Tropical Cyclone Track Prediction

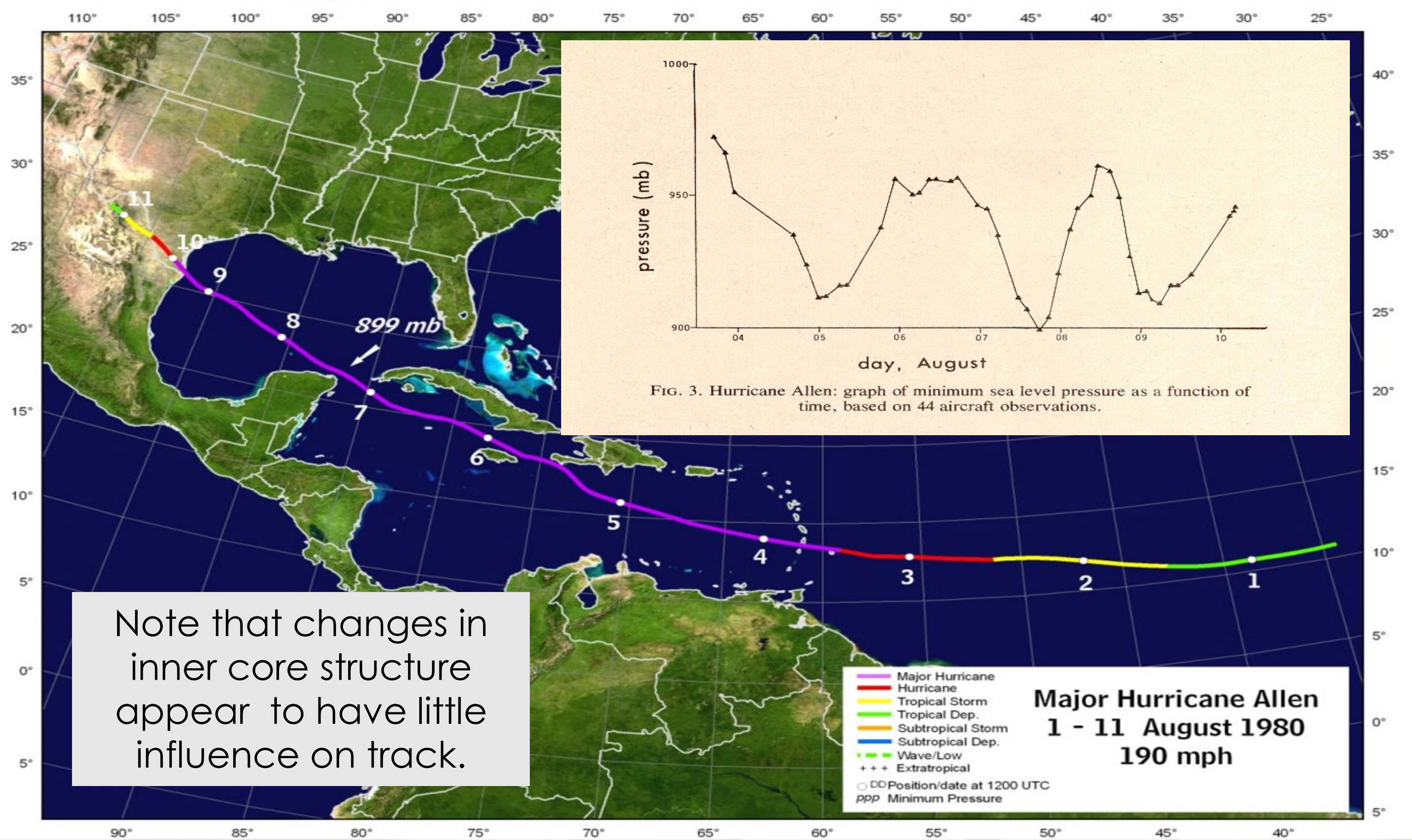
Richard J. Pasch and David A. Zelinsky

National Hurricane Center

RA-IV Workshop on Hurricane Forecasting and Warning

April 9, 2024

Intensity impact on Track



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

Tropical Cyclone Motion

- 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.

SCALE ANALYSIS OF THE VORTICITY EQUATION

Use scales for tropical cyclone outer wind:

$L \sim 500 \quad km$

$Rotational \quad wind \quad V \sim 10 \quad m/s$

$Divergent \quad wind \quad U \sim 1 \quad m/s$

$\Delta P \sim 10^5 \quad Pa$

$T \sim \frac{L}{V} \sim 5 \times 10^4 \quad sec$

$\zeta \sim \frac{V}{L} \sim 2 \times 10^{-5} sec^{-1}$

$\delta \sim \frac{U}{L} \sim 2 \times 10^{-6} sec^{-1}$

$\omega \sim \delta \Delta P \sim 0.2 \quad Pa/sec$

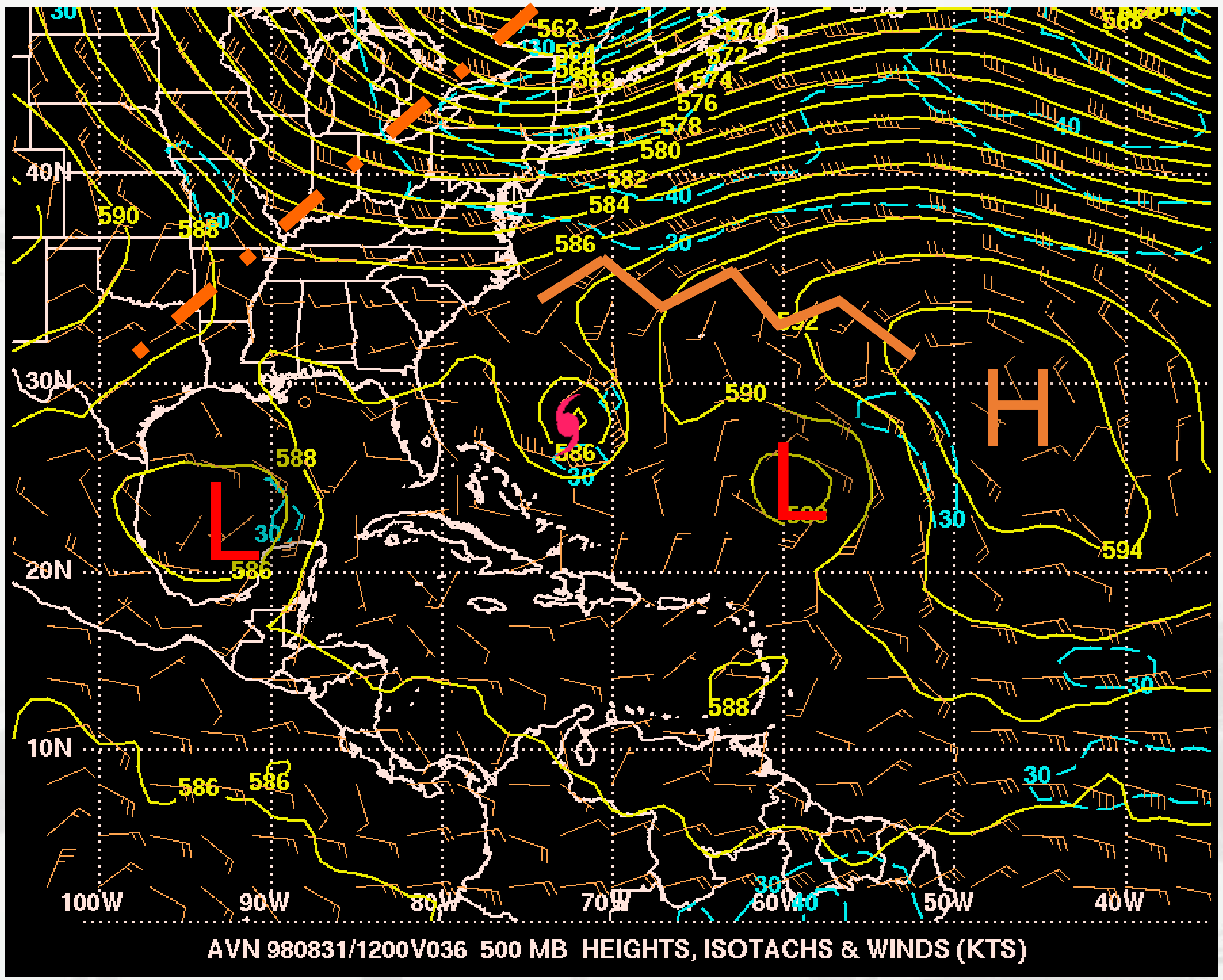
$$\frac{\partial \zeta}{\partial t} = -V \cdot \nabla \zeta - \omega \frac{\partial \zeta}{\partial P} - \beta v - (\zeta + f)\delta - k \cdot \nabla \omega \times \frac{\partial V}{\partial P}$$

(1) (1) (4) (2) (3) (4)

4×10^{-10} 4×10^{-10} 4×10^{-11} 2×10^{-10} 1×10^{-10} 4×10^{-11}

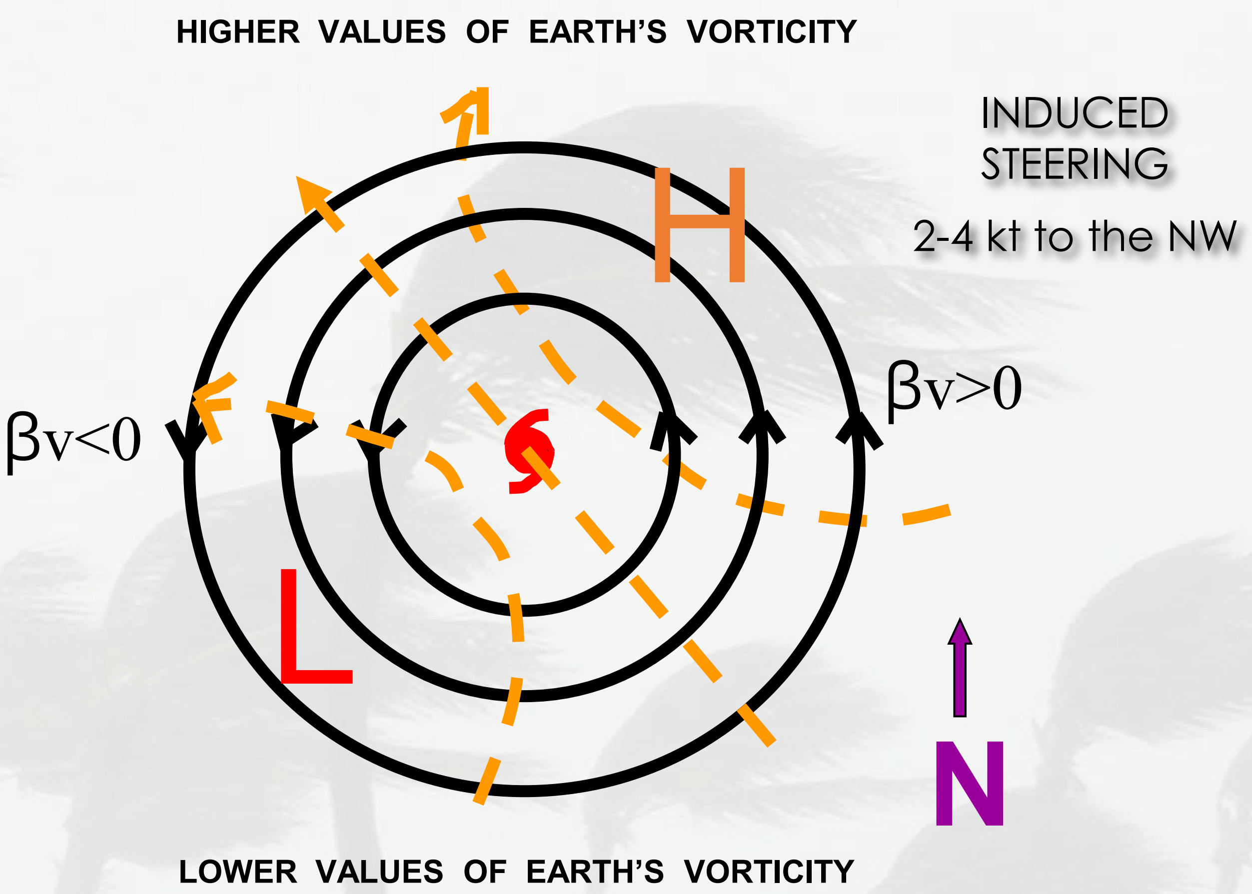
Large Scale Steering

- 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)

