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SIXTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 0.2: **Observations and Forecasts of Wind Distribution**

Rapporteur: S.T. Chan
Hong Kong Observatory
134A, Nathan Road,
Kowloon,
Hong Kong, China

E-mail: stchan@hko.gov.hk
Fax: +852-2375-2645

Working Group: Kevin Cheung, Akhilesh Gupta, Bruce Harper, Jeffrey D. Kepert, Kenichi Kusunoki

0.2.1 **Introduction**

Forecasting of wind distribution of a landfalling Tropical Cyclone (TC) is definitely an operational challenge. It is of great importance since the circulation of a TC making landfall would inflict huge losses and widespread damage on the coastal areas. As outlined in Willoughby et al. (2005a), one of the priorities of US Weather Research Program on TC is to make skillful forecasts of gale- and hurricane-force wind radii out to 48 hours with 95% confidence. While there has been much improvement over the years in the forecasting of TC tracks, relatively slow progress was seen during the same period on the problem in question, primarily due to the complexities in the physical processes involved, and the inability of Numerical Weather Prediction (NWP) models to be run at a resolution high enough to adequately resolve the TC structure in an operational manner. Only a limited number of objective guidance tools have been specifically designed for the task and statistical methodologies remain to be the mainstay in tackling the problem.

In this report, new developments since IWTC-V are reviewed. The recent researches on TC structural and wind distribution evolution arising from land-sea contrasts, in particular the influence of land-induced asymmetric friction on the boundary layer winds, and the effects of the moist processes in introducing asymmetries in TC structure at landfall, is covered in Sections 0.2.2a and 0.2.2b.

Damaging fine-scale surface wind features such as boundary-layer rolls, small-scale spiral bands, terrain-induced wind accelerations are frequently observed. A brief account of these features is given in Section 0.2.3a. Observational issues including a review of the wind-pressure relationship, deployment of surface wind observation network and the emergence of new wind speed averaging standards are discussed in Sections 0.2.3b, 0.2.3c and 0.2.3d.

On the forecasting aspects, the development and operational deployment of various empirical and parametric wind models are reviewed in Sections 0.2.4a and 0.2.4b. Latest progress in the modeling of the boundary layer processes in NWP is summarized in Section 0.2.4c.

0.2.2 **Recent Understanding of TC Structural Change due to Land-Sea Contrasts**

The wind structure of a mature TC is basically axisymmetric. However, when a TC makes landfall, part of the TC circulation is affected by increased surface friction over land. In addition, the surface sensible and latent heat fluxes, and moisture supply over land are different from those over ocean. The major goals of recent researches on TC landfall have been to understand how the contrasts between land and ocean will affect the various physical processes, thereby introducing asymmetries in the TC structure.

a) *Land-induced Asymmetric Friction*

The increased friction over land has long been recognized as an important influence on the wind structure changes that occur at landfall (for example, Powell 1987). More recently, it has been recognized that the landfall-induced asymmetric friction provides a predominantly wave-number one forcing, as does the motion-induced asymmetry. Thus the asymmetric boundary-layer wind structure in a stationary storm partly over land should be similar to that in a moving storm. Blackwell (2000) presented an observational analysis of the flow in Hurricane Danny while it was nearly stationary at landfall on the US Gulf Coast, which showed a marked wind asymmetry, with a 41 m s^{-1} maximum at about 500 m altitude in the offshore flow, in contrast to a 31 m s^{-1} maximum at 1500 m in the onshore flow. Kepert (2002a) argued that this asymmetry was similar to those in 3-dimensional models of a moving storm (Kepert 2001, Kepert and Wang 2001), and that the only essential difference was the source of the asymmetric frictional forcing: motion, or proximity to land. He presented model results, using the 3-dimensional boundary layer model of Kepert and Wang (2001), which were in excellent agreement with Blackwell's observations.

A subsequent study (Kepert 2002b) investigated the response when a moving storm makes landfall, that is, both sources of asymmetric forcing are present. It was found that as the storm makes landfall, the motion-induced wind maximum in the right forward quadrant weakens, while a secondary maximum appears in the offshore flow to the left of the track (in the Northern Hemisphere). Shortly before landfall, both are present, and the modeled surface wind field is strikingly similar to Powell's (1980) analysis of the landfall of Hurricane Frederic. In a landfalling cyclone, the wind speed over land is reduced less by friction than would be the case for straight flow, as the resulting enhanced inflow gives increased angular momentum advection which helps to maintain the azimuthal flow component. When the storm is near land, this strong inflow extends over the sea on the offshore-flow side of the storm, due to advection of this inflow by the swirling flow, and causes particularly strong surface winds in the offshore flow. Kepert (2002b) also included a comparison of modeled and GPS-dropsonde observed wind profiles in Hurricane Floyd, with strong agreement.

Schneider and Barnes (2005) analysed the landfall of Hurricane Bonnie, and similarly found a region of enhanced near-surface inflow to the southwest of the storm in the offshore flow (that is, to the left of the track). They argued that the unusual location here is consistent with greater frictional forcing over the land giving an enhanced cross-isobar angle. They noted also that this inflow, which entered the southern part of the eyewall, was relatively cool, dry and stable, consistent with its over-land origin.

Hurricane Mitch made an extraordinarily slow landfall upon Honduras, taking some 36 hours to travel the last 100 km. Kepert (2006b) analysed dropsonde data from a period when the storm was about 80 km off the coast and moving towards it at about 2 m s^{-1}. The flow showed most of the features that would have been expected from the motion-induced frictional asymmetry. In particular, the position of the strongest storm-relative winds rotated anticyclonically with height, and the strongest inflow was always about 90° of azimuth upstream of the strongest azimuthal winds and similarly rotated anticyclonically with height. However, the surface wind maximum was located to the left rear of the storm, rather than in the right front as would be expected if motion was forcing the asymmetry. Modelling results were presented which showed that land at roughly three times the RMW was able to produce a flow asymmetry that propagated inwards with the boundary-layer inflow to produce a marked asymmetry at the RMW.

