FORECASTING SURFACE IMPACTS OF WIND, WAVE AND STORM SURGE

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1. INTRODUCTION

Land-falling tropical cyclones are capable of delivering devastating impacts in the near-coastal environment due to the effects of damaging surface winds, waves and storm surge combined with rapidly growing coastal populations, and set against a background of potential climate change influences.

While the ultimate defence against disaster is mitigation through long-term strategic planning and resilient design, accurate forecasting and warning remains an essential tactical component of emergency management to help reduce risks to life and property (Figure 1).

This paper provides an overview and summary of the relevant impacts, assesses present observational practice, predictive capabilities and procedures and considers future research needs and initiatives.

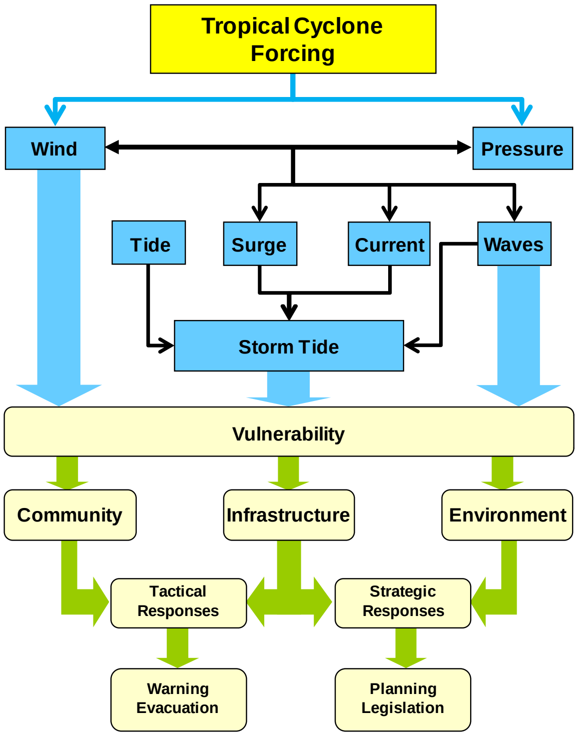

Figure 1 Schematic of tropical cyclone impacts.

2. NEAR-SURFACE WINDS

For effective use by emergency managers (land or sea) and for boundary forcing of ocean (wave, surge) models, gridded surface wind swaths are essential products in a land-falling tropical cyclone scenario. Within this context, mean and gust winds are separately required.

Near-surface extreme winds are subject to a wide variety of influences that affect the ability to make reliable measurements and to effectively forecast local conditions (Figure 2). Also accurate surface wind measurements provide essential feedback to the forecasting and modelling environments (whether in operational or research modes). While there is a comprehensive WMO standard for wind measurement (e.g. WMO 2008; Chapter 5) it would seem that the recommendations therein are rarely fully implemented. This may be because of physical limitations due to historical siting of instruments, urban development, cost of maintenance and calibration and the like, but also to a lack of appreciation of how significant some influences can be on the actual measurement of the wind in the near-surface land boundary layer.

The advent of remotely sensed near-surface winds over the ocean .e.g. by satellite (QuikScat, ASCAT, HIRAD) and aircraft (dropwindsonde and SFMR etc) and land-based Doppler radar introduces additional considerations in regard to sampling and averaging.

Observations

There are three essential aspects to be considered in respect of near-surface wind observations:

1. Instrument type and response
    - A fast response is desirable (low inertia, quality bearings) with a “response length” < 5m.
    - Cup and propeller sensors can suffer from over-speeding, sonic, hot-film and semi-conductor sensors may be rain-affected, buoys may be inertia and motion affected.
    - Ruggedness and reliability is required for surviving extreme conditions.
    - Maintenance and calibration requirements.
2. Sampling and processing
    - Instrument response, sampling and processing define the “*measurement chain*”, whereby each component acts as a series of filters.
    - Sampling of at least 4Hz is required for accurate measures of turbulence and gust detection
    - 10-min mean is the WMO standard synoptic metric to filter out high frequency turbulence and be more representative of numerical models.
    - Shorter averages are described as “*gusts*” and “*lulls*” relative to the mean and typically described by the standard deviation or coefficient of variation (*turbulence intensity* in this context).
    - The “*peak gust*” is the maximum (averaged over some duration) within a stated period of observation and so is a high-biased estimate of the true mean wind.
    - The 3-sec peak gust is typically used in wind engineering design to represent forces on (static) structures such as typical buildings and houses.

