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SIXTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 1.5 : **Operational guidance and skill in forecasting structure change**

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Abstract: Currently operational tropical cyclone structure change forecasts consist of the forecast of maximum intensity in terms of maximum surface winds and the radial extent of winds exceeding various wind thresholds, commonly 34-kt, 50-kt, and 64-kt.

A survey of operational forecasters suggests that the process of making intensity and wind radii forecasts has changed little since IWTC-5. During the same time, verification shows that intensity guidance has been steadily improving, albeit slowly, and is driving operational forecast improvements. This result was determined by using the historical databases available in the Automated Tropical Cyclone Forecast System and conducting a long-term verification of operational intensity forecasts and intensity guidance methods. Two metrics are used to verifying intensity change forecasting including the traditional measure of mean absolute errors (MAE) and the percent reduction in variance of the observed intensity change. Findings show that MAEs have very small decreasing trends and the percent reduction of variance has small increasing trends. Guidance for wind radii forecasting is currently not skillful and the best wind radii guidance is produced by statistical methods based on climatology and/or persistence. After examining the verification results, there is a clear need for continued tropical cyclone structure change guidance improvement and a few topics related to ongoing and future research to improve operational forecasting of TC structure are discussed.

1.5.1 **Introduction**

In the operational setting there are several aspects of TC structure that are analyzed and forecast. The maximum intensity has been long analyzed and forecast by operational centers. The intensity is often defined in terms of the maximum sustained wind (MSW) at 10-m over a time averaging period (1, 3, 10- minute), which varies by operational center or by the minimum sea level pressure (MSLP). To complement these TC metrics of intensity, several quantities that describe the structure of the TC vortex near the surface are also analyzed at each advisory period. These vary from operational center to operational center and include: the radius of maximum winds (RMW), eye diameter, the radius of outer closed (closed and circular) isobar (OCI), and the maximum extent of wind speed in quadrants (e.g., 34-kt, 50-kt and 64-kt wind radii). With the exception of OCI, these quantities describe the near surface wind field. A summary of the operational determination of structural aspects of the TC are provided in Section 1.4.

The MSW is directly related to the potential impact of the TC. This quantity has been long estimated and forecast by operational TC forecasting centers. The relatively long operational history of this quantity stems from the ability to estimate this quantity from satellite imagery and aircraft measured/estimated MSLP. In regions without routine aircraft reconnaissance, the primary technique to operationally estimate MSW was developed by Dvorak (1975, 1984), but more recently other techniques (Velden et al. 1998, Cocks et al, 1999; Bruske and Velden 2003; Demuth et al. 2004; 2006, Olander and Velden 2006) have aided these estimates. In operational centers that have access to aircraft reconnaissance, MSW is estimated using flight-level reduction, dropwindsonde observations, surface wind observations, MSLP observations (via wind-pressure relationships), and more recently, observations from an operational Stepped Frequency Microwave Radiometer (SFMR; Uhlhorn et al 2006). Despite the accuracy/precision and sometimes uncertainty associated with the various MSW estimate methods (Brown and Franklin 2002; 2004; Velden et al. 1998; Olander and Velden 2006), these MSW estimates provide a long history of observed structural variability of tropical cyclones. Because of this long operational history, this quantity is the primary metric of tropical cyclone structure and is forecast and verified at all operational TC centers.

While MSW is related to the potential destruction of a given TC near the region of strongest winds, it is the size of the wind field that is, in many instances, best related to the total impact of the TC. The extent or arrival time of strong winds (e.g., gale force winds) is very important for making pre-storm preparations by coastal residents, government agencies and other concerned parties. The relative size of the wind field is also important in the determination of other coastal impacts such as storm surge, and wave setup. For these reasons, some operational centers forecast the radial extent of various wind thresholds. The most common observed metric is the extent of gale force (34-kt) winds.

Mostly because of the difficulty in observing and therefore verifying the wind field associated with tropical cyclones, only a few operational centers provide forecasts of the wind field. As track and intensity forecasts have become better, there has been more emphasis on TC wind structure. Since the last IWTC, wind radii estimates have become part of the annual best track at Regional Specialized Meteorological Centre (RSMC), Tokyo, RSMC, Miami, RSMC, Honolulu and the Joint Typhoon Warning Center. Such information has lead to the recent development of simple models to predict the structure of the TC vortex. These simple models enable the verification of numerical weather prediction (NWP) wind field guidance and operational forecasts, which will be discussed here.

The topic of this report is the operational capabilities available to forecast the aspects of TC structure. In the next section a review of the guidance available and its use in preparing forecasts of TC structure (i.e., intensity and wind radii) will be presented. The following section will present a verification of intensity and wind radii forecasts made by both operational centers and by their guidance methods. A discussion of future needs, issues and directions along with a summary will follow.

1.5.2 **TC Structure Forecast Guidance**

a) Operational intensity change guidance

All operational TC forecasting centers issue MSW or intensity forecasts, but the guidance that is used in these forecasts varies considerably. There are several types of intensity guidance, including:

1. 24-h forecasts based on Dvorak (1984),
2. Purely statistical models developed from historical data,
3. Statistical-dynamical models which make use of environmental information from NWP models, climatology, persistence and satellite-derived data to make statistical forecasts
4. forecasts from NWP models

In addition to these guidance techniques operational centers make use of other predictive and diagnostic indices to aid in the intensity forecasting process.

An often utilized guidance technique is the 24-h forecast described in Dvorak (1984) whereby the forecast intensity is a forward extrapolation of the past 24-h change in T-number (not to exceed 1.5 T-number per day). This extrapolation is then modified by a set of rules related to the TC's cloud pattern and environment. These Dvorak forecasts are still used as the primary method for predicting 24-h TC intensity change at many operational centers.

Another common guidance technique is the use of purely statistical models. An example of one of these models is the SHIFOR model (Jarvinen and Neumann 1979) used at the RSMC, Miami, which has produces 3-day intensity forecasts from current location and intensity,12-h trends in intensity, and motion. Some of these simple models use purely climatological information from analogs (Sampson et al. 1990), while others employ the combined aspects of climatology and persistence (Chu et al. 1994; Jarvinen and Neumann 1979; Knaff et al. 2003). Such models can be used to make operational forecasts, however their primary role is as a skill reference during verification. In verification, these types of models provide a means to normalize forecasts that are more difficult than climatology or a combination of climatology and persistence. Often forecasts are considered skillful if they outperform climatology and persistence based forecasts. One potential drawback of using such models as benchmarks for intensity verification is that they do not take into account the effects of landfall. Thus models that take landfall into consideration when making intensity forecasts can gain skill through this effect (James Franklin, personal communication). Caution therefore should be used in interpreting the level of skill determined from this type of intensity verification for cases affected by land.

In the last 10 years or so, statistical-dynamical approaches have been developed to predict intensity change. These models make use of environmental information from NWP models' forecast fields, and SSTs along the forecast track along with information derived from climatology and persistence. Traditionally these models have been developed using a "perfect prog" assumption where NWP analyses and best track positions are used in the model development. The first and most advanced version of these is the Statistical Hurricane Intensity Prediction Scheme (SHIPS), which now makes forecasts every 6 hours through 5 days along the official forecast track and makes use of environmental information from US National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model along with information from weekly SSTs, infrared satellite imagery, and ocean heat content estimated from satellite-based altimeters (DeMaria et al. 2005a). Forecasts are created for the N. Atlantic, and combined Eastern and Central Pacific regions by separate versions of the SHIPS model created specifically for each basin. Another set of operational models include the Statistical Typhoon Intensity Prediction Scheme (STIPS) which makes 12-hourly forecasts through five days along the official forecast track (Knaff et al 2005). The STIPS model is currently run at the Joint Typhoon Warning Center (JTWC) and the US Naval Research Laboratory for all JTWC's areas of responsibility and a consensus/ensemble (consemble) of STIPS forecasts along a variety of forecast tracks and using a number of different NWP forecast was initiated in operations during 2005 with successful results (Sampson et. al. 2006). There are several other statistical-dynamical guidance models that have been developed that provide experimental guidance to operations, including the passive microwave version of SHIPS and STIPS (Cecil et al. 2006), and a Neural Network based model (Baik et al 2003). Many of these types of models adjust landfalling forecasts by the employment of one of a number of inland decay models (Kaplan and Demaria 1995; 2001; DeMaria et al. 2006). These statistical-dynamical models produce forecasts that are available either during the forecast cycle or as early guidance.

