Tropical Cyclone Wind Field Forcing for Surge Models: Critical Issues and Sensitivities

V. J. Cardone
and
A.T. Cox

Oceanweather, Inc.
Cos Cob, CT, USA

ABSTRACT

The attributes and remaining critical deficiencies of current methods for surface wind specification that are typically applied to hindcast tropical cyclone generated storm surges are reviewed. Several wind fields developed for Hurricane Katrina (2005) in the U.S. Gulf of Mexico are applied with the ADCIRC hydrodynamic model to explore the sensitivity of predictions of coastal surges to wind fields developed by alternative methods. We emphasize the issues peculiar to the 24-hour pre-landfall phase of the life cycle of a TC, which is the phase to which the coastal surge is primarily responsive.

INTRODUCTION

Specification of wind fields for forcing ocean response models in intense extratropical (ET) storms is best carried out using a kinematic analysis approach (e.g Cardone et al., 1994; Cardone et al., 1996; Swail and Cox, 2000), whose success relies on the availability of in-situ or remotely sensed surface wind measurements. In many ocean areas along continental margins, sufficient in-situ wind data are provided for the purposes of reliable ET storm reanalysis by moored buoys, offshore platforms, automatic coastal weather stations, well exposed conventional coastal and island weather stations and active (SCAT,ALT) and passive (SMMR) microwave satellite-borne sensors. The spacing and temporal resolution of in-situ observations and the footprint size (of order ¼ degree) of the remote sensors are well suited to the temporal and spatial scale of ET storm winds. On the other hand, in a tropical cyclone (TC) conventional in-situ data sources are inadequate in spatial and temporal coverage to resolve the time evolution of the critical inner core (say the area covered by wind speeds greater than about ½ of the maximum wind speed) TC structure and often the available wind data themselves (especially from low mounted anemometers on small moored buoys) are not as accurate at hurricane wind speeds (say average wind speeds greater than about 30 m/s) than at lower speeds. Therefore, in most regions affected by TCs, indirect methods using a variety of models are utilized to specify the time and space evolution of the surface wind field and associated wind stress for the purposes of forcing ocean models, including the hydrodynamic (HD) models used for shelf current and coastal surge prediction. Where extraordinary data types are available such as data collected by manned or unmanned airborne probes of TCs, specialized kinematic methods may be applied.

Aircraft reconnaissance of TCs began during World War II in the Western North Pacific where it continued until 1986, and in the western North Atlantic Ocean (NAO) and contiguous basins where it continues up to the present time. Aircraft provide invaluable additional sources of data on TC location, intensity and structure. Initially, aircraft provided basically navigational center fixes, eye characteristics from airborne radar presentation and vertically extrapolated estimates of minimum eye pressure. Soon the data included eye sounding and surface minimum pressure from eye dropsonde, flight level winds, temperature and D-value and radar images. Currently, aircraft probing of NAO cyclones provides, in addition, vertical wind profiles in the inner core from GPS dropwindsondes, remotely sensed surface wind speeds along all flight lines from the stepped frequency microwave radiometer (SFMR), Doppler radar images converted to relative wind velocity cross sections and more. These data have enabled the development and application of an additional arsenal of TC surface wind analysis approaches including kinematic analysis methods. What is notably lacking, however, is a database of accurate, over ocean in-situ measurements of the surface wind speed and direction on the most useful averaging interval (i.e. averaging intervals from 1 minute to about 30 minutes). The lack of these data places a limit to the development and validation of both model-based and kinematic-based methods of surface wind analysis and, therefore, surface wind fields analyzed for even well documented storms have some uncertainty, which leads naturally to errors in modeled ocean response.

In this paper, we discuss the attributes and remaining critical deficiencies of current methods for surface wind specification operated in a retrospective mode and explore in a preliminary way the sensitivity of coastal storm surge predictions to alternative wind fields developed for the catastrophic event (Hurricane Katrina, 2005) in the NAO. We emphasize the deficiencies peculiar to the 24-hour pre-landfall phase of the life cycle of a TC, which is the phase to which the coastal surge is primarily responsive. The storm surge calculations are made with the ADCIRC hydrodynamic (HD) as adapted to the Gulf of Mexico (GOM) with the grid domain shown in Figure 1.

TROPICAL CYCLONE ATMOSPHERIC FORCING

The hurricane marine boundary layer wind field and the hurricane inner-core sea level pressure and its gradient constitute the hurricane atmospheric forcing and the source of kinetic energy of storm-driven coastal currents, waves, storm surge and sediment transport associated with a land falling storm. The dominant forcing is the surface boundary layer wind field, which for the purposes of ocean model forcing is represented by the 10-meter elevation marine exposure wind speed and direction that represents a turbulence-filtered averaging interval of about 30 minutes. For other purposes, estimates of gust scale "peak sustained 1-minute wind speed" and "peak 3-second gust speed" may be derived from the turbulence filtered average wind speeds through statistical gust distribution models. The time step of the wind fields should be typically 30-minutes or less and the grid spacing, at least in the inner core, should be no greater than 2 km.

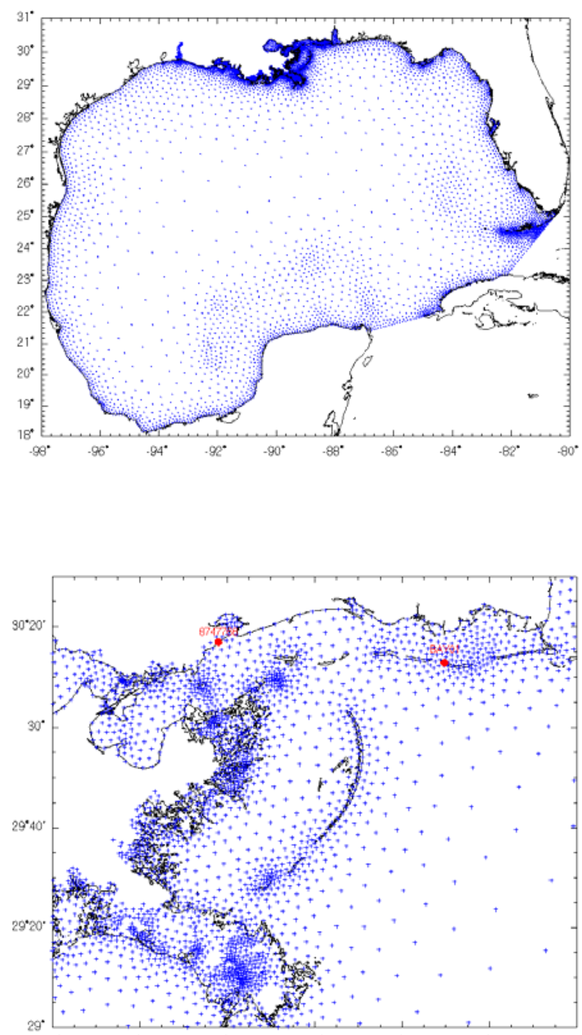

Figure 1. ADCIRC grid domain (top) with reference locations (bottom)

The main approaches to surface wind modeling in tropical cyclones may be categorized as:

(1) Simple analytical parametric models, such as Holland (1980)

(2) Steady-state dynamical such as the so-called PBL model of Chow (1970) as later developed by Cardone et al. (1976), Shapiro (1983), Thompson and Cardone (1996) and Vickery et al. (2000)

(3) Non-Steady dynamical such as MM5 (Chen et al. 2007), GFDL (Kurihara et al., 1998) and NOAA's WRF (Corbosiero et al., 2007)

(4) Kinematical methods, most notably the NOAA National Hurricane Research Division (NHRD) HWnd (Powell et al., 1996) and Oceanweather's (OWI) IOKA (Cardone and Cox, 2002).

Methods may be combined or "blended" such as utilizing a dynamical model solution as a background into which observations or inner core kinematically analyzed winds may be assimilated. For example, in a U.S. NOPP program, whose objective is to provide improved real time coastal wind, waves and surge forecasts for North Atlantic Basin hurricane affecting the US East and Gulf coasts, the PBL and HWnd solutions are blended (Graber et al., 2006).

