

SIXTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 3.2 : Improvements in understanding and prediction of Tropical Cyclone (TC) motion.

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3.2.1 Introduction

This Topic includes developments related to uni- and multi-model ensemble forecasting, data assimilation, and model developments as they relate to forecasts of tropical cyclone (TC) track. The TC track forecast is a critical component of the warning system, as it serves as the basis for forecasting the areas threatened by damaging winds, storm surge, and rainfall. The track errors are only averages from which there can be large deviations in any individual case, even at short ranges.

3.2.2 The current state of operational TC track forecasts

The current state of operational TC track forecasts globally is covered in Topic 3.1. The following is a short discussion of enhancements to operational track forecasts during the last four years. Comparisons between different basins should not be made because of varying numbers of cases and difficulty in forecasting.

3.2.2.1 North Atlantic Ocean

Official TC track forecasts in the North Atlantic Ocean were extended from 3 days to 5 days by the United States (US) National Hurricane Center (NHC) in 2003. Table 3.2.1 shows average official NHC track forecast errors from 2001-2005. Five-day forecasts are currently as accurate as the 3-day forecasts 15 years ago, and forecast errors from 24-72 h are now roughly half their 1990 values. The extended forecasts have not been produced long enough to assess any trends in their errors (Fig. 3.2.1).

<i>North Atlantic Ocean</i>	<i>0 h</i>	<i>12 h</i>	<i>24 h</i>	<i>36 h</i>	<i>48 h</i>	<i>72 h</i>	<i>96 h</i>	<i>120 h</i>
<i>Track Error (km)</i>	13.7	69.1	119.4	169.1	219.1	317.4	427.9	561.6

Table 3.2.1 Average official NHC track forecast errors in the North Atlantic Ocean from 2001-2005 for all TCs.

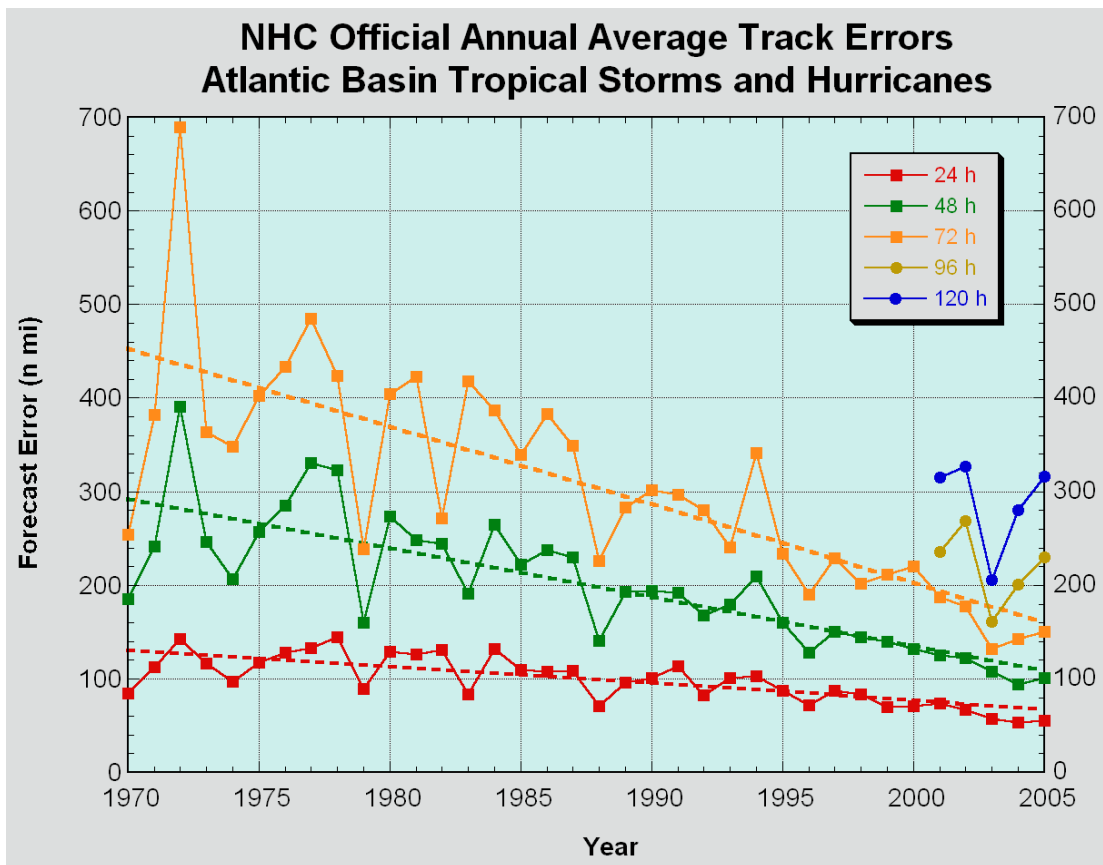


Figure 3.2.1. Annual average NHC official track errors for North Atlantic Ocean tropical storms and hurricanes for the period 1970-2005, with least-squares trend lines superimposed.

3.2.2.2 Eastern North Pacific Ocean

Official TC track forecasts in the Eastern North Pacific Ocean were extended from 3 days to 5 days by NHC in 2003. Average official NHC track forecast errors from 2001-2005 are shown in Table 3.2.2. The 4-day forecasts are currently as accurate as the 3-day forecasts were 15 years ago (Fig. 3.2.2). These extended forecasts have not been produced for a long enough period of time to assess any trends in their errors.

3.2.2.3 Central North Pacific Ocean

Official TC track forecasts in the Central North Pacific Ocean were extended from 3 days out to 5 days by the US Central Pacific Hurricane Center (CPHC) in 2003. Average official CPHC track forecast errors from 2001-2005 are shown in Table 3.2.3. Because of the relative inactivity of the basin, some seasons do not have forecasts reaching 72 h or beyond. These extended forecasts have not been produced for a long enough period of time to assess any trends in their errors (Fig. 3.2.3).

<i>Eastern North Pacific Ocean</i>	<i>0 h</i>	<i>12 h</i>	<i>24 h</i>	<i>36 h</i>	<i>48 h</i>	<i>72 h</i>	<i>96 h</i>	<i>120 h</i>
Track Error (km)	17.2	65.0	111.3	152.8	190.0	267.8	355.1	427.9

Table 3.2.2. Average official NHC track forecast errors in the Eastern North Pacific Ocean from 2001-2005 for all TCs.

