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WIND PROFILES IN PARAMETRIC HURRICANE MODELS

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Editor's Note: The recent release of Version 12.0 of the AIR Hurricane Model for the United States featured major enhancements to virtually all model components. One of these was the introduction of a new wind profile formulation. AIR Senior Scientists Dr. Ioana Dima and Dr. Melicie Desflots discuss the important role of wind profiles in tropical cyclone models and examine the advantages and disadvantages of the three most often implemented in tropical cyclone risk models.

by Dr. Ioana Dima and Dr. Melicie Desflots

INTRODUCTION

Hurricanes are tropical cyclones with winds greater than or equal to 74 mph. These giant spiraling storms (the average diameter of hurricane-force winds is about 100 miles) can generate winds of over 160 miles per hour and can wreak havoc when they come onshore. People's lives are threatened, homes are destroyed, and day to day life is brought to a standstill. The damage caused by hurricanes comes from the wind, storm surge and flooding induced by rainfall associated with the storm. All can be extensive and costly in terms of lives and property; thus catastrophe models of potential loss due to hurricanes are extremely useful.

The wind calculation is at the core of most tropical cyclone catastrophe models. It is generally performed using either a *parametric* or *dynamical numerical* approach. Both represent state-of-the-art methods that estimate the spatial distribution of the hurricane winds. Dynamical models make full use of the known physical laws and equations that govern the atmosphere. In order to give reasonable results for hurricane simulations, these models need to run on fine resolution grids, a process that is computationally expensive in terms of both run-time and computer memory. Parametric models, which compute an approximation of the hurricane wind field, offer an attractive alternative because they improve run-time costs while preserving most of the validity of the results. While dynamical models remain the choice of real-time hurricane forecasters at such agencies as the National Hurricane Center, particularly in light of their ability to forecast storm tracks, parametric models provide a cheap and virtually equally good alternative for estimating wind hazard for risk analysis purposes.

In parametric models, the wind distribution around the storm center, or wind field, is derived by way of a *wind profile.* Figure 1 shows the three-dimensional wind field (colored areas) and the wind profile (yellow line) of a typical hurricane. The wind profile captures the high winds in the region of the eyewall of the storm and the more or less rapid radial decay of the winds away from the eyewall region. The radial distance at which the strongest hurricane winds are observed is called the radius of *maximum winds (Rmax)* and it defines the region where the most severe damage is typically observed. Understanding the behavior of the hurricane wind profile, or how sharply the winds change with distance from *Rmax*, is a crucial step in estimating hurricane damage.

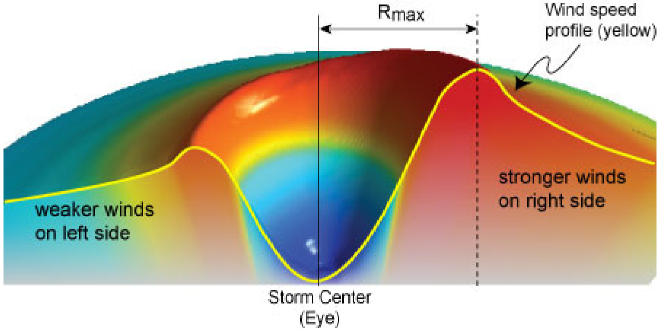

Figure 1. Schematic cross section of a hurricane wind field. Rmax is the distance from the center of the storm to the location of the maximum winds. Note how winds are strongest on the right-hand side of the hurricane (assuming a northward direction) due to the additive effect of the hurricane's winds and the storm's forward motion. Source: AIR.

Indeed the choice of the most appropriate wind profile for use in parametric models is critical to computing realistic wind speeds and estimating reliable losses from hurricanes. Not surprisingly, therefore, scientists have put a lot of effort in developing realistic representations of wind profiles and many have been published over the years. In this article, we will examine three of these analytical models: NWS-23 (1979), Holland (1980) and Willoughby et al. (2006), and point out their strengths and weaknesses. These three have been particularly favored for implementation in catastrophe models. The last—the wind profile published by Dr. Hugh Willoughby and co-authors—is the one implemented in the most recent release (Version 12.0) of AIR's U.S. hurricane model. We'll explain why.

