Tropical Cyclone Track Prediction

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• 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

- 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 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.
3/7/2023 Tropical Cyclone Track Prediction
Track Forecast Errors/Skill

NHC Official Track Error Trend
Atlantic Basin

NHC Official Track Skill Trend
Atlantic Basin
Average 72 h track forecast error in 1990
Average 72 h track forecast error in 2020
Average 72 h track forecast error in 2022
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 (e.g., 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.
<table>
<thead>
<tr>
<th>ATCF ID Tracker</th>
<th>Global/Regional Model Name</th>
<th>Horizontal Resolution</th>
<th>Vertical Levels and Coordinates</th>
<th>Data Assimilation</th>
<th>Convective Scheme</th>
<th>Cycle/Run Frequency</th>
<th>2022 TVCN INCLUSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>NVGM/NVGI</td>
<td>Navy Global Environmental Model</td>
<td>Spectral ~31km</td>
<td>60 Hybrid Sigma-pressure</td>
<td>NAVDAS-AR 4D-VAR</td>
<td>Simplified Arakawa-Schubert (SAS)</td>
<td>6 hr (144 hr)</td>
<td>00/06/12/18 UTC</td>
</tr>
<tr>
<td>AVNO/AVNI (GFSO/GFSI)</td>
<td>Global Forecast system</td>
<td>Finite Volume Cubed Sphere (FV3) 13km</td>
<td>127 Hybrid Sigma-pressure</td>
<td>GSI/4D-VAR EnKf hybrid, including TC central pressure</td>
<td>Simplified Arakawa-Schubert [Arakawa and Schubert (1974) / Pan and Wu (1994)]</td>
<td>6 hr (240 hr)</td>
<td>00/06/12/18 UTC</td>
</tr>
<tr>
<td>EMX/EMXI EMX2</td>
<td>European Centre for Medium-Range Weather Forecasts</td>
<td>Spectral ~9km</td>
<td>137 Hybrid Sigma-Pressure</td>
<td>4D-VAR</td>
<td>Tiedke mass flux [Tiedke (1989)]</td>
<td>12 hr (240 hr)</td>
<td>00/12 UTC</td>
</tr>
<tr>
<td>EGR/GRI EGR2</td>
<td>U.K. Met Office Global Model</td>
<td>Grid Point ~10km</td>
<td>70 Hybrid Sigma-Pressure</td>
<td>4D-VAR Ensemble Hybrid</td>
<td>UKMET [Gregory and Rowntree (1990)]</td>
<td>12 hr (144 hr)</td>
<td>00/12 UTC</td>
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<tr>
<td>CMC/CMCI</td>
<td>Canadian Deterministic Prediction System</td>
<td>Grid Point ~25km</td>
<td>80 Hybrid Sigma-Pressure</td>
<td>4D-VAR ensemble Hybrid</td>
<td>Kain-Fritsch [Kain and Fritsch (1990, 1993)]</td>
<td>12 hr (240 hr)</td>
<td>00/12 UTC</td>
</tr>
<tr>
<td>HWRF/HWFI</td>
<td>Hurricane Weather Research and Forecast System</td>
<td>Grid Configuration 3 nests 13.5-4.5-1.5 km</td>
<td>75 Hybrid Sigma-Pressure</td>
<td>4D-VAR Hybrid GDAS GFS IC/BC</td>
<td>SAS mom. mix. + GFS shallow convection (6km and 18km) 2km nest – none</td>
<td>6 hr (126 hr)</td>
<td>00/06/12/18 UTC</td>
</tr>
<tr>
<td>HMON</td>
<td>Hurricane Multi-scale Ocean-coupled Non-hydrostatic model</td>
<td>Grid Configuration 3 nests 18-6-2 km</td>
<td>51 None for this season</td>
<td>None for this season</td>
<td>SAS</td>
<td>6 hr (126 hr)</td>
<td>00/06/12/18 UTC</td>
</tr>
<tr>
<td>CTCX/CTCI</td>
<td>NRL COAMPS-TC (using GFS for IC and BC)</td>
<td>Grid Configuration 3 nests 45-15-5 km</td>
<td>40 None for this season</td>
<td>3D-VAR (NAVDAS) EnKf DART</td>
<td>Kain-Fritsch [Kain and Fritsch (1990, 1993)]</td>
<td>6 hr (126 hr)</td>
<td>00/06/12/18 UTC</td>
</tr>
</tbody>
</table>
### Coming soon… HAFS (FV3 hurricane models)

