Statistical Tropical Cyclone Wind Radii Prediction Using Climatology and Persistence

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ABSTRACT

An operational model used to predict tropical cyclone wind structure in terms of significant wind radii (i.e., 34-, 50-, and 64-kt wind radii, where 1 kt = 0.52 m s^{-1}) at the National Oceanic and Atmospheric Administration/National Hurricane Center (NHC) and the Department of Defense/Joint Typhoon Warning Center (JTWC) is described. The statistical-parametric model employs aspects of climatology and persistence to forecast tropical cyclone wind radii through 5 days. Separate versions of the model are created for the Atlantic, east Pacific, and western North Pacific by statistically fitting a modified Rankine vortex, which is generalized to allow wavenumber-1 asymmetries, to observed values of tropical cyclone wind radii as reported by NHC and JTWC. Descriptions of the developmental data and methods used to formulate the model are given. A 2-yr verification and comparison with operational forecasts and an independently developed wind radii forecast method that also employs climatology and persistence suggests that the statistical-parametric model does a good job of forecasting wind radii. The statistical-parametric model also provides reliable operational forecasts that serve as a baseline for evaluating the skill of operational forecasts and other wind radii forecast methods in these tropical cyclone basins.

1. Introduction

Tropical cyclone forecasts disseminated by the National Hurricane Center (NHC) and the Joint Typhoon Warning Center (JTWC) contain forecasts of the tropical cyclone wind field through 3 days. These forecasts are generated in terms of the radii of 34-, 50-, and 64-kt (1 kt = 0.52 m s^{-1}) winds in four geographical quadrants around the cyclone (hereafter, referred to individually as R34, R50, and R64, for 34-, 50-, and 64-kt wind thresholds, respectively, or collectively as wind radii) in units of nautical miles (n mi; 1 n mi = 1.85 km). These wind radii represent the maximum radial extent of winds reaching 34, 50, and 64 kt in each quadrant. The initial estimation and forecast of these wind radii is rather subjective, and strongly dependent on data availability and "in house" climatologies and analysis methods. This subjectivity and reliance on climatology is am-

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plified in regions where aircraft observations are rarely available. Recently, with the advent of easily accessible remote sensing–derived surface and near-surface winds [e.g., the Quick Scatterometer (QuikSCAT), the Special Sensor Microwave Imager (SSM/I), low-level atmospheric motion vectors, and Advanced Microwave Sounding Unit (AMSU) retrieval methods] and advances in real-time data analysis capabilities, the initial wind radii estimates have become less subjective in basins without routine aircraft reconnaissance. While better initial estimates of R34, R50, and R64 are becoming available, forecasting these wind radii remains a difficult task. Currently there are very few objective wind radii forecast methods, and current numerical weather prediction (NWP) models fail to produce forecasts that are better than climatology (Knaff et al. 2006; Knabb et al. 2006).

Wind radii forecasts are somewhat dependent on track, and very sensitive to the initial vortex initialization in NWP models and intensity forecasts. Over the past several years there have been large improvements in track skill (Franklin et al. 2003; Goerss et al. 2004; Sampson et al. 2007) and modest improvements in intensity skill (DeMaria et al. 2005, 2007; Knaff et al. 2005, 2006). However, it is still important to note that intensity and track errors at 48 h (for example) are still on the order of 15 kt and 100 n mi, respectively. These errors, particularly the intensity errors, will negatively affect wind radii forecasts. The effect of poor intensity forecasts is particularly pronounced when intensity forecasts fail to or falsely forecast winds that exceed the 34-, 50-, and 64-kt thresholds.

A common approach used to aid and assess the development of tropical cyclone track and intensity forecasting is to develop statistical models that employ a combination of persistence of the initial conditions and trends of the initial conditions along with climatology (e.g., Neumann 1972; Jarvinen and Neumann 1979; Merrill 1980; Chu 1994; Knaff and Landsea 1997; Aberson 1998; Knaff et al. 2003). These climatology and persistence (CLIPER) models play two roles in operational forecasting. They provide basic guidance that is always available to the forecaster and serve as a control forecast for verifying other techniques. CLIPER models are also used to account for year-to-year variability in forecast difficulty, which helps in the identification of long-term trends in forecast errors (McAdie and Lawrence 2000). It is with these issues in mind that basin-specific wind radii CLIPER models were developed and transitioned into operations at the NHC and the JTWC in 2004. The following sections will discuss the datasets and approach used to develop an operational (C. Landsea 2006, personal communication; E. Fukada 2006, personal communication) wind radii CLIPER model,[1] show independent operational test results, and provide a summary.

2. Tropical cyclone wind radii datasets

While track and intensity are included in the historical best track datasets (e.g., Jarvinen et al. 1984), wind radii estimates are not. Wind radii estimates have however been recorded as part of the 6-hourly advisories and warnings issued by the NHC and JTWC, respectively. Therefore, operational wind radii estimates issued in the advisories and warnings form the primary data for this study. These estimates are used in conjunction with the best-track dataset available from the NHC, JTWC, and the Central Pacific Hurricane Center (CPHC; Jarvinen et al. 1984; JTWC 2005) to form the development set for this model. Since tropical cyclone historical and operational forecasts of wind radii and intensity are in units of nautical miles and knots, respectively, these units will be used throughout this paper.