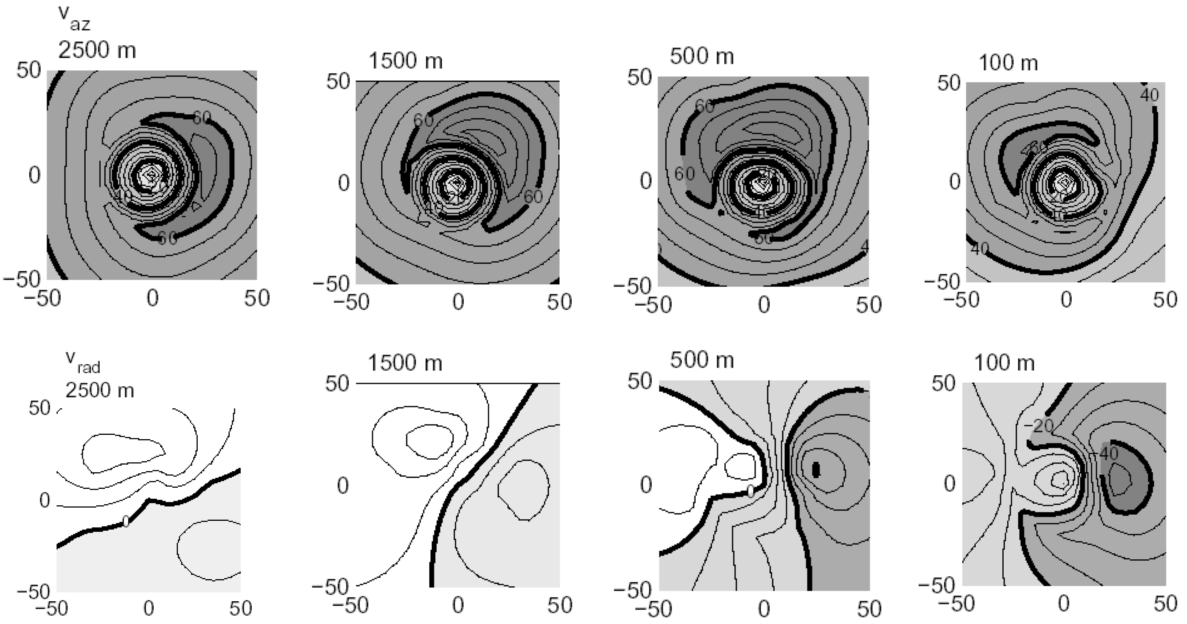

Figure 0.2.1: Objective analyses of the storm relative (top) azimuthal and (bottom) radial wind components of Hurricane Mitch, for levels as shown, based on dropsonde data. Contour interval is 5 m s^{-1}, with multiples of 20 m s^{-1} shown heavy. Darker shading corresponds to stronger azimuthal wind and stronger inflow, respectively (Kepert, 2006b).

As well as inducing a marked asymmetry in the inner core, friction due to proximity to land also produces larger-scale asymmetries in the storm. Wong and Chan (2006a) analysed the structure of the friction-induced surface convergence asymmetry, showing that this would be largest at the coast on the offshore-flow side of the storm in the core, but on the onshore-flow side at larger radii, which could be understood in terms of the storm-scale response to the asymmetric forcing. In another paper, Wong and Chan (2006b) studied the effect of this asymmetry on the storm motion, and found that it was capable of producing a landwards drift of ~1 m s^{-1} when the storm is 150 km offshore. They analysed the cause of this drift, and found that it was not primarily due to the asymmetric flow, but that generation of potential vorticity by the asymmetric vertical motion and diabatic heating was also important. The asymmetric vertical motion was produced partly as a response of the vortex to vertical tilt of its axis, and partly by asymmetric boundary layer convergence. This kind of effect on storm motion is important in considering the rate of increase in wind magnitude when a TC is approaching the coastline.

Shum and Chan (2006) extended this study to the case of a moving storm. The surface wind structure was in good agreement with that described by Kepert (2002b), but their study also analysed the vertical motion and rainfall. They find a marked tendency for the updraft at the top of the boundary layer to lie to the right front of the storm, and strengthen after landfall. The rainfall field is significantly less asymmetric than the updraft at the top of the boundary layer, and displays a distinct cyclonically-propagating maximum after landfall. They also observe an increase in the low-level tilt of the vortex after landfall, and argue that this contributes to the storm weakening, as well as the reduction in the surface thermodynamic fluxes at landfall.

b) *Moisture Supply and Thermodynamic Flux Changes*

Chan and Liang (2003) conducted simulations of the landfall process of a vortex on an f-plane using the fifth-generation Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5). Sensitivity experiments were performed by applying different land conditions: no sensible heat flux, no moisture flux, a higher surface roughness, or moisture supply limited to the lowest level over ocean. The results show that the change in sensible heat flux has little effect in modifying the convective structure of the TC, and that the moisture flux is the dominant factor. Due to the latter, maximum precipitation is found to the front and left quadrant (with respect to the landfall direction) of the TC, which is consistent with observations (Chan et al. 2004). However, the low-level convergence along the coast line does not significantly change the inner structure of the TC in the simulations. Rather, the overall stability (and thus the convection distribution) is modified when the dry air over land is advected by the TC primary circulation.

Chen and Yau (2003) also performed MM5 simulations of an idealized landfall process but with higher resolution (6 km vs. 15 km) so that moist processes can be simulated explicitly. Then potential vorticity (PV) and Eliassen-Palm (EP) flux analyses were utilized to diagnose the physical processes during landfall. Probably due to the higher resolution in the Chen and Yau simulations, more storm-scale features were identified. There is a band of positive PV ahead of the TC that develops along the coastline (Fig. 0.2.2), and the interaction of this PV band with the eyewall PV ring leads to fluctuation in the intensity. The authors suggested that this type of interaction in the boundary layer could be responsible for some eyewall replacement cycles. In fact, an eyewall contraction, breakdown and reformation process was observed in a typhoon during landfall (Wu et al. 2003). Another important conclusion from the Chen and Yau study is that the effect of diabatic heating was found to be quite important in the spinning down of the TC vortex during landfall. Computations show that the contribution at the lower levels to the tangential wind change before landfall is ~30 m s^{-1} h^{-1} by diabatic heating and only ~10 m s^{-1} h^{-1} by the eddies.

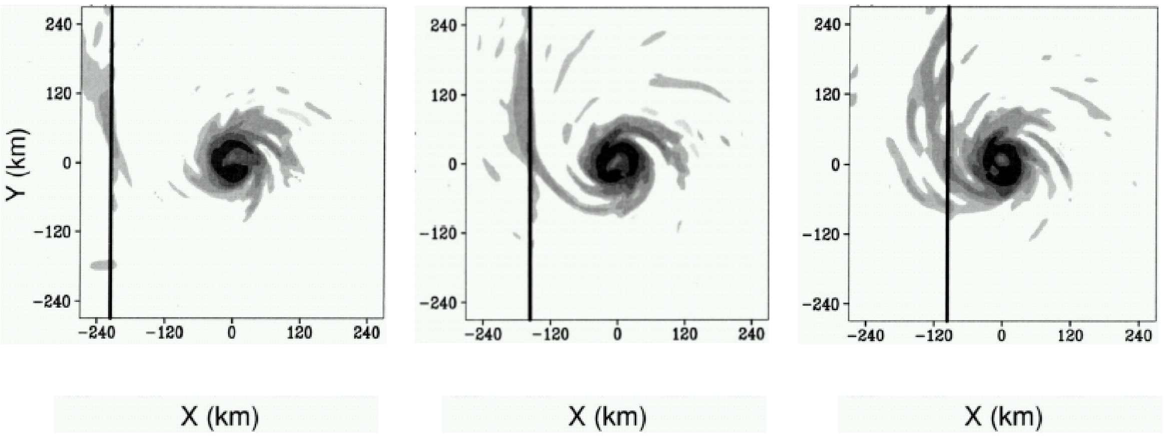

Figure 0.2.2: Model simulated evolution of the horizontal structures of PV (darker more positive). The thick lines denote the shore (Chen and Yau, 2003).