For the purposes of open ocean deep water wave hindcasting of well documented recent NAO basin hurricanes, such as Floyd (2002), Lili (2002, Cardone et al., 2004), Ivan (2004, Cox et al., 2005), the solutions of carefully initialized PBL solutions and operational HWnd snapshots provide wave hindcasts with second or third-generation spectral wave prediction models that are comparable in skill though the blended solutions hold a small margin of skill over pure PBL or HWnd derived wind fields. In such simulations typically the entire life history of the cyclone is modeled and the time scale of significant changes in wind intensity and structure are of the order of one day. The wave response in deep water appears to filter higher frequency fluctuations caused say by temporary deepening or filling associated with eye wall replacement cycles or rotation of the location of wind maximum from one quadrant to another. However, given that the storm surge is generated on the continental shelf and a hurricane typically crosses the shelf in much less than 24 hours, it may be expected that the modeled storm surge response is critically dependent on accurately specifying wind field changes on a time scale of hours. The shallow shelf waters also affect the effective roughness of the sea surface, which in turn affects the boundary layer wind profile and the air-sea momentum transfer coefficient, C10.

In this study, we apply representative dynamical, kinematical and blend wind fields for Hurricane Katrina (2005) in the GOM as generated both in a real time context and in a careful reanalysis mode. We also explore the sensitivity to alternative assumptions of pre-landfall filling and structural changes Simple parametric models are not considered because they have been largely supplanted by wind fields developed by PBL or kinematic approaches and 3-D models are not considered because they have to date been applied mainly to real time forecasting or to simulations of long-term climatologies of TCs (e.g. Emanuel et al., 2006) rather than to hindcasting the best possible wind field of a given historical storm.

Steady PBL Model Wind Field

The variant taken to typify the steady dynamic model approach is the PBL model usually referred to as TC96 (after Thompson and Cardone, 1996). A similar PBL model formulation was developed by Shapiro (1983) except in a cylindrical coordinate system. TC96 is an application of a theoretical model of the horizontal airflow in the boundary layer of a moving vortex (Chow, 1970). That model solves, by numerical integration, the vertically averaged equations of motion that govern a boundary layer subject to horizontal and vertical shear stresses. The equations are resolved in a Cartesian coordinate system whose origin translates at constant velocity, V_f, with the storm center of the pressure field associated with the cyclone. Variations in storm intensity and motion are represented by a series of quasisteady state solutions. The method starts from raw data whenever possible and includes an intensive reanalysis of traditional cyclone parameters such as track and intensity (in terms of pressure) and then develops new estimates of the more difficult storm parameters, such as the shape of the radial pressure profile and the ambient pressure field within which the cyclone is embedded. The time histories of all of these parameters are specified within the entire period to be hindcast. Storm track and storm parameters are then used to drive a numerical primitive equation model of the cyclone boundary layer to generate a complete picture of the time-varying wind field associated with the cyclone circulation itself. TC96 has been widely applied and validated mainly in terms of its success in forcing ocean response models. Many such studies have been reported (see e.g., Forristall et al., 1978; Cardone and Resio, 1998; Jensen et al., 2006).

As presently formulated, the wind model is free of arbitrary calibration constants that might link the model to a particular storm type or region. For example, differences in latitude are handled properly in the primitive equation formulation through the Coriolis parameter. The variations in structure between tropical storm types manifest themselves basically in the characteristics of the pressure field of the vortex itself and of the surrounding region. The interaction of a tropical cyclone and its environment, therefore, can be accounted for by a proper specification of the input parameters.

The principal challenge in the model initialization is to describe the PBL pressure gradients in terms of the azimuthally dependent radial pressure profile, most recently expressed as a double exponential form:

$$P(r) = Po + \sum_{i=2}^{n} dp_i e^{-\left(\frac{R_{pi}}{r}\right)^{Bi}}$$

where Po is central pressure, and in its unimodel form dp is the pressure differential between the eye pressure and the storm environment, Rp is a scaling radius related to (but not equal to) the radius of maximum wind and B is the profile peakedness parameter, usually called Holland’s B after Holland (1980). Other assignable parameters of the planetary boundary layer (PBL) formulation include the planetary boundary layer depth and stability, and the sea surface roughness formulation. Recent field studies and analyses of aircraft dropwindsonde wind profile data in the inner core of hurricanes (e.g. Powell et al., 2003) have provided new insights and models for these characteristics.

For application to storms into which there is no aircraft reconnaissance (i.e. the vast majority of cyclones on a global basis), the input parameters are derived rather indirectly. Central pressure is usually related to Dvorak (1984) intensity estimates made by skilled interpreters of satellite imagery. The scale radius is estimated from satellite image depictions of the eye diameter and occasionally the eye wall itself. Near land, the pressure profile may be fitted directly but only for its unimodal mode and with an assumed value of B. For storms viewed by QuikSCAT, Cox and Cardone (2000) describe an inverse model approach that utilizes data outside the inner core, and which also may be applied to estimates of the radius of 35 knot and 50 knot wind speeds as often estimated by warning centers.

Where aircraft reconnaissance data are available, the central pressure is reliably known from dropsonde and the pressure profile may be fitted directly to flight level D-value legs that typically radiate out from the center along several azimuths. Thompson and Cardone (1996) describe a software-assisted method applicable to fitting the double exponential pressure profile parameters. A more sophisticated method based on the profile form and cost function approach of Willoughby et al. (2006) is utilized in the updated tropical analysts workstation described by Cox and Cardone (2007).

In a typical application, a trial PBL model solution obtained from starting input data is compared to time histories of measured surface winds outside the inner core from buoys, and to aircraft wind speeds reduced from flight level to

10-meters using empirical ratios. Model input parameters are varied and the model solution iterated until good agreement is obtained between the modeled wind field and the better-quality wind observations available. Note, however, that buoy measurements in the inner core are extremely rare and the measurements must be viewed as suspect in storms of severe intensity (say average wind speeds above about 30 m/s). Typically, modeled cyclone tropical wind field are blended into a basin-wide field which incorporates both atmospheric modeled winds, in-situ measurements from buoys, CMAN stations, ship reports as well as satellite estimates of wind from altimeter and scatterometer instruments using a kinematical method such as IOKA.. (Cox et al., 1998). Such a wind field description can also serve as the reference for modifications of wind speed and direction in coastal waters (bays, inland lakes etc.) and over freshly inundated areas to reflect different (i.e. from nominal deep water) in-situ and upstream surface roughness (Atkinson and Wamsley, 2007).

HWnd.

Since about 1998 a new kinematic analysis system for tropical cyclone surface wind fields known as HWnd (Powell et al., 1998) has been applied in real time to most TCs in the NAO basin by the NOAA NHRD. HWnd wind field "snapshots" are in general generated at 6-hourly intervals once regular aircraft reconnaissance missions into a given system have commenced. The analysis employs a scale controlled wind speed objective analysis system to synthesize into a continuous field, observations of winds from aircraft, SFMR, QuikSCAT, buoys, C-MAN stations, GPS dropwindsonde, offshore platforms and towers, coastal towers and the like. The main challenge of HWnd is to first transform each observation from its intrinsic time averaging interval, and for remote sensors from their intrinsic spatial average, to the HWnd standard representation of the so-called peak "sustained" wind speed, which is defined as the peak 1-minute gust (see Powell et al., 1998). As such, HWnd wind fields should not be used for ocean forcing unless the "sustained" wind speeds are transformed to an averaging interval that has effectively filtered turbulence scale fluctuations (normally an averaging interval of at least 30 minutes satisfies this objective) and used to force an ocean model at a spatial resolution and time interval appropriate for intense hurricanes (normally the grid spacing required is 2 km or so and the time step is no greater than 30 minutes).

The considerable archive of HWnd analyses generated in real time over the past decade do not constitute a homogeneous historical data set because the elevation and averaging interval transformations applied to the most ubiquitous data sets, namely flight level winds and SFMR, have undergone several revisions over time. The introduction of GPS winds especially has provided a basis to revise and improve the flight-level to surface wind speed ratios (Franklin et al, 2003) and the geophysical model function (GMF) used to relate SFMR emissivity to surface wind speed (Uhlhorn and Black,. 2003, Uhlhorn et al., 2006). However, as noted above, the lack of a truly representative and accurate in-situ data base of measured winds in the inner core of a number of storms has prevented an absolute calibration and validation of these transformations.