FORMULATION OF THE HURRICANE WIND PROFILE

The hurricane wind profiles in parametric models (and those discussed in this article) may be empirically-derived statistical representations or modified versions of a theoretical *gradient wind equation*—or some combination of the two.

The gradient wind equation is a mathematical representation of the balance between the three dominant forces in hurricanes:

1. Pressure gradient force—arising from the difference between atmospheric pressure at the periphery of the hurricane and atmospheric pressure at the storm's center, over the distance that these pressures are observed
2. Centrifugal force—arising from the hurricane's spin around its center
3. Coriolis force—arising from the earth's rotation around its axis

The winds calculated in the gradient wind equation are called the *gradient winds*, and they offer a close approximation of the wind distribution around the storm.

NWS-23 (1979): An Early and Reliable Workhorse

The NWS-23 hurricane wind profile is the oldest of the three profiles we discuss here. In 1979, the Coastal Services Center of the National Oceanic and Atmospheric Association (NOAA) issued a technical report, NWS-23, which contained specific official guidelines for the meteorological representation of a standard hurricane. The NWS-23 formulation was based on observational data that was recorded during hurricane reconnaissance flights in the North Atlantic from 1957 through 1969. Every hurricane season, Hurricane Hunters' aircrafts fly reconnaissance missions into hurricanes to collect important wind data (among other parameters) to help the forecasters and researchers at the National Hurricane Center (NHC). They gather crucial information with sophisticated instruments to relay information on the tropical cyclone's location, movement and strength, to the NHC. As the aircrafts fly into the storm, they essentially record a wind profile, representative of the radial structure of the storm at that time.

The wind speed decay rate at a particular location using the NWS-23 wind profile depend on two parameters only: *Rmax* and distance from the eye. To capture the faster wind decay rate from *Rmax* to the center of the storm and the more gradual wind decay between *Rmax* and the periphery of the storm, the NWS-23 wind profile uses two distinct empirical equations: inside ***Rmax***, the wind profile decay is exponential and outside *Rmaxit* is logarithmic. Despite its minimal parameter dependence, the NWS-23 radial profile has provided a robust representation of the structure of hurricanes since it was introduced—and particularly for North Atlantic hurricanes. Indeed, it was the one used in AIR's U.S. hurricane model until the most recent model update.

Holland (1980): An Innovative Alternative

Unlike NWS-23, the Holland wind profile is not simply a statistical fit to observed data; rather, it represents a *modified gradient wind equation*. In 1980, when Dr. Greg Holland published his wind profile, it had been tested on 12 hurricanes from the Atlantic and the Australian basins and was found to perform reasonably well. The modifications introduced to the gradient wind equation basically control the "peakness" of the wind profile, meaning that the region of the highest winds can be made broader or narrower at will through a parameter called the Holland B parameter, which allows for a better adherence of the theoretical profile to the data (see Figure 2).

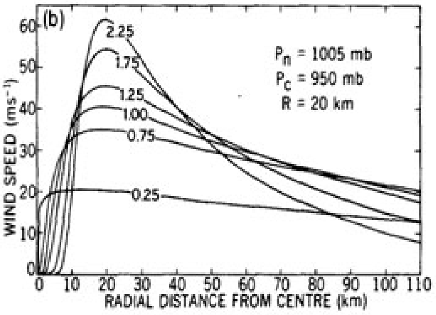

Figure 2. The effect of varying the Holland B parameter on the Holland wind profile (from Holland, 1980).

The wind speed decay rate at a particular location using the Holland wind profile depend on distance from the eye, *Rmax* and the above-mentioned B parameter. As seen from Figure 2, as B increases, the wind profile becomes more sharply peaked; that is, winds close to the eyewall increase more rapidly and those outside of *Rmax* decrease more rapidly.

It is important to note that a change in B affects not only the shape of the profile but also the value of the maximum winds of the storm, *Vmax*. Hence, any adjustments to the shape of the profile (via B) must be made in conjunction with the observed maximum wind of the storm.

