Hurricane Hazard Modeling: The Past, Present and Future

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ABSTRACT

Hurricane hazard models have become a commonly used tool for assessing hurricane risk. The type of hurricane risk considered varies with the user and can be an economic risk, as in the case of the insurance and banking industries, a wind exceedance risk, a flood risk, etc. The most common uses for hurricane hazard models today include:

(i)   Simulation of wind speed and direction data for use with wind tunnel test data for the estimation of wind loads vs. return period for design of structural systems and cladding
(ii)   Estimation of design wind speeds for use in buildings codes and standards
(iii)   Coastal hazard risk modeling (storm surge elevations and wave heights vs. return period)
(iv)   Insurance loss estimation (probable maximum losses, average annual losses)

This paper presents a brief overview of the history of the modeling process, concentrating on the modeling of the wind, as it is the key input to each of the examples presented above. We discuss improvements in wind field modeling, modeling uncertainties, and possible future directions of the hurricane risk modeling process.

1. BACKGROUND

The mathematical simulation of hurricanes is the most accepted approach for estimating wind speeds for the design of structures and assessment of hurricane risk. The simulation approach is used in the development of the design wind speed maps in the United States (ANSI A58.1, 1982; ASCE-7, 1993 through to the present), the Caribbean (CUBiC, 1985) and Australia (SAA, 1989). The approach is used for developing coastal flood estimates, setting flood insurance rates and minimum floor elevations for buildings along the hurricane coastline of the United States, and the approach is routinely used in the banking and insurance industries for setting insurance rates. Virtually all buildings and bridges that have been wind tunnel tested and are to be built in hurricane and typhoon areas have had the wind tunnel test data combined in some fashion with the results of a hurricane hazard model. The modeling approach has improved significantly since the pioneering studies performed in the late 1960's and early 1970's. In principle, the overall approach has not changed since the original work of Russell in 1968, but the details have changed, particularly in the modeling of the hurricane wind field. The improvements have come about through the use of more sophisticated physical models, driven partially

by improved computing capabilities, but also to a large extent because of the enormous increase in quantity and quality of measured data available now to improve and validate the physical and statistical models used to model the hurricane hazard. The paper discusses the probabilistic and physical models used in the modeling process, examining the changes and improvements to the various components and looks briefly at what to expect in the next generation of hazard models.

2. PROBABILISTIC MODELS

2.1 Single Site Probabilistic Models

The simulation approach was first described in the literature by Russell (1968, 1971), and since that pioneering study, for US applications, others have expanded and improved the modeling technique, including Tryggvason, et al. (1976), Batts, et al. (1980), Georgiou, et al. (1983), Georgiou (1985), Neumann (1991), and Vickery and Twisdale (1995b). The basic approach used in all these studies is similar in that site specific statistics of key hurricane parameters including central pressure deficit, radius to maximum winds (*RMW*), heading, translation speed, and the coast crossing position or distance of closest approach are first obtained. The modeling techniques used in these models are valid for a single site, or small regions only, owing to the fact that the statistics for central pressure, occurrence rate, heading, etc, have been developed using site specific data, centered on the sample circle or coastline segments. Given that the statistical distributions of these key hurricane parameters are known, a Monte Carlo approach is used to sample from each distribution, and a mathematical representation of a hurricane is passed along the straight line path satisfying the sampled data, while the simulated wind speeds are recorded. The intensity of the hurricane is held constant until landfall is achieved, after which time the hurricane is decayed using a filling rate model (e.g., DeMaria, et al. 2006).

The approaches used in the previously noted studies are similar, with the major differences being associated with the physical models used, including the filling rate models and wind field models. Other differences include the size of the region over which the hurricane climatology can be considered uniform (i.e. the extent of the area surrounding the site of interest for which the statistical distributions are derived), and the use of a coast segment crossing approach (e.g. Russell, 1971; Batts, et al., 1980, Tryggvason, et al. (1976), or a circular sub-region approach (e.g. Georgiou, et al., 1983; Georgiou, 1985; Neumann, 1991; Vickery and Twisdale, 1995b). Other differences include the selection of a probability distribution to fit a given parameter, such as central pressure (or central pressure difference), *RMW*, translation speed, etc. The overall simulation methodology associated with the aforementioned simulation models is outlined in Figure 1. The risk model developed by Neumann (1991) differs from the other models in that instead of modeling the central pressure within a hurricane, he modeled the maximum surface wind speed in the hurricane, as defined by the HURDAT database (Jarvinen, et al., 1984).
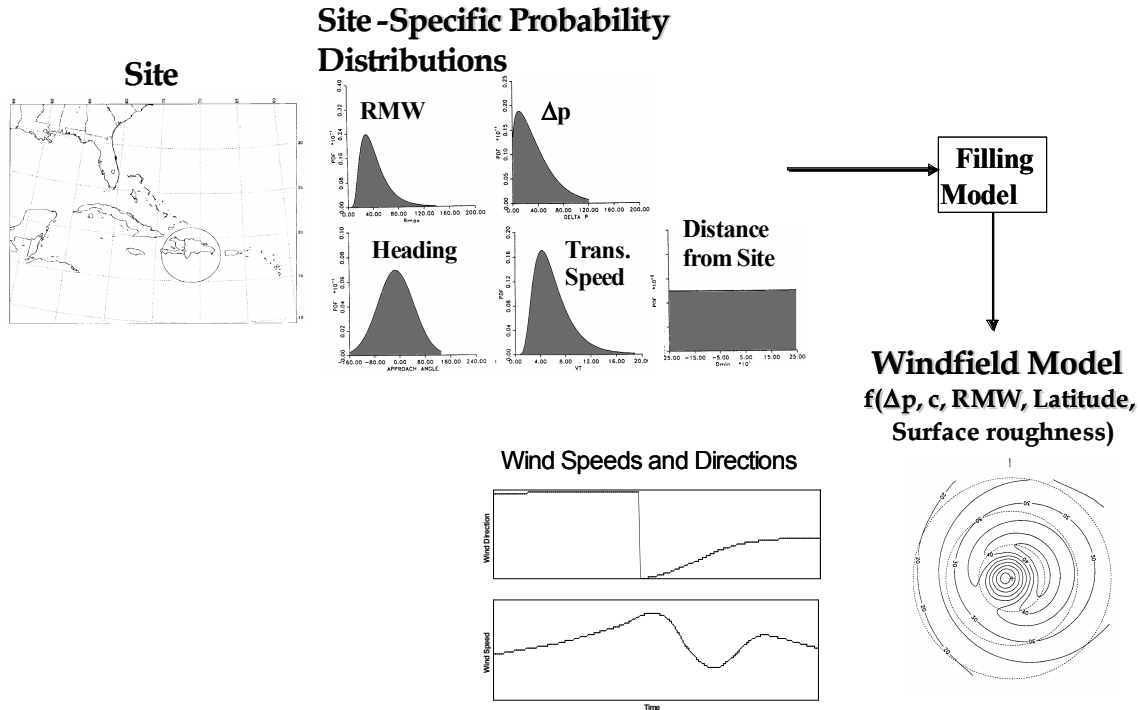
Figure 1. Overview of simulation modeling approach (site specific modeling)

The Batts, et al. (1980) model was used to develop the design wind speeds along the hurricane prone coastline of the United States, while the model described by Tryggvason, et al. (1976), was likely the first attempt to couple wind tunnel data with simulated hurricane wind speeds to develop design wind loads for individual buildings. In none of the works described in Russell (1968), Tryggvason, et al. (1976), or Batts, et al. (1980), was there any attempt to verify that the simple wind field models used in the simulations were able to reasonably reproduce the wind speeds and directions in real hurricanes. Georgiou (1985) was probably the first researcher to attempt to validate a wind field model used in the hurricane simulation methodology.

Darling (1991), took a slightly different approach to modeling the hurricane risk. Instead of developing statistical distributions for the central pressure, he developed distributions for the relative intensity of a hurricane and applied his model to hurricane risk in the Miami, FL area. The relative intensity is a measure of the intensity of a storm (as defined by wind speed or central pressure) compared to the theoretical maximum potential intensity of the storm (as defined by wind speed or central pressure). The maximum potential intensity (MPI) used by Darling (1991) is defined in Emanuel (1988). A key advantage associated with the introduction of the MPI into the simulation process was that it eliminated (at least for South Florida[1]), the need to artificially truncate the distribution of central pressure, as the MPI imposed a physical limit associated with the minimum central pressure of a simulated storm.

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[1] Relative intensities greater than one are possible in the case of intense fast moving storms that track over cold waters, and therefore have intensities greater than the theoretical maximum.