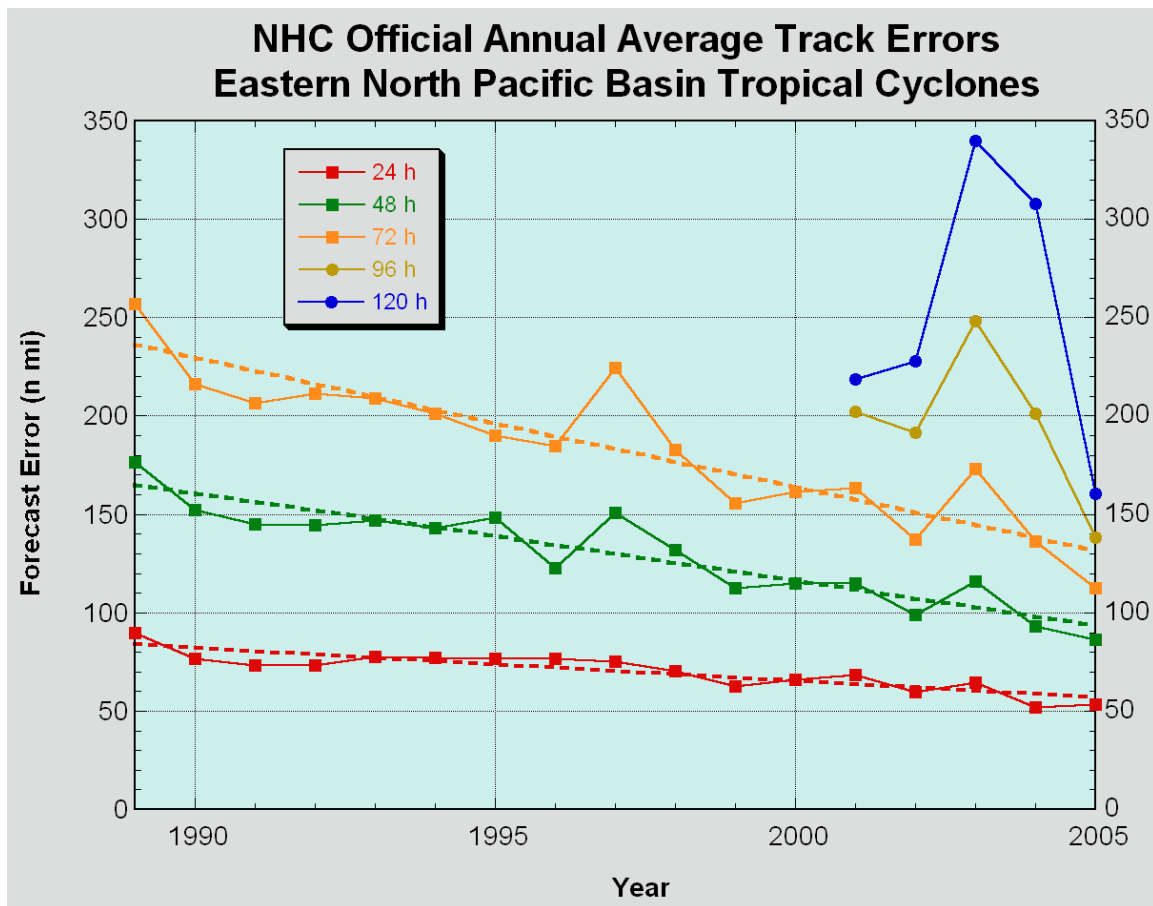


Figure 3.2.2. Annual average NHC official track errors for Eastern North Pacific Ocean tropical storms and hurricanes for the period 1970-2005, with least-squares trend lines superimposed.

3.2.2.4 Joint Typhoon Warning Center

The U. S. Joint Typhoon Warning Center (JTWC) extended their TC track forecasts in the Western North Pacific Ocean, the Southern Pacific Ocean, and the Indian Ocean from 3 days out to 5 days in 2001. Average JTWC track forecast errors from 2001-2005 are shown in Fig. 3.2.4. Though 48-h forecasts are now as accurate as 24-h forecasts were in 1976, and 72-h forecasts are now as accurate as 48-h forecasts were in 1999, these extended forecasts have not been produced for a long enough period of time to assess any trends in their errors.

Central North Pacific Ocean	12 h	24 h	36 h	48 h	72 h	96 h	120 h
Track Error (km)	50.4	139.2	187.4	241.4	337.1	376.5	376.2

Table 3.2.3. Average official CPHC track forecast errors in the Central North Pacific Ocean from 2001-2005 for all TCs.

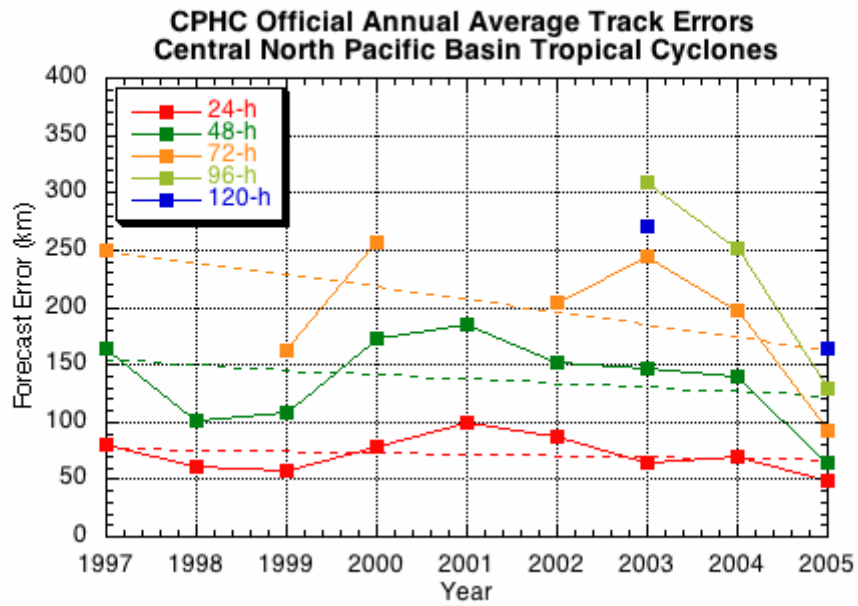


Figure 3.2.3. Annual average CPHC official track errors for Central North Pacific Ocean tropical storms and hurricanes for the period 1997-2005, with least-squares trend lines superimposed.

3.2.3 Numerical Weather Prediction globally

The best objective track guidance tools for TC forecasters are now dynamical models. These models have improved steadily in recent years due to improvements to data, data assimilation, resolution, and vortex initialization. A number of global and limited area (regional) numerical weather prediction models are now available at the various TC centers. Typically, the forecaster must resolve significant differences among the forecasts from these models under limited time constraints. A consensus forecast based on an ensemble of model runs yields better forecasts, on average, than those from any single member of the ensemble. For hurricane track forecasts, the most successful ensembles so far are those made up of independent models, rather than ensembles drawn from multiple runs of a single model. Furthermore, a sense of the reliability of the individual track forecasts is nearly as important as the actual forecasts. Various techniques to improve track forecasts and to provide estimates of their reliability have been devised based upon combining ensembles of tracks from individual and multiple modeling systems. The following sections provide information on these ensembles, followed by information on research and plans for next-generation TC forecasting systems.