Two time periods are used for the development of the operational wind radii CLIPER models. In the Atlantic, operational wind radii estimates are used for the period 1988–2003 for storms west of 55°W, where aircraft reconnaissance was routinely available. The aircraft data heavily influenced the wind radii estimates and, thus, make them more reliable. This time period is chosen because the operational radii estimates from the NHC were available in an "extended best track" dataset (Kimball and Mulekar 2004), which supplemented the standard NHC best track with wind structure information. In the eastern, central, and western North Pacific tropical cyclone basins, wind radii estimates from the period 2001 through 2003 are used to compute model coefficients. During this period operational centers used several satellite-derived products (low-level atmospheric motion vectors, passive microwave, and scatterometry) in their wind radii estimates. We do not consider these data to be as accurate as the data influenced by aircraft reconnaissance; nevertheless, we use these wind radii datasets and accept their inherent shortcomings.

Wind radii data through 2003 are used for the development of the original version of the coefficients. This

[1] Efforts described here are independent of those of McAdie (2004), who developed a 3-day wind radii CLIPER model for the Atlantic basin that is used in this study for comparison purposes.

version of the model was implemented operationally at the JTWC and NHC for the 2004 season. In addition, data through 2004 are used to refit the model with a slightly more general solution technique. Both methods used to fit the models are described in the next section.

Because of their recognized importance and the desire to begin verifying wind radii forecasts, the NHC and JTWC began adding wind radii information to the best track beginning in 2004. Using these postseason reanalyzed wind radii, the techniques developed here will be evaluated.

3. Methodology

Several methodologies could be utilized to develop a model to estimate wind radii based on climatology and persistence. For example, McAdie (2004) used a standard regression technique to predict wind radii out to 72 h. Different regression equations are used for each radii in each quadrant at each forecast time, with up to 60 predictors considered. In addition to the complexity of the large number of regression equations and predictors, the use of independent prediction equations can potentially result in solutions that are not physically consistent. For example, there is no guarantee that forecasts of R34 will always be greater than the radius of maximum winds because regression seeks to minimize the square error, not produce physically consistent forecasts. Similarly, sampling methods based on Markov chains will have difficulty predicting wind radii when the forecast intensity transition; the operational wind thresholds of 34, 50, and 64 kt; and R34, R50, and R64 appear or vanish. Finally, the authors believe that development data from the eastern and western Pacific suffer from physical inconsistencies due to a dearth of high quality aircraft observations. These physical inconsistencies led the authors to choose a parametric vortex model over regression or Markov chains.

One of the simplest parametric models is that of a modified Rankine vortex, where V is the wind speed as a function of radius r and azimuth θ. For the model development, a storm motion relative coordinate system, where the azimuth is measured counterclockwise, starting from the direction 90° to the right of the storm motion vector is used. A generalization of the usual modified Rankine vortex is performed since it includes a wavenumber-1 azimuthal asymmetry:

$$V(r,\theta) = (\upsilon_m - a)\left(\frac{r_m}{r}\right)^x + a\cos(\theta - \theta_0) \quad \text{for} \quad r \ge r_m,$$
$$V(r,\theta) = (\upsilon_m - a)\left(\frac{r}{r_m}\right) + a\cos(\theta - \theta_0) \quad \text{for} \quad r < r_m. \tag{1}$$

Equation (1) has one known parameter (υ_m) and four free parameters (r_m, x, a, and θ_o), where υ_m is the maximum wind, r_m is the radius of maximum winds, x is the size parameter, a is the wavenumber-1 asymmetry magnitude, and θ_0 is the degree of rotation of υ_m from the direction 90° to the right of the storm motion vector. If the four free parameters in Eq. (1) can be estimated, then R34, R50, and R64 can be determined by solving the equation, which estimates the velocity as a function of the radius and azimuth.

The authors freely admit that there are many limitations to the modified Rankine vortex model in that it can only depict a monotonic decrease of wind speed outside the radius of maximum winds and therefore will never predict secondary wind maxima or the details of complex radial wind profiles associated with very broad vortices that are sometimes observed at high latitudes or following landfall. This limitation also applies to the operational estimates of R34, R50, and R64, which at present also can only depict a monotonic decrease of winds beyond a single radius of maximum winds. In addition, this model can depict only wavenumber-1 asymmetries, so the prediction of complex asymmetries is also impossible. Luckily, tropical cyclone asymmetries occur primarily in wavenumbers 0 and 1 (Shapiro and Montgomery 1993). On the other hand, the parametric model used here is simple and has been shown in the past to be useful for depicting the operational/best-track wind radii used as the developmental dataset (e.g., Demuth et al. 2004, 2006; Mueller et al. 2006).

The free parameters in Eq. (1) are assumed to be functions of climatological factors available in the best-track data (latitude, storm translational speed, and storm maximum winds):

$$\left\{\begin{aligned} \theta_{0c} &= t_0 + t_1\gamma + t_2 c \\ a_c &= a_0 + a_1 c + a_2 c^2 + a_3\gamma \\ x_c &= x_0 + x_1\upsilon_m + x_2\gamma \\ r_{mc} &= m_0 + m_1\upsilon_m + m_2\gamma \end{aligned}\right\}, \quad \text{where} \quad \left\{\begin{aligned} \gamma &\equiv \text{latitude} - 25° \\ c &\equiv \text{storm speed} \\ \upsilon_m &\equiv \text{maximum wind} \end{aligned}\right\}, \tag{2}$$

where t_0–t_2, a_0–a_3, x_0–x_2, and m_0–m_2 are all constants. This functional form was chosen to approximate known variations to tropical cyclone structure. Asymmetries in tropical cyclone structure have been shown to be a function of translational speed (Schwerdt et al. 1979). It is also anticipated that the orientation of the wind asymmetries (θ_0) may be affected by interaction with the midlatitudes and/or monsoon westerlies and is likely a function of latitude. It has also been shown that tropical cyclone size is not only a function of intensity but of latitude and life cycle; tropical cyclones tend to grow larger as they move poleward and evolve (Merrill 1984; Weatherford and Gray 1988). Finally, the radius of maximum winds has been shown to be both a function of latitude and intensity (Willoughby and Rahn 2004; Demuth et al. 2004, 2006; Mueller et al. 2006; Kossin et al. 2007).

