# A New Method for Determining Tropical Cyclone Wind Forecast Probabilities

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## 1. INTRODUCTION

In the early 1980's, the National Hurricane Center (NHC) recognized that a probabilistic forecast should accompany the deterministic tropical cyclone track forecast. Beginning in 1983, track probabilities were issued as an operational advisory product for selected coastal and island locations from 12 to 72 hours. Except for periodic updating of the track error statistics on which the probabilities were based, very little has changed in how the probabilities are generated.

These probabilities would be more useful if they included the forecast uncertainties of intensity and size as well as track. To meet this need, a "Monte Carlo" (MC) method was developed for the Atlantic basin to estimate the spatial distribution of the probability of winds exceeding specified thresholds within various time windows. A large sample of plausible tracks (termed "realizations") relative to a given forecast track are generated by randomly selecting from error distributions determined from a historical database of NHC track forecasts. A similar method is used to provide the intensity and wind radii for each of the MC realizations. Probabilities are then determined by summing the number of times a grid point comes within the radius of a given wind speed threshold (34, 50, 64 or 100 kts), divided by the total number of MC realizations.

## 2. THE MONTE CARLO MODEL

The MC wind probability model uses the error characteristics of the NHC official track and intensity forecasts along with the climatological variations of tropical cyclone size. These errors are sampled using a random number generator to provide an ensemble of tropical cyclone tracks, intensities and sizes. All NHC Atlantic forecast cases from 1997 to 2002 have been used to determine the error distributions for these tests. The forecast errors have unique and non-normal probability distributions. An advantage of the MC method is that these error distributions are sampled directly, so it is not necessary to fit an assumed functional form to the error distributions.

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The MC technique was designed to include the effect of serial correlation. For example, if the 12-h track forecast was to the left of the actual track, the 24-h forecast also tended to be to the left of track. To include this effect, the realization is started by randomly selecting from the 12- h error distribution. Then, the 24-h error is predicted from the 12-h error, and a perturbation is added from the sample distribution of the 24-h errors with the serial correlation included. This process is repeated for all subsequent forecast periods.

Special procedures were also developed to account for landfalling MC track realizations. If the NHC track forecast was over land, it was assumed that the effects of landfall are already accounted for. If, on the other hand, the official forecast remained over water but the MC realization took the track over land, an empirical inland decay model (Kaplan and DeMaria, 1995) was applied to the NHC intensity forecasts before the intensity perturbations were added. This technique prevents unrealistically high probabilities of strong winds being estimated at inland locations.

To account for variations in tropical cyclone size in the MC realizations, a climatological wind radii forecast model was developed. This wind radii model uses an idealized wind structure which combines a symmetric vortex and a constant proportional to the storm motion vector. The climatological wind model (outside of the radius of maximum winds) is given by

$$V(r,\lambda) = (V_m-\alpha)(r_m/r)^x + \alpha[\cos(\lambda-\lambda_o)], \qquad (1)$$

where r is the radius from the storm center (nmi), $\lambda$ is the angle measured counterclockwise starting from a direction 90$^o$ to the right of the storm motion, $V_m$ is the maximum wind (kt), $r_m$ is the radius of maximum wind (nmi), x is a size parameter (non-dimensional), and $\alpha$ is an asymmetry parameter (kt) that is a function of the storm speed of motion.

The climatological model was determined by fitting the free parameters (x, $r_m$ ,$\alpha$ and $\lambda_o$) in (1) to a large sample of NHC forecast wind radii (1988-2002 Atlantic storms, west of 55$^o$W) for which aircraft reconnaissance data are most likely to be available. It was found that $r_m$ and x can be estimated as functions of the maximum wind speed and latitude using

$$r_m = 35.37 - 0.111V_m + 0.570\,(\theta\text{-}25) \qquad (2)$$

$$x = 0.285 + 0.0028V_m \quad (3)$$

and $\alpha$ can be determined as a function of the storm speed of motion from

$$\alpha = 0.337c - 0.003c^2 \quad (4)$$

where $\theta$ is latitude ($^o$N) and c is the storm speed of motion (kt). The best fit value of $\lambda_o$ was zero, so the asymmetry is always positioned with a maximum $90^o$ to the right of the storm motion.

Figure 1 shows the wind radii as a function of maximum wind and latitude from the climatological wind model defined by (1)-(3) for a stationary storm (c=0).