0.2.3 **Observational Aspects**

a) *Fine-scale Surface Wind Structure*

Recent significant progress has been made in understanding the dynamics of small-scale features in the boundary layer winds, on both the observational and theoretical fronts. One area of difference between these has been that the observational studies have necessarily focused on storms near land, while the theory has so far ignored the role of landfall on these processes. From the observational studies, one could perhaps draw the incorrect conclusion that these small-scale features are only present near land, but it would be more correct to say that it is near land that the observations available with sufficient spatial and temporal resolution to capture these small-scale features, while theory suggest that they should be ubiquitous. The dynamics of these fine-scale features are considered in more detail in Topic 1.2.

Boundary-layer rolls are very common in the atmospheric boundary layer (see e.g. Etling and Brown 1993 for a review). Wind circulations associated with these rolls may produce highly organized and damaging surface winds (Wakimoto and Black 1994). Wurman and Winslow (1998) presented the first Doppler radar evidence for their existence in tropical cyclones, indicating intense horizontal roll vortices with an average wavelength of 600 m roughly aligned with the mean azimuthal wind. Several papers have since presented similar evidence. Katsaros et al. (2002) examined SAR images of Hurricanes Mitch and Floyd and also found periodic kilometer-scale variation. More recently, Morrison et al. (2005) describe features that are significantly less streaky in appearance, to the extent that it is not entirely clear that they are the same phenomenon. Possibly the different radar technology used by the groups may have contributed to this difference, since Morrison et al. (2005) also show a SAR image which displays parallel streaks more similar to classical boundary layer rolls. In Japan, a new ground-based observational study of typhoons using Doppler radar for Airport Weather (DRAW) has been conducted from 2005 (Kusunoki and Mashiko 2006; Kusunoki 2006). The preliminary analysis in the inner core of Typhoon Songda (2004) before and during landfall on the Okinawa Island indicates that the perturbation reflectivity field has many small-scale spiral structures spiraling outward from the eyewall (Figure 0.2.3), which are approximately similar to those shown by Gall et al. (1998), Wurman and Winslow (1998), and Morrison et al. (2005). Lorsolo et al. (2006) and Wurman et al. (2006) analyse the vertical structure of the rolls, and find them to be coherent through the depth of the boundary layer (~500 m), and compare radar- and tower-measured winds with fair agreement, demonstrating that the roll circulation extends to the surface, albeit with attenuation and other scales of motion superimposed.

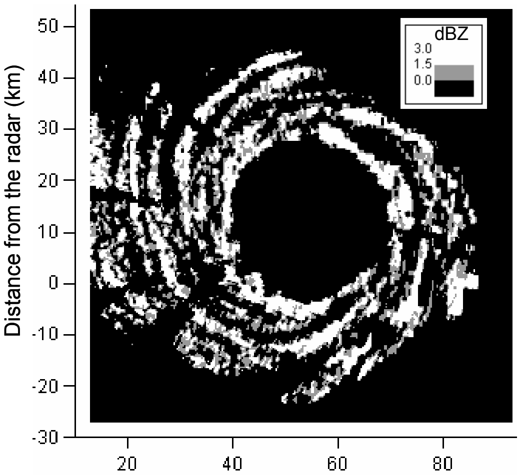

Figure 0.2.3: Perturbation reflectivity field for the inner-core region of Songda taken at 1203 JST 5 September 2005 (Kusunoki and Mashiko, 2006).

Theoretical analyses of roll development in tropical cyclones were provided by Foster (2005) and Nolan (2005). Foster (2005) argues that the tropical cyclone boundary layer is an ideal environment for roll development. His argument extends the classical theory of roll development as an inflection-point instability of the frictionally-induced cross-isobar flow to the case of a tropical cyclone. Here, the cross-stream shear and hence instability are strong because the boundary layer is relatively shallow, and the cross-stream component in analytical solutions is stronger than in classical Ekman-like solutions for straight flow (Kepert 2001). Nolan (2005) presents a stability analysis of a symmetric vortex, and finds both symmetric and asymmetric responses. The instabilities acquire some energy from the shear in the radial flow near the top of the boundary layer, in which regard they are similar to Foster's (2005) rolls. However, Nolan (2005) shows that the vertical shear of the azimuthal wind can also contribute energy to the instability, and that the relative importance of these mechanisms depends on the inertial stability of the storm and on the orientation of the mode.

The GPS dropsonde has now been operational for close to a decade, and several thousands have been deployed in the eyewall of hurricanes. Extreme gusts have been reported in both horizontal and vertical wind components (Aberson and Stern 2006, Henning 2006, Stern and Aberson 2006). Such extreme events contribute greatly to the extensive wind damage brought by a landfalling TC that could not be adequately represented by broad-brush destructive potential scales such as the Saffir Simpson Scale. While the extreme gusts are (by definition) rare events, the steadily increasing sample is beginning to enable statistical characterization of their nature.

Another type of fine-scale feature that is definitely unique to landfall is topographically-induced accelerations. These may take the form of shear lines, reversed flow, small-scale vortices, streaks, and downslope winds, due to the complex interaction of topography and flow. Shun et al. (2003) presented interesting Doppler radar observations of some of these phenomena in Hong Kong, and well illustrated the range and complexity of the problem. Mueller et al. (2006) compared exposure-based engineering models with observed damage on Bermuda during Hurricane Fabian. This is important work, as such models are foundational to the design of structures and to climatological risk analysis, but have not been extensively verified in tropical cyclones. Similar analysis is being undertaken in Australia following the extremely damaging landfall of Severe Tropical Cyclone Larry in northern Queensland in 2006.

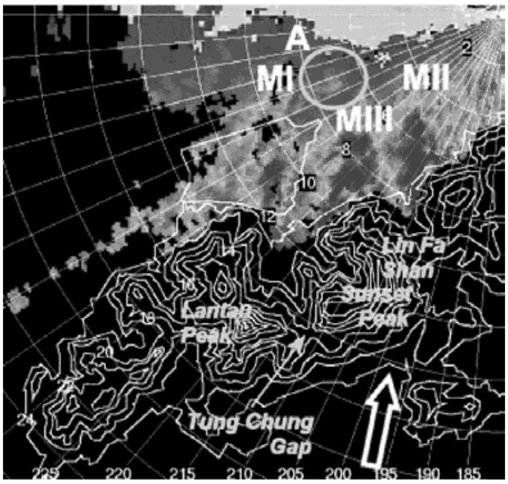

Figure 0.2.4: Doppler radar observation of high speed streaks (positions M-I, M-II, and M-III) and vortex (position A) on 7 June 1999 as Typhoon Maggie was making landfall some 150 km west of Hong Kong. White arrow indicates the background flow direction (details in Shun et. al, 2003).