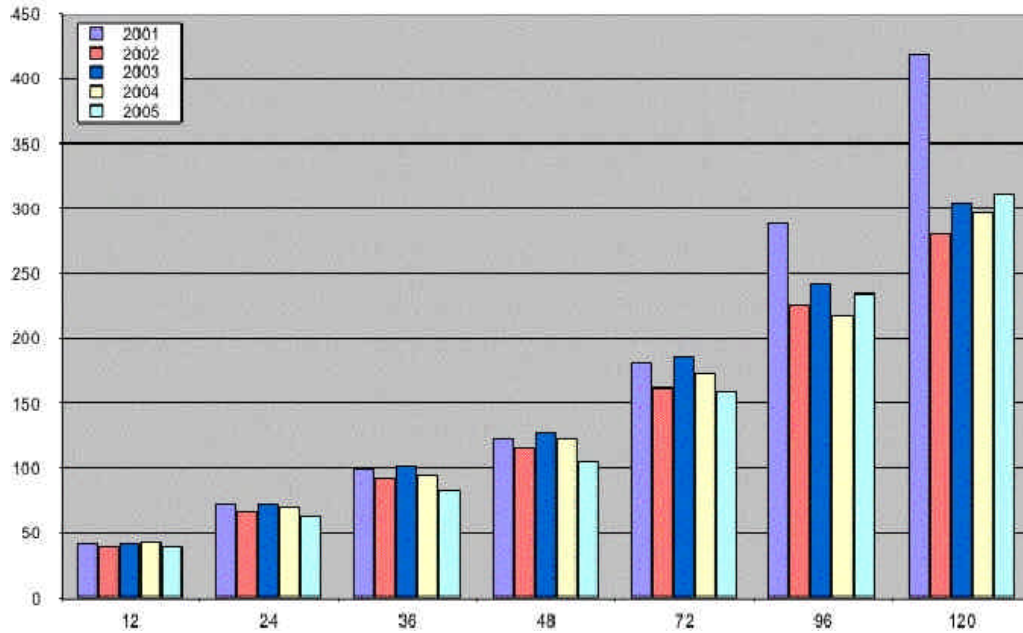


Figure 3.2.4. Annual average JTWC track errors for Western North Pacific Ocean, South Pacific Ocean, and Indian Ocean tropical cyclones for the period 2001-2005, in nm.

3.2.3.1 Single-model ensembles

Ensemble forecasting techniques are increasingly used in TC track prediction. Single-model ensembles generally perturb initial conditions of the deterministic run that represents the best estimate of the initial state. These perturbations are done either randomly (Cheung and Chan 1999a,b) or in a way that represents analysis uncertainty or maximizes perturbation growth. These latter techniques include singular vectors (Leutbecher 2005), bred-modes (Cheung and Chan 1999a,b, Toth and Kalnay 1997), or an ensemble transform (Wang and Bishop 2003). Benefits of these techniques include state-dependent estimates of perturbation structures that are dynamically constrained and fast growing. Disadvantages include the fact that the dynamically generated perturbations are only approximations to actual analysis errors and the individual single-model ensemble runs are not fully independent of the other runs of the ensemble; this limits the ability of the ensemble to span the space of possible solutions.

In recent years, services producing ensemble forecasts have been increasing the number of ensemble members and upgrading the models. Improvements to singular vector techniques and the introduction of Ensemble Kalman Filter (EnKF) techniques to produce initial conditions has occurred. Specifically, ensembles have been used to predict TC tracks, especially to provide probabilistic track forecasts that have been useful to operational forecasters in the medium range. Also, a number of centers are introducing short-range ensembles.

Australian Bureau of Meteorology (BoM) runs ensembles of the Limited Area Prediction System (LAPS) incorporating prediction of TC tracks. An ensemble of Weber's Barotropic Model (WBAR) based on perturbations to the steering layer is being developed for use at BoM. Statistical post-analyses of the past season are included in the generation of its deterministic and probabilistic output. In combination with the computational efficiency of a barotropic model in comparison with 3-D models, large statistical

samples can be produced that provide statistically-significant estimates of its future deterministic and probabilistic performance quality. Furthermore, the possibility of large numbers of runs allows the model to be used as a benchmark for the general capabilities of single-model ensembles, a task that can hardly be achieved for the more complex models. Analog ensemble forecast model has been developed for tracks in the Australia region (Fraedrich et al. 2003).

The Canadian Meteorological Centre (CMC) produces 8 ensemble members twice daily at T149L28 resolution with the global spectral model, and an additional 8 members twice daily at 1.2 degree resolution with GEM, both through 16 days. Because two different models are used, this can also be considered to be a multi-model ensemble. The 16 models have different physical parametrizations, data assimilation cycles and sets of perturbed observations that are assimilated with an Ensemble Kalman Filter with 96 members to define the model error covariance terms. Boundary conditions such as sea surface temperature, albedo and roughness length have been perturbed as well. The control forecast is initiated from the ensemble mean and performed with the spectral model. The ensemble may be soon upgraded to run twice daily.

The China Meteorological Administration (CMA) has developed an ensemble forecasting system for TC tracks that will run experimentally during 2006. It is expected to provide track forecasts and forecasts of the area of high winds and rains produced by TCs. The global model is run at T106L19 resolution through 30 days, with perturbations calculated using singular vectors.

The European Centre for Medium-Range Weather Forecasts (ECMWF) singular vector-based perturbations targeted on TCs were revised in 2004. In the old configuration, singular vectors were computed for systems of at least tropical storm intensity between 25S-25N. Furthermore, the optimization regions were centered on the reported TC position and limited to a latitude band from 25S-25N. The perturbations were limited to the tropics in order not to duplicate extratropical singular vectors. However, this resulted in an unrealistic reduction of spread in TC positions during extratropical transitions. Perturbations are now targeted on systems of at least tropical depression intensity between 40S and 40N. A duplication of extratropical perturbations is avoided by computing the singular vectors targeted on a TC in the subspace orthogonal to the extra-tropical singular vectors. Optimization regions are specific for individual TCs if possible and account for the predicted movement of the TC by using track information from the previous ensemble forecast. The maximum number of TC computations has been increased from 4 to 6. Pre-operational testing of the revised perturbations for TCs indicates an improvement of the 5-day strike probability forecasts produced operationally. The ensemble resolution is T399L62, with perturbations at T42L62, and is now run twice per day. The ensemble prediction system will be upgraded in several steps to a variable resolution system which is coupled to an ocean model --- most likely from day 10 onwards (the exact configuration of the 3rd phase of this system has not yet been defined, but very likely it will be T399L62 to 10 days twice daily, T255L62 to 15 days twice daily, and T255L62 to 32 days once a week).

The Japan Meteorological Agency (JMA) instituted a global ensemble prediction system in 2003 for the medium range. It is a 25-member global ensemble run at T106L40 through 9 days, and the perturbations calculated with bred modes. Effective point typhoon strike probability products are created using this ensemble. JMA plans to upgrade the system in 2006 to T319L60 with 50 members, and to produce a typhoon-specific ensemble for track prediction in 2007. This typhoon ensemble will run four times daily through 84 h for probabilistic typhoon forecasts. This probabilistic system will help to define operational reliability circles.

The Korea Meteorological Administration (KMA) currently runs a 32-member global ensemble at T106L21 resolution to 10 days using breeding of growing modes for perturbations. They expect to increase the resolution to 30 level. KMA is working toward developing a perturbation scheme that fully reflects initial condition uncertainty in the region of the TC.