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2.2 Hurricane Track Modeling

A technique for modeling the entire tracks of tropical cyclones was first published by Vickery, et al. (2000a). Their approach employed the relative intensity approach pioneered by Darling (1991), but the major advantage of the approach developed by Vickery, et al. (2000a) was the ability to model the hurricane risk along the coastline of an entire continent, rather than being limited to a single point, or a small region. Vickery, et al. (2000), introduced an additional non-deterministic simulation parameter to the modeling approach, with the inclusion of the Holland B parameter (Holland, 1980) as a random variable. The track modeling approach has since been duplicated or expanded upon by Powell, et al. (2005), Hall and Jewson (2005), James and Mason (2005), Emanuel, et al. (2006), Lee and Rosowsky (2007), and proprietary insurance loss modeling companies. The track model developed by Emanuel, et al. (2006), combined a stochastic track model, with a deterministic axis-symmetric balance model and a 1-D ocean mixing model to model the life cycle of a hurricane. The axis-symmetric balance model used by Emanuel, et al. (2006) is described in detail in Emanuel, et al. (2004). Given information on sea surface temperature (SST), tropopause temperature, humidity and a few other parameters, coupled with a training set of historical storms, the model is able to mimic the strengthening and weakening of hurricanes as they progress along the modeled tracks, taking into account the effects of wind shear and ocean mixing, without using statistical models to model the changes in hurricane intensity. One of the key differences between the model developed by Emanuel et al. (2006) and those of Vickery, et al. (2000) and Powell, et al. (2005), is that the Emanuel, et al. (2006) model is "calibrated" to match National Hurricane Center estimates of sustained (maximum one minute average) wind speeds rather than central pressures. The impact of this key difference is discussed later. Vickery and Wadhera (2008), developed a hybrid model that combines some of the features of the Emanuel, et al. (2006) model and the Vickery, et al. (2000) model.

The track modeling approach represents the current state-of-the-art in hurricane risk assessment. It is the stepping stone for the next advancement, already pioneered by Emanuel, where the track models will be coupled with more advanced fully dynamic 3-D numerical weather prediction models such as an MM5 (Warner, et al. 1978) or a WRF (Skamarock, et al., 2005) type model. Whether or not the introduction of advanced numerical models will reduce the overall uncertainty in the track modeling process (owing primarily to the limited data associated with the historical record of hurricanes) remains to be seen.

3. HURRICANE WIND FIELD MODELING

The wind field modeling approach can be considered as a three step process where in the first step, given key input values (central pressure, *RMW*, etc.) an estimate of the mean wind speed at gradient height is obtained, in the second step, this gradient wind speed is adjusted to a surface level value, and in the third step, this surface level wind is adjusted for terrain and averaging time.

3.1 Gradient Wind Field Modeling

The sophistication of the wind field models used within the hazard simulation models has improved significantly since the 1970's, and continues to improve. In the Batts, et al. (1980) model, the maximum gradient wind speed is modeled as:

$$V_{G\max} = K\sqrt{\Delta p - \frac{RMWf}{2}} \approx K\sqrt{\Delta p} \tag{1}$$

where Δp is the central pressure difference (the difference between the pressure at the center of the storm and the far field pressure, normally taken as the pressure associated with the first anticyclonically curved isobar), *RMW is* the radius to maximum winds, *f* is the Coriolis parameter and *K* is an empirical constant. The variation of the wind speeds away from the maximum was described using a nomograph. Similar simple models were used in Russell, (1968) and Schwerdt, et al., (1979). The maximum gradient wind speed in the model used Tryggvason, et al., was also proportional to $\sqrt{\Delta p}$ but they used an analytic representation of the entire wind field rather than using a nomograph approach as in Batts, et al. (1980).

Holland, (1980) introduced a representation of the gradient hurricane wind field that has been employed in many hurricane risk studies, (e.g., Georgiou, et al., 1983, Harper, 1999, Lee and Rosowsky, 2007). Holland introduced an additional parameter to define the maximum wind speed in a hurricane, now commonly referred to as the Holland *B* parameter. Georgiou, et al. (1983), used Holland's model, but assigned a constant value of unity to *B*. Using Holland's model, the pressure, *p(r)*, at a distance *r* from the center of the storm is given as:

$$p(r) = p_c + \Delta p \exp[-(\frac{RMW}{r})^B] \tag{2}$$

The gradient balance velocity, V_G, for a stationary storm is thus:

$$V_G = \left[(\frac{RMW}{r})^B \frac{B\Delta p \exp[-(\frac{RMW}{r})^B]}{\rho} + \frac{r^2 f^2}{4} \right]^{1/2} - \frac{fr}{2} \tag{3}$$

where ρ is the density of air. The maximum wind speed at the *RMW* is

$$V_{G\max} \approx \sqrt{\frac{B\Delta p}{e\rho}} \tag{4}$$

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and thus the maximum velocity in the hurricane is directly proportional $\sqrt{B\Delta p}$ rather than simply being proportional to $\sqrt{\Delta p}$ alone as in most other models.

Georgiou, (1985) was the first to use a numerical model of the hurricane wind field for use in risk assessment when he employed the model described in Shapiro (1983), coupled with the Holland model to define the wind speeds at gradient height. In Georgiou's implementation of the Holland model, he constrained B to have a value of unity. Vickery, et al. (2000a) also used a numerical model to define the hurricane wind field model, employing a model similar to that of Thompson and Cardone (1996), and driving the model with the pressure field as described in (2), but not constraining B to be equal to 1. The models used by both Georgiou (1985) and Vickery, et al. (2000) were 2-D slab models, and in both cases techniques were implemented in such a way that they used pre-computed solutions to the equations of motion of a translating hurricane in the simulation process. The main reasons for using a 2-D numerical model are they provide a means to take into account the effect of surface friction on wind field asymmetries, they enable the prediction of super gradient winds and they model the effect of the sea-land interface (caused by changes in the surface friction) as well the enhanced inflow caused by surface friction.

To date, no 3-D models have been used in any peer-reviewed published hurricane risk studies, however, with the advances in computing power such studies are likely to become more common in the future. In all of the above noted examples, the estimated gradient wind speed is associated with a long period averaging time of the order of ten minutes to an hour. In each of the gradient-level wind field models noted in the earlier section the pressure field driving the wind field is assumed to be axisymmetric, which can be a significant simplification.

3.2 Hurricane Boundary Layer, Sea-Land Transition and Hurricane Gust Factors

Given an estimate of the mean wind speed at "gradient" height, this wind speed is then adjusted to the surface (10m above water or ground) through the use of a boundary layer (BL) model or a wind speed reduction factor V_{10}/V_G. The simple reduction factors for winds over the ocean used in the past (and to some extent, still used today) vary from as high as 0.95 (Schwerdt, et al., 1979) to a low of about 0.65 (Sparks and Huang, 2001). A value of 0.865 was used by Batts, et al. (1980), and Georgiou (1985), used a value of 0.825 near the eyewall, reducing to 0.75 away from the eyewall.

The wind speed ratios for the overland cases associated with the four examples are 0.845 at the coastline reducing to 0.745, 19 km inland (Schwerdt, et al., 1979), 0.45 (Sparks and Huang, 2001), 0.62 (Georgiou, 1985) and 0.74 (Batts, et al., 1980). These wind speed ratios correspond to reductions in the mean wind speed as the wind moves from the sea to the land of an immediate 11% reduction up to a 22% reduction (Schwerdt, et al., 1979), 30% reduction (Sparks, 2003), 16%-25% reduction (Georgiou, 1985), and a 15% reduction (Batts, et, al, 1980). In the case of Batts, et al. (1980), the roughness of the land is characterized by a surface roughness length of 0.005 m. In the case of Sparks and Huang (2001), open terrain is implied as they state that the 0.45 ratio applies to an airport

location a few km inland. The Georgiou (1985) wind speed reduction is also applicable to open terrain. In Schwerdt, et al., (1979), no reference is given to the land roughness other than to specify it is not rough.

Vickery, et al., (2000a), modeled the V_{10}/V_G ratio using hurricane boundary layer model based on Monin-Obukov similarity theory, coupled with an ocean drag coefficient model, with the drag coefficient C_d linearly increasing with wind speed as developed by Deacon (Roll 1965), yielding wind speed ratios that varied with both wind speed and the air-sea temperature difference. Vickery, et al., (2000a) introduced an empirical adjustment (increase in the wind speed ratio) of 10% near the eyewall. In the case of relatively intense storms with an air-sea temperature difference of zero, near the eyewall, the typical ratios of V_{10}/V_G in the Vickery, et al. (2000a) model were in the range of 0.70 to 0.72. In the Vickery, et al. (2000a) model, the reduction in the wind speed as the wind moves from the sea to the land is wind speed dependent because of the use of an un-capped[2] drag coefficient model. In Vickery, et al. (2000a), an un-capped drag coefficient model was used to estimate the ocean surface roughness, which was then coupled with the ESDU (1992, 1983) wind speed transition models to estimate the mean wind speed in open terrain. The resulting reduction in the mean wind speed associated with the Vickery, et al. (2000a) model varied from ~14% for intense storms to as much as ~20% for weaker storms.

Powell, et al. (2005) modeled the mean surface wind speed as equal to 80% of the boundary layer average wind speed, yielding $V_{10}/V_G \approx 0.73$, but varying some with wind speed. (The most recent update Powell, et al. model has been updated to use a 78% factor instead of an 80% factor, Powell, 2007). In their transition from sea-to-land, Powell, et al. (2005), used an un-capped drag coefficient model[3] to estimate the over water surface roughness, and then used the terrain transition model described in Simiu and Scanlan (1996) to compute the reduced over land mean wind speeds, yielding reductions in the mean wind speed similar to those estimated by Vickery, et al. (2000a). A summary of the values of V_{10}/V_G for a sample of hurricane "boundary layer" models available in the literature is given in Table 1.

