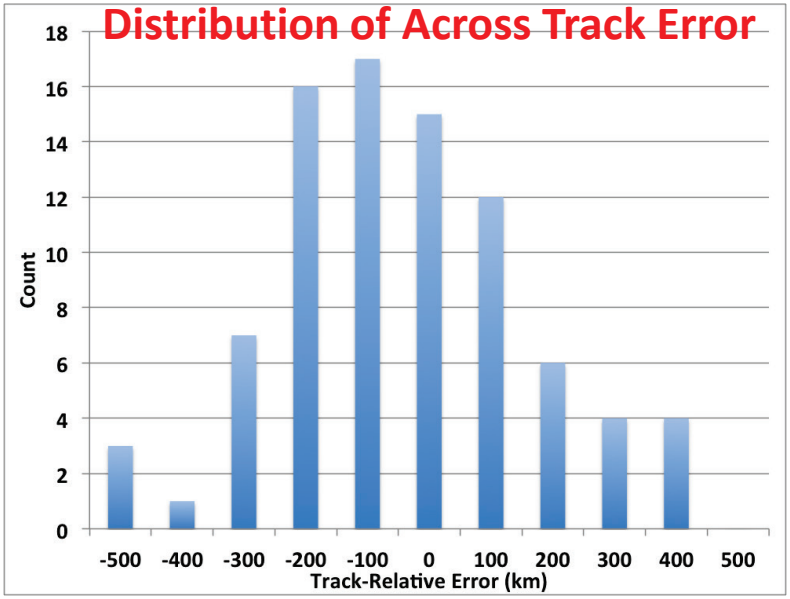
Western G.O.M. Late-Recurvature TC Composite Analysis and Case Study

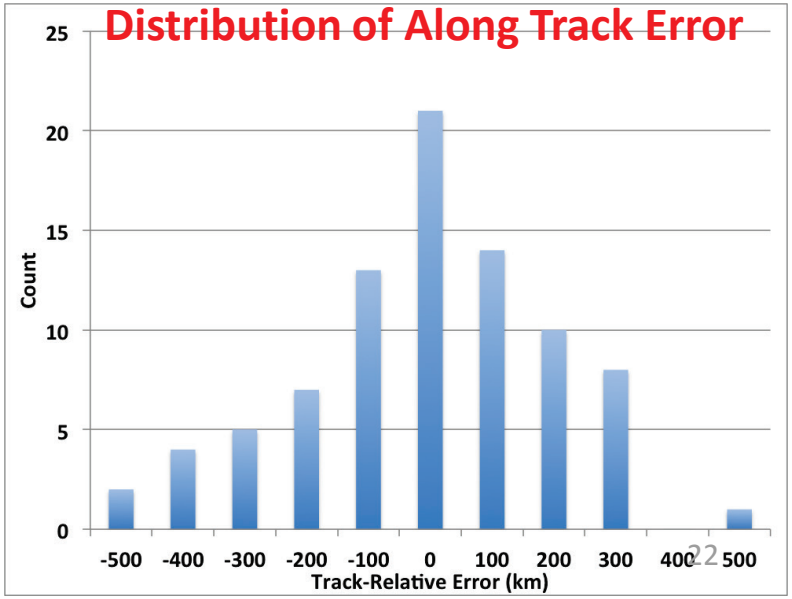
- **Left-of-track errors are characteristic of TC track forecasts in the western Gulf of Mexico**
- **TC-relative composites highlight contributions from synoptic-scale flow forecast errors**
- **Case study analysis of TC Rita (2005) forecast initialized at 00Z/22 Sept shows complexity of vortex-environment interaction**

Western G.O.M. 72-h TC Track Forecasts

Forecast TC Tracks with 72-h Forecast Position in Green Box



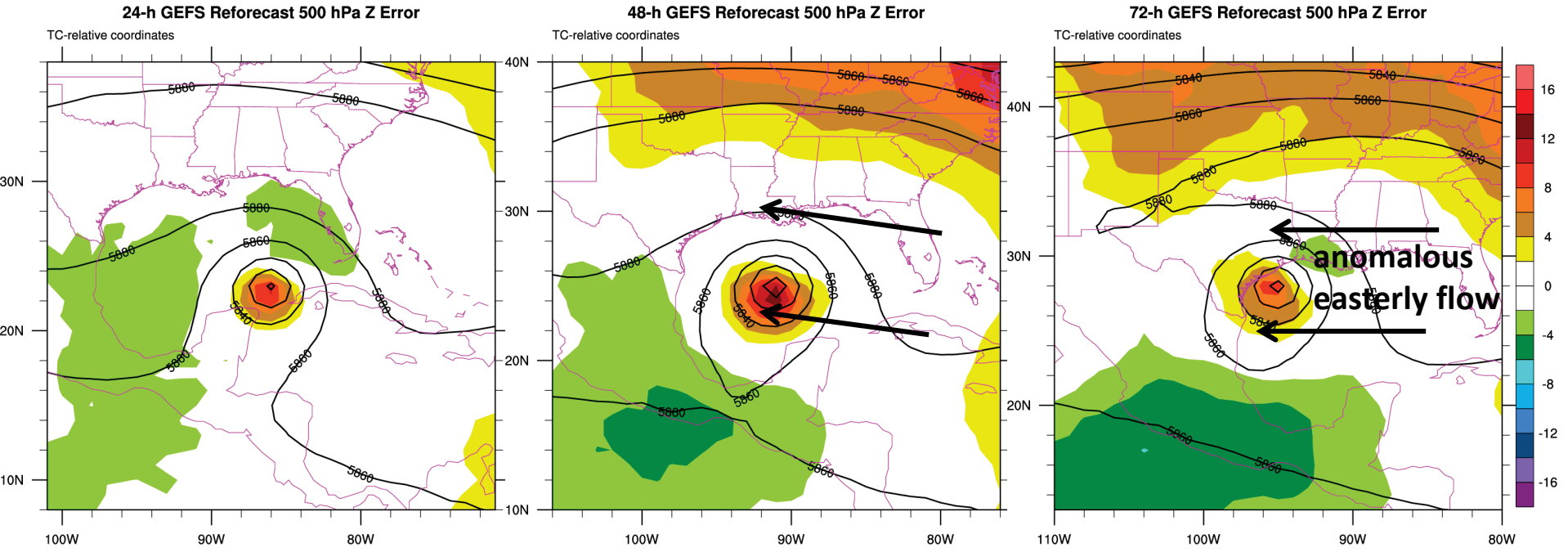




- **Distribution of across-track error skewed to left-of-track**

TC-Relative Composite 500 hPa Z

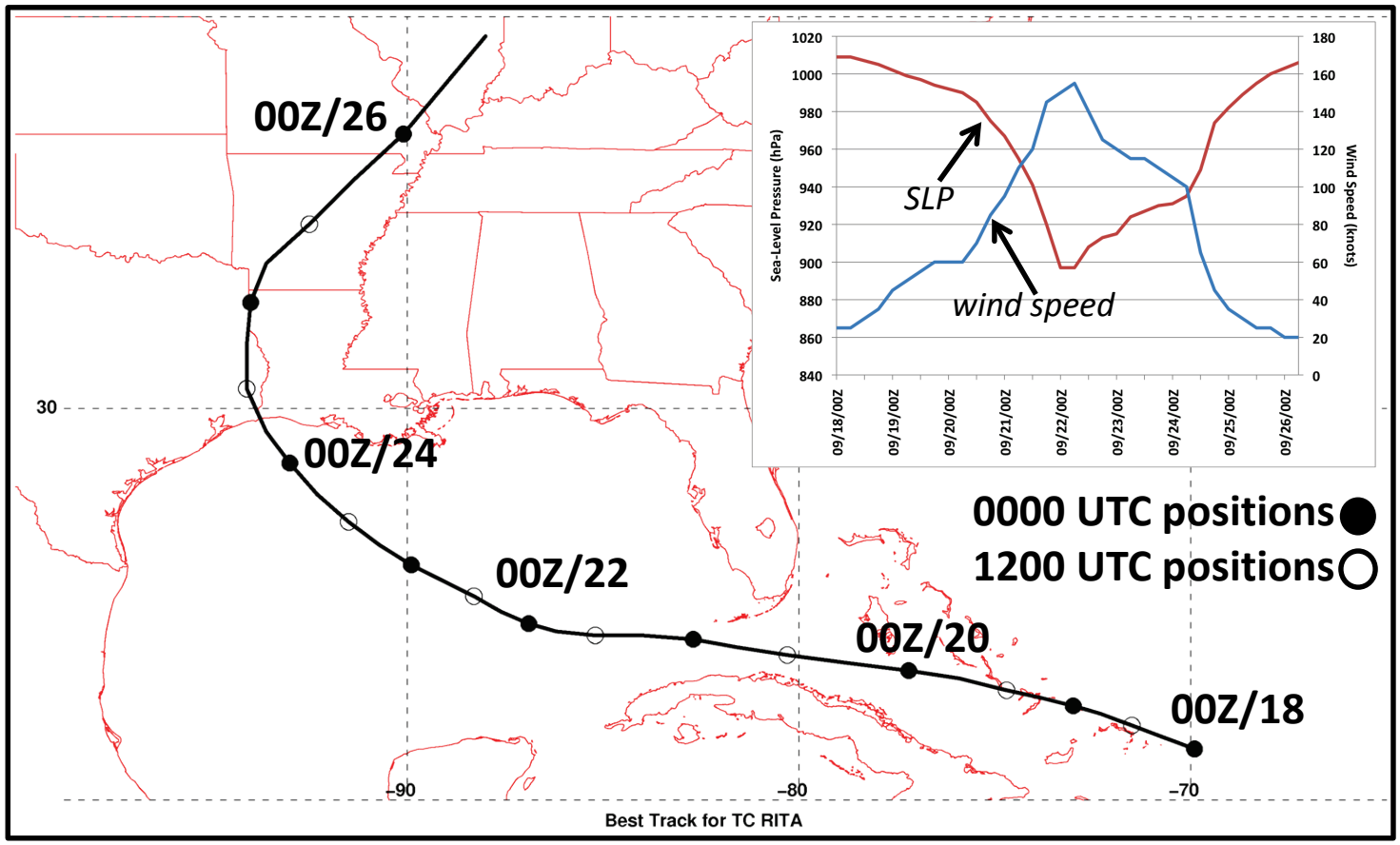
Composite (n=85) 500 hPa Height (every 20 m) and Height Error (shaded in m)



- **TC-relative composite for western G.O.M. TC forecasts shows negative (positive) height errors south (north) of the TC**
- **Height error configuration consistent with anomalous easterly steering flow – a contributor to left-of-track error**

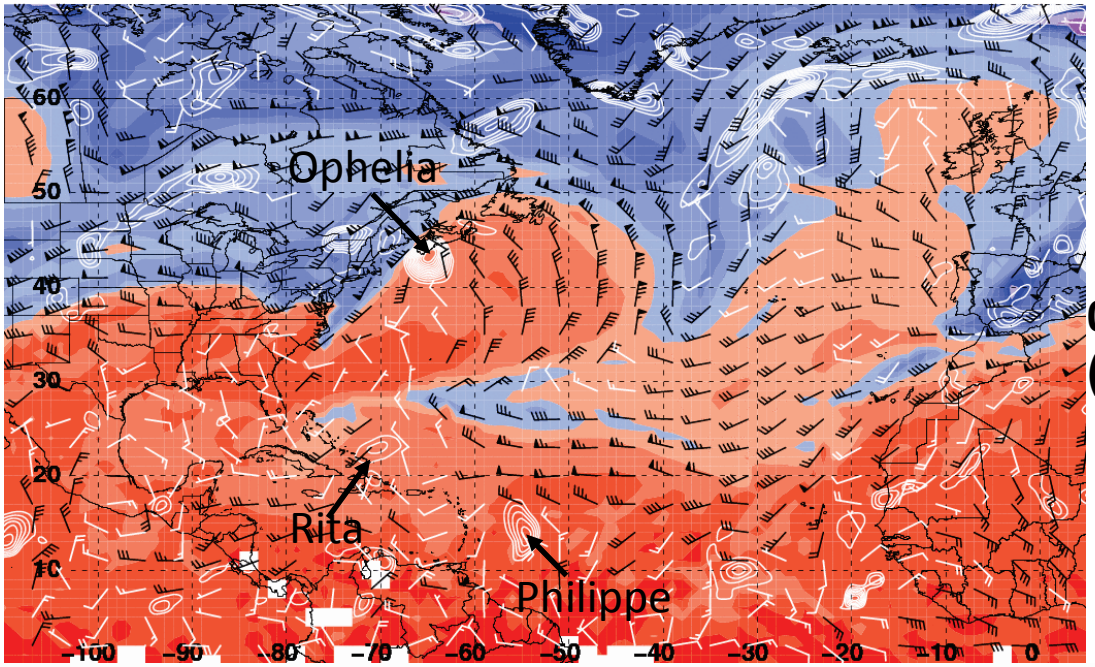
G.O.M. Case Study: TC Rita (2005)

- Example of recurving TC over western Gulf of Mexico
- Explore factors contributing to TC track forecast errors

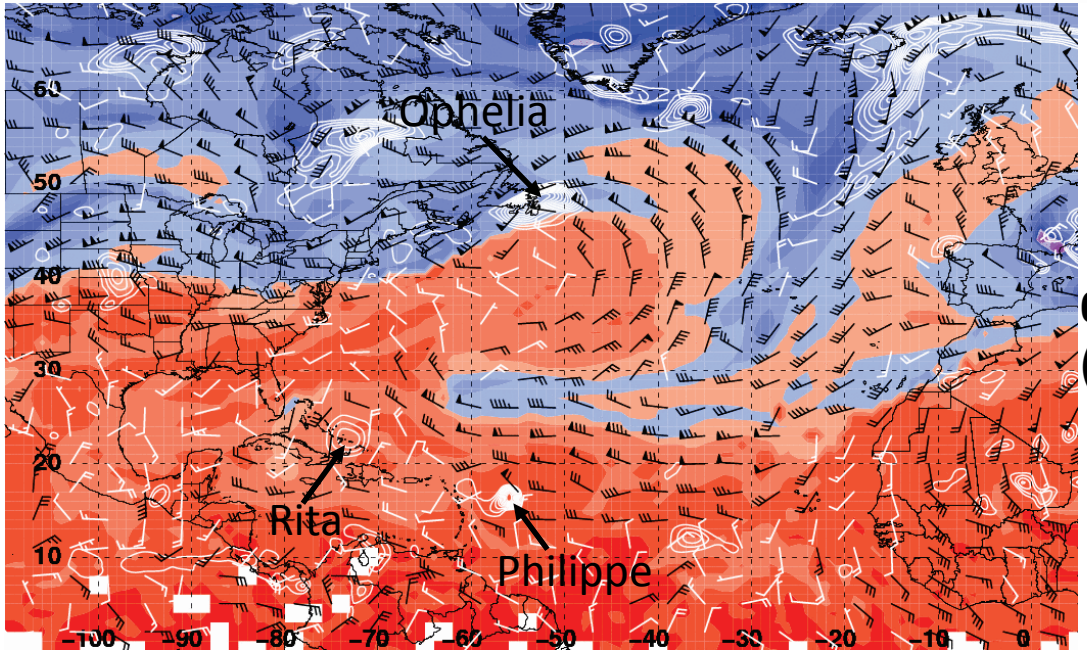


DT pressure (hPa), DT–850 hPa vertical wind shear (knots), and 925–850 hPa layer-mean vorticity ($\times 10^{-5}$ s^{-1})

- Anticyclonic wave breaking (enhanced by Ophelia) drove upper-level PV streamer into subtropics
- Pre-Rita disturbance interacted with trough and developed
- As Rita developed, upper-level trough fractured and weakened – reduced vertical wind shear



