Technical Summary of the National Hurricane Center Track and Intensity Models

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a. Introduction

"Forecast model" is a generic term that refers to any objective tool used to generate a prediction of a future event, such as the state of the atmosphere. Generation of such forecasts is usually created through mathematical computations. The National Hurricane Center (NHC) utilizes many models in their preparation of the official track and intensity forecasts. The most commonly used models at NHC are summarized in Table 1.

Forecast models range from fairly simple methods, which can be run in a few seconds on an ordinary computer, to those that require a number of hours on a supercomputer. Dynamical models, also known as "numerical models" use high speed computers to solve the physical equations of motion governing the atmosphere. Statistical models, in contrast, do not explicitly consider the physics of the atmosphere but instead are based on historical relationships between storm behavior and storm-specific details such as location and date. Statistical-dynamical models use both dynamical and statistical techniques by making a forecast based on establishing historical relationships between storm behavior and atmospheric variables provided by dynamical models. Trajectory models move a tropical cyclone (TC) along based on the prevailing flow derived from a separate dynamical model. Ensemble or consensus techniques are not true forecast models *per se*, but rather involve combinations of forecasts from multiple models. The following sections provide more detailed description of the types of modeling systems and a description of the more commonly used individual models used at NHC.

b. Early versus Late Models

Forecast models are characterized as either *early* or *late*, depending on whether they are available to the forecaster during the contemporary forecast cycle. For example, consider the 1200 UTC (12Z) forecast cycle, which begins with the 12Z synoptic time and ends with the release of an official forecast at 15Z. The 12Z run of the NWS/Global Forecast System (GFS) model is not complete and available to the forecaster until about 16Z, an hour after the forecast is released - thus the 12Z GFS would be considered a "late" model since it could not be used to prepare the 12Z official forecast. Conversely, the BAM models are generally available within a few minutes of the time they are initialized; therefore they are termed "early" models. Model timeliness is listed in Table 1.

Due to their complexity, dynamical models are generally, if not always, late models. Fortunately, a technique exists to take the latest available run of a late model and adjust its forecast to apply to the current synoptic time and initial conditions. In the example above, forecast data for hours 6-126 from the previous (06Z) run of the GFS would be smoothed and then adjusted, or shifted, so that the 6-h forecast (valid at 12Z) would match the observed 12Z position and intensity of the TC. The adjustment process creates an "early" version of the GFS model that becomes part of the most current available guidance for the 12Z forecast cycle. The adjusted versions of the late models are known, largely for historical reasons, as "interpolated" models.

c. Interpreting Forecast Models

It is important to note that forecast models are complex, each with their own sets of strengths and weaknesses. Interpretation of forecast model output is often aided by professional training and years of experience. On average, NHC official forecasts usually have smaller errors than any of the individual models (http://www.nhc.noaa.gov/verification/verify3.shtml). A given NHC forecast never relies solely on any one individual model (i.e. "model of the day" or "best model"), but rather reflects consideration of all available guidance as well as forecaster experience. Therefore, users should consult the official forecast products issued by the NHC and local National Weather Service Forecast Offices rather than simply looking at output from the forecast models themselves. Users should also be aware that uncertainty exists in every forecast issued by the NHC, and proper interpretation of the NHC forecast must incorporate this uncertainty. NHC forecasters typically discuss forecast uncertainty in the Tropical Cyclone Discussion (TCD) product. NHC also provides probabilistic forecasts which can also be used to evaluate forecast uncertainty (http://www.nhc.noaa.gov/aboutnhcprobs.shtml). Finally, NHC provides detailed information on the verification of its past forecasts with a yearly verification report (http://www.nhc.noaa.gov/verification/verify3.shtml).

d. Statistical Models

Statistical models are based on established relationships between storm-specific information, such as location and time of year, and the behavior of historical storms. While these models provided key forecast guidance in past decades, today these models are most often used as benchmarks of skill against which other more sophisticated and accurate models, such as dynamical models, are compared. Models that perform worse than a simple statistical model are considered "unskillful" and models that perform better than statistical models are considered "skillful". Due to their simplicity, statistical models are among the quickest to run and are typically available to forecasters within minutes of initialization.