Table 1. Example model values of V_{10}/V_G and sea-land wind speed reductions

Source	V_{10}/V_G over water (near eyewall)	Sea-Land Transition (% Reduction of Mean Wind Speed)
Schwerdt, et al. (1979)	0.95 (PMH) 0.90 (SPH)	11% at coast, 22% 19 km inland
Batts, et al. (1980)	0.865	15% at the coast
Georgiou (1985)	0.825 (eyewall)	0% at coast 25% 50 km inland
Sparks and Huang (2001)	0.65	30% a few km inland
Vickery, et al. (2000)	~0.70 to 0.72	14% to 20%, at the coast 23% to 28%, 50 km inland
Powell, et al. (2005)	~0.73	15% to 20% at the coast

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[2] Prior to Powell, et al. (2003), it was incorrectly theorized that the wind speed dependent surface drag coefficient was "un-capped" or that it continued to increase monotonically in > 40 m/sec winds
[3] A capped representation of the marine drag coefficient was implemented after the 2005 publication (Powell, 2007),

Powell, et al. (2003)	~0.71	N/A
Vickery, et al. (2007)	~0.71 (varies from 0.67 to 0.74)	18% to 20% at the coast

Analysis of dropsonde data collected during the period 1997 through to the present has improved our understanding of the overall characteristics of hurricane boundary layer (at least in the case of the marine boundary layer), but has also raised a few questions. The analysis of Powell, et al. (2003) revealed the following:

(i)   the marine boundary layer is logarithmic over the lower ~200 m

(ii)   the mean wind speed at a height of 10 m is equal to ~78% of the mean boundary layer wind speed (average wind over the lower 500 m)

(iii)   the mean wind speed at 10 m is equal to ~71% of the maximum (or gradient) wind speed

(iv)   the sea surface drag coefficient increases with wind speed up to a mean wind speed (at 10 m) of about 40 m/sec, after which the drag coefficient levels off or perhaps even decreases with increasing wind speed.

(v)   the boundary layer height decreases with increasing wind speed.

Vickery, et al. (2007), also examined the dropsonde data, separating the data by storm size as well as wind speed and coupled their analysis of the dropsonde data with a simplified version of the linearized hurricane model developed by Kepert (2001). In agreement with Kepert (2001), the data showed that the boundary layer height decreases with increasing inertial stability, and the boundary layer is logarithmic over the lower two hundred meters or so. Figure 2 shows the variation of mean wind speed with height derived from the analysis of dropsondes for a range of mean boundary layer wind speeds and storm radii as given in Vickery, et al. (2007). All profiles shown in Figure 2 were taken at or near the *RMW*. Vickery, et al. (2007) empirically modeled the variation of the mean wind speed, $U(z)$ with height, z, in the hurricane boundary layer using:

$$U(z) = \frac{u_*}{k}\left[\ln(\frac{z}{z_o}) - 0.4(\frac{z}{H^*})^2\right] \tag{5}$$

where k is the von-Karman coefficient having a value of 0.4, u_* is the friction velocity, z_o is the surface roughness length, and H^* is a boundary layer height parameter that decreases with increasing inertial stability according to:

$$H^* = 343.7 + 0.260/I \tag{6}$$

where the inertial stability I is defined as:

$$I = \sqrt{(f + \frac{2V}{r})(f + \frac{V}{r} + \frac{\partial V}{\partial r})} \qquad\qquad (7)$$

V is the azimuthally averaged tangential gradient wind speed, f is the Coriolis parameter and r is the radial distance from the center of the storm. The boundary layer model described in Vickery, et al., (2007), represents an azimuthally averaged model and ignores the predicted variation in the shape of the hurricane boundary layer as a function of azimuth in the hurricane as predicted by Kepert (2001).
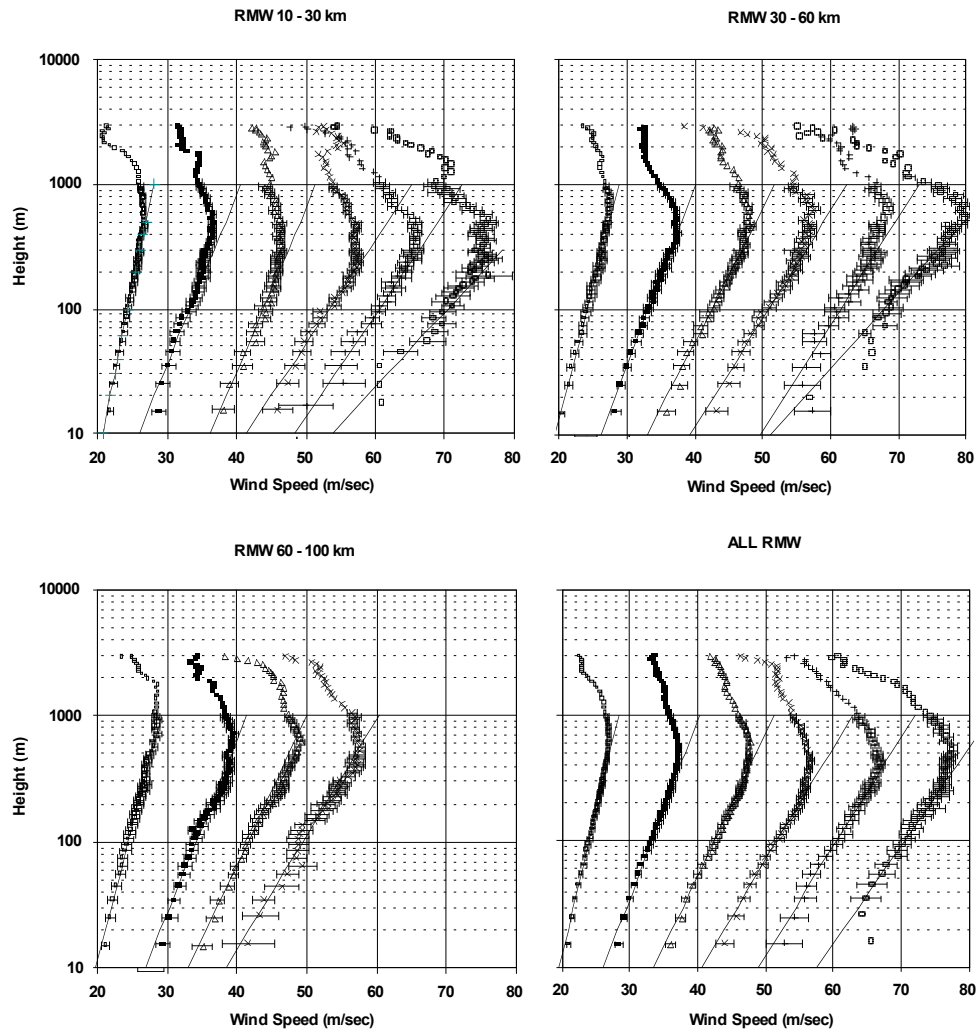
Figure 2. **Mean and fitted logarithmic profiles for drops near the *RMW* for all MBL cases. Horizontal error bars represent the 95th percentile error on the estimate of the mean wind speed. LSF fits are for the 20 – 200 m case. (MBL cases correspond to 20-29 m/sec, 30-39 m/sec, 40-49 m/sec, 50-59 m/sec, 60-69 m/sec, and 70-85 m/sec)**

As in Powell, et al. (2003), the sea surface drag coefficient estimated from the dropsondes described in Vickery, et al., (2007) initially increases with wind speed in a

fashion similar to that modeled by Large and Pond (1980) and then reaches a maximum value and levels off or decreases (Figure 3). The mean wind speed at 10 m (U_{10}) at which the sea surface drag coefficient reaches this maximum is only about 25 m/sec, (i.e. less than in Powell, et al. 2003) but varied some with storm radius. This lower threshold is consistent with the values estimated in Black, et al. (2007), of about 23 m/sec., although there were limited measurements taken at wind speeds above 25 m/sec. The combination of the empirical boundary layer model and the variable cap on the sea surface drag coefficient yield ratios of V_{10}/V_G over the ocean of about 0.67 to 0.74, varying with both storm size and intensity.