In 2005, the US National Centers for Environmental Prediction (NCEP) improved their global ensemble

forecasting system to allow for vortex relocation in the initial conditions. This eliminated problems with erroneous location of the initial vortex and improved the system's reliability. For the 2006 season, the ensemble forecasting system was upgraded to have 14 members four times daily, with a new perturbation technique based on an ensemble transform. The model is run at T126L28 through 384 h. The first upgrade allowed the ensemble mean to improve upon the high-resolution control track forecast for the first time (Fig. 3.2.5) and for an improved relationship between the spread of the ensemble and the actual error of the ensemble mean. A companion short-range ensemble prediction system is also run with regional models, but no special vortex processing is done.

One major problem with these ensemble forecasting systems is dissemination of large amounts of data (over 200 Gbytes of data daily from all ensemble forecast systems globally), and the necessity of gathering these data from geographically diverse centers. To address this, the North American Ensemble Forecast System (NAEFS) is a new weather modeling system run jointly by the Meteorological Service of Canada (MSC) and NCEP to provide numerical weather prediction products to weather forecasters in both countries for a forecast period that runs to 2 weeks. The NAEFS combines the Canadian global forecast model ensemble and the NCEP global ensemble into a joint ensemble that will create weather forecasts for all of North America. At present, the national weather agencies in North America are participating in NAEFS - MSC, the National Meteorological Service of Mexico, and NCEP.

The THORPEX Asian Regional Committee is arranging the exchange of TC track forecasts among its members. The plan is to develop a multi-model ensemble and deliver probabilistic forecasts to its members by 2008 as part of a proposed THORPEX Interactive Global Grand Ensemble (TC-TIGGE) to accelerate the improvements in the accuracy of 1-day to 2-week high-impact weather forecasts for the benefit of humanity. The goals of TIGGE are: (1) enhanced international collaboration between operational centers and universities on the development of ensemble prediction, (2) development of new methods combining ensembles of predictions from different sources and of correcting for systematic errors (biases, spread over-/under-estimation), (3) increased understanding of the contribution of observation, initial and model uncertainties to forecast error, (4) increased understanding of the feasibility of operationally employing, an interactive ensemble system that responds dynamically to changing uncertainty (including the use of adaptive observing, variable ensemble size, on-demand regional ensembles) and which exploits new technology for grid computing and high-speed data transfer, (5) development of a prototype future Global Interactive Forecasting System, and (6) communication of probabilistic forecasts to the public.

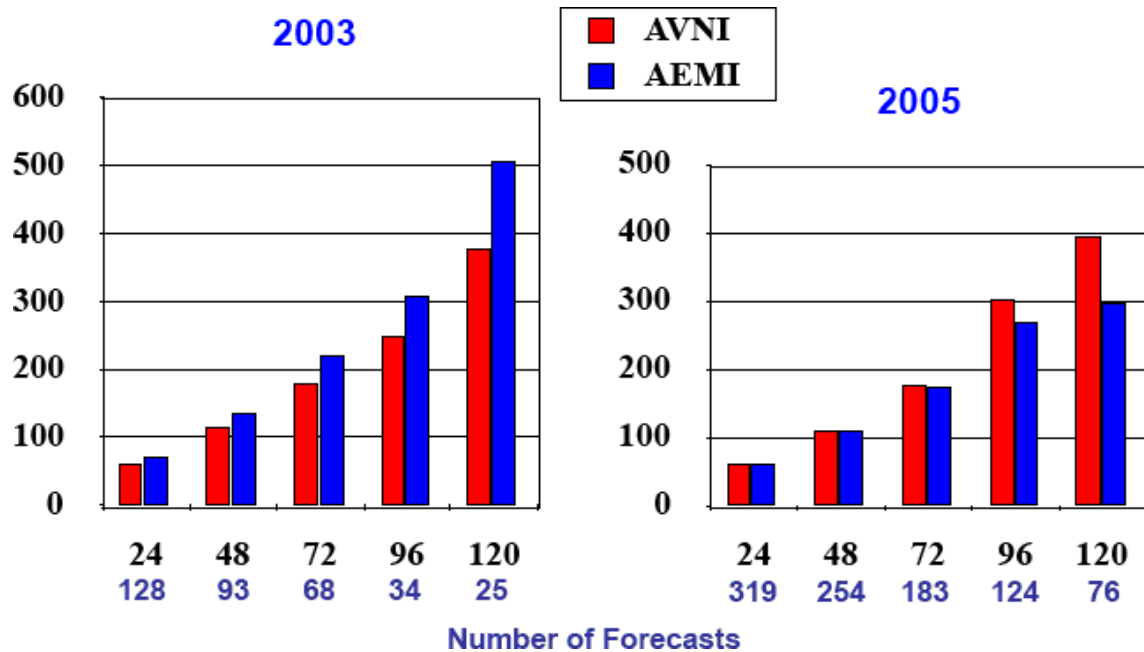


Figure 3.2.5. Track forecast error (nm) during 2003 and 2005 for the NCEP Global Forecasting System (AVNI) and the mean of the Global Ensemble Forecasting System (AEMI).

3.2.3.2 Multiple-model ensembles

The simplest form of ensemble forecast involves post-processing of existing deterministic forecasts produced routinely from operational centers. This technique has the advantage of very low computational overhead (only post-processing) and is fairly successful (Goerss 2000, 2006, Williford et al. 2003, Vijaya Kumar et al. 2003), but suffers from small ensembles (limited to the number of operational centers) and the fact that the ensemble members are not equally likely, independent, realizations. Bias removal techniques are difficult with single-model ensembles since the individual forecasts are not independent, but have proven useful (Williford et al. 2003 and Vijaya Kumar et al. 2003), and Bayesian model averaging (Raftery et al. 2005) would also probably significantly improve the skill of these forecasts. Verifications show that the multiple model ensemble approach results in noticeable improvements in TC forecast track errors (Goerss 2000; Lee and Wong 2002).

CMC produces 8 ensemble members twice daily at T149L28 resolution with the global spectral model, and an additional 8 members twice daily at 1.2 degree resolution with GEM, both through 16 days. Because two different models are used, this can also be considered to be a multi-model ensemble. See Section 3.2.3.1 for more information.

CMA has developed a multi-model ensemble forecasting technique based on canonical correlation analysis. The system utilizes six track forecasts from numerical weather prediction models and from forecasting centers, and calculates mean forecasts based on multivariate linear regression, weighting based on past forecasts, and a simple arithmetic mean. Each of these tracks improve upon any of the individual forecasts.

The Hong Kong Observatory is experimenting with ensembles of their mesoscale model system.

JMA has used an arithmetic mean of the JMA, United Kingdom Meteorological Office (UKMO) global

model, and ECMWF track forecasts since 1991. This ensemble mean has performed better than any of the individual components each year since 1996.

