Tropical Cyclone Track Prediction

David A. Zelinsky and Richard J. Pasch

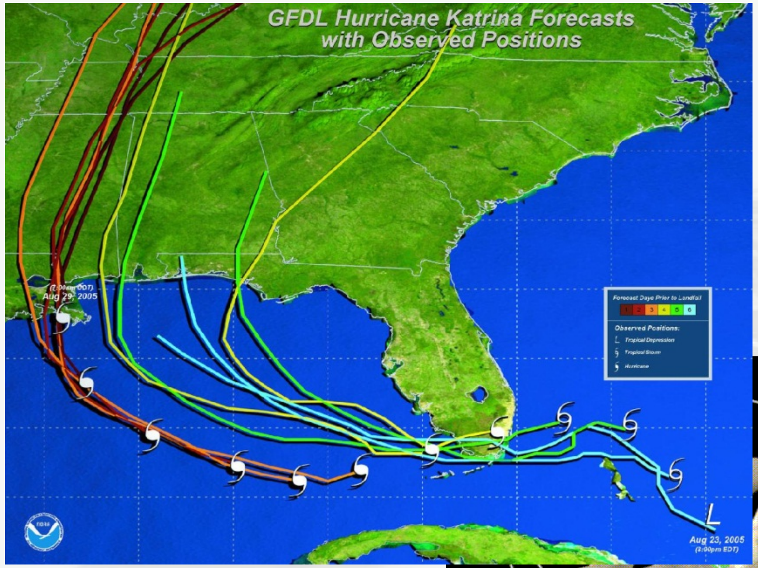
National Hurricane Center

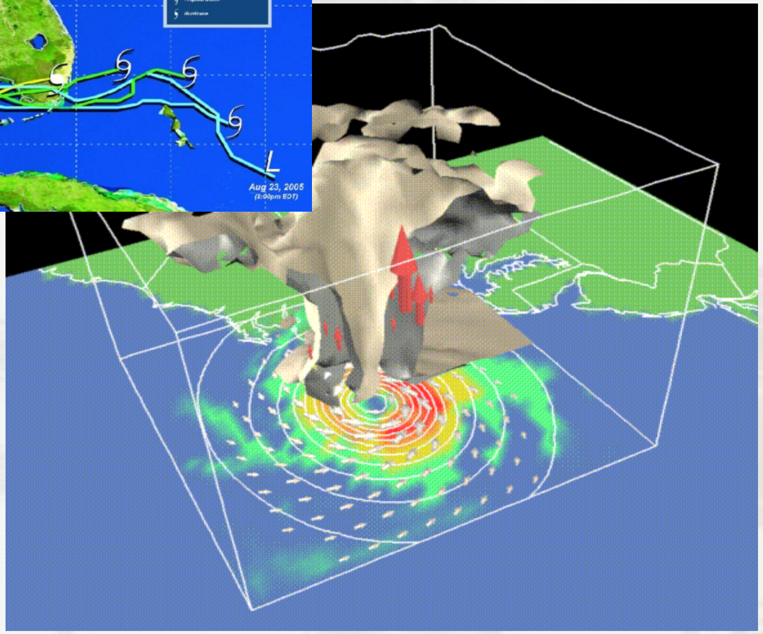
2021 RA-IV Workshop on Hurricane Forecasting and Warning

April 28, 2021

Outline

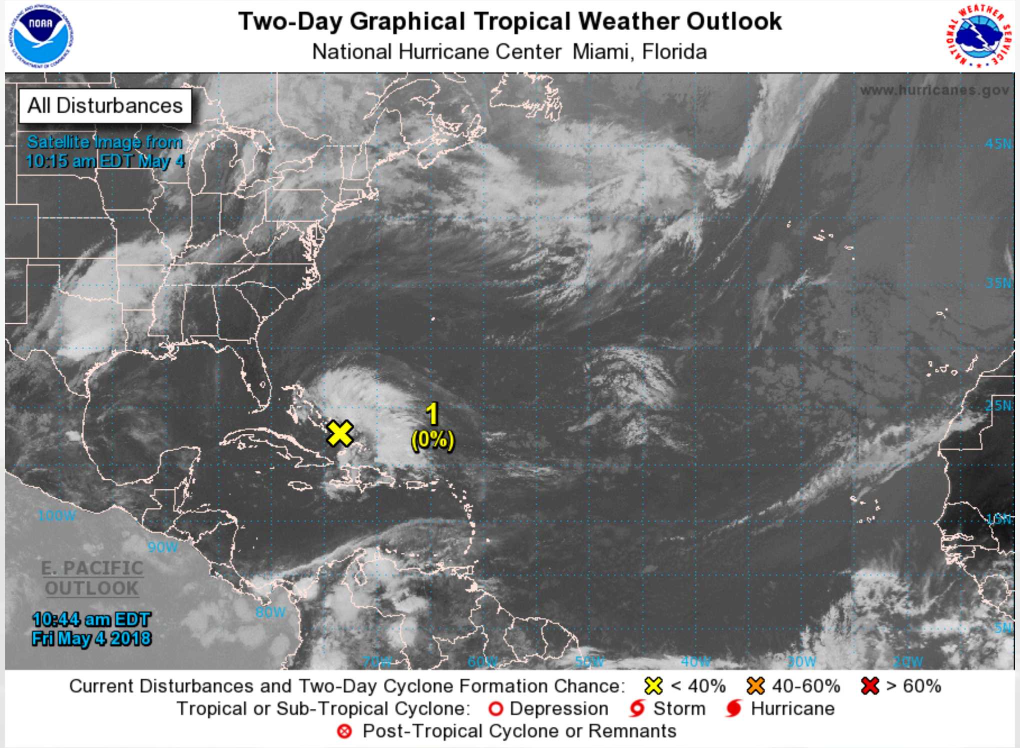
- Basic Dynamics
- Guidance Models
- Track Forecasting at NHC
  - Practical considerations
  - Verification





Tropical Cyclone Motion

- Tropical Cyclones generally move with the large-scale atmospheric flow
  - Similar to a leaf or a cork in a stream
- Track Forecasting is a relatively well-understood problem
- Important atmospheric features are often large and identifiable
- Numerical computer models forecast track fairly well (most of the time)



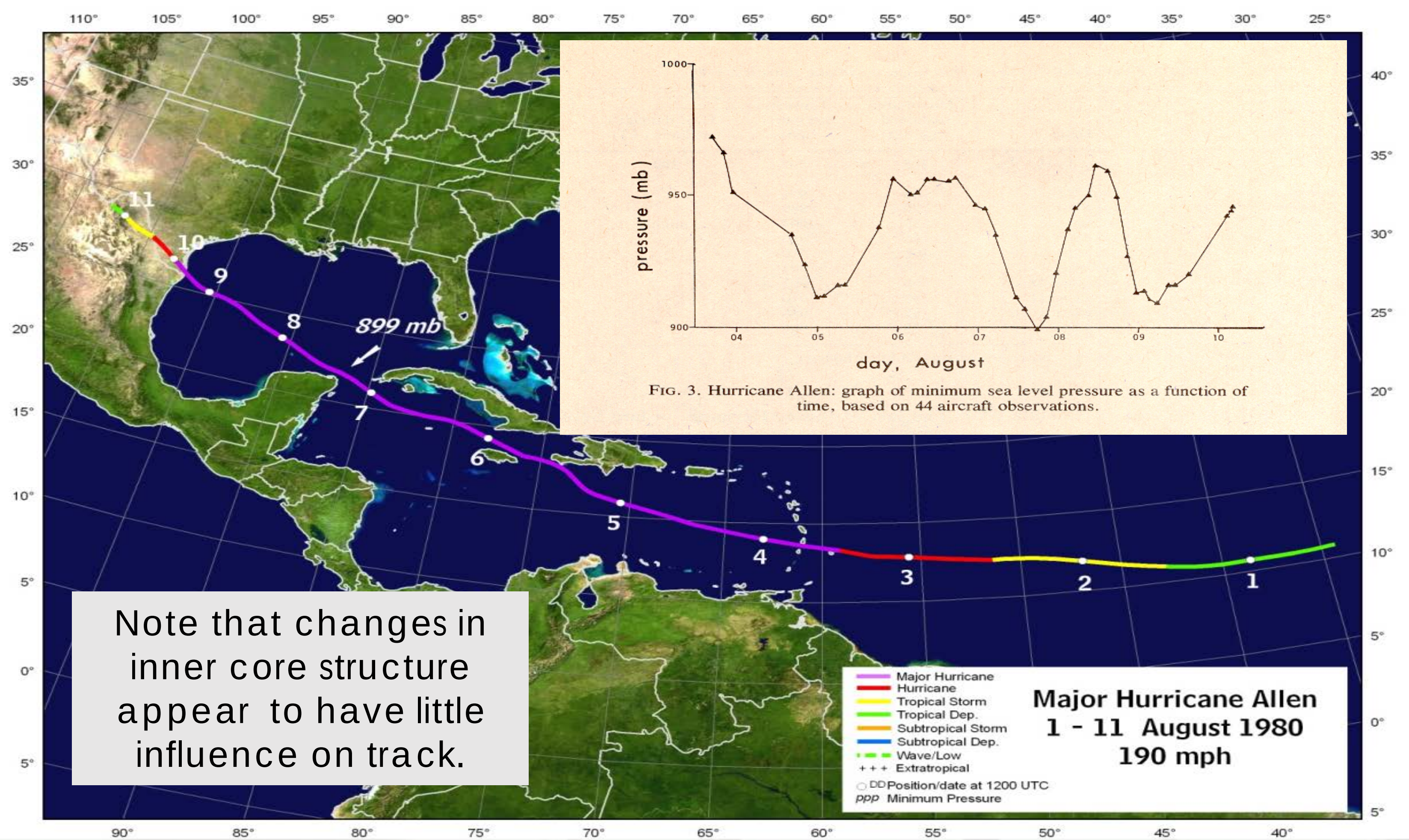
Tropical Cyclone Motion

$$\frac{\partial \zeta}{\partial t} = -V \cdot \nabla \zeta - \omega \frac{\partial \zeta}{\partial P} - \beta v - (\zeta + f)\delta - k \cdot \nabla \omega \times \frac{\partial V}{\partial P}$$

$\frac{\partial \zeta}{\partial t}$	$-V \cdot \nabla \zeta$	$-\omega \frac{\partial \zeta}{\partial P}$	$-\beta v$	$-(\zeta + f)\delta$	$-k \cdot \nabla \omega \times \frac{\partial V}{\partial P}$
(1)	(1)	(4)	(2)	(3)	(4)
4×10^{-10}	4×10^{-10}	4×10^{-11}	2×10^{-10}	1×10^{-10}	4×10^{-11}

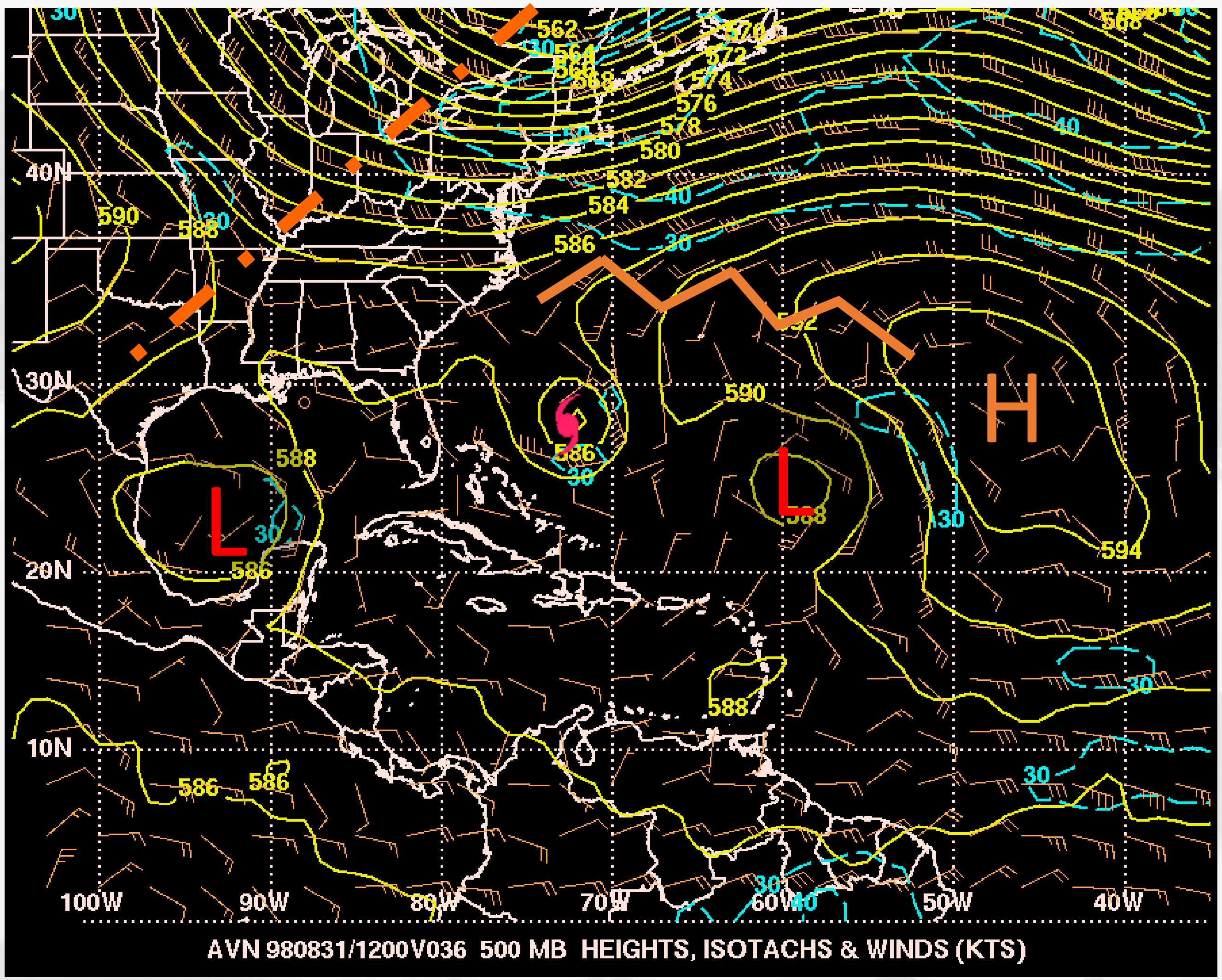
- To a first approximation, TC motion is governed by conservation of relative vorticity (vortex moves with the large-scale steering flow).
- Second order includes the Beta term (conservation of absolute vorticity).
- Divergence term (e.g., wavenumber 1 asymmetry in convection, interactions with orography, friction)
- Vertical motions (e.g., twisting term) less important.
- 3-d dynamical model includes all of these terms.

Intensity impact on Track



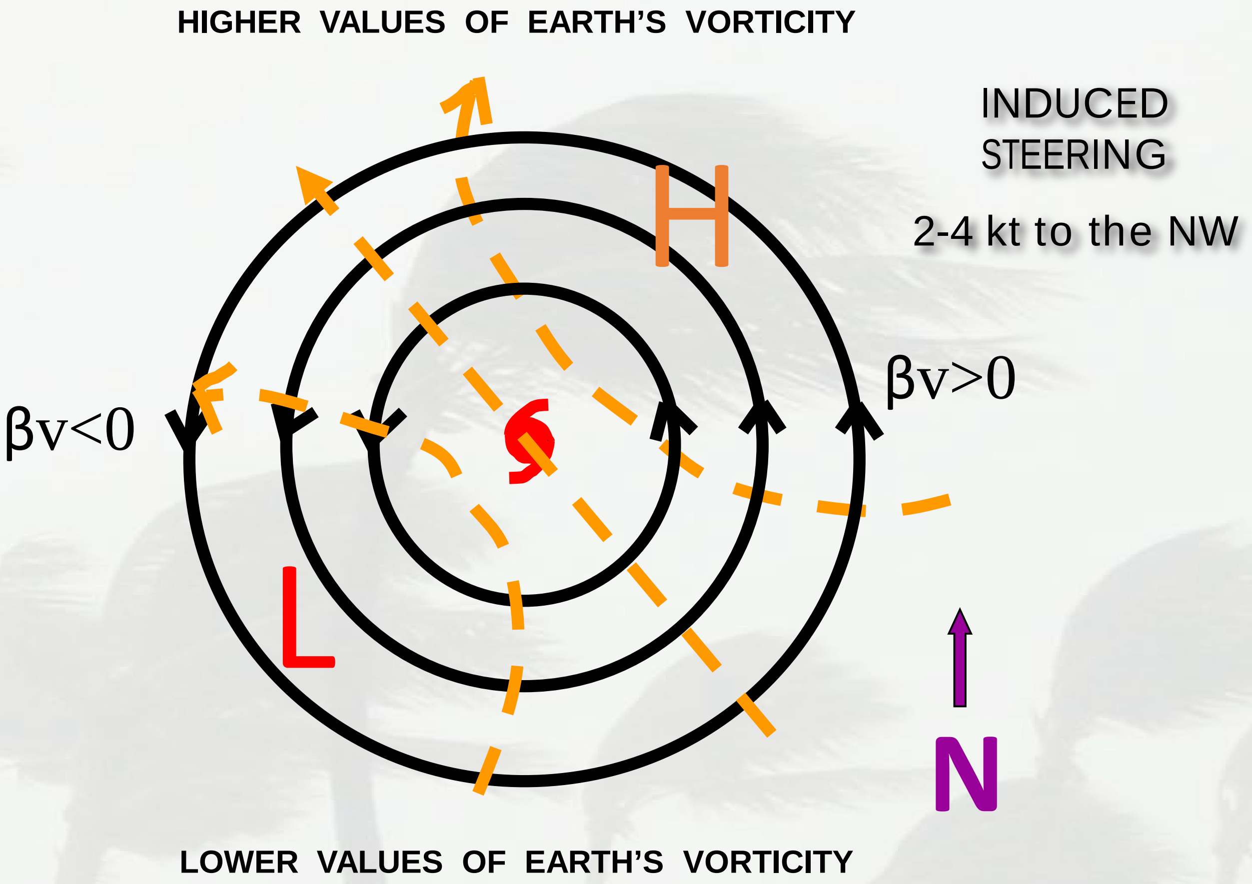
Note that changes in inner core structure appear to have little influence on track.