Intensity guidance is also provided from a variety of global, regional and specialized NWP models. The global NWP models US Navy Operational Global Analysis and Prediction System (NOGAPS; Hogan and Rosmond 1991; Goerss and Jeffries 1994), Japanese global spectral model (JGSM;Kuma 1996), the NCEP Global Forecast System (GFS; Lord 1993), United Kingdom Meteorological Office (UKMO) global model (Cullen 1993; Heming et al. 1995) are operationally available for intensity prediction. Because of the relatively limited spatial resolutions of the global models, it is common that intensity estimates from these models are created by adding the intensity change forecast by these models to the observed initial intensity as part of the interpolation process discussed below. To complement the global models there are a number of regional and specialized NWP models which have finer spatial resolutions. These include the US Geophysical Fluid Dynamics Laboratory hurricane model (GFDL; Kurihara et al. 1993; 1995; 1998), GFDN (GFDL with a NOGAPS initialization; Rennick 1999), the Japanese typhoon model (JTYM; Kuma 1996), the US Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®; Hodur 1997), Australia's TC-Limited Area Prediction System (TC-LAPS; Davidson and Weber 2000), the fifth-generation Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5; Grell et al. 1995) run operationally by the Air Force Weather Agency (AFWA).

The NWP models take a number of different approaches to initialize the hurricane vortex. For example, the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model, one of the most advanced regional models, uses output from the GFS for initial and lateral boundary conditions; however it removes the coarse-resolution vortex found in the global model analysis fields. The GFDL system utilizes near-surface wind radii observations provided by RSMC, Miami to generate a 3-dimensional bogus vortex which is then inserted into the initial fields. Other regional models use similar wind radii - based initialization (MM5, GFDN) while others are initialized using the pressure field (e.g., TC-LAPS and JTYM). Currently, the operational centers provide the information used to create the model initialization. Improved methods to initialize tropical cyclone vortices in NWP models are an area of active research and development.

Most models also assume that the SST fields remain constant throughout the forecast integration, except for the GFDL hurricane model. In 2001, the GFDL model was coupled with a 3-dimensional ocean model (Bender and Ginis, 2000) thus including the effects of turbulent ocean mixing and upwelling. The primary benefits of the ocean coupling are to simulate the cold ocean wake left behind the storm and to inhibit the over-development of tropical cyclones that move slowly over very warm waters. The coupling of atmospheric and oceanic physics has been shown to improve intensity forecasts.

It is important to note that the intensity guidance from the NWP models, both regional (e.g. GFDL, JTYM etc.) and global (e.g., NOGAPS, UKM, etc.), arrives to the RSMCs and other operational centers too late in order to be used as guidance for the current synoptic cycle's forecast package. For example, the 12 UTC run of the GFDL model does not finish until a few hours after the 12 UTC forecast package has been issued by RSMC, Miami. In order to maximize the utility of the NWP model forecasts, interpolated versions of forecasts from these models are created by calculating the difference between the 6-h forecast intensity and the observed intensity at that hour and then adding that difference to the forecast intensity at all subsequent forecast hours. These interpolated results are often referred to as early guidance.

In addition to traditional guidance that provides a deterministic estimate of TC intensity, there are a few predictive and diagnostic indices that provide probabilistic information related directly or indirectly to intensity change. An operational example of such an index is the rapid intensification index (Kaplan and DeMaria 2003), which provides the probability of rapid intensification (increase of 30 kt or greater in 24 h) in the next 24 h. Other indices that relate to structural or environmental changes that may lead to intensity changes are the Secondary Eyewall Formation Index (SEFI; Kossin et. al.,cited 2006), the Annular Hurricane Index (AHI; Cram et al. 2006) and storm relative shear tendency (Gallina and Velden 2002). The SEFI uses information from the environment and from passive microwave imagery along with a Bayes Classifier algorithm to predict the probability of secondary eyewall formation. Secondary eyewall formation is shown to cause short-term fluctuations in TC intensity. The AHI determines the probability of a given TC being annular. Annular hurricanes have been found to have a stable structure and maintain their current intensity longer than non-annular hurricanes (Knaff et al. 2003; Cram et al. 2006). The shear tendency is calculated from satellite feature drift winds and has been routinely emailed to operational offices. The SEFI and AHI are to be tested during the later half of 2006 in the Atlantic and East Pacific.

b) Shortcoming of Operational Intensity Guidance

Intensity guidance has a number of shortcomings. Purely statistical models do not take environmental factors or landfall into consideration and as a result have very conservative forecasts. Statistical-dynamical models also have a conservative nature built into them. Like the purely statistical models, these models are based primarily on multiple linear regressions and will predict the mean of the sample. As a result, these models cannot predict rapid changes in intensity. In addition, current statistical-dynamical models employ time averaging and as a result, large environmental changes have little effect at long forecast leads. Global NWP does not have the spatial resolution necessary to capture the intensification process, whereas regional/specialized NWP models often suffer from poor vortex initialization that affects their short-term forecasts. Because of operational time constraints, all of the current operational models rely on physical parameterizations for the smaller scale processes (convection, turbulence, boundary-layer, ice microphysics etc.). The continued and necessary use of parameterizations, including convective parameterization, handicaps current NWP. With the exception of the GFDL hurricane model, the effects of turbulent ocean mixing and upwelling cannot affect intensity change, leading in some cases to over-development of tropical cyclones moving slowly over warm waters. Finally, all guidance suffers from errors associated with timing of tropical cyclone intensification as the process of intensification is still an area of active research and model development (see Booth et al 2006; Blackerby 2005, and Lambert 2005 for details).

c) How Intensity Change Guidance is Used

Operational intensity forecasting remains, as it always has been, a somewhat subjective exercise. Unlike track forecasting, intensity forecasting involves a complex interaction between many spatial and temporal scales ranging from convective to synoptic. These interactions and the incomplete understanding of the structural change process limit the ability and utility of operational intensity change forecasts. As a result, operational intensity forecasts are a blend of the guidance and the judgment of the operational forecaster. In this respect, the best operational guidance serves as a baseline on which the subjective forecast is based. Thus it follows that if the best guidance or the baseline improves, so should the operational forecasts.

This blend of guidance and human judgment varies from operational center to center as well as from situation to situation. At many operational centers the number of intensity guidance tools is rather limited and even when available the guidance has limited utility. The short-term (first 24-hours) forecasts of intensity are most often based on recent intensity trends that are modified by ongoing or anticipated changes in the environment and the storm, which come from a blend of satellite interpretation, and numerical model forecast fields. This procedure is either identical or very similar to the method proposed by Dvorak (1984) for making 24-h intensity forecasts and has changed little in the last ten years, while the availability and quality of satellite imagery and model analyses/forecasts of the environment has greatly improved. Changes in atmospheric moisture, vertical wind shear, sea surface temperature, and outflow conditions are often examined in a storm relative manner to help predict the timing and magnitude of intensity change. Forecasters also examine the current structure of the tropical cyclone for convective structure (e.g. for evidence of vertical wind shear, concentric eyewalls, eyewall formation/dissipation, etc.), and trends in convective symmetry and strength. Simple statistical models as well as statistical-dynamical models aid in this process by serving as a baseline or first guess. As the forecast lead increases to 36 through 72 hours, there is a greater reliance on intensity trends in NWP, modified by subjective analysis of the forecast environment changes and trends in the statistical–dynamic guidance. At the farthest lead times, 5-day at some operational forecast centers, forecasts are often relaxed toward climatology for that situation.

d) Operational wind radii guidance, its use and shortcomings.