The NCEP uses multiple techniques for multi-model ensembles. One such technique, GUNA, is the mean of the Geophysical Fluid Dynamics Laboratory (GFDL) Hurricane Model, UKMO, US Navy Operational Global Atmospheric Prediction System (NOGAPS), and US NCEP Global Forecasting System (GFS) forecasts available only when all four models provide tracks. The second technique, CONU, uses tracks from the GFDL, GFS, NOGAPS, GFDN (the GFDL model run by the U. S. Navy using NOGAPS for boundary conditions), and the UKMO, and is available when every individual forecast may not be. Another technique available at JTWC, CONW, includes up to nine model forecasts. Goerss (2006) developed a product to predict the reliability of the ensemble mean forecast based on a stepwise linear regression using predictors from previous seasons. The result is a set of radii at each forecast time for each individual forecast within which the storm center will reside with 75% likelihood. The size of the circles is representative of the likely reliability of the forecast. Results have generally been positive, but this system requires that the verification lie within the spread of the individual models. NHC forecasters have come to rely on these techniques as some of their primary guidance.

The National Center for Hydro-Meteorological Forecasting (NCHMF) or Vietnam has used an arithmetic mean of advisory forecasts available from JMA, JTWC, and CMA. This mean forecast has outperformed available model and forecasting center tracks in 2004 and 2005.

Sophisticated multi-model ensemble approaches include the Florida State University (FSU) Superensemble and the JTWC Probabilistic Ensemble System for the Prediction of TCs (PEST; Weber 2005). In the Superensemble, past numerical and official TC forecasts are regressed to the observed tracks and intensities for past storms for each forecast time at 12-h intervals through 5 days during a training period. A simple multiple linear regression technique generates weights for each model, and bias estimates are calculated. The coefficients are then used during the forecast phase. Future forecasts made by the multiple models and the aforementioned statistics are used to construct the superensemble forecasts. These forecasts have outperformed other multi-model ensembles in the Atlantic basin during 2004 and 2005 (Fig. 3.2.6). PEST uses all available (early) model forecasts during a training period (the previous season) and produces a deterministic and probabilistic position and intensity prediction by application of the results of a statistical analysis of all model forecasts. The track guidance quality is approximately the same as that of CONW (within $\pm 5\%$ in skill) and is better than all other models in use in the western North Pacific.

3.2.4 Data Assimilation

Most operational systems currently use a three-dimensional variational (3D-VAR) or a four-dimensional variational (4D-VAR) assimilation system each analysis cycle. Increased resolution of numerical models and of high-density remotely sensed data make the problem of assimilation increasingly important. For example, an advanced data assimilation system in H-WRF will make use of real time airborne Doppler radar data to initialize the three dimensional storm scale structure. The initial plan is to use a 3D-VAR Gridpoint Statistical Interpolation (GSI) technique to assimilate these data. During the 2006 NOAA Hurricane Field Program, airborne Doppler radar data will be quality controlled on the aircraft and transmitted in real time to NCEP for potential assimilation into the model. Initial attempts at this assimilation have been promising (Liu et al. 2006), and further studies with a 4D-VAR or ensemble-based systems are pending.

Preliminary EnKF studies for TCs (Chen and Snyder 2006, Hakim and Torn 2006, Torn and Hakim 2006, Aberson and Etherton 2006) suggest that this technique has significant potential that warrants further research. Hakim and Torn (2006) and Torn and Hakim (2006) explored the use of an EnKFs at 10 km and 30 km horizontal resolution for ensemble analysis and prediction of Hurricanes Katrina (2005) and Rita (2005). All conventional observations were assimilated except satellite radiances.

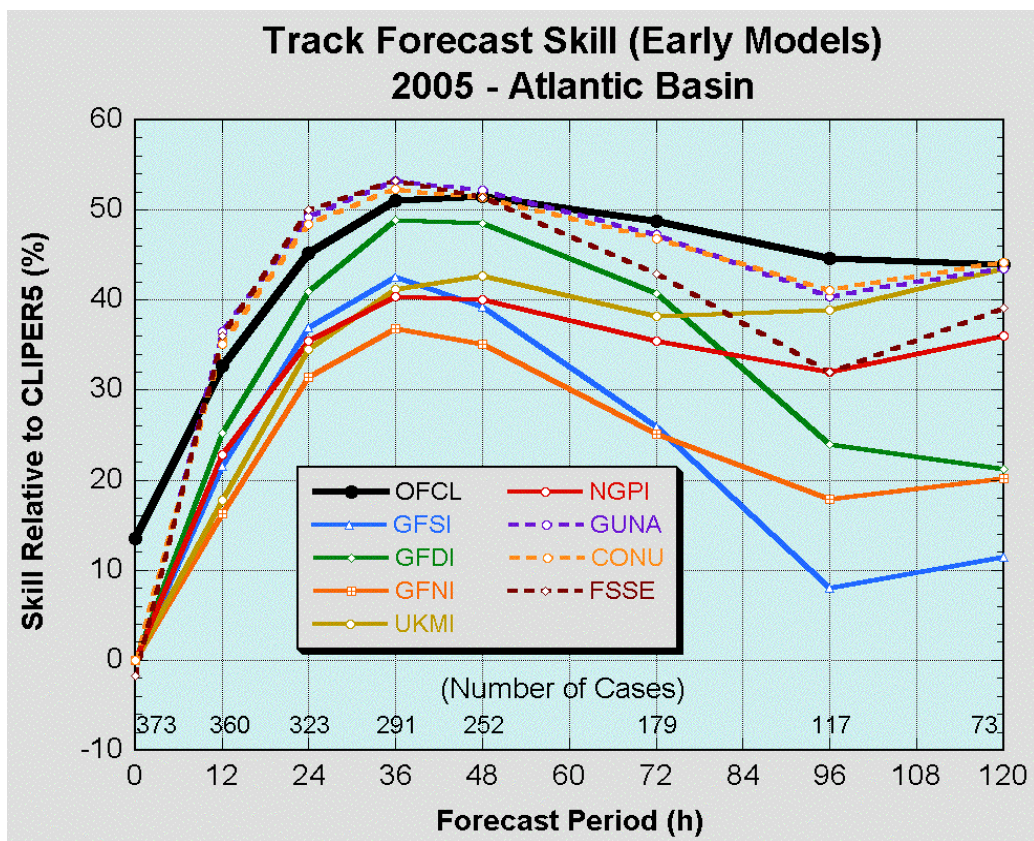
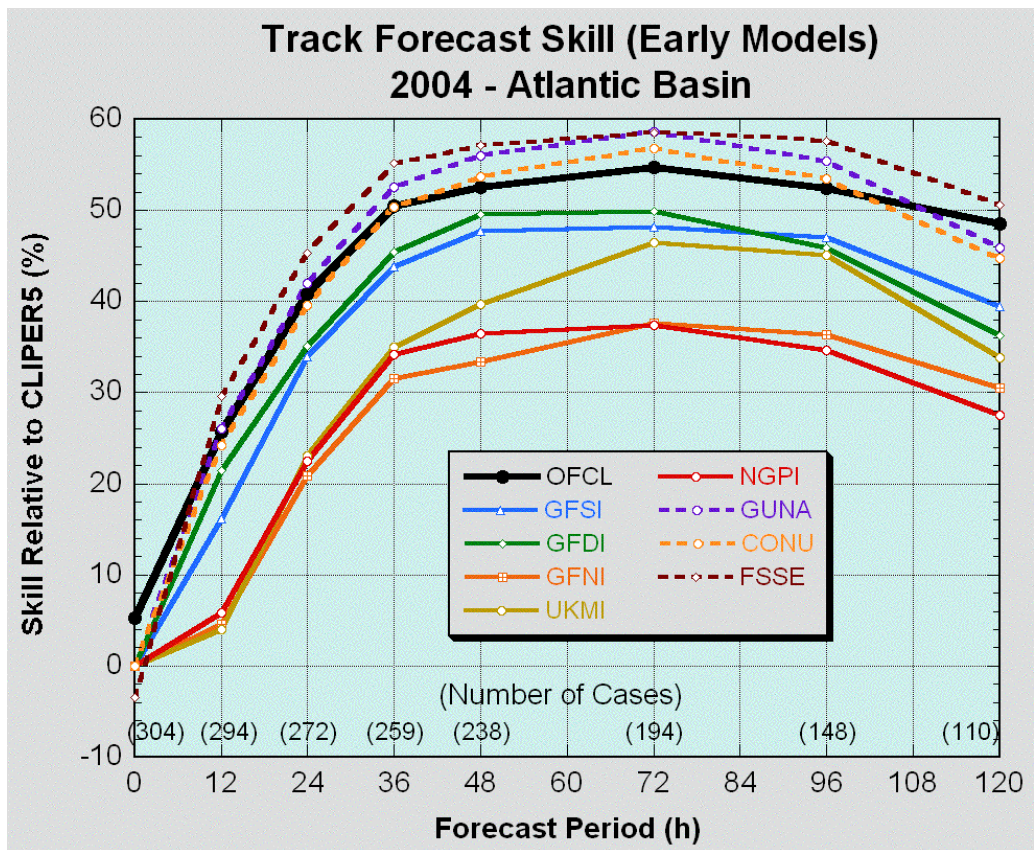