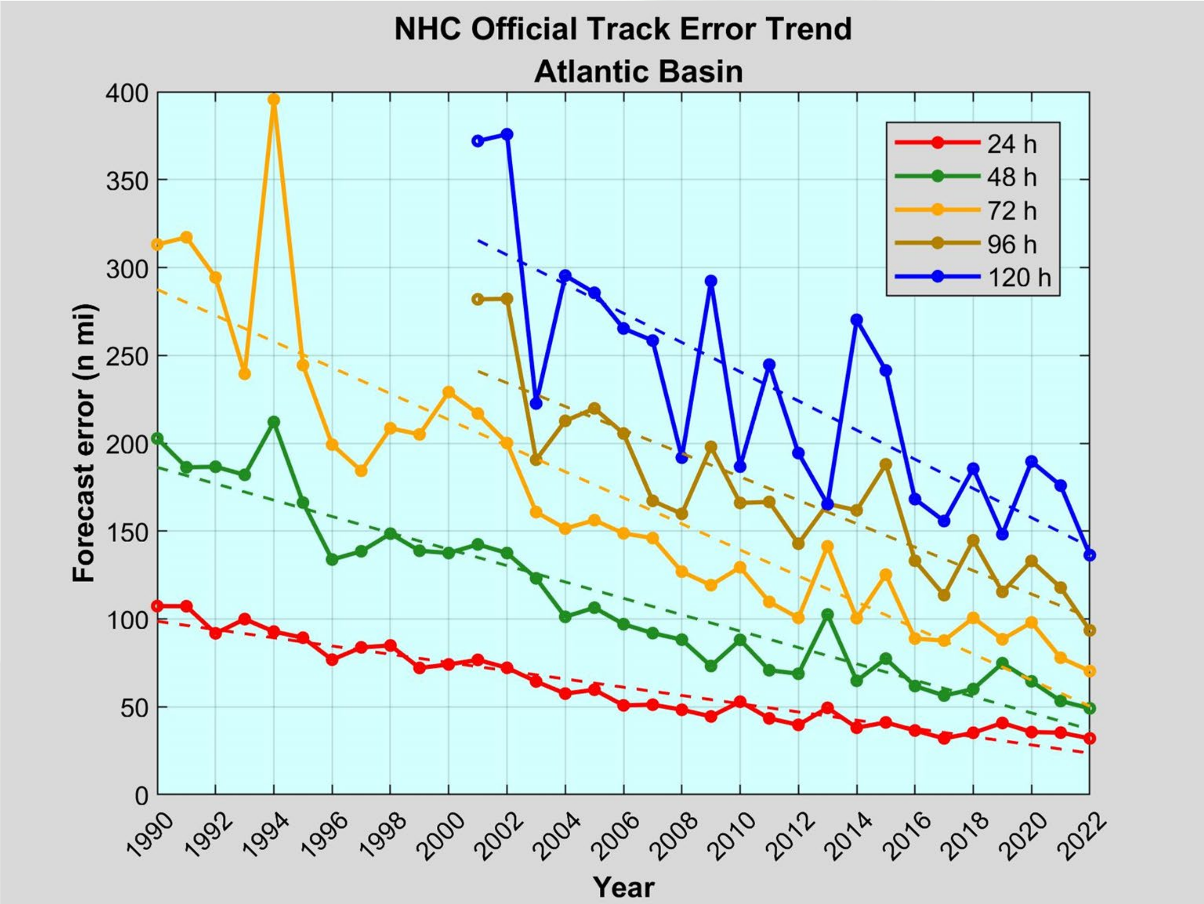


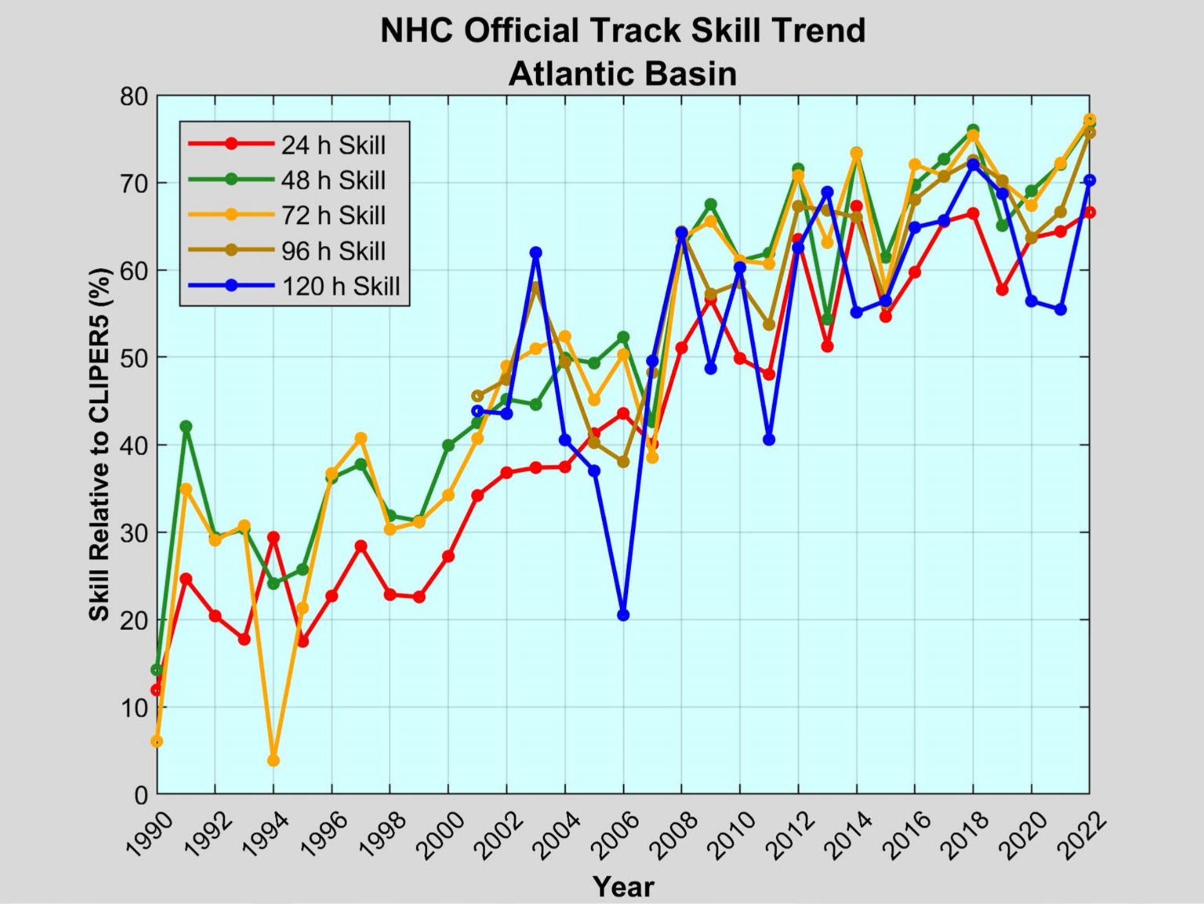
The Beta Effect

- 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.



Track Forecast Errors/Skill at NHC





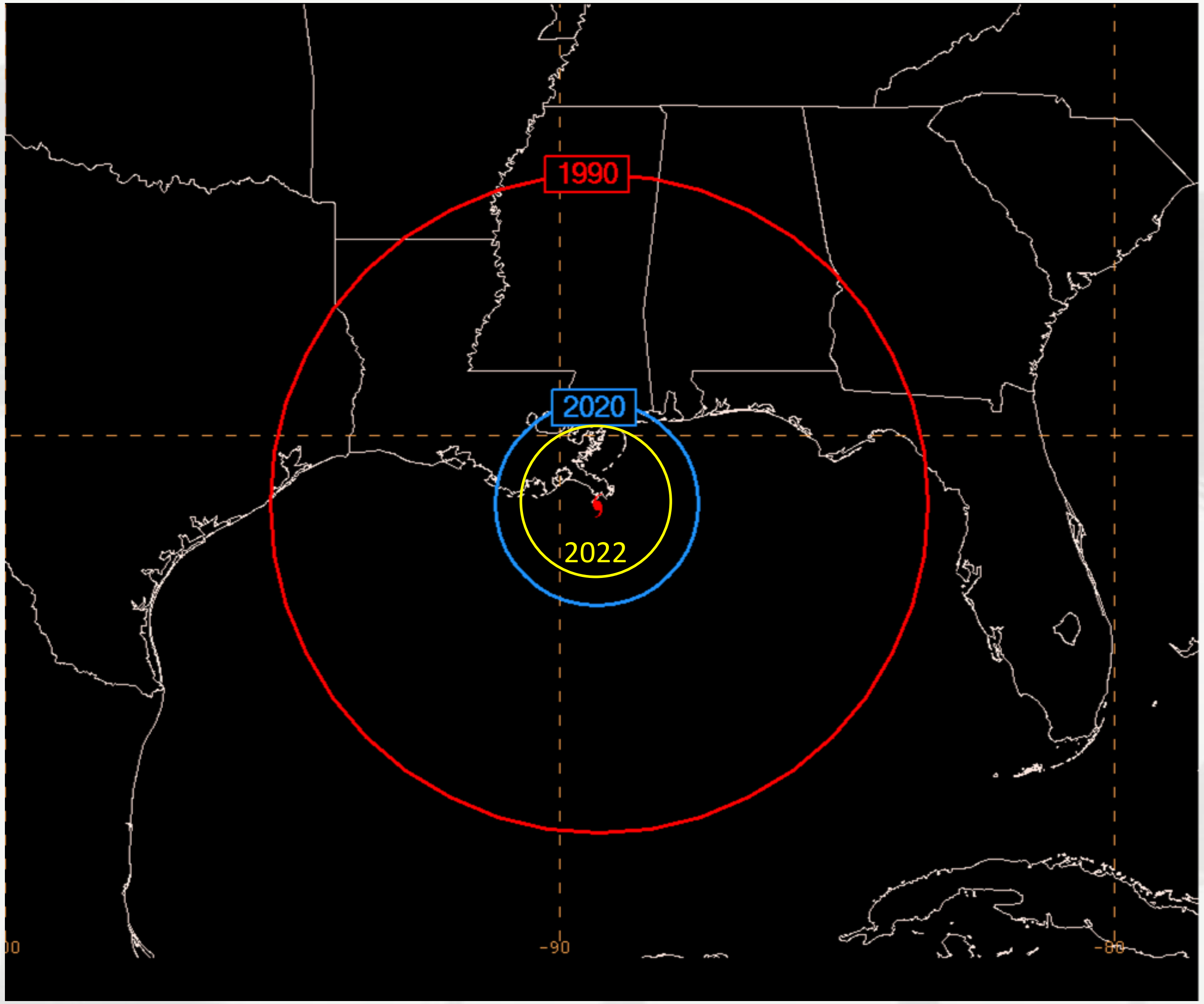
Track Forecasting Review

What is the most important factor for tropical cyclone track? Select the best answer. 0

Large-scale steering flow	0%
Internal dynamics of the eyewall	0%
Beta effect	0%
Storm intensity	0%

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

Average 72 h track forecast error in 2022



How to convert to a point forecast?

How do you convert from a model to something that NHC can use to make a point forecast? Select the best answer.

0

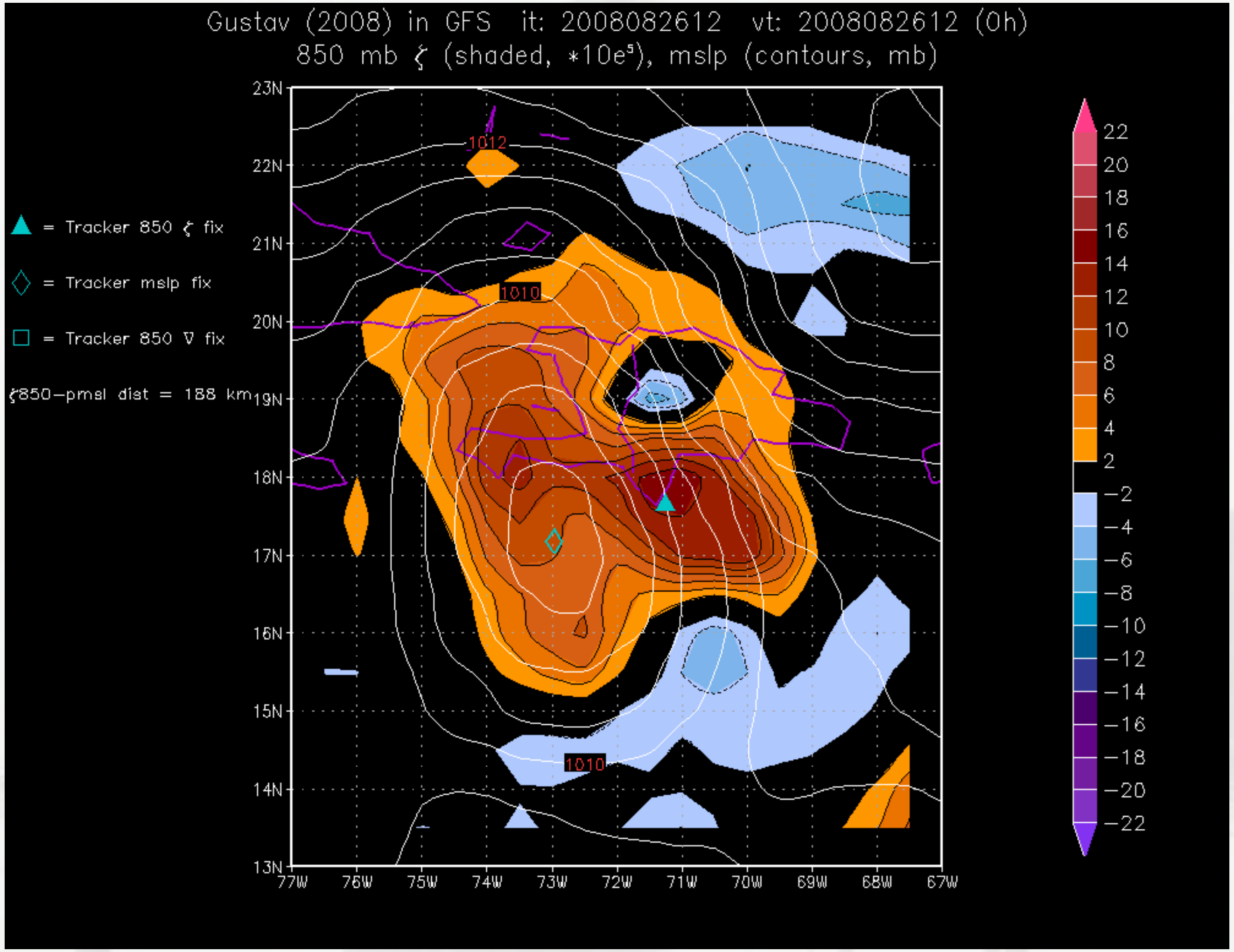
Manually find the location of the storm based on simulated satellite imagery (Dvorak)	0%
The model reports location of local pressures minimums in pressure	0%
Run a tracker on the model output that uses multiple levels/variables	0%
Use Artificial Intelligence to produce a forecast	0%

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

How do we get the model track plots?

- 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?



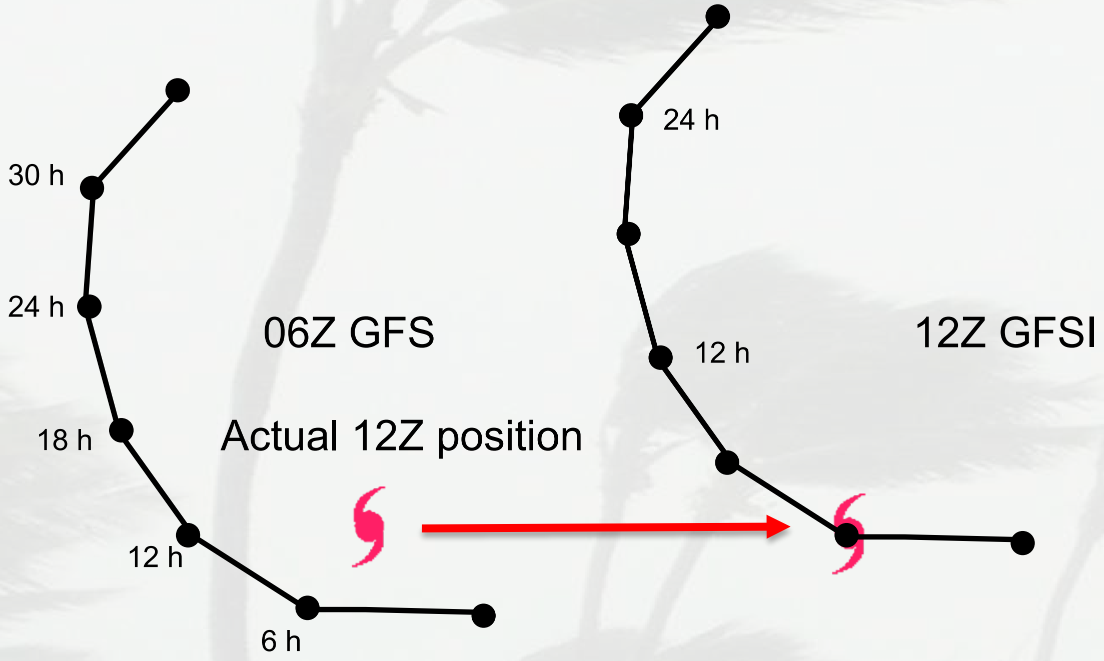
Gustav in GFS: The SLP center was found 188 km from the vorticity center

Early vs. Late Models

- 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

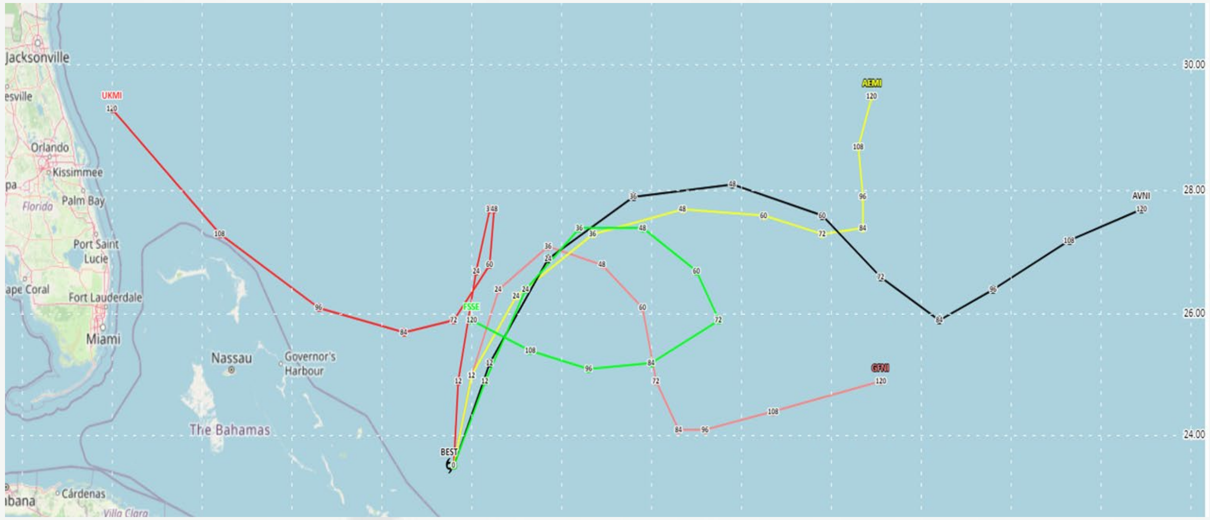
- Interpolated models are created by adjusting the previous model run such that its 6 h forecast position exactly agrees with the current storm position. Then the rest of the forecast is adjusted, with the magnitude of the adjustment generally decreasing with time.