b) *Wind-Pressure Relationship*

Harper (2002) provided an overview of the historical development of wind-pressure relationships and their application within the Australian region, highlighting many aspects that affect the quality of the best track databases throughout the world, and challenging the justification for using basin-specific wind-pressure curves. Harper argues that the variability in wind-pressure balance within and between individual storms is likely much greater than any regional “average” and that it is important to incorporate storm spatial scale and profile shape to allow for the expected natural variability in the wind-pressure balance. These conclusions supported, in principle, the operational experience already documented by, for example, Callaghan and Smith (1998) and Guard and Lander (1996) on how to characterise “midget” systems. In particular, Harper retraced the early development of the Dvorak technique to show that the current Atlantic wind-pressure relationship was actually developed using mainly NWP storms but was dropped in preference to the Atkinson and Holliday (1977) results. Aspects of this investigation have also been reported in Velden et al. (2006). Harper also argued for reconsideration of the Holland (1980) B parameter as an indicator of the wind pressure variability. Recently, Knaff and Zehr (2006) have further examined the basis of the Atkinson and Holliday (1977) relationship and provide a modified best-fit to the original dataset, which yields a result closer to the Dvorak Atlantic curve. Their method also provides a basis for utilising the readily available operational parameters of size, latitude and environmental pressure to enable forecasters to adopt specific wind-pressure pairings on a case by case basis. The authors claim that using the proposed unifying equations, the MSLP can be estimated from the Vmax within 5 to 6 hPa and the wind can be estimated from the MSLP within 7 to 8 kt. Recently Weber (2006) has also proposed an alternative wind profile approach that uses radius of outermost close isobar and central and environmental pressure. As noted by Knaff and Zehr (2006), improved accuracy in estimating central pressure will also have value in the better initialization of NWP models.

c) *Surface Wind Observation Network*

Notwithstanding the increasing importance and utility of remote sensing systems (e.g. satellite MI proxy and scatterometer) for estimating surface wind speeds, there remains a critical need to maintain and expand surface wind measurement networks in all areas where communities are at risk from tropical cyclone impacts. Verification of forecast/modelled winds must remain a priority if real improvements in techniques and procedures are to be realized. There are several challenges in this regard, the first being the costs of establishing and maintaining instrument systems. Others include the need to optimally locate such instrumentation or in lieu, to ensure that less than optimum sites are adequately calibrated. Finally, baseline instrumentation needs to be ruggedised and possess backup power and data storage to enable full recovery of information from extreme wind events (recent instrument failures of note include TC’s Ingrid and Monica across Northern Australia and Hurricane Katrina on the US Gulf Coast).

A critical development in recent years, mainly in the US, has been the availability of mobile wind instrumentation systems, typically owned and operated by research organizations (e.g. Schroeder and Smith 2003). These systems are now highly developed and their use has added an enormous amount of knowledge to the science of the near-surface land boundary layer under tropical cyclone conditions. The impetus and initiative for these systems has come mainly from a wind engineering focus but there should be no reason why such mobile systems could not be usefully deployed as a part of a comprehensive forecast and verification system by mainstream meteorological agencies.

Opportunities for utilising new technologies should also be considered. For example, the proliferation of wireless networking protocols and low-cost low-power electronics continues to widen the opportunities for “smarter” wind sensing systems, potentially delivering a much greater density of measurements at a lower cost. The use of “infrastructure of opportunity” rather than relying on baseline installation of standard height towers also has the capacity to reduce capital costs. Such infrastructure can include power transmission line towers, communications towers and the like. Typically, operators of such equipment also have a vested interest in having access to long term wind measurements (e.g. for power transmission efficiencies or damage assessment etc) and symbiotic relationships and partnerships may well develop. Cheaper and even disposable (nil maintenance or “bolt-and-forget”) wind sensor systems should be possible with existing technologies. Importantly though, the adopted infrastructure site must be calibrated so that the attached sensor delivers a known directional response that can be reliably converted to standard exposure and directly ingested by forecast and/or modelling systems.

Standardisation of wind sampling and analysis is essential so that data collected from one environment can be reliably compared with another and work to build a reliable ground truth, from which better models and procedures can emerge. Without attention to these basic needs, the still significant “noise level” in wind forecast capabilities will never be reduced. Powell et al. (2004) presented a project in the United States to photographically document exposures of over 200 automatic weather stations in hurricane-susceptible areas. Roughness lengths for each octant of wind direction for all documented stations were estimated, from which the wind measurements can be corrected to open terrain for use in real-time analyses of hurricane wind fields. The exercise demonstrates that mean wind measurements associated with significant upstream terrain may underestimate the open-terrain wind by about 30%.

d) *Wind Speed Averaging Standards*

One of the difficulties in transferring forecast techniques from one region to another has been the use of different “standards” for reporting the wind strength. While the WMO standard remains as the 10 minute average wind for synoptic reporting, adopted by RA I and RA V, other approaches have developed over time due to local preferences. RA IV (Americas and Caribbean) have adopted a 1-minute average (termed “sustained”) for all warning purposes. The remaining regions (ESCAP TC and Typhoon) use the 10-minute average but allow a 3-minute average for non-recording observations and, in China, a 2-minute average is recognised. Paradoxically, none of the WMO associations define a “gust” wind standard, although it is recognized that short period wind gusts (say 2- to 3-second) are responsible for the greater proportion of community damage and are typically the averaging values used by planning and standards bodies that oversee the mitigation of tropical cyclone threats through improved building codes and the like.

Additionally, the adoption of a 1-minute “sustained” wind by RA IV, US territories in the Western North Pacific and the US military globally, has led to the 1-minute wind becoming the de facto standard for the application of the Dvorak (1984) technique, with other regions applying conversions (e.g. WMO 1993, Table 4.2) to suit their local needs. Unfortunately, there is evidence that the need for such conversions may have contributed to the introduction of systematic errors in some best track archives (e.g. Harper and Callaghan 2006). Also, it is typically not appreciated that the Dvorak “Atlantic” wind-pressure relationship has no stated wind averaging context but was simply the maximum expected surface wind (Velden et al. 2006) and, by association with the wind and pressure curve has been interpreted as 1 minute. These differences and/or misunderstandings have allowed a situation to develop over many decades whereby some potentially avoidable variance (of the order of 20%) in wind measurements and/or estimation has entered the science, notwithstanding that TC intensity estimation is an already extremely difficult problem.

Following IWTC V in Cairns in 2002, the WMO acted to reduce the uncertainty in converting between the various wind averaging contexts by commissioning a best practice review (Harper et al. 2004), which is expected to be finalized soon. The review considers the theoretical turbulence framework within which wind-averaging conversions are valid (or indeed invalid) and also extensively reviews both historical data (especially TC data) and theoretical statistical models for estimating such conversions. A revised set of conversion factors is planned that will supercede that presently in WMO (1993) and provide guidance on when and how to apply such conversions in both forecast and research environments.