    - 1-min "*sustained*" winds used in tropical cyclone contexts are long peak gusts that overestimate the true mean.
3. Exposure
    - Surface wind observations are made in the lowest part of the boundary layer where vertical shear is high, and the height of the sensor above local ground level is a critical parameter; the WMO standard height over land being 10m.
    - On land, "o*pen terrain*" is a basic requirement for the immediate siting of instrumentation to avoid upstream aerodynamic effects. WMO (2008) defines open terrain as an area where the distance between the anemometer and any obstruction is *at least* 10 times the height of the obstruction.
    - At sea, avoidance of local flow distortions (bridges, funnels, towers, cranes) should take precedence over standard height (it is difficult to remove localized effects from ship obs).
    - Floating buoy measurements should be made at the highest possible elevation dependent on the diameter of the buoy (10m preferably).
    - When sensors are located on the side of masts, they should be placed on booms with a length of at least three mast widths to avoid local blocking effects. Sensors placed on top of buildings or similar bluff bodies should be raised at least one building width above the top and data adjusted for non-standard height if necessary (likewise cliff-top locations should be particularly avoided).
    - Obstacle and vegetation locations, height and terrain elevation changes should be documented on a map within a 2km radius and changes over time monitored to facilitate adjustments.
    - Measured winds should be adjusted to account for site exposure, considering adjustments for azimuthally varying surface roughness and topographic effects (e.g. Powell et al. 1996). Analytic procedures are available and wind tunnel testing may be advisable in some circumstances.

For an up-to-date overview of the many specific observation platforms (land and sea) available for tropical cyclones and the associated uncertainties in their measurements, the reader is referred to Powell (2009).

Issues:

- The majority of surface wind observing stations are unlikely to meet the WMO guidelines in terms of response, sampling and exposure (Wieringa 1996). Airports are the most reliable sub-set.
- Changes over time in instrumentation, sampling and processing can introduce undetected biases and inconsistencies into wind observing networks.
- Manufacturers often do not publish detailed response characteristics of sensors.
- Definitions of how gusts are determined can appreciably affect the magnitudes (e.g. Miller 2007).
- WMO regional association documents presently do not adequately or consistently define mean and gust wind speed metrics and there has traditionally been lack of good guidance (Harper et al. 2006).
- Use of 1-min "sustained" winds in a mean wind context will overestimate ocean response (waves, storm surge) and total energy unless magnitudes or drag coefficients are reduced.
- Doppler radar-measured winds must be attenuated to obtain near-surface winds.
- Tropical cyclone wind turbulence characteristics appear essentially similar to extra-tropical.

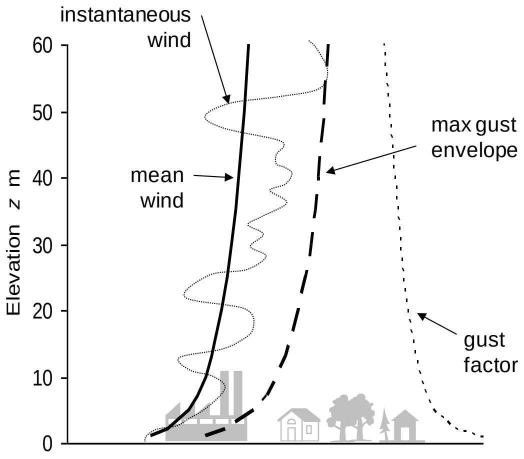

Figure 2 Schematic of the vertical wind profile in a built environment.

Forecasting and Modelling

Outside of the Atlantic Basin, the Dvorak method remains the principle means of assigning the peak intensity of surface winds in a tropical cyclone, although there are many variants in detail that are regionally applied (e.g. Velden et al. 2006). Even with targeted direct surface wind measurements in the Atlantic (e.g. aircraft transects, dropwindsondes, SFMR, QuikScat if applicable), the Dvorak method influences intensity estimates through a variety of "model" pathways.