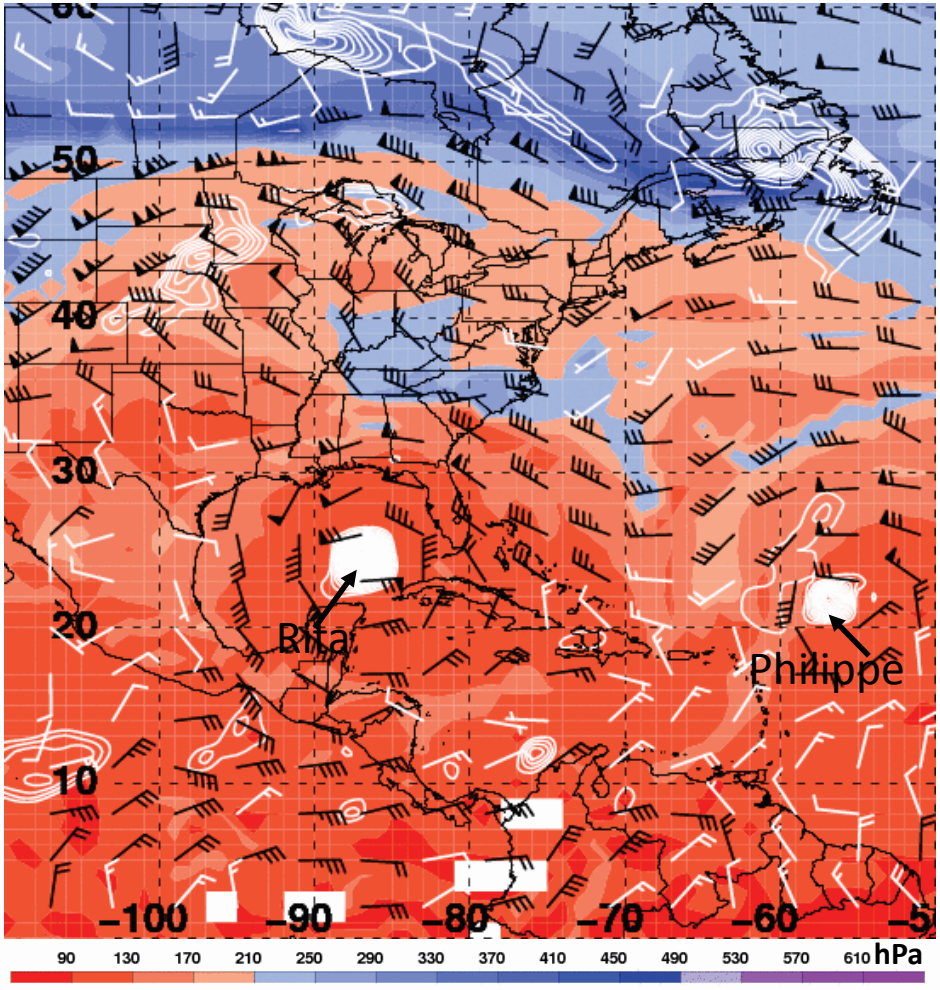
00Z/18 Sept 2005
(Tropical Depression)

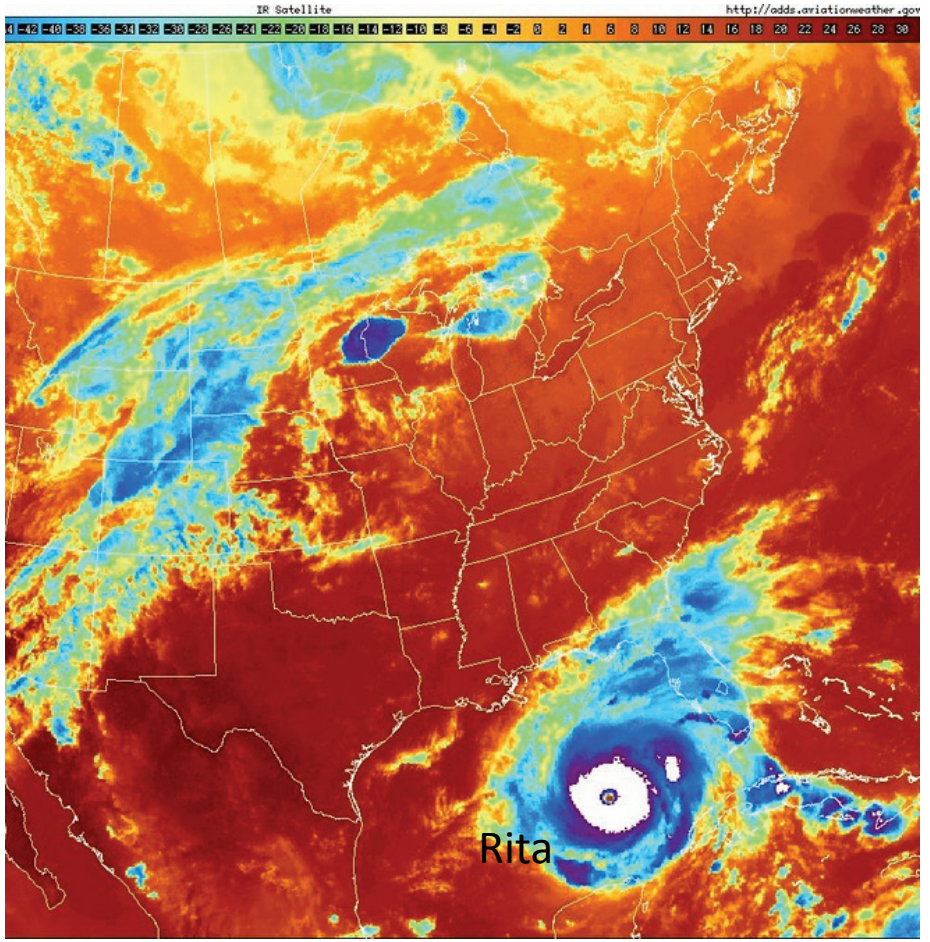


00Z/19 Sept 2005
(Tropical Storm)

Data: GFS analysis

DT Analysis and IR Imagery: 00Z/22 Sept 2005

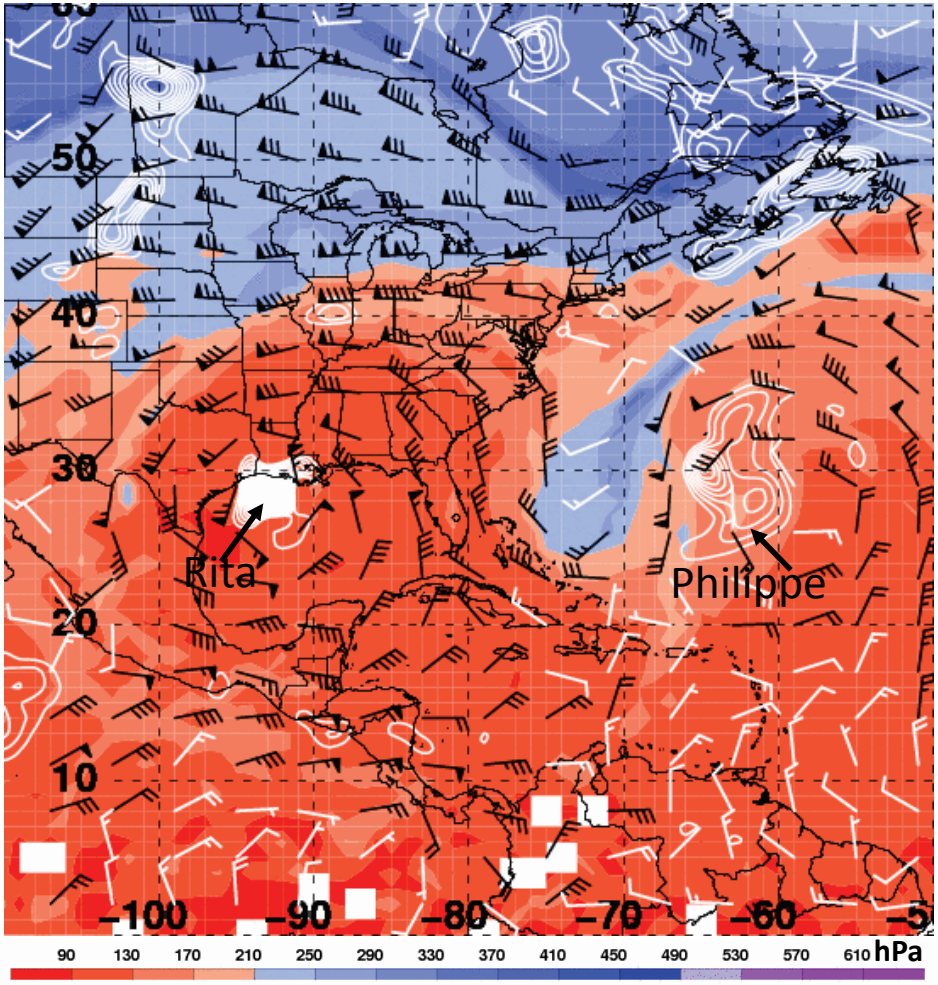


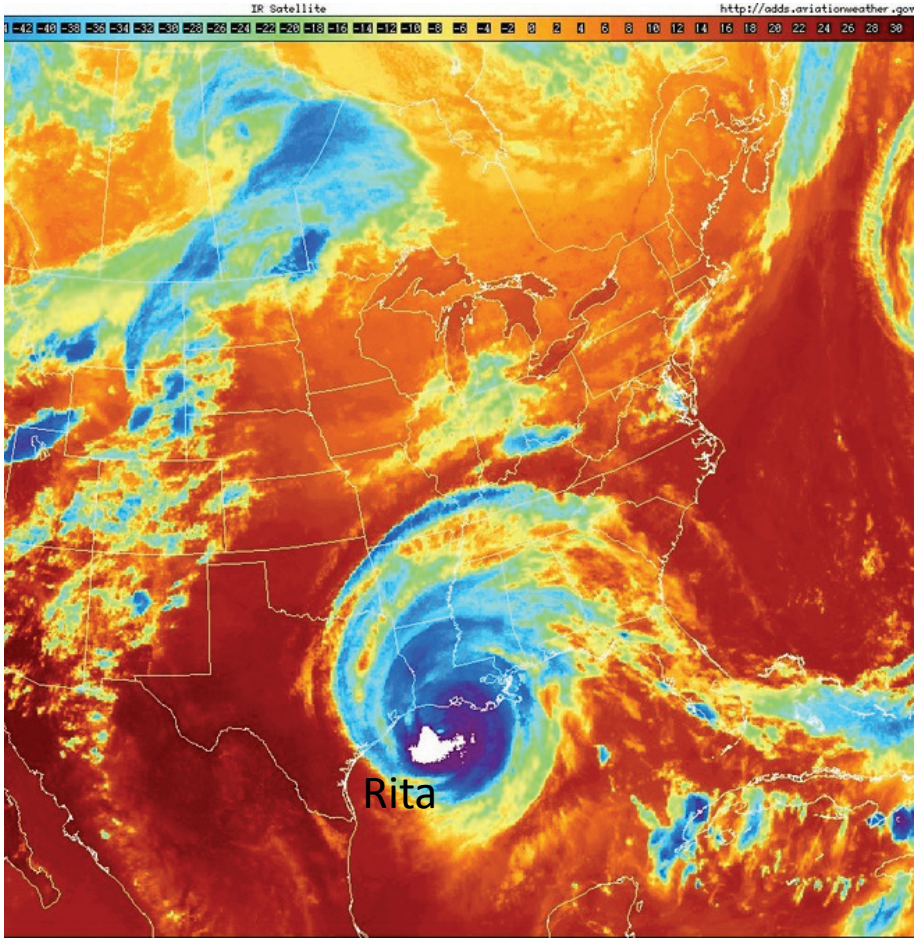


Source: NCAR case selection archive

Data: GFS analysis

DT Analysis and IR Imagery: 00Z/24 Sept 2005

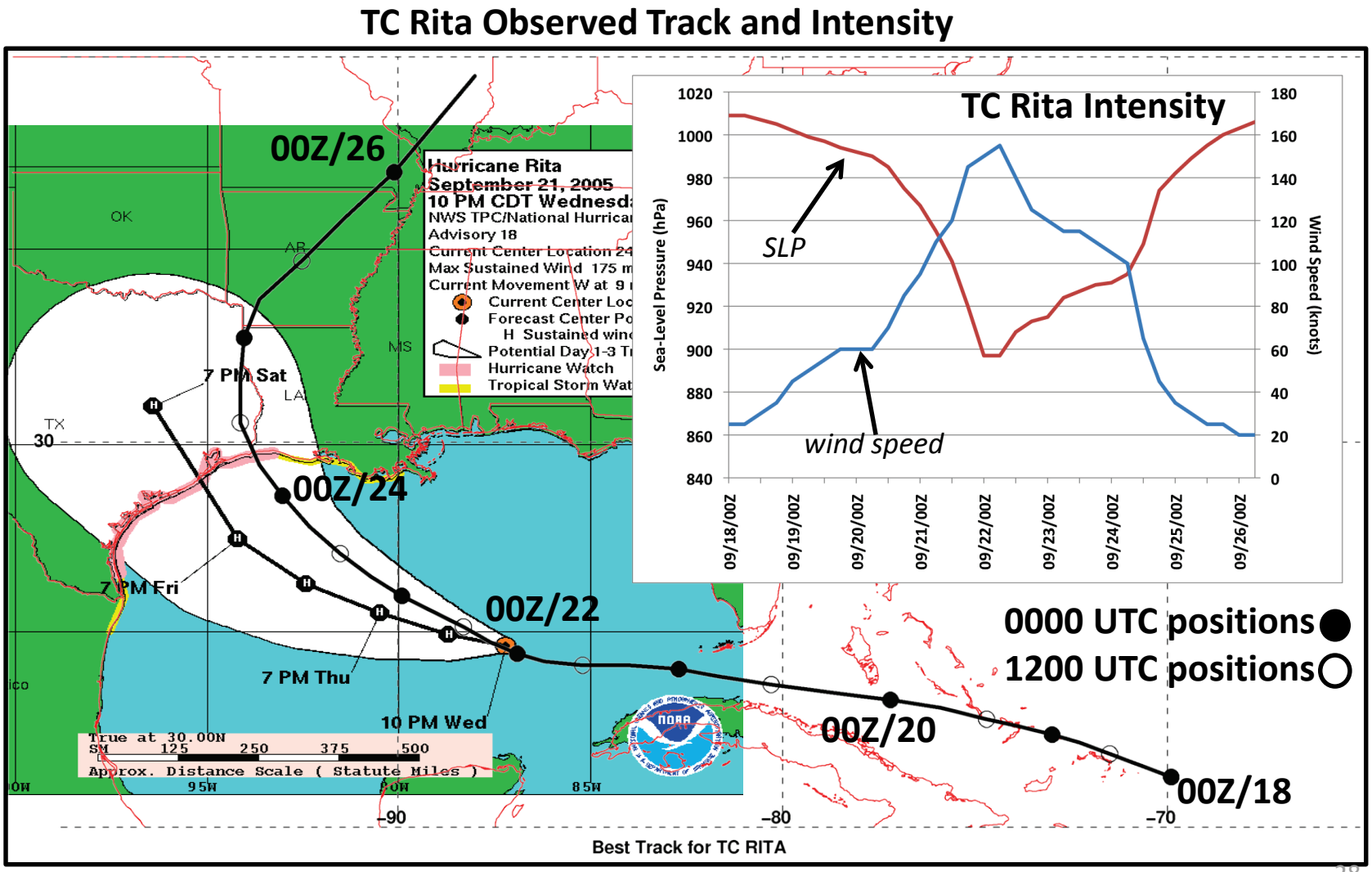




Source: NCAR case selection archive

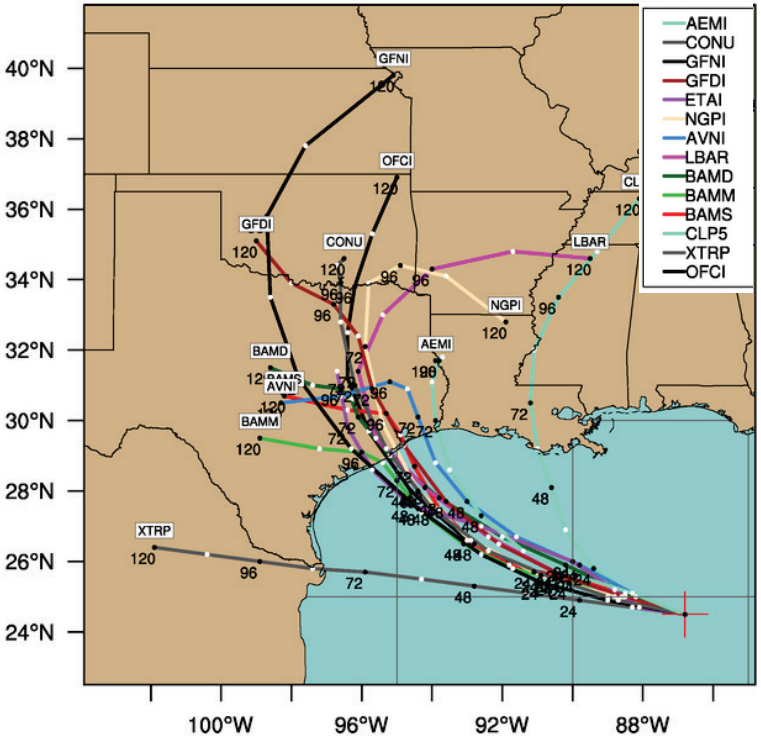
Data: GFS analysis

TC Rita Best Track and Official Forecast (issued 03Z/22 Sept 2005)

