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

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HFIP Awards First Year Review 2012  
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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 by ½ Decade

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

½ to 1 day decrease in error
from 1985–89 to 2005–10
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
Recall that recurvature stage is defined for the forecasted TC.
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• 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 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 (×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

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

Data: GFS analysis

Source: NCAR case selection archive
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)

TC Rita Observed Track and Intensity

TC Rita Intensity

TC Rita Observed Track and Intensity

00Z/26

00Z/24

00Z/22

00Z/20

00Z/18

0000 UTC positions

1200 UTC positions

Sea-Level Pressure (hPa)

Wind Speed (knots)

SLP

wind speed
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
Use of “Regional Reforecasts”

- 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?

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

Horizontal grid spacing: 36, 12, 4 km (two-way nests)
Vertical levels: 36, 36, 36
Time steps: 180, 60, 20
IC and BC: 11-member GEFS reforecast
Cumulus: Tiedtke, Tiedtke, explicit
PBL: YSU
Microphysics: WRF single-moment 6-class
Land surface: Noah
Turbulence: 2D Smagorinsky
Shortwave radiation: Goddard
Longwave radiation: RRTM
Diffusion: Second-order diffusion
Scalar advection: Positive definite

Figure by R. Torn
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 $\zeta$ and $\delta$ 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

- 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

\[
V_{model} - V_{obs} = \frac{1}{p_b - p_{LM}} \int_{P_{LM}}^{P_b} (\dot{\psi}_{m} - \dot{\psi}_{o}) dp + \frac{1}{p_b - p_{LM}} \int_{P_{LM}}^{P_b} (\dot{\psi}_{m} - \dot{\psi}_{o}) dp \\
+ \frac{1}{P_{LM} - P_{LM}} \left[ \int_{P_{LM}}^{P_b} \left( \frac{P_{LM} - P_{LM}}{P_b - P_{LM}} \right) \dot{\psi}_{m} dp + \int_{P_{LM}}^{P_b} \dot{\psi}_{m} dp \right] + \text{residual term}
\]

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

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 $V_{env}$ 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 (vortex removed)

Axisymmetric Tangential Wind

24-h Forecast verifying at 00Z/23 Sept 2005
Environment Wind and Vortex Structure

- 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

• 2\textsuperscript{nd} 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)


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

- Correlation computed following Lin et al. (2008)
- 1985-1989
- 1990-1994
- 1995-1999
- 2000-2004
- 2005-2010

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 Observed Track and Intensity

TC Earl Intensity

wind speed

SLP

00Z/24

00Z/26

00Z/28

00Z/30

00Z/1

00Z/3

00Z/5

0000 UTC positions

1200 UTC positions

Best Track for TC EEARL
Dynamic tropopause (DT) pressure (hPa; shaded),
850–DT vertical wind shear (knots; barbs),
925–850 hPa layer-average relative vorticity ($\times10^{-5}$ s$^{-1}$; contours)
Time-Lag Ensemble

- 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