Critically, there is seemingly an attraction to the use of a *Vmax* as the single intensity estimate of a tropical cyclone for simplifying what is an otherwise extremely complex phenomenon. However, it is always necessary to also describe the spatial structure of the storm to obtain meaningful impact information of use to emergency managers and to provide boundary conditions for ocean (wave and surge) models.

Accordingly, many agencies provide graphical representations of areas likely to be impacted by surface winds of various strengths. These are typically banded by Beaufort-scale descriptions of "gale", "storm" and "hurricane" force winds, aligned with forecast advisories based on largely symmetric wind radii and in some cases with probability contours. The way in which these products are prepared, however, seems to have remained largely undocumented and proprietary within agencies. One suspects therefore, that few if any of the present graphical wind structure products have an underlying robust "model" of the wind structure.

The graphical surface wind products could, for example, be underpinned by full 3D numerical modelling (e.g. MM5, HWRF, GFM etc albeit at generally crude resolution), diagnostic numerical boundary layer models (3D:

e.g. Kepert 2001, 2002; depth-averaged or "slab" models e.g. Shapiro 1983, Thompson and Cardone 1996, Vickery et al. 2000), parametric modelling (e.g. Harper and Holland 1996, Willoughby at al. 2005), statistical best tracks data, real time observations, simply approximations or perhaps a subjective combination of the above. In some cases, allowance of decay of winds over-land might also be explicitly applied (e.g. Kaplan and DeMaria 1995, DeMaria et al 2006).

H*Wind, the sophisticated NOAA/AOML data assimilation tool (e.g. Powell 2009) is capable of fine scale depiction of surface winds over land and sea but remains experimental in an operational context, perhaps due to its apparently limited prognostic capabilities. Nevertheless it has much appeal for post-event impact assessments and the development underpinning H*Wind addresses the many complicating aspects of wind observations listed earlier.

Issues:

- The basis of the Dvorak *Vmax* representing a peak 1-min gust is weak; conversions to 10-min mean are also (historically) inappropriate for open sea.
- The traditional tendency to assign a single wind speed metric to a tropical cyclone is of limited practical value in a landfall situation, where detailed spatial and temporal information is essential for emergency management and also for ocean model boundary conditions.
- Warning products typically do not enforce the spatial context as a "wind scale", which can lead to public misunderstanding.
- "Wind scales" remain non-standard globally due to varying intensity intervals, descriptors and wind-averaging practices.
- Graphical wind speed products seem not to be underpinned by a "model" of the storm structure
- Impact models (wind, wave and surge) require tropical cyclone structure information and are generally "reconstructed" for that purpose outside of the mainstream intensity forecast process.
- Prognostic numerical models need to ingest winds that are consistent with their spatial and temporal scale (observation/data assimilation issues).
- Structural damage models are based largely on empirical calibration against actual events, which vary greatly for a range of regional and demographic reasons.

Possible Initiatives

The foregoing development in regard to forecasting of near-surface land-falling wind impacts suggests a range of possible initiatives (research and operational) for providing future improvements:

- Standardise wind nomenclature across WMO regions and national agencies.
- Standardise wind-scales to reduce public confusion (e.g. use of internet resources).
- Fully adopt WMO (2008) recommendations in regard to instrumentation, sampling and exposure. This should lead to detailed wind-tunnel or mesoscale modelling of some key compromised measurement sites to ensure they are calibrated to standard exposure. Software GIS-based tools could be developed to assist in analytical anemometer adjustment for less complex sites.
- Ensure all measured surface winds ingested by numerical models are standard exposure.
- Apply consistent exposure-based wind-averaging conversion factors (e.g. Harper et al. 2006).
- Regularly revisit and revise WMO guidelines on exposure, height adjustments and gust factors to keep pace with scientific developments.
- Ensure instrument reliability in extreme conditions.
- Increased density of surface land and sea wind sensors. Consider mobile instruments for research (e.g. Masters et al. 2005; Schroeder et al. 2009) or developing low cost mesonets.
- Cross-calibration of wind sensors to account for response, spatial and temporal averaging, matching with Doppler winds and identified coherent features such as boundary layer rolls.
- Utilise mesoscale data assimilation (e.g. H*Wind)
- Develop standardized models of wind structure (wind-pressure, scale, asymmetry, gradient to surface, surface roughness) to provide uniformity of descriptors, accumulate storm statistics and provide prognostic impacts guidance.
- Wind damage, economic and insurance loss models need significant investment to reduce uncertainties and assist in justifying mitigation efforts