Large Scale Steering



The Beta Effect

- The circulation of a TC, combined with the North-South variation of the Coriolis parameter, induces asymmetries known as Beta Gyres.
- Beta Gyres produce a net steering current across the TC, generally toward the NW at a few knots. This motion is known as the Beta Drift.

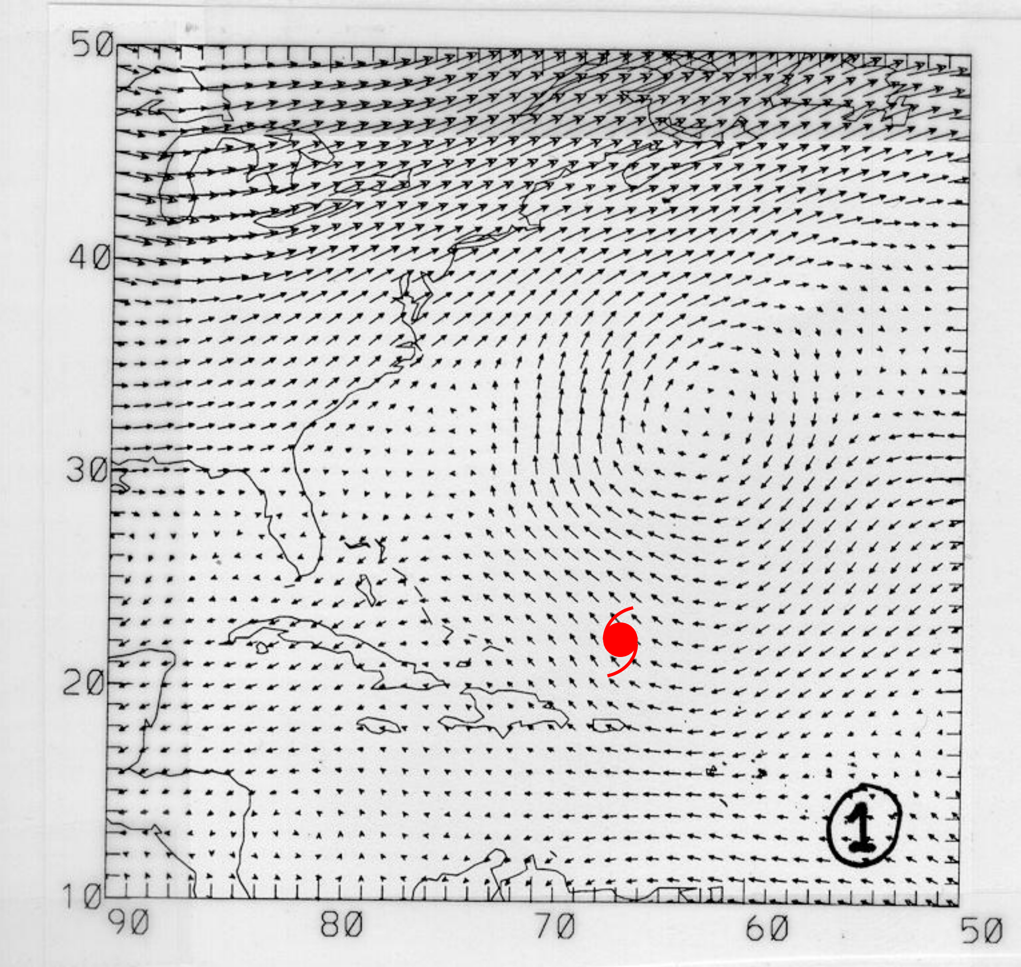


Exercise 1

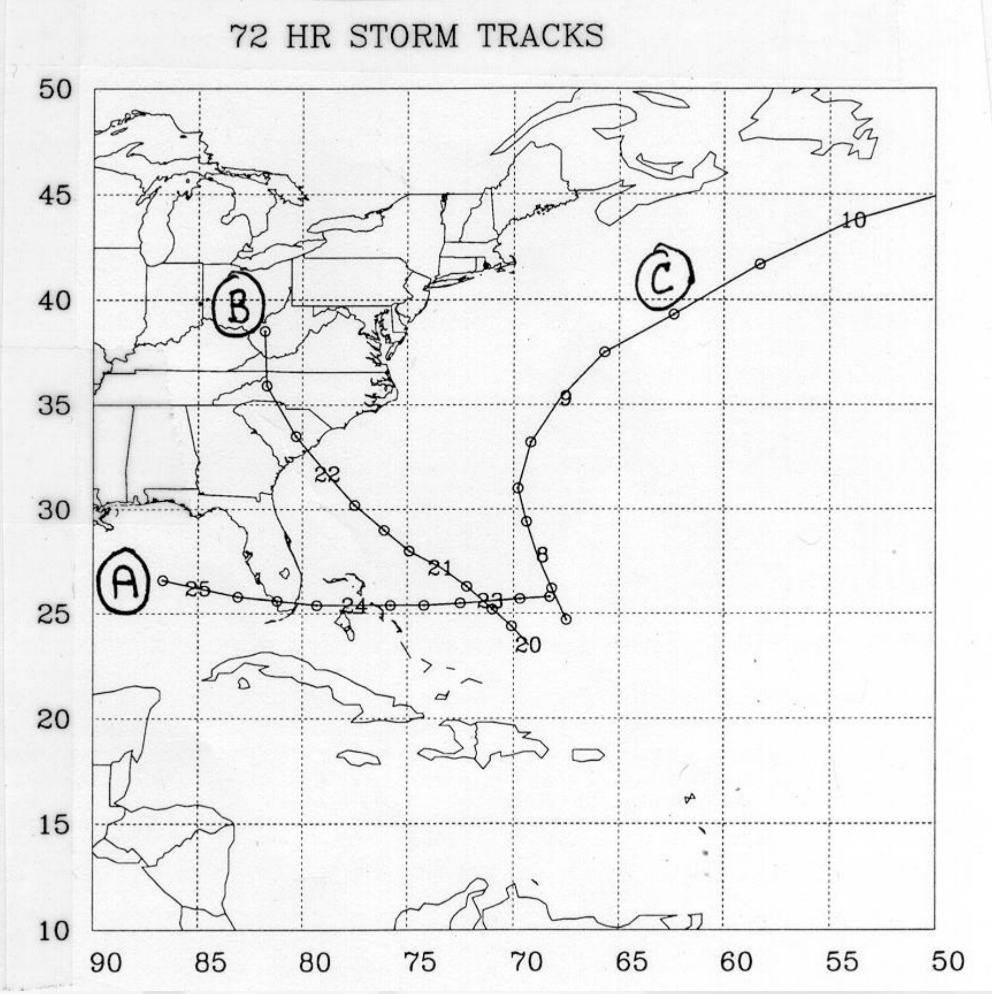
- You are given deep-layer mean wind plots for 3 tropical cyclones (TCs) that were located in the vicinity of 24-25°N 67-70°W.

- Also shown are the subsequent 72-h tracks taken by the 3 TCs.

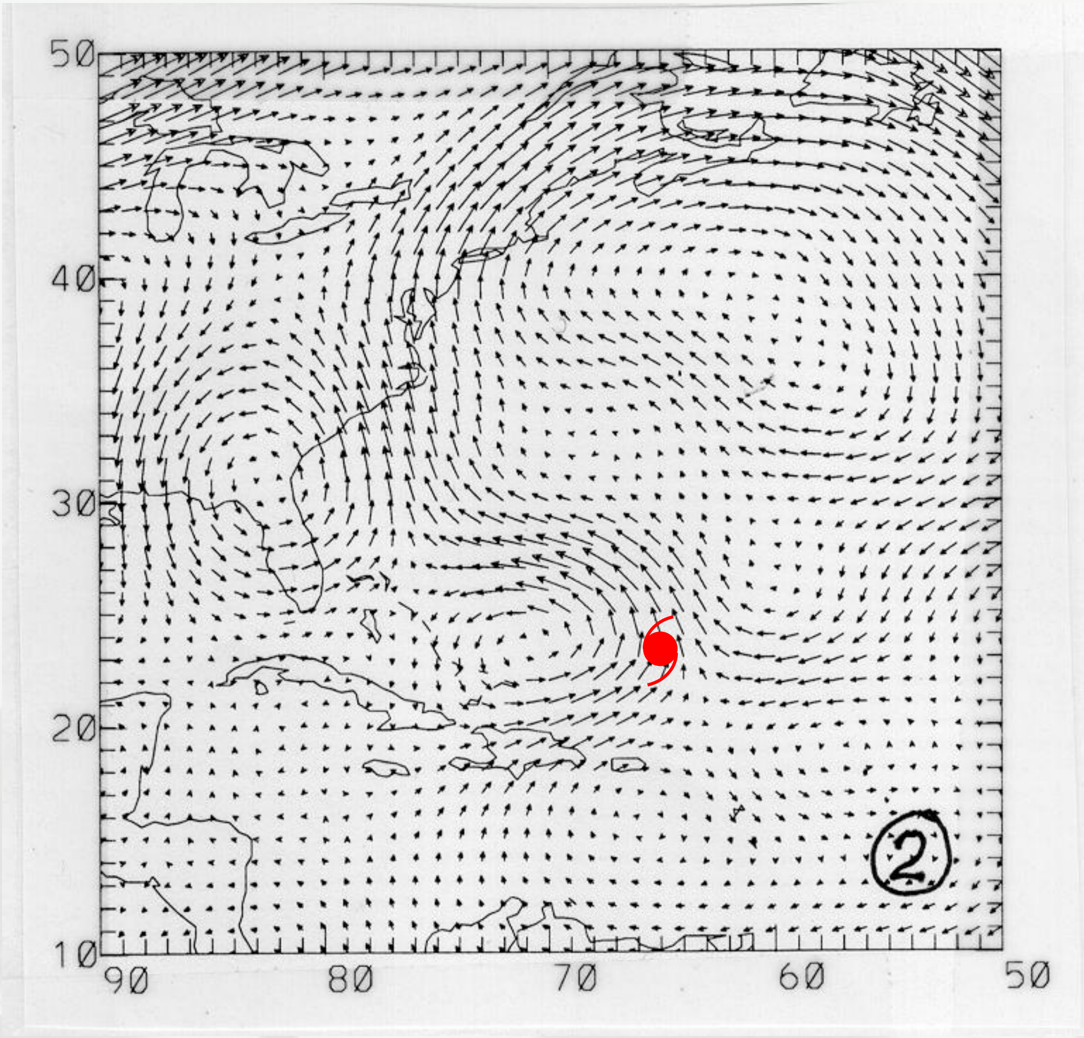
- Match up each deep-layer flow chart with the correct track.



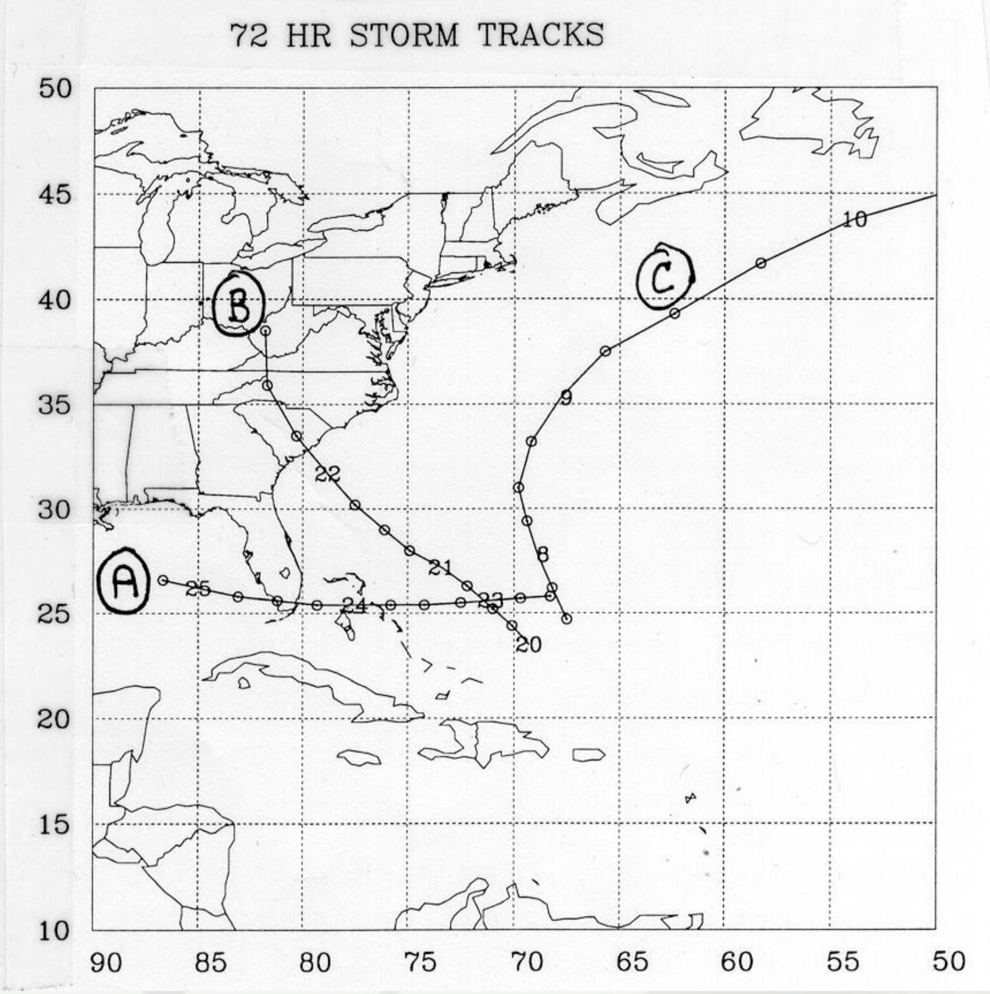
50
40
30
20
10
90
80
70
60
50
1



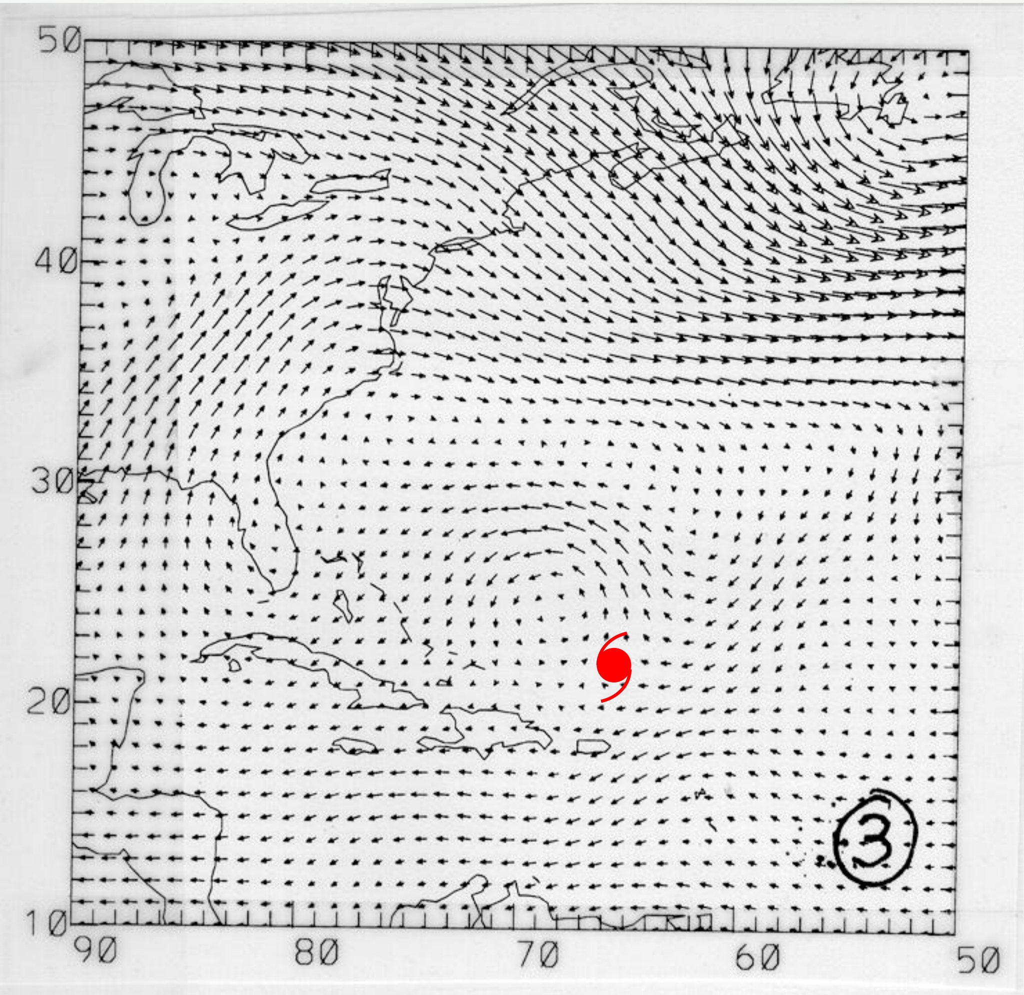
72 HR STORM TRACKS
50
45
40
35
30
25
20
15
10
90
85
80
75
70
65
60
55
50
A
B
C
25
24
23
22
21
20
10
9
8