Figure 4 presents a comparison of the modeled and observed marine wind speed profiles computed using the drag coefficients shown in Figure 3, and the boundary layer model described by equations (5) through (7), with the only input to the model consisting of the maximum (gradient) wind speed and distance from the center of the storm.
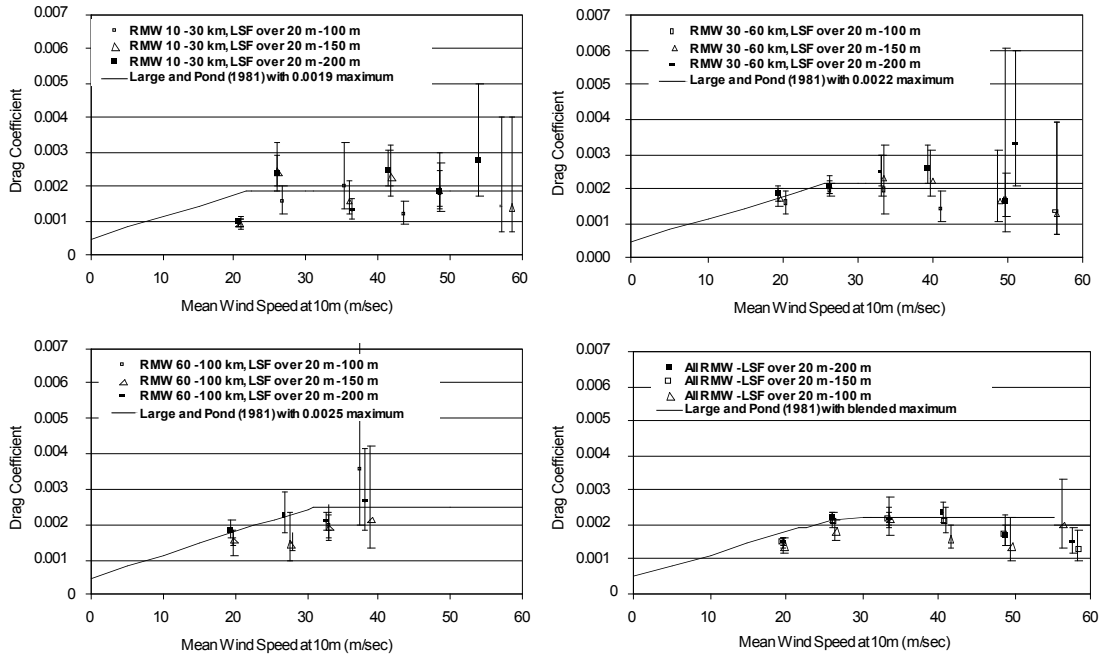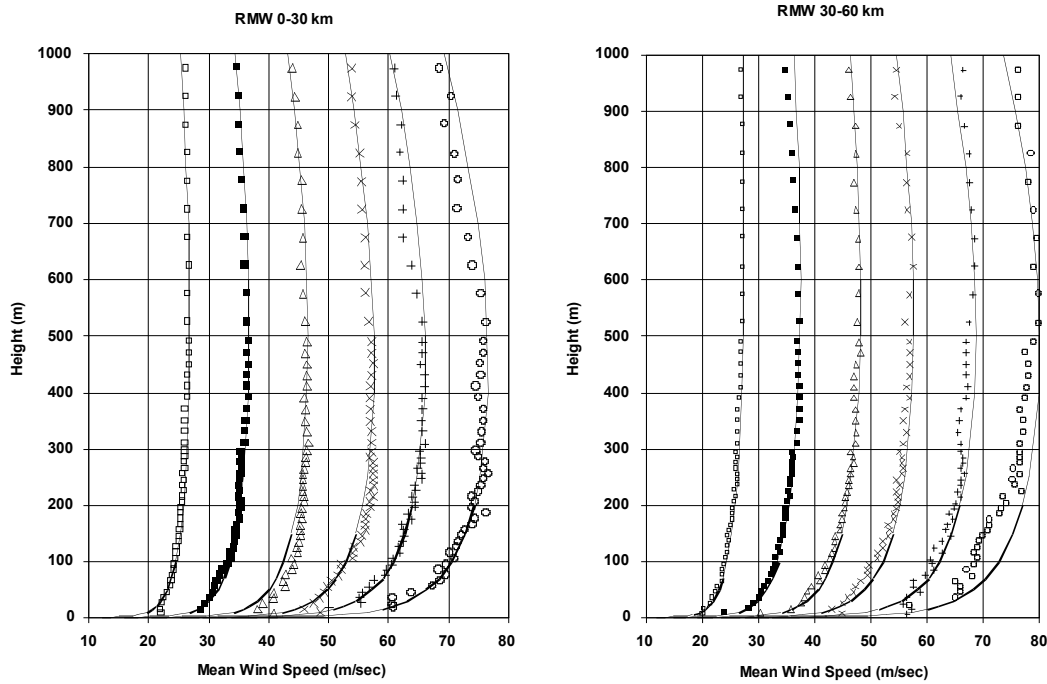

Figure 3. **Variation of the sea surface drag coefficient with U_{10} near the *RMW*.**

Figure 4. **Modeled and observed hurricane mean velocity profiles over the open ocean for a range of wind speeds**

Unfortunately dropsonde data is limited for velocity profiles over land, and as a result, there is more reliance on models to estimate the characteristics of the hurricane boundary layer over the land. The standard engineering approach to modeling terrain change effects is to assume that the wind speed at the top of the boundary layer remains unchanged (but the boundary layer height is free to change) and adjust the winds beneath the BL height to be representative of those associated with the new roughness length. Vickery, et al. (2007), estimated the change in the BL height using Keperts (2001) linear BL theory, but further increased the BL height increase predicted by Keperts (2001) model so that the reduction in the surface level winds predicted by the model matched the ESDU values for large BL height. The net result of the Vickery, et al., (2007) approach is estimated BL height increases (from marine to open terrain) in the range of 60% to 100%, implying overland BL heights in the range of ~800m to ~1500m depending on wind speed and *RMW*. Powell, et al. (2005) used a 100% increase in the BL height as the wind transitioned from sea to land.

Figure 5 presents the results of the BL height increase used in Vickery, et al. (2007) as seen through a comparison of the resulting reduction in the surface level winds brought about by the combined effects of a BL height increase and a surface roughness increase as the wind transitions from marine to open terrain conditions. The upper curve denoted cyclonic flow in Figure 5, presents the reduction in the wind speed computed using Keperts (2001) BL height method, assuming no change in the mean wind speed at the top of the BL.
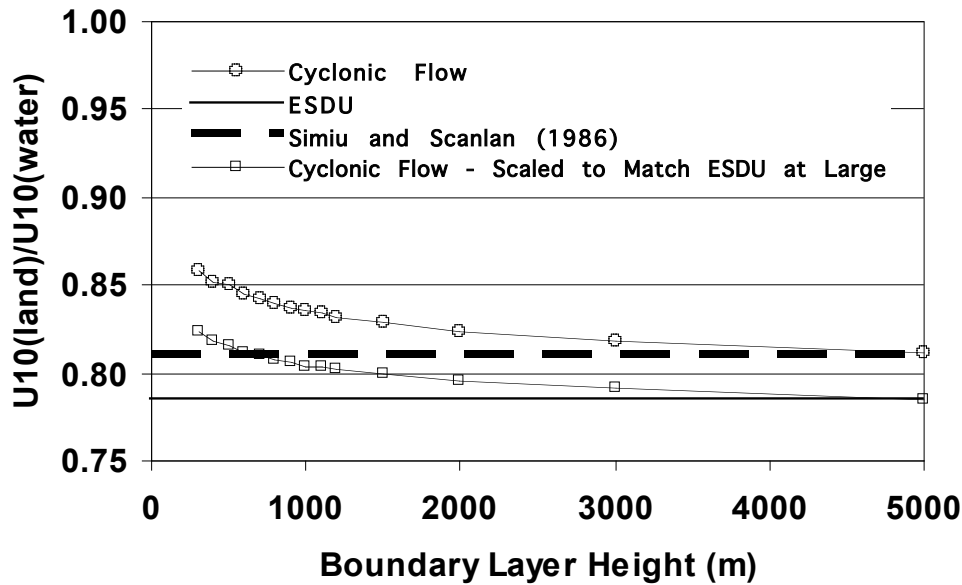
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Figure 5. **Ratio of the fully transitioned mean wind speed over land (z_o=0.03m) to the mean wind speed over water (z_o=0.0013m) as a function of boundary layer height.**

3.3 Hurricane Gust Factors

In many cases, estimates wind speeds associated with averaging times different to that produced by the basic hurricane wind field model are required in the final application (e.g. one minute average winds, peak gust wind, etc.). Various representations of a gust factor model for use in hurricanes/tropical cyclones have been employed within different hurricane hazard models. In the case of Batts, et al., (1980), they used the gust factor model described by Durst (1960). Krayer and Marshall, (1992) developed a gust factor model for hurricane winds, which indicated that the winds associated with hurricanes are "gustier" than those associated with non-hurricanes. Schroeder, et al. (2002), and Schroeder and Smith (2003) using data collected from North Carolina hurricane wind speeds also suggested that hurricane gust factors are larger than those associated with extra-tropical storms.

Sparks and Huang (1999) examined a large number of wind speed records and concluded that there was little evidence to suggest that gust factors associated with hurricanes are different than those associated with extra-topical storms. Vickery and Skerlj (2005) re-analyzed the data used by Krayer and Marshall (1992), added additional data and also concluded that there was little evidence to suggest that gust factors associated with hurricanes are different than those associated with extra-topical storms and furthermore, the mean gust factors in hurricanes could be adequately described using the ESDU (1982, 1983) formulations for atmospheric turbulence developed for extra-topical storms. Both Sparks and Huang (1999) and Vickery and Skerlj (2005) attributed the larger gust factors apparent in the Krayer and Marshall (1992) model to surface roughness larger than that

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typically associated with open terrain (i.e. z_o=0.03 m). Miller (2006) concurred with the analysis of Vickery and Skerlj, (2005), that there was little difference between hurricane gust factors and those associated with non-hurricane winds. Figure 6 presents a comparison of the gust factors (with respect to a 60 second averaging time wind speed) derived from the ESDU model to those presented by Masters, (2005), suggesting that the mean gust factors associated with hurricanes are comparable to those predicted using the ESDU models.