Some operational centers provide forecasts of wind radii. These forecasts are a subjective blend of guidance and common sense forecasting. All wind radii forecasts start with a current assessment of the tropical cyclone's wind structure. An important ingredient to this assessment is satellite imagery and products, particularly in those regions without aircraft reconnaissance data. Since there are rarely enough ship, bouy or synoptic observations to estimate the wind structure, scatterometry (QuickScat, NScat etc.), which allows the estimation of the gale force winds, has become a vital tool to the operational forecaster. The reliance on scatterometry is important to mention as few new instruments of this type are planned in the future. Other in-house techniques that rely on infrared and passive microwave imagery have been and continue to be used at various operational centers. These techniques simply relate features in the imagery to storm size and with the addition of an intensity estimate provide a wind profile estimate. An example of such a method is the Holland & Martin Technique (Martin 1990). Some forecasters also utilize analyses from NWP models, but because of poor representation of the storm vortex of many models their utility is limited. Finally, in some instances the forecaster will rely on climatological vortex structure from in-house programs, tabular forms, nominal values of wind radii, and from analysis from high resolution NWP. These initial conditions along with anticipated changes of storm intensity and the environment form the basis for most wind radii forecasts. Further details of methods used to evaluate tropical cyclone structure are discussed in Section 1.4.

To address some of the subjective nature associated with these initial wind radii estimates and the distinct possibility of no future scatterometry, new techniques have been developed and are working their way into operations. Initial wind radii estimates are now also being provided by a number of recently developed techniques that use microwave sounders (Demuth et al. 2004; 2006) and infrared imagery (Kossin et al. 2006; Mueller et al 2006).

Current wind radii guidance is very limited, most of which are very simple methods. These include:

1. Climatologies in tabular or equation form as a function of the intensity forecast
2. Purely statistical models that make forecasts based on climatology and persistence
3. NWP guidance
4. Climatological means

The utility of each of these methods is also limited. Climatology has the longest history. There are several programs, tables and equations used in forecast offices that provide a first estimate of wind radii. One example is the Huntley model used at the JTWC for several years based, though documentation on the tables used in the program is elusive (Cocks and Gray 2002). Some experienced forecasters use their own climatologies developed from personal experience while others rely on parametric model estimates of various wind radii as a function of intensity.

Of the potential guidance methods, only NWP can account for complex interactions with the environment. In saying this, it should also be noted that NWP models often poorly represent the wind field due to model resolution and poor initialization. And even when the NWP model can represent the vortex, an accurate intensity forecast is often needed to assign wind radii at future times. In the last couple of years, statistical models have been developed in some of the basins that predict wind radii based on climatology and persistence (Knaff et al 2006; McAdie 2004). In operations these models make forecasts of wind radii based on the initial wind radii conditions, the forecast track, and the forecast intensity. At this time, few forecasters use such guidance in preparing their forecasts as it is a rather new tool, but these are being used as benchmarks to evaluate and verify wind radii forecasts from other models.

Based on a quick survey of operational forecasters, the use of climatologies stratified by size is a useful and often employed method of making forecasts. Size is often assessed from the initial conditions as described above (also Section 1.4). Often forecasts of wind radii are derived by modifying a blend of initial conditions and climatology according to the concurrent intensity forecast. Asymmetries in these forecast wind radii are routinely added to account for translation speed, synoptic conditions (e.g., interaction with westerly flow), gradient changes associated with landfall, and vortex structure (i.e. tilting associated with vertical wind shear). Higher resolution numerical models are also sometimes utilized for the qualitative assessment of size of wind radii and their extent and asymmetries. For instance, a forecaster in the Brisbane Tropical Cyclone Centre will sometimes make use of the ECMWF wind fields assigning gales where the 850 hPa wind is 45 kt and similarly the GFDL model may be used by a forecaster in Miami. One thing is certain, wind radii forecasting is a very subjective activity which varies from forecast center to forecast center and from forecaster to forecaster.

e) Guidance for outer closed isobar

To be complete in this report on forecasting and verifying tropical cyclone structure, there should be some mention of the operational use of outer closed isobar. The quantity of outer closed isobar has been long used as a tropical cyclone size parameter. In fact, quite a few studies concerned with understanding and forecasting tropical cyclone size changes (e.g. Merrill 1984; Weatherford and Gray 1988; Cock and Gray 2002) have used this parameter. The outer closed isobar is often used along with a surface pressure estimate to initialize some regional and global models (e.g., Japan Typhoon Model and TC-LAPS). Recently it has been found that the outer closed circular isobar, which is routinely provided by Australian forecast centres, produces an improved vortex initialization in TC-LAPS (Harry Weber, personal communication). At this time no operational center is forecasting the change of this quantity, but there is a long history of the use of this size parameter in operational centers from which future techniques could be developed.

1.5.3 **TC Structure Verification**

The previous section discussed the guidance available for making tropical cyclone structure forecasts as well as a summary of how this guidance is utilized to make operational forecasts of intensity and wind radii. This section will try to address three issues:

1. How good are operational forecasts of TC intensity and structure?
2. How good are the guidance methods available to the operational centers?
3. How have the intensity guidance and forecasts changed over time?

The intensity and wind radii forecasts and best track information used in these verifications come from the ATCF (Sampson and Schrader 2000) databases archived at the RSMC, Miami and the Joint Typhoon Warning Center (JTWC). This will allow the comparison of intensity forecasting in four primary basins; the North Atlantic, the East Pacific, the northwest Pacific and the Southern Hemisphere. These are then compared with other published verifications from the RSMCs.

There are two methods used to verify intensity forecasts. The first is the traditional measure of Mean Absolute Error (MAE) of the wind speed forecasts. The second is to determine the percent reduction in variance (PRIV) by the intensity forecasts. This quantity is calculated by subtracting the ratio of the sum of the square intensity errors to the variance of the intensity change from the value of 1 as shown in Eq. 1, where o is the observed intensity change and p is the predicted intensity change and the overbar represents a mean value.

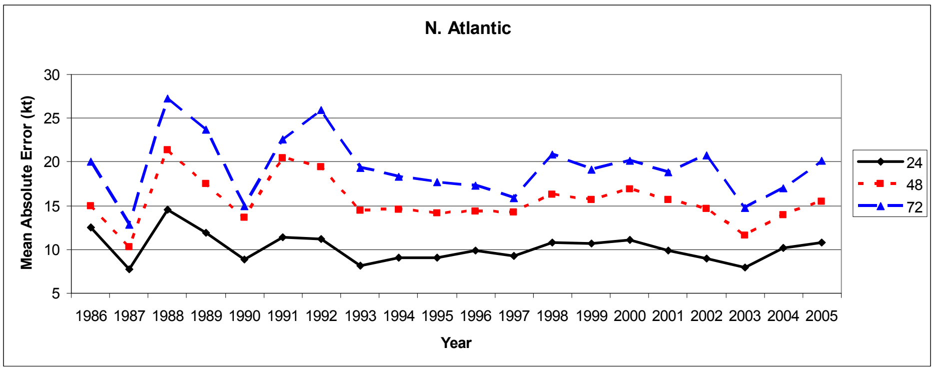
$$PRIV = 100\left\{1.0 - \frac{\sum_{1}^{N}(o_n - p_n)^2}{\sum_{1}^{N}(o_n - \bar{o})^2}\right\} \qquad (1)$$

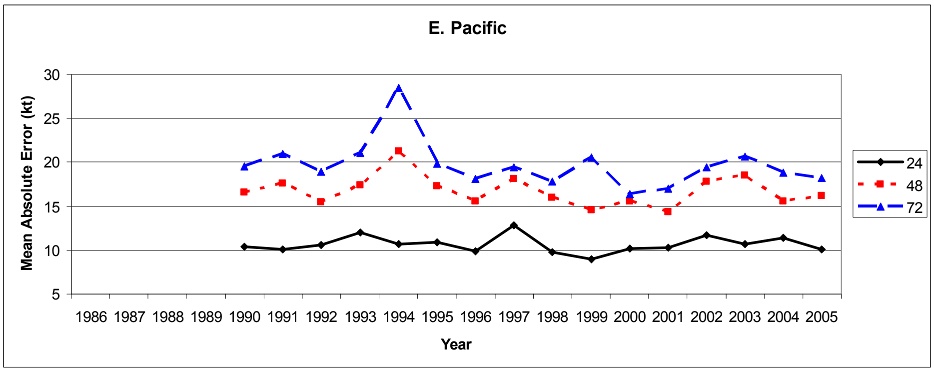
The variance of intensity change can be thought of as the square errors associated with a climatological forecast (i.e., the mean intensity change for the sample). Thus if the forecast errors are greater than those produced by climatology the reduction of variance can be negative (i.e., worst than climatology).