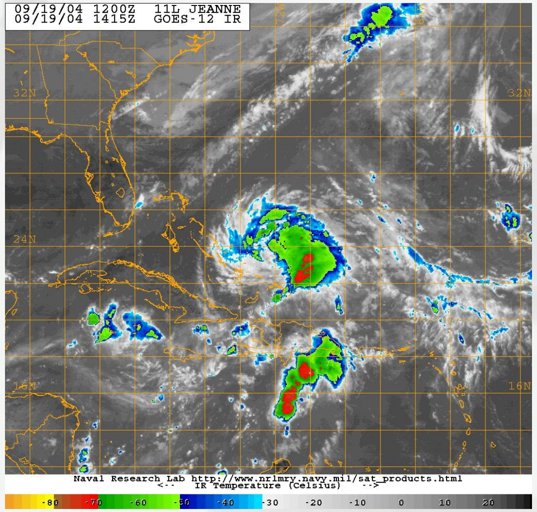


The “early” version of the model is what the forecasters actually have available to them when making a forecast

OFCL is verified against the early models

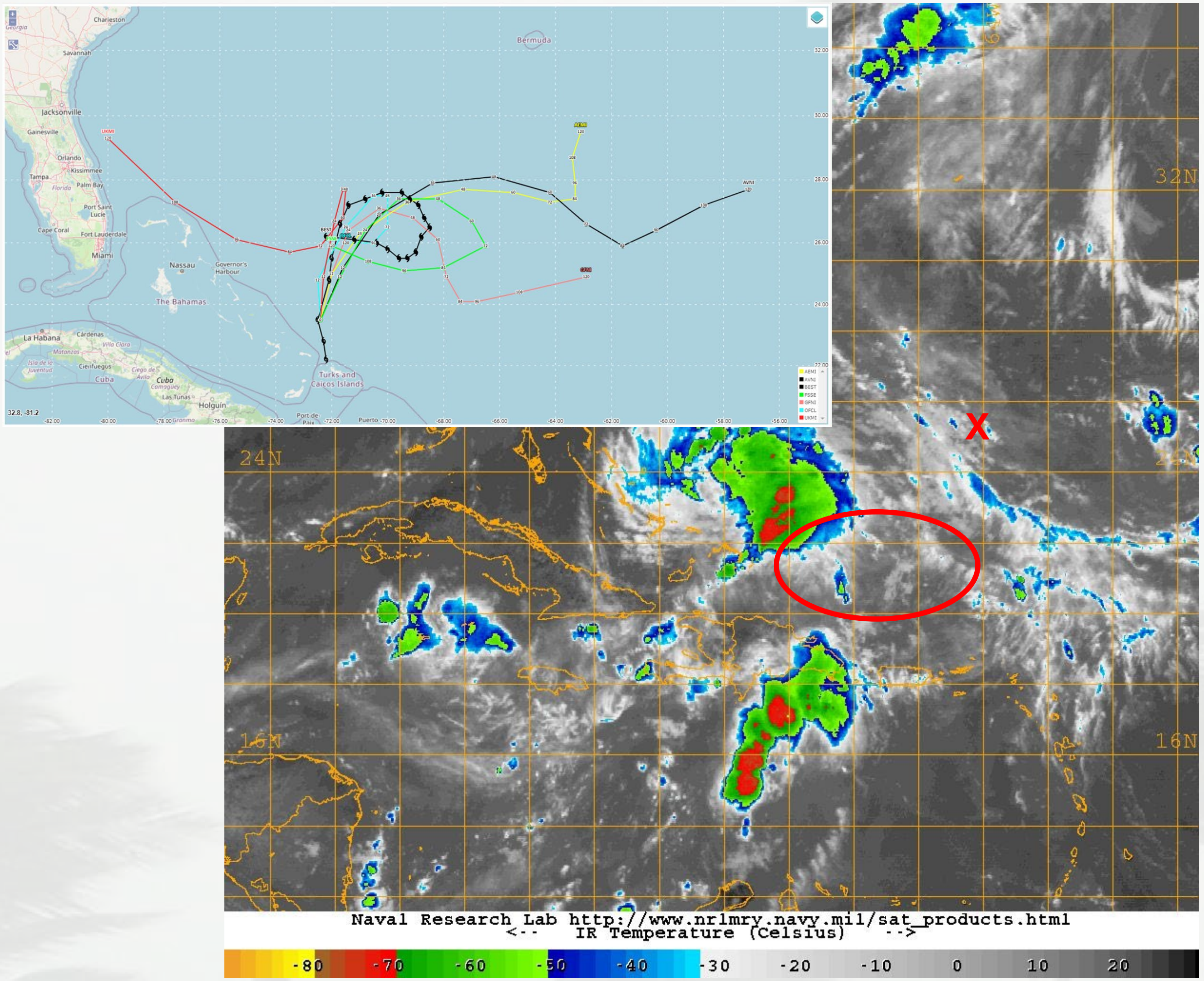
How do you resolve this difference in model guidance for your forecast?





Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

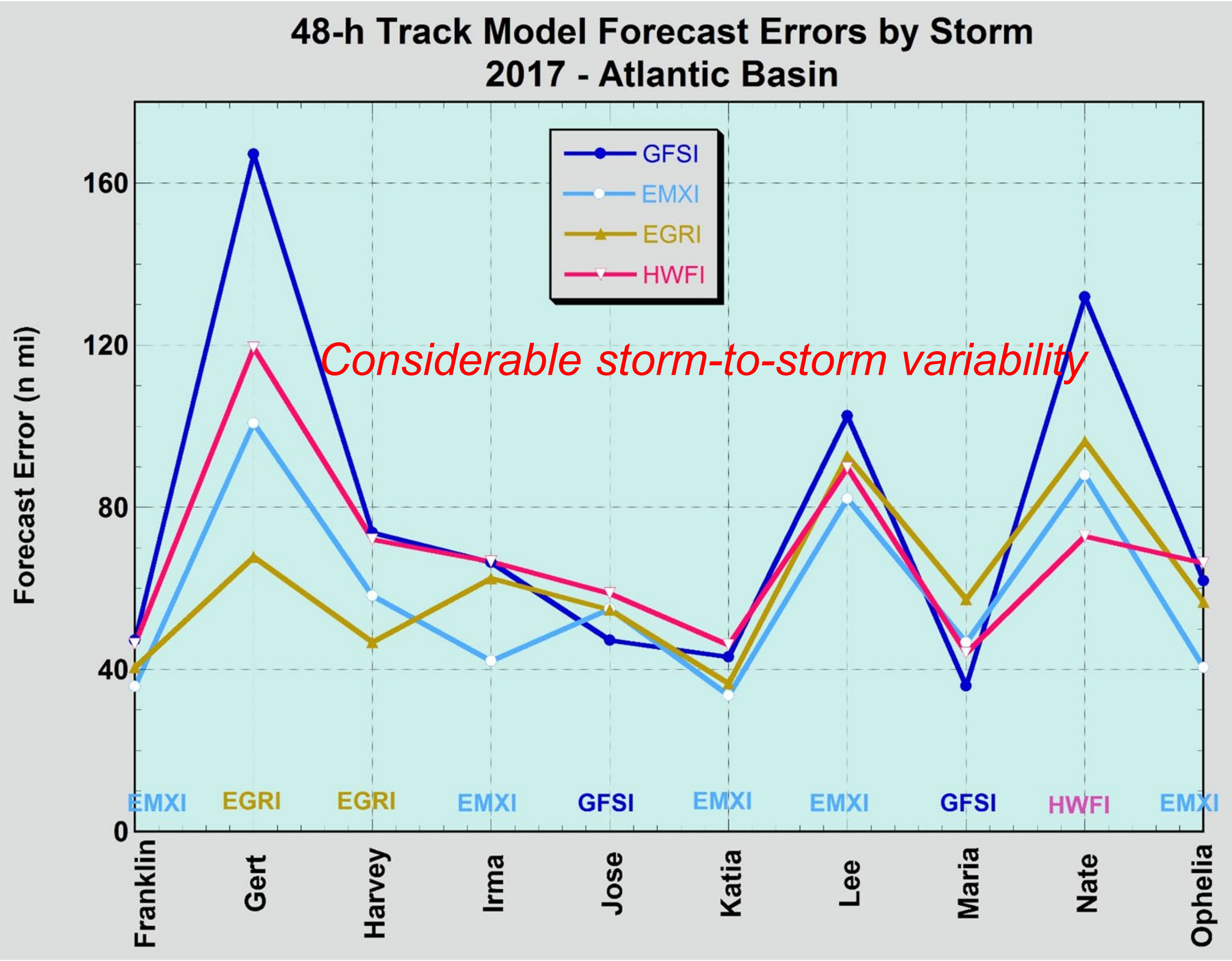
How do you resolve the difference between guidance models?



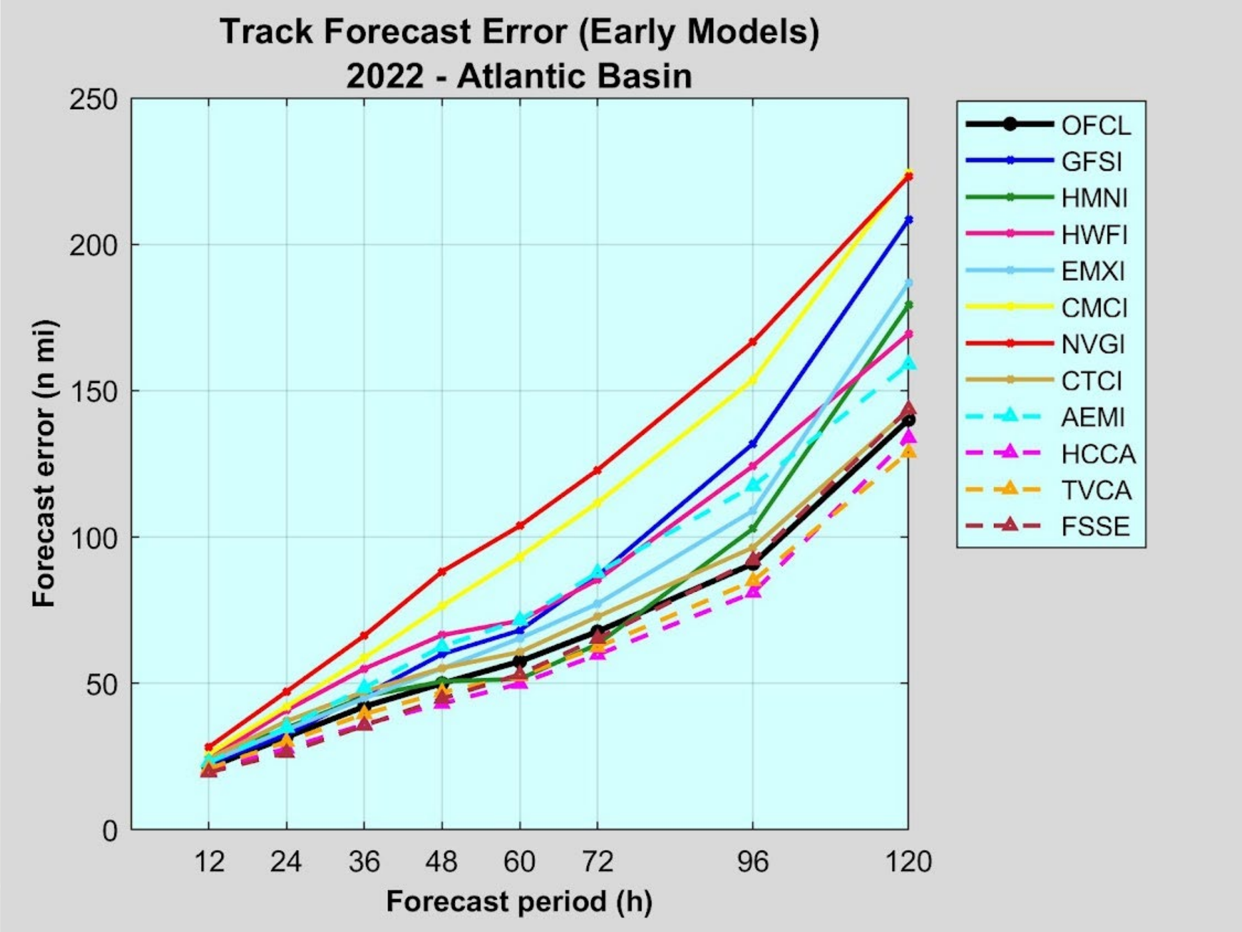
Poor organization (esp. lack of deep convection in the core) would argue against Jeanne being carried eastward by upper-level westerlies.

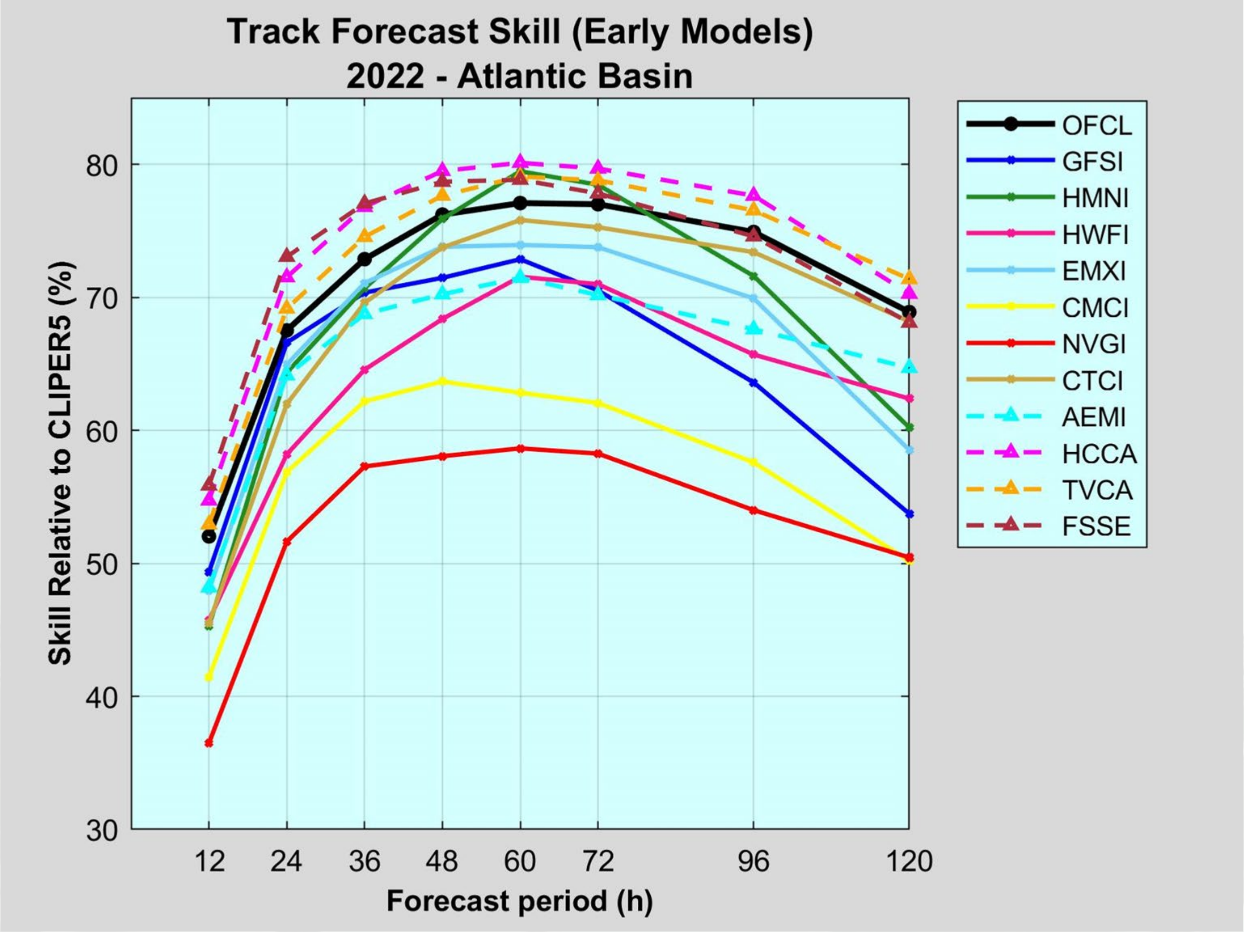
This reasoning allowed the forecasters to largely disregard the GFS and form a "selective consensus" of the remaining models.