Although the wind speed records obtained in hurricanes suggest that for the most part, the near surface gust factors in hurricanes are similar to those in non-hurricanes, there is enough evidence to indicate that there are additional sources of turbulence that may contribute to infrequent and relatively small scale, strong winds, that are much larger than would be predicted by the ESDU gust factor model. These anomalous gusts may be associated with wind swirls generated by horizontal shear vorticity on the inner edge of the eyewall (Powell et al., 1996), coherent linear features e.g. rolls in the boundary layer (Wurman and Winslow, 1998, Foster, 2005), or other convective features of the storms. While it appears that the ESDU gust factor model provides an adequate description of the gust factors associated with hurricane winds near the surface, additional research is needed to enable modeling of other small scale, but potentially important meteorological phenomena.
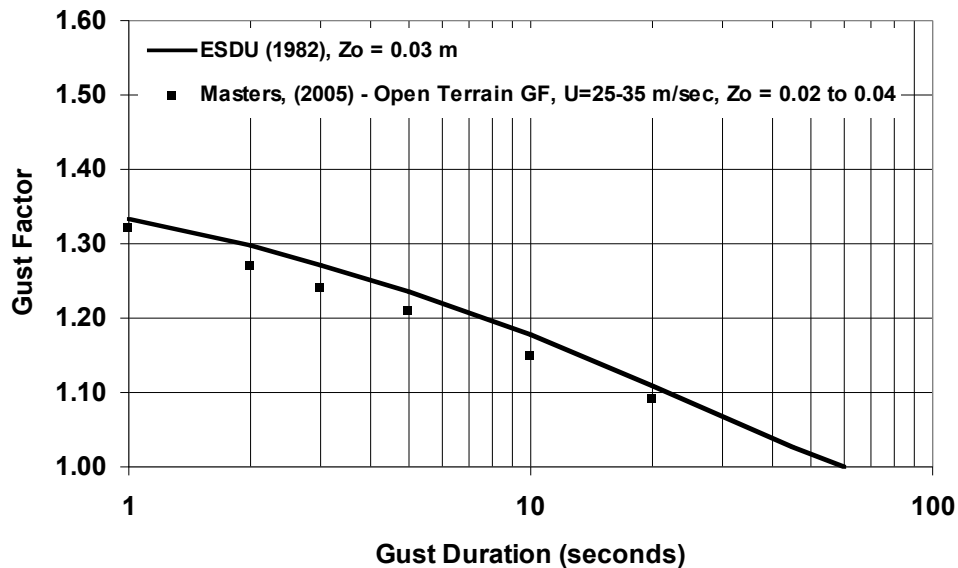

Figure 6. **Comparison of the ESDU gust factor model to those derived from hurricane winds as reported in Masters, 2005**

3.4 Wind Field Model Validation

An important step in the entire hurricane risk modeling process is the ability of the wind field model used in the simulation procedure to reproduce measured wind speeds, varying only those parameters which are free to vary within the simulation approach. Georgiou, (1985) was probably the first to attempt to validate a hurricane wind field model used in a

simulation model, looking at the time variation of both wind speeds and wind directions. Vickery and Twisdale (1995), and Vickery, et al. (2005) performed similar validation analyses and extended the comparisons of wind speed to examine both the mean and gust wind speeds. Similar but limited validation studies for models to be used hurricane risk assessment have been presented, for example, in Harper, (1999) and Lee and Rosowsky, (2007). In the comparisons of modeled and observed wind speeds given Vickery, et al., (2007), comparisons are given for wind speeds, wind directions surface pressures, ensuring that the wind model is able to reproduce the observed winds without compromising the ability to model the pressure field, which is a basic input to the simulation. Figure 7 presents an example of comparisons of modeled and observed wind speeds showing pressures, gust and average wind speeds and wind directions. The pressure verification step has been omitted in all other model verification studies given in the literature.
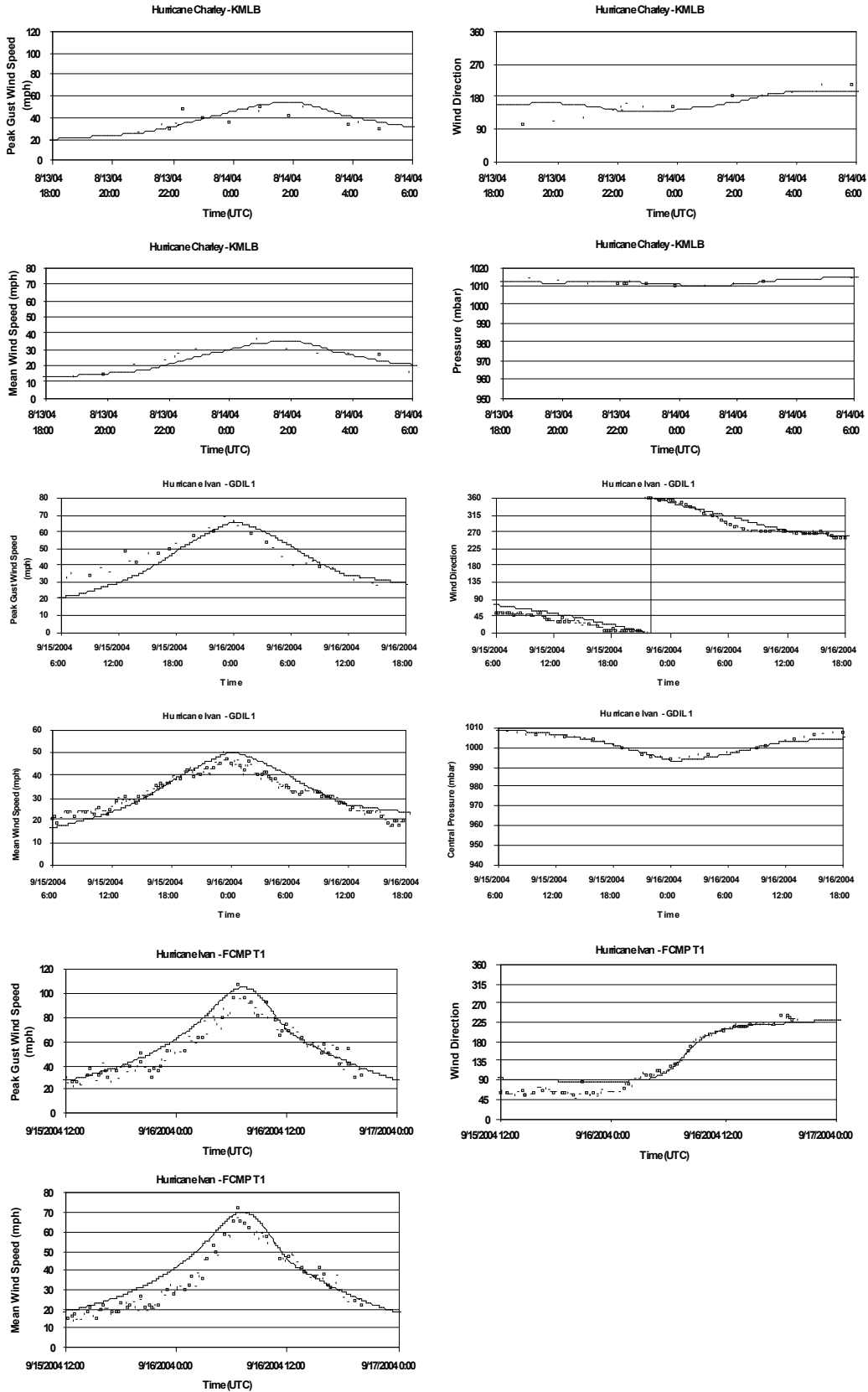
Figure 7. Example comparisons of model an observed wind speeds, directions and pressures
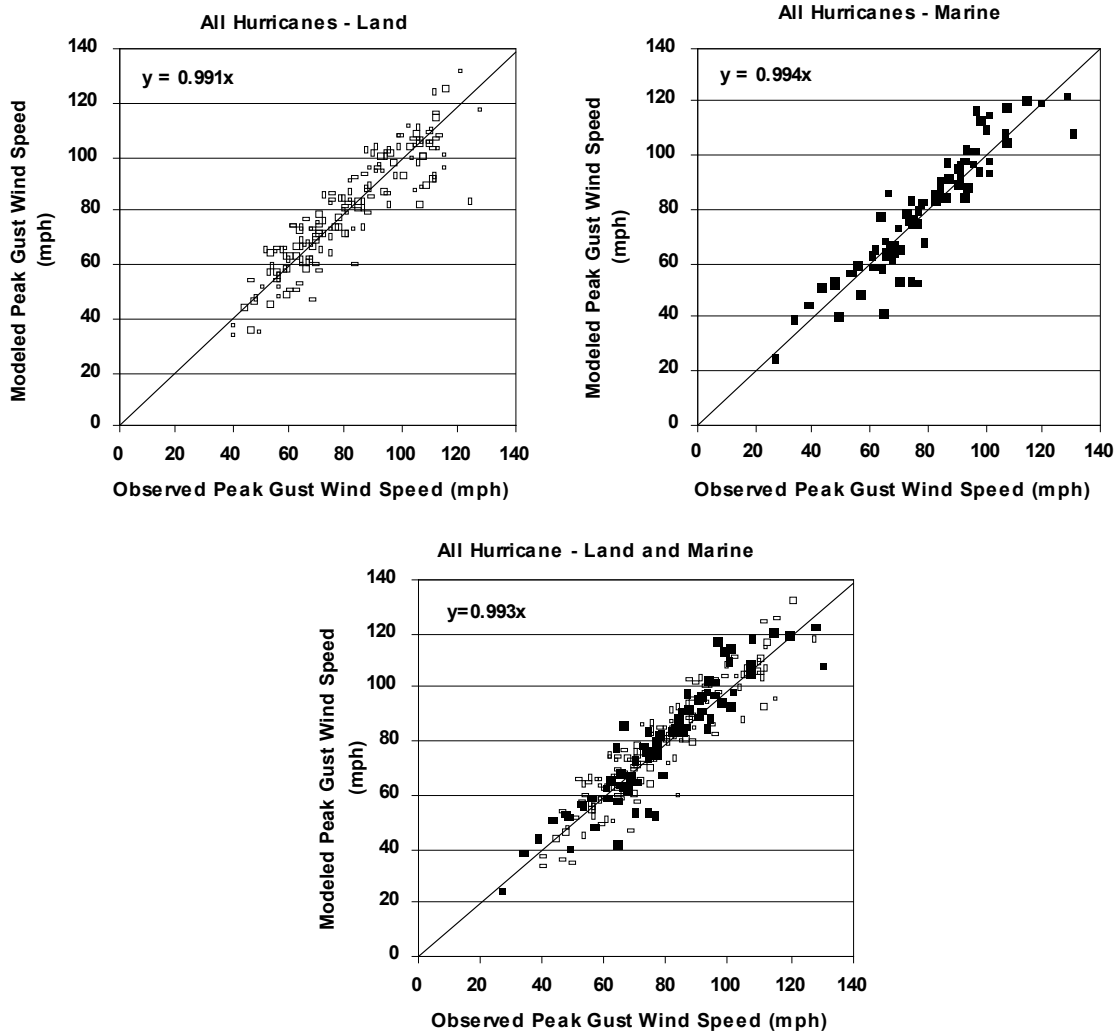
The wind field model comparisons are important to identify any biases in the wind model portion of the simulation process, but good validations can be a result of compensating errors. For example, the high gust factors associated with the use of the Krayer-Marshall gust factors used by Vickery and Twisdale (1995) partially compensated for an overall underestimate of the mean wind speed at the surface. Similarly, it should be noted that when the hurricane wind models are validated, the validation process is performed using surface level winds, and even though the basic input to the wind field model is nominally a gradient level wind, verification of surface winds does not constitute a verification of the upper level winds. This distinction regarding at what height the validation is performed may be important in cases where the hurricane simulation results are used in combination with wind tunnel test data for high rise buildings. In both Georgiou, (1985) and Vickery and Twisdale, (1995), the use of a Holland B parameter of unity coupled with the Shapiro model is now known to yield an underestimate of the gradient wind speed. The underestimate was compensated for by a boundary layer model that was too shallow (i.e. ratios of V_{10}/V_G that were too high), resulting in reasonable estimates of the surface level wind speeds, and underestimates of gradient level wind speeds.