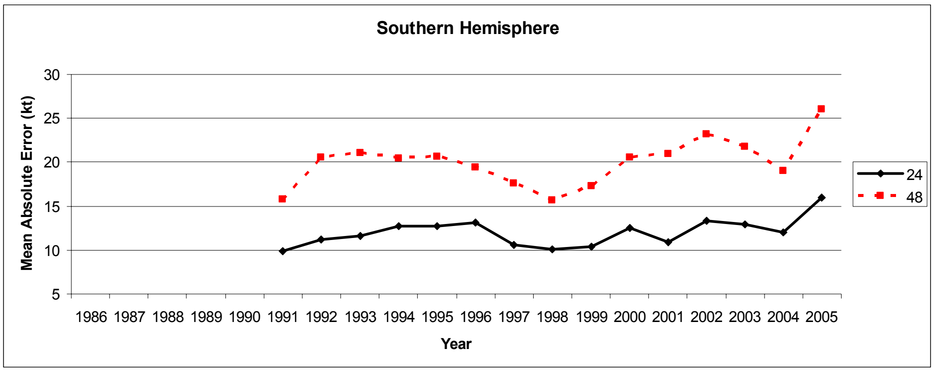
Three aspects of the wind radii forecast will be examined. They are the probability of detection (or Hit Rate), the False Alarm Rate (Mason and Graham 1999) and the mean absolute errors (in units of n mi). The Hit rate is defined as the ratio of the number of times specific wind radii (e.g., R34) are forecast to exist to the number of times those wind radii are observed to exist. The false alarm rate is the ratio of the number of times wind radii are forecast to the number of cases when wind radii were not observed.

a) Operational intensity change verification.

Traditionally intensity error verification has been expressed in terms of mean absolute error (MAE) or root mean square error (RMSE). The post-season reanalyzed or "best track" intensity estimates are used for this verification. Historical (1986-2005) MAEs associated with intensity forecasts in the North Atlantic, East Pacific (1990-2005) as forecast by RSMC, Miami (i.e., NOAA/TPC), West Pacific and Southern Hemisphere (1991-2005) as forecast by the Joint Typhoon Warning Center (JTWC) are presented in Fig. 1.5.1. These intensity errors are consistent with those reported by other operational forecast centers. Table 1.5.1 shows the 2004-2005 official forecast errors produced by RSMC, La Reunion and Table 1.5.2 shows the official forecast errors reported by RSMC, Tokyo. These historical values of MAE show little improvement has been made in the last 20 years. The MAE associated with intensity forecasts improved only slightly in three of the basins, and actually increased over time in the Southern Hemisphere. Table 1.5.3 shows the observed trends of the intensity errors in units of knots (1 kt = .514 ms^{-1}) per decade by forecast hour and basin. These trends are marginally significant (p>.80) using a Student's t Test, except in the Southern Hemisphere. The largest downward trends are observed at the longer lead times with little improvement at 24 hours.







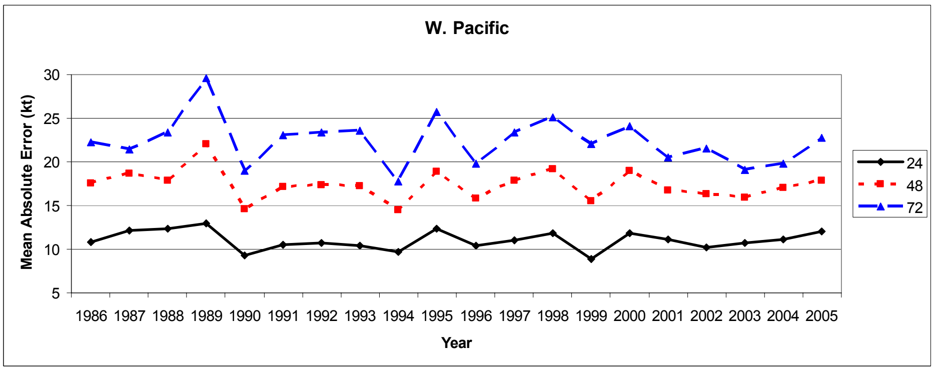


Figure 1.5.1: Mean absolute errors associated with annual tropical cyclone forecasts of intensity in the North Atlantic, East Pacific as forecast by RSMC, Miami, and Southern Hemisphere and West Pacific tropical cyclone basins as forecast by JTWC. Errors resulting from 24, 48 and 72- hour forecasts are shown by black, red and blue lines. Units are in knots.

1.5.1

2004-2005 seasonal intensity mean absolute errors, root mean square errors and bias in units of kt accumulated at RSMC, La Reunion, which makes forecasts in portions of the South Indian Ocean (Philippe Caroff, personal communication).

Range	**0h**	**12h**	**24h**	**48h**	**72h**
Average error (kt)	**3**	**6**	**9**	**14**	**16**
RMSE (kt)	**4**	**6**	**9**	**12**	**13**
Bias (kt)	**-1**	**-1**	**-2**	**-4**	**-2**
Skill against persistence		**6%**	**31%**	**43%**	**50%**
Sample (number of forecasts verified)	**310**	**303**	**291**	**255**	**213**

1.5.2

RMSE in ms^{-1} and kt in parentheses associated with annual intensity forecasts at RSMC, Tokyo, which makes forecasts in the western North Pacific basin (JMA, cited 2006).

	24-h	48-h	72-h
2004	5.1 (9.9)	7.1 (13.8)	**8.1 (15.8)**
2003	4.9 (9.5)	6.5 (12.7)	**7.6 (14.8)**
2002	5.0 (9.7)	7.0 (13.6)	**N/A**
2001	5.2 (10.1)	6.9 (13.4)	**N/A**
2000	5.9 (11.5)	N/A	**N/A**

1.5.3

Trends of the mean absolute intensity forecast in terms of MAE per decade in units of knots for the North Atlantic (ATL), East Pacific (EPAC), Southern Hemisphere (SHEM) and West Pacific (WPAC) at forecast times of 24, 48 and 72 hours. Results based upon forecasts produced by RSMC, Miami (ATL, EPAC) and JTWC (WPAC, SHEM).

	24-h	48-h	72-h
ATL (1986-2005)	-0.8	-1.0	-1.4
EPAC (1990-2005)	0.0	-0.8	-1.9
SHEM (1991-2005)	2.0	2.8	N/A
WPAC (1986-2005)	-0.2	-0.6	-1.1

The annual percent reduction of the intensity change variance is also examined for these annual forecasts. This analysis shows much greater interannual variability exists in this verification statistic (Fig. 1.5.2). Despite the greater variability, a slow but steady increase in the percent reduction in variance is seen in all basins over the times of record, even in the Southern Hemisphere where the trends in MAEs of intensity forecasts were shown to be increasing. These upward trends in % per decade are shown in Table 1.5.4 and are greatest again at the longer forecast lead times. Trends in the Atlantic are highly significant (P > 0.99) and marginally significant (P > 0.80) in the East Pacific and West Pacific using a Student's t Test.