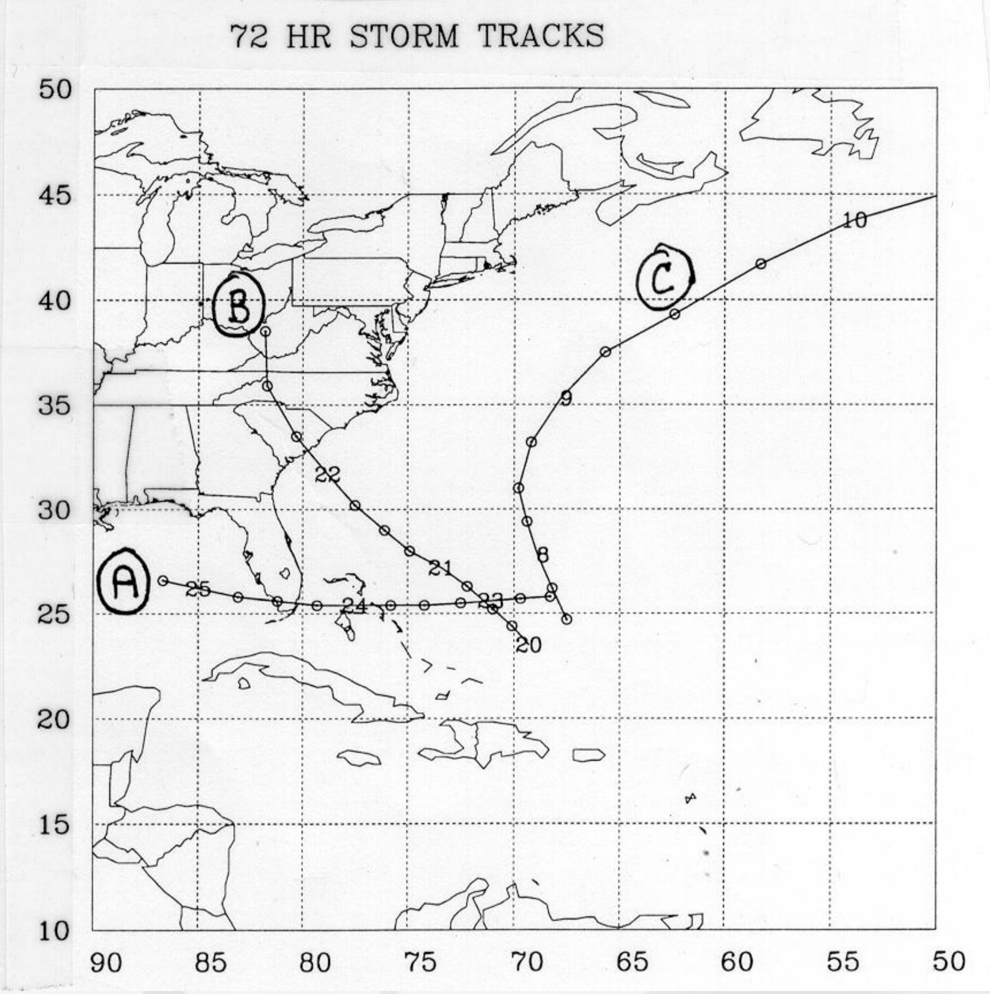
50
40
30
20
10
90
80
70
60
50
2



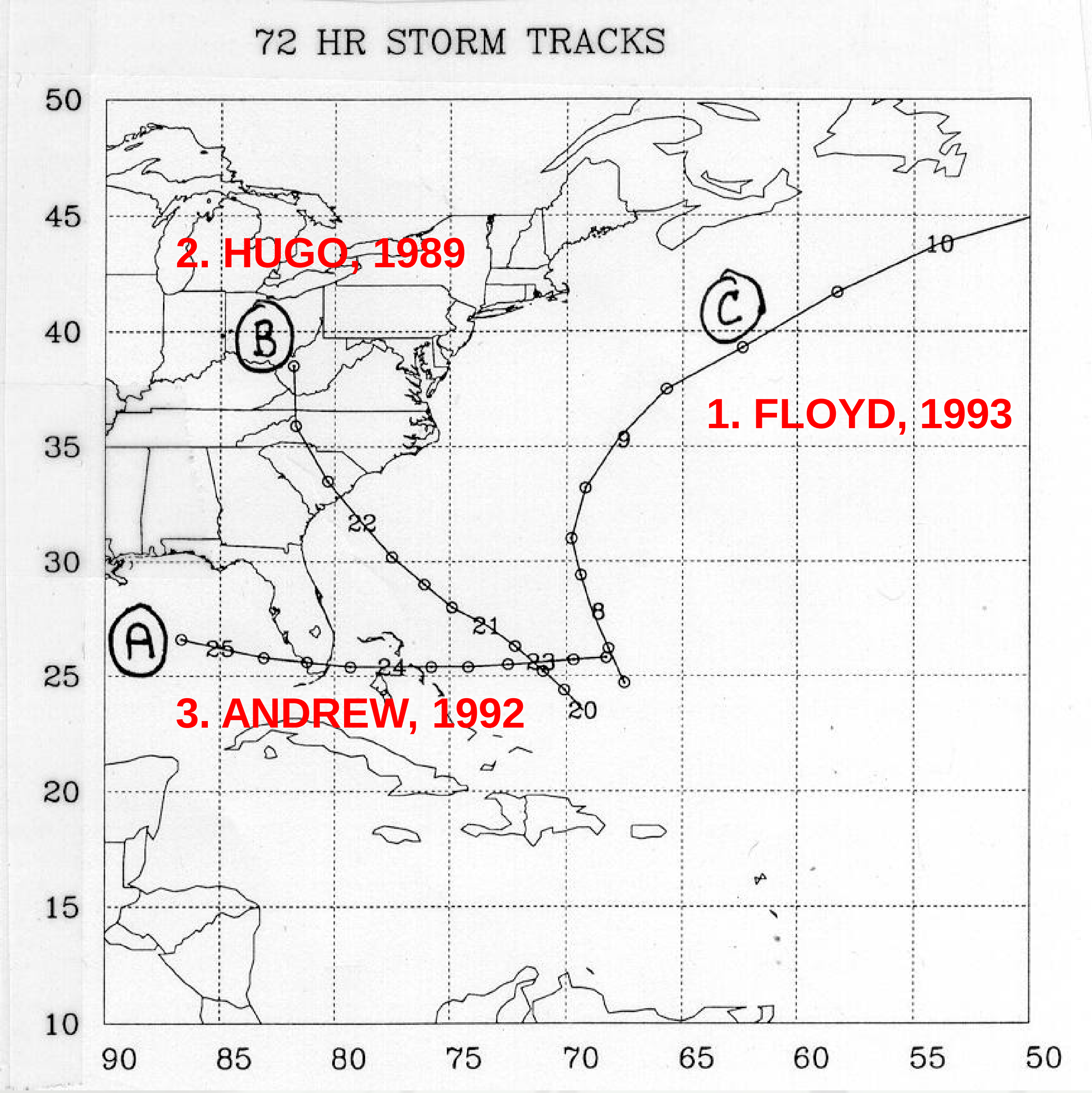
72 HR STORM TRACKS
50
45
40
35
30
25
20
15
10
90
85
80
75
70
65
60
55
50
A
B
C
25
24
23
22
21
20
10
9
8