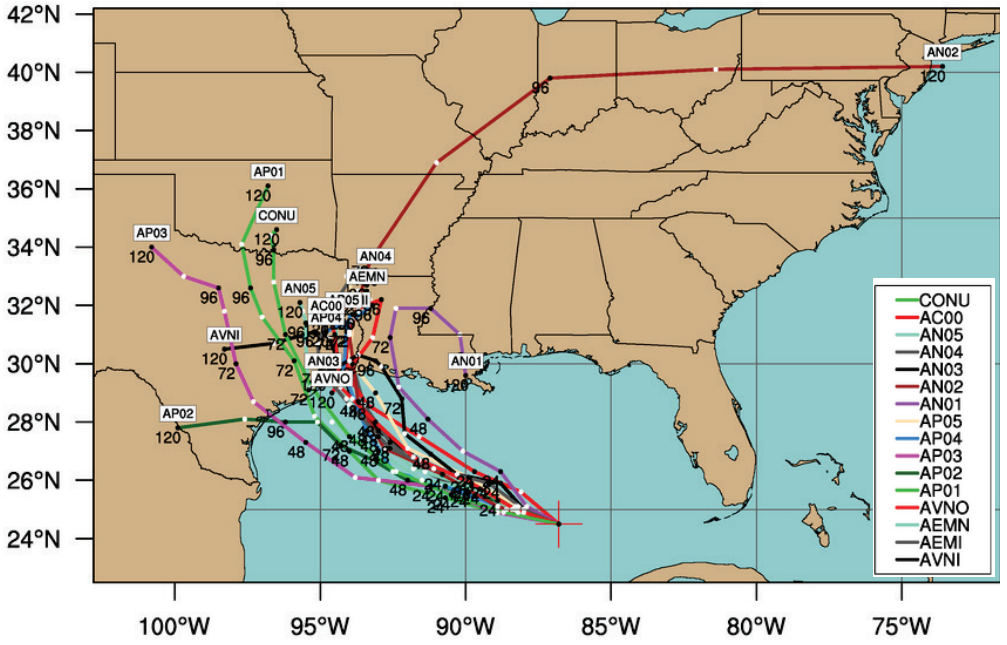


Operational Track Forecast Guidance: Initialized 0000 UTC 22 Sept 2005

Early-Cycle Track Guidance (i00Z/22)



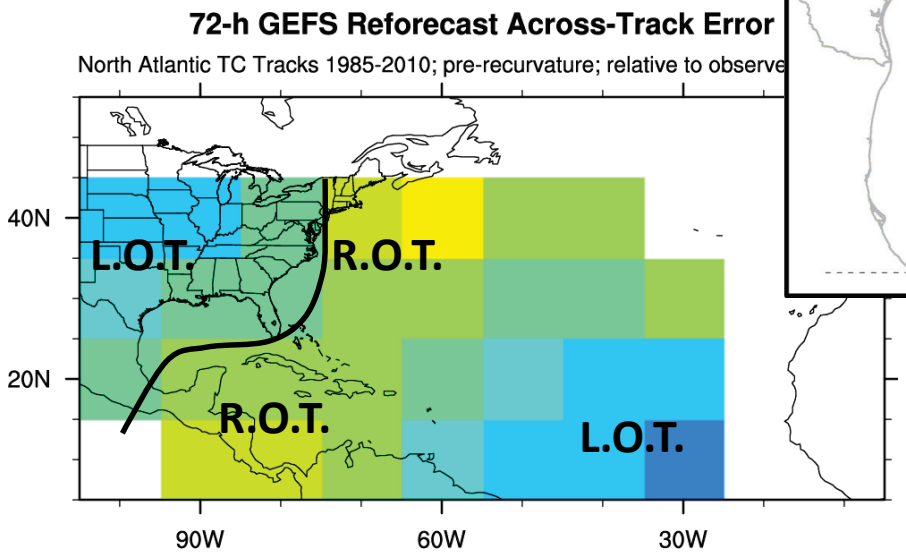
NCEP GFS Ensemble Track Guidance (i00Z/22)

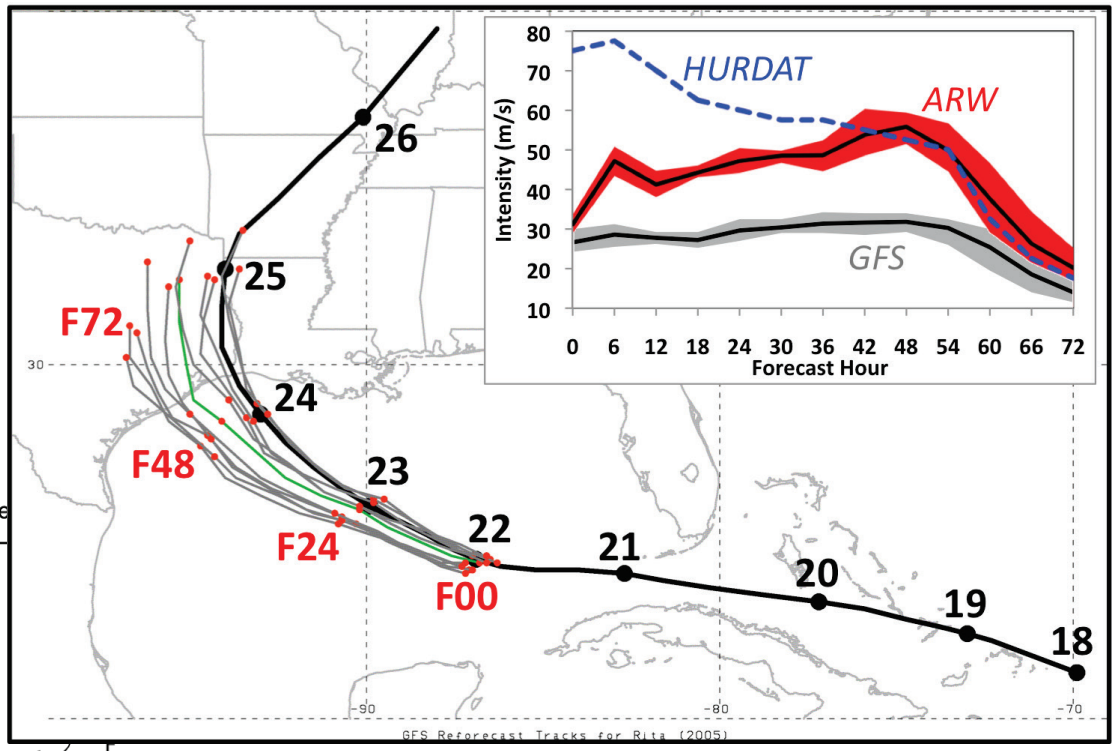


Source: J. Vigh (http://www.ral.ucar.edu/hurricanes/)

Reforecast Track Forecast Guidance: Initialized 0000 UTC 22 Sept 2005

- Global reforecast ensemble is consistent with NHC forecast; indicating potential impact on Houston
- Significant left-of-track error and intensity was underestimated
- Illustrative example of L.O.T. bias in western G.O.M. (1985–2010)





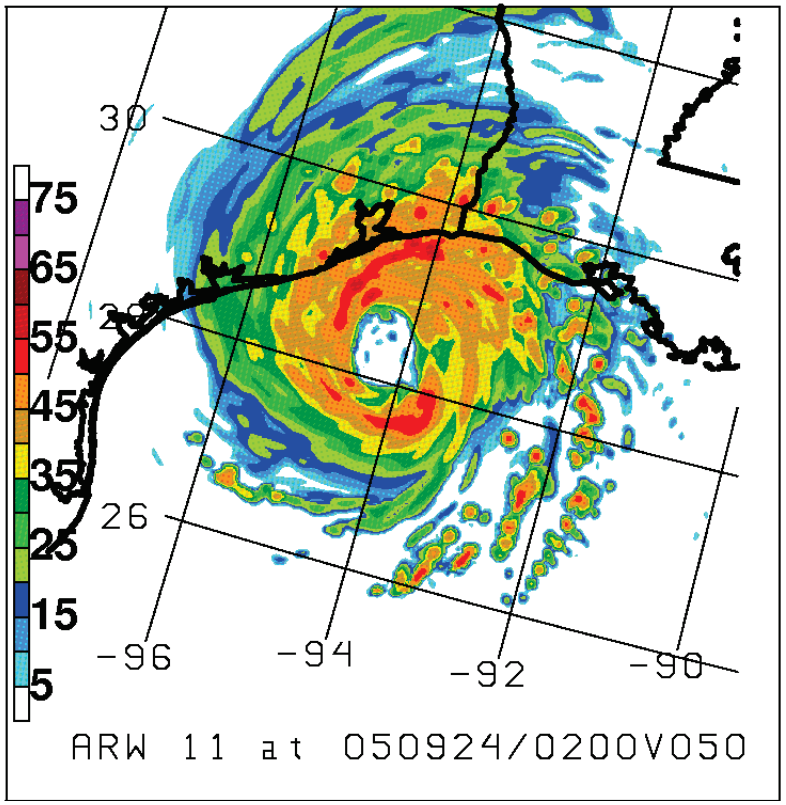
HURDAT

GEFS reforecast control member

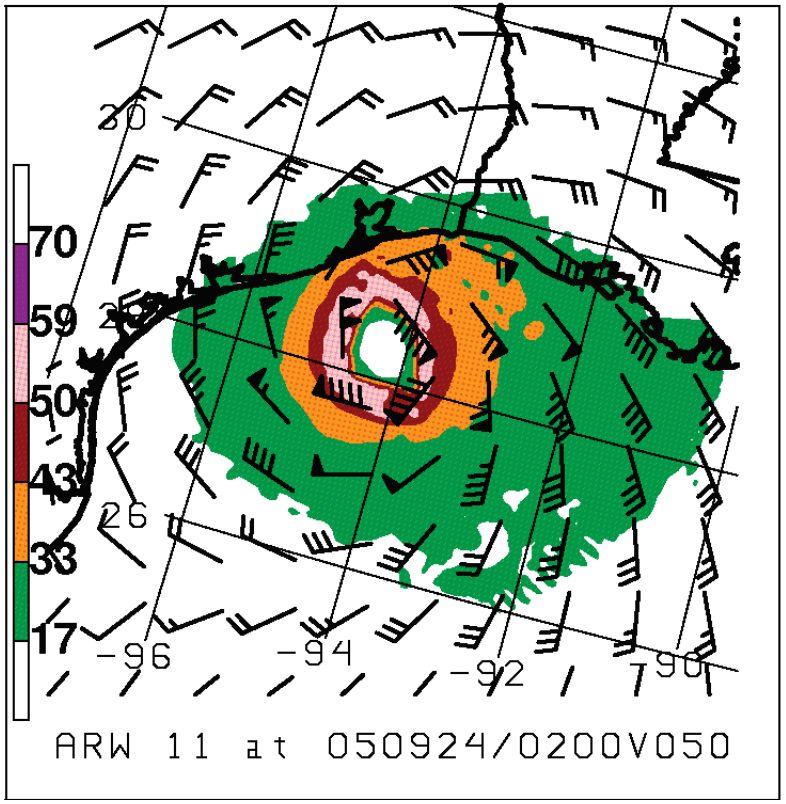
GEFS reforecast perturbation members

Use of "Regional Reforecasts"

AHW Composite Reflectivity



AHW 10-m Wind

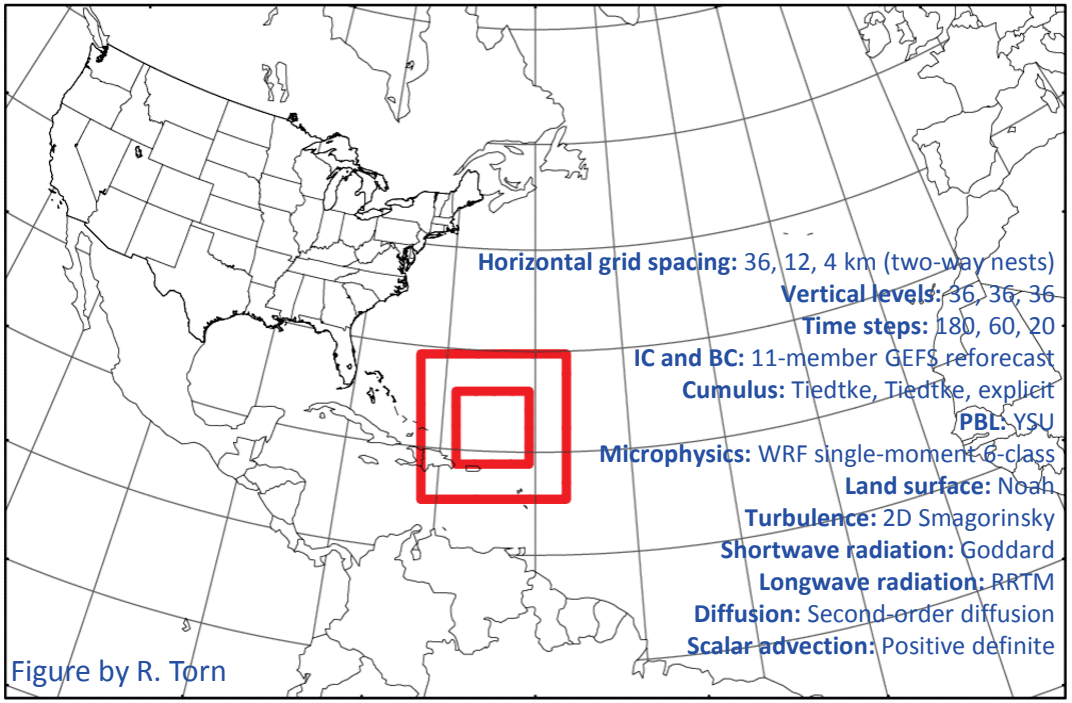


AHW 50-h forecast verifying at 02Z/24 September 2005 (Control member)

- **AHW regional ensemble simulation of Rita using global reforecast data as IC/BCs**
- **Do not get false skill from using analysis data as IC/BCs**
- **Will examine factors that influenced forecast track errors**
- **Might information from explicit nest help improve global forecast?**

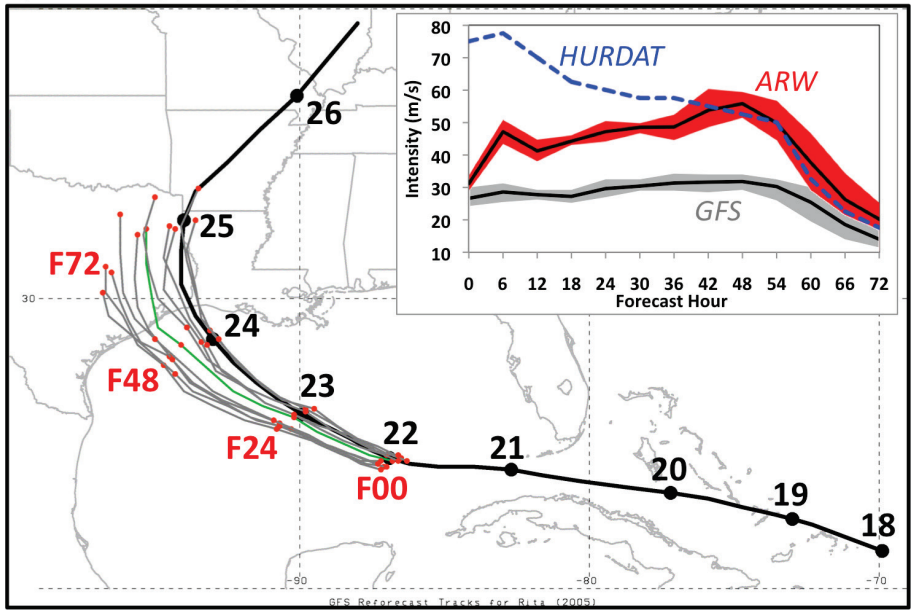
Regional Model Ensemble Configuration

- **Use Advanced Hurricane WRF (AHW), 2011 HFIP retrospective configuration (Davis et al. 2008, 2010)**
- **Initial and 3-hourly boundary conditions from 11-member GEFS reforecast dataset (full grids from DOE)**
- **Generated 11-member AHW ensemble 72-h forecast**
- **Initialized at 00Z/22 Sept 2005 – threat for Houston, Texas**