Because of the peakness parameter B, essentially all the storms with high *Vmax* will be have a narrow region of high wind speeds, while weaker storms will necessarily exhibit a broader region of relatively high winds. Thus this profile is not suitable for representing atypical, but still possible, intense storms that have a *broad* wind field.

Willoughby et al. (2004, 2006): The Offer of Greater Fidelity to Reality

Like NWS-23, the **Willoughby** wind profile was developed as a statistical fit to the observations, but in this case the data used were much more extensive and the statistical approach was entirely different. The authors used 493 hurricane wind profiles from reconnaissance data, from 1977 to 2000, obtained from flights in both the Atlantic and Eastern Pacific basins.

In this formulation the wind profile is defined by three equations: one for the area inside the eyewall, one for the eyewall region (or transition region) and one for the area farther away, towards the periphery. Over a short distance (typically 25 kilometers) in the vicinity of *Rmax*, where winds are strongest, the wind profile has a particular evolution, different from the rest of the profile. The introduction of the transition region, which describes the wind behavior around the eyewall, is thus noteworthy, as it promises to better capture the highest winds of the storm, as well as their extent. Thus this is extra "knob" is key to obtaining a profile that approximates reality with greater accuracy.

In terms of its formulation, to best capture the steep decay inside the eyewall, the Willoughby profile uses a power law. Outside the eyewall, the profile is defined by a dual exponential in order to capture the two different decay rates outside the eyewall: the fast decay close to the eyewall and the more gradual decay farther away from the storm. This dual-exponential treatment is an innovative feature that adds true value to capturing both the high winds close to the eyewall as well as the reduced winds at the periphery of the storm (Figure 3). For example, in the hurricane profile depicted in Figure 3, winds decrease from 94 mph (42 m/s) to 67 mph (30 m/s) over a 25 km distance. Farther away from the eyewall, more moderate winds persist over longer distances: between 100 and 125 km, the winds decrease from 47 mph (21 m/s) to 40 mph (18 m/s).

The decay rate of the Willoughby wind profile takes into account a total of three parameter dependencies: *Rmax* latitude, and *Vmax*. The storm's complexity is better represented using a larger number of its characteristic parameters, and so the shaping of the profile promises to be a better reflection of the actual structure of the storm.

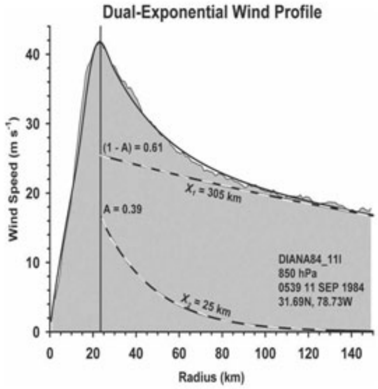

Figure 3. Dual-exponential profile (dark curve) used to approximate the observed wind (shaded). Two distances x1 and x2 (dashed curves) control the decay rate of the wind profile outside Rmax. (From Willoughby, 2006).

COMPARING THE THREE: THE BOTTOM LINE

The three profiles discussed in this article are a reflection of the standard—or "average" —tropical cyclone, but each employs a different number and combination of storm-parameters. Depending on the parameter dependence, a particular formulation could be better suited to capturing a larger range of hurricane wind profiles that represent departures from the average.

To explore this question, the three formulations were compared for a number of North Atlantic hurricanes at various moments in their life cycle before landfall. Four of these comparisons are shown in Figure 4. What we call the "true" structure of the hurricane was determined using flight-level data from NOAA's Hurricane Hunters' aircraft. In constructing the profiles, we also made use of the so-called "best track" data from the NHC's official hurricane database HURDAT (which covers the period 1851-2008), to infer central pressure values for the dates and times when the flight observations took place.