<table>
<thead>
<tr>
<th>HAFSv1.0</th>
<th>Domain*</th>
<th>Resolution*</th>
<th>DA/VI</th>
<th>Ocean/Wave Coupling</th>
<th>Physics</th>
<th>Basins</th>
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</thead>
<tbody>
<tr>
<td>HFSA (HWRF replacement)</td>
<td>Storm-centric with one moving nest, parent: ~78x75 degree, nest: ~12x12 degree</td>
<td>Regional (ESG), ~6/2 km, ~L81, ~2 hPa model top</td>
<td>Vmax &gt; 50 kt warm-cycling VI and 4DEnVar DA</td>
<td>Two-way HYCOM, one-way WW3 coupling for NHC AOR</td>
<td>Physics suite-1</td>
<td>All global Basins NHC/CPHC/JTWC Max 7 Storms Replace HWRF</td>
</tr>
<tr>
<td>HFSB (HMON replacement)</td>
<td>Storm-centric with one moving nest, parent: ~75x75 degree, nest: ~12x12 degree</td>
<td>Regional (ESG), ~6/2 km, ~L81, ~2 hPa model top</td>
<td>Vmax &gt; 40 kt warm-cycling VI and 4DEnVar DA</td>
<td>Two-way HYCOM No Wave</td>
<td>Physics suite-2</td>
<td>NHC/CPHC Max 5 Storms Replace HMON</td>
</tr>
</tbody>
</table>

**Diagram:**
- ATM (FV3)
- CMEPS
- OCN (HYCOM/MOM6)
- WAVE (WWIII)
But how do you make a track/intensity forecast from raw model output?
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 after it finishes running that uses multiple levels/variables

d) Use Artificial Intelligence to produce a forecast
• 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.).
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?
But which model should you use?

a) The model that performed best for the previous full hurricane season
b) The model that performed best for the current storm (so far)
c) A consensus of several good-performing models
d) The ECMWF
Preliminary 2022 Verification
(Error vs Skill)

Track Forecast Error (Early Models)
2022 - Atlantic Basin

Track Forecast Skill (Early Models)
2022 - Atlantic Basin
48-h Model Track Errors by Storm

Considerable storm-to-storm variability
Florence and Michael

NHC and Model Track Errors
Hurricane Florence (2018)

- OFCL
- GFSI
- EMXII
- EGRI
- OFCL 5-year mean

NHC and Model Track Errors
Hurricane Michael (2018)

- OFCL
- GFSI
- EMXII
- EGRI
- OFCL 5-year mean
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).
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.
120-hr observed center location of Isaac

120-hr TVCA Forecast
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!
“Smart” consensus models

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

• 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
• Official forecast near model consensus in extreme western FL panhandle.
Guidance shifts sharply westward toward New Orleans. Official forecast nudged westward into AL.
Little overall change to guidance, but NGPI shifts slightly eastward. Little change in official forecast.
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.)
Consistency Matters

Forecast Consistency (FSTDV4)
Atlantic Basin 2017-21

OFCL Track Error and Consistency (FSTDV4)
Atlantic Basin 1970-2021

- OFCL
- GFSI
- EMXI
- EGRI
- HWFI
- TVCN

(Number of Cases)

Forecast Period (h)

Forecast Error/Consistency (n mi)

Year

Annual Average 48-h Error
Annual Average 48-h Consistency (FSTDV4)
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.
  - 12-h NHC forecast is heavily weighted by the initial motion estimate.

- Not always easy to determine, particularly for systems with ill-defined centers.

*2003-7 Atlantic Basin Track Errors Operational vs Best Track CLIPER*

- 43% improvement w/BT motion
  - 25%
  - 16%
  - 11%

3/7/2023 Tropical Cyclone Track Prediction
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.
Recent studies show that recon data can improve track forecasts from 10-25% in the GFS.

- G-IV is worth 10-15% improvement.
- Hurricane Ian: Forecasts degraded by 10-15% through day 5 when G-IV dropsondes were removed.
Synoptic Surveillance

The impact of aircraft synoptic observations is maximized by targeting largest sources of uncertainty.
6 and 7 day forecasts
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)
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
If 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.