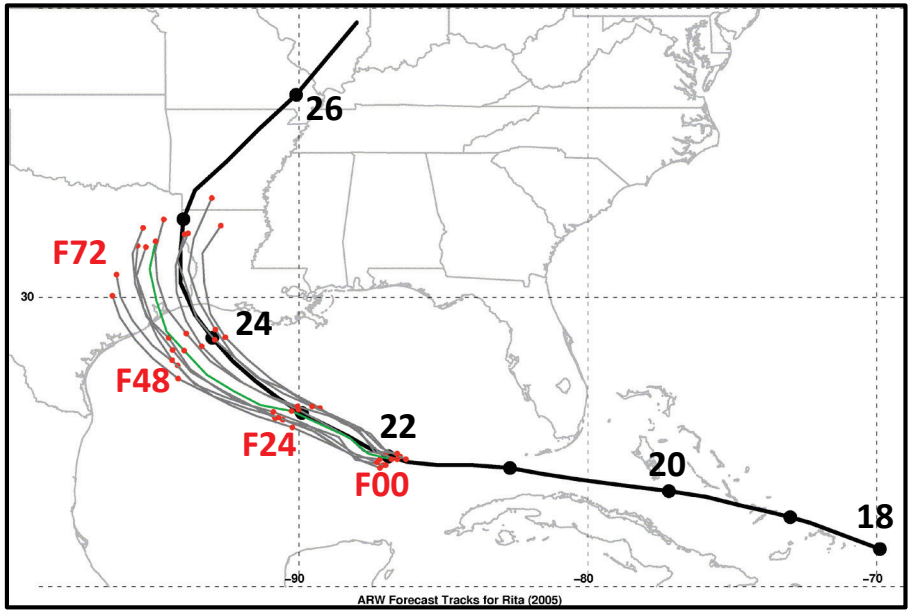


AHW Reforecast Ensemble Results

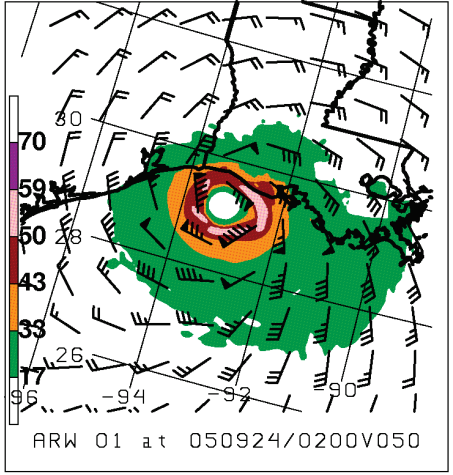
a) TC Rita (2005) 72-h GFS Ensemble Reforecast

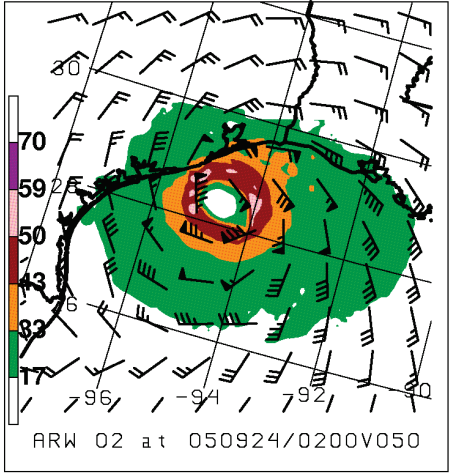


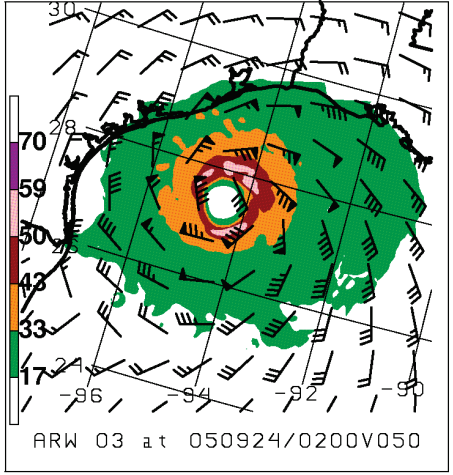
b) TC Rita (2005) 72-h AHW Ensemble Reforecast

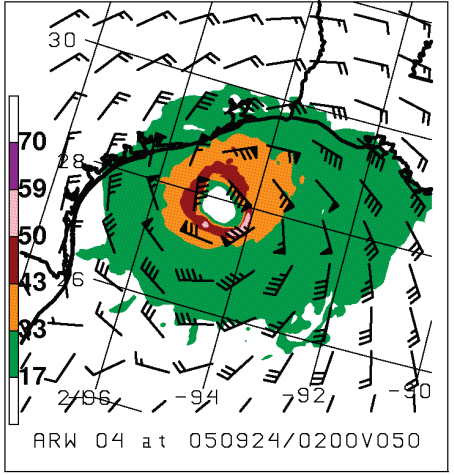


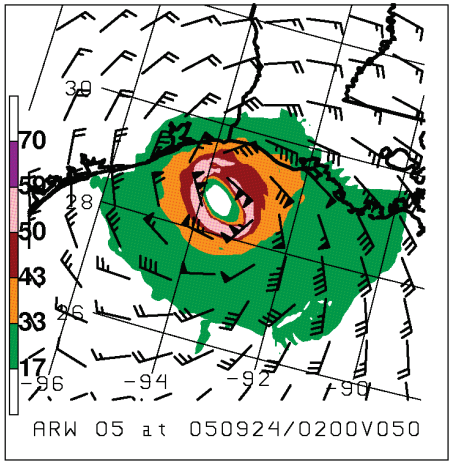
- Rita vortex intensified in AHW regional reforecast despite terrible initial vortex
- Similar left-of-track error in AHW; suggests large-scale control on TC motion

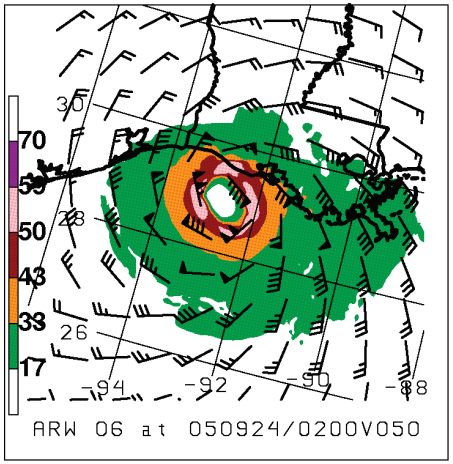


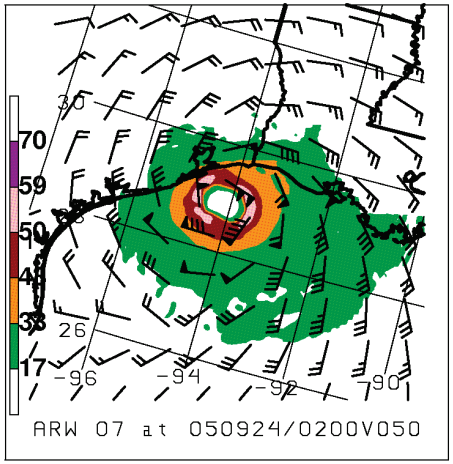


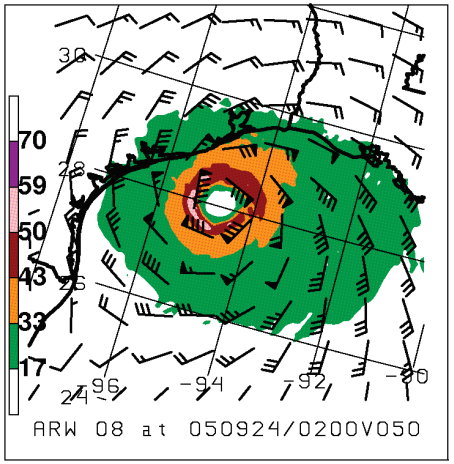


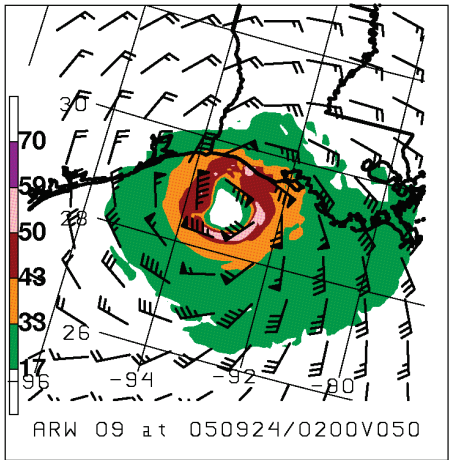


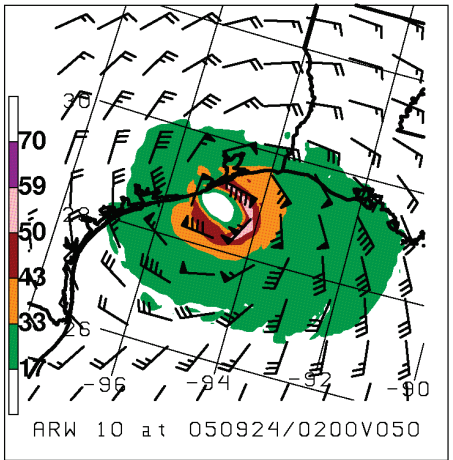


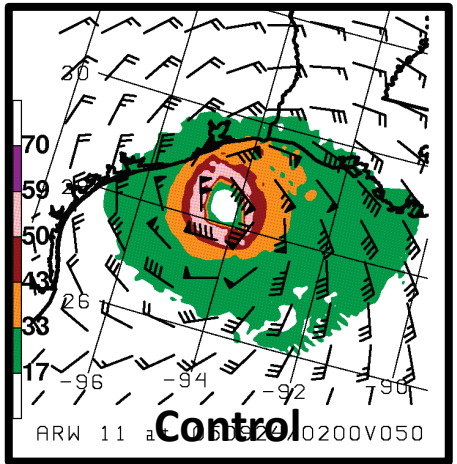








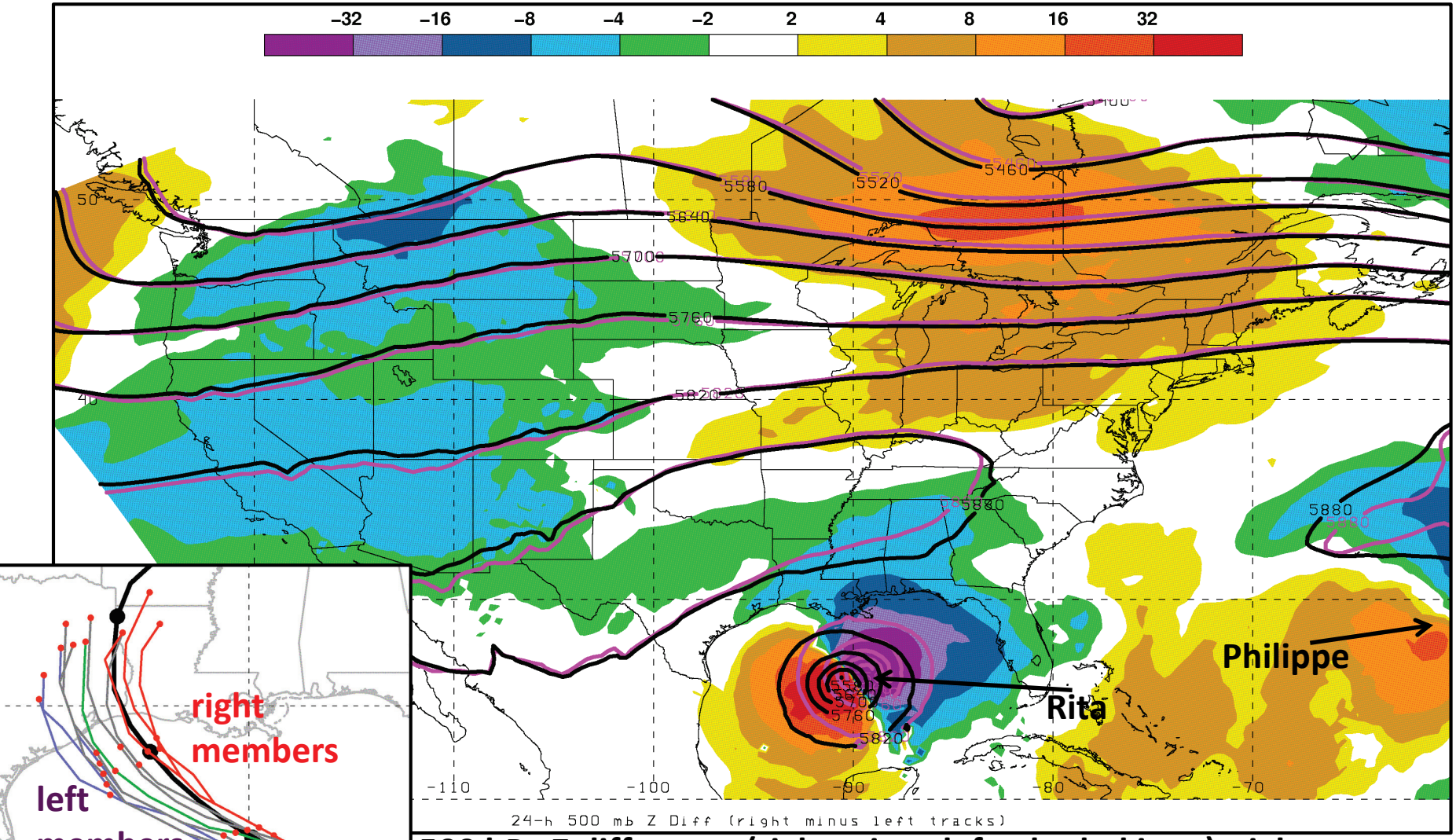




10-m wind speed (m/s)
10-m wind (barbs in knots)
50-h AHW Forecast
Verifying 02Z/24 Sep '05

Ensemble Analysis: 500 hPa Z

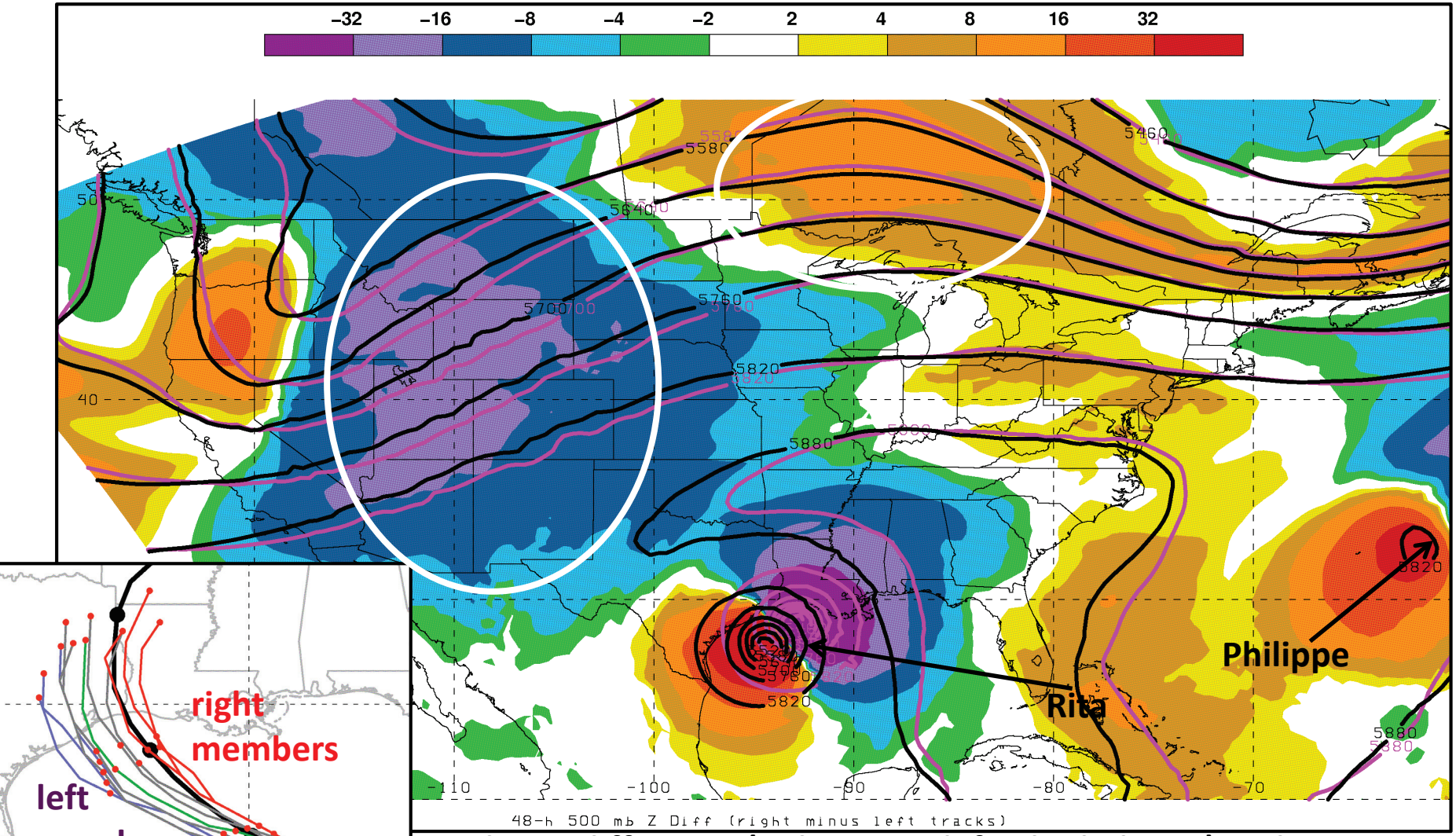
24-h AHW Forecast (36-km domain) verifying 0000 UTC 23 Sep 2005