Figure 8 presents a summary comparison of the maximum peak gust wind speeds computed using the wind field model described in Vickery, et al., (2007) to observations for both marine and land based anemometers. There are a total of 245 comparisons summarized in data presented in Figure 8 (165 land based measurements and 80 marine based measurements). The agreement between the model and observed wind speeds is good, however there are relatively few measured gust wind speeds greater than 100 mph (45 m/sec). The largest observed gust wind speed is only 128 mph. The differences between the modeled and observed wind speeds is caused by a combination of the inability of wind field model to be adequately described by a single value of B and RMW, errors in the modeled boundary layer, errors in height, terrain and averaging time adjustments applied to measured wind speeds (if required) as well as storm track position errors and errors in the estimated values of Δp, RMW and B. The model-observed error information gleaned from the comparisons does provide one of the pieces of information required to assess the overall uncertainty of the simulation process.

An alternative method of validation is to compare the entire modeled wind field "snapshot" at a particular time, to a gridded output from an objective analysis of all available observations over a relatively short (4-6 h) period of time during which stationarity is assumed. Such analyses are the products of the Hurricane Wind Analysis System (H*Wind, Powell, et al., 1998). An archive of H*Wind analyses are available over the web at: http://www.aoml.noaa.gov/hrd/data_sub/wind.html. Example wind model-H*Wind comparisons are given in Figure 9.

An estimate of the "observed" Holland B parameter to use in the model may be diagnosed from the H*Wind field by subtracting the storm motion, computing the axi-symmetric radial profile of the surface wind speed, dividing by a gradient to surface wind reduction factor to get a gradient wind estimate, and finally fitting various values of B until the peak gradient wind is matched.

All Hurricanes - Land

y = 0.991x

All Hurricanes - Marine

y = 0.994x

All Hurricane - Land and Marine

y=0.993x

Figure 8. **Example comparisons of modeled and predicted maximum surface level peak gust wind speeds in open terrain from US landfalling hurricanes. Wind speeds measured on land are given for open terrain and wind speeds measured over water are given for marine terrain.**

A series of such snapshots may then be combined to construct a "swath" of maximum winds over a gridded domain. The Florida Public Hurricane Loss Model (Powell, et al., 2005) incorporates both snapshot and swath comparisons for the validation process. The grid point comparisons are conducted for all points in which the model winds are above wind damage threshold speeds (gust wind speed of ~55 mph) and vice versa. While the shapes of the modeled and observed fields have similar features, it is noted that the extent of damaging winds can vary considerably between the fields. Such analyses are especially helpful for identifying biases in the choice of the correct Holland parameter. However, even a *B* parameter diagnosed from the observations may not be enough to overcome limitations in the Holland pressure profile (Willoughby, et al., 2004, 2006).
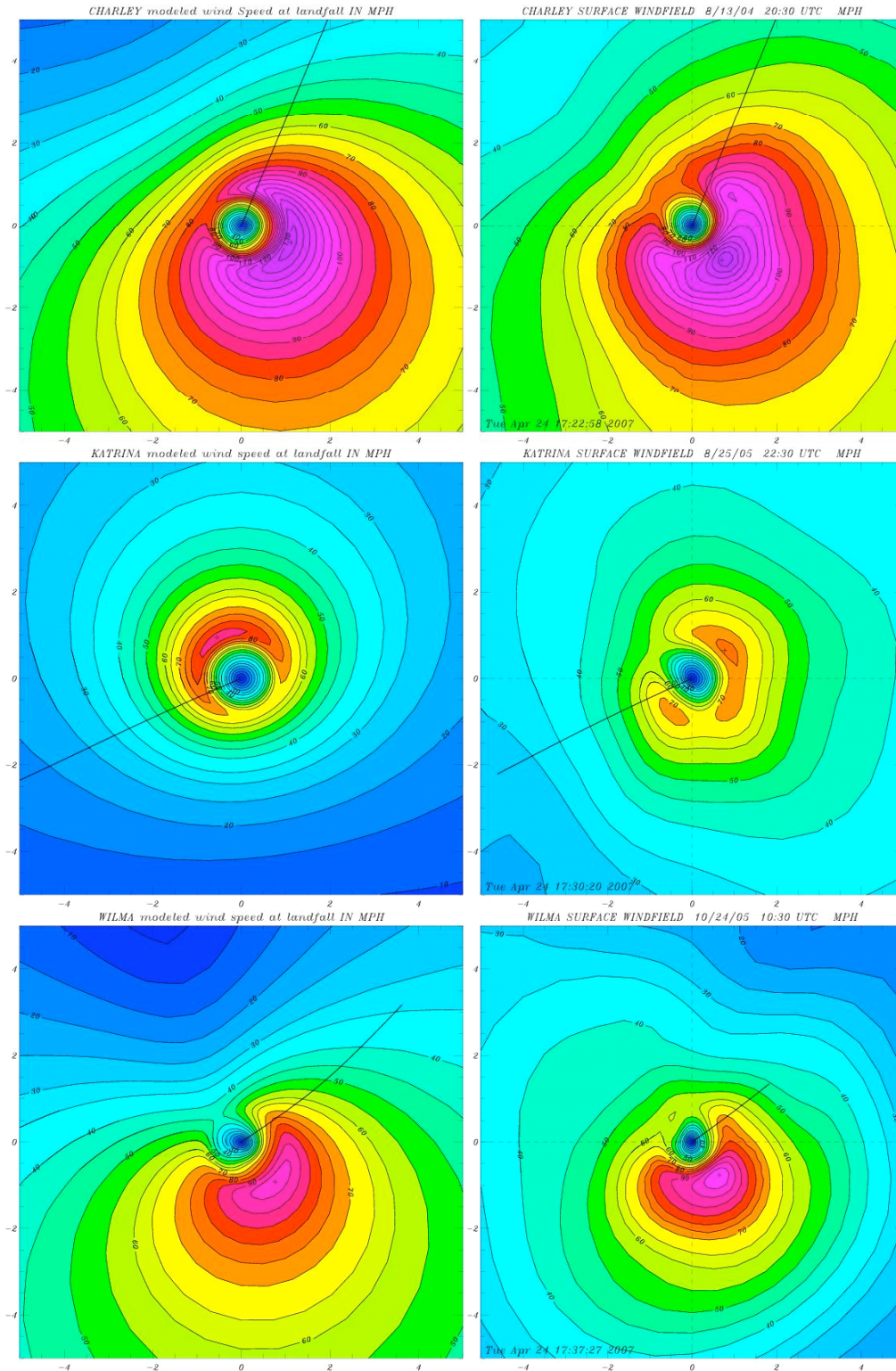
Figure 9. Comparison of observed (right) and FPHLM modeled (left) landfall wind fields of Hurricanes Charley (2004, top), and 2005 Hurricane Katrina in south Florida (middle), and Hurricane Wilma (bottom). Line segment indicates storm heading. Horizontal coordinates are in units of *r/RMW*. Winds are for marine exposure.