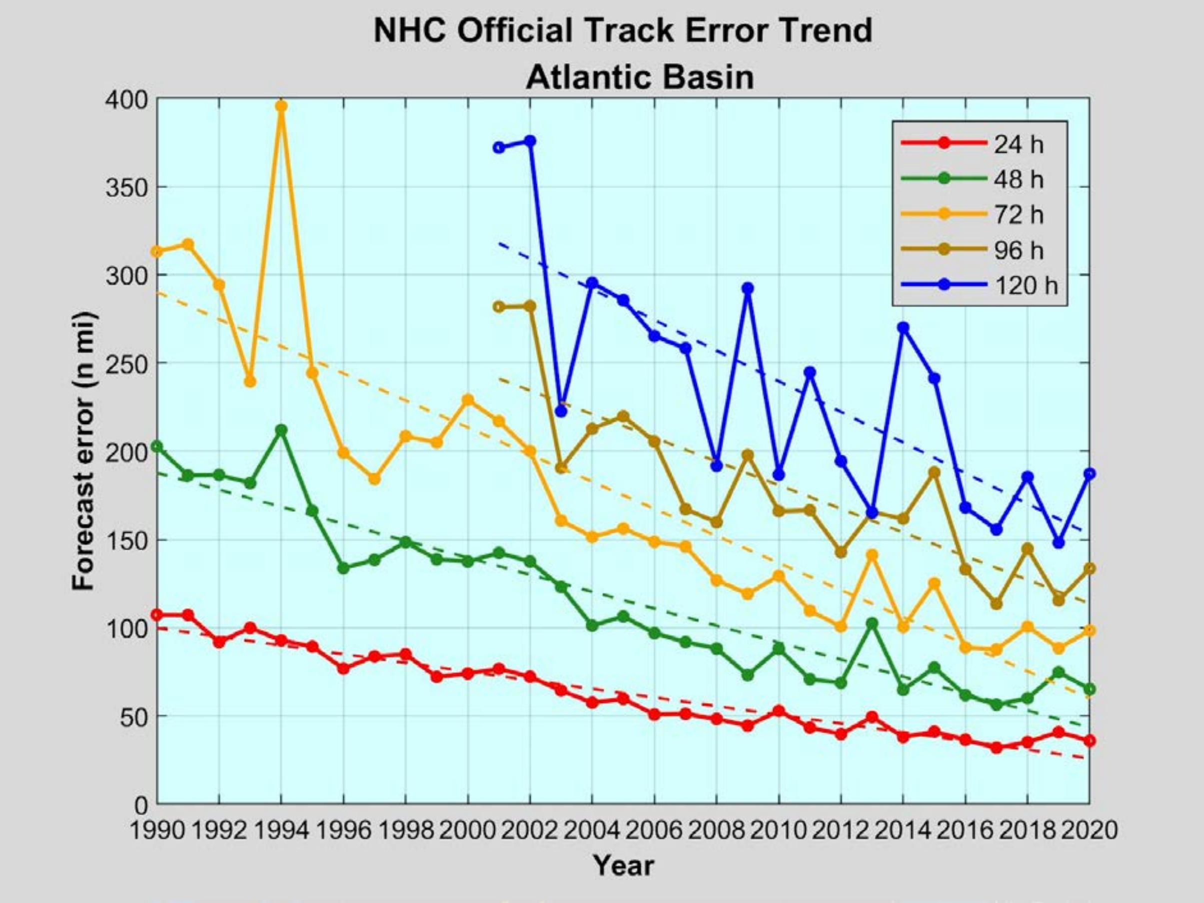
50
40
30
20
10
90
80
70
60
50
3

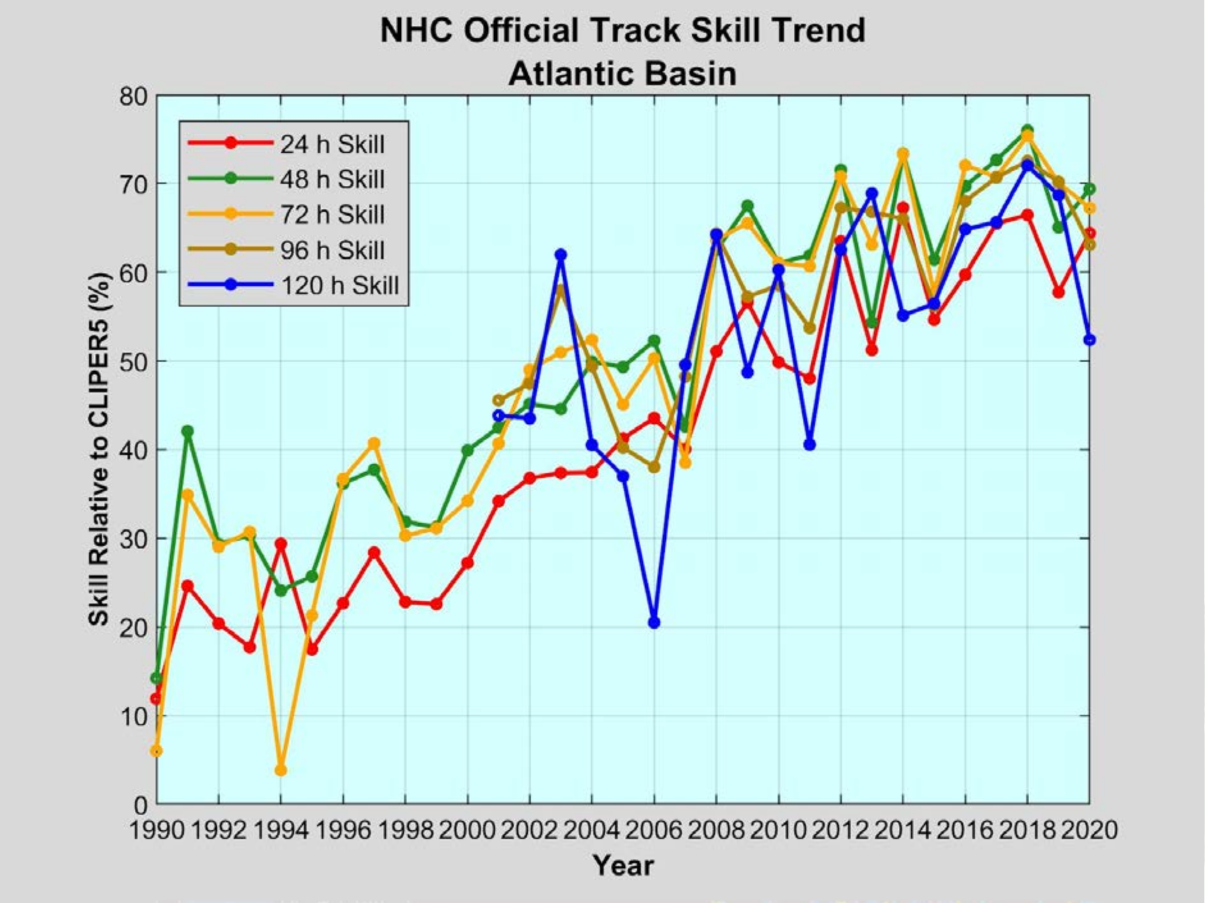


72 HR STORM TRACKS
50
45
40
35
30
25
20
15
10
90
85
80
75
70
65
60
55
50
A
B
C

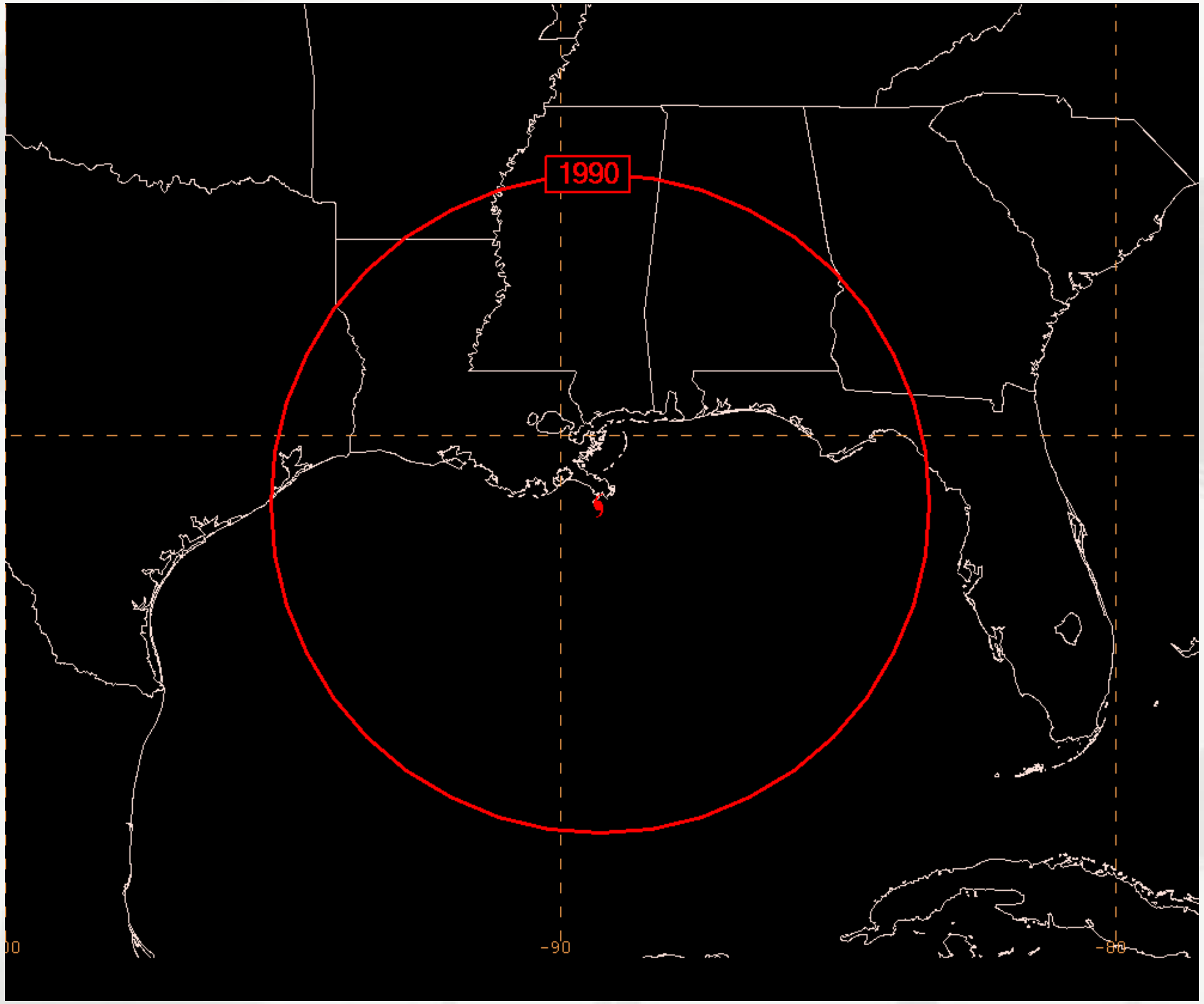

72 HR STORM TRACKS
2. HUGO, 1989
1. FLOYD, 1993
3. ANDREW, 1992
A
B
C
50
45
40
35
30
25
20
15
10
90
85
80
75
70
65
60
55
50

Track Forecast Errors/Skill

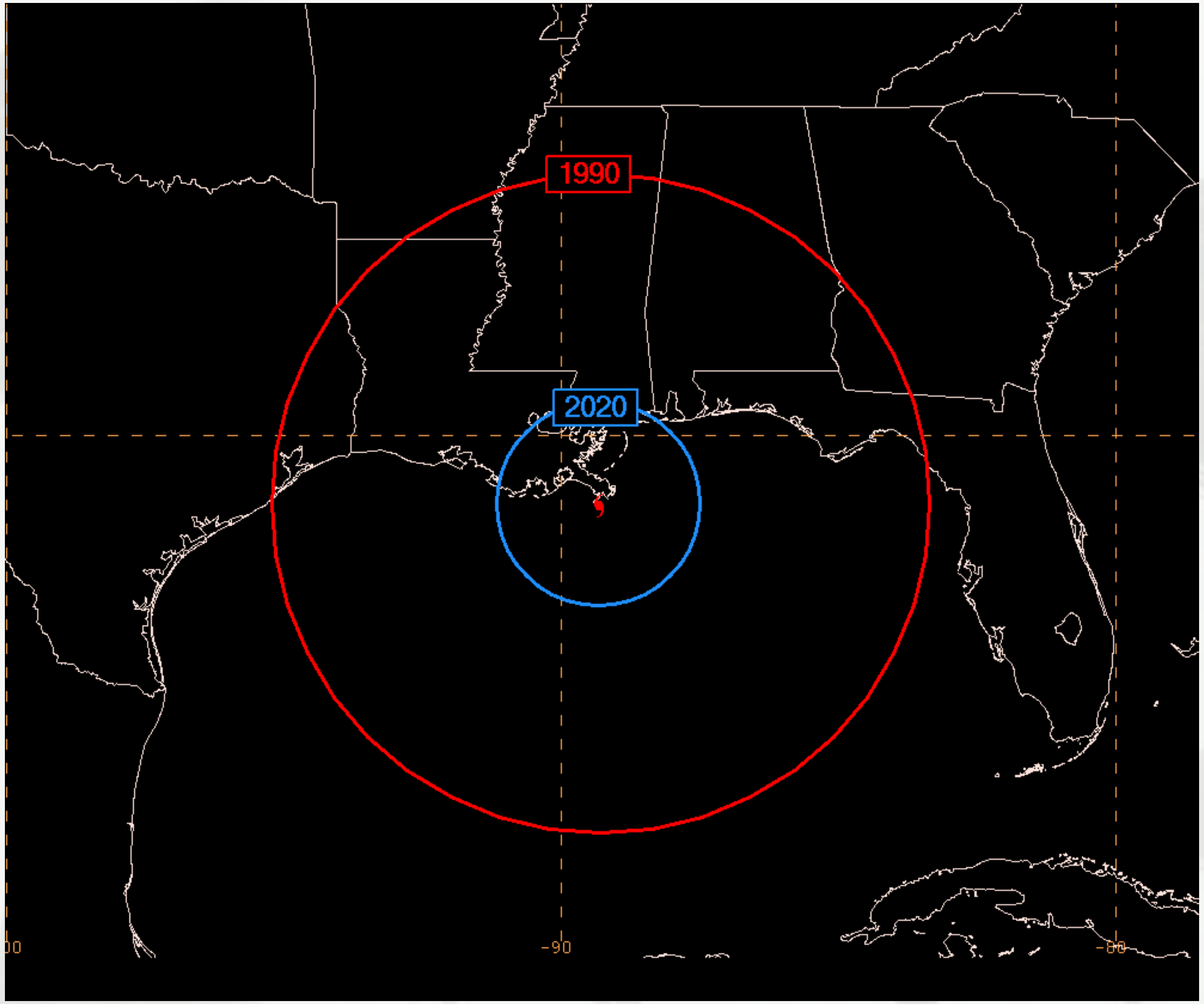




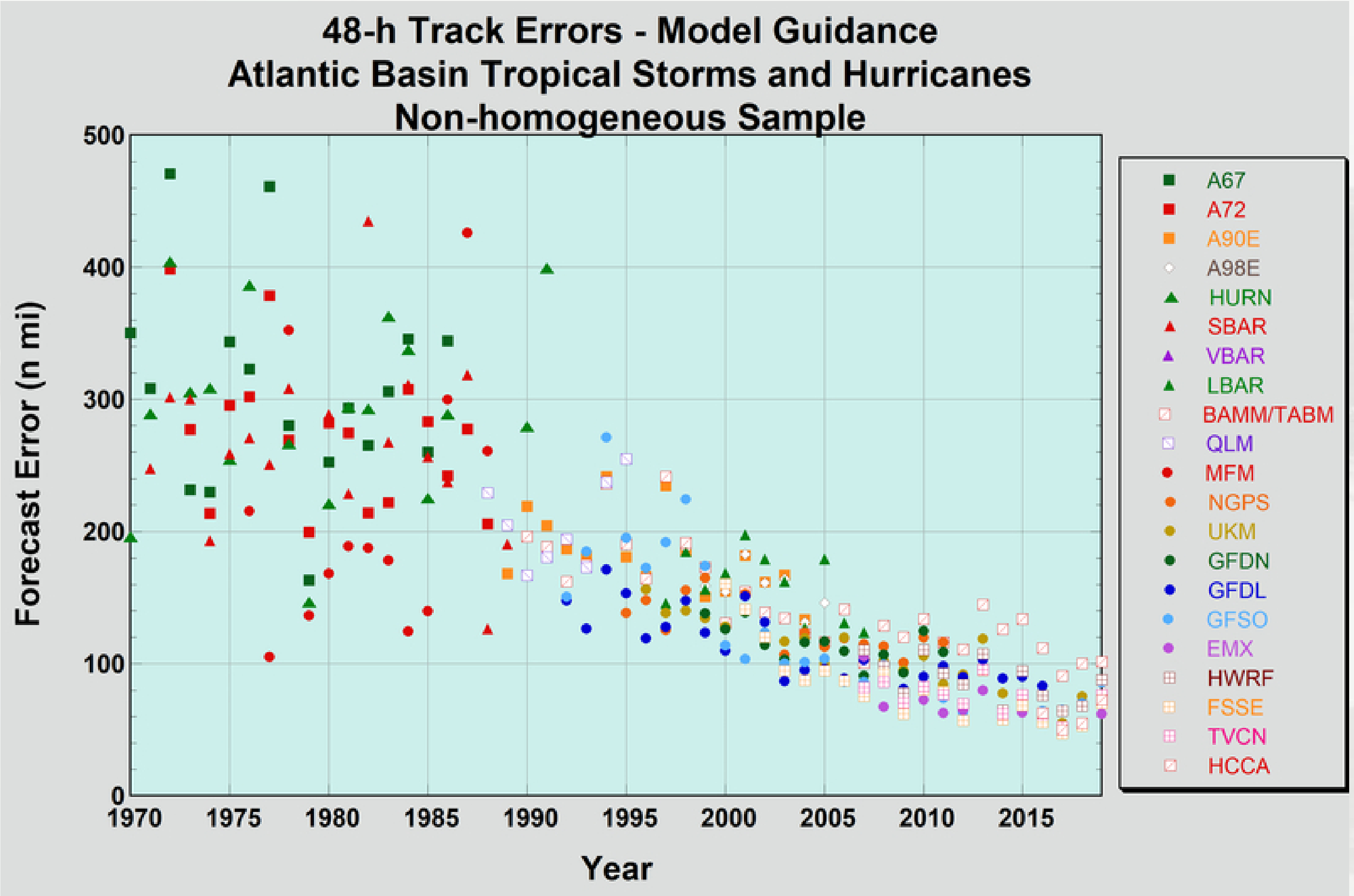
Average 72 h track forecast error in 1990



Average 72 h track forecast error in 2020



Model track forecast error trends



Advancements in technology and science are primarily responsible for these large improvements

Hierarchy of Tropical Cyclone Models

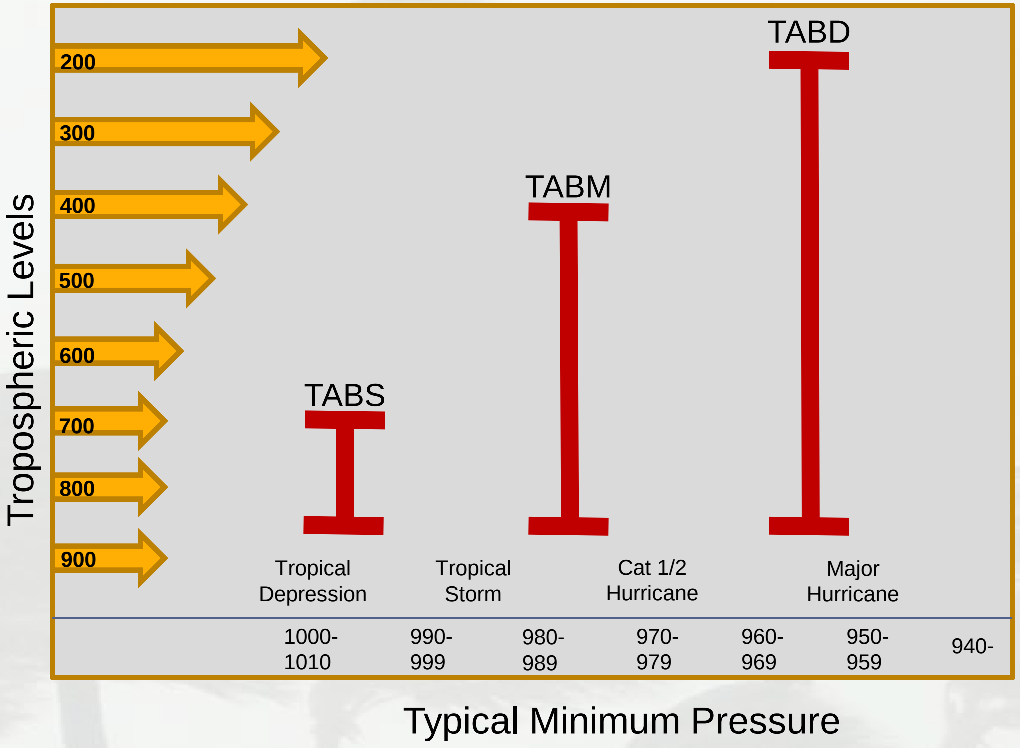
- Statistical
  - CLIPER/SHIFOR: Forecasts based on established relationships between storm-specific information (i.e. location and time of year) and the behavior of previous storms
  - XTRP: Extrapolation from recent trends (or persistence)
- Simplified Dynamical
  - TABS,TABM,TABD: Forecasts based on simplified dynamic representation of the interaction between the vortex and prevailing flow (trajectories)
- Dynamical (Numerical Weather Prediction)
  - Solve the equations of motion that govern the atmosphere (GFS, HWRF, etc)
- Statistical-Dynamical
  - Use NWP forecasts and other input to statistically predict desired variables based on past storm behavior (eg, regression, neural networks) (SHIPS, LGEM)
- Consensus
  - Based on multi-model or single-model ensembles (TVCN, IVCN, HCCA, etc)

Climatology and Persistence Model (CLIPER)

- Statistical model, developed in 1972, extended from 3 to 5 days in 1998, re-derived in 2005.
  - Developmental sample is 1931-2004 (ATL), 1949-2004 (EPAC).
- Required inputs:
  - Current and 12-h old speed and direction of motion
  - Current latitude and longitude
  - Julian day, maximum wind
- No longer provides useful operational guidance, but is used as a benchmark for other models and the official forecast. If a model has lower mean errors than CLIPER it is said to be "skillful".
- New version has been developed that can be extended to 7 days (or beyond).