Blend

In recent applications, HWnd snapshots have been utilized in several ways to enhance model generated wind field solution.. For example, the HWnd snapshots may by used in an "inverse-modeling" sense (see. e.g. Cox and Cardone, 2002) to find those PBL model inputs that provide a solution consistent with the HWnd patterns. In this way, quite complex and anomalous size and shape storm properties (such as, for example, the double wind maximum associated with the eye wall replacement cycle or the shelf-like radial wind profiles found in some storms) may be modeled through the double exponential representation of the PBL pressure field used in TC96. HWnd winds may also be used as a source of data that may be assimilated into a pre-existing model solution within a direct kinematic analysis using a system such as IOKA. The advantage of this approach is that it operates as an expert system and the analyst is, therefore, able to utilize off-hour and time history information, to bring in information from satellite such as TRMM. A new system of processing Doppler radar imagery from multiple coastal sites called VORTRAC (Lee and Bell, 2007) promises to be able to monitor structural and intensity changes in the coastal zone on a time scale of minutes. This system may be especially useful for countries with extensive radar networks but no program of aircraft reconnaissance (e.g. Korea).

HURRICANE KATRINA WIND FIELDS

As Katrina moved northwestward in the GOM in late August, 2005 it exhibited two separate bursts of intensification, the first late on August 26 which took Katrina to Category 3 intensity and the second late on the 27^{th} and early the 28^{th} which took Katrina to Category 5 intensity. These changes were accompanied by fairly typical structural changes in the size and degree of organization of the storm, particularly in the well monitored evolution of two distinct eye-wall replacement cycles, each of which was characterized by the formation of an outer eye wall near a radius of about 40 nm from the center and its contraction to between 15 nm and 20 nm from the center. The minimum central pressure attained by Katrina was 902 mb at about 1800 UTC August 28 with peak winds of 150 knots (this is the official NOAA Tropical Prediction Center (TPC) intensity expressed in terms of the maximum 1-minute average wind speed expected in one hour, or the so called "sustained wind"), when the center was located about 170 n mi southeast of the mouth of the Mississippi River. At maximum intensity, the radius of maximum wind was about 15 nm which is fairly large for a Category 5 hurricane. Rapid weakening of Katrina ensued over the subsequent 18 hours and Katrina, now moving almost due north, made its first Gulf landfall as a Category 3 hurricane at 1100 UTC August 29 at the southern tip of the Mississippi Delta. The pre-landfall weakening was accompanied by a radical change in wind structure as the inner eye-wall seen at maximum intensity collapsed as a new outer wind maximum formed, which instead of contracting maintained itself and thereby imparted a shelf-like structure to the radial distribution of wind speed, especially on the right side of the wind circulation. This transformation is revealed vividly in comparative aircraft tail Doppler radar wind speed cross section images contained in the TPC report (2006).

Experiments were conducted with the following six wind fields in order of increasing levels of analysis:

<u>1. PBL Real Time (Base Case).</u> This case is comprised of a series of TC96 PBL solutions produced at OWI in real time to represent the analysis at 6-hourly intervals, from the estimates of eye coordinates, intensity (maximum sustained wind speed) and radii of 35 knot and 50 knot winds contained within the official advisories issued by the TPC. The central pressure is transformed from the maximum wind speed through the relationship of Kraft (1961). This wind field will likely be more accurate than a comparable wind field produced in other basins by this method because the TPC forecasters have access to reconnaissance data not available in other basins, but it nevertheless should be expected to provide a wind field of lower accuracy than a hindcast.

<u>2. PBL Hindcast</u>. This case also represents a pure PBL solution but with the storm track and input variables derived within a month or so after real time for the purposes of preliminary assessment of storm impact offshore on infrastructure. For the analysis of the model input parameters, a sufficient period of time has elapsed after real time to allow use of a preliminary "best track" reported by TPC in its storm report on Katrina and to fit the parameters of the exponential profile at a given analysis time by compositing all aircraft and surface measurement of surface pressure within a window of say +/-3-hours centered on the analysis time (this is not possible in real time) and imposing continuity in the PBL snapshots by being able to refer to the entire time history of the storm. A hindcast also allows some iteration of the PBL parameters after the wind field solution is compared to reliable wind data such as reduced aircraft flight level winds, winds measured at buoys (within their range of reliability), from offshore platforms, and outside the inner core by QuikSCAT.

3. HWnd Real Time Snapshots-IPET95. During Katrina's movement through the Gulf of Mexico, HWnd snaphots were produced at NHRD at 3 or 6-hourly intervals, in general. This series of analyses were turned into a continuous field, known as the IPET95 wind field because it was used in support of the US IPET study (IPET, 2007), through the application of IOKA. The HWnd analyses typically extend outward only to about 450 km from the center. The wind field outside the HWnd domain and in the periphery of the storm is specified from the 10-meter wind field analysis produced from an IOKA blend of NCEP/NCAR Reanalysis winds and available insitu/satellite wind data available in the basin. The wind field is interpolated in time to 30-minutes using a Lagrangian interpolation algorithm that conserves the azimuth and range of each grid point with respect to the translating storm center.

4. HWnd Reanalyses- IPET99. As a part of the IPET project, NHRD was commissioned to produce a set of reanalyses of Katrina during its lifecycle within the Gulf of Mexico. These analyses provide an alternative picture of the inner core of Katrina in the pre-landfall period. These HWnd analyses took advantage of a complete recalibration of the SFMR wind dataset and aircraft reduction methodology used to run the HWnd system (Powell, personal communication)

5. MMS Blend. This wind field is a blend of HWnd reanalyzed snapshots and a final set of PBL solutions generated long after real time. The final blending involves kinematic analysis techniques that are by no means restricted to the outer core. In the kinematic approach both HWnd and PBL solutions may be overridden if supported by wind data. This blend solution is the only wind field of those referenced here that more fully models the rapid decay and expansion of the surface wind field in the 18-hour period before landfall. This wind field is further documented and validated by Cardone et al. (2007), who describe a definitive ocean response hindcast study of Katrina in the GOM supported by the US Minerals Management Service (MMS). That study was carried out to support engineering studies of damage and loss of offshore infrastructure. This "MMS" wind field has also been used to drive a very high resolution adaptation of ADCIRC for validation of coastal surge modeling and subsequent coastal flood risk reassessment along the GOM coast in studies supported by the US Federal Emergency Management Administration (FEMA).

6. Lagged Blend. Hurricane Katrina exhibited a remarkable change in intensity and wind structure during the 24-period before landfall, essentially decreasing in peak intensity from a storm of Category 5 intensity on the Saffir-Simpson Scale to Category 3 at its first landfall on the Mississippi River Delta. There is some evidence that the pre-landfall weakening exhibited by Katrina is characteristic of intense hurricanes that approach the northern GOM coast (e.g. Cooper and Stear, 2006) and indeed pre-landfall filling of very intense north-central GOM hurricanes is now recognized in the forecasting practices of TPC (Rappaport, 2006). Hurricane Camille (1969), whose pre-landfall track was only slightly east of Katrina's track, is a notable exception to this "rule" as it maintained Category 5 intensity all the way to the coast of Mississippi. To represent some variability in the pre-landfall filling rate of a Category 5 storm, the MMS blend wind field was simply shifted northward to simulate an intensity change by 6-hours.

Figure 2 shows the time history of the modeled radius of maximum wind, Rmax, and maximum wind speed (30-minute average at 10-meter elevation over water) during a 42-hour period that includes first the 12-hours offshore leading up to maximum intensity followed by a nearly 18 hour period of weakening preceding the first eye wall coast encounter at the Mississippi Delta, followed by a six hour period following landfall during which, of course, rapid weakening continued. Figure 2 includes all available estimates of Rmax and Vmax from flight level data. The factor of 0.76 used to reduce flight level winds to 10-meter “average” wind speeds is lower than the more commonly applied factor of 0.90 which is intended to transform flight level wind speeds to peak 1-minute “sustained” wind speeds. The flight level Rmax was not modified though is should be expected that due to eye-wall tilt the surface Rmax may be smaller than the flight level Rmax.