Climatology and Persistence Model (CLIPER5)

CLIPER5 is a statistical track model originally developed in 1972 and in 1998 was extended to provide forecasts out to 120 h. As the name implies, the CLIPER5 model is based on climatology and persistence. The model predictors, chosen using multiple regression, are the current and past movement during the previous 12- and 24-hour period, the direction of motion, current latitude and longitude, date, and initial intensity. The CLIPER5 model is now used primarily as a benchmark for evaluating forecast skill of other models and the official NHC forecast rather than as a forecast aid. Forecasts having errors larger than CLIPER5 are not considered skillful.

Statistical Hurricane Intensity Forecast (SHIFOR5)

SHIFOR5 is a simple statistical intensity model that uses climatology and persistence as predictors.

Decay-SHIFOR5

Decay-SHIFOR5 is the SHIFOR5 with an inland decay component included to account for the effects of land in the rate of intensity decay when TCs encounter land. Decay-SHIFOR5 is most often used as a benchmark for evaluating forecast skill of other models and the official NHC intensity forecast.

e. Statistical-Dynamical Models

NHC91/NHC98 Models

The NHC98 (Atlantic) and NHC91 (east Pacific) models are referred to as statistical-dynamical models because they reflect statistical relationships between storm behavior and predictors obtained from dynamical model forecasts, such as the deep-layer-mean GFS geopotential heights fields (averaged from 1000 to 100 mb).

Statistical Hurricane Intensity Prediction Scheme (SHIPS)

The SHIPS model is a statistical-dynamical intensity model that bases its forecasts on statistical relationships between storm behavior and predictors obtained from dynamical model forecasts. Due to the use of dynamical predictors in addition to climatology and persistence, the average intensity errors from SHIPS are typically 10%-15% less than those from SHIFOR5. In addition, SHIPS has historically outperformed most of the dynamical models, including the GFS, which provides the dynamical input to SHIPS. SHIPS has traditionally been one of the more skillful sources of intensity guidance for the NHC. However, the GFDL model has recently become more competitive with the SHIPS. Additionally, consensus intensity techniques have emerged in the last few years as skillful intensity prediction tools.

SHIPS is based on standard multiple regression techniques. The predictors for SHIPS include climatology and persistence, atmospheric environmental parameters (e.g., vertical shear, stability, etc.), and oceanic input such as sea surface temperature (SST) and upper-oceanic heat content. The developmental data from which the regression equations are derived include open ocean tropical cyclones from 1982 through the present. Each year the regression equations are re-derived based upon the inclusion of the previous year's data. That is, the equations used in the 2007 SHIPS are based on developmental data from 1982 through 2006. Therefore, the weighting of the predictors can change from year to year. The predictors found to be most statistically significant are currently: the difference between the current intensity and the estimated maximum potential intensity (MPI), vertical wind shear, persistence, and the upper-tropospheric temperature. SHIPS also includes predictors from satellite data such as the strength and symmetry of convection as measured from infrared satellite imagery and the heat content of the upper ocean determined from satellite altimetry observations.

Decay-SHIPS

Decay-SHIPS is the SHIPS with an inland decay component included. Since land interactions result in weakening, the Decay-SHIPS will typically provide more accurate TC intensity forecasts when TCs encounter or interact with land. Over open waters with no land interactions, the intensity forecasts from Decay SHIPS and SHIPS will be identical.

Logistic Growth Equation Model Summary (LGEM)

LGEM is a statistical intensity forecast model that utilizes the same input as SHIPS but in the framework of a simplified dynamical prediction system, instead of a multiple regression. The evolution of the maximum wind (i.e., intensity) is determined by a logistic growth equation which constrains the solution to lie between zero and the maximum potential intensity (MPI), where the MPI is estimated from an empirical relationship with sea surface temperature (SST). The evolution of the maximum wind depends on the growth rate coefficient, which is estimated from a subset of the input to the SHIPS model. No satellite input is currently included in the LGEM forecast. An important difference from SHIPS is that the longer range forecast depends more strongly on the environmental parameters at the later times (SST, vertical shear, etc). Most of the SHIPS predictors are averaged over the entire forecast period, while most of the LGEM predictors are averaged only over the 24 hours prior to the forecast valid time. The MPI in the LGEM prediction is the instantaneous value, rather than the forecast period average used in SHIPS. This difference makes the LGEM prediction more sensitive to environmental changes at the end of the forecast period, but also makes the prediction more sensitive to track forecast errors. Another difference from SHIPS is that because the LGEM forecast is based on a time stepping procedure, the forecast can better represent intensity changes of storms that move from water to land and then back over water.

f. Dynamical Models

Dynamical models are the most complex and most computationally expensive numerical models utilized by the NHC. Dynamical models make forecasts by solving the physical equations that govern the atmosphere, using a variety of numerical methods and initial conditions based on available observations. Since observations are not taken at every location around the world, the model initialization can at times vary tremendously from the atmosphere, and this is one of the primary sources of uncertainty and forecast errors within dynamical models. Errors in the initial state of a model tend to grow with time during the actual model forecast; therefore small initial errors can become very large several days into the forecast. It is largely for this reason that forecasts become increasingly inaccurate in time.