Simplified Dynamical Models

- **Trajectory and Beta** (TABS, TABM, TABD)
  - Two-dimensional "trajectory" model. Uses steering determined from a global model (GFS), averaged over a 400km radius circle around the storm location at a given time.
  - Adds a correction to simulate the Beta effect (about 0.7 m/s)
  - Includes a small component of persistence
  - Three versions, representing different depths of steering flow. The spread of these is a useful indicator of environmental vertical shear:
    - TABS (shallow): 850-700 mb
    - TABM (medium): 850-400 mb
    - TABD (deep): 850-200 mb



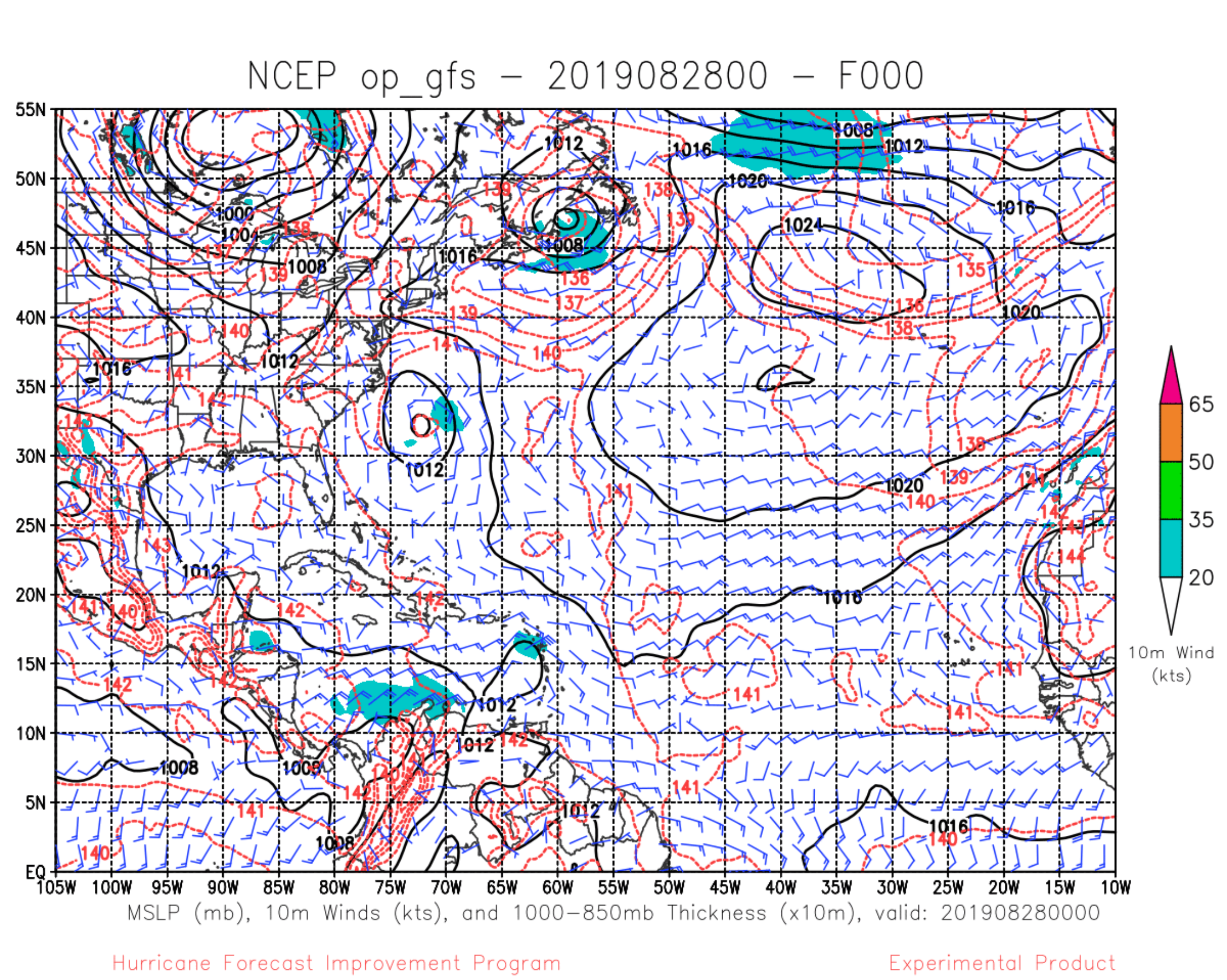
Three-Dimensional Dynamical Models

- Dynamical models
  - May be global or limited area.
  - May be grid point or spectral.
  - May employ a “bogussing” scheme to represent the TC vortex.
- Global models
  - Have inadequate resolution to define the TC inner core (eye and eyewall structure).
  - Are often useful for forecasting TC size and outer wind structure.
  - Have no lateral boundary conditions and therefore should have better performance at longer ranges than limited area models.
- Limited Area (Regional) models
  - Generally have higher horizontal resolution and are therefore more capable of representing core structure and intensity change.
  - Performance degrades at longer ranges.

SUMMARY OF NWP MODELS USED BY NHC FOR TC TRACK PREDICTION

ATCF ID Tracker	Global/Regional Model Name	Horizontal Resolution	Vertical Levels and Coordinates	Data Assimilation	Convective Scheme	Cycle/Run Frequency	2020 TVCN INCLUSION
NVGM/NVGI	Navy Global Environmental Model	Spectral ~31km	60 Hybrid Sigma-pressure	NAVDAS-AR 4D-VAR	Simplified Arakawa-Schubert (SAS)	6 hr (144 hr) 00/06/12/18 UTC	NO
AVNO/AVNI (GFSO/GFSI)	Global Forecast system	Finite Volume Cubed Sphere (FV3) 13km	127 Hybrid Sigma-pressure	GSI/4D-VAR EnKF hybrid, including TC central pressure	Simplified Arakawa-Schubert [Arakawa and Schubert (1974) / Pan and Wu (1994)]	6 hr (240 hr) 00/06/12/18 UTC	YES
EMX/EMXI EMX2	European Centre for Medium-Range Weather Forecasts	Spectral ~9km	137 Hybrid Sigma-Pressure	4D-VAR	Tiedke mass flux [Tiedke (1989)]	12 hr (240 hr) 00/12 UTC 06/18 UTC tracks available in 2021	YES
EGRR/EGRI EGR2	U.K. Met Office Global Model	Grid Point ~10km	70 Hybrid Sigma-Pressure	4D-VAR Ensemble Hybrid	UKMET [Gregory and Rowntree (1990)]	12 hr (144 hr) 00/12 UTC	YES
CMC/CMCI	Canadian Deterministic Prediction System	Grid Point ~25km	80 Hybrid Sigma-Pressure	4D-VAR ensemble Hybrid	Kain -Fritsch [Kain and Fritsch (1990, 1993)]	12 hr (240 hr) 00/12 UTC	NO
HWRF/HWFI	Hurricane Weather Research and Forecast System	Grid Configuration 3 nests 13.5-4.5-1.5 km	75 Hybrid Sigma-Pressure	4D-VAR Hybrid GDAS GFS IC/BC	SAS mom. mix. + GFS shallow convection (6km and 18km) 2km nest – none	6 hr (126 hr) 00/06/12/18 UTC Runs commence on NHC/JTWC request	YES
HMON	Hurricane Multi-scale Ocean-coupled Non-hydrostatic model	Grid Configuration 3 nests 18-6-2 km	51	None for this season	SAS	6 hr (126 hr) 00/06/12/18 UTC Runs commence on NHC/JTWC request	NO
CTCX/CTCI	NRL COAMPS-TC (using GFS for IC and BC)	Grid Configuration 3 nests 45-15-5 km	40	3D-VAR (NAVDAS) EnKF DART	Kain-Fritsch Kain and Fritsch (1990, 1993)	6 hr (126 hr) 00/06/12/18 UTC Runs commence on 1st NHC/JTWC advisory	YES

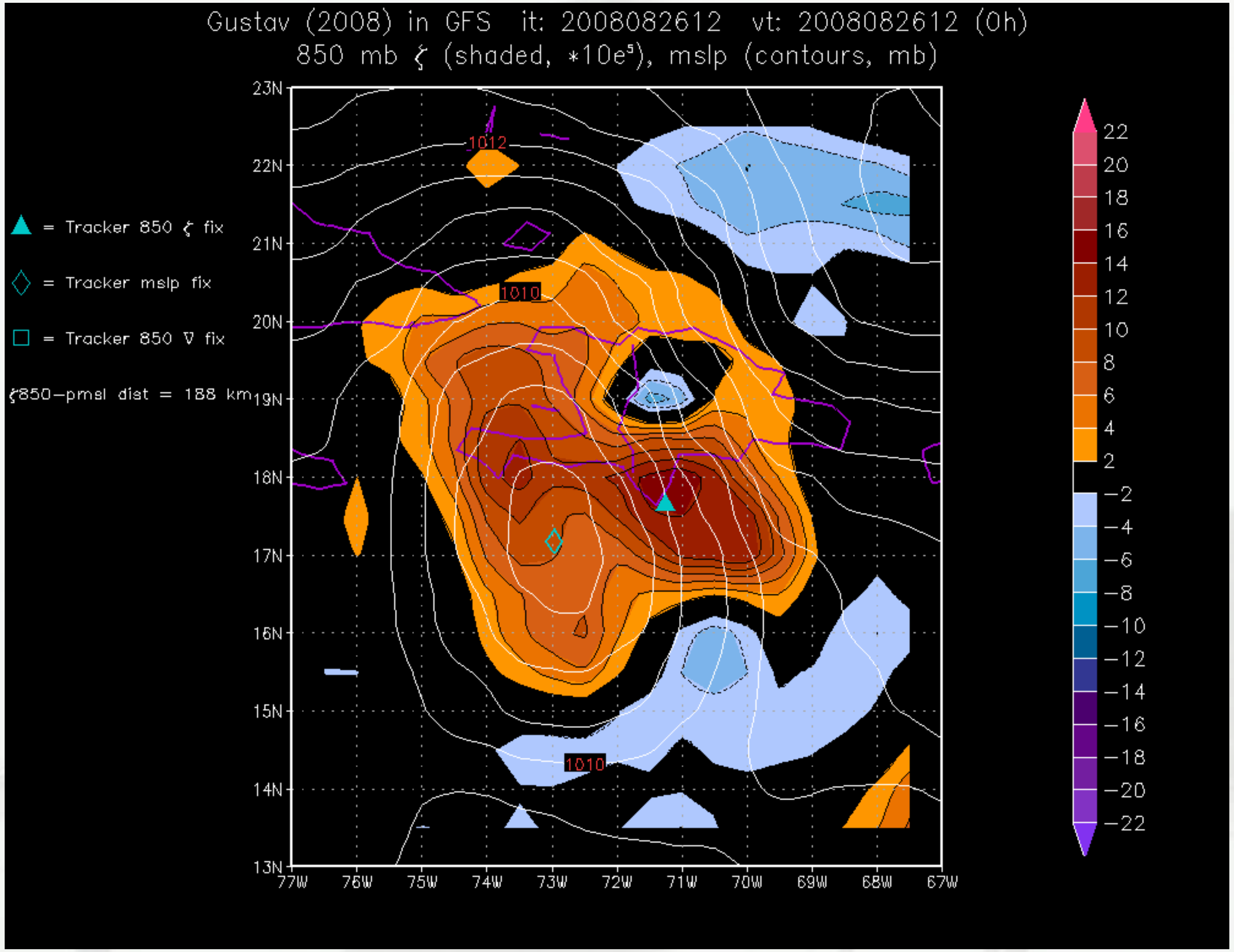
But how do you make a track/intensity forecast from raw model output?



Tracker Design

- Need to determine a point location and maximum winds of a storm in model output to use while making a track or intensity forecast
- An external tracker is applied to the model fields *after* the model run is complete
- A weighted average of the centroid positions of several low-level variables is used:
- 850 mb vorticity
- 700 mb vorticity
- Surface/10m vorticity
- 850 mb geopotential height
- 700 mb geopotential height
- Mean Sea Level Pressure
- 3 secondary parameters (850 mb/700 mb/10m wind speed minimum)

Why the need for a multi-variate external tracker?



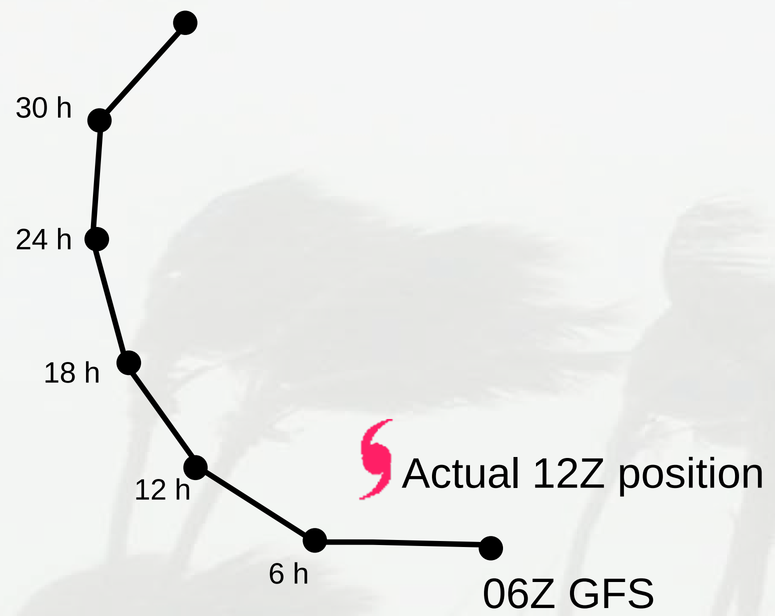
Gustav in GFS: The SLP center was found 188 km from the vorticity center

Early vs. Late Models

- Forecast cycle begins at synoptic time (e.g., 12Z), and forecast is released at t+3 h (15Z).
- The 12Z runs of the dynamical models (HWRF, GFS, etc.), are not available until 16Z-19Z, well after forecast is made and released.
  - These models are known as “late models”
- Forecasts that are available in time for forecast deadlines are called “early” models (TABs, CLIPER).
- For the 12Z forecast cycle, the latest available run of each model is taken (from the 06Z or even 00Z cycle), and adjusted to apply at 12Z. These modified forecasts are known as “interpolated” models (HWFI, GFSI, etc.).

Early vs. Late Models

- Interpolated models are created by adjusting a smoothed version of the previous model run such that its 6 h forecast position exactly agrees with the current storm position. Then the rest of the forecast is adjusted by the same vector.



Early vs. Late Models

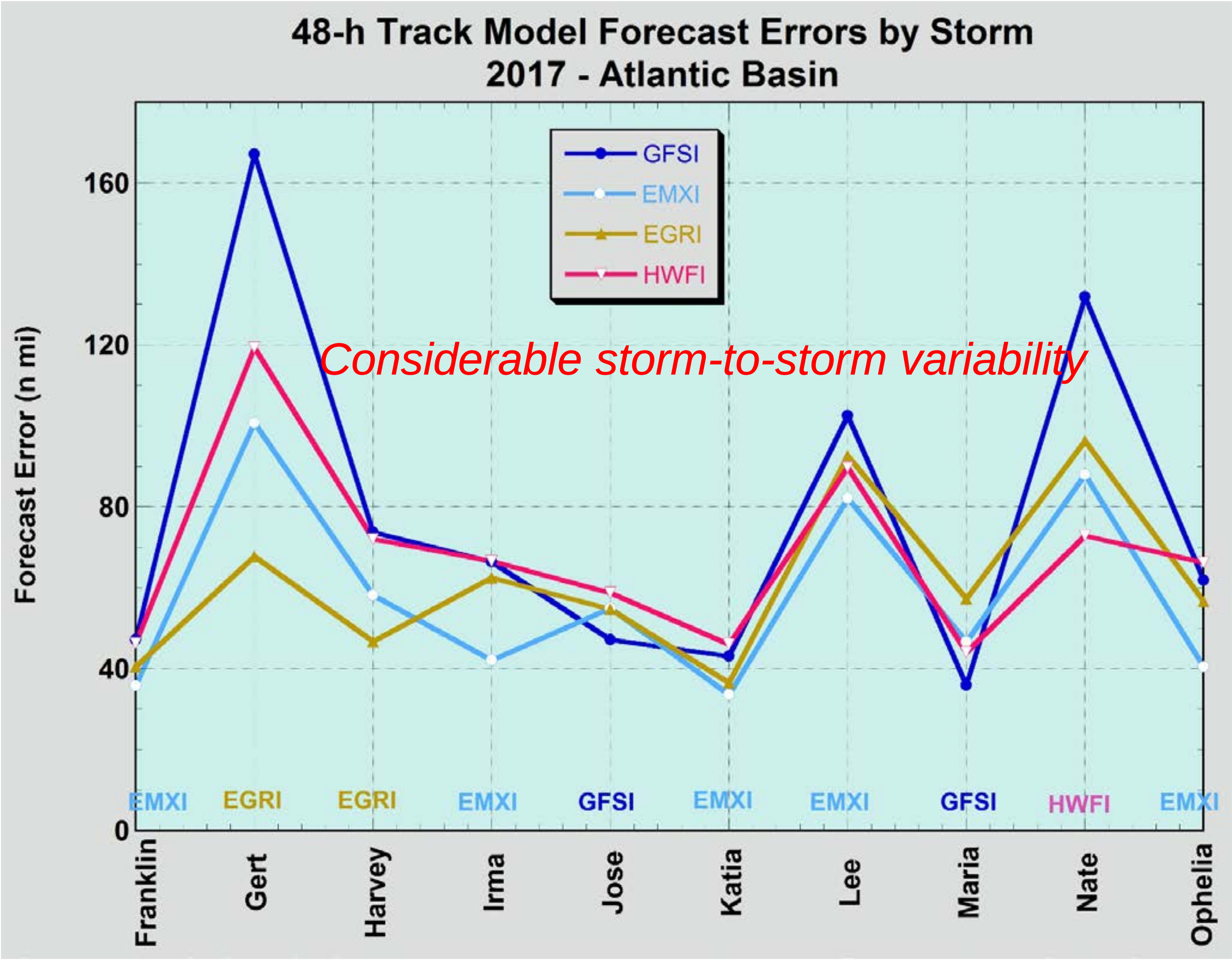
- Interpolated models are created by adjusting the previous model run such that its 6 h forecast position exactly agrees with the current storm position. Then the rest of the forecast is adjusted, with the magnitude of the adjustment generally decreasing with time.