0.2.4 **Forecasting Aspects**

a) *Empirical Models of Wind Distribution for Landfalling TCs*

For operational early warning and disaster mitigation purposes, some empirical models of wind distribution for landfalling TCs are currently applied. Some of these models derive empirical laws of the weakening of a TC during landfall based on historical cases (e.g., Vickery 2005 for the Gulf of Mexico Coast and the coast of the Florida Peninsula). In some others, the maximum sustained surface wind of a TC is assumed to decay exponentially during landfall (e.g., Roy Bhowmik et al. 2005 for the east coast of India). However, note that the mentioned applications of empirical models are for relatively flat coastal areas. When orographic influence is effective, the TC track may be deflected and the wind distribution in the landfall area will be much different from that without topography (e.g., Lin et al. 2005).

b) *Parametric Wind Field Modelling*

This is an area that remains potentially under-utilized and under-valued by many forecast centers, where the traditional use of Dvorak (1984) has perhaps been seen as the only legitimate technique for estimating intensity when aerial reconnaissance is not available. For example, in IWTC IV Topic 4.3 (WMO 1998) a number of parametric modelling tools were presented, typically based on the Holland (1980) or similar technique, or even involving the conceptual Rankin vortex etc. Such techniques do rely on having some relevant surface wind (and/or pressure) observations but can be readily applied within a simplified modelling context to add significant value to satellite-only intensity estimates. The parametric model has the advantage of providing a stable theoretical quasi-static force balance which, with the benefit of time-history and spatial contexts, can readily augment the Dvorak analysis, which has neither of these attributes.

The operation of parametric models has been boosted in recent times by the ready availability of sea surface scatterometer data, which can now very effectively provide the outer spatial scale of storm systems (e.g. Rgales). When combined with an independent estimate of the inner scale (Rmax), typically via satellite (VIS or EIR or MI), a full parametric wind field can be readily estimated. The emerging EIR method by Kossin et al. (2006) promises to also provide both of these parameters as well as estimates on the entire two-dimensional surface wind field within 200 km of the storm centre in an automated fashion. With such objective data, parametric models could also include asymmetries and conservative properties such as angular momentum can also be considered. Parametric models have the capability of providing a significantly similar quality of surface wind estimates to full NWP models but at a fraction of the cost and effort. Such models could readily be used to replace what are still typically hand-drawn warning and evacuation zone products at many centers.

A potentially significant advance in parametric modelling was recently made available through the work of Willoughby et al. (2005b), whereby several decades of US aerial reconnaissance flights were analysed to obtain a family of radial gradient windspeed profiles. This analysis represents the most significant advance yet in describing the radial wind field of tropical cyclones and has additionally provided very valuable information on data dependencies of spatial scale, intensity and latitudinal variations, at least within the Atlantic basin. Other techniques that remain promising include the “double Holland” concept introduced by Thompson and Cardone (1996), which can be used to represent eyewall replacement cycles, and the more sophisticated yet efficient analytical Ekman modelling approach as presented by Kepert (2001), which provides for radially and azimuthally varying inflow and gradient height reduction, albeit within the assumption of an applied Holland gradient level pressure profile.

SHIPS (Statistical Hurricane Intensity Prediction Scheme) is a successful statistical-dynamical model deployed by NHC for operational intensity forecasting in the Atlantic and East Pacific basins. The scheme involves multiple linear regression of environmental and “CLIPER”-type parameters. A method to adjust the real-time forecasts over land using a simple empirical exponential decay model has since been introduced in 2000 to the scheme (DeMaria et al., 2005). The inclusion of the effects of the decay over land reduced short-range Atlantic and East Pacific intensity errors up to 72 hours. DeMaria et al. (2006) further presented a modified decay model for storms that move over narrow landmasses. The modified decay model includes a factor equal to the fraction of the storm circulation that is over land and it was applied to SHIPS in 2005. The new scheme reduced the intensity forecast errors by up to 8% relative to the original decay model for cases from 2001 to 2004 in which the storm was within 500 km from land (Figure 0.2.5). The version of SHIPS for the western North Pacific basin - Statistical Typhoon Intensity Prediction Scheme (STIPS), was developed and implemented operationally at the Joint Typhoon Warning Center (JTWC) in July 2002 and updated in mid June 2003 (Knaff et al., 2004).

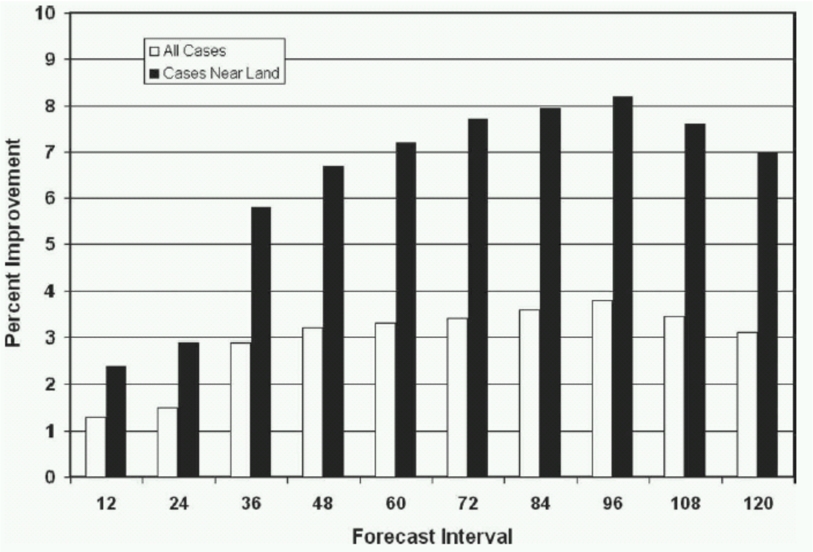

Figure 0.2.5: Percentage improvement in the mean absolute intensity error of the 2001-04 operational SHIPS forecasts when the modified decay model is introduced. Results are shown for the total sample and the sample in which the best track was within 500 km of land (DeMaria et al., 2006)

Several modifications are being planned for SHIPS, which include predictors from aircraft flight-level observations (with inner-core wind field structure information), daily SST analyses from Advanced Microwave Scanning Radiometer for the Earth-Observing System (AMSR-E) and total precipitable water analysis from microwave imagery.

c) *Modelling of Boundary Layer Processes in NWP*

As seen from the discussions on theoretical development, the evolution of the intensity and structure of a TC has strong dependence on changes in the surface conditions. Successful prediction of structural changes of a landfalling TC depends much on the adequacy of our current NWP models in simulating the boundary layer processes (e.g., Shen et al. 2002).