Figure 3.2.6. Track forecast skill for various dynamical models and multi-model ensembles in the Atlantic basin during 2004 and 2005.

Preliminary results suggest that the EnKF is able to accurately constrain both analysis and forecast errors. Future research will extend this work to smaller scales and to a larger sample of cases. Aberson and Etherton used an Ensemble Transform Kalman Filter to assimilate environmental dropwindsonde data into a simple barotropic model, changing the initial condition in a way constrained by the model and the ensemble, and improving the ultimate track forecast over what was possible with a 3D-VAR data assimilation system (Fig. 3.2.7).

The emergence of ensemble data assimilation methods such as the EnKF brings with it the possibility of casting the more general problem of numerical weather prediction, and specifically involving TCs, in a probabilistic framework. Since any single model forecast is only one of infinitely many possible realizations of a random process, the evolution of which depends strongly on the realizations of other random variables (e.g. the observations which impact the analysis used to initialize the forecast), it is important to focus not only on the forecast itself but also on the associated forecast error (Lewis and Tripoli 2006). Figure 3.2.8 shows the results from a single assimilation cycle and represents the ensemble mean forecast for 1 km wind 18Z on 25 October for Hurricane Wilma. The resulting improvement in the analysis is evident when comparing a) and b) to the verifying field in c). Here, the assimilation process is not viewed as one of obtaining a deterministic analysis, since not even satellite data can ever be expected to resolve basic cumulus cells in space or time. Instead, the assimilation is aimed at a cloud resolving probabilistic ensemble analysis and ultimately a cloud resolving probabilistic ensemble forecast. With these analyses and forecasts, the width of the ensemble determines the probability of the analysis (or forecast) and the mean of the ensemble determines the most likely analysis (or forecast). This eliminates the need to generate an initial ensemble from a deterministic analysis and sets more realistic goals for a cloud resolving analysis of a convective field. Moreover, as a developing TC becomes more focused on the storm scale circulation and is less dependent on individual clouds or embedded mesoscale convective systems, the analyses and forecasts will naturally narrow and convey its increasing predictability.