48-h Model Track Errors by Storm



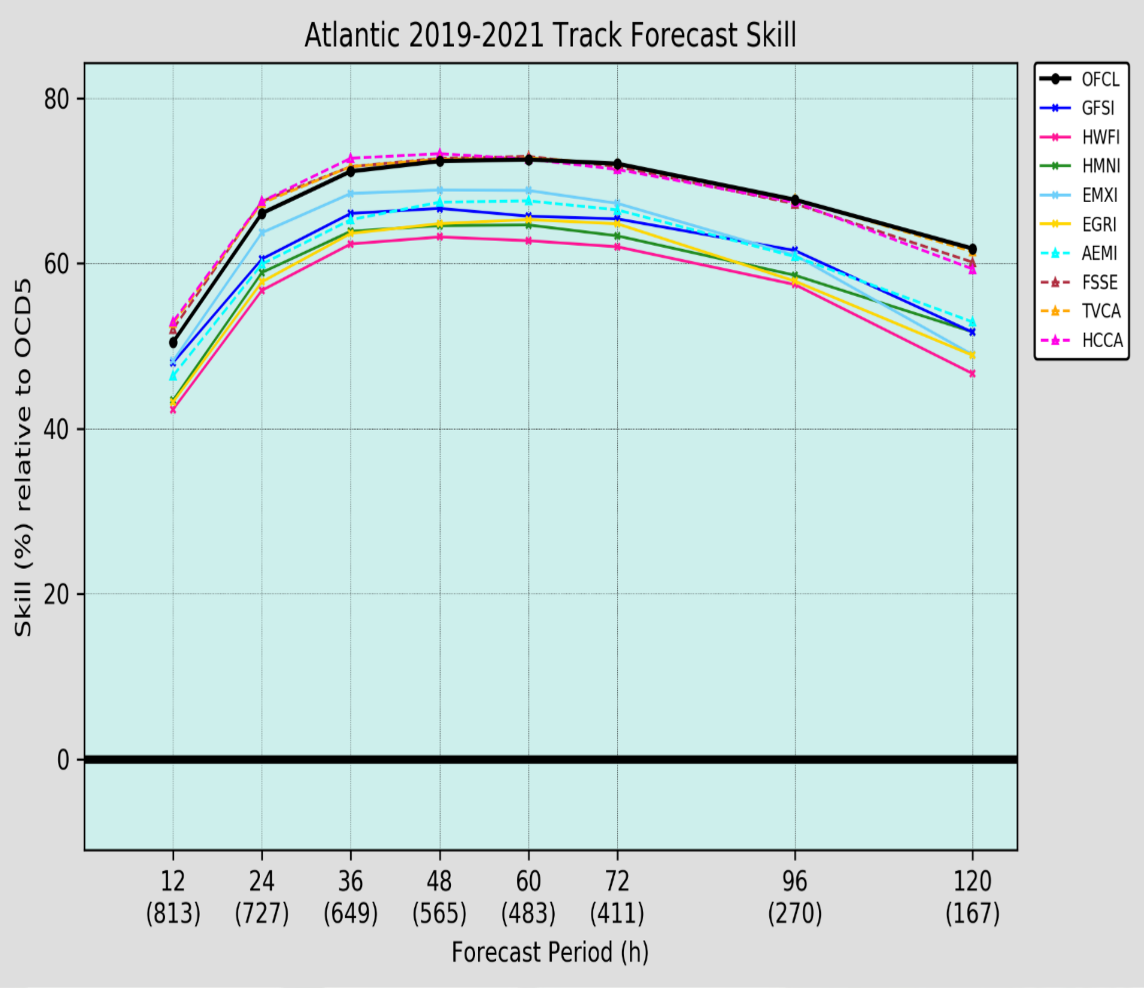
Consensus on average performs better than any individual model

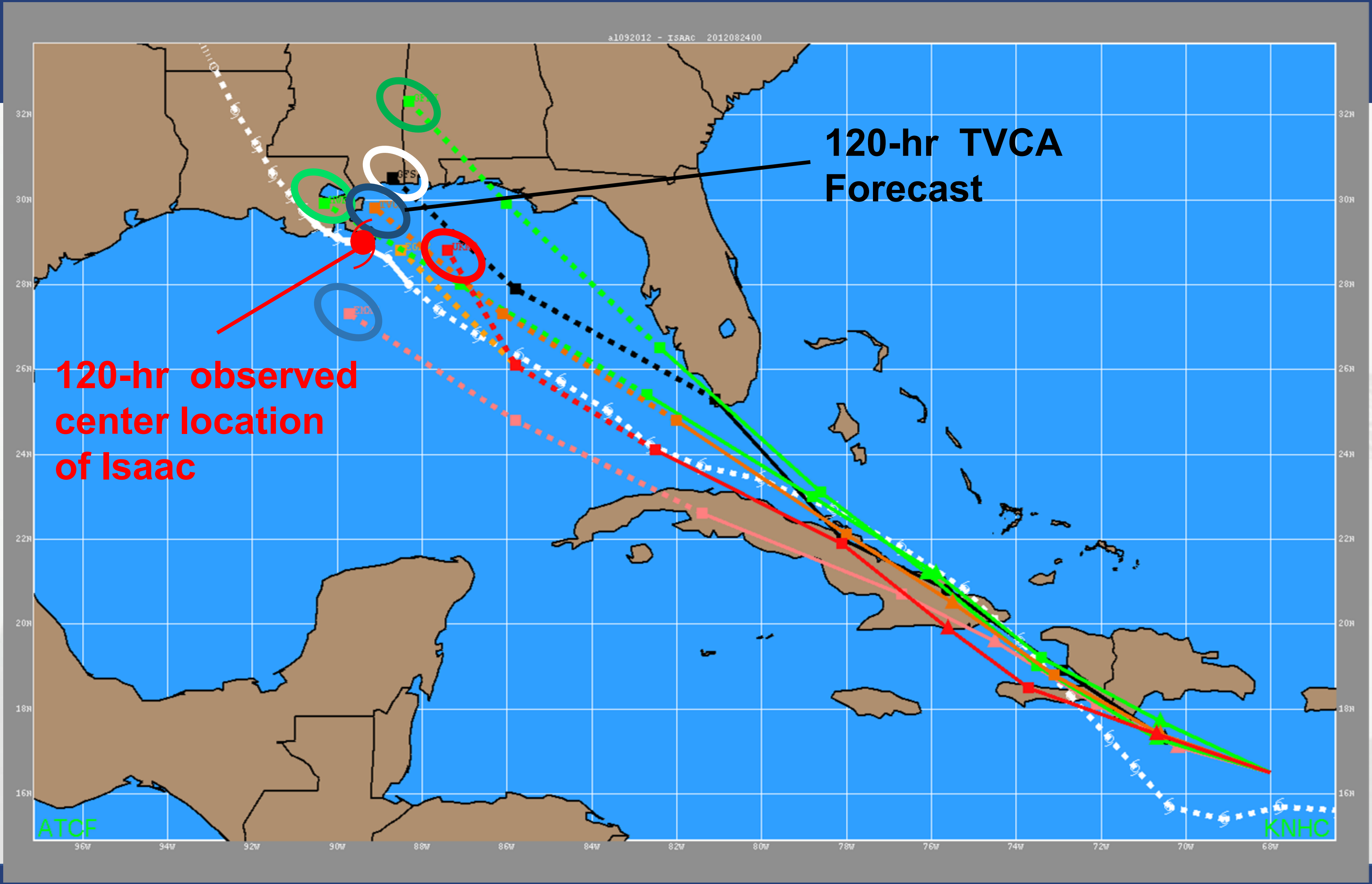




Ensembles and Consensus

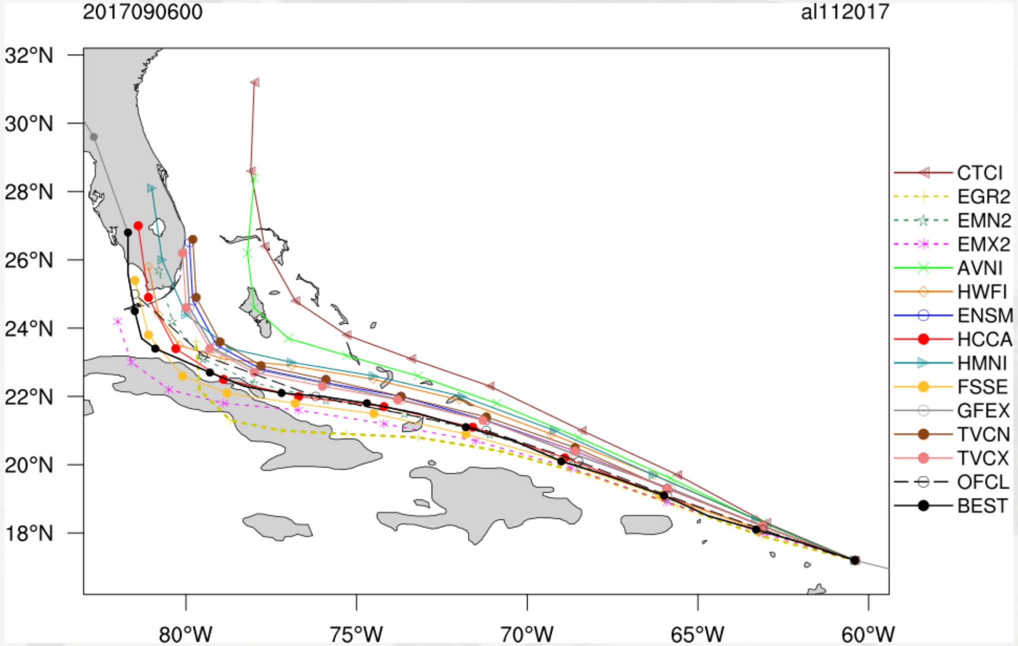
- Often, the most successful models are consensus aids formed from an ensemble of good performing models with a high degree of independence.
- Recently, some single-model consensus models (like the GFS and ECMWF ensembles) have performed as well as the deterministic version of the same model especially at longer ranges (day 5 and beyond).

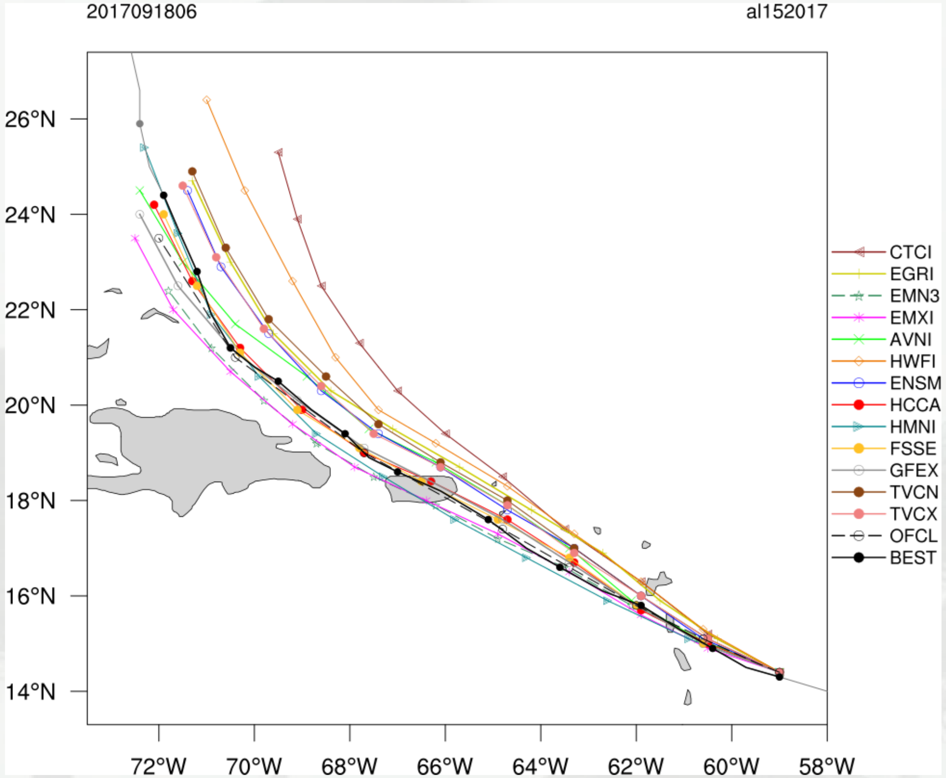



al092012 - ISAAC 2012082400
120-hr TVCA Forecast
120-hr observed center location of Isaac
ATCF
KNHC

"Smart" consensus models

- HCCA and FSSE
- Multiple linear regression to unequally weigh models based on past errors and biases





Which of the following is typically the best type of guidance or model to use for track forecasting? Select the best answer.