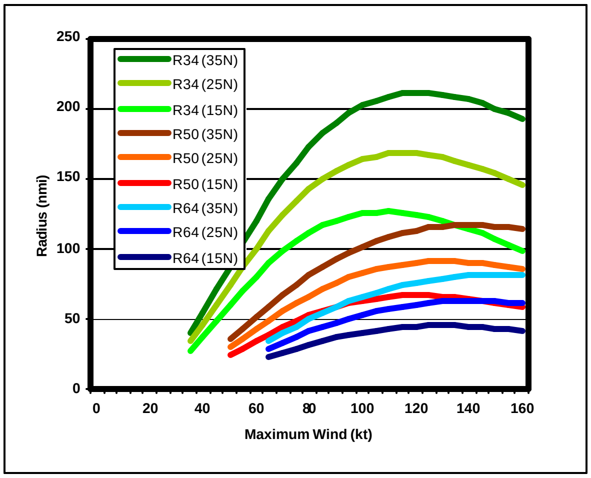


*Figure 1. The radii of 34, 50 and 64 kt winds (nmi) from the climatological wind model as a function of storm intensity and latitude.*

Direct sampling from each of the radii error distributions proved to be unsatisfactory because the resulting wind structure was not always physically consistent. Rather than picking the radii errors randomly from the fit of the climatological wind model, the size parameter x is adjusted for each case in the 1988-2002 sample to best fit the observed radii for that case. Then, the distribution of x parameter errors can be randomly sampled to provide the wind radii for each realization. Because the radii are still calculated from the parametric model (1), but with a randomly sampled size parameter x, they remain physically consistent.

The above technique of generating radii for the MC realizations also provides a method to account for the initial size of the storm, as determined from the initial radii in the operational forecast/advisory. Instead of choosing the initial value of the error in x randomly, it can be chosen as the difference between the value from the climatological model (3) and the value that provides the best fit to the observed radii at t=0. At the forecast periods (12, 24, … h), the x error is chosen as a linear combination of the initial value of the x error, and a random component. The relative weights for the above linear combination are determined by the strength of the correlation between the x errors from the large sample of developmental cases at 12-h intervals. The influence of the initial fit to x becomes negligible after about 48 h.

## 3. RESULTS

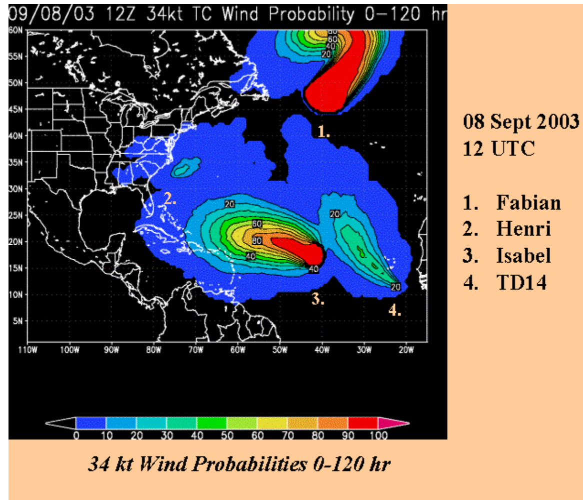


*Figure 2. An example of MC wind probability output being produced at the NHC. Shown is the cumulative probability of experiencing 34kt or greater wind speeds over a 120-h period based on NHC's forecast of 4 active tropical cyclones on 8 September 2003 at 12 UTC. The values of the probabilities (%) are indicated by the gray scale at the bottom of the figure.*

The MC model code was installed at NHC August 8, 2003. Wind probabilities associated with 34, 50 and 64 kt wind speeds were produced in real-time every six hours for the remainder of the Atlantic season, on a half-degree latitude-longitude grid that covers the Atlantic tropical cyclone basin. An example is provided in Fig. 2.

## 4. FUTURE PLANS

A preliminary evaluation of the products generated by this project identified several aspects of the MC model that can be improved. Among these are further refinement of the wind radii model and the treatment of initial wind radii asymmetries, inclusion of other factors (initial intensity and distance inland) important to the serial correlation of track and intensity errors, and improved methods for randomly sampling the error distributions. Information gathered from the 2003 season will allow us to further refine the Atlantic MC model and apply these methods in other tropical cyclone basins. This work was funded by the Insurance Friends of NHC and is currently being funded by the U.S. Weather Research Program's Joint Hurricane Testbed.

## 5. REFERENCES

Kaplan, J., and M. DeMaria, 1995: A simple empirical model for predicting the decay of tropical cyclone winds after landfall. *J. Appl. Meteor.*, **34**, 2499-2512.