U.S. National Weather Service Global Forecast System (GFS)

The term “GFS” technically refers to all code that supports the production of the National Weather Service (NWS) global model suite of products, including the global data assimilation system (GDAS). The GFS model itself is a global spectral model truncated at total wave number T382 (equivalent to about 35-km horizontal grid spacing) with 64 vertical levels. This resolution is maintained through 180 hours of the forecast. Thereafter, the GFS is truncated to wave number T190 (equivalent to about 80-km grid spacing) with 64 vertical levels out to 384 hours. The GFS employs a hybrid sigma-pressure vertical coordinate system, a simplified Arakawa-Schubert (SAS) convective parameterization scheme, and a first-order closure method to represent the planetary boundary layer (PBL). All GFS runs obtain their initial conditions from a three-Dimensional Variational (3-D VAR) Gridpoint Statistical Interpolation (GSI), which is updated continuously throughout the day. Rather than inserting data corresponding to an artificial TC vortex (“bogusing”), the GFS relocates the globally-analyzed TC vortex in the first-guess field to the official NHC position. An assimilation of the available (real) data is then performed to create the initial state. The globally analyzed vortex is, however, often an incomplete representation of the true TC structure. For this reason, the GFS is typically more suited to producing track and outer wind structure forecasts. Developed and maintained by the Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP), the GFS is run four times per day (00 UTC, 06 UTC, 12 UTC, and 18 UTC) out to 384 hours.

Limited Area Sine Transform Barotropic (LBAR) Model

Compared to the GFS, LBAR is a simple two-dimensional dynamical track prediction model. It solves the shallow-water wave equations initialized with vertically averaged (850-200 hPa) winds and heights from the GFS global model. An idealized symmetric vortex and a constant wind vector (equal to the initial storm motion vector) are added to the GFS global model analysis to represent the storm circulation. The model equations are solved using a spectral sine transform technique over an area near the hurricane. The lateral boundary conditions are obtained from the GFS global model forecast. LBAR includes no horizontal gradients in temperature (and as a consequence, no vertical wind shear), making the LBAR a relatively poor performer beyond 1-2 days or outside of the deep tropics.

Vigh, J., S.R. Fulton, M. DeMaria, and W.H. Schubert, 2003: Evaluation of a multigrid method in a barotropic track forecast model. *Mon. Wea. Rev.,* **131,** 1629-1636.

Canadian Meteorological Centre (CMC) Global Environmental Multiscale Model (GEM)

The CMC's GEM is a hydrostatic global grid point model laid on a latitude/longitude coordinate system with 0.3 latitude-0.45 longitude (approximately 33 km at 49 degrees latitude) horizontal grid spacing and 58 vertical eta levels. The eta vertical coordinate system used in the CMC's GEM depicts the bottom atmospheric layer within each grid box as a flat step. The CMC's GEM employs an advanced and computationally expensive four-dimensional data assimilation scheme (4-D Var) where temporal variations in the initial data are included. The condensation package includes the Kain-Fritsch scheme for deep moist convection and Kuo Transient scheme for shallow convection. The Bougeault and Lacarrere (1989) mixing length is used for vertical diffusion due to atmospheric turbulence. The CMC's GEM is run through 144 hours at 12 UTC, 240 hours at 00 UTC, and 360 hours on Saturdays. The CMC's GEM has limited ability to provide useful intensity forecasts.