500 hPa Z difference (right minus left; shaded in m), right mean (magenta every 60 m), and left mean (black every 60 m)

Ensemble Analysis: 500 hPa Z

48-h AHW Forecast (36-km domain) verifying 0000 UTC 24 Sep 2005



500 hPa Z difference (right minus left; shaded in m), right mean (magenta every 60 m), and left mean (black every 60 m)

Steering Flow Definition

- **The environment wind (v_{env}) is the residual wind that results from the removal of local winds associated with the TC vortex**
  - **Remove all ζ and δ within a radius, *r***

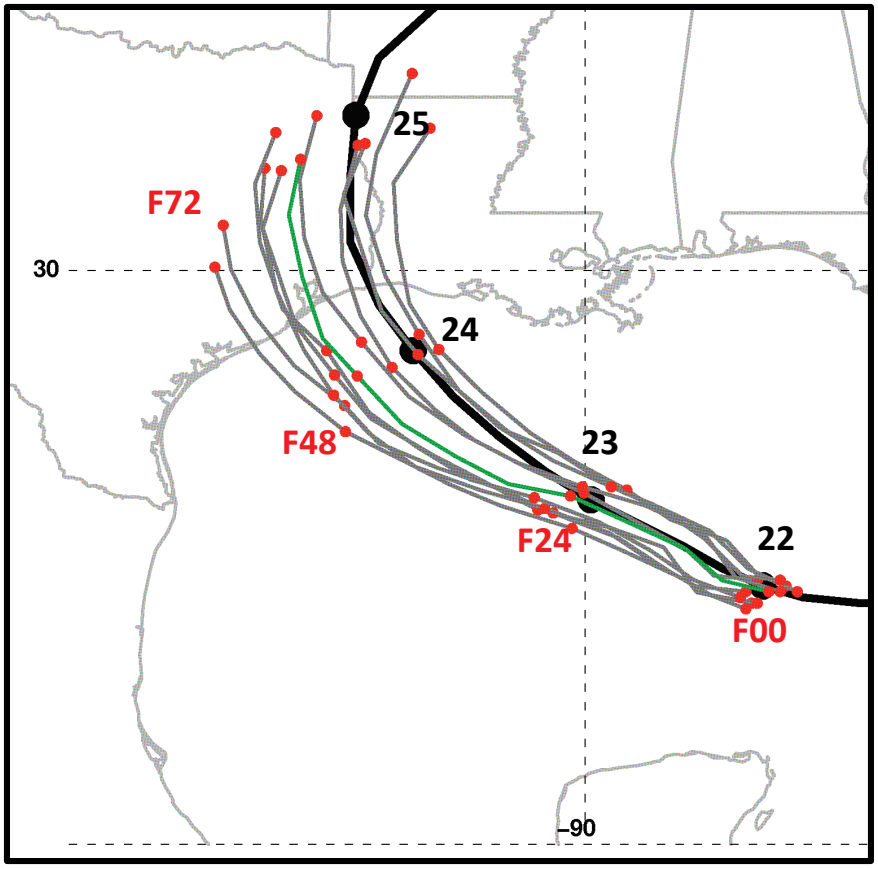
- **The steering flow is the spatially averaged v_{env} that matches the TC motion, and so is a function of v_{env}**

Steering Flow Computation

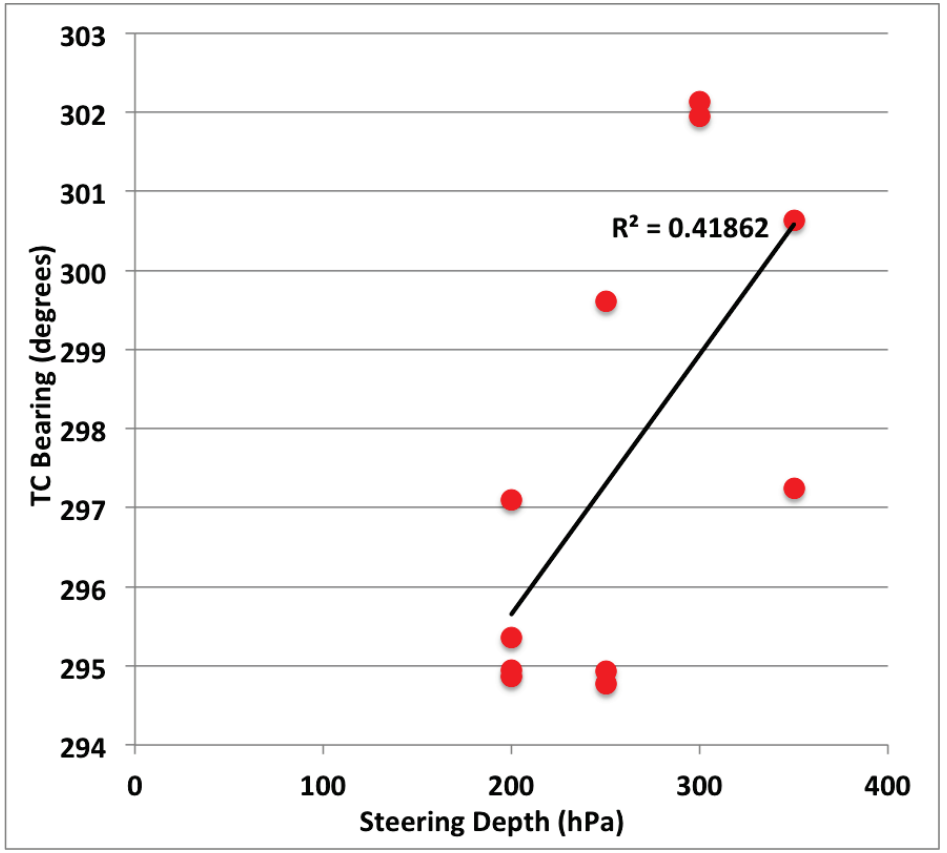
- Compute an area-average v_{env} every 50 hPa in the 850–200 hPa layer using eight different radii ranging from 1°–8° from the TC center
- Compute the pressure-weighted vertical average v_{env} for layers of increasing depth
  - shallowest layer of 850–800 hPa
  - deepest layer of 850–200 hPa
- Select the steering flow depth and radius combination that best matches TC motion
  - minimize steering layer residual error

Steering Flow Analysis

TC Rita (2005) 72-h AHW Ensemble Reforecast



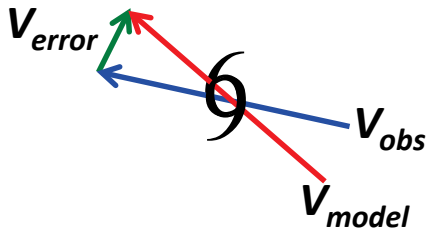
24-h AHW forecast TC Motion versus Optimal Depth



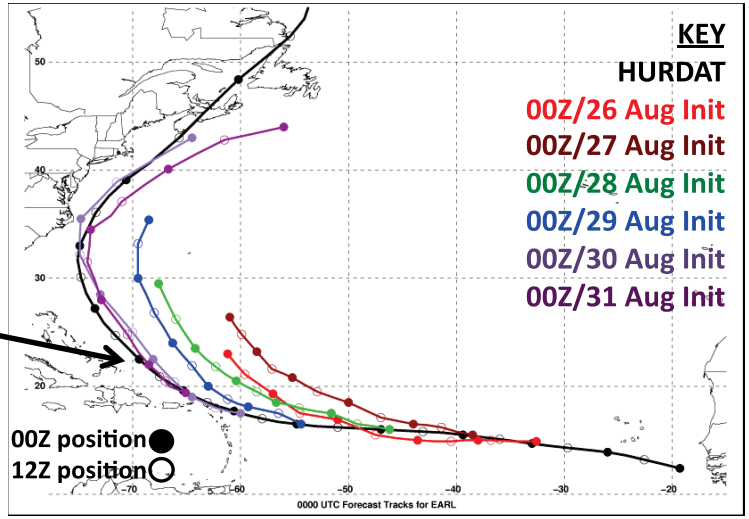
- Steering flow analysis suggests that forecasted TCs with more westward component to motion responded to a shallower steering layer depth
- Will now diagnose motion differences for two ensemble members

Methodology: Diagnosing Forecast Errors in Tropical Cyclone Motion

- Method for computing steering layer flow and diagnosing TC motion errors in any NWP model
- Allows quantification of the intersection between TC structure and position errors



AHW TC Earl (2010) Track Forecasts



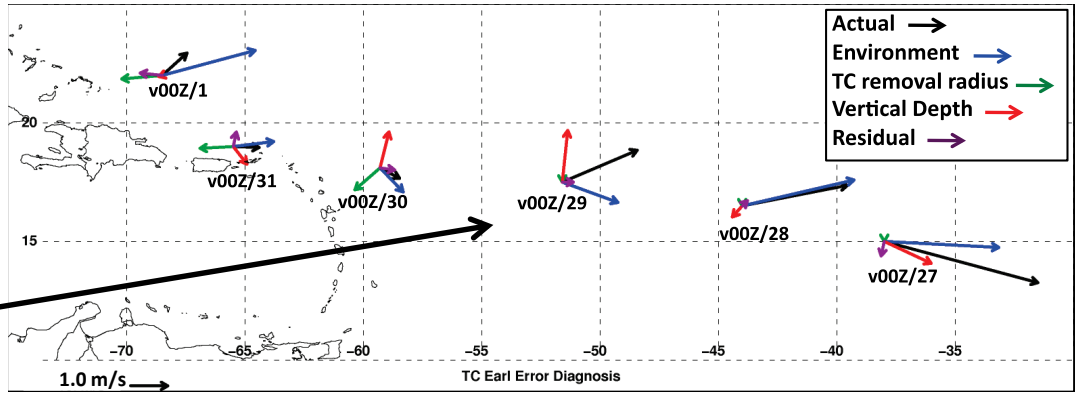
Slow, right of track error in AHW

$$\underbrace{\mathbf{V}_m - \mathbf{V}_o}_{\text{storm motion error}} = \underbrace{\frac{1}{p_b - p_{t,o}} \int_{p_{t,o}}^{p_b} (\hat{\mathbf{v}}_m - \mathbf{v}_o)\, dp}_{\text{environment wind error}} + \underbrace{\frac{1}{p_b - p_{t,m}} \int_{p_{t,m}}^{p_b} -(\hat{\mathbf{v}}_m - \mathbf{v}_m)\, dp}_{\text{TC removal radius error}}$$

$$+ \underbrace{\frac{1}{p_b - p_{t,m}} \left[\int_{p_{t,o}}^{p_b} \left(\frac{p_{t,m} - p_{t,o}}{p_b - p_{t,o}} \right) \hat{\mathbf{v}}_m\, dp + \int_{p_{t,m}}^{p_{t,o}} \hat{\mathbf{v}}_m\, dp \right]}_{\text{TC steering depth error}} + \text{residual term}$$

Motion error = Environment wind error
+ near-storm vorticity asymmetry error
+ steering depth error
+ residual error

24-h AHW Forecast TC Earl (2010) Motion Error Diagnosis

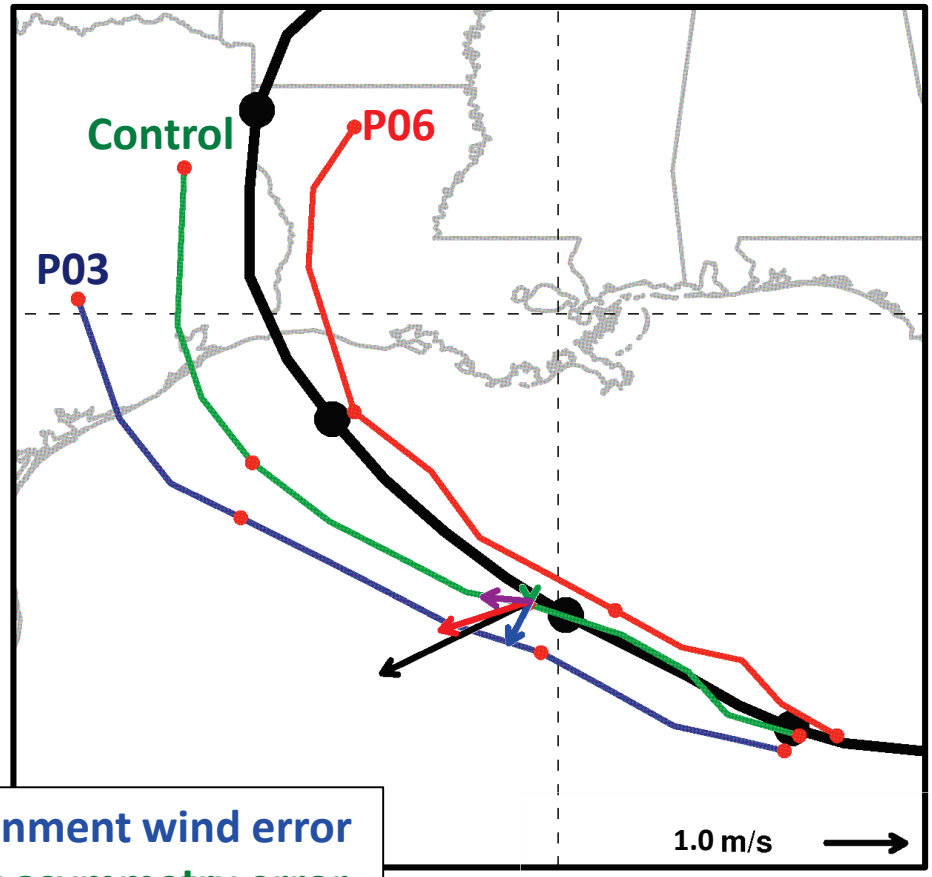


Error attributed to persistent eastward environment wind error; other terms are large at individual times