Using the above functional form, a climatological wind model can be created by finding the 13 constants t_0–t_2, a_0–a_3, x_0–x_2, and m_0–m_2 that minimize the mean square differences between the observed wind radii and those calculated from the parametric model for a large sample of cases. For the 1988–2003 Atlantic developmental sample, there are 8576, 6064, and 4320 radii of 34-, 50-, and 64-kt winds, respectively, that are used to fit Eqs. (1) and (2). While this concept is rather straightforward, the solution is not.

The model has a multitude of valid and invalid solutions that locally minimize the mean square errors associated with wind radii estimates. Since the vortex parameters are not independent (i.e., they use the same predictors) and there is the potential for 12 predicted wind radii (i.e., 3 wind radii in four quadrants), simple linear regression techniques do not work. In addition, conventional methods that depend on the gradient information also fail to produce a good solution. One could simply search the entire parameter space of all 13 coefficients, but if a reasonable set of choices (about 100) for each of the 13 parameters were included, this method would require on the order of 10^{26} evaluations of the mean square error, which is also not feasible. Thus, alternate solutions are developed to fit the model coefficients, as described below.

There are two solutions presented here. The first describes how the coefficients of the current operational models were fit. The second is a more elegant method that scales the input and output variables, and includes the constraints on the vortex parameters through the inclusion of a penalty term in a cost function that is minimized. For both solution methods, the coefficients in Eq. (2) are determined by minimizing the root-mean-square (RMS) difference between the observed wind radii and the wind radii determined by solving Eq. (1) outside the radius of maximum winds for r (i.e., finding the R34, R50, and R64) for the case where the four free parameters are determined from Eq. (2).

TABLE 1. Operational coefficients for Eq. (2) for the three tropical cyclone basins used to develop the parametric wind radii CLIPER model. Coefficients t_1, a_1, and x_0 are dimensionless. The units for the higher-order coefficients are shown in column 1. Developmental data were through 2003.

	North Atlantic	Eastern Pacific	Western Pacific
θ_{0c} (°)	17.0000	−25.0000	15.0000
t_1	0.0800	0.0200	−0.5500
t_2 (° kt^{-1})	−1.0500	0.2200	1.0200
a_c (kt)	1.0600	0.1700	0.6300
a_1	0.2800	0.0100	−0.0100
a_2 (kt^{-1})	−0.0026	−0.0009	0.0006
a_3 (kt °$^{-1}$)	−0.0800	−0.0200	−0.0300
x_0	0.1147	0.0897	−0.0059
x_1 (kt^{-1})	0.0055	0.0054	0.0055
x_2 (°$^{-1}$)	−0.0010	−0.0010	−0.0031
m_0 (n mi)	36.1000	27.3000	20.0000
m_1 (n mi kt^{-1})	−0.0492	−0.0484	0.0000
m_2 (n mi °$^{-1}$)	0.5740	0.0330	0.0000

The solution to the current operational version of model begins by substituting a_c, x_c, r_{mc}, and θ_{0c} from Eq. (2) in place of a, x, r_m, and θ_0 in Eq. (1). Then on the first pass, the mean square error is minimized for the case with all 13 coefficients equal to zero except t_0, a_0, x_0, and m_0. Following this initial step, the other coefficients in Eq. (2) are varied one at a time over a reasonable range of values to find the result for the minimum mean square error. These values at the minimum are then used as the new initial conditions. During this procedure a_c is constrained to be positive, $r_{mc} \geq 37$ km (20 n mi), and $x_c \leq 1.0$. This process is repeated 150 times. Since there can be several valid solutions, initial conditions of t_0, m_0, a_0, and x_0 are also varied within the parameter space and the searching method is repeated. The final solution to Eq. (1) is the minimum found by the above searching method. In this manner, climatological model solutions are found for the North Atlantic, combined eastern and central North Pacific, and western North Pacific tropical cyclone (TC) basins. The resulting coefficients, which are used in the operational versions of the models, are listed in Table 1. For completeness, Table 2 shows the resulting climatological values of the four-quadrant averages of R34, R50, and R64 for each of the basins, which shows that central–eastern Pacific storms are generally smaller than storms occurring in the other basins.

One difficulty with the above approach is that the independent variables in Eq. (2) (γ, c, and v_m) and most of the vortex parameters being estimated have dimen-

TABLE 2. Climatological four-quadrant average values of R34, R50, and R64 in the North Atlantic, combined central and eastern Pacific, and the western North Pacific tropical cyclone basins. The number of cases for each value is given in parentheses and the years of the climatology are for 1988–2004 in the Atlantic and 2001–04 in the Pacific basins.

	North Atlantic	Central and eastern Pacific	Western North Pacific
R34	107 (2346)	82 (1063)	115 (1453)
R50	66 (1663)	45 (605)	55 (1107)
R64	42 (1195)	29 (356)	30 (842)

TABLE 3. Coefficients for Eq. (2) obtained using a standard variational technique. Shown are coefficients for the three tropical cyclone basins used to develop the parametric wind radii CLIPER model. Coefficients t_1, a_1, and x_0 are dimensionless. The units for the higher-order coefficients are shown in column 1. Developmental data were through 2004.