http://www.smc-msc.ec.gc.ca/cmc/op_systems/recent_e.html

European Center for Medium-range Weather Forecasting (ECMWF) Model

Developed and maintained by an international organization supported by 28 European member states, the ECMWF model is the most sophisticated and computationally expensive of all the global models currently used by NHC. Due to model complexity/resolution, data assimilation, and operational requirements of the member states, the ECMWF model run is among the latest arriving of all available dynamical model guidance. The ECMWF model is a hydrostatic spectral model where the linear terms are triangularly truncated to 799 waves (the nonlinear terms are calculated at a coarser resolution) with 91 vertical levels (TL799L91). This corresponds to a horizontal grid spacing of about 25 km. The ECMWF model employs a hybrid vertical coordinate system which is terrain following in the boundary layer (sigma) and becomes purely isobaric (pressure) near the tropopause. The ECMWF was the first modeling center to use four-dimensional (4-D VAR) data initialization which allows better assimilation of off-time (non-synoptic) observations, particularly from satellite data. The ECMWF system provides forecasts out to 240 hours (10 days) twice daily. Beyond the good medium-range tropical cyclone track prediction skill of the ECMWF model, its high spatial resolution has shown potential for useful intensity forecasting.

http://www.ecmwf.int/products/forecasts/guide/

Navy Operational Global Atmospheric Prediction System (NOGAPS)

The NOGAPS model is a global spectral model with triangular truncation at 239 waves (approximately 55 km horizontal grid spacing) with 30 vertical levels (T239L30). The NOGAPS uses a hybrid sigma-pressure vertical coordinate system. This configuration results in approximately six terrain-following sigma levels below 850 mb and the remaining 24 levels occurring above 850 mb at near-pressure surfaces. The NOGAPS time step is five minutes, but is reduced if necessary to prevent numerical instability associated with fast-moving weather features. The NOGAPS model uses a 3-D VAR analysis scheme. The model is run out to 180 hours at each of the synoptic times (00Z, 06Z, 12Z, 18Z). The NOGAPS model utilizes the Emanuel convective parameterization scheme with non-precipitating convective mixing based on the Tiedtke method. Like other global models, the NOGAPS model cannot provide very skillful intensity forecasts but can provide skillful track forecasts.

http://www.meted.ucar.edu/nwp/pcu2/nogaps/index.htm

NWS Geophysical Fluid Dynamics Model (GFDL) Hurricane Model

The GFDL Hurricane model is a limited-area, grid-point model that was designed specifically for TC prediction. The GFDL model consists of a triply-nested grid configuration. The outer grid spans 75° x 75° at 1/2° horizontal resolution (approximately 30 km). The middle grid spans 11° x 11° at 1/6° horizontal resolution (approximately 15 km). The inner grid domain size spans 5° x 5° at 1/12° horizontal resolution (approximately 7.5 km). This high resolution, compared to other dynamical models, allows the GFDL to resolve relatively small scale features within a tropical cyclone such as the eye and eyewall. Still, even the GFDL is not able to fully resolve the highly complex structure of a tropical cyclone. The GFDL uses a sigma vertical coordinate system with 42 vertical levels. It employs a simplified Arakawa-Schubert convective parameterization scheme and non-local PBL scheme. The large-scale condensation scheme contains the Ferrier micro-physics package, and the air-sea momentum flux parameterization is designed to account for strong wind conditions to give a better estimate of surface winds. The GFDL is coupled with a high-resolution version of the Princeton Ocean Model (POM), which allows tropical cyclone-induced ocean modification, such as sea-surface temperature cooling, and begins to account for the feedback of the modified ocean on the tropical cyclone. In the Atlantic, the POM is configured at 1/6° horizontal resolution with 23 vertical sigma levels. For the initialization, the GFDL replaces the GFS TC vortex with an axisymmetric vortex spun up in a separate model simulation. The axisymmetric vortex model utilizes TC specifications as provided by NHC forecasters. Since the horizontal resolution of the GFDL is sufficiently high to simulate *some* of the inner core tropical cyclone structure, the GFDL model has up to now been the only purely dynamical model that can provide both skillful intensity and track forecasts (http://www.nhc.noaa.gov/verification/verify3.shtml). The GFDL is run for up to four TCs every six hours out to 126 hours as requested by the NHC and the Central Pacific Hurricane Center.

Bender, M.A., I. Ginis, R. Tuleya, B. Thomas, and T. Marchok, 2007: The operational GFDL coupled hurricane-ocean prediction system and summary of its performance, 2007. *Mon. Wea. Rev.* (in press).