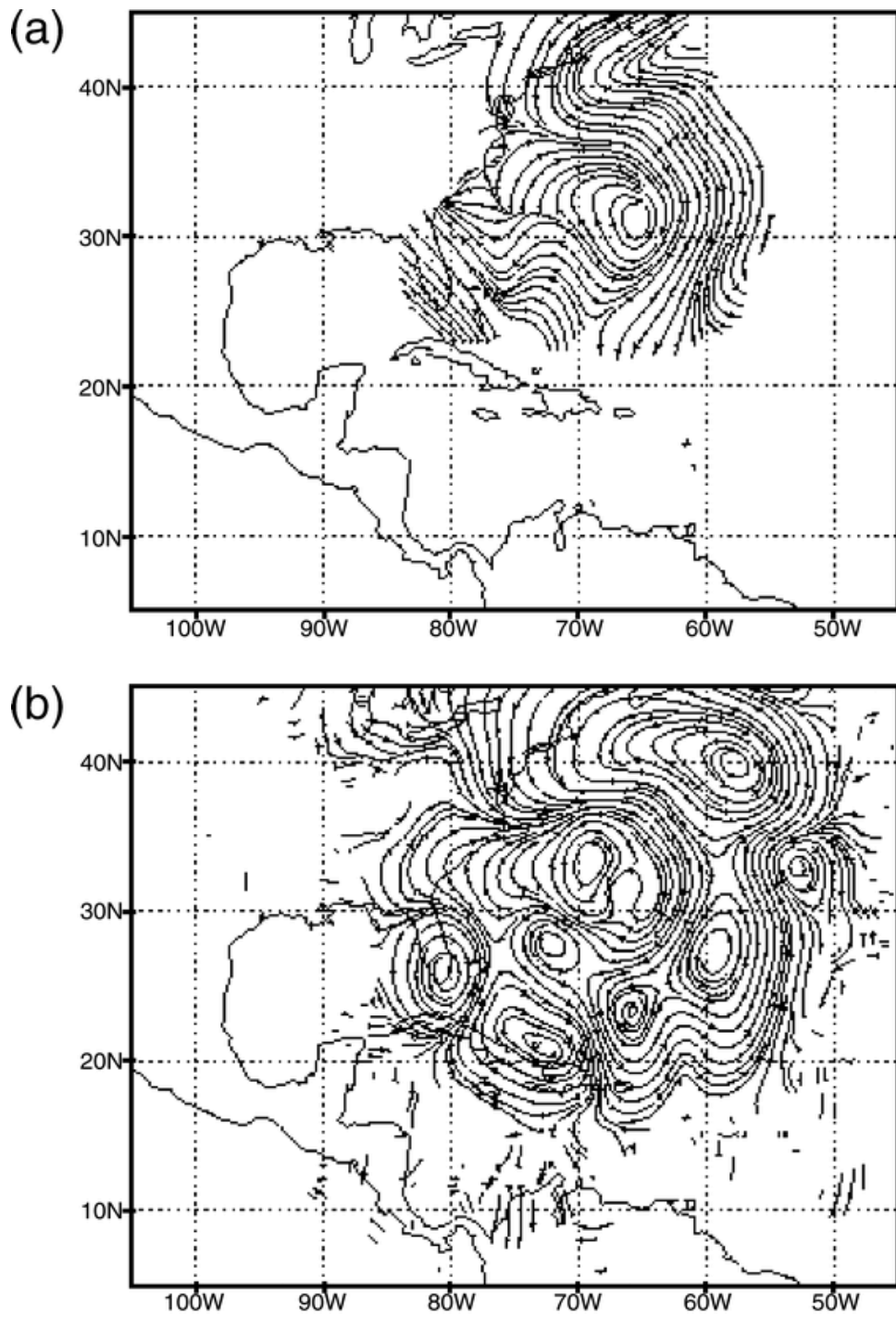


Figure 3.2.7 Streamline analysis of the increments to the VICBAR DLM wind field first guess using (a) isotropic and (b) ensemble-based error statistics at 0000 UTC 24 Sep 2001 on dropwindsonde data from a synoptic surveillance mission around Hurricane Humberto (From Aberson and Etherton 2006).

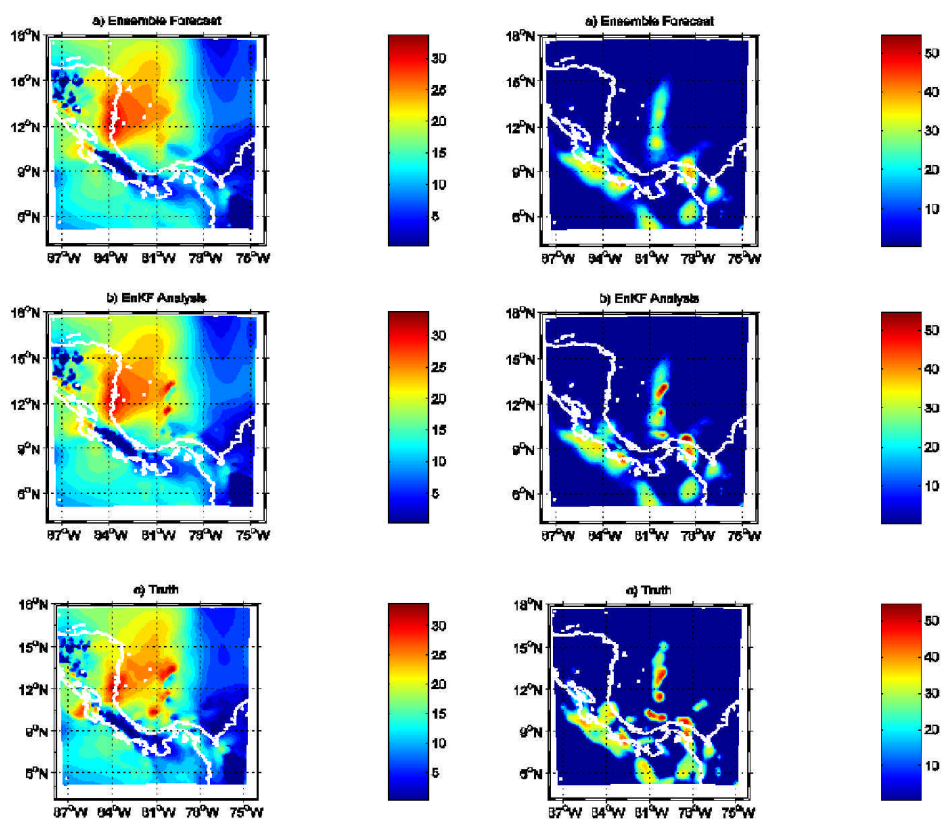


Figure 3.2.8. Left: 1-km windspeed (kt) valid at 18Z 25 October: a) ensemble mean before assimilation, b) ensemble mean after assimilation, c) verifying analysis. Right: 1-km simulated reflectivity factor (dBZ) valid at 18Z 25 October: a) ensemble mean before assimilation, b) ensemble mean after assimilation, c) verifying analysis.

3.2.5 Model developments

The following is a list of current global and regional models used around the world for TC track forecasting, and recent and planned upgrades. Like with ensemble forecasts, the amount of data produced by the modeling systems is very large. Unfortunately, the different centers do not necessarily share model output with each other so model intercomparisons are difficult. Such comparisons would allow for divining what data assimilation and modeling techniques work best, especially with regard to vortex initialization when data are limited.

3.2.5.1 Global Models

The BoM Global Analysis and Prediction (GASP) Model is run at T239L29 resolution twice daily to 7 days.

The Global/Regional Assimilation Prediction System (GRAPES) is the CMA next-generation unified numerical weather prediction system that includes a data assimilation system, a regional mesoscale numerical weather prediction model, and a global medium-range numerical weather prediction model.

It has a unified multi-scale dynamic core for both the regional and the global models and has physics applicable to both systems. Data are assimilated currently with 3D-VAR, with ongoing development of 4D-VAR and EnKF. Specifically for typhoon track forecasting, CMA utilizes its Global Model for Typhoon Track Prediction (GMTTP) coupled to the global mediumrange spectral model run at T213L31 resolution. This system became operational model in 2006. It provides 5-day forecasts four times daily for up to three TCs at each time. Typhoons are initialized with a synthetic vortex, but work on a relocation technique is ongoing. The global model itself is also run at T213L31 resolution, and is run through 10 days.

The resolution of the ECMWF data assimilation and modeling system was recently increased to T799L90. No special processing near the vortex is used.

The India National Center for Medium-Range Weather Forecasts (NCMRWF) currently runs its global model at T170L28 resolution to five days.

The JMA Global Spectral Model (GSM) has a 3D-VAR data assimilation system and is run at a resolution of T213L41 through 216 h. The cyclone is initialized by using an axisymmetric vortex and adding an asymmetry derived from the first-guess field, a 6-h forecast. The model is hydrostatic and is coupled to the sea using a 1-degree resolution analysis with a climatic trend. It is run twice daily (to 90 h at 0000 UTC, and to 216 h at 1200 UTC). TC track forecasts are only made through 90 h. The data assimilation was expected to be upgraded to 4D-VAR in 2005.

KMA recently upgraded the Global Data Assimilation and Prediction System (GDAPS) to run to 10 days with a resolution of T426L40 concurrently with an upgrade to the model physics for best performance. This led to an improvement in the representation and forecast of typhoons in the model.

MeteoFrance uses its global model ARPEGE, a variable-mesh system with a horizontal resolution as low as 4.23 km and 41 levels in the vertical. Data are assimilated with a 4D-VAR system, and the model is run to 102 h. A special tropical version of ARPEGE for the tropics is run at T384L41 resolution over the Indian Ocean, and is run through 72 h.