Ref: Galarneau and Davis (2013), MWR

Diagnose TC Motion Differences in Ensemble Members: Control vs. P06

Motion Error Diagnostic: 24-h AHW forecast v00Z/23



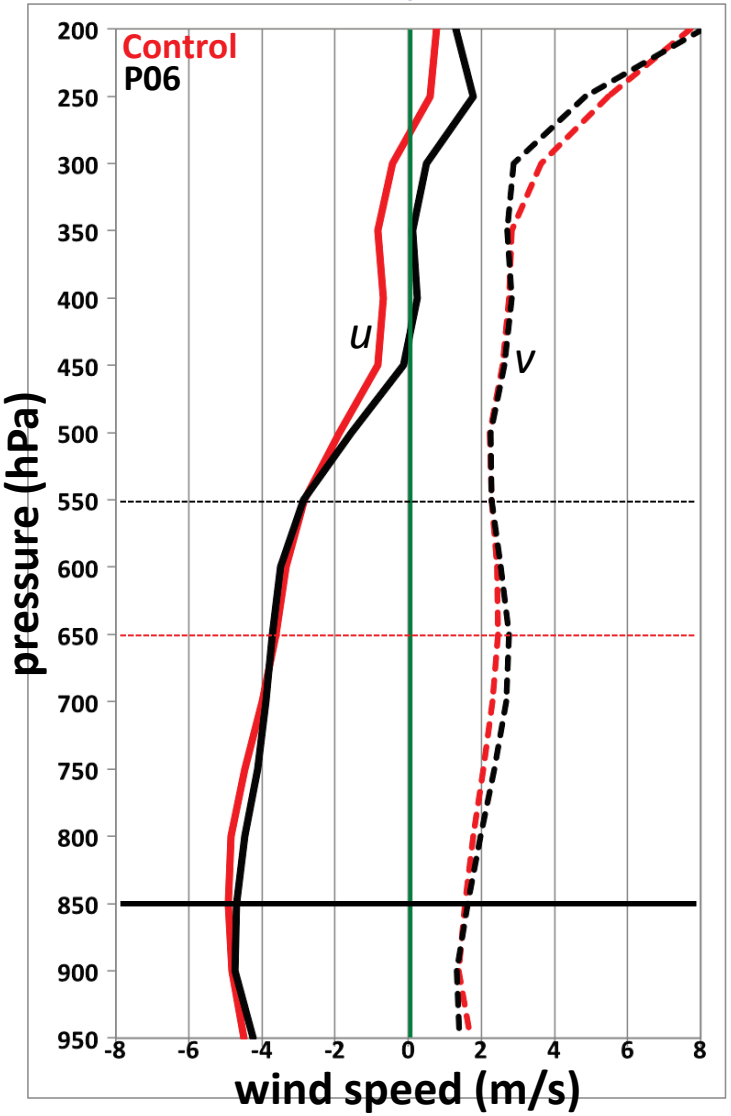
- Southward $\mathbf{V_{env}}$ contribution is consistent with slower progression of midlatitude flow pattern for late-recurving members
- Southwestward steering depth contribution is consistent with shallower steering layer for late-recurving members

Motion error = Environment wind error
+ near-storm vorticity asymmetry error
+ steering depth error
+ residual error

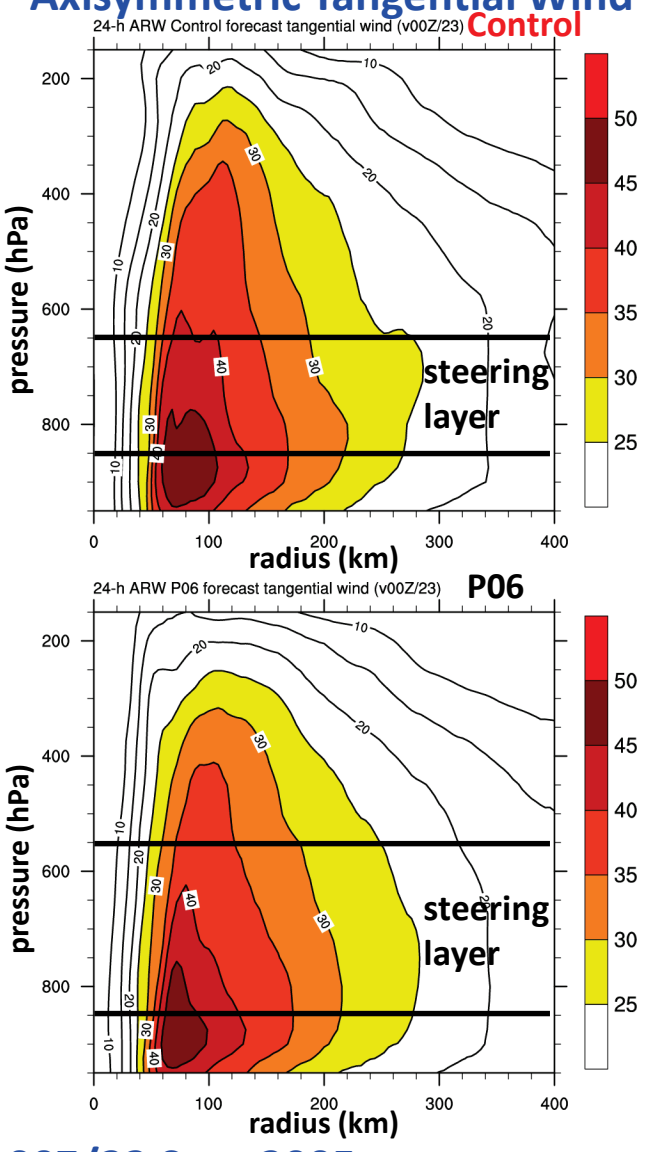
"Error" = Control minus P06

Environment Wind and Vortex Structure

Environment Wind (vortex removed)



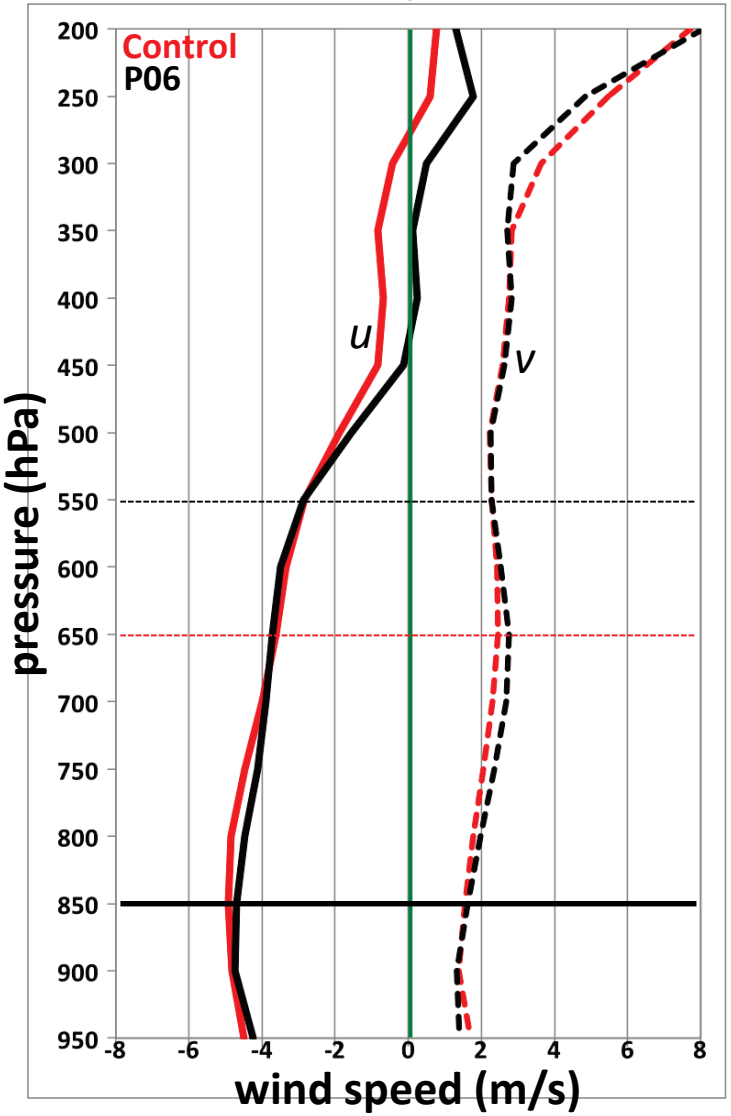
Axisymmetric Tangential Wind



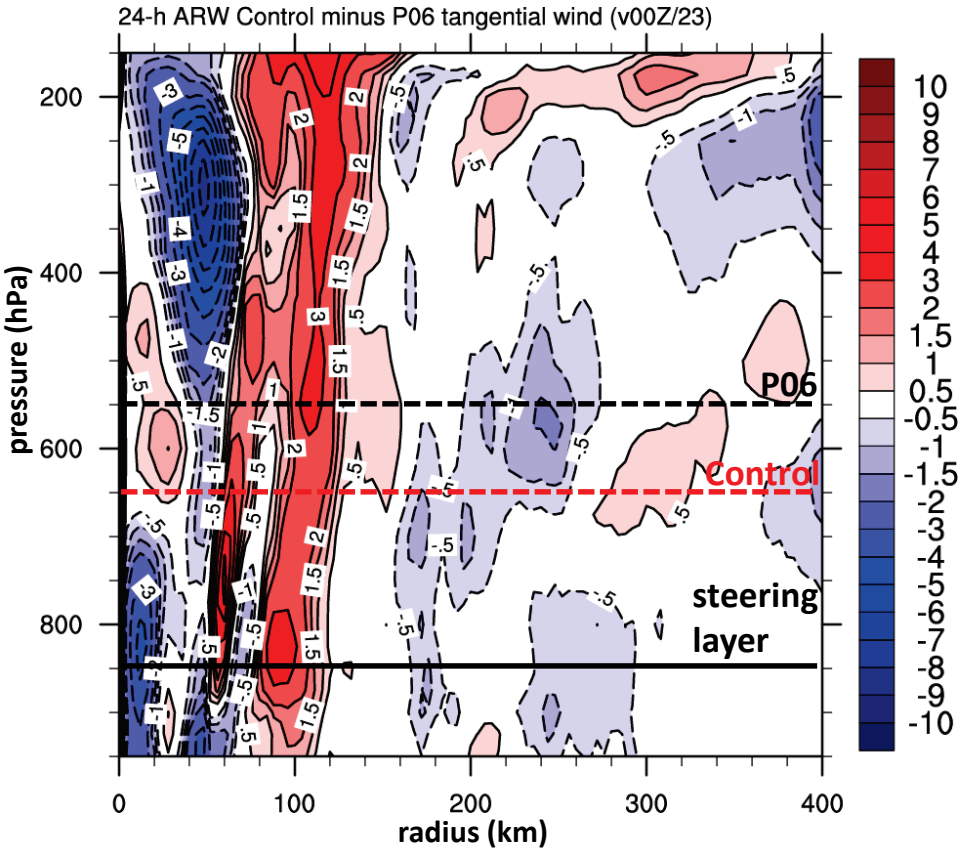
24-h Forecast verifying at 00Z/23 Sept 2005

Environment Wind and Vortex Structure

Environment Wind (vortex removed)



Axisymmetric Tangential Wind Difference



- Subtle differences in vortex structure may contribute to differences in steering layer depth
- Relatively small differences in steering layer depth can contribute to large TC motion differences in vertically sheared environment flow

24-h Forecast verifying at 00Z/23 Sept 2005

Final Comments

- **2nd generation GEFS reforecast ensemble data (gridded fields and TC tracks) are now available**
- **Analysis of North Atlantic TC track forecasts suggest:**
  - **slow and right-of-track error for pre-recurvature over much of North Atlantic basin**
  - **slow for post-recurvature everywhere**
  - **left-of-track error for Gulf of Mexico**

Final Comments

- **Western G.O.M. TC-relative composite analysis**
  - Analysis of 72-h track forecasts show left-of-track error on average
  - Left-of-track error associated with easterly environment wind error in conjunction with positive (negative) height errors north (south) of the TC
- **Regional reforecast for TC Rita (2005):**
  - Suggests sensitivity of track to phase speed of midlatitude transients
  - Additional contribution to TC track error from vertical extent of steering depth and vortex structure

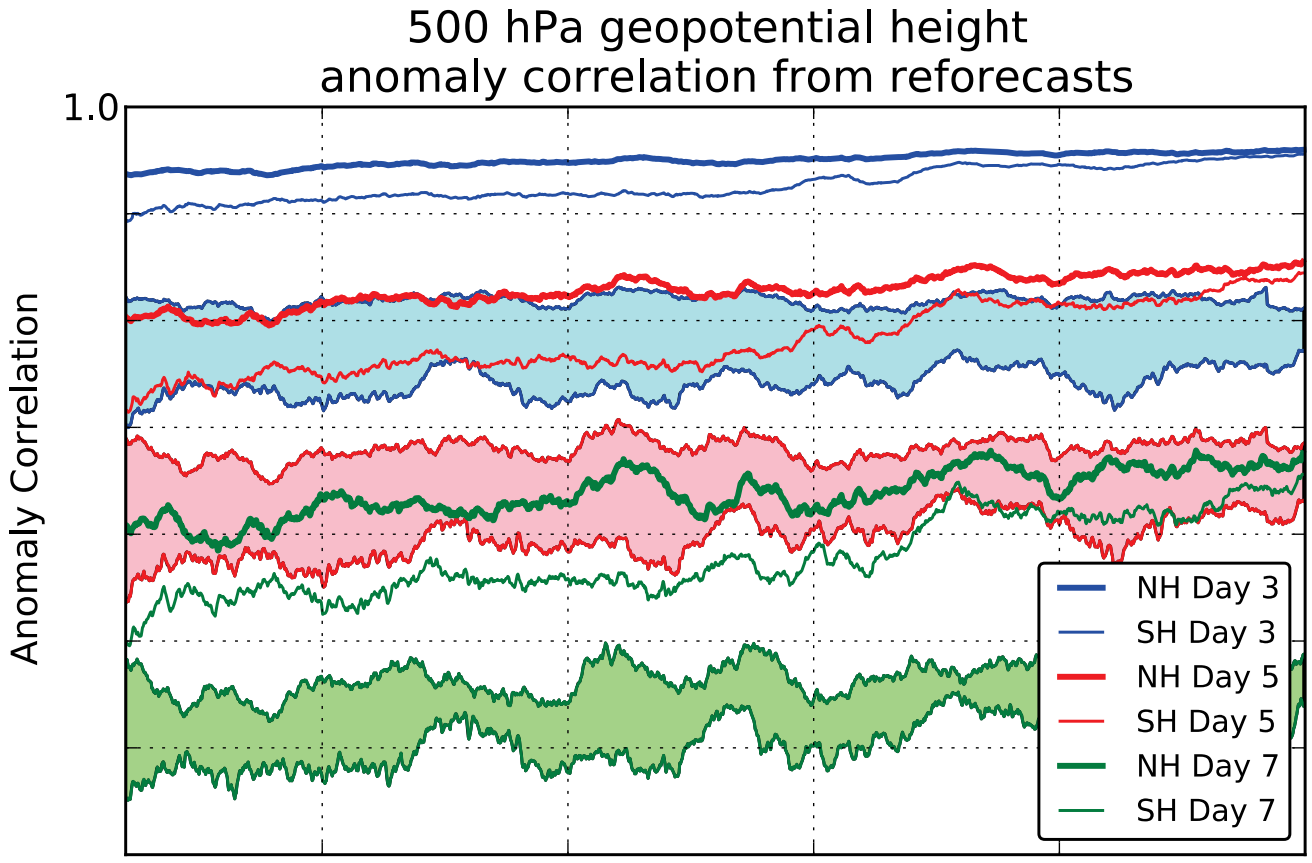
Proposed Milestones for Remainder of Year 1 and Year 2

- **Fine-tune TC track forecast statistics to implement real-time bias-corrected TC track forecasts**
- **Continue to investigate individual cases to improve understanding of how GEFS reforecast model behaves**
  - **Link persistent synoptic-scale flow errors to model physical processes**
- **Extend TC track forecast analysis to other basins**
- **Extend analysis to include other TC-related forecast products**
  - **TC intensity**
  - **Precipitation products: near vortex rainfall and predecessor rain event forecasts**

Extra slides

500 hPa Z Anomaly Correlation

(from deterministic control member)



Lines w/o filled colors for second–generation reforecast (2012, T254)

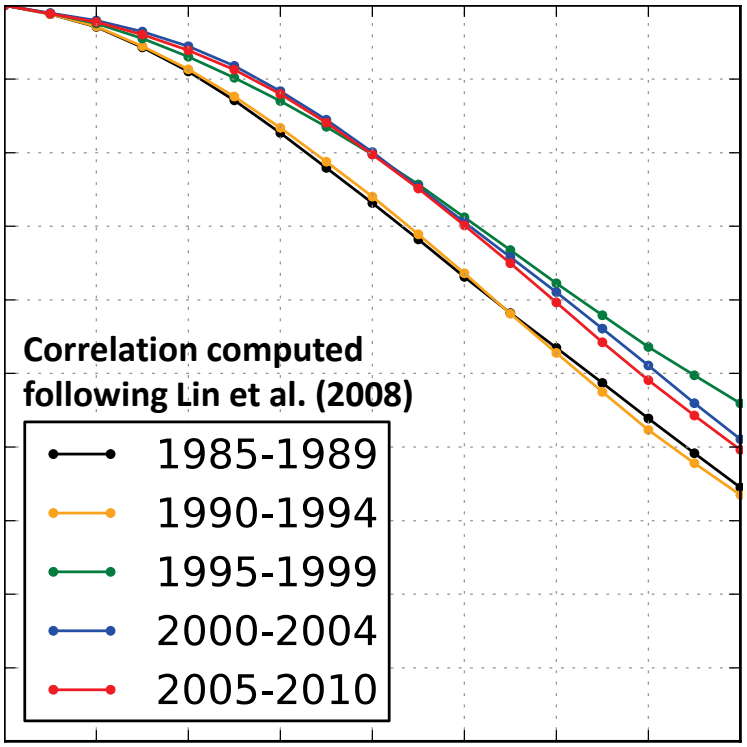
Lines with filled colors for first-generation reforecast (1998, T62).