Hurricane Weather Research and Forecasting Model (HWRF)

The Hurricane Weather Research and Forecast (HWRF) model was developed by the National Centers for Environmental Prediction (NCEP) Environmental Modeling Center and implemented operationally in 2007. The non-hydrostatic HWRF model solves the equations that predict vertical air motions, allowing the model to explicitly represent the mesoscale vertical motions that exist in the inner core of TCs. The HWRF model uses a nested grid system with horizontal grid spacing of 27 km (9 km) on the outer (inner) domain and 42 sigma vertical levels. The GSI 3DVAR data assimilation scheme uses a first guess vortex based on the 6-hour forecast from the previous HWRF run to produce an initial representation of the tropical cyclone that matches intensity and structure parameters provided by NHC forecasters. The HWRF is coupled to the Princeton Ocean Model (POM) in the Atlantic basin to better represent the interaction of the atmosphere and ocean in the hurricane environment, an important factor in tropical cyclone intensity prediction. While the HWRF currently has a configuration and physics package similar to that used in the GFDL model, the HWRF will ultimately evolve into a more advanced hurricane prediction system. Future versions of the model will employ enhanced data assimilation techniques (especially within the cyclone's inner core), higher resolution, and more sophisticated physics. Specifically, the HWRF model will make use of airborne and land-based Doppler radar observations to better represent the initial cyclone structure, which is expected to provide further advancements in the prediction of track, intensity, and rainfall. While the HWRF model will eventually replace the GFDL model, they are currently both being run and evaluated in parallel during the 2007 season.

United Kingdom Meteorological Office (UKMET) Model

The UKMET model is a non-hydrostatic global model that utilizes an Arakawa C-grid resulting in an east-west horizontal grid spacing of 0.5° longitude and a north-south grid spacing of 0.4° latitude. This configuration equates to an approximate horizontal grid spacing of 40 km in the mid-latitudes. The UKMET utilizes a hybrid vertical coordinate system with 50 vertical levels. The UKMET model is run twice daily at 0000Z and 1200Z producing forecasts out to 144 hours. The model's 4-D Var data assimilation scheme utilizes observations taken within 3 hours of the forecast start time. That is, the 1200Z run uses observations made between 0900Z and 1500Z. Accordingly, the actual forecast computations for the 0000Z and 1200Z runs are started at approximately 0245Z and 1545Z respectively. Intermediate runs initialized around the 0600Z and 1800Z data cycles are run at approximately 1300Z and 0100Z, but only produce forecasts to 48 hours. In 2002, the U.K. Met Office introduced a completely new formulation of the UKMET model. The upgrades included new formulation of the model's dynamical core, the fundamental equations, and physical parametrizations. The physics package was again modified in 2005. The UKMET typically provides useful tropical cyclone track forecasts but has limited ability to produce valuable intensity forecasts.

http://www.metoffice.gov.uk/research/nwp/publications/nwp_gazette/jun06/um_config.html

g. Ensemble Models

Ensemble forecasts are derived from a combination of forecasts from multiple models, commonly called a consensus forecast, or from an ensemble of forecasts from a single model. Consensus models are not true forecast models *per se*, but represent combinations or averages of forecasts from other models. The simplest way to form a consensus forecast is to average the output from each prediction model, e.g., one computes the mean of each model's predicted latitudes and longitudes of the TC center at some forecast time. At the NHC the most commonly-used consensus forecasts are GUNA, CONU, and FSSE, which are described below. On average, consensus forecasts are typically more accurate than the predictions from the individual models they are comprised of. The variation or spread of individual model forecasts can provide a measure of forecast uncertainty.

Single-model ensembles are multiple predictions from the same starting time for a given model, using different initial conditions. This is a way to account for the uncertainties in the initial state of the atmosphere for a prediction model. A simple average of all of the ensemble forecasts (ensemble mean) often produces a more skillful forecast than any single ensemble run, since errors associated with the individual forecasts tend to cancel each other. However the ensemble mean often smoothes out the finer-scale details associated with the individual ensemble member forecasts. In some cases, the ensemble runs of a given model are made at relatively coarse resolution compared to its parent model.

GUNS

GUNS is a simple track consensus calculated by averaging the track guidance provided by the GFDI (interpolated GFDL), UKMI (interpolated UKMET) and NGPI (interpolated NOGAPS) models. All three member models must be available to compute the GUNS consensus.

GUNA

GUNA is a simple track consensus calculated by averaging the track guidance provided by the GFDI (interpolated GFDL), UKMI (interpolated UKMET), NGPI (interpolated NOGAPS), and GFSI (interpolated GFS) models. All four member models must be available to compute GUNA.