	North Atlantic	Eastern Pacific	Western Pacific
θ_{0c} (°)	9.9450	−11.665	14.4000
t_1	0.3420	−0.0165	−0.0288
t_2 (° kt^{-1})	−0.3645	−0.0488	1.8000
a_c (kt)	2.64	4.8380	6.68
a_1	0.0513	−0.1000	−0.1020
a_2 (kt^{-1})	0.0031	−0.0033	−0.0028
a_3 (kt °$^{-1}$)	−0.1284	0.1192	0.1620
x_0	0.3525	0.3645	0.2355
x_1 (kt^{-1})	0.0034	0.0030	0.0039
x_2 (°$^{-1}$)	−0.0042	−0.0065	−0.0028
m_0 (n mi)	51.55	42.7500	38.0
m_1 (n mi kt^{-1})	−0.1861	−0.1612	−0.1167
m_2 (n mi °$^{-1}$)	0.3340	−0.0068	−0.0040

sions, so the coefficients vary considerably in magnitude. Also, the physical constraints on the resulting values of x_c, a_c, and r_{mc} are applied in a rather rigid fashion (i.e., during the search procedure, all values of the coefficients that resulted in vortex parameters outside the constraints for any case were eliminated from the possible choices). To overcome these issues, a more general solution method was developed to determine the coefficients in Eq. (2). First, the input and output variables in Eq. (2) were scaled so that they are of order 1. The scaling factors were 30 kt, 1, 100 n mi, and 90° for a_c, x_c, r_{mc}, and θ_{0c}, respectively, and 165 kt, 50°, and 30 kt for v_m, γ, and c, respectively. The physical constraints on the vortex parameters (which are the same as described above for the operational solution) were included by adding a penalty term to the RMS difference between the estimated and observed radii. The penalty term is calculated by multiplying the amount of vortex parameters that are out of range by a large coefficient (10^6). This method allows the searching algorithm to consider coefficients where vortex parameters are out of range for a few cases. Even this more generalized search does not produce cases with vortex parameters that violate the physical constraints.

The iterative solution for the 13 coefficients in Eq. (2) is similar to that described for the operational solution. The first guess sets all coefficients to zero, except m_0 and x_0, which were determined from the mean values of the radius of maximum winds and the size parameter from the Atlantic sample (36 n mi, 0.35). Other initial conditions were not examined; however, it should be noted that this solution methodology is still dependent on the choice of initial conditions. The parameter space is searched in the same manner as before, moving up and down from the last minimum, using 100 increments of 0.0005 on each of the coefficients, and the solution is iterated to convergence. Because of the scaling, the same increment was used on the search for all of the coefficients. Solutions using this methodology, a single set of initial conditions, and wind radii data through 2004 are shown in Table 3, where the final coefficients were converted back to parameter space after the iterative procedure so that they are comparable to those shown in Table 1. While the coefficients are quite different than those in Table 1, estimates of R34, R50, and R64 are almost always within 5 n mi of the operational model, which is well within the accuracy of the measurements of the developmental data. Both sets of coefficients result in an expanding vortex as a function of latitude. For example, the mean values of R34 at 15° latitude for a 100-kt hurricane are 126 and 129 n mi, and at 40° latitude are 209 and 211 n mi, using the coefficients in Tables 1 and 3, respectively. Also note that for this example, Tables 1 and 3 produce radii within 5 n mi of each other. Based on these results, the authors believe that the operational version of the model based on Table 1 is appropriate for a skill baseline.

The coefficients in Table 1 show some subtle sensitivity to the input data. In the two regions that have little or no reconnaissance data (east and west Pacific), the developmental data of R50 and R64 and thus the model estimates of these quantities show much less variability than in the Atlantic. Most notable are the limited variability of the radius of maximum wind (RMW) in both of those basins (small values of m_1 and m_2), while the shape parameter (x) increases at approximately the same rate. The result is less variation of R50 and R64 in these regions. As a result, the model estimates of R64 and R50 are expected to be less accurate in those basins.

The parametric vortex with the parameters determined from the coefficients in Table 1 is the climato-

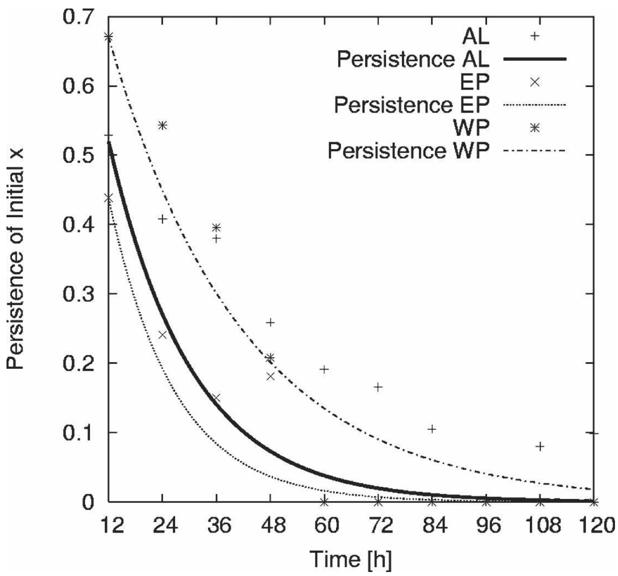

FIG. 1. Points represent the linear regression coefficient associated with the relationship between the initial size parameter x and the observed x for each time period and in each basin. Curves are the approximation used in the parametric wind radii CLIPER again for each basin.

logical part of the model. The next step is to include persistence. Both the symmetric and asymmetric wind structures are adjusted using the initial observed radii of each storm case. This procedure is described next.