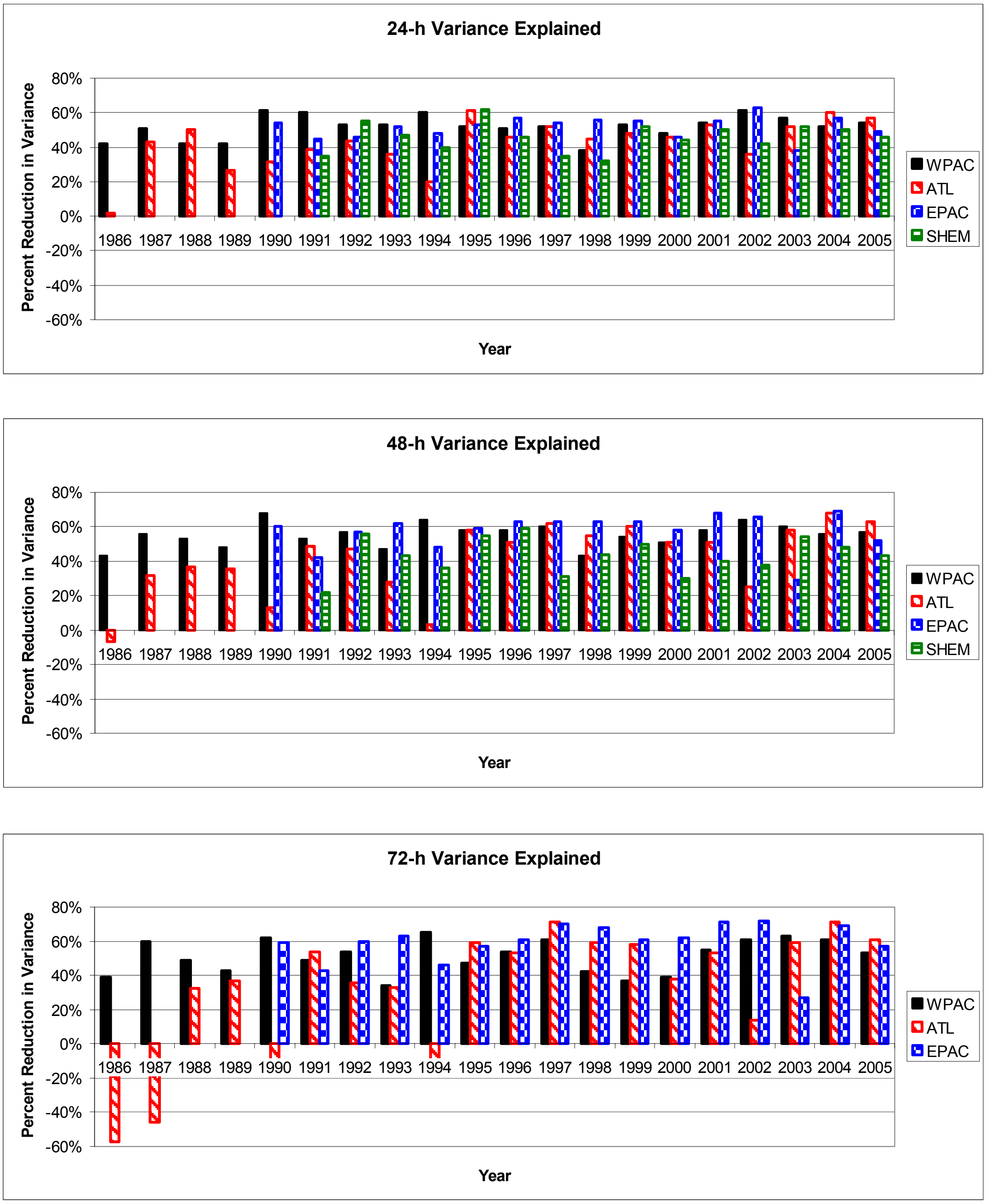


Figure 1.5.2: Time series of the percent reduction of the variance of tropical cyclone intensity change associated with the JTWC forecasts in the West Pacific (WPAC) and Southern Hemisphere (SHEM) and RSMC, Miami forecasts in the North Atlantic (ATL) and East Pacific (EPAC) for the 24-, 48- and 72-hour forecasts. Note that 72-h forecasts are not currently issued in the Southern Hemisphere.

1.5.4

Long-term trends in the percent reduction of variance associated with 24-,48- and 72-hour forecasts in four tropical cyclone basins. Results are given for the North Atlantic (ATL), East Pacific (EPAC), Southern Hemisphere (SHEM) and West Pacific (WPAC) in terms of % increase per decade. Results are based upon forecasts produced by RSMC, Miami (ATL, EPAC) and JTWC (WPAC, SHEM).

	24-h	48-h	72-h
ATL (1986-2005)	14.7	22.3	41.0
EPAC (1990-2005)	1.5	1.4	3.3
SHEM (1991-2005)	2.0	2.8	N/A
WPAC (1986-2005)	3.2	3.0	3.6

The large trends in the Atlantic basin are primarily due to the rather poor forecast performance during the late 1980's and early 1990's when the only guidance was from SHIFOR, a purely statistical model. The first versions of the SHIPS model and of the GFDL hurricane model were available to Atlantic forecasters in 1991 and 1992, respectively. Other basins do not show these dramatic changes associated with more guidance. In the East Pacific, the period 1995-1996 saw the number of guidance tools increase as the GFDL hurricane model and the SHIPS model became available in that basin. Similarly in the West Pacific, the GFDN became available in 1996, a 5-day statistical model in 2002, the STIPS model in 2003 and the STIPS consemble in 2005. The Southern Hemisphere has had relatively little change in guidance with only the addition of the GFDN in 2000-2001, the TC-LAPS for the Australian regions in 2004 and a 5-day CLIPER model in 2004.

While the number of intensity guidance tools has increased, especially with the addition of intensity forecasts from the global models in the last several years, the quality of the guidance is more important. To determine if the guidance is influencing the forecast the 15-year period 1991-2005 is used to examine the homogeneous verification of the official forecasts and the available guidance. For this verification, the guidance had to be available 60% of the verification period to be considered "available".

Figure 1.5.3 shows the percent reduction of variance for the official (i.e., JTWC or RSMC, Miami) 48-hour forecasts along with the percent reduction of variance of the best guidance tool available to the forecasters at that lead time. Note results are similar for 24-hour and 72-hour forecasts (not shown). These time series show great variability between basins. The East Pacific forecasts, for instance, show relatively large reductions in variance since 1991, whereas the other basins show much larger interannual variability in this statistic, which is particularly apparent in the Atlantic. Also shown is that the percent reduction in variance from the guidance has an upward trend in all basins, especially in the Atlantic and West Pacific.