0

Statistical-dynamical model (SHIPS/LGEM)	0%
High-resolution global model (ECMWF/GFS)	0%
Multi-model consensus (TVCN/HCCA)	0%
Regional hurricane model (HWRF/HMON)	0%
Trajectory and Beta Models (TABS/TAMS)	0%
CLIPER	0%

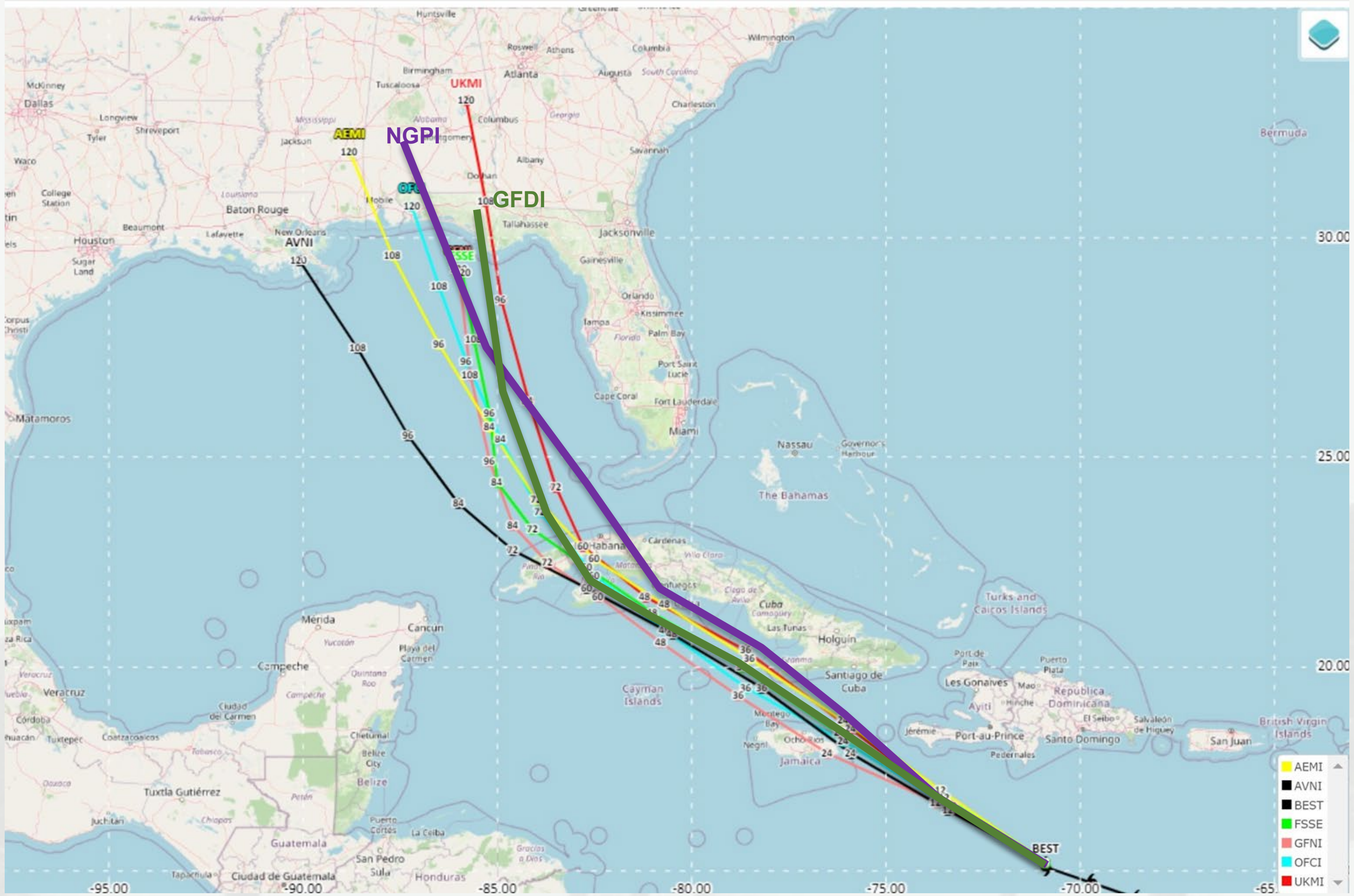
Track Forecasting at the NHC: Using Models

- 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

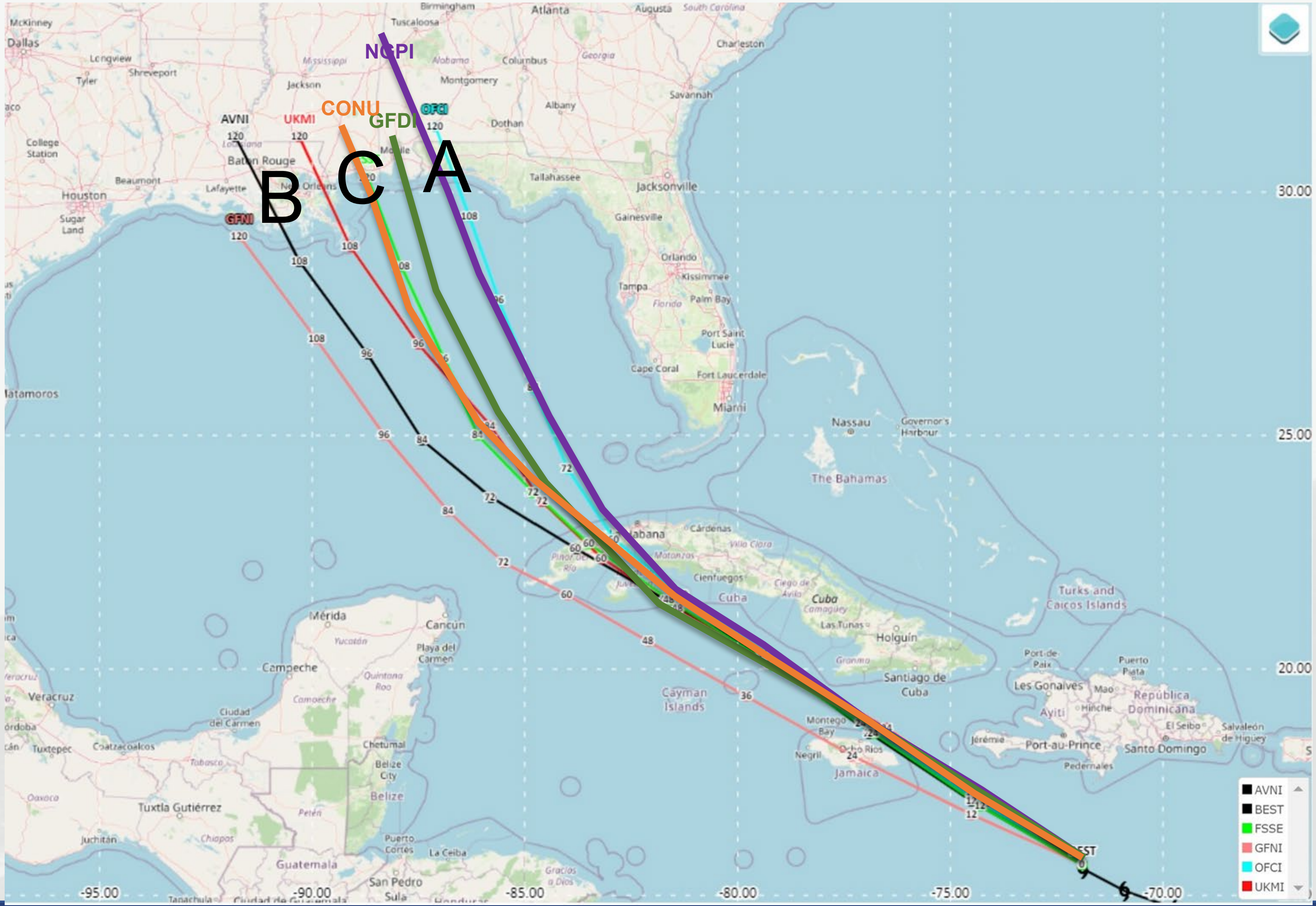
- Compare the models' forecast of the environmental features, not just the TC tracks.
  - Evaluate the initialization of the TC in the model fields. Unrealistic TC can affect the likelihood of a successful forecast.
  - Consider the recent performance of the various models, both in terms of accuracy and consistency.
  - Spread of models can dictate forecaster confidence.

Dennis Guidance 6 July 1200 UTC



- Scenario: you have just created a forecast for Storm Dennis based on the track guidance on July 6th at 12Z. There is a lot of spread in the models at 120-hrs, so you went close to the multi-model consensus.

Dennis Guidance 6 July 1800 UTC: 6 hours later, Guidance shifts sharply westward toward New Orleans.

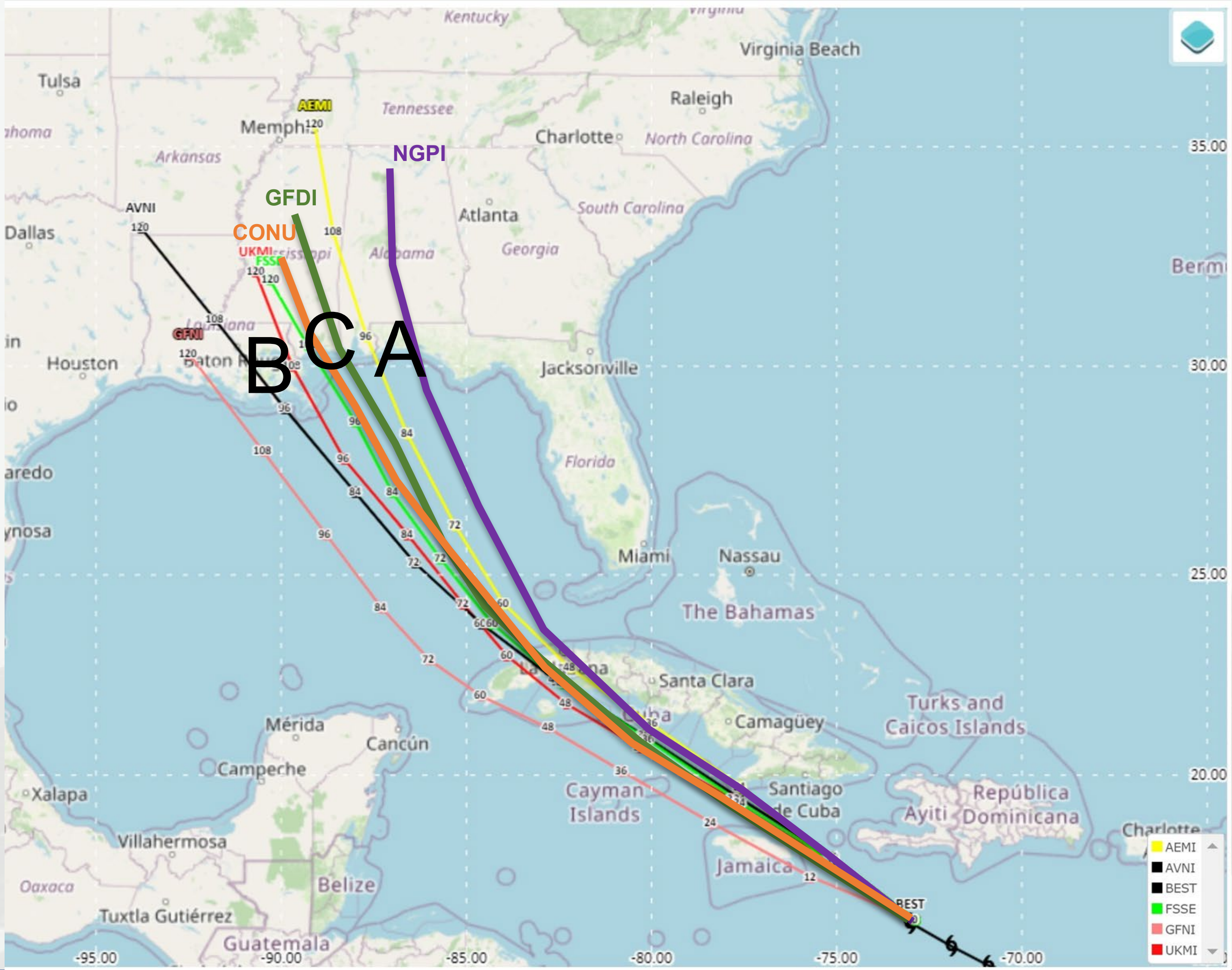


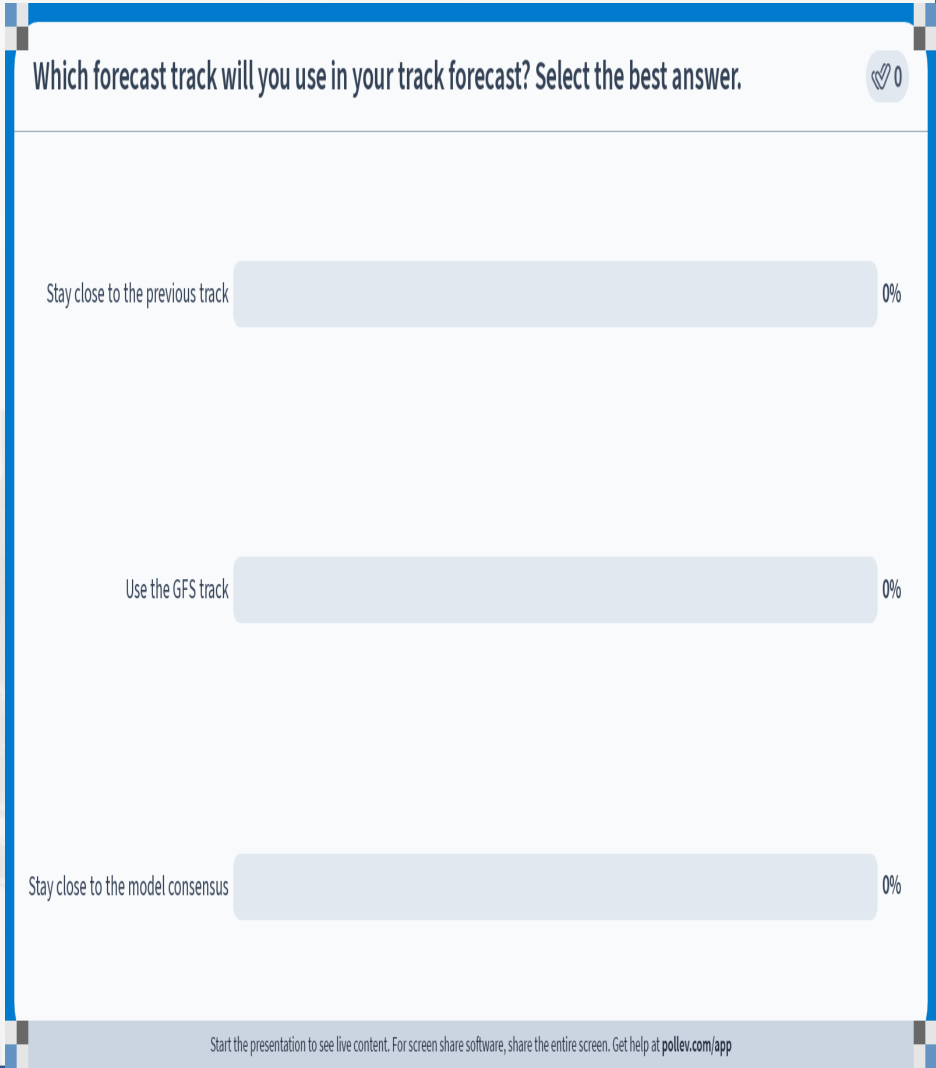
Which forecast track will you use in your track forecast? Select the best answer.