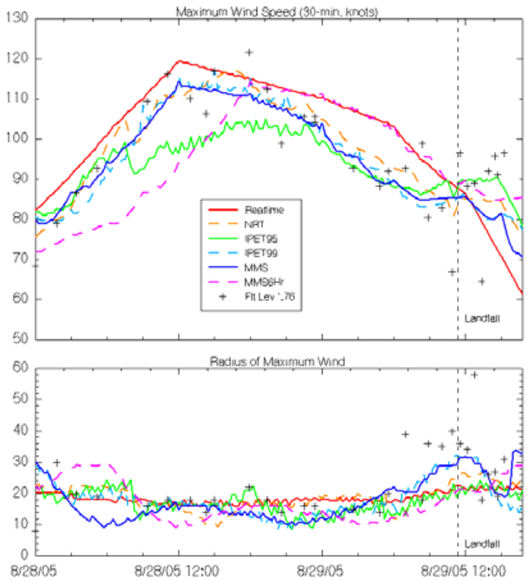

Figure 2. Comparison of maximum winds (30-min, 10-m, m/s) and radius of maximum winds (Nmi) for 6 alternate Katrina wind fields with reference aircraft estimates.

There is a remarkable degree of variability in the solutions of these important properties of the inner core of Katrina. The real time solution is the most energetic, probably because the Kraft transformation provided an eye-pressure estimate that was lower than the true central pressure. The real time PBL wind field also fails to simulate the rapid expansion of Rmax before landfall and it overestimates the post landfall decrease of peak wind speeds.

There is a large difference in peak wind speed between the real time and reanalyzed HWnd snapshots over about an 18-hour period straddling the time of peak storm intensity. The later IPET99 peak winds are nearly 20 knots higher than in IPET95. This change probably reflects a change in the flight level-surface wind speed reduction factor between the two analyses (this ratio is a user selectable feature of the HWnd user interface). The MMS wind field tracks the IPET99 winds closely except immediately before and after landfall because the blending process highly weights the HWnd in the inner core. Before and after landfall the MMS wind field was strongly influenced by rapid change in the airborne tail Doppler radar cross section representation of the wind field before landfall (see Figure 3) as noted above (see also Cardone et al. 2006 and TPC, 2005). Finally, we note that the fast-response near real time PBL solutions comes remarkably close to the final MMS wind field in terms of Vmax and associated Rmax.

Figure 4 compares the alternative wind fields as color contours of the envelope of maximum wind speed fields during the part of the storm history to which the storm surge at the coast is most sensitive. The base case wind field appears to be too energetic and too broad relative to the MMS and both IPET solutions. The near real time PBL winds are close to the IPET solutions. The MMS blend solution shows more broadening of the wind field to the right of the center before landfall as suggested by the airborne Doppler radar wind cross section. The lagged wind field, of course, allows an inner core with Category 5 peak winds to approach nearly to the edge of the continental shelf offshore Mississippi.

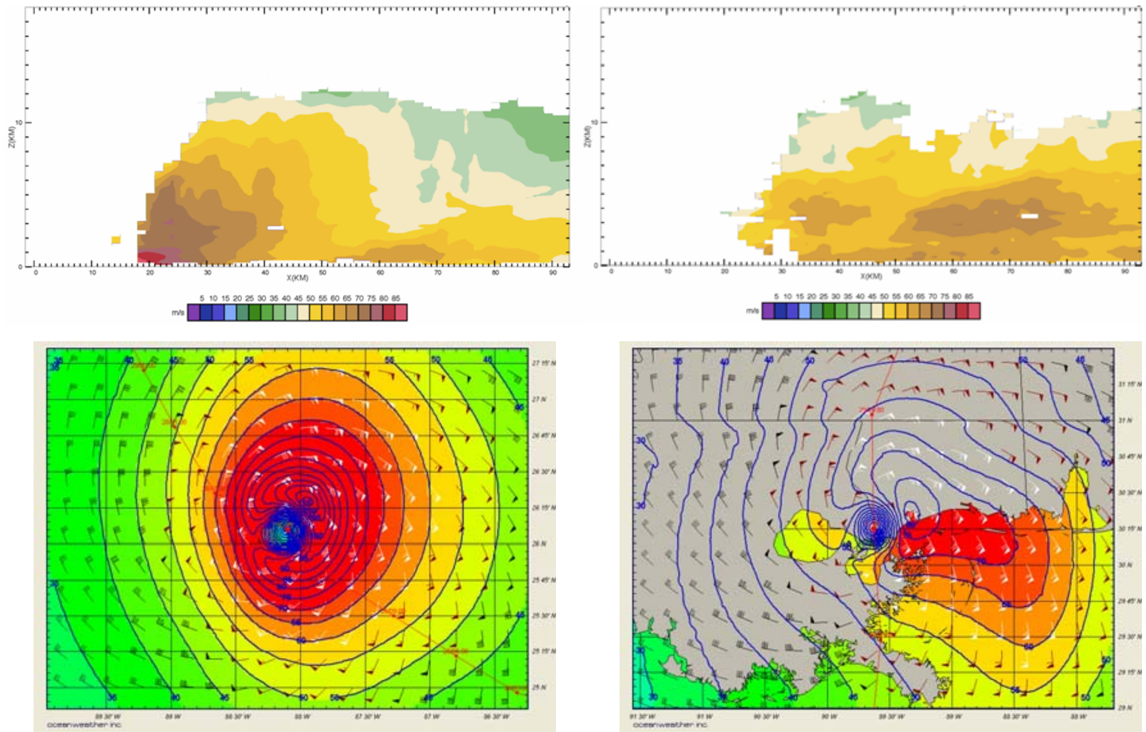

Figure 3. Upper panels show vertical cross section of the wind field of Hurricane Katrina derived from airborne tail Doppler radar images at 1800 UTC August 25, 2005 (left) when the storm was at Category 5 intensity and at 1200 UTC August 26, 2005 (right) shortly after Katrina's second landfall (from TPC, 2006). Lower panels: show "MMS blend" wind field snapshots corresponding to the times of the upper panels.