The "early" version of the model is what the forecasters actually have available to them when making a forecast

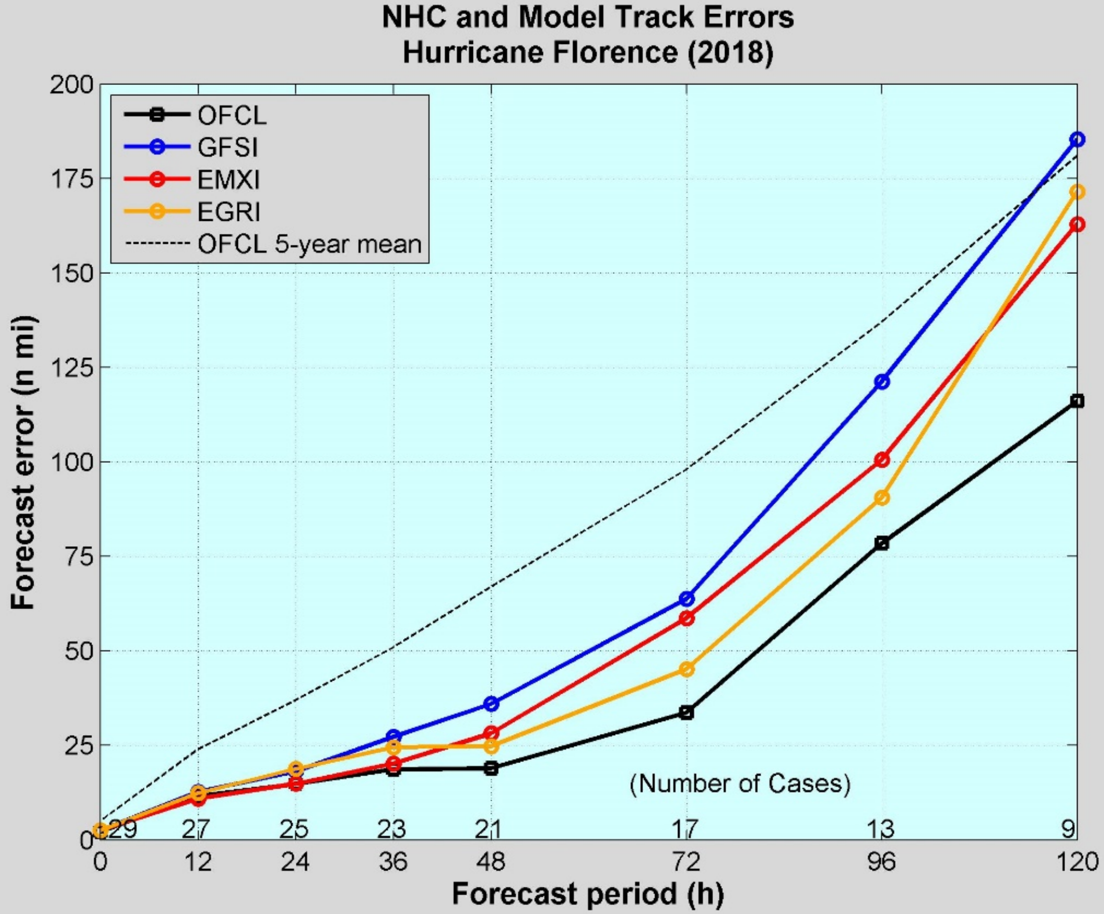
OFCL is verified against the early models

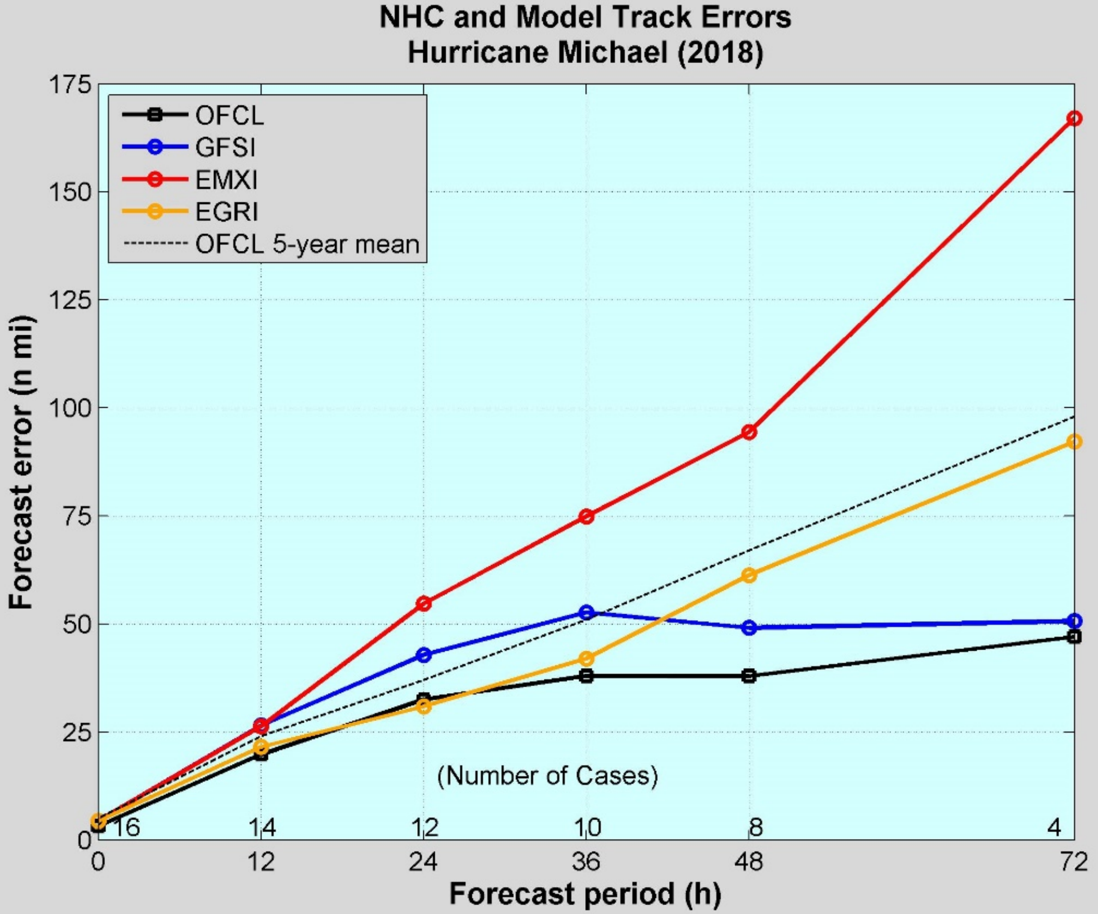
But which model should you use?

48-h Model Track Errors by Storm



Florence and Michael

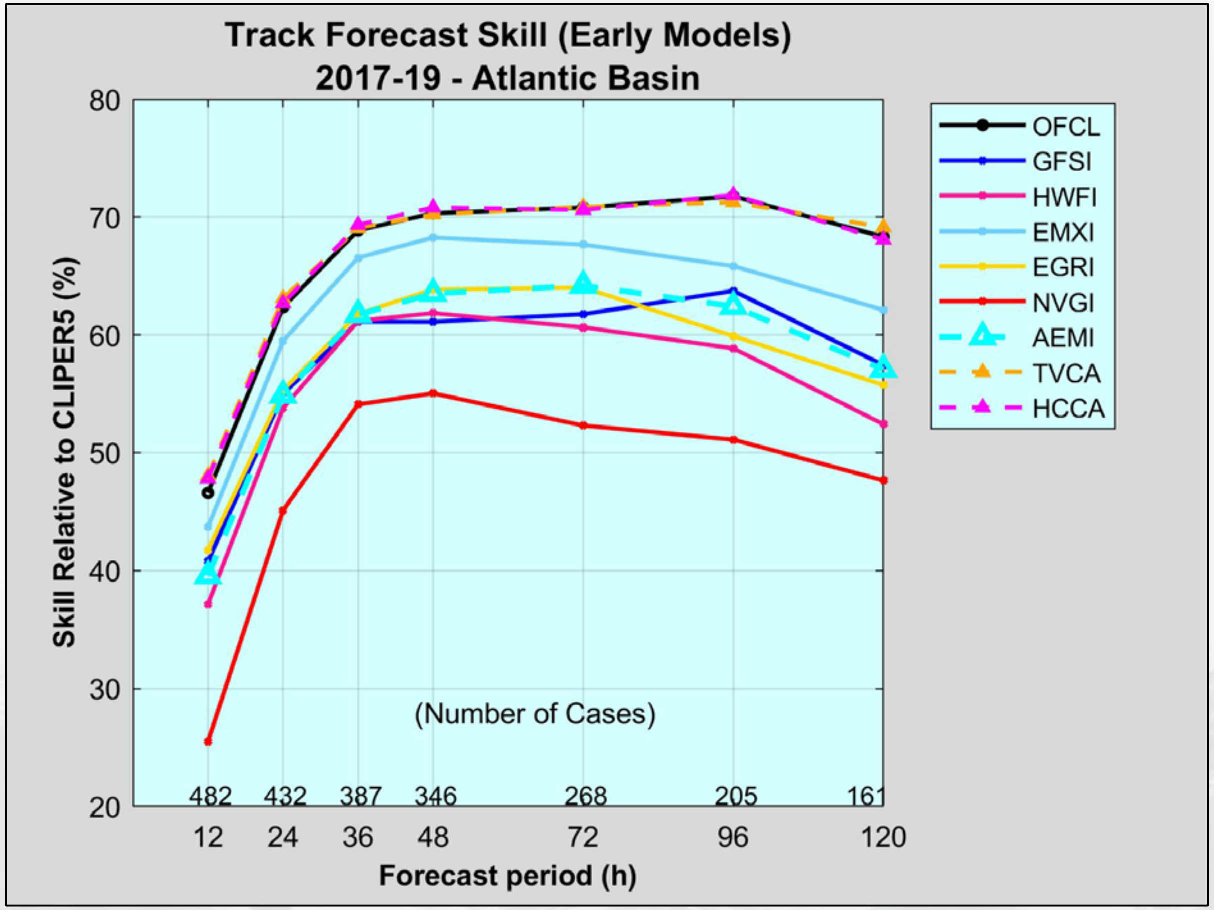




Ensembles and Consensus

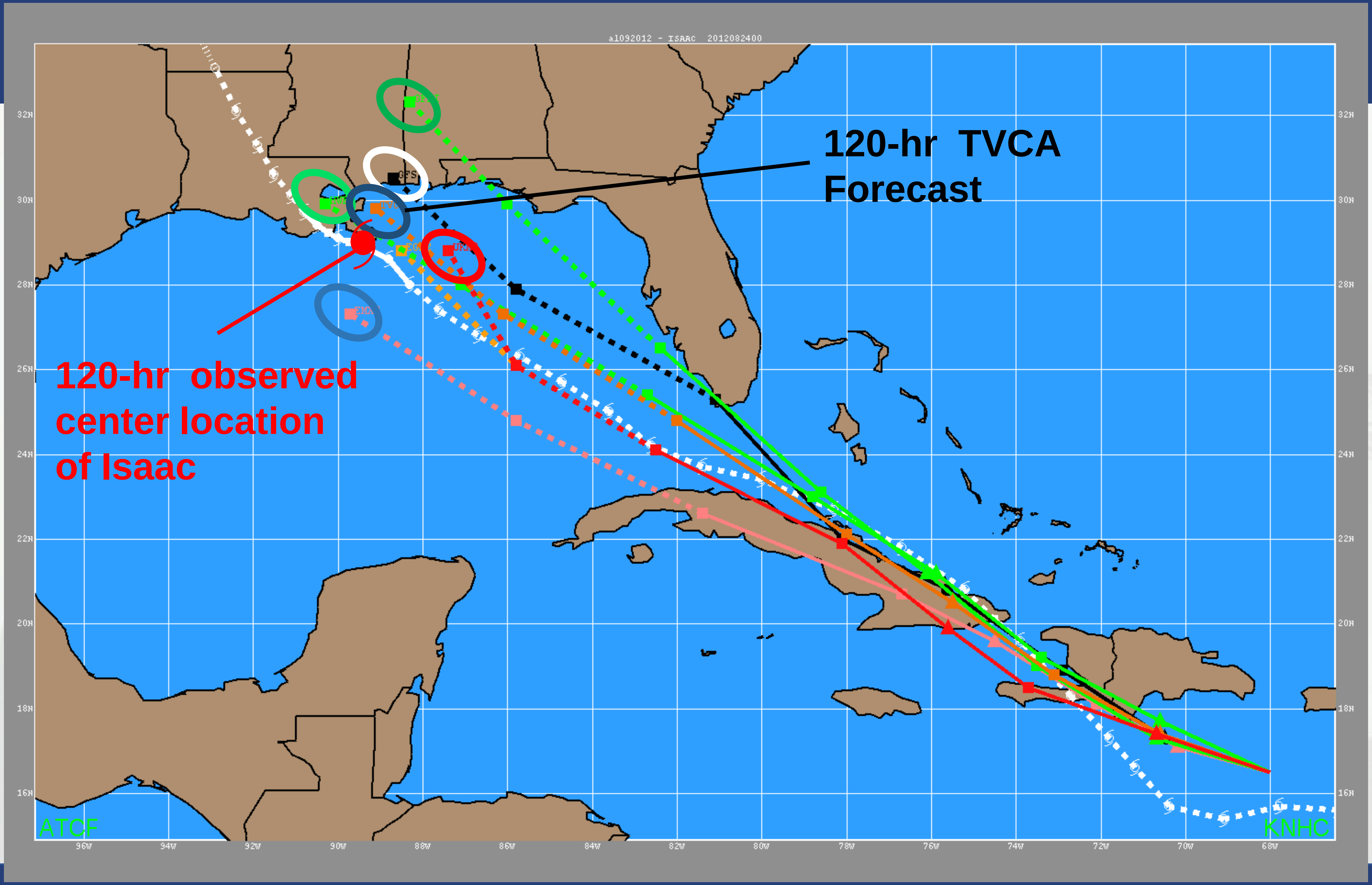
- Often, the most successful models are consensus aids formed from an ensemble of good performing models with a high degree of independence.

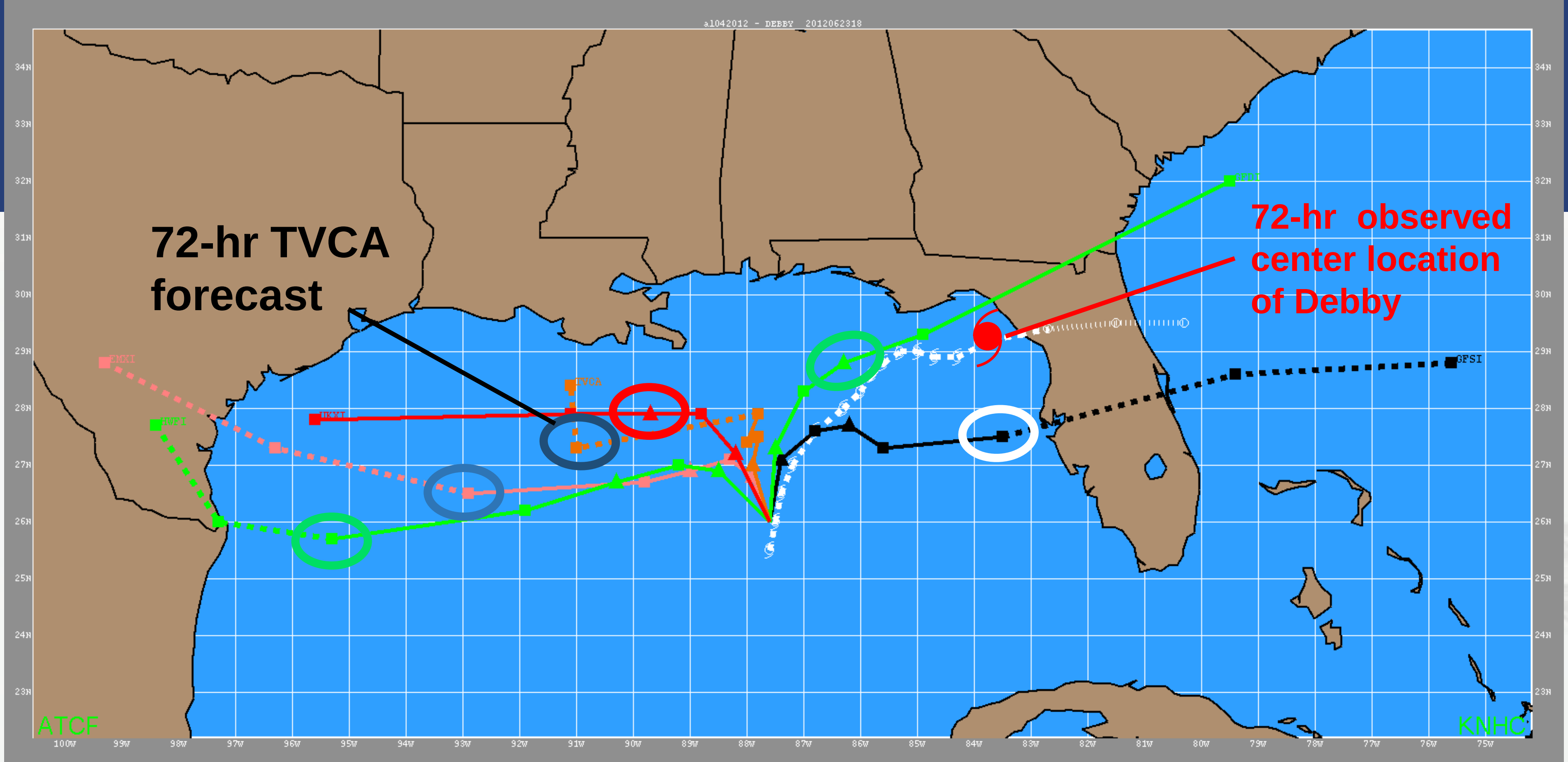
- Recently, some single-model consensus models (especially the GFS ensemble) have performed as well as the deterministic version of the same model especially at longer ranges (day 5 and beyond).