Stay close to the previous track	0%
Use the GFS track	0%
Stay close to the model consensus	0%

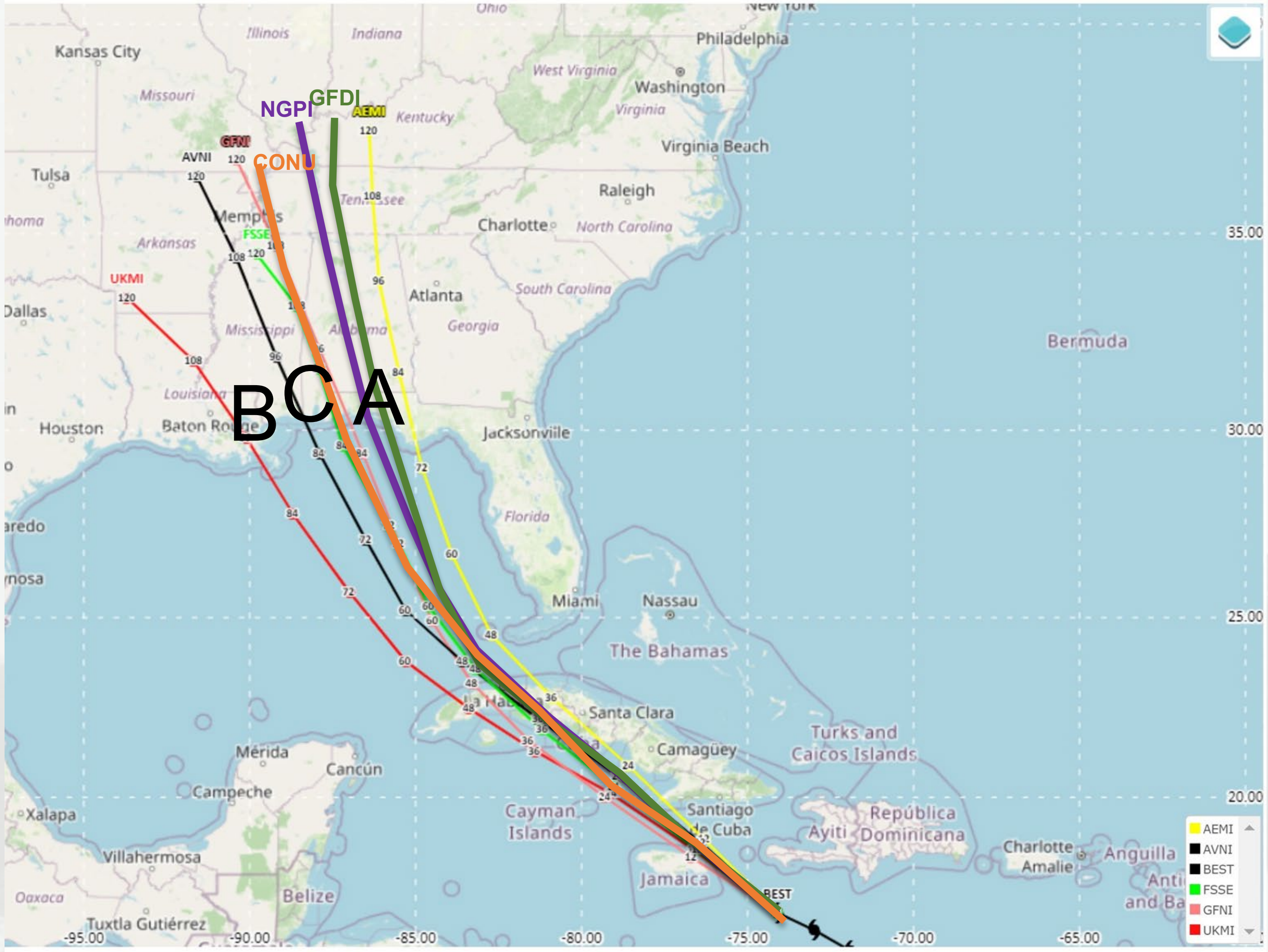
Start the presentation to see live content. For screen share software, share the entire screen. Get help at pollev.com/app

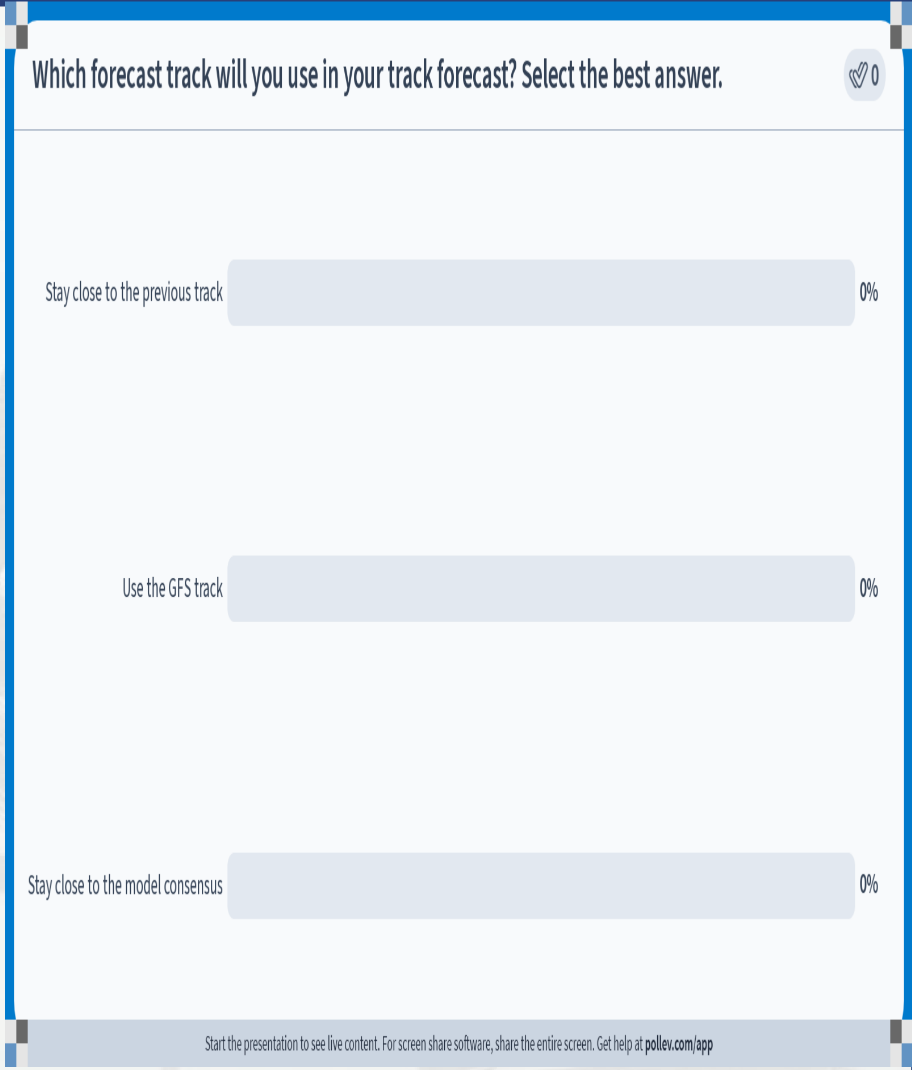
Dennis Guidance 7 July 0000 UTC: Little overall change to guidance, but NGPI shifts slightly eastward.



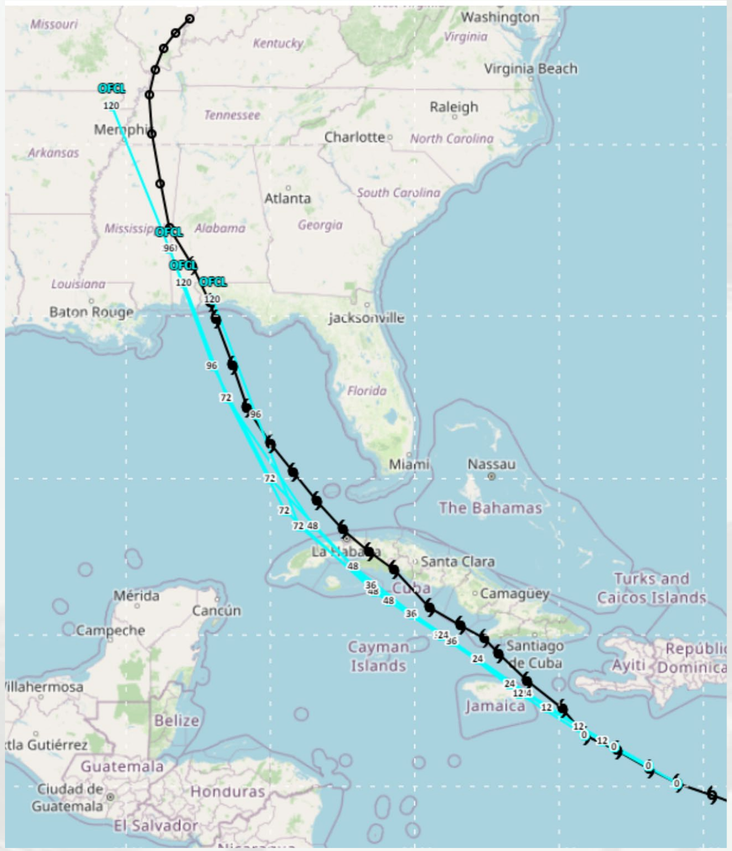


Dennis Guidance 7 July 0600 UTC: Rest of the guidance shifts sharply eastward, leaving official forecast near the center of the guidance envelope





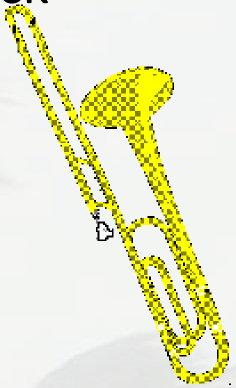
Additional Track Forecasting Considerations



- 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

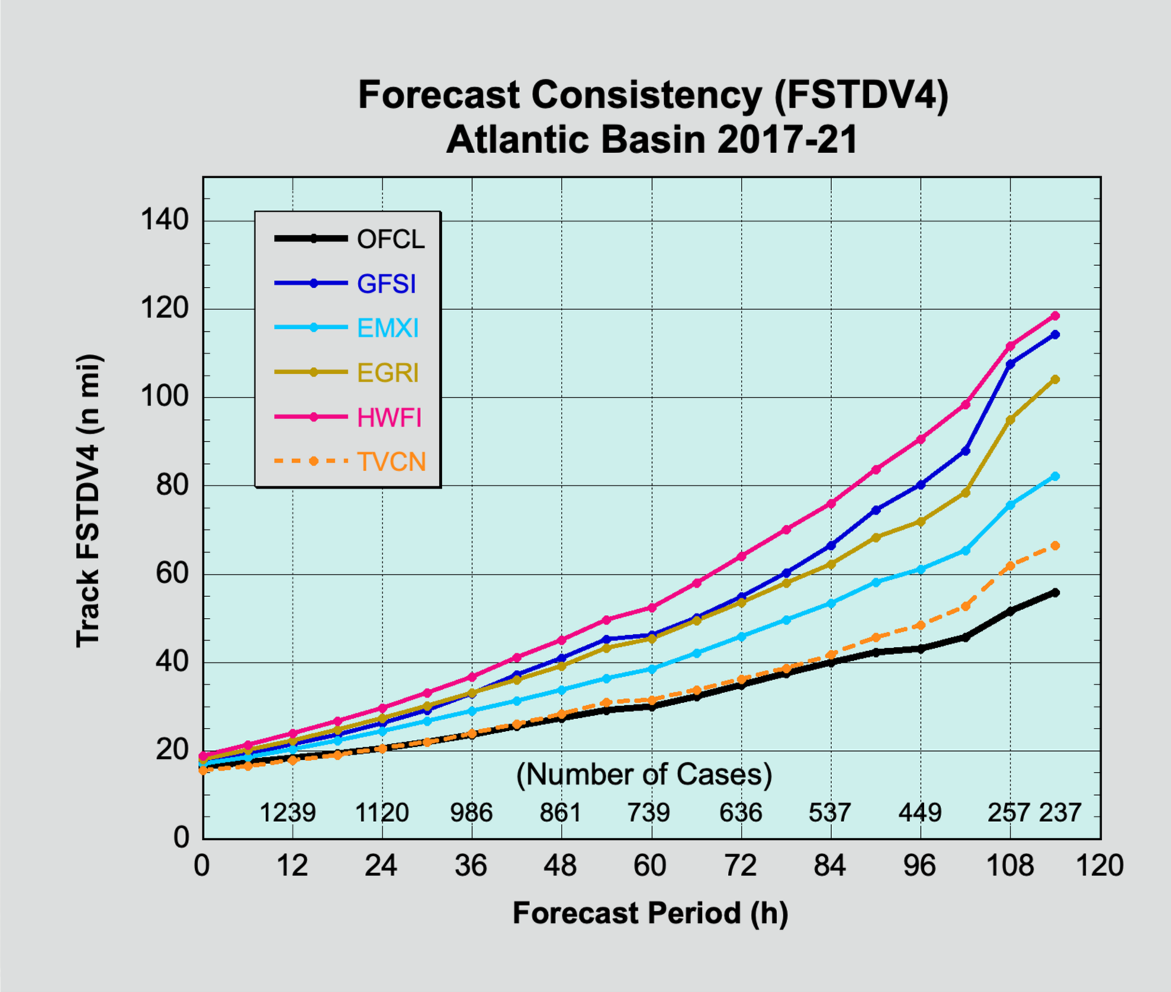
Windshield Wipering

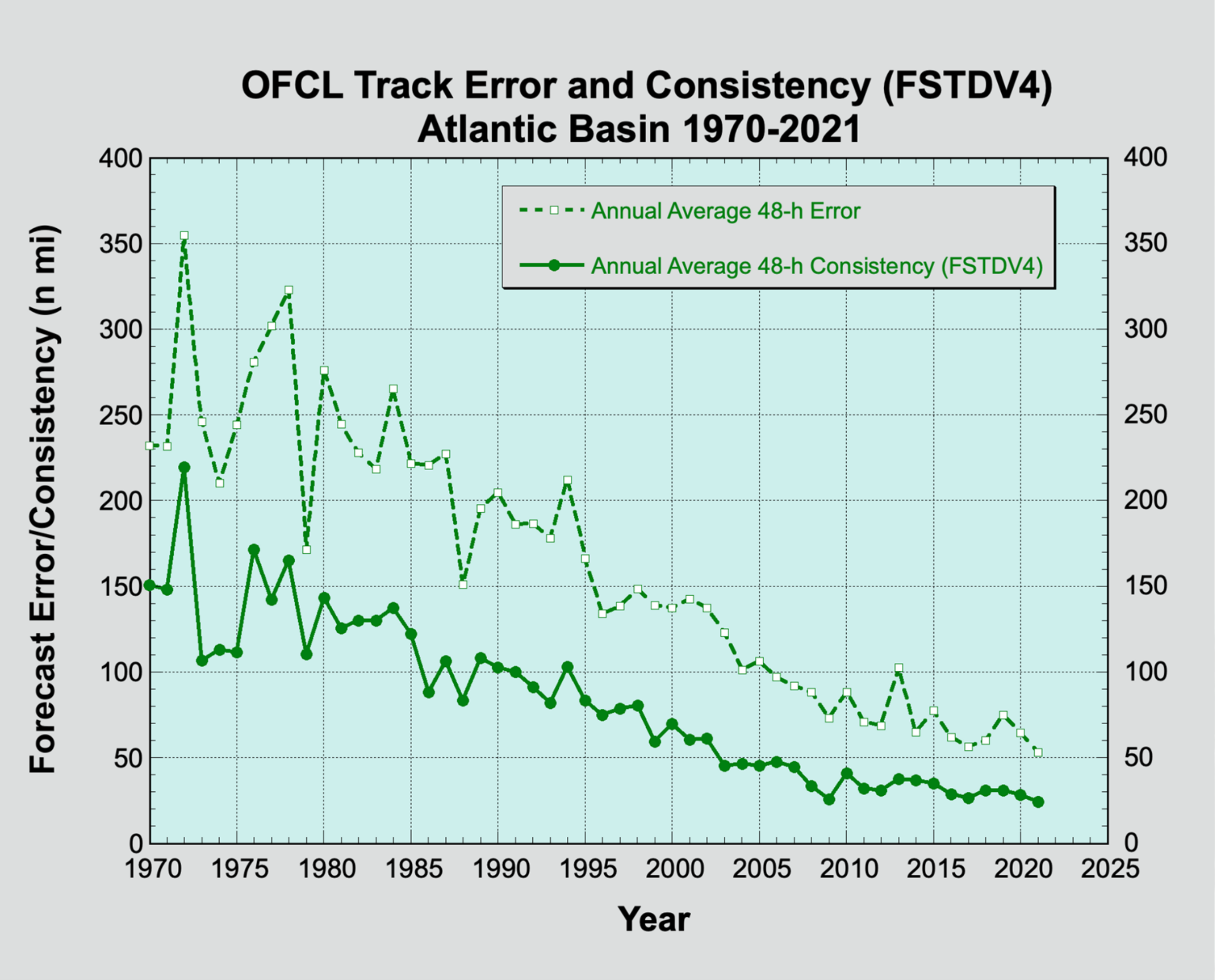
Trombonning



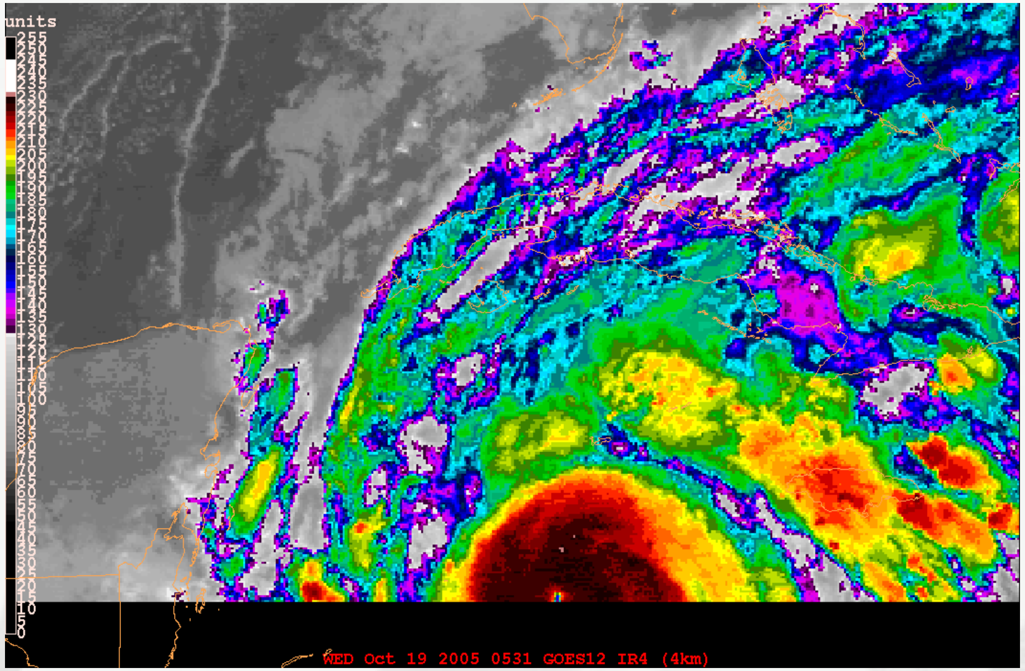
- Consequently, changes to the previous forecast are normally made in small increments
- Continuity is also important within a given forecast
  - Gradual/steady changes in direction or speed from 12 to 24 to 36 h, etc