Tropical cyclones can have both symmetric and asymmetric differences from the climatological model that can greatly influence the estimation of wind radii. In the parametric model, size is accounted for by the parameter x. In the simplest terms, an individual storm can be larger or smaller than the climatology. Using the initial observed wind radii, along with the climatological radius of maximum wind (r_{mc}), an observed value of x (x_{obs}) was calculated for each storm at each synoptic time that provided the best fit of the parametric vortex to the symmetric mean of the observed wind 34-, 50-, and 64-kt wind radii. The difference between x_{obs} and x_c is the initial symmetric error. An individual storm can also have asymmetries that are different than those produced by the climatological model. These can be thought of as asymmetric errors. The persistence of both symmetric and asymmetric errors is examined using our developmental datasets.

Persistence in the size factor is calculated by regressing x_{obs} at various time lags. The persistence of the size factor x in these three tropical cyclone basins is shown in Fig. 1. The persistence of size is greatest in the western North Pacific and least in the eastern North Pacific. The shapes of these curves are quite similar and storms tend to maintain their size to some degree through 36 h or so. To capture this persistent nature of TC size in our simple parametric model, we first calculate the value of x_{obs} from the initial observations. The 12-h basin-specific, linear regression coefficient (a_c) and intercept (b_c) are then applied to this to create the predicted value of x at 12 h or $x_{12} = x_c + [a_c(x_{obs} - x_c) + b_c]$, where x_c is the climatological value of x calculated using the forecast position and intensity. As an example, the Atlantic version of the model has $a_c = 0.53$ and $b_c = 0.03$. This calculation is repeated to estimate x at 24–120 h using the same values of a_c and b_c, where x_{obs} is replaced by the previous 12-h forecast. For example, $x_{48} = x_c + [a_c(x_{36} - x_c) + b_c]$, where x_c is the climatological value of x calculated using the forecast position and intensity at 48 h. This methodology approximates the points fairly well through 36–48 h as shown in Fig. 1, but without the added complication of carrying nine additional regression coefficients and intercepts. This approximation however does result in less persistence of the size factor than is observed in the Atlantic.

Persistence of the asymmetric errors is handled in a similar way. The initial wind radii estimates are again used to calculate x_{obs}. Then, x_{obs} is used in Eq. (1) to predict wind radii in each quadrant at $t = 0$. The differences between predicted and observed wind radii in each quadrant are calculated and treated as initial errors in each observed wind radii. At $t = 0$, these errors are added back to the predicted values so that the observed wind radii equal the predicted wind radii. The *e*-folding times, a measure of persistence, of these errors is found to be approximately 32 h. These initial errors are applied to each predicted set of wind radii (i.e., $t = 12, 24, \ldots, 120$ h), but in an exponentially decreasing manner. If the storm is predicted to intensify and higher wind threshold wind radii are being forecasted than were available initially, the initial errors from the next smaller wind radii threshold are used to estimate the asymmetries of these higher-threshold wind radii. For instance, the initial R34 asymmetries for a storm that has maximum winds of 45 kt and values for R34 at $t = 0$ are used to adjust the predicted R50 for that same storm when the maximum winds exceed 50 kt. Again, the asymmetries decrease to climatology using a 32-h *e*-folding time.

A final bias correction is then applied to the wind radii. During the development process, biases were found in the estimates of R34 and R64. Estimates of R34 (R64) were too small (large) for storms with intensities greater than 94 kt. Additionally, estimates of R64 were systematically 6% too large for all intensity ranges. To rectify the biases that are related to intensity, a bias that increases (decreases) R34 (R64) by 0.25% for each knot of intensity greater than 94 is ap-

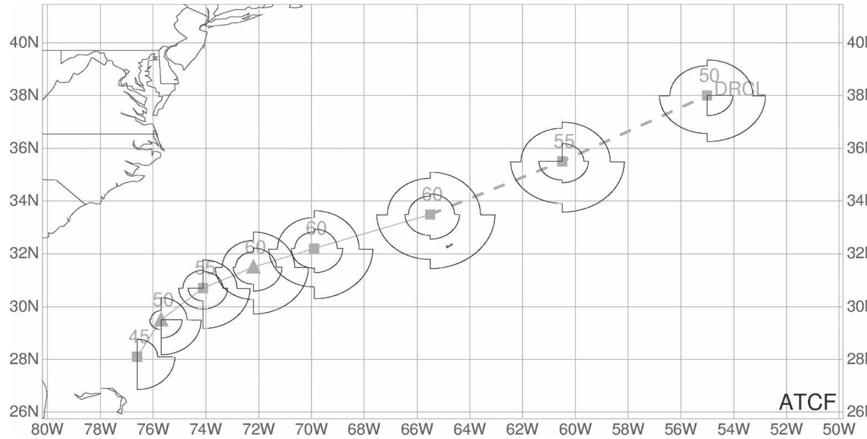

FIG. 2. An example forecast produced by the parametric form of the wind radii CLIPER model (DRCL) for Tropical Storm Franklin at 0000 UTC 23 Jul 2005. Initial 34-kt wind radii are 40, 75, 0, and 0 n mi in the NE, SE, SW, and NW quadrants, respectively. The forecast intensities are listed in the figure at each forecast point valid for 0, 12, 24, 36, 48, 72, 96, and 120 h.

plied. For instance, a storm with 140-kt intensity would result in an 11.5% increase (decrease) of the estimated R34 (R64). To remove the systematic R64 biases, estimates of R64 are multiplied by 0.94. Both bias corrections are applied only to the climatological vortex model and do not affect the initial wind radii estimates or the asymmetries.