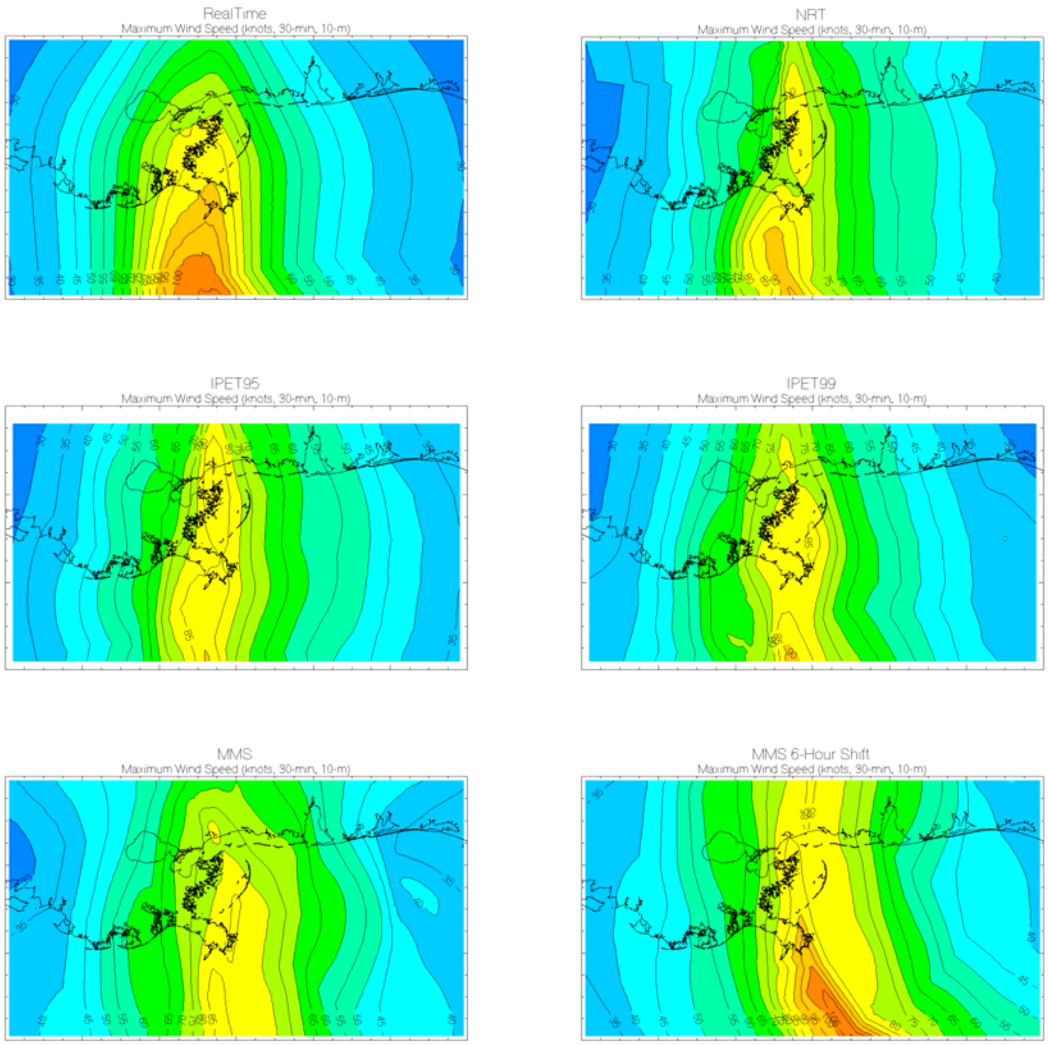

Figure 4. Maximum wind speed (knots, 30-min, 10-m) for 6 alternate Katrina solutions: Base Case PBL from real-time track, intensity and wind radii (top left), PBL solution hindcast developed shortly after landfall (top right), initial IPET solution based on real-time HWnd (middle left), final IPET solution based on HWnd reanalysis (middle right), kinematic analysis of Katrina applied in MMS and FEMA validation studies (bottom left) and 6-hour shift of MMS solution to show effects of pre-landfall filling.

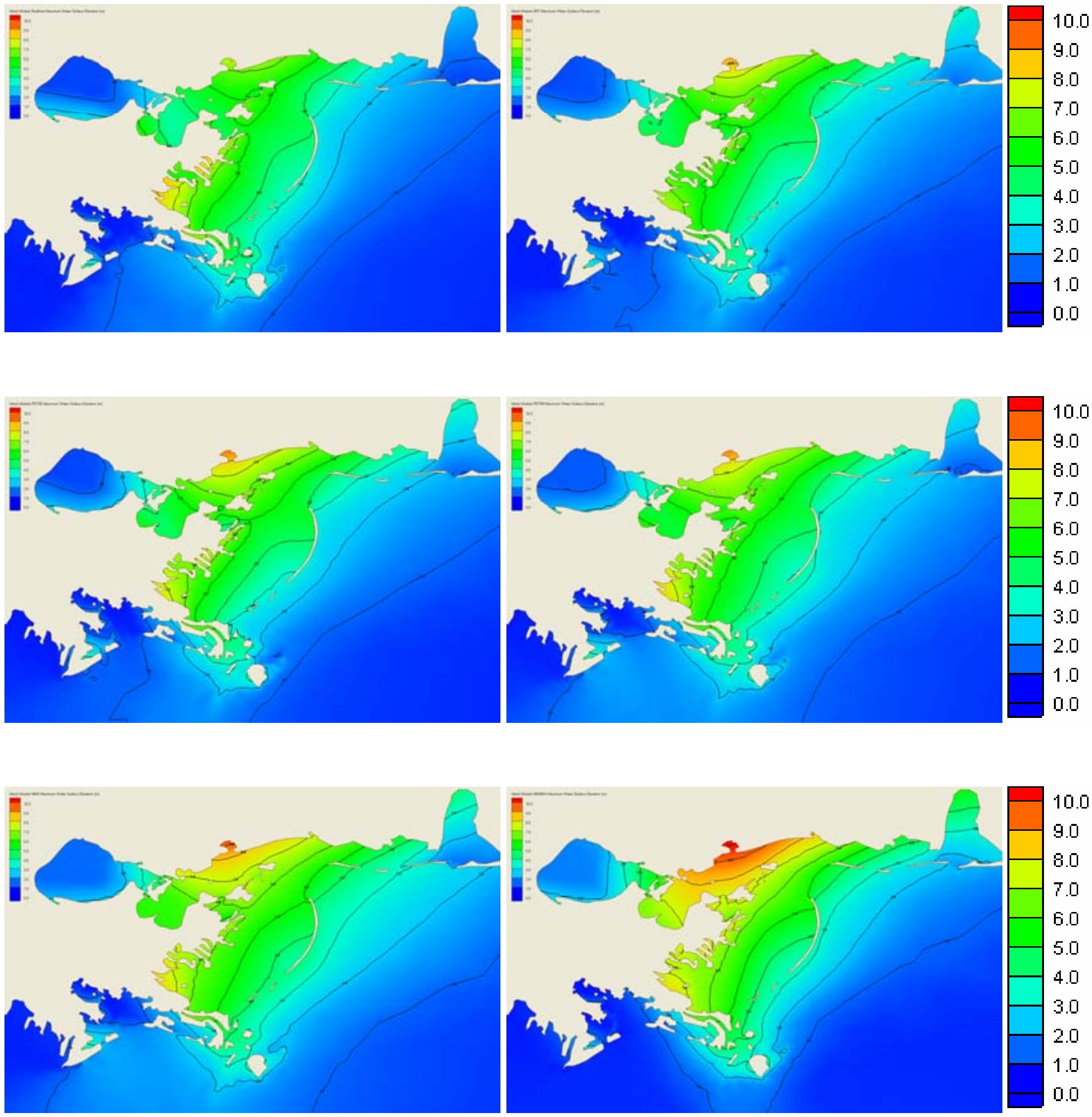

Figure 5. Maximum water elevation (m) for 6 alternate Katrina solutions: Base Case PBL from real-time track, intensity and wind radii (top left), PBL solution hindcast developed shortly after landfall (top right), initial IPET solution based on real-time HWnd (middle left), final IPET solution based on HWnd reanalysis (middle right), kinematic analysis of Katrina applied in MMS and FEMA validation studies (bottom left) and 6-hour shift of MMS solution to show effects of pre-landfall filling.