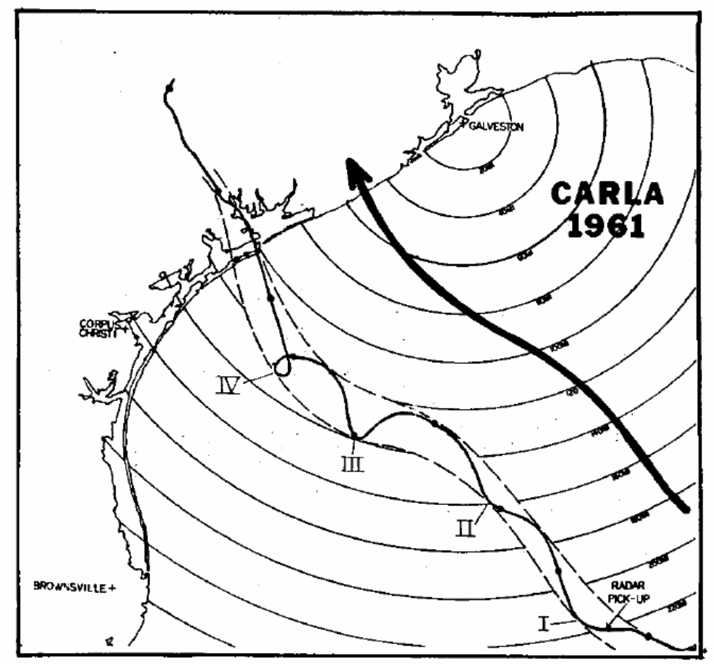
Consistency Matters





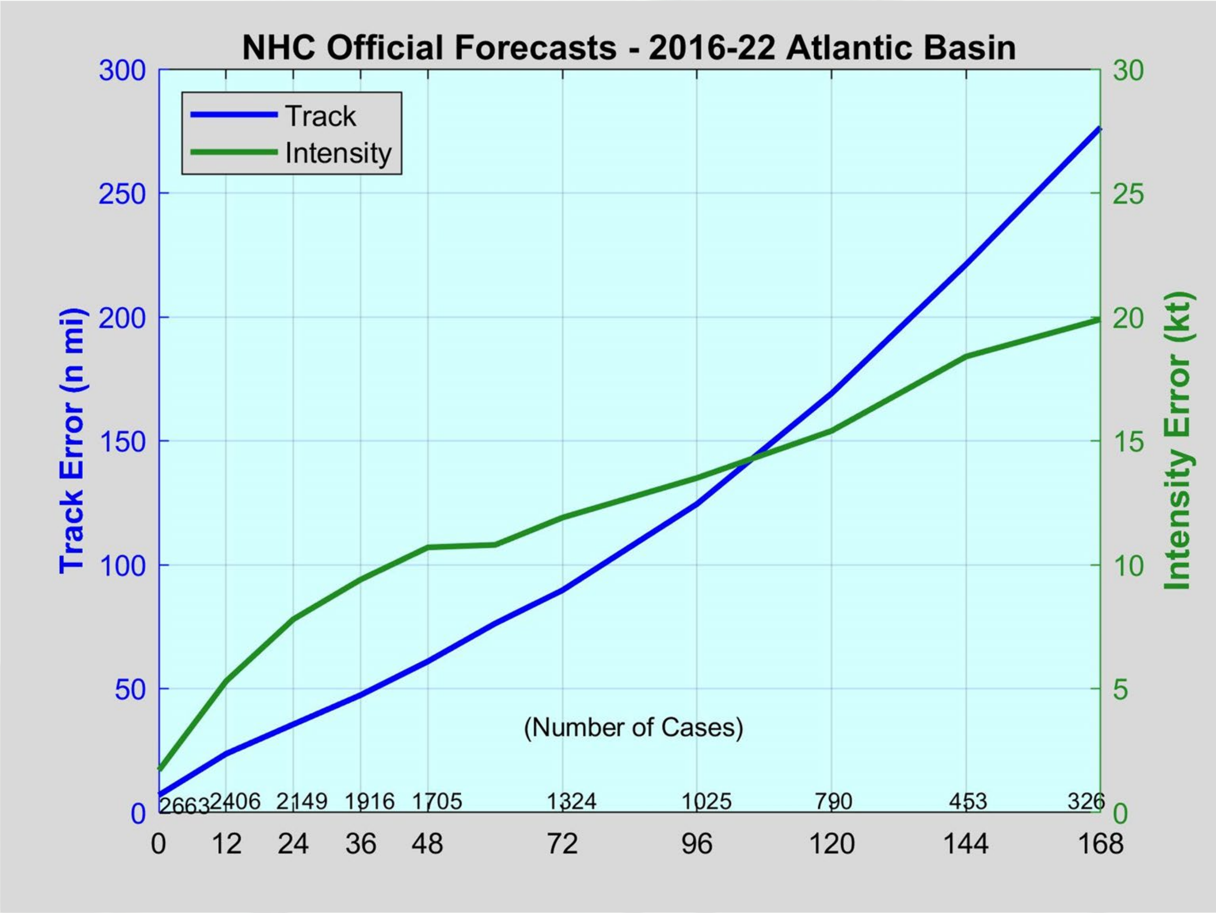
Trochoidal Motion

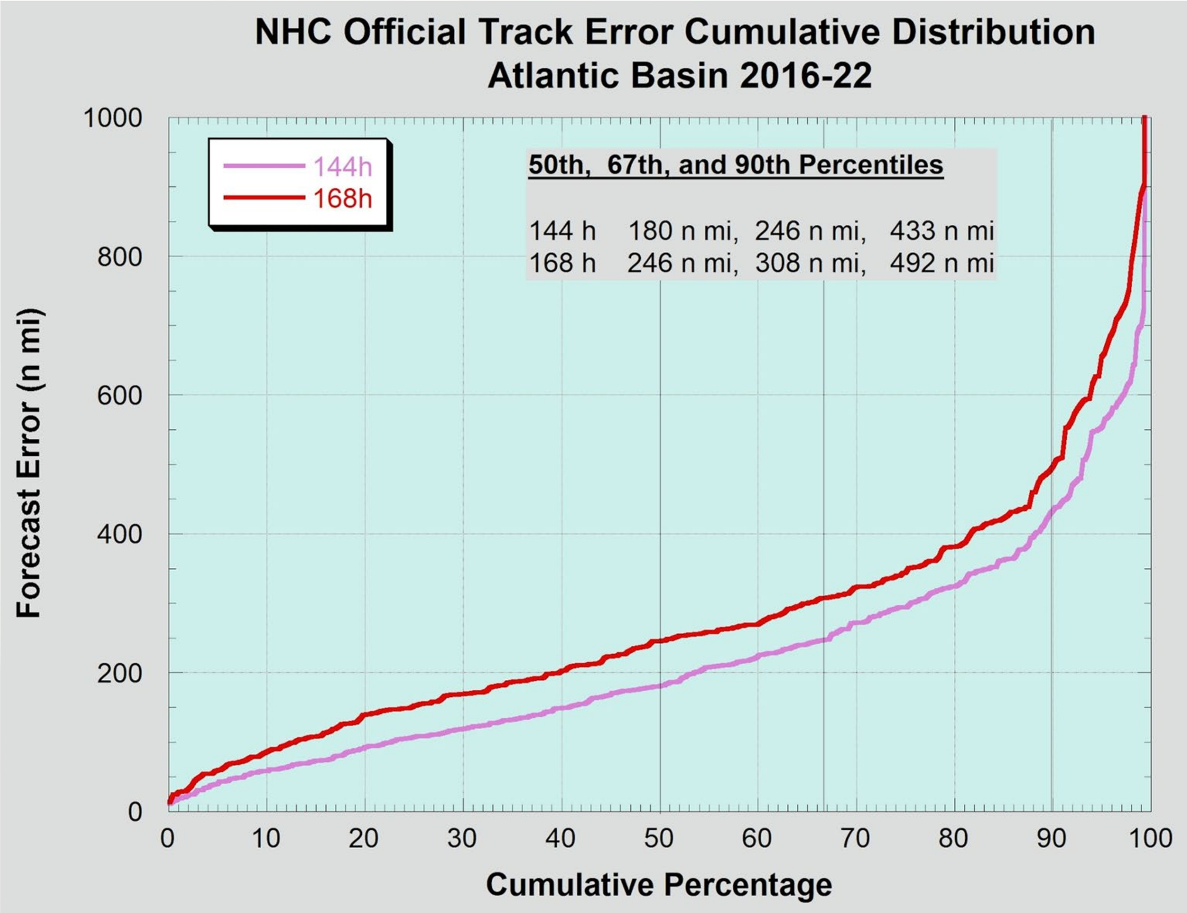




- Substantial oscillation (wobble) of the center of a TC about its mean motion vector
- Primarily a side effect of convective asymmetries in the inner core
- Amplitude of motions varies but higher-frequency “wobbles” lost in ‘best track’ smoothing process
- Virtually impossible to forecast!

6 and 7 day forecasts





Questions

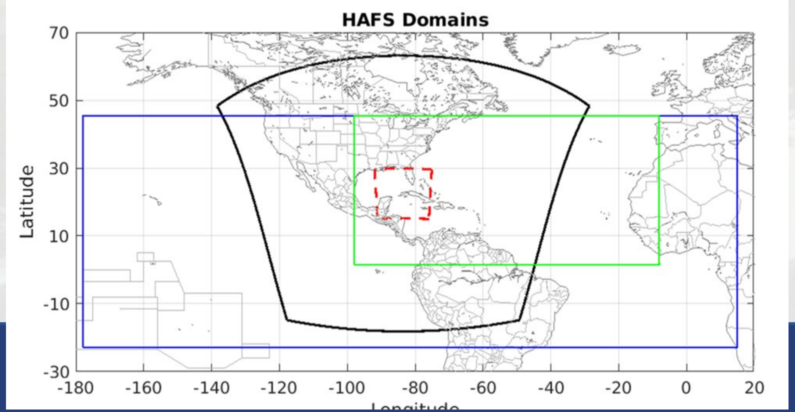
Questions?

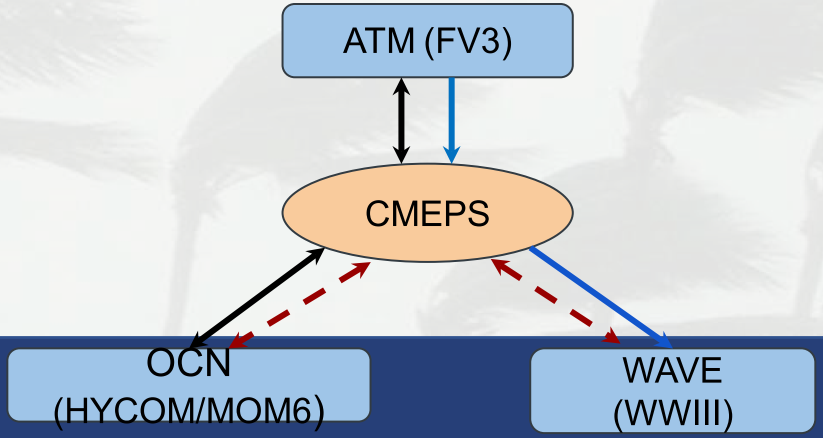
SUMMARY OF NWP MODELS USED BY NHC FOR TC TRACK PREDICTION

ATCF ID Tracker	Global/Regional Model Name	Horizontal Resolution	Vertical Levels and Coordinates	Data Assimilation	Convective Scheme	Cycle/Run Frequency	INCLUSION IN CONSENSUS
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 forecasts out to 90 hr	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 ~15km	80 Hybrid Sigma-Pressure	4D-VAR ensemble Hybrid	Kain -Fritsch [Kain and Fritsch (1990, 1993)]	12 hr (240 hr) 00/12 UTC	NO
HAFSA/HAFSB (also HWRF)	Hurricane Analysis and Forecast System	Grid Configuration Nested; 5.4-1.8 km	81 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 (HWRF)
HMON	Hurricane Multi-scale Ocean-coupled Non-hydrostatic model	Grid Configuration 3 nests 18-6-2 km	51	None	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

HAFS (Hurricane Analysis and Forecast System)

HAFSv1.0	Domain	Resolution	DA/VI	Ocean/Wave Coupling	Physics	Basins
HAFS-A (HWRF replacement)	Storm-centric with one moving nest, parent: ~78x75 degree, nest: ~12x12 degree	Regional (ESG)), ~5.4/1.8 km, ~L81, ~2 hPa model top	Vmax > 40 kt warm-cycling VI and 4DEnVar DA	Two-way MOM6, one-way WW3 coupling for NHC AOR	Physics suite-1	All global Basins NHC/CPHC/JTWC Max 7 Storms Replace HWRF
HAFS-B (HMON replacement)	Storm-centric with one moving nest, parent: ~75x75 degree, nest: ~12x12 degree	Regional (ESG), ~6/2 km, ~L81, ~2 hPa model top	Vmax > 40 kt warm-cycling VI and 4DEnVar DA	Two-way HYCOM No Wave	Physics suite-2	NHC/CPHC Max 5 Storms Replace HMON





Track Forecasting Review

What is the most important factor for tropical cyclone track? Select all that apply.