CGUN

CGUN is a version of GUNA that is corrected for model biases. The biases are derived statistically, based on parameters known at the start of the forecast, such as model spread, initial intensity, location, etc.

CONU

CONU is a simple track consensus calculated by averaging the track guidance provided by the GFDI (interpolated GFDL), UKMI (interpolated UKMET), NGPI (interpolated NOGAPS), GFNI (interpolated GFDN model) and GFSI (interpolated GFS) models. CONU requires at least two of the five member models be present.

CCON

CCON is a version of CONU that is corrected for model biases. The biases are derived statistically, based on parameters known at the start of the forecast, such as model spread, initial intensity, location, etc.

ICON

ICON is a simple intensity model consensus computed as the average of the Decay-SHIPS and GHMI (adjusted GFDI forecast) intensity output.

Florida State University Super Ensemble (FSSE)

The Florida State University Superensemble (FSSE) is a weighted multi-model consensus that uses both dynamical models and the previous official NHC forecast as the basis of its prediction. Rather than simply averaging the member models, the FSSE assigns different weights to each member model in an attempt to account for the biases of each individual member model. Individual model biases are computed based on the past performance of each member model, and the weights are determined using linear multiple regression during a training phase. The training phase includes approximately 75 individual sets of past forecasts from each of the member models. This makes the FSSE somewhat different from other models used at NHC, since the FSSE represents a form of artificial intelligence, as it constantly is learning from the past performance of the models that comprise it. One limitation of the superensemble technique occurs when the past performance of the member models does not accurately represent their present performance, e.g., if major changes are made to a member model between successive hurricane seasons. The FSSE technique is most accurate when no major changes are made to any of the member models between the training phase and operational forecast phase. The FSSE technique originated at Florida State University. NHC currently receives real-time FSSE output from a version of the technique provided by Weather Predict, Inc.

National Weather Service Global Ensemble Forecast System (GEFS)

The GEFS is an ensemble prediction system based on the GFS model. It consists of a low-resolution (T126L28, or approximately 100 km horizontal grid spacing with 28 vertical levels) control run of the GFS, and 20 ensemble members at the same resolution. Uncertainties in the initial conditions are addressed by the use of so-called Ensemble Transform Bred Vectors. These generate different variations, or perturbations, in the initial states of each of the 20 member runs. Vortex relocation of TCs is applied to each member initial state, i.e., the starting locations of TCs are assumed to be well-known and are therefore identical in the initial states of all ensemble members. The GEFS produces forecasts out to 16 days, four times per day. The mean of the 20-member ensemble forecasts is typically used as forecast guidance, however the individual ensemble runs can yield useful prognostic information as well. For instance, the variability of TC forecast tracks in the ensemble may provide insight on forecast uncertainty. It should be noted however that, on average, track forecasts produced by the GEFS have been somewhat less skillful than those produced by a multi-model consensus forecast such as GUNA. The GEFS can also be used for guidance on TC genesis. For instance if many, or all, ensemble members predict the formation of a TC, the forecaster would consider more seriously the prospect of cyclone development.

h. Trajectory Models

Trajectory models are much simpler than dynamical or statistical models as they merely move a TC along a track based on the prevailing flow derived from a separate dynamical model. While trajectory models utilize information from dynamical models to represent the prevailing flow, they do not allow the cyclone to interact with the surrounding atmosphere. Another limitation associated with trajectory models is their reliance on static levels in the atmosphere to represent the prevailing flow. To account for the variation in the prevailing flow with height, multiple versions of the same trajectory model based on varying depths are typically employed.

Beta and Advection Model (BAM)

The Beta and Advection Model (BAM) refers to a class of simple trajectory models that utilize vertically-averaged horizontal winds from the GFS to compute the trajectories. These trajectories include a correction term to account for the drift of the storm due to the "beta-effect" caused by the earth's rotation. The BAM concept is based upon the relationship between storm intensity/depth and steering levels. Strong cyclones typically extend through the entire depth of the troposphere and thus steered by deeper layer-averaged winds, while weaker cyclones are steered by shallower layer-average winds. Accordingly, the BAM is run in three versions corresponding to the different depths used in the trajectory calculation: BAM shallow (850-700 hPa), BAM medium (850-400 hPa), and BAM deep (850-200 hPa), known as BAMS, BAMM and BAMD, respectively. The performance of the BAM is strongly dependent on the dynamical input from the GFS. A divergence of the three versions of the BAM indicates varying steering flow within the parent GFS model. Hence, spread among the three versions of the BAM also serves as a rough proxy for vertical shear as well as the complexity and uncertainty in the track forecast.