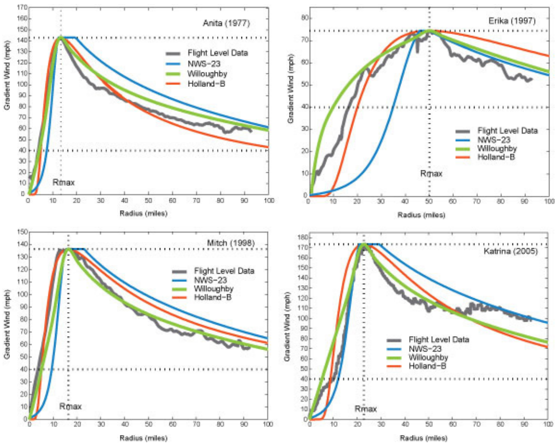

Figure 4. Comparing the NWS-23, Holland and Willoughby wind profiles with flight-level observation data for Hurricanes Anita (1977), Erika (1997), Mitch (1998) and Katrina (2005). Of the three profiles, Willoughby offers the best fit to the data in the vicinity of the eyewall (where the winds are strongest—near and on either side of Rmax) and where the estimation of winds is most critical to hurricane risk analysis.

In most instances, NWS-23 does a reasonable job at capturing the winds inside *Rmax* and again towards the periphery of the storm (Figure 4), but tends to overestimate—sometimes significantly—the winds in the vicinity of the eyewall, outside *Rmax*. In this region, when using the best value in shaping the profile, the Holland formulation performs better than NWS-23, but still tends to overestimate the winds around *Rmax*. Clearly, overestimation in the region of the highest wind speeds of the tropical cyclone leads inevitably to higher loss estimation. Over large areas the differences between observed and Holland-modeled winds seem to be small; however, since the relationship between wind speed and the damage to property is non-linear, the differences between observed losses and modeled losses could be large. Of the three profiles, Willoughby offers the best fit to the data in the vicinity of the eyewall, where the winds are strongest—and where the estimation of winds is most critical to hurricane risk analysis.

The case of Hurricane Erika (1997) in the top right panel of Figure 4 is an interesting one. Inside the eyewall, the observed wind profile exhibits a somewhat atypical curvature. Only the Willoughby profile can accommodate this sort of feature, which is more likely to be observed in large, but less intense hurricanes. NWS-23 does a particularly poor job in this instance and the Holland profile does particularly poorly outside *Rmax*.

CONCLUDING REMARKS

The analysis presented in Figure 4 represents snapshots in the lifetime of these storms; generally, wind profiles can vary greatly from storm to storm and even from hour to hour for a single storm. Nevertheless, the results shown in Figure 4 are representative of similar analyses performed at AIR for many more storms than are shown here.

As the previously long-standing wind profile of the AIR tropical cyclone models, NWS-23 represents a reliable formulation that has been widely tested and validated. As portrayed in several other storm analyses (not shown here), the strength of the NWS-23 wind profile lies in its good representation of the winds inside the radius of maximum winds, primarily for smaller and stronger hurricanes; as was seen in the case of Erika (1997), it does less well with larger, weaker storms.

The modified gradient wind equation used to build the Holland profile is a good approximation of the wind distribution within a hurricane. The Holland B formulation is more rigid in essence: as a continuous profile it is more difficult to have control over the shape of the different regions of the radial distribution of the wind. Recently, Holland has tried to improve his formulation by computing the "peakness" parameter as a function of the storm parameters and no longer allowing for an arbitrary choice (Holland, 2008). What is clear is that research in this area will continue and new formulations will be published.

In the meantime, AIR has performed extensive validation for a significant number of tropical cyclones and of the three radial decays presented here, the Willoughby profile consistently performs the best. In particular, it does a good job of capturing the high winds in the critical eyewall region. The large amount of data used in the profile's development, as well as the unique methodology employed, has allowed for a versatile formulation. The set of best-fit equations makes use of a larger number of storm parameters compared to the other profiles, which helps to produce a better representation of not just the average storm but also of the atypical ones.

Through the more explicit dependence on *Rmax*, latitude and *Vmax*, the Willoughby profile is also set to offer a better representation of transitioning storms, which usually become larger and weaker as they travel towards higher latitudes. Outside the eye, Willoughby considers two differently scaled exponentials to capture the fast decaying wind near the storm center and the slow decaying wind farther away from the eyewall, allowing for a good validation for the whole spectrum of winds from borderline damaging to destructive. The increased fidelity in representing hurricane winds offered by the Willoughby wind profile offers, in turn, a more reliable depiction of wind-induced losses to property.

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