4. OTHER IMPORTANT MODEL COMPONENTS

Other modeling components important to the overall simulation procedure include the modeling of the radius to maximum winds, the Holland B parameter (for some models) and modeling the weakening of the hurricanes after they make land fall. As demonstrated in Equation 4, the Holland B parameter plays as important a role in the estimation of the maximum wind speeds as does Δp. According to Holland (1980), B can vary from about 0.5 to about 2.5, however; variations in the range of about 0.7 through 2.2 (Willoughby, et al., 2004, Powell, et al., 2005, Vickery and Wadhera, 2007) are more typical and reasonable, but this is still a factor of about 3 or about a 70% variation in wind speed. Modeling the variation of B has become an important part of the hurricane simulation process, affecting both the magnitude of the maximum wind speeds and the aerial extent over which these large winds extend.

Although given a value of the *RMW* it has no effect on the magnitude of the maximum wind speeds (all else being equal), the *RMW* has a significant impact on the area affected by a storm, and for a single site wind risk study, the modeling of the *RMW* impacts the likelihood of the site experiencing strong winds in cases of near misses. Modeling of the *RMW* is critical to storm surge and wave modeling as well as for estimating probable maximum losses for insurance modeling purposes. It is generally accepted that the magnitude of the *RMW* is negatively correlated with the central pressure difference, so that more intense storms (larger central pressure difference) are have smaller RMW than the weaker storms. The *RMW* also increases with increasing latitude. In most models, the *RMW* is modeled as log-normally distributed with the median value of *RMW* modeled as function of central pressure and/or latitude and there is significant scatter of the data about the modeled *RMW*- Δp relationships.

4.1 Statistical Model for Holland B Parameter

As indicated previously, the Holland B parameter can play an important role in the estimation of the maximum wind speeds in a hurricane. Harper and Holland (1999) indicate that for Australian Cyclones, B is a linear function of central pressure so that B can be modeled as:

$$B = 2.0 - (p_c\text{-}900)/160 \tag{8}$$

so that as the central pressure decreases (i.e. Δp increases) then B increases.

Vickery, et al. (2000) found a very weak relationship between B and both *RMW* and Δp, with B decreasing with increasing *RMW* and increasing with increasing Δp.

In Powell, et al. (2006), using the values of B computed by Willoughby, et al. (2004) using flight level data of wind speeds, modeled the Holland B parameter as a function *RMW* and latitude, ψ, in the form:

$$B = 1.881 - 0.00557 RMW - 0.01097\ \psi, \qquad\qquad r^2 = 0.200,\ \sigma_B = 0.286 \tag{9}$$

where *RMW* is in km and ψ is the latitude expressed as degrees N. Powell, et al, (2005) found no relationship between *B* and central pressure.

Vickery and Wadhera, (2007) used the same flight level data as used by Willoughby, et al, (2004, 2006), but fit the radial pressure profiles rather than the radial velocity profiles. As shown in Figure 10, Vickery and Wadhera (2007) found that *B* could be modeled as a function of a non-dimensional parameter, *A*, defined as:

$$A = \frac{RMW \cdot f}{\sqrt{2R_d T_s \cdot \ln\left(1 + \frac{\Delta p}{p_c \cdot e}\right)}} \tag{10}$$

The numerator of *A* is the product of the *RMW* (in meters) and the *f* represents the contribution to angular velocity associated with the Coriolis force. The denominator of *A* is an estimate of the maximum potential intensity (as defined by wind speed) of a hurricane. In Equation 10, R_d is the gas constant for dry air, p_c is the central pressure, T_s is the sea surface temperature in degrees K and p_c is the pressure at the storm center. Both the numerator and denominator of *A* have the units of velocity, and *A* is non-dimensional. The relationship between *B* and *A* is expressed as:

$$B = 1.732 - 2.237\sqrt{A} \; ; \qquad\qquad r^2 = 0.336, \; \sigma_B = 0.225 \tag{11}$$
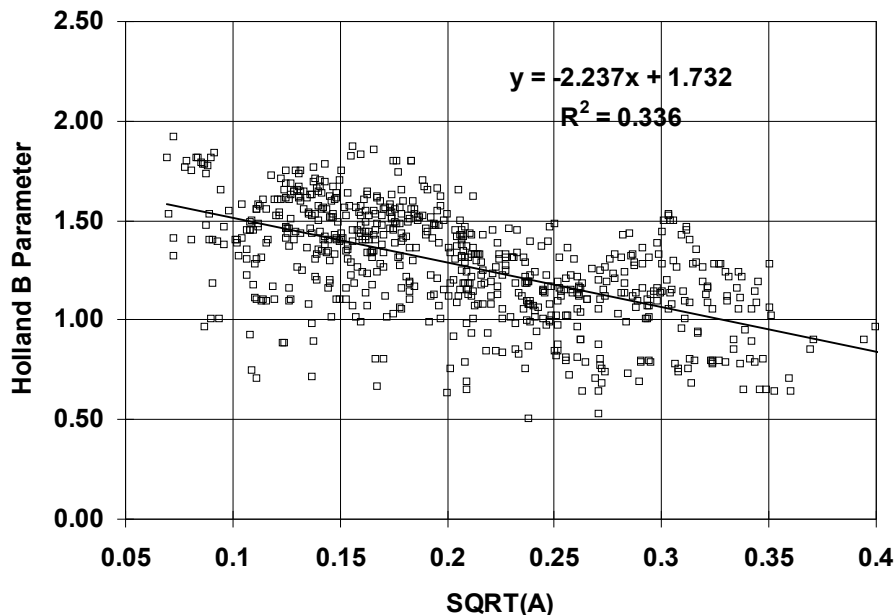

Figure 10. Relationship between the Holland *B* parameter dimensionless parameter, *A*.

Both Powell, et al. (2005) and Vickery, et al. (2007) found that *B* decreases with increasing *RMW* and increasing latitude, and is weakly (if at all) dependent on the central pressure, in contrast to the relationship suggested by Harper and Holland (1999).

Although, the inclusion of the modeling *B* in the simulation process is a significant improvement over the use of a single and constant value of *B* (usually 1 for Atlantic storms), as discussed for example in, Willoughby, et al., (2004, 2006) and Thompson and Cardone (1996), a single value of *B* cannot model all storms at all times. The simple single parameter model is unable to reproduce the wind fields associated with eyewall replacement cycles, and also has a tendency to underestimate winds speeds well away from the center of the storm. Fortunately, as indicated indirectly in the comparison of modeled and observed wind speeds shown in Figures 7 and 8, modeling hurricanes with a single value of *B* is satisfactory in many cases. Hurricane Wilma in South Florida (2005) is an example of a landfalling hurricane that is poorly modeled using a single value of *B*. (Wind speed comparisons for hurricane Wilma are included in those given in Figure 8.) Both surface level anemometer data and remotely sensed data indicate that the strongest surface level winds occurred on the left side of the storm rather than the right as is estimated by modeling the storm with an axi-symmetric pressure field modeled with single values of *B* and *RMW*.

4.2 Filling Models

Once storms make landfall, they fill or weaken as the central pressure increases. This filling is not to be confused with the additional reduction in wind speeds associated with the increased land friction. Accurate estimates of filling are important for estimating wind speeds at locations removed from the coast by as little as a few tens of km, and becomes even more important as the distance inland increase. The rate of filling varies with geography, local topography, local climatology and individual cyclone characteristics. Statistically based filling models should not be applied to regions outside those used to develop the models.

Most filling models (e.g. Batts, et. al, 1980, Vickery and Twisdale 1995, Kaplan and DeMaria) weaken the storms as a function of time since landfall. Georgiou (1985) departed from this approach and weaken the storms as a function of distance since landfall. Vickery, 2005, revisited the filling of storms impacting the coastal United States and found that the rate of filling is best modeled as a function of $c\Delta p_o/RMW$, where *c* is the translation speed of the hurricane at landfall, and Δp_o is the central pressure difference at landfall. The dependence of the filling rate on translation speed at the time of landfall is in general agreement with the findings of Georgiou, (1985) who suggested that distance inland is a better indicator of filling than time since landfall.