i. Acknowledgements

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Name/Description	ATCF ID	Type	Timeliness (E/L)	Parameters
Official NHC forecast	OFCL			Trk, Int
NWS/Geophysical Fluid Dynamics Laboratory (GFDL) model	GFDL	Multi-layer regional dynamical	L	Trk, Int
NWS/ Hurricane Weather Research and Forecasting Model (HWRF)	HWRF	Mutlti-layer regional dynamical	L	Trk, Int
NWS/Global Forecast System (GFS)	GFSO	Multi-layer global dynamical	L	Trk, Int
National Weather Service Global Ensemble Forecast System (GEFS)	AEMN	Consensus	L	Trk, Int
United Kingdom Met Office model (UKMET)	UKM	Multi-layer global dynamical	L	Trk, Int
Navy Operational Global Prediction System (NOGAPS)	NGPS	Multi-layer global dynamical	L	Trk, Int
Navy version of GFDL	GFDN	Multi-layer regional dynamical	L	Trk, Int
Environment Canada Global Environmental Multiscale Model	CMC	Multi-level global dynamical	L	Trk, Int
European Center for Medium-range Weather Forecasting (ECMWF) Model	EMX	Multi-layer global dynamical	L	Trk, Int
Beta and advection model (shallow layer)	BAMS	Single-layer trajectory	E	Trk

Name/Description	ATCF ID	Type	Timeliness (E/L)	Parameters
Beta and advection model (medium layer)	BAMM	Single-layer trajectory	E	Trk
Beta and advection model (deep layer)	BAMD	Single-layer trajectory	E	Trk
Limited area barotropic model	LBAR	Single-layer regional dynamical	E	Trk
NHC98 (Atlantic)	A98E	Statistical-dynamical	E	Trk
NHC91 (Pacific)	P91E	Statistical-dynamical	E	Trk
CLIPER5 (Climatology and Persistence model)	CLP5	Statistical (baseline)	E	Trk
SHIFOR5 (Climatology and Persistence model)	SHF5	Statistical (baseline)	E	Int
Decay-SHIFOR5 (Climatology and Persistence model)	DSF5	Statistical (baseline)	E	Int
Statistical Hurricane Intensity Prediction Scheme (SHIPS)	SHIP	Statistical-dynamical	E	Int
SHIPS with inland decay	DSHP	Statistical-dynamical	E	Int
Previous cycle OFCL, adjusted	OFCI	Interpolated	E	Trk, Int
Previous cycle GFDL, adjusted	GFDI	Interpolated-dynamical	E	Trk, Int
Previous cycle GFDL, adjusted using a variable intensity offset correction that is a function of forecast time.	GHMI	Interpolated-dynamical	E	Trk, Int
Previous cycle HWRF, adjusted	HWFI	Interpolated-dynamical	E	Trk, Int
Previous cycle GFS, adjusted	GFSI	Interpolated-dynamical	E	Trk, Int

Name/Description	ATCF ID	Type	Timeliness (E/L)	Parameters
Previous cycle UKM, adjusted	UKMI	Interpolated-dynamical	E	Trk, Int
Previous cycle NGPS, adjusted	NGPI	Interpolated-dynamical	E	Trk, Int
Previous cycle GFDN, adjusted	GFNI	Interpolated-dynamical	E	Trk, Int
Previous cycle EMX, adjusted	EMXI	Interpolated-dynamical	E	Trk, Int
Average of GFDI, UKMI, NGPI, and GFSI	GUNA	Consensus	E	Trk
Version of GUNA corrected for model biases	CGUN	Corrected consensus	E	Trk
Previous cycle AEMN, adjusted	AEMI	Consensus	E	Trk, Int
Average of at least 2 of GFDI, UKMI, NGPI, GFSI, and GFNI	CONU	Consensus	E	Trk
Version of CONU corrected for model biases	CCON	Corrected consensus	E	Trk
Average of GHMI and DSHP	ICON	Consensus	E	Int
FSU Super-ensemble	FSSE	Corrected consensus	E	Trk, Int

Table 1. Summary of the mostly commonly used National Hurricane Center track and intensity models. “E” refers to early and “L” refers to late in the timeliness column. “Trk” refers to track and “Int” refers to intensity the parameters forecast column.