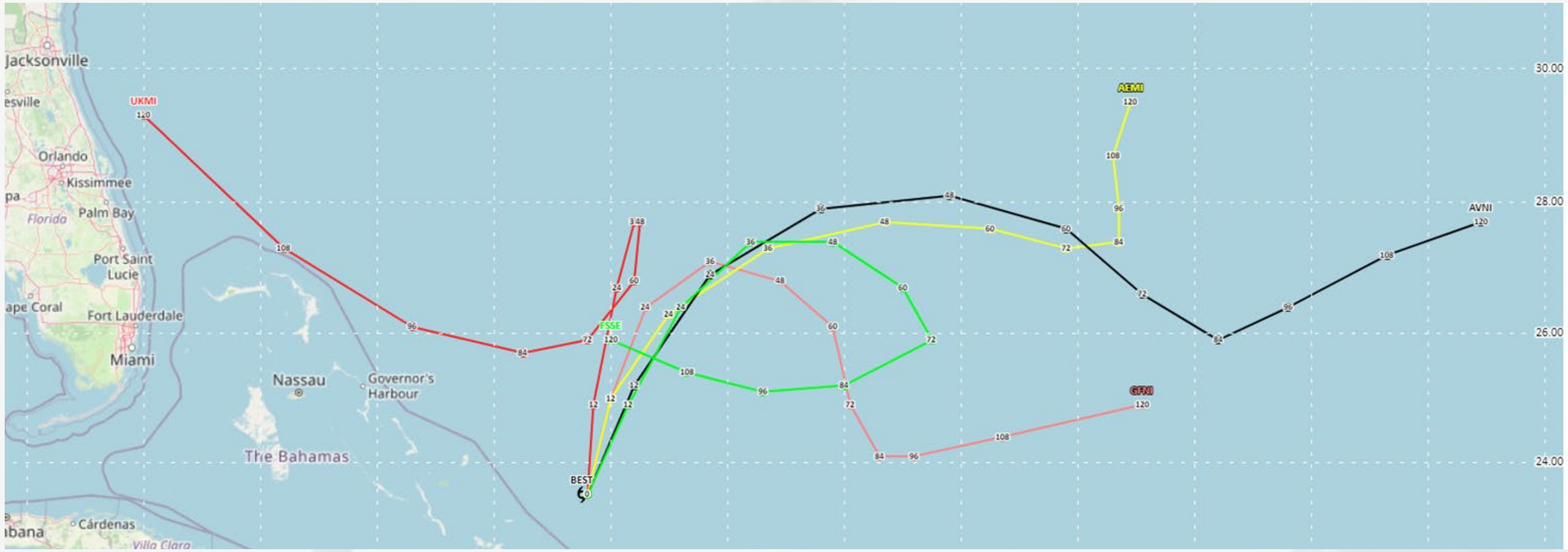
a) Large-scale steering flow
b) Internal dynamics of the eyewall
c) Beta effect
d) Storm intensity

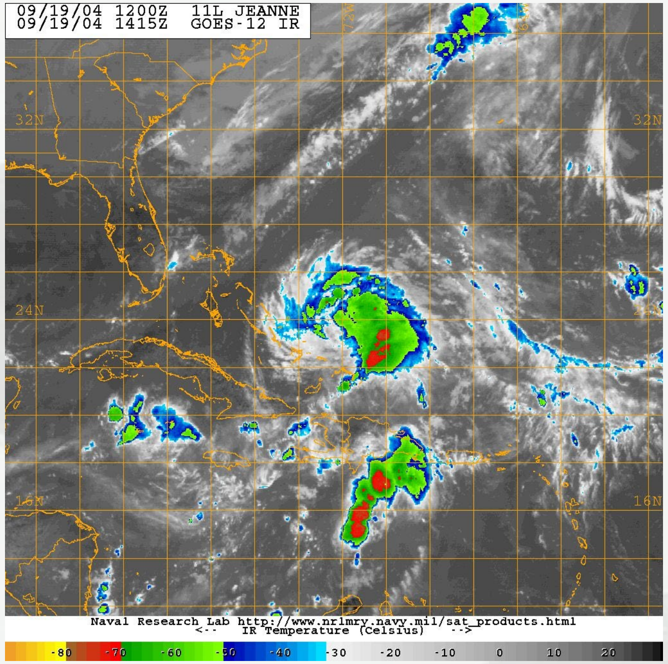
How to convert to a point forecast?

How do you convert from a model to something that NHC can use to make a point forecast?

a) Manually find the location of the storm based on simulated satellite imagery (Dvorak)
b) The model reports location of local pressures minimums in pressure
c) Run a tracker on the model output that uses multiple levels/variables
d) Use Artificial Intelligence to produce a forecast

My models are not helping me out!





How do you resolve this difference in model guidance for your forecast?

A. It's best to just automatically select the model consensus in this situation

B. Take a deeper look at the storm structure and surrounding environment and try to determine which tracks do and do not make sense

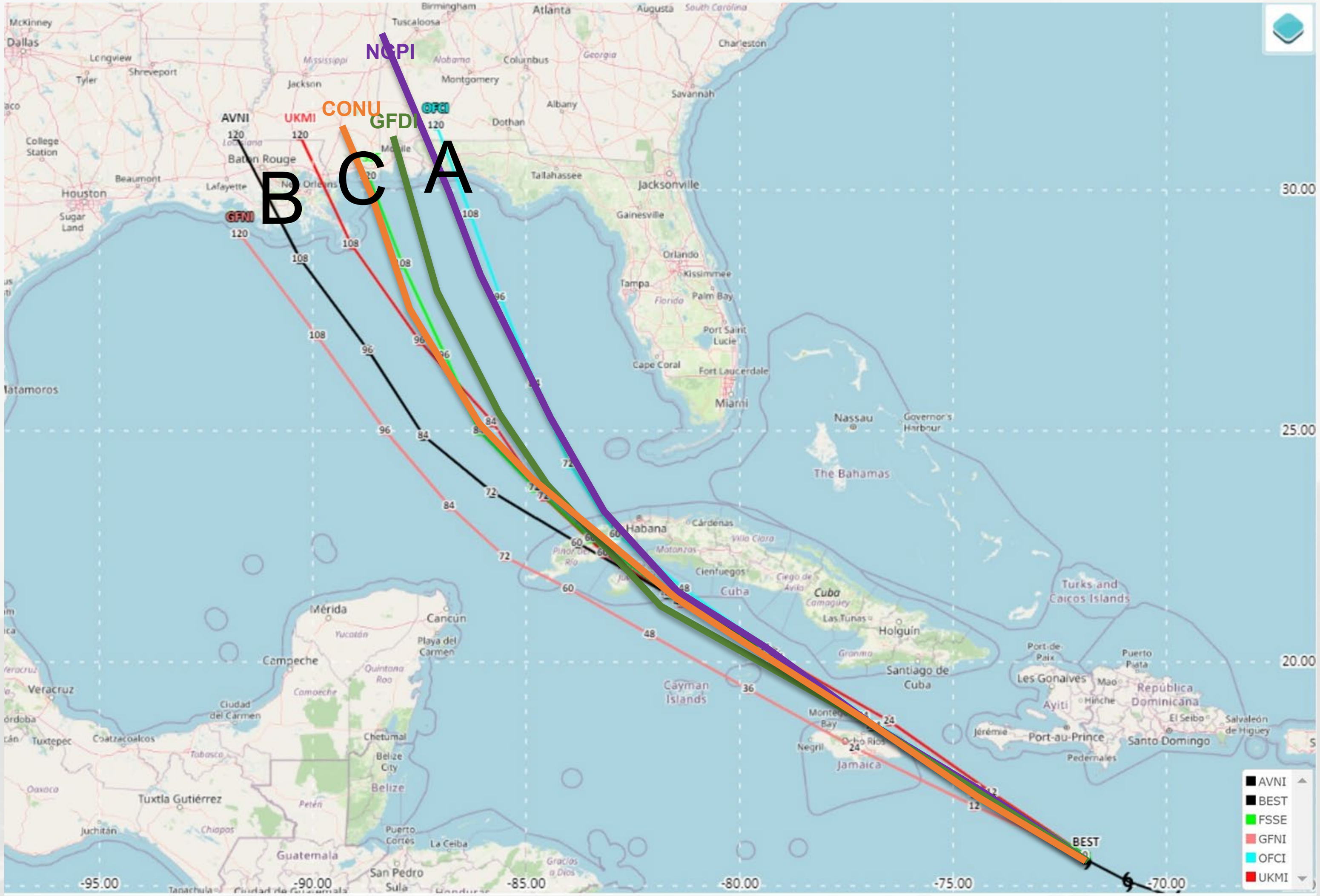
C. It is best to rely on the ECMWF consistent performance

Which Model is the Best?

Which of the following is typically the best type of guidance or 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)
e) Trajectory and Beta Models (TABS/TAMS)
f) CLIPER

Dennis Guidance 6 July 1800 UTC



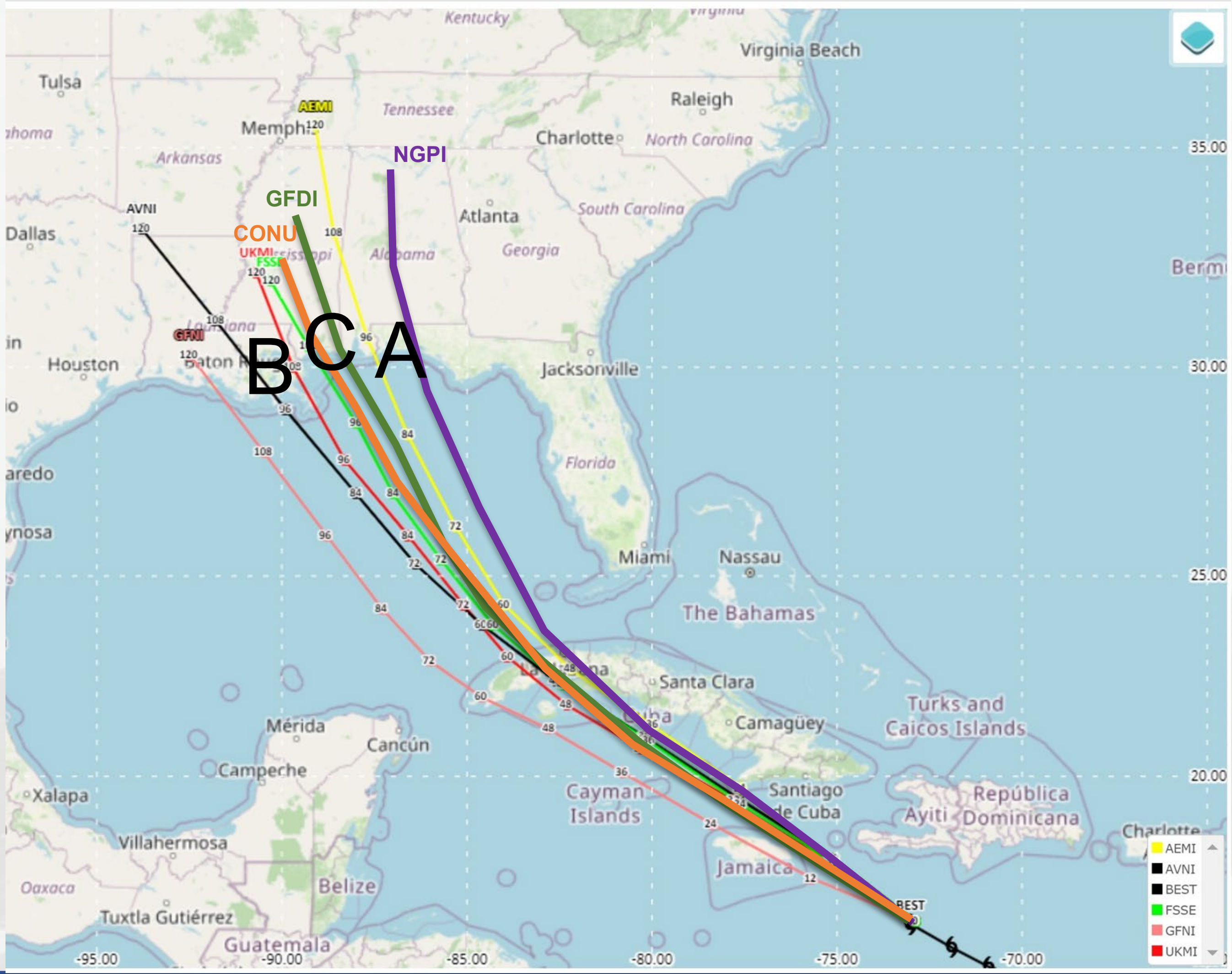
- 6 hours later, Guidance shifts sharply westward toward New Orleans.
- Where should you put your forecast (where will landfall occur)?

A – On previous track

B- GFS!

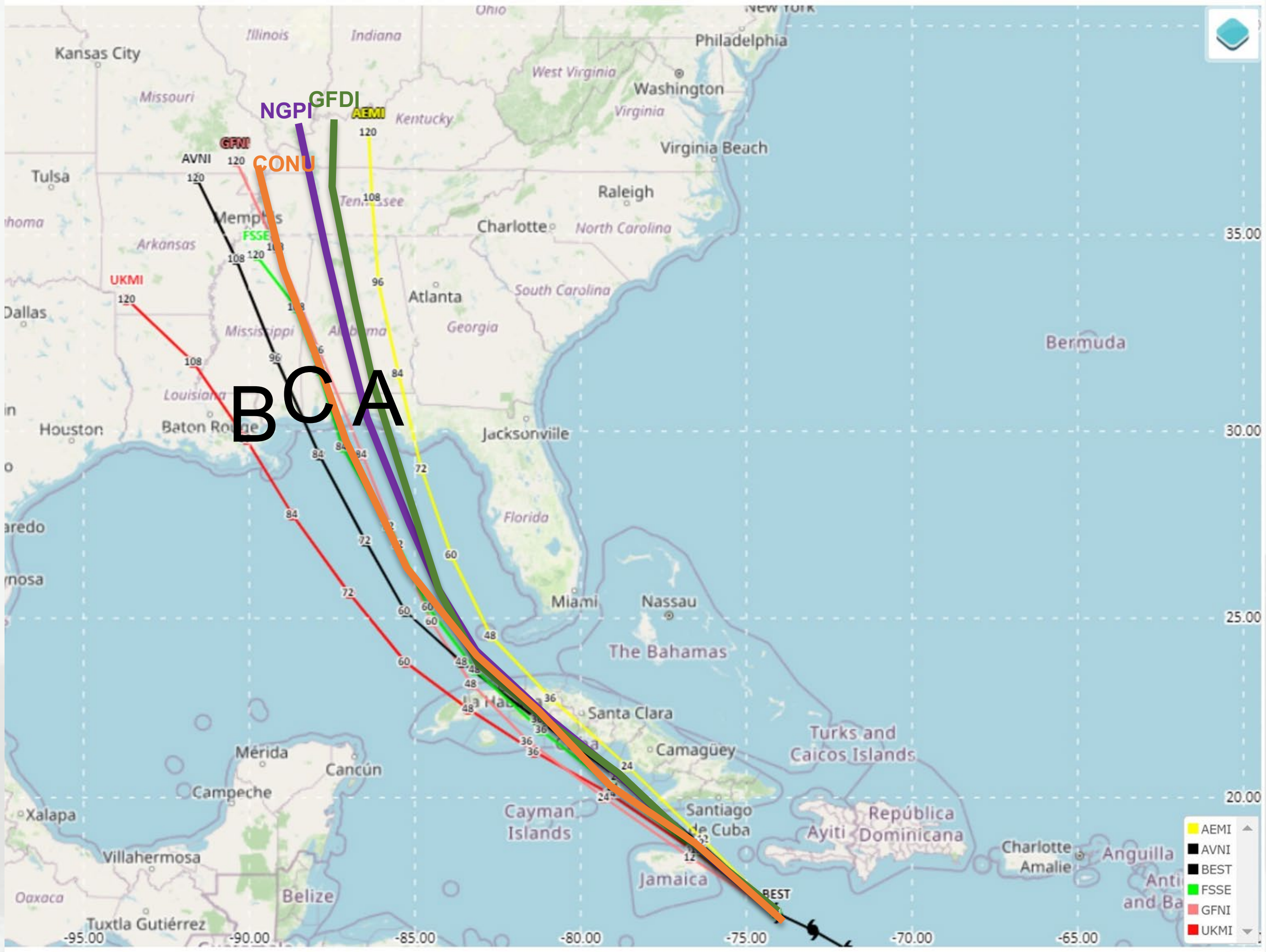
C- consensus

Dennis Guidance 7 July 0000 UTC: Little overall change to guidance, but NGPI shifts slightly eastward.



- Little overall change to guidance, but NGPI shifts slightly eastward.
- Revote (A, B or C)

Dennis Guidance 7 July 0600 UTC



- Rest of the guidance shifts sharply eastward, leaving official forecast near the center of the guidance envelope
- Revote