5. MODELING UNCERTAINTY

An assessment of the errors associated with the hurricane simulation process has received very little attention in literature, and even when estimates of the potential errors are presented, they are unlikely to be used. Batts, et al., (1980) carried out a rough error

analysis through a combination of sensitivities studies and judgment and suggested that the confidence bounds (± one standard deviation) of their predicted wind speeds were about 10% (independent of return period). Twisdale and Vickery (1993) performed an uncertainty study for predicted wind speeds in the Miami area and found a comparable uncertainty.

Using an updated version of the hurricane hazard model described in Vickery, et al. (2000), estimates of the uncertainty in the prediction of the *N*-year return period peak gust wind speeds are performed using a two loop simulation approach. Using this two loop approach, the 100,000 year simulation used to estimate the *N*-year return period wind speed is repeated 1,000 times (outer loop), where for each new 100,000 year realization, fully correlated errors in the statistical distributions of landfall central pressure, Holland *B* parameter and occurrence rate, are sampled, and used to perturb these key input variables. An inner loop consists of sampling an un-correlated wind field modeling error (derived from Figure 8), having a mean of zero and a coefficient of variation of 10%. The outer loop uncertainty results in a CoV of the estimated 100 year return period wind speed of about 8%, varying somewhat with location. The uncertainty in the wind model (treated here as uncorrelated) appears as a shift in the mean wind speed vs. return period curve, rather than appearing as an additional component of the uncertainty in the *N*-year wind speed. Figure 11 presents an example of the estimated uncertainty in the 100 year return period wind speed along the coast of the US, as well as an example of the impact of the wind field model uncertainty on the mean estimate of the N-year return period wind speed. Note that the uncertainty examples given here are representative wind speeds associated with US landfalling hurricanes and would not be representative of the uncertainties in other countries. For example, the landfall pressures for most US landfalling storms have been carefully reconstructed over a 107 year period using combinations of surface and aircraft measurements of pressure, whereas, the Northwest pacific typhoon database is comprised of a combination of aircraft and satellite estimated pressures, which are subject to large and potentially time varying uncertain errors, covering a much shorter time span.
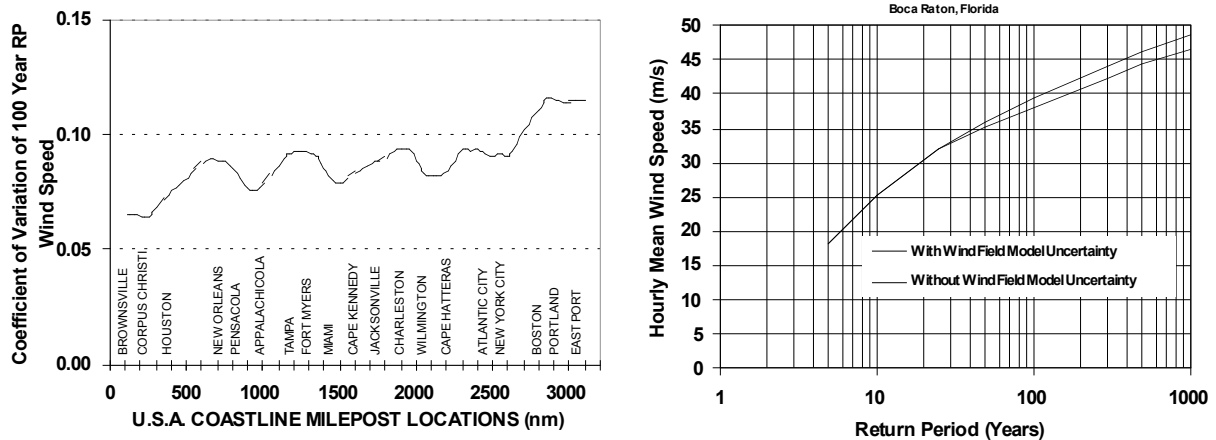
Figure 11. Estimate coefficient of variation (smoothed) of the 100 year return period wind speed along the coastline of the US (left plot), and effect of windfield modeling uncertainty of the predicted wind speed vs. return period for a single location.

6. HISTORICAL RECORD, CLIMATE CHANGE AND LONG PERIOD OSCILLATIONS

Trends in frequency and intensity of tropical cyclone impacts are of special import to hurricane modelers, as ultimately the model output *n*-year recurrence interval wind speeds are determined from site-specific climatology on a timescale that far exceeds the lifecycle of the infrastructure, assets, etc. at that location. The effects of annual to multi-year (El Niño / La Niña) and multi-decadal oscillations (AMO) are generally accepted, owing to basin-wide databases (e.g. HURDAT) in the Atlantic and Pacific oceans. However, the effect of long-term variations from anthropogenic (human-influenced) global warming is an ongoing and controversial issue still under debate among climatologists and tropical meteorologists, especially so in light of the prolific 2004 and 2005 hurricane seasons.

Knutson and Tuleya (2004) used a high-resolution GFDL model and a spectrum of climate model boundary conditions and hurricane model convection schemes to estimate the effects of a CO_2-warmed environment. The aggregate results indicate a 14% increase in central pressure fall, a 6% increase in maximum surface wind speed, and an 18% increase in average precipitation rate within 100 km of the storm center. However, Webster, et al. (2005) concluded that a doubling of CO_2 would not increase the frequency of the most intense cyclones. Emanuel (2005) linked global warming to the destructiveness by tropical cyclones in the Atlantic and western North Pacific basins after he established that hurricane power dissipation is highly correlated with tropical sea surface temperature. Based on projections of emissions scenarios, the Intergovernmental Panel on Climate Change concluded that it is likely that intense tropical cyclone activity will increase throughout the 21st century (IPCC 2007). These conclusions, however, are receiving considerable scrutiny concerning their basis in the global hurricane data. Landsea, et al. (2006) and Landsea (2007) found existing tropical cyclone databases to be sufficiently unreliable in the detection of trends in the frequency of extreme cyclones. Reanalysis of satellite imagery suggests that there were at least 70 additional, previously unrecognized category 4 and 5 cyclones in the Eastern Hemisphere during 1978-1990. The 1970 Bangladesh cyclone, which killed between 300,000 to 500,000 people, does not even have an official intensity estimate on record.

7. NUMERICAL WEATHER PREDICTION MODELS

As previously discussed, the first published hurricane risk model incorporating a numerical weather prediction (NWP) type of model is that of Emanuel, et al., (2006), where they coupled Emanuel's CHIPS (coupled hurricane intensity prediction system) hurricane intensity model with the NCAR climate re-analysis data. Two different versions of the hurricane risk model were developed, with both versions using a deterministic 1-D numerical hurricane intensity model (Emanuel, et al., 2004), a simple ocean feedback model and a statistically based wind shear model. Two different track models were developed, one using a Markov modeling approach similar to that of Vickery, et al., (2000) and the other modeling the hurricane track using a weighted average of an environmental flow as a track predictor, also derived from the NCAR re-

analysis data. The model was validated through comparisons of model estimated maximum winds with NHC best track data. No validation of storm size was presented, nor was the wind model validated with comparisons with surface level anemometer data or H*Wind data.

Similar approaches have been taken by others using the GFDL model, MM5 and the WRF model, however; results have not been published in the peer reviewed literature, and therefore it is impossible to determine the validity of the approaches. Modeling hurricane risk with NWP models reduces, to an extent, the need to rely on statistical models, however; as noted in Chen, et al., (2007), the model results are sensitive to modeling details, such as the modeling of the sea surface drag coefficient, boundary layer parameterization, grid resolution (both horizontal and vertical), and factors that affect surface heat flux modeling such as sea spray, etc.

To be useful in hurricane risk assessment studies, the NWP models will have to be validated both through comparisons of modeled and observed wind speeds for historical storms using only parameters that are used in the stochastic model version. The stochastic versions of the NWP models must also be able to reasonably well reproduce observed historical landfall rates, RMW-Δp relationships, storm weakening characteristics, etc. NWP models are likely to be used in the next generation of hurricane risk models, but it remains to be seen, at least in the short term, what improvements will be made in terms of reducing the overall modeling uncertainty.

8. SUMMARY

Hurricane hazard models provide data that drives wind tunnel and risk modeling for a wide range of applications, including insurance loss estimation, prescription of design wind loading and prediction/reconstruction of catastrophic hurricane wind fields. The basis of most models are parametric track and intensity projections that provide gradient wind speeds, which are adjusted to site-specific terrain and particular gust-averaging periods. Inland decay is also considered once the storm transitions onto land. Sensitivity studies have shown that uncertainty in the N-year return period wind speed estimate is of the order of ~10% along the US coastline. A critical step in the modeling process is the validation of the outputs, which are compared to climatological or event specific wind speed and barometric pressure data and estimations from land-, marine-, aircraft- and satellite-based observing platforms.

Hurricane hazard modeling has evolved significantly since its origin in the late 1960's, especially in the aftermath of the 2004 and 2004 hurricane seasons. Regarding the future, next generation models may incorporate the effects of climate change and utilize advancements in numerical weather prediction. It is debatable how advances in our understanding of climate change will alter current modeling practice, however. Tropical meteorology and climatologists have not reached a consensus opinion on the effect of long-term trends, owing, in part, to short and often incomplete tropical cyclone databases.

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