The MSC Global Environmental Mesoscale (GEM) Model is run on a 0.9-degree grid with 28 levels through 360 h once each day and to 240 h another time each day. Data are assimilated into the model using an EnKF system. The model has proven effective in predicting TC tracks.

UKMO runs a non-hydrostatic global model four times daily on a grid with a resolution of 0.556 degrees latitude and 0.833 degrees longitude with 38 levels. Data are assimilated using 4D-VAR.

The US GFS is run at T382L64 four times daily through 180 h, and at T190L64 through 2384 h. Data are assimilated with a 3D-VAR system, and the TC vortex is relocated from its position in the first-guess field to its analyzed location at each cycle. The model is part of the primary guidance used at NHC. Future upgrades include a change in the assimilation system from spectral statistical interpolation to a gridpoint statistical interpolation.

Recent upgrades to NOGAPS have included an increase in resolution to T239L30, the use of a 3D-VAR technique for data assimilation, and improvements to the synthetic vortex technique. The model is run four time daily providing 5-day TC forecasts globally.

3.2.5.2 Regional Models

The BoM TC-LAPS forecast systems provides very reliable forecasts in the Australia and western South Pacific regions. The current model has an inner mesh of 0.15 degree resolution centered on the TC with 29 levels in the vertical. Recent upgrades have involved improved specification of the TC vortex, a new bulk explicit microphysics scheme, and inclusion of data from new sources such as

surface winds and heating rates derived from satellite-based instruments. These upgrades are leading toward an ultimate goal of a fully coupled ocean-atmosphere version of the model.

In addition to CMA models discussed in Section 3.2.5.1, some provincial centers continue to use statistical-dynamical techniques and mesoscale models such as MM5 to forecast for their area. A triply-nested version of MM5 with a nudging technique for data assimilation and maximum horizontal resolution of 3 km and 36 levels is run through 48 h. The Shanghai Typhoon Institute currently runs GRAPES as a regional model with a resolution of 0.25 degrees and 31 vertical levels. The cyclone is initialized with a 4DVAR bogus data assimilation in which all model fields are adjusted to fit the bogus fields with the constraint of the forecast model. The observations are then assimilated using 4D-VAR. Future work on the model will be to develop new boundary layer and convective parameterization schemes, to couple the atmospheric model with an ocean and a land model, and to improve the 3D- and 4D-VAR schemes, especially in regard to initializing the vortex.

The Hong Kong Observatory Operational Regional Spectral Model (ORSM), a doubly-nested mesoscale model with highest resolution of 20 km in the horizontal and 36 levels in the vertical, is run eight times each day to 24 h; the low-resolution (60 km grid) outer mesh is run four times per day to 48 h. Data are assimilated with a three-dimensional optimal interpolation scheme, and hourly rainfall data are initialized physically. JMA's GSM is used as boundary conditions. The Observatory is currently experimenting with higher resolution (up to 5 km) non-hydrostatic models with three-dimensional or four-dimensional variational and Extended Kalman Filtering data assimilation systems to assimilate high-resolution Doppler data.

NCMRWF currently runs a triply-nested version of the MM5 with maximum horizontal resolution of 10 km and 23 levels in the vertical through 5 days, and are planning an upgrade to 42 vertical levels. The NCMRWF global model is used for initial and boundary conditions. NCMRWF also runs a version of the mesoscale Eta model with 48 km resolution and 38 vertical levels through 5 days. Again, the NCMRWF global model is used for initial and boundary conditions. Model output is available to the India Meteorological Department (IMD) for forecasting. For cyclones, a quasi-Lagrangian model with a 3D-VAR data assimilation system is run at 40 km resolution with 16 levels to 36 h.

The JMA Typhoon Model (TYM) is run four times daily through 84 h for a maximum of two TCs at each forecast time. The model has a 3D-VAR data assimilation system using a 6-h GSM forecast as its first guess. The cyclone initialization involves an axisymmetric vortex with an asymmetry derived from the previous TYM model run tuned so that the initial motion fits the analyzed track. The vortex is blended with the initial fields using a linear weighting function in an annulus with a maximum size of 800 km thus preserving asymmetric components. The model is hydrostatic and is run at a resolution of ~ 24 km in the horizontal, with 25 levels in the vertical. A 1-degree analysis of sea surface temperature is used for the lower boundary.

The KMA Regional Data Assimilation and Prediction System (RDAPS) was recently upgraded to have a larger domain to allow for longer forecasts of systems moving westward. The model is run with a horizontal resolution of 5 km to 24 h and 30 km to 48 h, both with 43 vertical levels, using GDAPS as boundary conditions. Additionally, KMA also runs a typhoon model (KTM) with 1/6-degree horizontal resolution and 18 levels through 72 h, also using GDAPS as boundary conditions. KMA runs a Double-Fourier Series Barotropic Typhoon Model (DBAR). Tests with a nextgenerational regional model based on a version of WRF with 10 km horizontal resolution and 31 vertical levels is ongoing.

The Macao Meteorological and Geophysical Bureau (SMB) Mesoscale Model is a nested version of the MM5 with highest resolution of 18 km in the vertical and 22 horizontal levels to 60 h.

The Mexican Meteorological Service (MSM) runs a non-hydrostatic version of the MM5 using the NCEP GFS as boundary conditions. The horizontal resolution is 45 km, and the model is run with 20 levels through 72 h.

MeteoFrance uses its fine-mesh limited area model ALADIN over the Indian Ocean in a configuration known as ARPEGE-Tropique. The model is run at 31 km resolution over the Indian Ocean using ARPEGE for boundary conditions. The TC is bogusged and the model physics are tuned to the tropics.

MSC GEM is run in regional mode on a 15 km grid with 28 levels over North America through 48 h.

NCHMF runs two barotropic models (WBAR and BARO) when a TC is in their area of interest. Additionally, NCHMF runs a mesoscale model to three days with a horizontal resolution of 28 km, and 20 levels in the vertical.

The Philippines Atmospheric, Geophysical & Astronomical Services Administration (PAGASA) runs the MM5 at 26 km resolution with 36 levels through 72 h using the NCEP GFS as boundary conditions.

The US GFDL coupled hurricane model has provided the most reliable track guidance in the Atlantic and Eastern North Pacific Oceans during the 2003 – 2005 seasons. The current model is hydrostatic with a resolution has 42 levels and is 1/12 degrees in the inner mesh. The 2006 season will see a planned upgrade to Ferrier microphysics (a simplified scheme that includes only cloud and rain water and ice and advects only the combined condensate) that is likely to improve forecasts of sheared storms. The addition of dissipative heating due to friction is likely to improve forecasts of strong TCs as its effect increases with the cube of the wind speed. In tests with cases during the 2004 and 2005 seasons, the new model provided track forecasts up to 12% better than the previous version. The U.S. Navy also runs this model using NOGAPS fields as boundary conditions (GFDN). This is likely to be the last major upgrade of the GFDL model before the next-generation Hurricane Weather Research and Forecast (HWRF) model, a non-hydrostatic, high-resolution, coupled air-sea-land prediction system with advanced physics, becomes operational at the NCEP in coming years.

3.2.6 References

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