An example of a wind radii forecast made by the statistical-parametric model is shown in Fig. 2 for Tropical Storm Franklin for a forecast beginning at 0000 UTC 23 July 2005. The model captures several features that are consistent with the observations including the following.

1) The forecast wind radii evolve from asymmetric initial R34 conditions toward, but not completely to, a vortex dominated by wavenumber-1 asymmetries with respect to motion.
2) The vortex expands as it moves to higher latitudes.
3) R50 wind radii in some quadrants become zero instead of a physically unrealistic small value.

4. Independent results

The statistical-parametric vortex model, which has been assigned the four-letter identifier DRCL in the Automated Tropical Cyclone Forecast System (ATCF; Sampson and Schrader 2000), was successfully run at NHC starting at 1800 UTC on 31 July 2004 (for the first tropical cyclone of the Atlantic season). This model has been integrated into the ATCF and executes as part of the ATCF wind radii dialog. The ATCF wind radii dialog is available to the forecasters only after the initial position and forecast track have been specified, the initial and forecast intensity have been determined, and the initial wind radii have been defined. Thus, the information required to execute the wind radii CLIPER algorithm is always available at the time they are run.

An evaluation of the average operational R34, R50, and R64 Atlantic errors for the 2004 season soon after the DRCL model was implemented (storms 6–16) and the entire 2005 season is shown in Fig. 3. Wind radii estimates from the NHC best tracks (Jarvinen et al. 1984) are used as ground truth in the evaluation. For simplicity, an average of the errors from all four quadrants (NE, SE, SW, and NW) is shown for the DRCL model along with the model developed by McAdie (2004) (MRCL, which is also in the ATCF) for comparison. Hit rates (HRs; fraction of wind radii that are properly detected) and false alarm rates (FARs; fraction of zero wind radii that were improperly detected) were also calculated as they are considered important to operations. All results presented in this evaluation are homogeneous. Note that initial errors (mean absolute errors) are greater than 0 for both statistical models as well as the official forecasts (Fig. 3). The 2004 season was the first in which postseason corrections were made to the NHC best tracks, and this is reflected in the 0-h results.

For R34 (Fig. 3a), the MRCL average errors are slightly lower (significant at the 99% level using a Student's t test) than those of DRCL at all forecast times. The significance testing has serial correlation within 30 h removed (von Storch and Zwiers 1999). The average 34-kt wind radius for both models and the official forecast during the evaluation period increased from 96 n mi at 12 h to 106 n mi at 72 h, so average R34 errors as

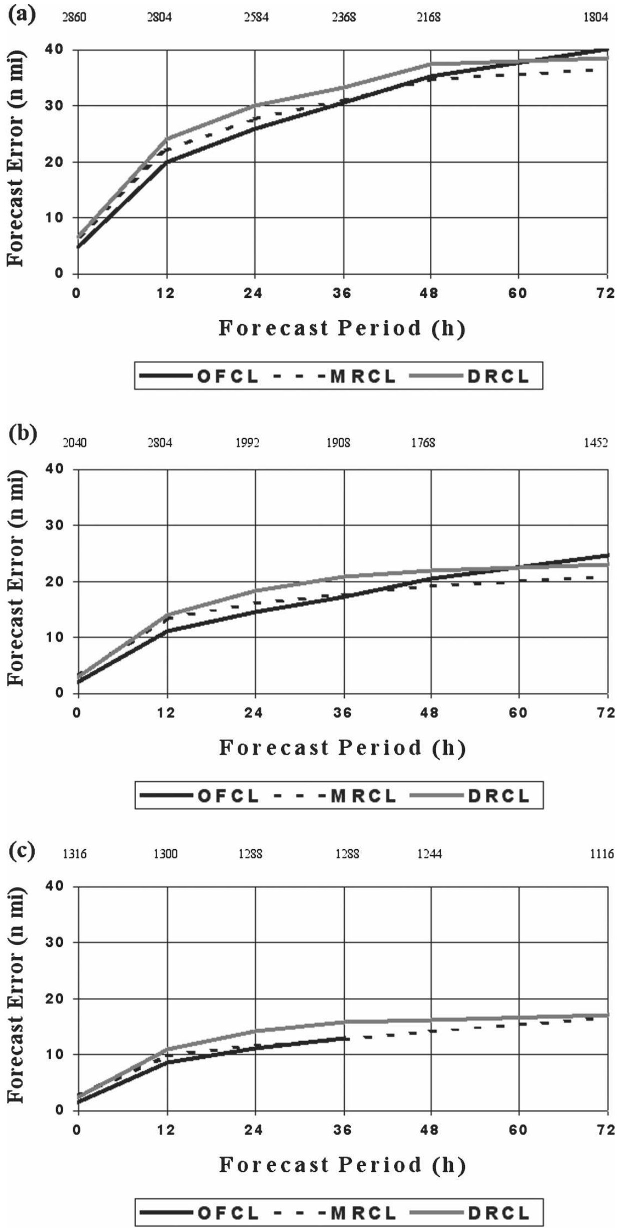

FIG. 3. The 2004–05 verification of wind radii forecasts through 3 days. Shown are plots of mean absolute error in nautical miles (1 n mi = 1.85 km) for (a) R34, (b) R50, and (c) R64 for the official forecast (OFCL), the regression wind radii CLIPER (MRCL), and the parametric wind radii CLIPER (DRCL). The number of cases is listed at the top. Confidence intervals about the means are all less than 2 n mi.

a percentage of the average wind radii increased from approximately 25% at 12 h to approximately 36% at 72 h. The official forecast (OFCL) outperforms MRCL at 12 and 24 h (significant at the 99% level).