So far, little has been known about the exchange and drag coefficients at high wind conditions largely due to the fact that measurements under extremely high wind conditions are very difficult to make. Based on GPS dropsonde measurements, Powell et al. (2003) showed that as surface winds increase above 40 m s^{-1}, the sea becomes completely covered by a layer of foam which impeded the transfer of momentum form the wind to the ocean. As a result, drag coefficients would decrease with the wind speed. This finding helps reduce the uncertainties in the calculation of surface fluxes and thus improving TC intensity forecast by NWP models. In their review, Wang and Wu (2004) called for a prompt development of a new parametrization scheme for the drag coefficient based on Powell et al. (2003) and an evaluation of its effect on TC intensity.

Kasheta and Chang (2002), based on a “dry” hurricane boundary-layer model, demonstrated that the downward transfer of high momentum aloft played a significant role in the maintenance of high wind speeds at the surface with the surface wind maxima being observed on the lee sides of high terrain. They suggested that a refined surface roughness length scheme over land should be considered for real terrain studies, e.g. a scheme based on the surface canopy as well as terrain height. Such a scheme in conjunction with a very fine grid (say 1 km mesh) would allow the microscale structure of terrain-induced downdrafts to be captured.

Recently, Wu et al. (2003) studied the eyewall evolution of Typhoon Zeb (1998) and found that the eyewall evolution comprised an eyewall contraction just before landfall at Luzon, followed by a breakdown after landfall and then a reformation of the eyewall upon reentering the ocean as the storm left Luzon. They showed that a high-resolution model could reproduce such an eyewall evolution but the physical processes responsible for that are not yet understood. Further investigations into such eyewall evolution processes would improve our understanding of TC structure and intensity changes for TCs making landfall and interacting with mesoscale terrains (Wang and Wu, 2004).

In the coming years, studies on sensitivities to various parameters in a land surface model when simulating a TC landfall and evaluation of the skill of the NWP models in forecasting the associated wind distribution are needed (e.g., Farfán and Cortez 2005; Rodell et al. 2005).

0.2.5 **Summary and Recommendations**

A summary of possible research efforts and recommendations about future research directions in dealing with the roadblocks and requirements discussed in the previous sections is given below.

1. It is expected that the motion and landfall contributions to asymmetric friction will more commonly be of comparable magnitude. The interaction between them and their impact on TC structural evolution may be important and full investigation of this topic is needed.

2. Extreme wind gusts observed in landfalling TC, whether induced by convective, coherent (e.g. rolls) or vortex-related structural features could be responsible for increased damage at ground level. These are not necessarily represented by the broad-brush destructive potential scales currently used. With the accumulation of more observational data, by combining GPS dropsondes, Doppler radar and fine scale tower surface wind measurements, better characterization of such destructive phenomenon should become possible.

3. The recent important work using an exposure-based engineering model to quantify the impact of topographic speed-up effects on the observed damage to structures during Hurricane Fabian in Bermuda was noted. Such models are foundational to the design of structures and to climatological risk analysis, and should be extensively verified in tropical cyclones.

4. Parametric wind field models could usefully augment the Dvorak analysis to provide quality surface wind estimates at a fraction of the cost and effort required for NWP modelling. More extensive use of them by operational forecast centres is recommended.

5. A refined surface roughness length scheme over land should be considered for real terrain studies. Such a scheme in conjunction with a very fine grid would be able to capture the microscale structure of terrain-induced downdrafts.

6. Studies on sensitivities to various parameters in a land surface model when simulating a TC landfall and evaluation of the skill of the NWP models in forecasting the associated wind distribution are needed. In particular, progress has been made in understanding the air-sea exchange under high

wind speeds, efforts in similar validation of the land surface schemes are also required.

7. Verification of forecast/modelled winds must remain a priority if real improvements in techniques and procedures are to be realized. Agencies should consider the need for enhancing and expanding surface wind networks in tropical cyclone prone areas and investigate more innovative alternatives to conventional fixed multi-parameter weather stations so as to improve the chances of obtaining verifying surface wind data. Wind measurement and reporting standards must also be improved to ensure consistency across the various forecast techniques and NWP estimates.

Bibliography

Aberson, S. D., and D. P. Stern, 2006: Extreme horizontal winds measured by dropwindsondes in hurricanes. *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 – 28. Paper 16B7.

Atkinson G. D., and C. R. Holliday, 1977: Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for the Western North Pacific. Mon. Wea. Rev., **105**, 421-427.

Bessho K., M. DeMaria and J. A. Knaff. 2006: Tropical Cyclone Wind Retrievals from the Advanced Microwave Sounding Unit: Application to Surface Wind Analysis. *J. Appl. Met. and Clim.*, **45**, 399-415.

Blackwell K.G., 2000: The evolution of Hurricane Danny (1997) at landfall: Doppler-observed eyewall replacement, vortex contraction/intensification, and low-level wind maxima. *Mon. Wea. Rev.***128**, 4002-4016.

Callaghan J. and R. K. Smith, 1998: The relationship between surface wind speeds and central pressure in tropical cyclones. Aust Meteorological Magazine, **47**, 191-202.

Campo, K. D. and T. M. Riskenback, 2006: Eyewall evolution of Hurricane Katrina newr landfall using NEXRAD reflectivity and radial velocity data. *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper P7.10

Chan, J. C. L., and X. Liang, 2003: Convective asymmetries associated with tropical cyclone landfall. Part I: f-plane simulations. J. Atmos. Phys., **60**, 1560-1576.

Chan, J. C. L., K. S. Liu, S. E. Ching, and E. S. T. Lai, 2004: Asymmetric distribution of convection associated with tropical cyclones making landfall along the South China coast. Mon. Wea. Rev., **132**, 2410-2420.

Chen, Y., and M. K. Yau, 2003: Asymmetric structures in a simulated landfall hurricane. J. Atmos. Phys., **60**, 2294-2312.

Cubukcu, N., R. L. Pfeffer, D. E. Dietrich, 2000: Simulation of the effects of bathymetry and land-sea contrasts on hurricane development using a coupled ocean-atmosphere model. *J. Atmos. Sci.* **57**, 481-492.

DeMaria M., M. Mainelli, L. Shay, J. Knaff and J. Kaplan, 2005: Further Improvement to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531-543.

DeMaria M., J. A. Knaff and J. Kaplan, 2006: On the Decay of Tropical Cyclone Winds Crossing Narrow Landmasses. *J. Appl. Met. and Clim.*, **45**, 491-499.

Dvorak V. F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Technical Report NESDIS 11, 45pp.

Eckman, R. M., R. J. Dobosy, T. W. Strong and P. G. Hall, 2006: In situ measurements of 3d turbulence in Hurricanes Frances and Ivan using a pressure-sphere anemometer. *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper 10C4.

Farfán, L. M., and J. A. Zehnder, 2001: An Analysis of the Landfall of Hurricane Nora (1997). *Mon. Wea. Rev.*, **129**, 2073-2088.

Farfán, L. M., and M. Cortez, 2005: An observational and modeling analysis of the landfall of Hurricane Marty (2003) in Baja California, Mexico. Mon. Wea. Rev., **133**, 2069-2090.