Perhaps a 1.5-2.5 day improvement.

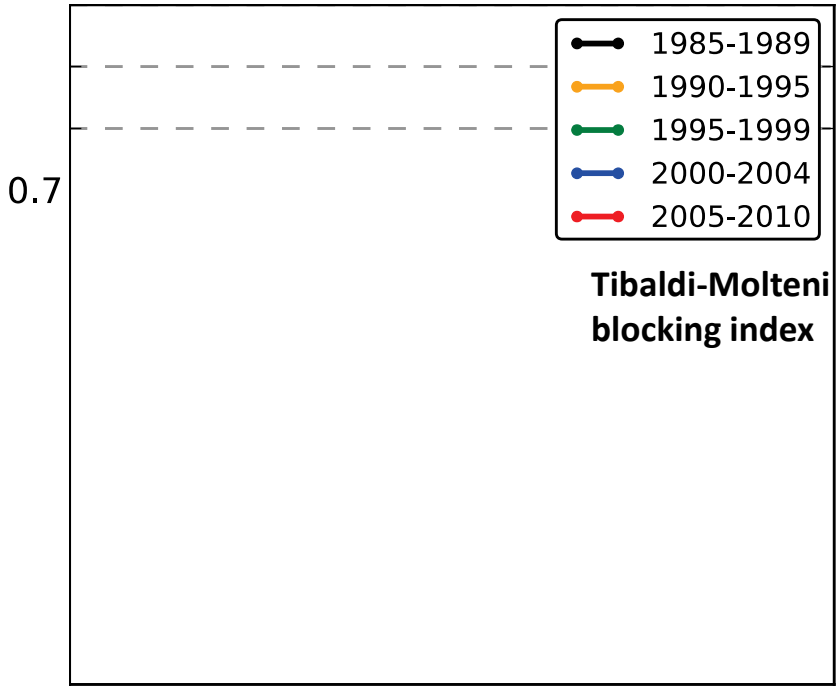
Source: Figure 1 from Hamill et al. (2013; BAMS "in press")

GEFS Forecast Skill: MJO and Blocking Examples

Forecast Skill for MJO Phase



Forecast Skill for North Atlantic Blocking



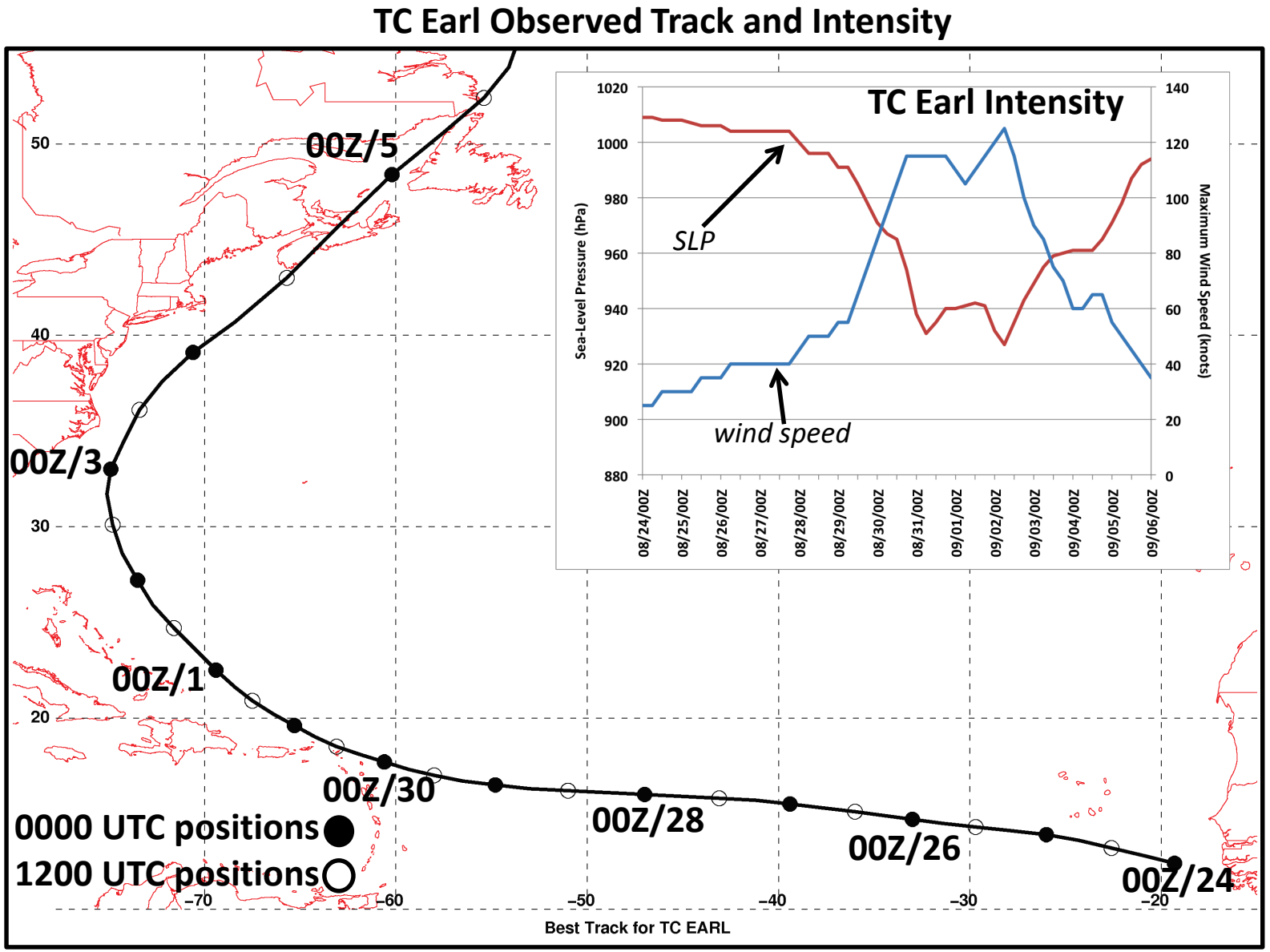
Decreased skill in 1985–1989 (both) and 1990–1994 (MJO) periods

Source: Tom Hamill

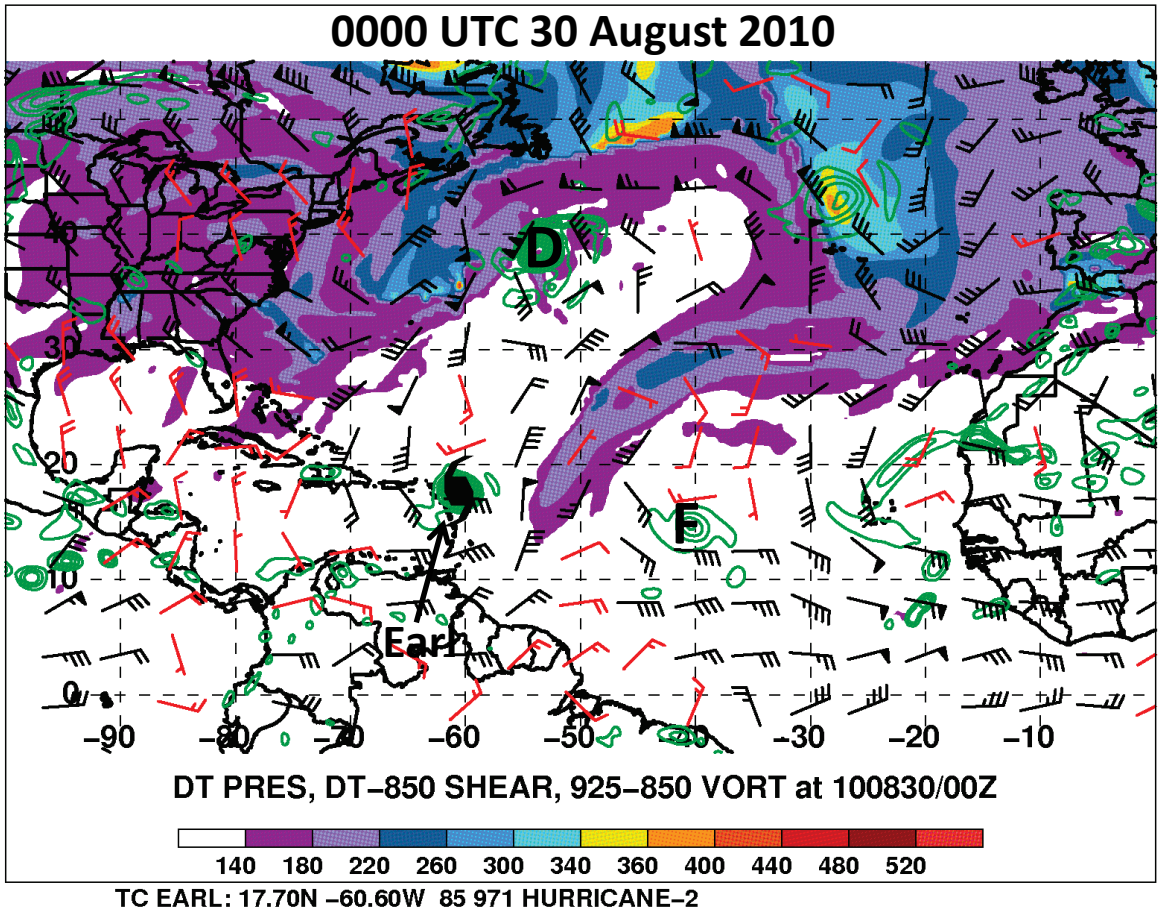
Western North Atlantic Early-Recurvature Example: TC Earl (2010)

- **Example of TC track forecast plagued by "early recurvature" problem**
- **Highlights rich complexity on the synoptic and subsynoptic scale that contributes to case-to-case variability**
- **Draws attention to "interacting TCs" problem**
- **Illustrates how the track forecast of a precursor TC (Danielle) potentially impacts the forecast of a subsequent TC (Earl)**

Ensemble Analysis of TC Earl (2010)

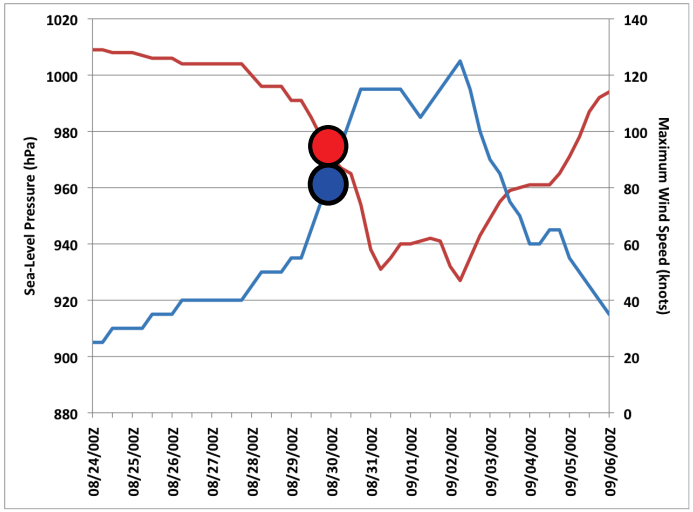


TC Earl (2010): Synoptic-Scale Analysis



SLP

Wind speed



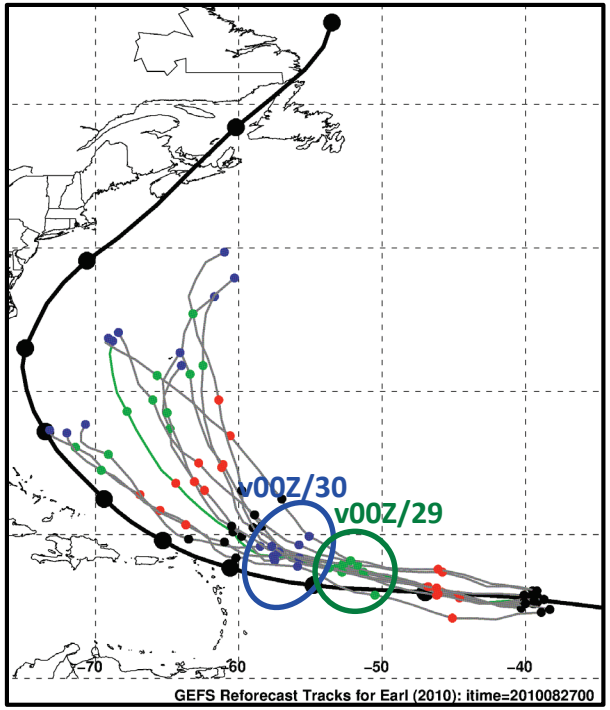
TC Earl Best Track data

- Period noteworthy for interacting TCs

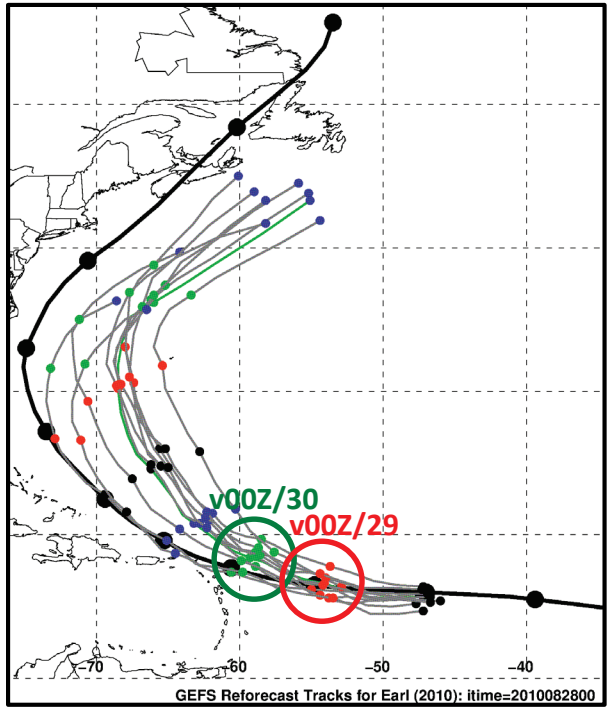
Dynamic tropopause (DT) pressure (hPa; shaded),
850–DT vertical wind shear (knots; barbs),
925–850 hPa layer-average relative vorticity ($\times 10^{-5}$ s^{-1}; contours)