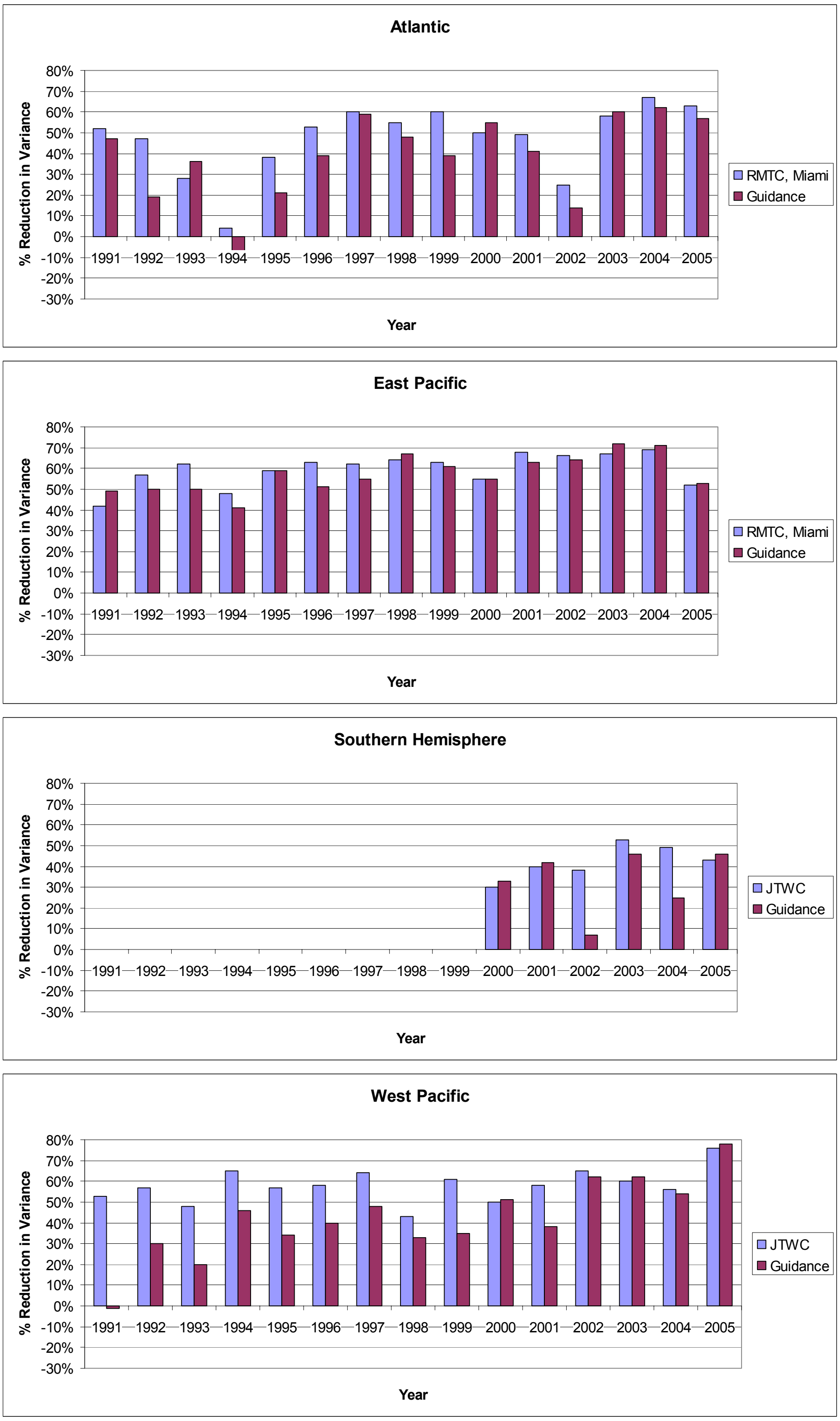


Figure 1.5.3: Homogeneous time series of annual percent reduction in variance associated with 48-hour official forecasts and the best guidance available for that year. Results are shown for the Atlantic, East Pacific, Southern Hemisphere and West Pacific.

In tabulating the results shown here, two guidance types have accounted for the increase in forecast ability in the last several years. The GFDL and GFDN models as well as the statistical-dynamical models SHIPS and STIPS have accounted for most of the improvement in guidance in these basins. Despite the efforts to utilize intensity change information from the global models, these models are unable to predict intensity change better than a persistence forecast during most years and are therefore not useful as intensity guidance. In the last couple of years, ensemble and consensus methods to make intensity forecasts have been tested or transitioned to operations. These methods include the STIPS consemble (Sampson et al. 2006) and the Florida State Superensemble (FSSE; Mackey et al., 2005), both of which have been shown to have increased skill above that of existing guidance. An interesting result was presented by Sampson et al (cited 2006) and was also reported in Franklin et al (2006) in that the average results of existing and skillful intensity models (the SHIPS model with inland decay and interpolated GFDL model) outperformed all intensity guidance including the FSSE during 2005, and further improvements can be made by adding the information from the interpolated official forecast. Such results support the idea of using a consensus of skillful intensity forecasting methods in operations. As the guidance has improved, so have the forecasts, though this is not all that evident in the Southern Hemisphere, where guidance has only improved very recently. Thus it appears that improvements in guidance (regional NWP and statistical-dynamical models) since ~2000 have lead to small but steady improvements in operational intensity forecasts.

b) Operational wind radii verification.

It has been just recently that operational centers (RSMC, Tokyo, RSMC, Miami, and JTWC) have been conducting a postseason reanalysis of wind radii. Such reanalysis makes the verification of operational wind radii forecasts and forecast guidance possible. However, the short history of these forecasts and the recent improvement in best tracks does not allow a comprehensive verification of tropical cyclone wind radii like was possible with intensity. Instead of a historical verification, this section will concentrate on the verification of gale force (34-kt) winds of a single well observed year and basin - 2005 in the Atlantic.

The verification of wind radii presents new issues. In addition to the MAE associated with the individual forecast methods, there is also the underlying issue of the detection of wind radii, which is a function of intensity. For instance if the 48-h forecast predicts an intensity of 60 kt, 64-kt winds will not be detected. To study this sensitivity to intensity prediction a statistical-parametric model (Knaff et al. 2006) is utilized where one set of forecasts used the official intensity forecast (DRCL) and another set of forecasts used the best track intensities (DRCC). Figure 1.5.4 shows the probability of detection (or Hit Rate) and False Alarm Rate (Mason and Graham 1999) and the mean absolute errors in n mi (1 n mi = 1.85 km) of gale force wind radii in all four quadrants for the official forecast (OFCL) and the two sets of statistical forecasts. Note that if the forecast or the best track has zero for the wind radii, the forecast is verified if the best track intensity exceeds the threshold of the wind radii. A perfect intensity forecast results in a 3 to 11 % increase in the probability of detection and a 15 to 70% decrease in the false alarm rate. According to this analysis, the official forecast is also skillful thru 72 hours, though its lower MAE may partially be due to a larger false alarm rate. As a result, any improvement in intensity forecasting will likely lead to greater detection and better forecasting of wind radii. Note that the mean absolute intensity errors for this sample are 7.4, 11.3, 13,7, 16.0, 20.8, 20.9, and 21.5 kts, with biases of -.7, -1.6, -3.4, -5.4, -7.9, -11.0, -and 11.5 kts at 12, 24, 36, 48, 72, 96,and 120 hours.

Using the same verification method used above, the verification the wind radii guidance is now examined. There are four models that are evaluated. They are the GFDL hurricane model (GFDT), the NCEP GFS (AVNI) global model, and two models based on climatology and persistence DRCL (Knaff et al. 2006), MRCL (McAdie 2004). The NWP guidance has been interpolated. Figure 1.5.5 shows the verification statistics associated with these models. It is clear that the NWP-based guidance is inferior to the statistical models. In the case of the AVNI the problem is clearly one of detection suggesting that the intensity estimate is too poor to produce wind radii forecasts directly. GFDT still has problems with detection, but since the GFDL model produces skillful intensity forecasts (Franklin, cited 2006), its detection problem is likely due to other issues related to model resolution or the representation of the vortex in the model. Both statistical models perform well, but there seems to be a trade off with MAE and false alarm rate for these models as was the case with the OFCL forecasts. As the false alarm rate increases, the model MAEs decrease. In summary, this analysis suggests that NWP is unable to better predict wind radii associated with tropical cyclones than simple statistical models. This agrees with the assessment of Knabb (cited 2006) and answers questions posed at IWTC-V. The causes are likely threefold and are a combination of unskillful intensity forecasts, poor vortex initialization and insufficient resolution to capture the correct vortex structure. A possible solution may be to correct the model output statistically to produce improved forecasts.