The average R50 errors (Fig. 3b) are approximately half as large as the 34-kt wind radii errors at each time period. For the period of record, the average 50-kt wind radius is 51 n mi at 12 h and 61 n mi at 72 h, so the average R50 errors as a percentage of the average wind radii increased from approximately 27% to approximately 31%. The official forecast is skillful with respect to MRCL to 24 h. The R64 errors (Fig. 3c) are about 1/3 smaller than the 50-kt wind radii errors. The average 64-kt wind radius for the period of record increases from 35 n mi at 12 h to 39 n mi at 72 h. As a result, the average R64 errors increased from approximately 29% at 12 h to approximately 33% at 72 h. The official forecast, which is created through 36 h, is skillful only at 12 and 24 h. The R50 and R64 forecast errors for both of these models level off at 72 h.

It is noteworthy that there appears to be a trade-off between false alarm rate and MAE; both the OFCL and MRCL forecast, while having lower MAE statistics, also had larger false alarm rates. To answer how well the forecasts discriminated zero from nonzero wind radii, a Hanssen and Kuipers discriminant (HKD) is used (Stephenson 2000), which is defined as hit rate minus false alarm rate. This statistic ranges from −1 to 1, where 0 indicates no skill and a perfect score is 1. The results of this analysis suggest that both the OFCL and MRCL forecasts are not as skillful in discriminating whether 34- and 50-kt winds occur in a particular quadrant (Fig. 4). With standard errors associated with this statistics being on the order of a few percent, there are large and significant differences between the HKD values calculated for R34 for all of the models, and small and significant differences between the HKD values calculated for MRCL and DRCL. These results suggest that some of the smaller MAEs associated with OFCL and MRCL come through the overdetection of R34 and R50 wind radii and that the DRCL model, while having larger MAEs, has more skill at discriminating between zero and nonzero R34 and R50 wind radii.

North Pacific R34 forecast errors are shown in Fig. 5. The wind radii errors for the eastern North Pacific (Fig. 4a) are generally lower than those of the western North Pacific (Fig. 4b) and Atlantic. For the period analyzed, the average 34-kt wind radius for the eastern North Pacific increases from 71 n mi at 12 h to 78 n mi at 72 h. The average R34 errors as a percentage of the average wind radii increased from approximately 27% at 12 h to approximately 37% at 72 h. The official forecast is skillful to 48 h in the eastern North Pacific. The western North Pacific average R34 errors are of the same magnitude as those for the Atlantic. The average 34-kt wind radius in the western North Pacific increases from 104 n mi at 12 h to 117 n mi at 72 h. The average R34 errors as a percentage of the average wind radii increased from approximately 18% at 12 h to approximately 29% at 72 h. The official Joint Typhoon Warning Center