Time-Lag Ensemble

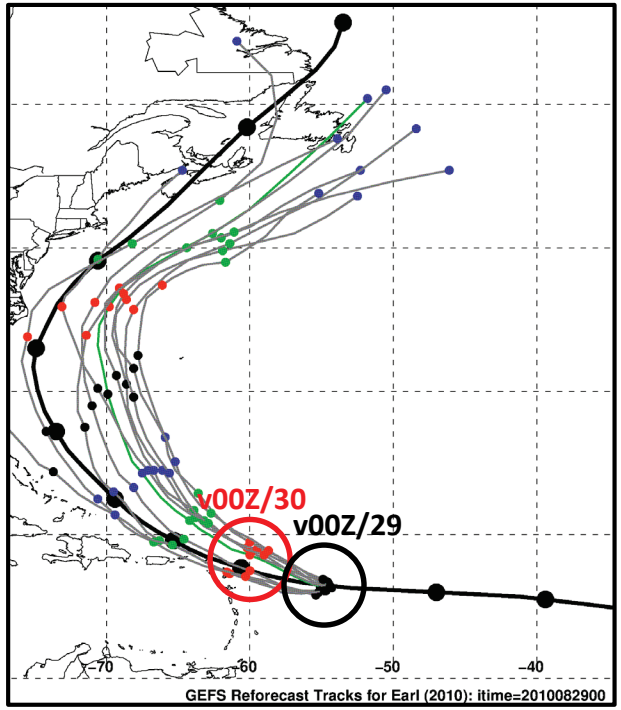
Initialization time: 00Z/27 Aug 2010



Initialization time: 00Z/28 Aug 2010



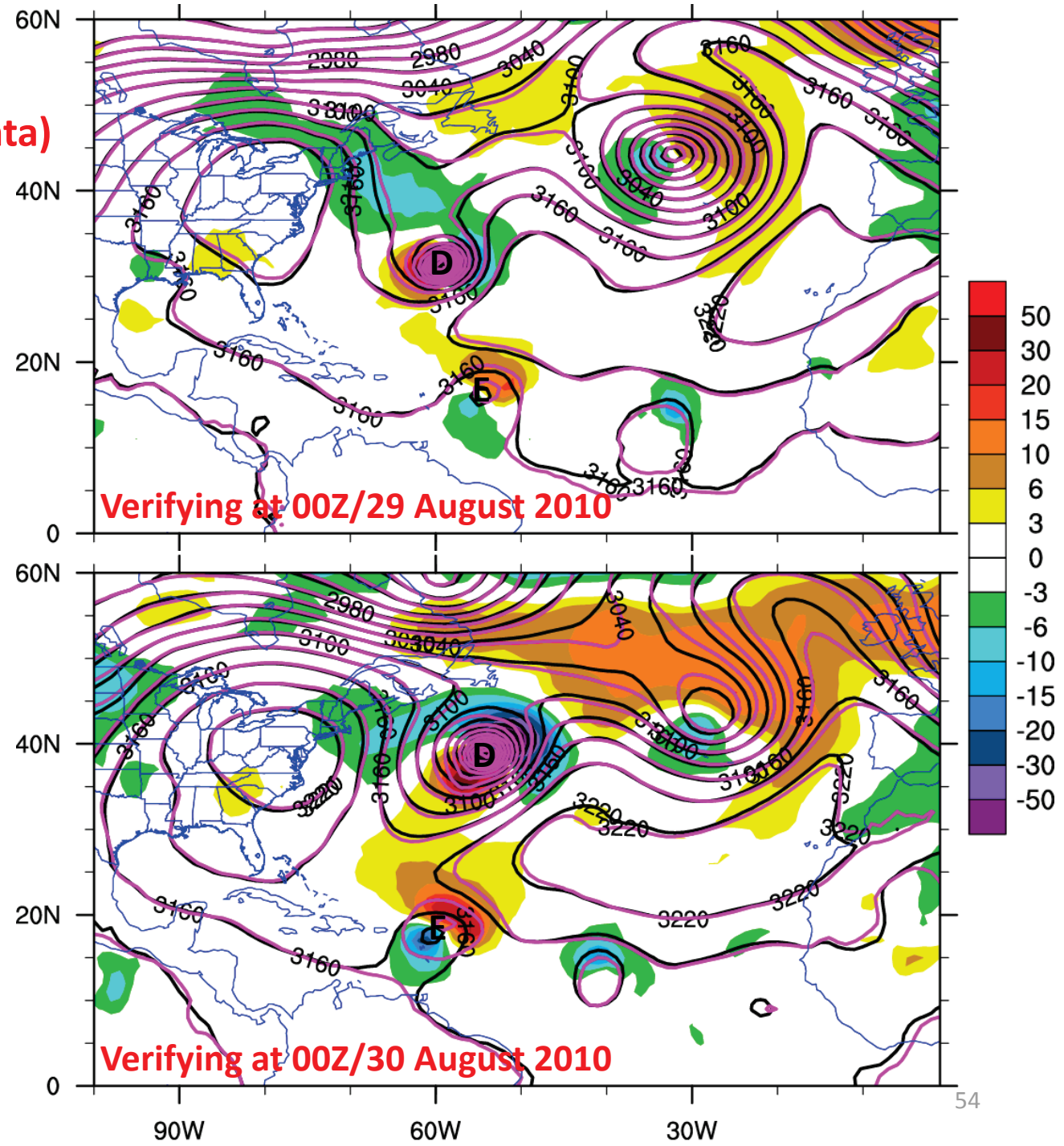
Initialization time: 00Z/29 Aug 2010



- Select three (3) farthest left and right TC tracks from each initialization time to generate time-lagged ensemble of two groups consisting of nine (9) members each
- Examine differences between left (late recurvature) and right (early recurvature) groups to determine factors that contributed to recurvature in the GEFS reforecast ensemble

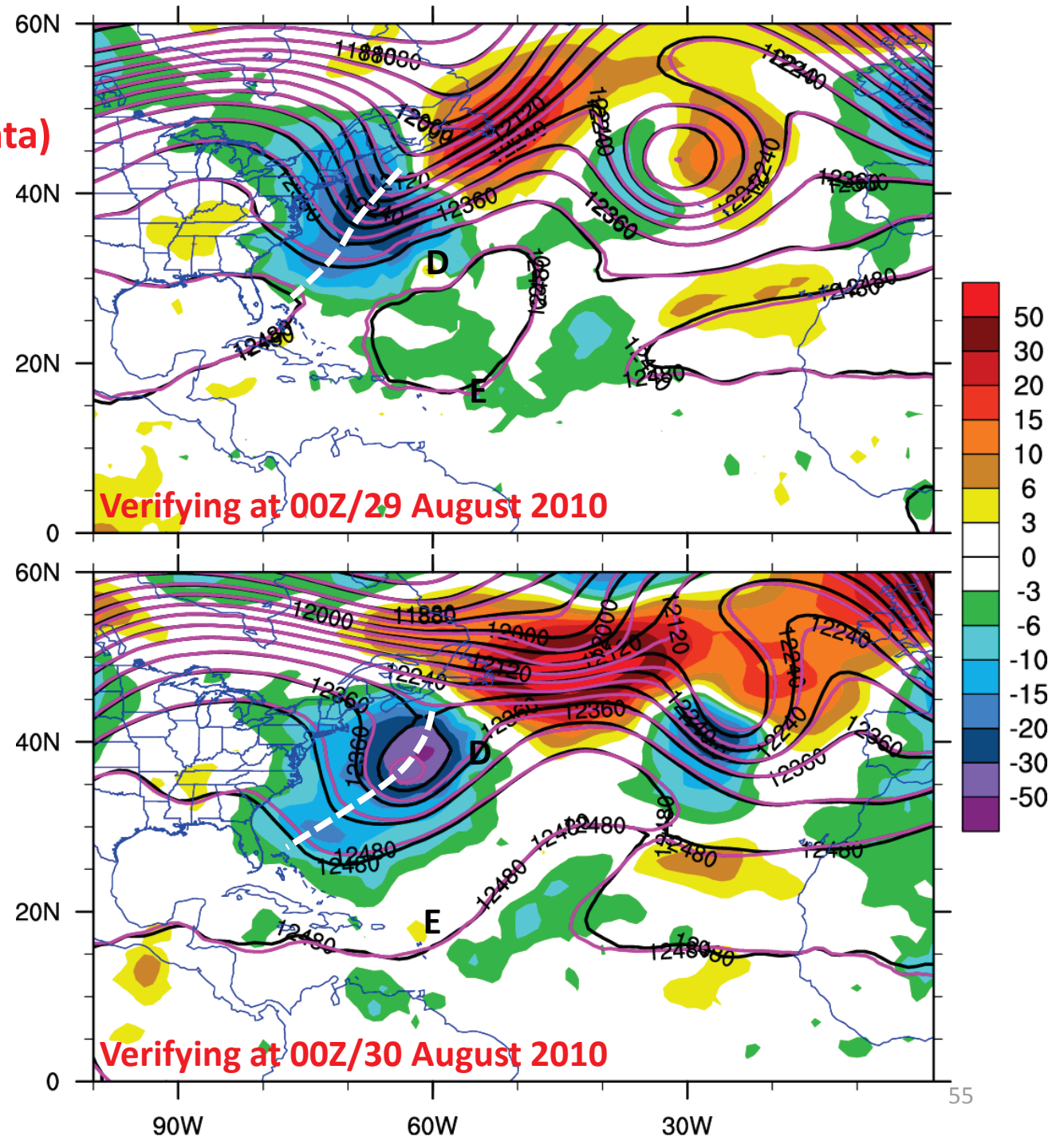
700 hPa height (m)
Late recurve (n=9; black)
Early recurve (n=9; magenta)
Late minus early (shaded)

- TC Danielle moved northeastward slightly faster in late recurvature ensemble composite
- Increased 700 hPa ridging north of TC Earl influenced more westward track



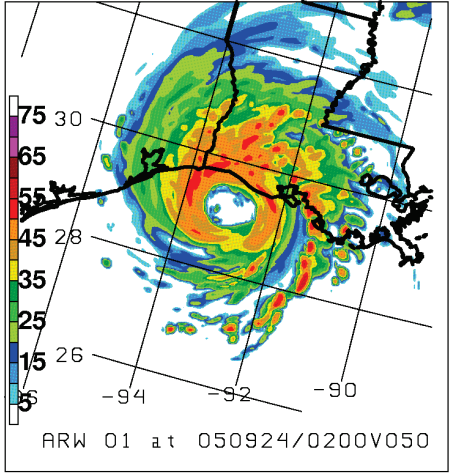
200 hPa height (m)
Late recurve (n=9; black)
Early recurve (n=9; magenta)
Late minus early (shaded)

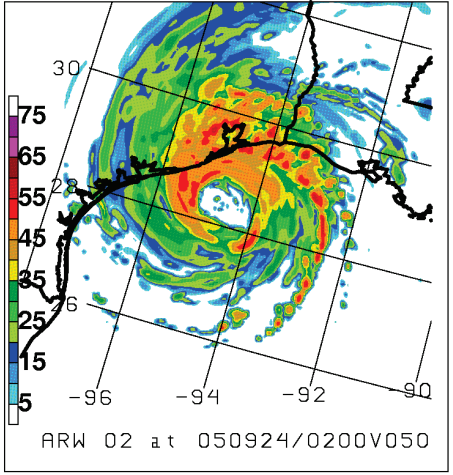
- More amplified pattern and enhanced southwesterly jet over western North Atlantic at 200 hPa in late recurvature composite
- Core of 200 hPa trough extends farther southwestward
- Role of Danielle's outflow?

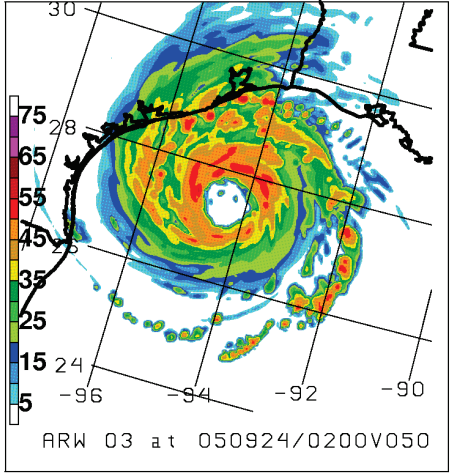


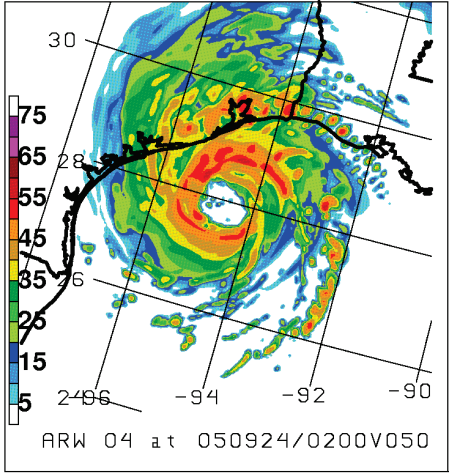
Final Comments: TC Earl (2010)

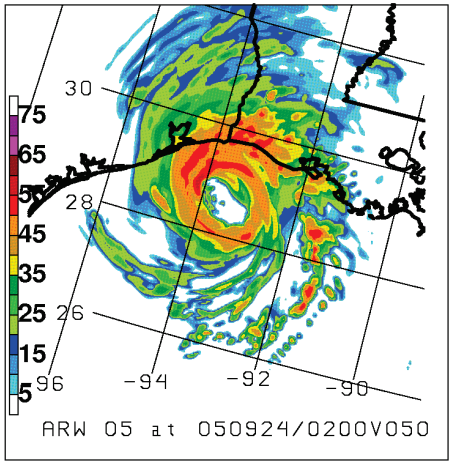
- **Ensemble analysis for TC Earl (2010) over western North Atlantic:**
  - **shows characteristic slow and right-of-track error for pre-recurvature stage**
  - **suggests that forecast recurvature is influenced by structure of subtropical ridge north of Earl**
  - **westward extent of subtropical ridge influenced by western North Atlantic trough and forward speed of Danielle (interacting TCs problem)**

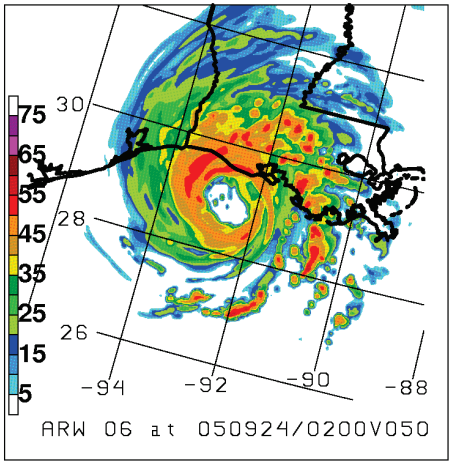


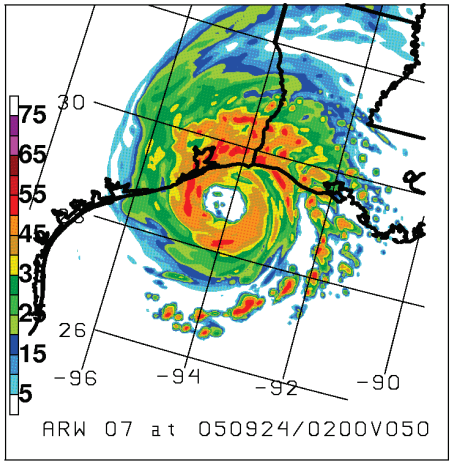


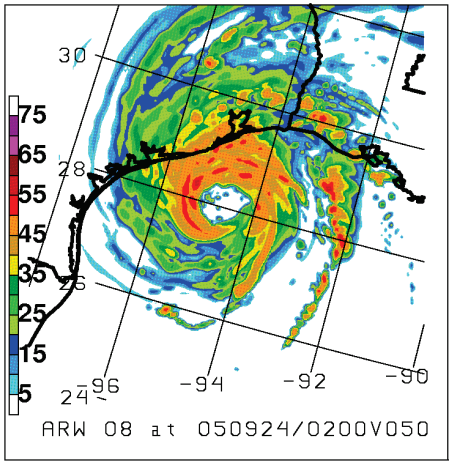


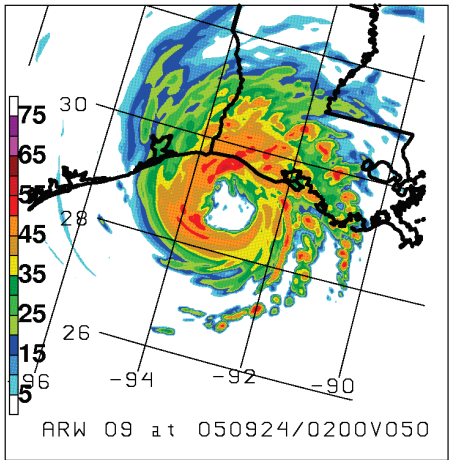


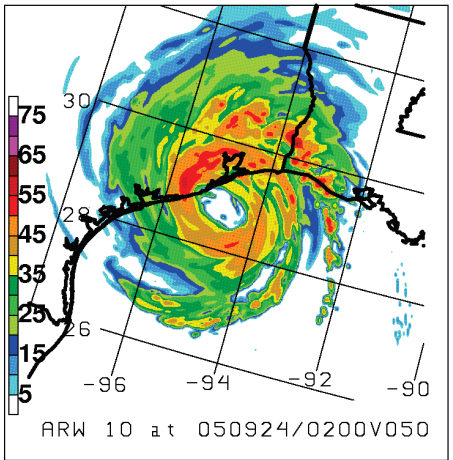


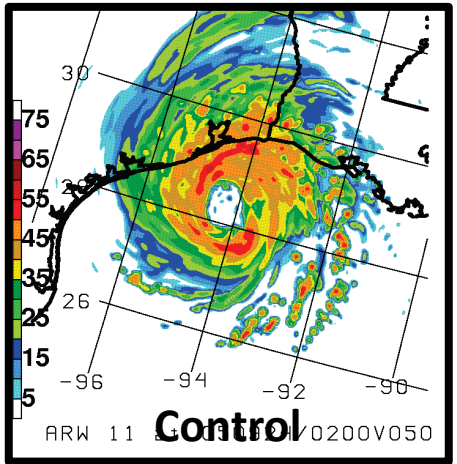












Maximum reflectivity (dBZ)
50-h AHW Forecast
Verifying 02Z/24 Sep '05