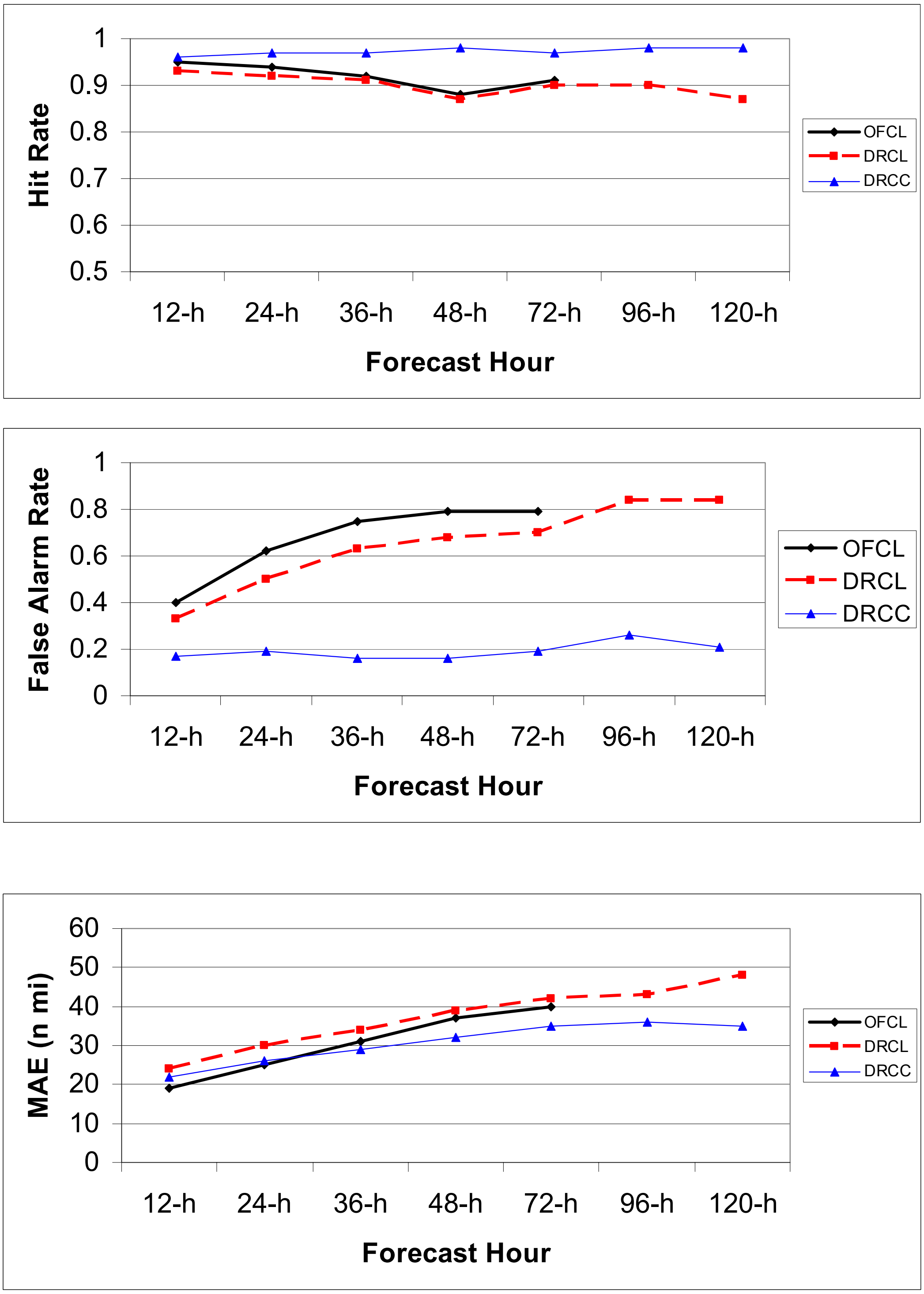


Figure 1.5.4: Hit rate, False Alarm Rate and MAE [n mi] associated with a homogeneous sample of various forecasts of 34-kt wind radii. Results are shown for the official RSMC, Miami forecast (OFCL), a statistical-parametric model using forecast intensities (DRCL), and that same model using observed intensities (DRCC).

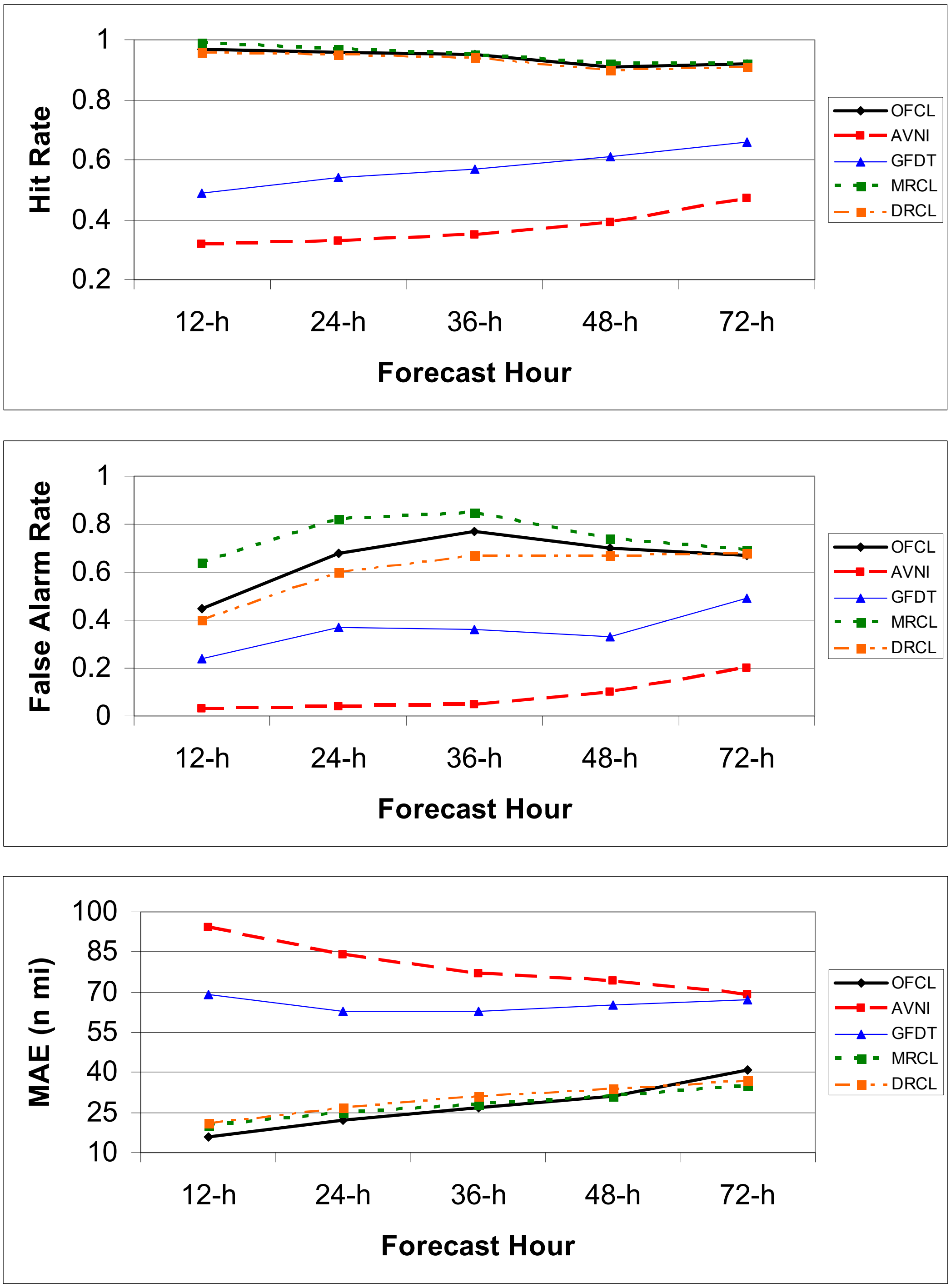


Figure 1.5.5: Hit rate, False Alarm Rate and MAE [n mi] associated with a homogeneous sample of various forecasts of 34-kt wind radii. Results are shown for the official RSMC, Miami forecast (OFCL), the NCEP GFS (AVNI), the GFDL hurricane model (GFDT), a statistical-parametric CLIPER model (DRCL) and a purely statistical CLIPER model (MRCL).

1.5.4 **Summary, recommendations, and directions for the future.**

a) Summary

The first part of this paper reviews how tropical cyclone structure, both intensity and wind radii, are forecast in an operational setting and what guidance is available. After surveying operational forecasters and centers, findings suggest that the process of making operational tropical cyclone structure forecasts is still subjective and the degree of subjectivity depends on the quality of the guidance.

The best guidance is often used as a baseline for intensity forecasts, which is modified by the forecaster, based on his assessment of the future environmental conditions, knowledge of guidance weaknesses, and her/his experience. The shortest term forecasts are based on observations of recent trends and an assessment of the environment. As the forecast lead time increases beyond 24-h, guidance become more influential in the intensity forecasting process, but only through ~72 hours, where errors in tracks and environmental forecast errors make the guidance less useful. The longest range forecasts are often a blend of the guidance through 72 or 96 hours and a relaxation toward climatology.

Wind radii forecasting is even more subjective than intensity forecasting. The process of making wind radii forecasts varies from forecast center to forecast center and from forecaster to forecaster and is dependent on the initial wind radii estimates and the future intensity forecasts. Operational forecast centers use tabular climatologies with respect to intensity, climatological averages, parametric models and statistical models to provide a baseline forecasts. The baseline forecast is then modified to include the effects of storm translation, and synoptic interactions (increasing the asymmetries in the wind field).

The verification of intensity forecasts shows that operational forecast mean absolute errors (skill) are decreasing (increasing) very slowly and that the increases are largest at longer leads (see Tables 1.5.3 and 1.5.4). It also appears that the improvements in intensity guidance have improved more rapidly over the last 15 years and are now driving current and future intensity forecast improvements. The improvements in operational guidance, which are resulting in better operational forecasts, come as primarily the result of advancement in statistical-dynamical models and of regional/specialized/mesoscale hurricane models.