Foster, R. C., 2005: Why rolls are prevalent in the hurricane boundary layer. *J. Atmos. Sci.*, **62**, 2647-2661.

Gall, R., J. Tuttle, and P. Hildebrand., 1998: Small-scale spiral bands observed in Hurricanes Andrew, Hugo, and Erin. *Mon. Wea. Rev.*, **126**, 1749-1766.

Geerts B., Heymsfield G. M., Tian L., Halverson J. B., Guillory A., Mejia M. I., 2000: Hurricane Georges's landfall in the Dominican Republic: Detailed airborne doppler radar imagery. *Bull. Amer. Meteor. Soc.*, **81**, 999-1018.

Guard C. P. and M. A. Lander, 1996: A wind-pressure relationship for midget TCs in the Western North Pacific. In: 1996 Annual Tropical Cyclone Report, Naval Pacific Meteorology and Oceanography Centre / Joint Typhoon Center, Section 7.9, p 311.

Harper B. A. and J. Callaghan, 2006: On the importance of reviewing historical tropical cyclone intensities. American Meteorological Society, 27th Conference on Hurricanes and Tropical Meteorology, 2C.1, Monterey, Apr.

Harper B. A., 2002: Tropical cyclone parameter estimation in the Australian region: Wind-Pressure Relationships and Related Issues for Engineering Planning and Design, Systems Engineering Australia Pty Ltd for Woodside Energy Ltd, Perth, May, 83pp.

Harper B. A., J. Kepert and J. Ginger, 2004: Guidelines for converting between various wind averaging periods in tropical cyclone conditions. WMO, TCP Sub-Project, June, 45pp, (draft).

Henning, R. G., 2006: The intensity of wind gusts underneath areas of deep eyewall convection in Hurricanes Katrina and Dennis at landfall. *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper 3B1.

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

Holmes, J., K. G. Blackwell, R. A. Wade and S. K. Kimball, 2006: Collapsing precipitation cores in open-eyewall hurricanes at landfall: Are these cores actually downbursts associated with extreme surface wind gusts? *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper 7B7.

Houston, S. H., and M. D. Powell, 2003: Surface Wind Fields for Florida Bay Hurricanes. *J. Coastal Res.*. **19**, 503-513.

Kasheta, T.E. and C.B. Chang, 2002: Development of a hurricane boundary-layer wind model. Meteorology and Atmospheric Physics, **79,** 259-273.

Katsaros, K. B., P. W. Vachon, W. T. Liu, and P. G. Black, 2002: Microwave remote sensing of tropical cyclones from space. *J. Oceanogr.*, **58**, 137-151.

Kepert, J. D., 2001: The dynamics of boundary layer jets within the tropical cyclone core. Part I: Linear theory. *J. Atmos. Sci.*, **58**, 2469-2484.

Kepert, J. D. and Y. Wang, 2001: The dynamics of boundary layer jets within the tropical cyclone core. Part II: Nonlinear enhancement. *J. Atmos. Sci.*, **58**, 2485-2501.

Kepert, J. D., 2002a: The impact of landfall on tropical cyclone boundary layer winds. *Extended abstracts, 25th Conference on Hurricanes and Tropical Meteorology*, Amer. Meteor. Soc., San Diego, California, 29 April - 3 May, 2002, 335-336.

Kepert, J. D., 2002b: Modelling the tropical cyclone boundary layer wind-field at landfall. *Extended abstracts, 14th BMRC Modelling Workshop: Modelling and Predicting Extreme Events*, Melbourne, Australia, 11-13 November, 81-84.

Kepert, J. D., 2002c: *The Wind-Field Structure of the Tropical Cyclone Boundary-Layer*. PhD thesis, Monash University, Melbourne, Australia. 350 pp.

Kepert, J. D., 2006a: Observed boundary-layer wind structure and balance in the hurricane core. Part I: Hurricane Georges. In press, *J. Atmos. Sci.*

Kepert, J. D., 2006b: Observed boundary-layer wind structure and balance in the hurricane core. Part II: Hurricane Mitch. In press *J. Atmos. Sci.*

Knaff, J. A., M. DeMaria and C. R. Sampson, 2004: An introduction to the statistical typhoon intensity prediction scheme (STIPS). *Extended abstracts, 26th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Miami, FL, May 3 - 7. Paper P14.A1.

Knaff, J. A. and M. Zehr, 2006: Reexamination of tropical cyclone wind-pressure relationships. Weather and Forecasting, Apr, submitted [see also AMS 27th Hurricanes Conf].

Knupp, K. R., J. Walters, and E. W. McCaul, Jr., 2000: Profiler observations of Hurricane Georges during landfall. *Geo. Res. Letters,* **27**, 3361-3364.

Knupp, K. R., J. Walters, and M. Biggerstaff, 2006: Doppler profiler and radar observations of boundary layer variability during the landfall of Tropical Storm Gabrielle. *J. Atmos. Sci.* **63**, 234-251.

Kossin J. P., J. A. Knaff, H. I. Berger ,D. C. Herndon, T. A. Cram, C. S. Velden, R. J. Murnane and J. D. Hawkins, 2006: Estimating hurricane wind structure in the absence of aircraft reconnaissance. Weather and Forecasting, submitted Dec.

Kusunoki, K., 2006: Assessment of the Doppler Radar for Airport Weather (DRAW) system in Japan as a research tool for studying typhoon. Preprints, 27th Conf. on Hurricanes and Tropical Meteorology, Amer. Meteor. Soc., P5.10

Kusunoki, K. and W. Mashiko., 2006: Doppler radar investigations of the inner core of Typhoon Songda (2004) - polygonal / elliptical eyewalls, eye contraction, and small-scale spiral bands. Preprints, 27th Conf. on Hurricanes and Tropical Meteorology, Amer. Meteor. Soc., P4.10

Larson, J., Y. Zhou, and R. W. Higgins, 2005: Characteristics of Landfalling Tropical Cyclones in the United States and Mexico: Climatology and Interannual Variability. *J. Clim.* **18**, 1247-1262.

Li, M., L. Zhong, W. C. Boicourt, S. Zhang, and D. -L. Zhang, 2006: Hurricane-induced storm surges, currents and destratification in a semi-enclosed bay . *Geophys. Res. Lett.*. **33**.

Lin, Y.-L., S.-Y. Chen, C. M. Hill, and C.-Y. Huang, 2005: Control parameters for the influence of a mesoscale mountain range on cyclone track continuity and deflection. J. Atmos. Phys., **62**, 1849-1866.

Lin, Y. -L., L. C. Savage III and C. M. Hall, 2006: Effects of landfall location and the approach angle of a cyclone encountering a mesoscale mountain range. *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper P4.22.

Lorsolo, S. and J. L. Schroeder, 2006: Tower and Doppler radar observations from the boundary layer of Hurricanes Isabel (2003) and Frances (2004). *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper 10C5.