Track Forecasting at the NHC: Using Models

- Dynamical model consensus is an excellent first guess for the forecast (and often a good final guess!). Continuity dictates that it must be considered in view of the previous official forecast.
- Evaluate the large-scale environment using conventional data and satellite imagery (e.g., water vapor)
  - Try to assess steering influences so that you understand and perhaps evaluate the model solutions
- Compare the models' forecast of the environmental features, not just the TC tracks.
  - Evaluate the initialization of the TC in the model fields. Unrealistic TC can affect the likelihood of a successful forecast.
  - Consider the recent performance of the various models, both in terms of accuracy and consistency.
  - Spread of models can dictate forecaster confidence.


al092012 - ISAAC 2012082400
120-hr TVCA
Forecast
120-hr observed
center location
of Isaac
GFS
ATCF
KNHC
32N
30N
28N
26N
24N
22N
20N
18N
16N
96W
94W
92W
90W
88W
86W
84W
82W
80W
78W
76W
74W
72W
70W
68W

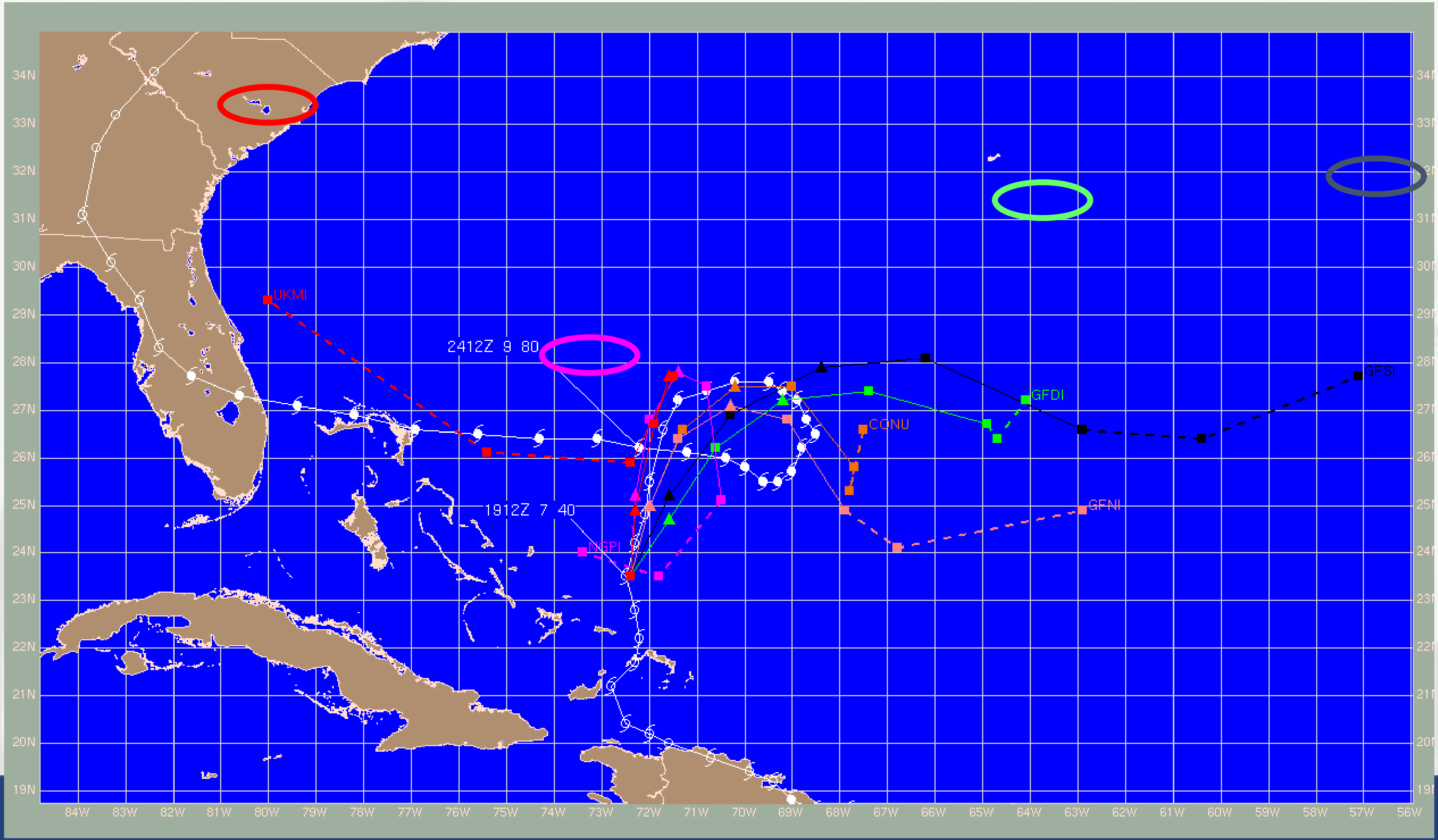


Tropical Storm Debby 1800 UTC 23 June 2012

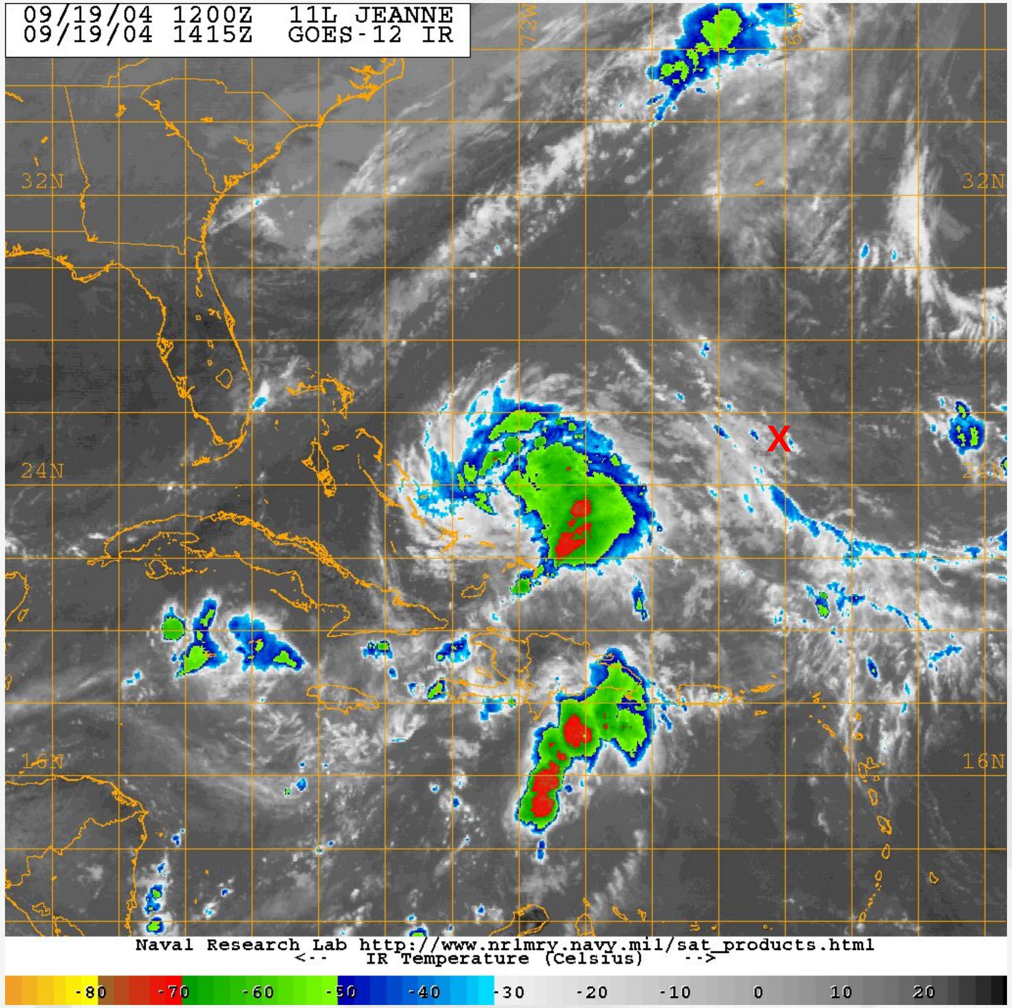
Of course, the consensus approach doesn't always work! Sometimes the forecaster might want to exclude certain models and form a "selective consensus", if the discrepancies among the models can be resolved.

Resolving these discrepancies is often more difficult than some may have you believe!

How do you resolve the difference between guidance models?



How do you resolve the difference between guidance models?



Poor organization (esp. lack of deep convection in the core) would argue against Jeanne being carried eastward by upper-level westerlies.

This reasoning allowed the forecasters to largely disregard the GFS and form a “selective consensus” of the remaining models.

Additional Track Forecasting Considerations

- Previous official forecast exerts a strong constraint on the current forecast
  - Can damage credibility by making big changes from one forecast to the next, and then having to go back to the original

Windshield Wipering

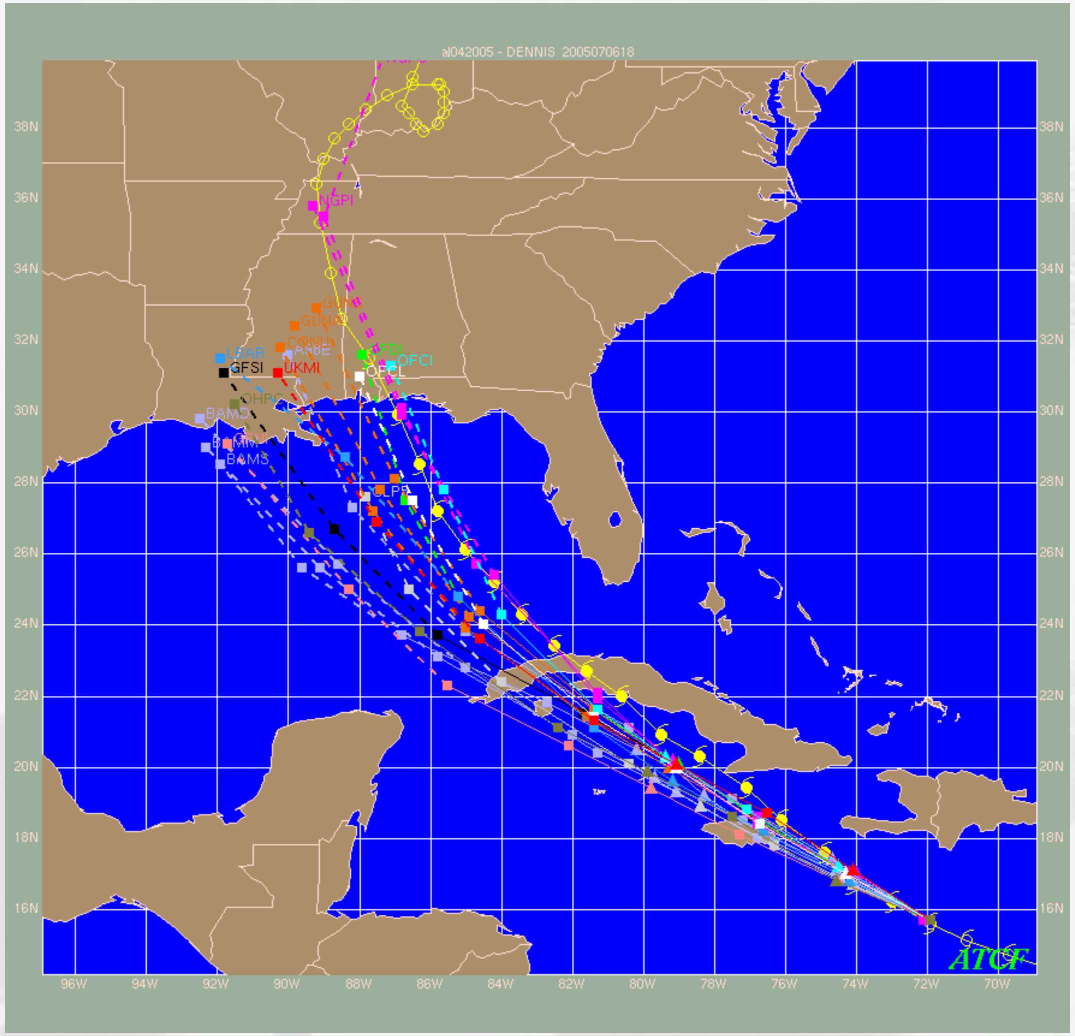
Tromboning

- Consequently, changes to the previous forecast are normally made in small increments
- Continuity is also important within a given forecast
  - Gradual/steady changes in direction or speed from 12 to 24 to 36 h, etc

Dennis Guidance 6 July 1200 UTC

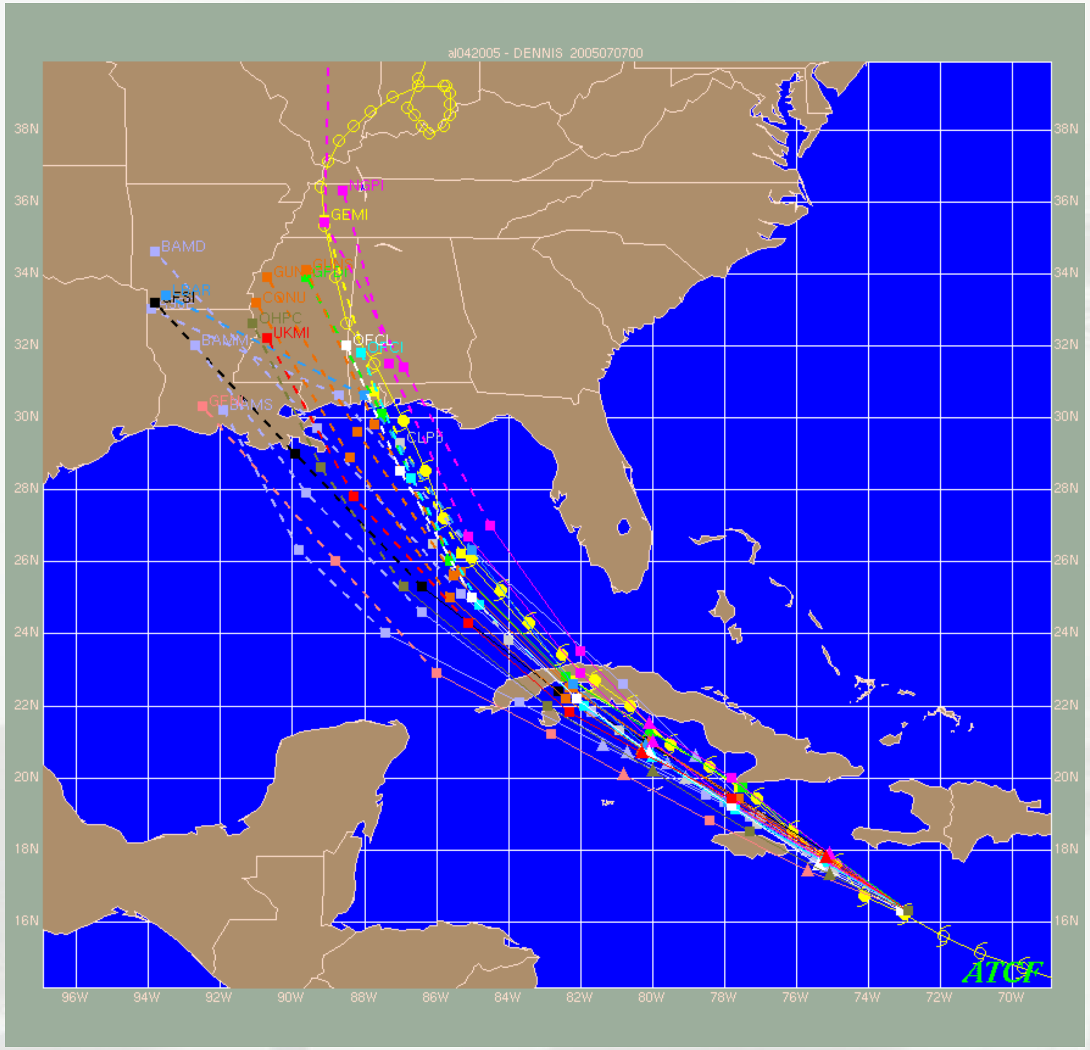
- Official forecast near model consensus in extreme western FL panhandle.