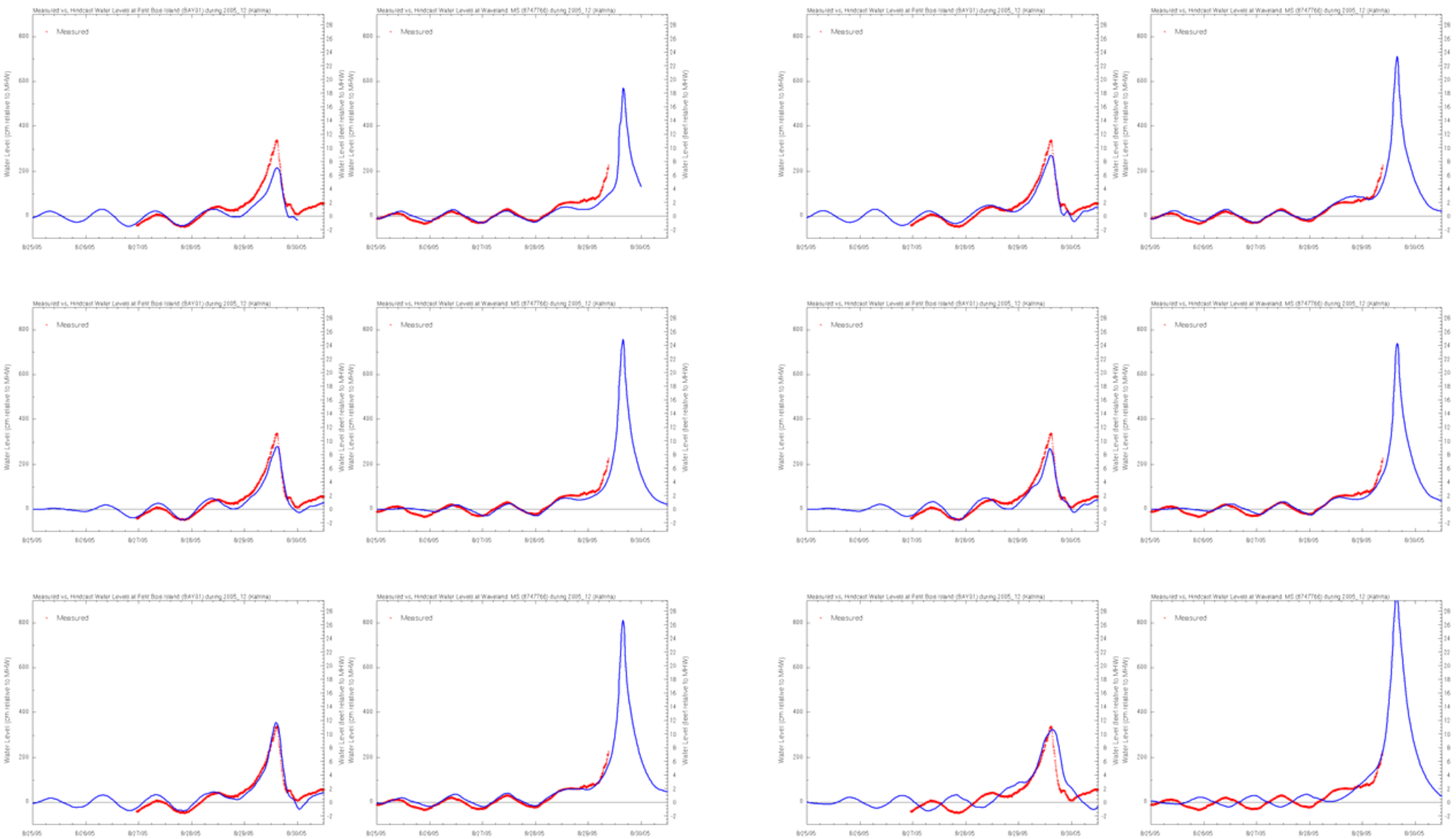

Figure 6. Water elevation (m) for 6 alternate Katrina solutions at Petit Bois Island and Waveland for: Base Case PBL from real-time track, intensity and wind radii (top left), PBL solution hindcast developed shortly after landfall (top right), initial IPET solution based on real-time HWnd (middle left), final IPET solution based on HWnd reanalysis (middle right), kinematic analysis of Katrina applied in MMS and FEMA validation studies (bottom left) and 6-hour shift of MMS solution to show effects of lag in pre-landfall filling.

STORM SURGE RESPONSE TO ALTERNATIVE WIND FIELDS

Surge Model

The alternative wind fields are each used to simulate the evolution of the storm surge in Hurricane Katrina using an adaptation of ADCIRC. Computations are performed using ADCIRC-2DDI, the depth-integrated option of a set of two- and three-dimensional fully nonlinear hydrodynamic codes. The model grid, shown in Figure 1, was developed using a digital bathymetry developed at the U.S. Army Corps of Engineers in its IPET study. ADCIRC-2DDI uses the vertically averaged equations of mass and momentum conservation, subject to the hydrostatic pressure approximation. The two-dimensional, depth-integrated velocity field is appropriate to use for the tidal simulations performed herein due to the assumption that the vertical fluid velocities are negligible as compared to the horizontal fluid velocities of the tidal flow within the computational domain. For the applications presented in this report, the hybrid bottom friction formulation is used, baroclinic terms are neglected, and the advective and lateral diffusion/dispersion terms are employed, leading to a set of balance laws in primitive, non-conservative form, expressed in a spherical coordinate system Considerably more detailed presentations of ADCIRC-2DDI are given in Leuttich et al. (1992), Kolar et al. (1994) and (Westerink et al. 1991).

The zonal and meridional surface stress components are supplied by the familiar surface drag formulation as a function of the 10-meter average wind speed and direction. We use the 30-minute averaged wind speed, which is the only appropriate averaging interval to adopt for ocean response forcing though we have seen some applications in which winds referred to shorter averaging intervals have been used, no doubt in an attempt to indirectly scale up the wind stress. In addition, while most ADCIRC modelers use a standard drag coefficient formulation (e.g. Large and Pond, 1981) or similar linear law, capped or uncapped, we have found that since most of the surge is generated over the shallow shelf waters, it is necessary to scale up the deep water drag coefficient by a tunable factor.

Results

The storm surge generated by Hurricane Katrina at the coast is, of course, of great interest because of the breach of the levees protecting New Orleans and the catastrophic coastal damage east of the track along the coasts of Mississippi and Alabama. The extensive field surveys and modeling studies conducted after the event indicate that peak storm surge at the coast to the right of where the center crossed the coast occurred near Waveland, Mississippi and was about 27 feet (e.g. IPET, 2007). Unfortunately, there are no reliable gage traces at or near where the peak surge occurred because the gage at Waveland failed well before the peak surge. The nearest gage station at which a complete record is available appears to be at Petit Bois Island, one of the barrier islands offshore Mississippi and located about 100 km to the right of the track. The peak surge measured at Petit Bois was 12 feet. Figure 1 shows the location of the grid meshes taken to represent Waveland and the grid point taken to represent Petit Bois.

Figure 5 compares the alternative ADCIRC solutions in terms of color contours of the envelope of the peak modeled surge and Figure 6 compares the ADCIRC solutions of the time histories of water level at Waveland and Petit Bois to the available measured gage traces. Table 1 gives the modeled and measured (Petit Bois only) peak surges at both locations.

The run with the base case wind field greatly underestimates the peak near Waveland (19 feet modeled versus best field estimate of 27 feet and MMS run peak of 27 feet) apparently because of the too rapid decay of the intensity of the peak winds in the inner core between the first and second landfalls. The real time wind field also failed to simulate the expansion of the wind field especially to the right of the center. There is a trend to increasing agreement between modeled and measured (or consensus) peak surge as one progresses to the PBL hindcast, the IPET solutions and finally to the MMS blend wind field, which provides excellent agreement at Petit Bois. Despite the large differences between IPET96 and IPET99 peak winds offshore, the differences in the coastal surge response between these two runs is small , which is a reflection the dominating importance of the wind field on the continental shelf, where IPET95 and IPET 99 are quite similar. As expected, the lagged MMS blend solution allows the peak surge to overshoot the consensus peaks at both Waveland but not at Petit Bois by about 10%. What is somewhat encouraging is that except for the real time PBL wind field the range between alternative peak surge solutions and the observed peaks is only about +/- 10%.

Solution	Waveland ADCIRC	Petit Bois Island ADCIRC	Petit Bois Island Meas
PBL Real Time	19	9	
PBL Hindcast	23	9	
IPET95	25	9	11
IPET99	24	9	
MMS	27	12	
MMS 6Hr	30	11	

Table 1. Measured and hindcast water levels at Waveland and Petit Bois Island (ft).

DISCUSSION

Given the copious in-situ, airborne and satellite monitoring of GOM TCs, carefully hindcast fields using either steady state PBL or kinematic methods can provide rather skillful hindcasts of peak storm surge in the inner core even for a catastrophic event such as Katrina. However, wind fields produced in real time from estimates of maximum wind speed and storm size contained in warning center advisories may possess an uncertainly of up to about 20% in the inner core surface wind speed, which leads to a comparable uncertainly in peak surge at the coast. The base case run and the lagged run also suggest that the specification of peak coastal surge is critically dependent on an accurate representation of any changes in storm intensity and structure during the time that the inner core is crossing the continental shelf. Skill in real time forecasts of changes in storm intensity and structure is very low so errors in real time storm surge forecasts will be limited in skill until 3D models have advanced to the point where real skill in forecasting intensity and structural changes in the surface wind field is realized.