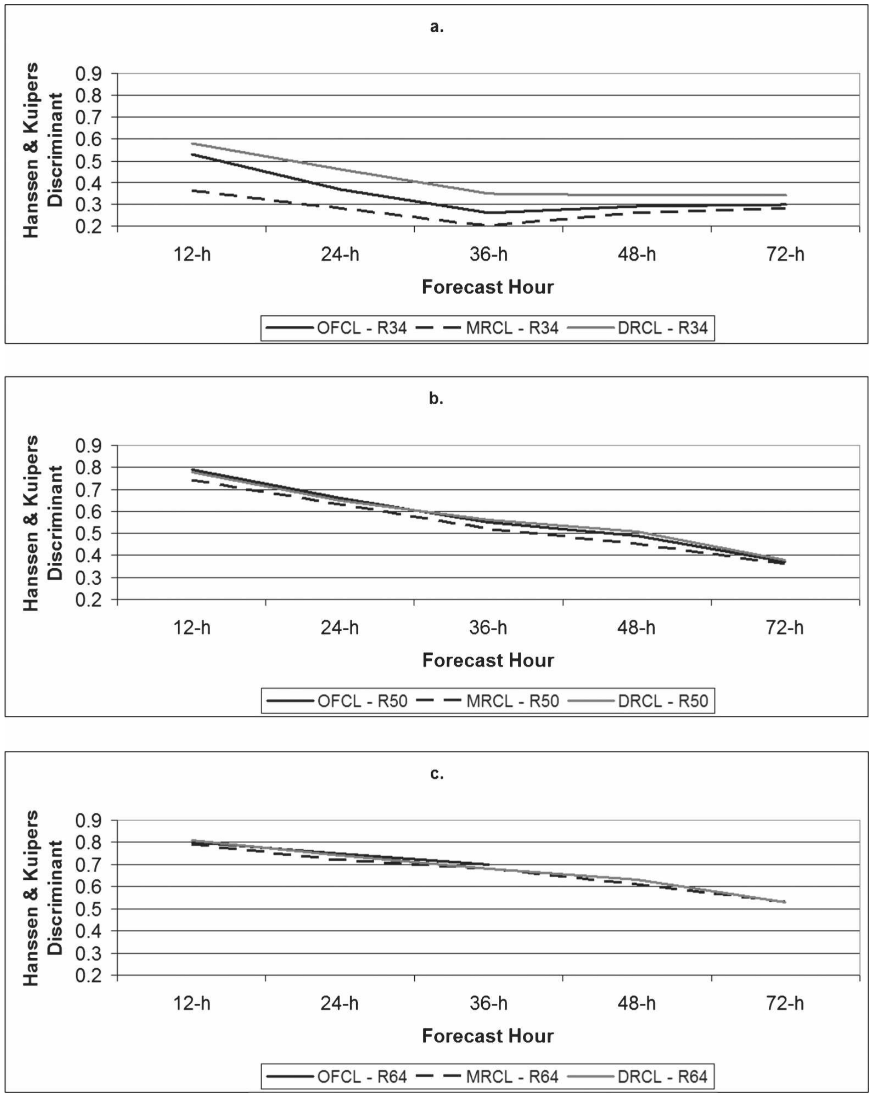

FIG. 4. The Hanssen and Kuipers discriminant associated with forecasts of (a) R34, (b) R50, and (c) R64 for OFCL, MRCL, and DRCL during 2004–05 in the Atlantic and corresponding to the MAE statistics shown in Fig. 3.

(JTWC) forecast is skillful through 72 h in the western North Pacific. Note that the initial wind radii errors for the western North Pacific are approximately zero because the JTWC does not routinely perform a postseason analysis of the wind radii. The errors of R50 and R64 for the eastern and western North Pacific are not presented because the authors feel that the data quality may not be appropriate for evaluation at this time.

5. Summary

The development of a statistical-parametric model that employs climatology and persistence to predict tropical cyclone wind radii estimates is described. This model (DRCL in the ATCF) uses a modified Rankine vortex that has been generalized to allow for a wavenumber-1 asymmetry. DRCL was developed for the Atlantic, and eastern and western North Pacific basins and produces forecasts through 120 h. The results of DRCL are compared to another model (MRCL), which uses multiple linear regressions to predict each wind radii (R34, R50, and R64) in each quadrant. MRCL was only developed for the Atlantic basin and makes forecasts through 72 h (McAdie 2004).

A 2-yr independent evaluation suggests that DRCL does an good job of predicting wind radii variations. As might be expected, MRCL, with its greater flexibility from using 60 independent equations outperforms

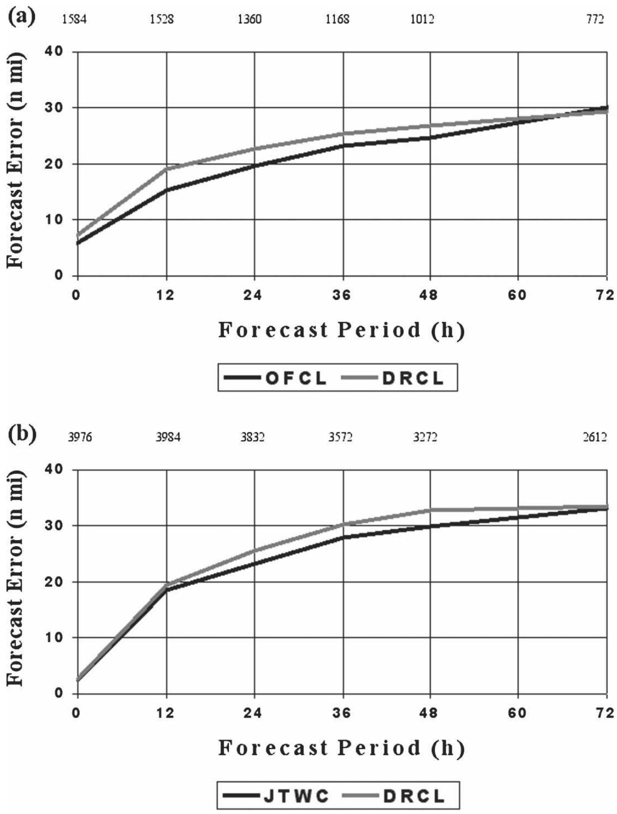

FIG. 5. The 2004–05 verification of R34 forecasts for (a) the east Pacific and (b) the western North Pacific. Shown are plots of the MAE in n mi associated with each forecast time for the official and DRCL forecasts. The official forecasts are OFCL and JTWC in the east Pacific and western North Pacific basins, respectively. The number of cases for each forecast time is listed at the top of the figure. Confidence intervals about the means are all less than 2 n mi.

DRCL in terms of mean absolute error. On the other hand, it appear that some of this superior performance comes at the expense of overall discrimination between zero and nonzero wind radii, especially R34 and R50. Average errors for each model and each radius are approximately 18%–28% of the average radii at 12 h and increase to approximately 29%–37% of the radii at 72 h. Both models (DRCL and MRCL) generally produce forecasts with errors that level off as the forecast time increases. Despite the differences between DRCL and MRCL, both methods can be used as skill baselines for other wind radii forecast methods and operational forecasts. DRCL offers the advantages of producing 5-day forecasts in three tropical cyclone basins and scores higher in terms of the Hanssen and Kuipers discriminant. MRCL is slightly more skillful in mean absolute error, but forecasts only to 72 h and is only available in the Atlantic. Finally, the official R34, R50, and R64 forecasts are shown to outperform these simple models through approximately 36 h in the case of MRCL and 48–72 h in the case of DRCL.

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