Dennis Guidance 6 July 1800 UTC



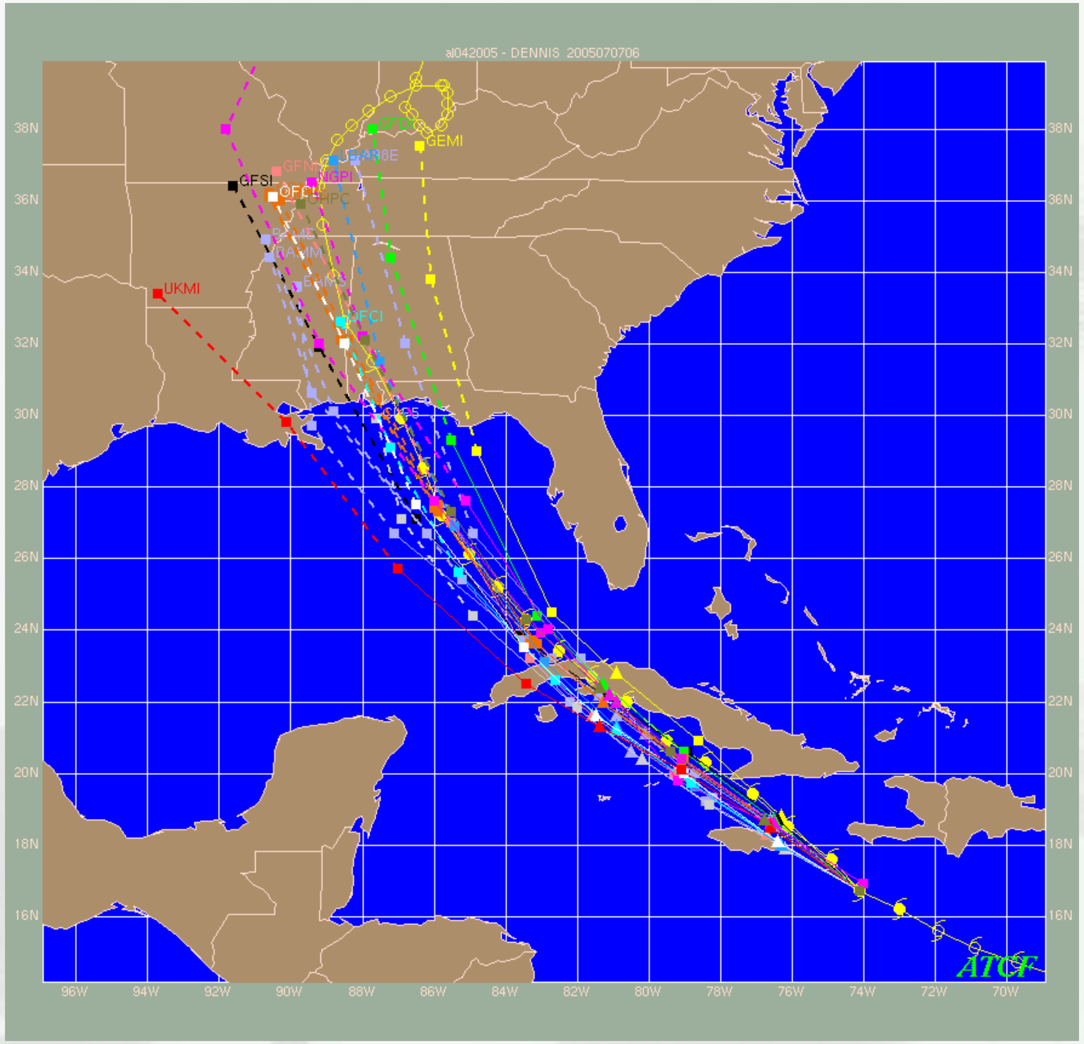
- Guidance shifts sharply westward toward New Orleans. Official forecast nudged westward into AL.

Dennis Guidance 7 July 0000 UTC



- Little overall change to guidance, but NGPI shifts slightly eastward. Little change in official forecast.

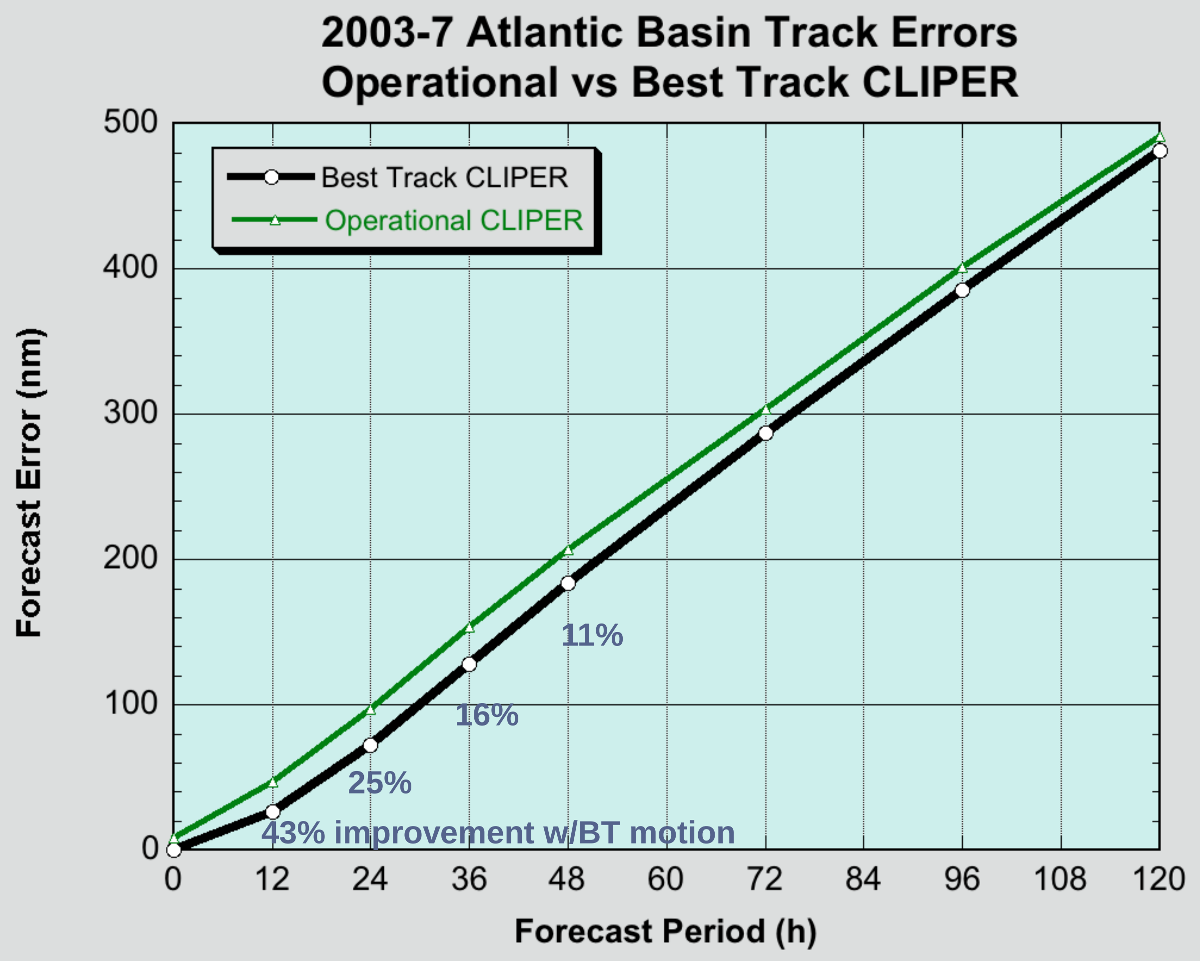
Dennis Guidance 7 July 0600 UTC



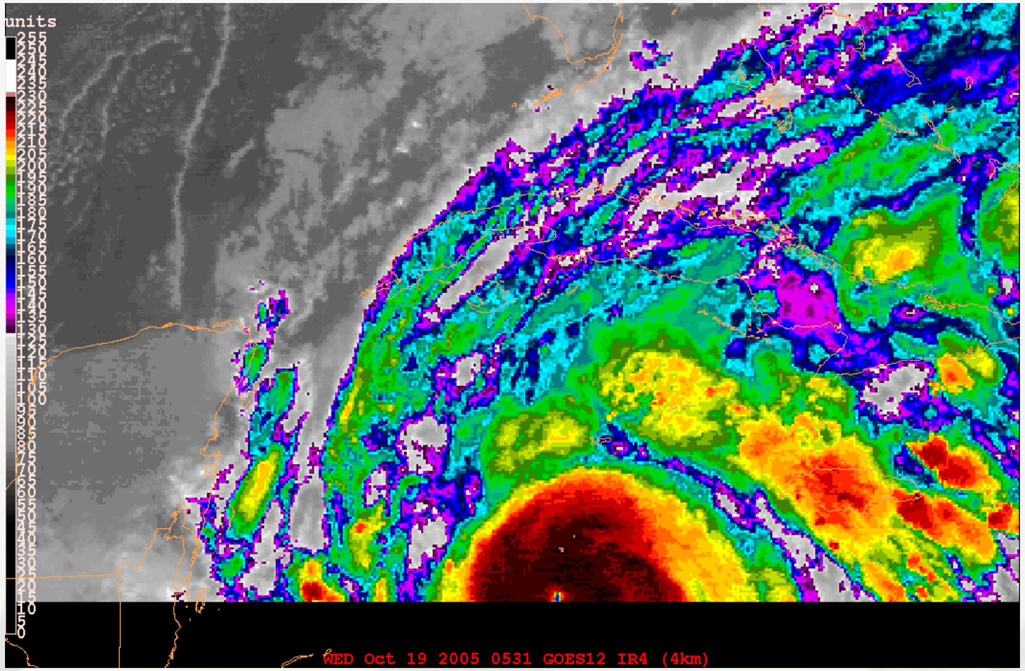
- Rest of the guidance shifts sharply eastward, leaving official forecast near the center of the guidance envelope (and very close to the actual track of Dennis.

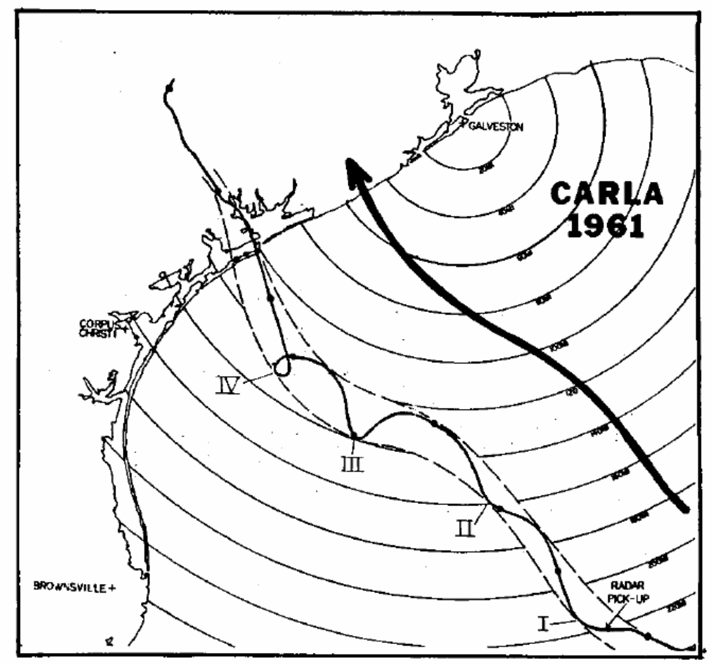
Track Forecasting at the NHC: Importance of Initial Motion

- Accurate estimate of initial motion is extremely important.
  - Has dramatic impact on accuracy of the CLIPER model at shorter ranges.
  - Initial motion vector is also used in some vortex bogussing schemes.
  - 12-h NHC forecast is heavily weighted by the initial motion estimate.
- Not always easy to determine, particularly for systems with ill-defined centers.



Trochoidal Motion

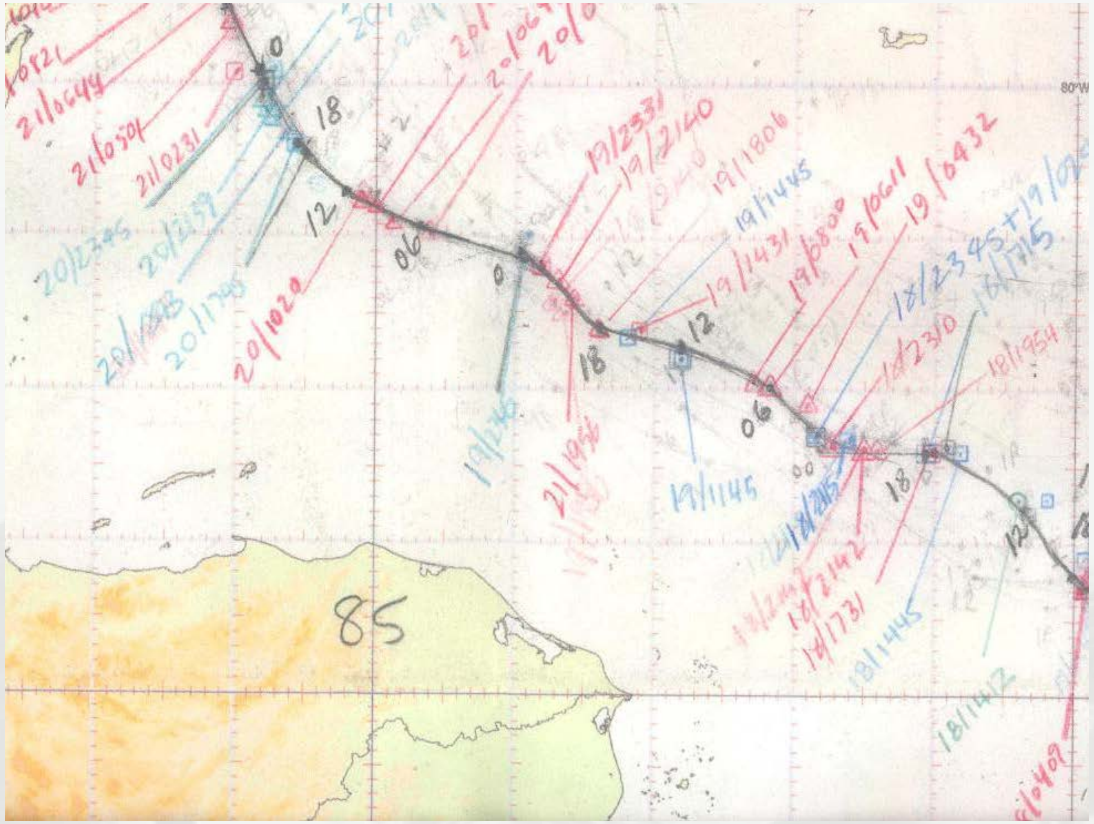




- Substantial oscillation (wobble) of the center of a TC about its mean motion vector
- Primarily a side effect of convective asymmetries in the inner core
- Amplitude of motions varies but higher-frequency “wobbles” lost in ‘best track’ smoothing process
- Virtually impossible to forecast!

Track Forecasting at the NHC: Determination of Initial Motion

- Initial motion typically computed using the average motion over the previous 6, 12, or 18 h.
  - Shorter when known changes in track are occurring, longer when center location is uncertain.
  - Initial motion estimate should not reflect short-term track wobbles (e.g., trochoidal oscillations) that will not persist.



- NHC philosophy is that it is better to lag events a little bit than to be going back and forth with analyses or forecasts. We will usually wait several hours before “calling” a change in track.

Track Forecasting Review

What is the most important factor for tropical cyclone track?

a) Large-scale steering flow
b) Internal dynamics of the eyewall
c) Beta effect
d) Storm intensity

Track Forecasting Review

Which of the following is typically the best type of model to use for track forecasting?

a) Statistical-dynamical model (SHIPS/LGEM)
b) High-resolution global model (ECMWF/GFS)
c) Multi-model consensus (TVCN/HCCA)
d) Regional hurricane model (HWRF/HMON)

Track Forecasting Review

If one the track of one model shifts significantly from its previous track, what is the best thing to do?

a) Change the locations of the Hurricane Warnings to agree with this model.
b) Make a significant change to the official forecast from the previous advisory.
c) Adjust the official forecast slightly, but generally maintain continuity with the previous one.
d) Make no change to the official forecast.