Morrison, I., S. Businger, F. Marks, P. Dodge and J. A. Businger., 2005: An Observational case for the prevalence of roll vortices in the hurricane boundary layer. *J. Atmos. Sci*., **62**, 2662-2673.

Mueller, K. J., C. Miller, K. Beatty and A. Boissonnade, 2006: Correlation of topographic speed-up factors and building damage ratios for Hurricane Fabian in Burmuda. *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper 5A8.

Nolan, D. S., 2005: Instabilities in hurricane-like boundary layers. Dyn. Atmos. Oceans, **40**, 209-236.

Otvos, Ervin G. 2004: Beach Aggradation Following Hurricane Landfall: Impact Comparisons from Two Contrasting Hurricanes, Northern Gulf of Mexico. *J. Coastal Res.* **20**, 326-339.

Powell M. D, P. J. Vickery and T. A. Teinhold, 2003: Reduced drag coefficient for high wind speeds in tropical cyclones. *Nature*, **422**, 279-283.

Powell, M., D. Bowman, D. Gilhousen, S. Murillo, N. Carrasco and R. St. Fleur. 2004: Tropical Cyclone Winds at Landfall: The ASOS-C-MAN Wind Exposure Documentation Project. *Bull. Amer. Meteor. Soc*., **85**, 845-851.

Rodell, M, P. R. Houser, A. A. Berg, and J. S. Famiglietti, 2005: Evaluation of 10 methods for initializing a land surface model. J. Hydrometeor., **6**, 146-155.

Roy Bhowmik, S. K., S. D. Kotal, and S. R. Kalsi, 2005: An empirical model for predicting the decay of tropical cyclone wind speed after landfall over the Indian region. J. Appl. Meteor., **44**, 179-185.

Schneider, R. and Barnes, G. M., 2005: Low-Level Kinematic, Thermodynamic, and Reflectivity Fields Associated with Hurricane Bonnie (1998) at Landfall. *Mon. Wea. Rev*. **133**, 3243-3259.

Schroeder J. L., and D. A. Smith, 2003: Hurricane Bonnie wind flow characteristics as determined from WEMITE. J. Wind Engineering and Industrial Aerodynamics, **91**, 767-789.

Shen, W., I. Ginis, and R. E. Tuleya, 2002: A numerical investigation of land surface water on landfalling hurricanes. J. Atmos. Phys., **59**, 789-802.

Shum, W. C. T. and J. C. L. Chan, 2006: Tropical cyclone landfall under the influence of uniform flow.

Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology. Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper 7B3.

Shun, C. M., S. Y. Lau, and O. S. M. Lee. 2003: Terminal Doppler Weather Radar Observation of Atmospheric Flow over Complex Terrain during Tropical Cyclone Passages. *J. Appl. Met.*. **42**, 1697-1710.

Skwira, G. D., J. L. Schroeder and R. E. Peterson. 2005: Surface Observations of Landfalling Hurricane Rainbands. *Mon. Wea. Rev.* **133**, 454-465.

Stern D. P., and S. D. Aberson, 2006. Extreme vertical winds measured by dropwindsondes in hurricanes. *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper 16B8.

Thompson E. F. and V. J. Cardone, 1996: Practical modelling of hurricane surface wind fields. J. Waterways, Port, Coastal and Ocean Engineering, ASCE, 122, 4, 195-205.

Velden C., B. Harper, F. Wells, J. L. Beven, R. Zehr, T. Olander, M. Mayfield, C. Guard, M. Lander, R. Edson, L. Avila, A. Burton, M. Turk, A. Kikuchi, A. Christian, P. Caroff, P. McCrone, 2006: The Dvorak tropical cyclone intensity estimation technique: a satellite-based method that has endured for over 30 years. Bulletin American Meteorological Society, to appear.

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. Appl. Meteor., **44**, 1807-1826.

Wakimoto, R. M., and P. G. Black, 1994: Damage survey of Hurricane Andrew and its relationship to the eyewall. *Bull. Amer. Meteor. Soc.*, **75**, 189-200.

Wang Y. and C. –C. Wu, 2004: Current understanding of tropical cyclone structure and intensity changes – a review. Meteor. and Atmos. Physics, **87**, 257-278.

Weber H. C., 2006: On the wind-pressure relationship in tropical cyclones. AMS, 27th Conf. Hurricanes and Tropical Meteorology, 14A.6, Monterey, Apr.

Willoughby H. E., E. N. Rappaport, F. D. Marks, 2005a: Hurricane Forecasting, the state of the art, paper submitted for the Hurricane Forecast socioeconomic working group, Pomona CA, 16-18 February 2005.

Willoughby H. E., R. W. R. Darling, and M. E. Rahn, 2005b: Parametric representations of the primary hurricane vortex. Part II: A new family of sectionally continuous profiles. Mon. Wea. Rev., 134, (4), 1102-1120.

WMO 1993: Global guide to tropical cyclone forecasting. Tropical Cyclone Programme Report No. TCP-31, World Meteorological Organization, WMO/TD No. 560, Geneva. [http://www.bom.gov.au/bmrc/pubs/tcguide/globa_guide_intro.htm]

WMO, 1998: Topic chairman and rapporteur reports of the fourth WMO international workshop on tropical cyclones (IWTC-IV). World Meteorological Organisation, WMO/TD - No. 875., April.

Wong, M. L. M. and J. C. L. Chan, 2006a: Effects of land-sea roughness contrast on tropical cyclone winds. *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper 11B6.

Wong, M. L. M. and J. C. L. Chan, 2006b: Tropical cyclone motion in response to land surface friction. *J.*

Atmos. Sci., **63**, 1324 - 1337.

Wroe, Derek R., Barnes, Gary M. 2003: Inflow Layer Energetics of Hurricane Bonnie (1998) near Landfall. *Mon. Wea. Rev.* **131**, 1600-1612.

Wu, C. -C., K. -H. Chou, H. -J. Cheng, and Y. Wang, 2003: Eyewell contraction, breakdown and reformation in a landfalling typhoon. Geophys. Res. Lett., **30**, 1887.

Wu, C. -C. and H. -J. Cheng, 2006: The dynamics of the eyewall evolution in a landfalling typhoon. *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper 6B4.

Wu, M. C., W. L. Chang and W. M. Leung. 2004: Impacts of El Niño-Southern Oscillation Events on Tropical Cyclone Landfalling Activity in the Western North Pacific. *J. Clim.* **17**, 1419-1428.

Wurman, J., C. Alexander, P. Robinson and F. Masters, 2006: Preliminary comparison of DOW and in situ wind measurements in Hurricane Rita. *Extended abstracts, 27th Conference on Hurricanes and Tropical Meteorology.* Amer. Meteorol. Soc., Monterey, CA, April 24 - 28. Paper 10C6.

Wurman, J., and J. Winslow., 1998: Intense sub-kilometer-scale boundary layer rolls observed in Hurricane Fran. *Science*, **280**, 555-557.