It is clear that intensity forecasting is more advanced than forecasting wind radii, which is still in its infancy. There is little or no guidance to aid the forecaster in making such forecasts better. The best guidance is in the form of statistical models based on climatology and persistence or climatology alone. All wind radii prediction models are affected by suboptimal intensity forecasts as shown in Figure 1.5.4 where the probability of detection is increase by about 10 percent by just having the correct intensity forecast. Numerical radii guidance suffers from three shortcomings: 1) coarse resolution and inability to correctly represent the vortex structure;2) poor vortex initialization; and 3) unskillful intensity forecasting. This poor performance is highlighted in Figure 1.5.5, which shows the hit rate, false alarm rate, and MAE associated with Atlantic wind radii guidance models during 2005.

The verification results suggest tropical cyclone structure is rather poorly forecast. Clearly there is a great opportunity for our field to develop better tropical cyclone structure forecasts whether it be by using existing model output to create new statistical models, by developing new statistical techniques, or by refining numerical weather prediction model capabilities. Clearly the latter will likely be the ultimate solution. In the mean time, other techniques should be also pursued.

b) Future and ongoing research and development

Future and ongoing research and development falls in two categories. The first is to use existing technology and data more efficiently to better diagnose and predict tropical cyclone structure. The second concerns itself with the development of new technology that will lead to improvements in the diagnosis and prediction of tropical cyclone structure.

In the first category, there are several items that should be considered for future work, but only a few are discussed. The first is the continued development of new statistical and probabilistic techniques that make use of existing data and technology. Examples include using model output from global and regional NWP models to statistically predict changes in intensity and structure. This is clearly needed as most current NWP models do not have skill in predicting wind radii or intensity. Another example is to develop methods that are designed specifically to predict the short-term (less than 24-h) intensity changes, which by design would address the issue of rapid intensification. Such techniques could leverage the advances in satellite data, the improved environmental analyses, and advanced statistical techniques. Current examples include the Secondary Eyewall Formation Index (Kossin et al, cited 2006), the Annular Hurricane index (Cram et al. 2006) and the Rapid intensity index (Kaplan and DeMaria 2003). Finally, in light of the slow improvement in intensity forecasting and the difficulties in predicting wind radii, there should be a continued emphasis on techniques that convey uncertainty associated with the forecast. A good example of this type of strategy is the Monte Carlo tropical cyclone wind probability model developed for the Atlantic, East/Central and northwest Pacific (Gross 2004; DeMaria et al 2005b) which provides probabilities of gale, 50-kt and 64-kt winds based on a 5-year sample of operational track and intensity errors and climatological wind radii errors. Such products aid in operational assessment of the extent and/or arrival time of strong winds (e.g., gale force winds), which is very important for making pre-storm preparations by coastal residents, government agencies and other concerned parties. Also included in this group is the use of consensus and ensemble methods not only to determine a better deterministic forecast, but to convey a sense of certainty with that forecast. A couple methods, the FSU Superensemble (Mackey et al., 2005) and the STIPS consemble (Sampson et al. 2006), have shown some additional improvement in intensity forecasting.

The second category of developing new technology in tropical cyclone forecasting concerns itself with the next generation of hurricane models. These models ideally will have their own initialization and data assimilation packages, include ocean and wave dynamics, and explicitly resolve convection. While the Geophysical Fluid Dynamics Laboratory (GFDL) has been the leader in the field and the current GFDL hurricane model is the operational state of the art. The GFDL model however is scheduled to be replaced in operations in 2007 by the Hurricane Weather Research and Forecast (HWRF) model, which National Centers for Environmental Prediction/Environmental Modeling Center (EMC) is actively developing the next generation hurricane modeling system. To accompany the HWRF development, EMC has developed new vortex initialization and data assimilation of real-time airborne Doppler data winds that will produce superior forecast of TC structure. In addition many GFDL studies have shown the positive impact of coupling the waves and the atmosphere on the hurricane structure forecasting.

One of the most significant modeling challenges to improve numerical forecasts of hurricane structure and intensity in high-resolution hurricane models is the initialization of the hurricane vortex. In the initial implementation of HWRF in 2007, data assimilation will use EMC's 3D variational analysis. To advance this effort in the HWRF, EMC is developing situation dependent background error (SDBE) covariances that will be incorporated into a local data assimilation scheme that will make use of real time Doppler radar data.

It is widely recognized that the major outstanding analysis problem is improved formulation of the background error part of the analysis equation. Many improvements over the past 10 years have been in this area, including major upgrades to the ECMWF and NCEP systems. The SDBE approach attacks the fundamental analysis problem directly and is particularly relevant to the hurricane problem by capturing more of the hurricane structure through the flow dependent algorithms. The airborne Doppler radar from NOAA's P-3's and the newly funded instrument upgrade package on the NOAA

G-IV will provide hurricane core observations from the outflow layer to the surface to describe the three-dimensional wind structure of the storm for the data assimilation and improved vortex initialization. For storms approaching landfall, the data assimilation will also make use of the coastal WSR-88D high resolution radar data. It is anticipated that by 2010 the SDBE will be incorporated into a 4-D variational analysis scheme, which is under development at EMC.

In previous versions of the GFDL hurricane model, the air-sea momentum flux was parameterized with a constant non-dimensional surface roughness regardless of wind speeds or sea states. This parameterization assumed a continual increase in C_d with wind speed. However, a number of studies (CBLAST, etc.) have suggested that the value of the drag coefficient and thus the Charnock coefficient (coefficient used by most MWP models to parameterize the boundary layer based on Monin-Obukhov similarity theory) depends on the sea state represented by the wave age. Lively debate is ongoing in the research community over this relationship. The major reason leading to the discrepancies among different studies is the paucity of in situ observations, especially in high wind speeds and young seas.

The Charnock coefficient under hurricane conditions was also examined using a coupled wind-wave (CWW) model that includes the spectral peak in the surface wave directional frequency from WAVEWATCH III and a parameterized high frequency part of the spectrum in an updated version of the GFDL system (Falkovich 2005). The wave spectrum was introduced in the wave boundary layer model to estimate the Charnock coefficient at different wave evolution stages. It was found that the drag coefficient levels off at very high wind speeds, which is consistent with recent field observations (Powel 2003). The most important finding of this study is that the relationship between the Charnock coefficient and the input wave age (wave age determined by the peak frequency of wind energy input) is not unique, but strongly depends on wind speed. The regression lines between the input wave age and the Charnock coefficient have a negative slope at low wind speeds and a positive slope at high wind speeds (Moon et al 2004a; 2004b, 2004c). This behavior of the Charnock coefficient in high winds provides a plausible explanation why the drag coefficient under tropical cyclones, where seas tend to be extremely young, may be significantly reduced in high wind speeds.

The above air-sea-wave coupling in the GFDL hurricane prediction system has shown very promising results on improving storm structure for Hurricane Ivan and TC's from the 05 season. The coupling to the waves will become operational in the coupled HWRF system in 2007 and is expected to have significant impact on storm structure.

Also included in the category of new technological developments are the new instruments and techniques needed not only to observe structure changes, but to develop a physical understanding of the important process related to tropical cyclone structure changes. A good example of this type of technology is the Stepped Frequency Microwave Radiometer (SFMR) (Uhlhorn et al. 2006), which when placed on a reconnaissance aircraft estimates the surface winds below the aircraft, in essence giving the forecaster and the researcher a two level analysis of the tropical cyclone wind structure.

c) Recommendations

After reviewing the state of tropical cyclone structure forecasting there are several recommendations that this working group has to make. The items range from operational instrumentation, to better use of existing technology. These are listed in numeric format.

1. There is a need for more operational scatterometery as it has become a vital tool for operational tropical cyclone forecasters and few future instruments are scheduled.
2. The development of consensus and ensemble based intensity forecast systems should be pursued to improve deterministic and probabilistic intensity prediction. These models/methods, including the STIPS consemble (Sampson et al 2006, cited 2006) and the FSU Superensemble forecast (Mackey et al., 2005), have out performed other intensity guidance.

3. At present none of the NWP guidance have skill in predicting wind radii, and NWP models that can predict both structure and intensity properly are likely several years away. In the mean time, some effort should be made to test whether output from existing NWP can be statistically fit to provide skillful guidance of tropical cyclone intensity and wind structure.
4. A concerted effort should be made to develop regional/specialized hurricane models that include specialized physical initialization and data assimilation packages.
5. New observational technology that benefits the tropical cyclone community should be made available to operational forecast centers.

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