Uncertainties in wind field hindcast by application of a steady state PBL approach arise mainly in uncertainty in specification of the input parameters. Storms with the same Saffir-Simpson Scale Number, same central pressure, and roughly comparable sizes and forward velocity in the same geographic area can have significantly different maximum winds and consequent ocean response. Within the context of steady state PBL models, uncertainty in modeling this variability stems mainly from natural variability in the shape of the radial pressure profile, some effects of which may be approximated by the peakedness parameter, B, of the exponential pressure profile. In general, however, storms may exhibit even more complex radial pressure and wind distributions, and may require double exponential representation of the radial pressure profile, as introduced in TC96. The new sectionally continuous parametric representation of radial wind distributions of Willoughby and Rahn (2006) is an important advance in this regard.

Apart from failure to model non-steadiness and the inability to model transient convectively induced changes in the inner core wind field (e.g. diurnally varying convective bursts) the scaling of peak surface winds in a steady PBL model in terns of the pressure field is most sensitive to the specification of surface friction though the drag or surface roughness parameterization. Recent studies make a compelling case for saturation of the drag coefficient to values of the order of 2.0 x 10**-3 at wind speeds in excess of about 30 m/s (Powell et al., 2003; Donelan et al. 2004; Chen et al., 2007). However, it remains to be demonstrated that a similar saturation effect occurs in shallow water. As a result, the drag formulation (and its possible saturation) is usually tuned (as in this study) with best wind fields and gage data to provide unbiased surge predictions.

Uncertainty in the kinematically based methods arise mainly in uncertainties in the process of homogenization of the various in-situ and remotely sensed data to reflect over-water surface winds at a selected averaging interval. The authors favor homogenization of the data to a wind speed averaging interval of 30-minutes, which should be the interval most suitable for forcing ocean models. The HWnd method favors homogenization of winds to a stochastic wind variable, namely the 1-minute peak sustained wind speed and associated direction. HWnd analyses, therefore, need to be transformed before they are used to drive ocean response models.

The data homogenization process is sensitive to assumptions regarding the accuracy of the vertical wind shear model used to reduce flight level winds to 10-meters, the calibration of the geophysical model function (GMF) used to convert SFMR emissivity to surface wind speed, the treatment of GPS dropwindsondes, which at best yield a random (not peak) 1-minute average wind speed as the probe falls through the lower 150 meters of the surface boundary layer, and possible bias in in-situ sensors associated with buoy motion, and for coastal stations, less than ideal marine exposure. As noted in the introduction, these aspects of data processing and transformation have not stabilized and continue to evolve. As a result, the existing database of TC wind fields produced in real time or shortly thereafter do not necessarily provide a consistent, homogeneous archive of the wind fields of historical storms. What is sorely needed are absolutely reliable and unbiased measurements of the surface wind speed and direction in the inner core from high quality well exposed anemometers whose output is recorded at high frequency. Winds measured by the larger moored buoys, such as the NOAA NDBC 10-meter and 12-meter discus buoys appear to satisfy as do winds from top of derrick mounted anemometers on offshore platforms. Newer towers such as the instrumented meterological towers installed at potential offshore wind farm sites and dedicated metocean towers such as the KORDI tower in the Sea of Japan hold the promise to build the in-situ database required over time.

There is no aircraft reconnaissance of TCs in most part of the globe, which removes output from eye radiosonde, high frequency flight level wind, D-value and temperature sampling, GPS dropwindsonde, SFMR and airborne Doppler radar from the arsenal of data available to analyze TC surface wind fields. Fortunately, research continues into the application of satellite information in increasingly sophisticated ways. Olander and Velden (2007) report on an advanced Dvorak technique that greatly reduces the subjectivity of estimating TC intensity from geostationary satellite (GEOS) imagery while maintaining the skill of the method when applied by the most experienced practicioners of this method. Kossin et al., (2007) report an objective method that can provide reliable estimates of Rmax from Infrared GOES imagery and even extend the method to the specification of the tangential wind profile in the inner core.

We have already noted how surface winds outside the inner core from an active microwave scatterometer, such as QuikSCAT may be used in an inverse modeling approach to estimate the parameters of the exponential profile (Cox and Cardone, 2000). Wimmers and Velden (2007) describe an advanced visualization approach that may be applied to passive microwave sensors on low earth orbit satellites to diagnose the continuous evolution of TC features such as eyewall character and diameter, secondary eyewall formation and inward migration (as part of the eyewall replacement cycle) from intermittent sampling typical of orbiting satellites.

Of course, it is to be expected that satellite data alone may not yield some of the more subtle characteristics of the inner core of TC such as the peakedness of the profile and the details of the asymmetry of the surface wind maximum. Hopefully, intensive studies of TCs in the NA basins will yield synoptic-climatological models for the mean properties of these secondary features. Finally, for storm surge modeling in particular, more research needs to be carried out to understand the cause of the sharp structural and intensity changes in the wind field sometimes seen as in the 12-24 hour period just before landfall in Katrina and other storms. Models of the rate of increase of central pressure in the post-landfall period (e.g. Vickery, 2005) need to be extended to the pre-landfall period. TC characteristic pre-landfall effects will no doubt have large regional and perhaps latitudinal variations. Longer term, it is to be expected that coupled ocean-atmosphere 3D models will naturally yield understanding of these changes and lead to improved forecasts.

ACKNOWLEDGEMENTS

This study is carried out under the U.S. Army Corps of Engineers MORPHOS project, supported in part at OWI through a contract with Woolpert, Inc. and the U.S. Army Engineer District (Philadelphia) Award W912BU-07-P-0232.

REFERENCES

Atkinson, J. and T. Wamselty 2007: Representation of Vegetation on the Wind Boundary Layer and Surface Bottom Friction. 10th International Workshop on Wave Hindcasting and Forecasting and Coastal Hazard Symposium, North Shore, Hawaii, November 11-16, 2007.

Cardone, V. J., W. J. Pierson, and E. G. Ward. 1976: Hindcasting the directional spectrum of hurricane generated waves. J. of Petrol. Tech., 28, 385-394.

Cardone, V. J., H. C. Graber, R. E. Jensen, S. Hasselmann, M. J. Caruso 1994. In search of the true surface wind field in SWADE IOP-1: Ocean wave modelling perspective. The Global Atmosphere and Ocean System, 3, 107-150.

Cardone, V. J., R. E. Jensen, D. T. Resio, V. R. Swail and A. T. Cox 1996. Evaluation of contemporary ocean wave models in rare extreme events: Halloween storm of October, 1991; Storm of the century of March, 1993. J. of Atmos. And Ocean. Tech., 13, 198-230.

Cardone, V. J., A. T. Cox, K. A. Lisaeter and D, Szasbo, 2004: Hindcast of Winds, Waves and Currents in Northern Gulf of Mexico in Hurricane Lili (2002). Offshore Technology Conference, Houston, TX, 3-6 May, 2004. Paper OTC 16821.

Cardone, V. J and D.T. Resio. Assessment of Wave Modeling Technology. Fifth International Workshop on Wave Hindcasting and Forecasting, 26-30 January, 1998, Melbourne, FL.

Cardone, V. J. A. T. Cox and G. Z. Forristall, 2007: Hindcast of winds, waves and currents in Hurricanes Katrina (2005) and Rita (2005). Offshore Technology Conference, Houston, TX., 30-April – 3 May, 2007. Paper OTC 18652.

Chow, S. H., 1970: A study of the wind field in the planetary boundary layer of a moving tropical cyclone. MS Thesis, School of Engineering and Science, New York University, New York, NY.

Chen, S.S., J. F. price, W. Zhao, M. A. Donelan and E. J. Walsh, 2007: The CBLAST-Hurricane Program and the next generation fully coupled atmosphere-wave-ocean models for hurricane research and prediction. B. Amer. Meteor. Soc., 88, (March), 311-317.

Cooper, C. and J. Stear, 2006: An historical perspective of hurricane intensity in the Gulf of Mexico during 2004-2005. Offshore Technology Conference, Houston, TX.

Corbosiero, K.L., W. Wng, Y. Chen, J. Dudhia and C. Davis, 2007: Advanced research WRF high frequency model simulations of the inner core structure of Hurricanes Katrina and Rita (2005). 8th WRF User's Workshop. National Center for Atmospheric Research, Boulder, CO., June 11-15, 2007.

Cox, A. T., V. J. Cardone, F. Counillon and D, Szasbo, 2004: Hindcast of Winds, Waves and Currents in Northern Gulf of Mexico in Hurricane Ivan (2004). Offshore Technology Conference, Houston, TX, 2-5 May, 2005. Paper OTC 17736.

Cox, A.T. and V.J. Cardone, 2000: Operational System for the Prediction of Tropical Cyclone Generated Winds and Waves 6th International Workshop of Wave Hindcasting and Forecasting. November 6-10, 2000, Monterey, California.

Cox, A.T., J.A. Greenwood, V.J. Cardone and V.R. Swail, 1995. An interactive objective kinematic analysis system. Proceedings 4th International Workshop on Wave Hindcasting and Forecasting, October 16-20, 1995, Banff, Alberta, p. 109-118.

Cox, A.T. and V.J. Cardone 2007. Workstation Assisted Specification of Tropical Cyclone Parameters from Archived or Real Time Meteorological Measurements. 10th International Workshop on Wave Hindcasting and Forecasting and Coastal Hazard Symposium, North Shore, Hawaii, November 11-16, 2007.

Dvorak, V. F., 1984: Topical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11, 47pp.

Donelan, M.A., B. K. Haus, N. Reul, W. J. Plant, M. Stiassnie, H. C. Graber, O. B. Brown, E. S. Saltzmann, 2004: On the limiting aerodynamic roughness of the ocean in very strong winds. Geophys. Res. Lett., 31, L18306, doi:10.1029/2004GL019460.

Emanuel, K., S. Raveal, E. Vivant and C. Risi, 2006: A statistical deterministic approach to hurricane risk assessment. BAMS. March, 299-314

Forristall, G. Z., E. G. Ward, V. J. Cardone, and L. E. Borgman. 1978. The directional spectra and kinematics of surface waves in Tropical Storm Delia. J. of Phys. Oceanog., 8, 888-909.

Franklin, J. L., M.L. Black and K. Valde, 2003: GPS dropwindsonde wind profiles in hurricanes and their operational considerations. Wea. Forecasting, 18, 32-44.

Graber, H. C., V. J. Cardone, R. E. Jensen, D. N. Slinn, S. C. Jagen, A. T. Cox, J. M. D. Powell and C. Grassl, 2006: Coastal forecasts and storm surge predictions for tropical cyclones: A timely partnership. Oceanography, 19, 1(March), 130-141.

Holland, G. J., 1980: An analytic model of the wind and pressure profiles in hurricanes. Mon. Wea. Rev. 108,1212-1218.

IPET, 2007. Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System. U.S. Corps of Engineers http://ipet.wes.army.mil

Jensen, R.E., V.J. Cardone and A.T. Cox, 2006: Performance of Third Generation Wave Models in Extreme Hurricanes. 9th International Wind and Wave Workshop, September 25-29, 2006, Victoria, B.C.

Kraft, R. H., 1961: The hurricanes central pressure and highest wind. Mar. Wea. Log., 5, 157.

Kolar, R. L., Gray, W. G., Westerink, J. J., and Luettich, R. A. Jr. (1994a). “Shallow water modeling in spherical coordinates: Equation formulation, numerical implementation, and application.” Journal of Hydraulic Research, 32(1), 3–24

Kossin, J.P., J. Knaff, H. Berger, D. Herndon, T. Cram, C. Velden, R. Murnanne and J. Hawkins. Estimating Hurricane Wind Structure in the Absence of Aircraft Reconnaissance. Weather and Forecasting, Vol. 22, Issue 1, pp. 89-101.

Kurihara, Y., R. Tuleya and M. Bender. The GFDL Hurricane Prediction System and Its Performance in the 1995 Hurricane Season. Monthly Weather Review, Vol. 126, Issue 5, pp.1306-1322.

Large, W.G. and S. pond, 1981: open ocean momentum flux measurements in moderate to strong wind. J. Phys. Oceanog., 11,324-336.

Lee, W-C and M.M. Bell, 2007: Rapid intensification, eyewall contraction and breakdown of Hurricane Charley (2004) near landfall. Geosphy. Res. Lett., 34, L02802, doc:10,1029/2006GL027889.

Leuttich, R. A. Jr., Westerink, J. J. and N. W. Scheffner, 1992. “ADCIRC”: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Esturarie. I: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL”. DRP

Tech. Rep. 1, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS

Olander and Velden 2007. The Advanced Dvorak Technique: Continued Development of an Objective Scheme to Estimate Tropical Cyclone Intensity Using Geostationary Infrared Satellite Imagery. Weather and Forecasting, Vol. 22, Issue 2, pp. 287-298.

Powell, M. D., S. H. Houston and T. A. Reinhold, 1996: Hurricane Andrew's landfall in South Florida. Part I: Standardizing measurements for documentation of surface wind fields. Wea. Forecasting, 11, 304-328.

Powell, M.D., P. J. Vickery and T. A. Reinhold, 2003: Reduced Drag Coefficient for High Wind Speeds in Tropical Cyclones. Nature, 422, 279-283.

Rappaport, E., 2006: (personal communications)

Shapiro, L. J., 1983: The asymmetric boundary layer flow under a translating hurricane. J. Atmos. Sci., 40, 1984-1998.

Swail, V.R. and A.T. Cox. On the use of NCEP/NCAR Reanalysis Surface Marine Wind Fields for a Long Term North Atlantic Wave Hindcast J. Atmo. Tech. Vol. 17, No. 4, pp. 532-545, 2000.

Thompson, E.F., and V.J. Cardone, 1996. Practical modeling of hurricane surface wind fields. Journal of Waterway, Port, Coastal, and Ocean Engineering, July/August 1996, pp. 195-205.

Tropical Prediction Center, 2005. Tropical Cyclone Report Hurricane Katrina. http://www.nhc.noaa.gov/

Ulhorn, E. W. and P. G. Black, 2003: Verification of remotely senses sea surface winds in hurricanes. J. Atmos. Oceanic Techn, 20-99-116.

Ulhorn, E. W., P. G. Black, J. L Franklin, M. Goodberlet, J. Carswell and Alan Goldstein, 2006: Huirricane surface wind measurements from an operational stepped frequency microwave radiometer. Submitted to Monthly Weather Review.

Vickery, P. J. P.F. Skerlj, A.C. Steckley and L. A. Twisdale, 2000: Hurricane wind field model for use in hurricane simulations. J. of Structural Engineering. 1203-

Vickery, P. J., 2005: Simple empirical models for estimating the increase in the central pressure of tropical cyclones after landfall along the coastline of the United States. J. of Appl. Meteor., 44, 1807-1825.

Vickery, P. J. and P. F. Skerlj, 2005: Hurricane gust factors revisited. J. of Structural Engineering. (May), 825-832.

Westerink, J. J., Muccino, J. C., and Luettich, R. A. Jr. (1991). "Tide and hurricane storm surge computations for the western North Atlantic and Gulf of Mexico." Proceedings of the 2nd International Conference on Estuarine and Coastal Modeling, ASCE, Tampa, Florida, 538–550.

Willoughby, H. E. and M. E. Rahn, 2004: Parametric representation of the primary hurricane vortex, Part II: Observations and evaluation of the Holland (1980) wind model.
Mon. Wea. Rev., 132, 3033-3048.

Willoughby, H. E. and M. E. Rahn, 2004: Parametric representation of the primary hurricane vortex, Part I: A new family of sectionally continuous profiles. Mon. Wea. Rev., 134, 1102-1120.

Wimmers, A. J. and C. Velden , 2007: MIMIC. A new approach to visualizing satellite microwave imagery of tropical cyclones. B. Amer. Met. Soc., (August).