3. NEAR-SHORE WAVES

Ocean waves are generated during the transfer of momentum from the wind to the sea. The growth of wave height is most rapid for higher wave frequencies (shorter periods or wavelengths) and when the wind speed matches the wave speed. As the wave field grows, complex wave-wave mechanisms then act to transfer the energy derived from the wind towards lower frequency (higher period or longer wavelength) components. If a constant wind speed persists for long enough, the wave growth process becomes self-limiting because wave breaking (e.g. white caps) prevents the sea from absorbing any more energy at that specific transfer frequency. This equilibrium condition is known as a *fully-arisen* or *fully-developed* sea and most commonly occurs under broad frontal storm conditions in open ocean environments at higher latitudes. In tropical waters, this condition may also occur during monsoons, periods of persistent trade winds or extra-tropical transition. Fully-developed seas are rarer close to the centre of tropical cyclones because of the constantly varying wind speed and direction in the inner vortex.

In the near-shore environment, the local coastal topography (capes, bays) typically limits the available *fetch* (or distance acted on by the wind) available for generating waves from some directions. Wave growth may be *fetch-limited* by the presence of barrier reefs, island chains and large sand shoals. Where the fetch is not physically limited, the wave height growth is termed *duration-limited*. Large, slow moving tropical cyclones, particularly in association with high-pressure ridges poleward, can create such conditions. Also, in fast moving extra-tropical transition settings the related effect of *fetch-trapping* can amplify wave heights in a resonance-like situation (e .g. Bowyer and McAfee 2005)

Individual ocean waves are dispersive, propagating through and away from the area of wind generation at speeds dependent upon their wavelength and the local depth, and at the mean angle of the wind. Traditionally the term *sea* is given to the shorter period (younger) wave, and *swell* to the longer period (older) wave. These two wave components exist together, the swell propagating from a remote wave generating system, the sea being generated locally, relative to the swell component. Because of these differing sources, the mean direction of the two (or more) components is often also different, especially in tropical cyclones (refer Figure 3).

Because wave speed depends on depth of water, any wave that approaches contours of changing depth at an angle will experience *refraction*, whereby embayments tend to experience *divergence* of energy and headlands experience *convergence*. This is accompanied by *shoaling* resulting in a change in the height of the wave relative to its original deepwater condition. *Diffraction* is an additional process whereby energy is transferred laterally along a wave crest after experiencing a sharp (normally man-made) disturbance.

As a wave enters increasingly shallow water wave breaking will occur where the water particle velocity at the crest begins to exceed the wave speed. Ultimately much of the energy of the wave is dissipated through turbulence and heat during the breaking process but the forward momentum flux or radiation stress within the surf zone can result in a quasi-steady superelevation of the local water level above the still water level. This phenomenon is termed *breaking wave setup* (Hanslow and Nielsen 1996). Coral reef cays and atolls can be especially susceptible to breaking wave setup effects (Gourlay 1996) in conjunction with tides. In swampy regions or when a coastal area is fully inundated and wave energy dissipates mainly through bottom friction, breaking wave setup diminishes. Likewise deep river entrances or channels may not experience or transfer wave setup. Wave setup is also often modulated by irregular wave height groupings, termed *surf beat*.

In addition to wave setup, any residual energy of individual waves is manifested as vertical *wave runup* of the upper beach face (Nielsen and Hanslow 1991). This allows some waves to attack at higher levels than the setup level alone or cause intermittent dune overtopping. Setup and runup influences are typically complementary whereby beaches having a low slope experience the majority of the energy dissipation as setup while very steep beaches experience higher levels of runup. In deepwater regions with sheer coastal cliffs, wave runup can become extreme and explosive, reaching elevations of twice the wave height (e.g. Cyclone *Heta* 2004, Niue).

Observations

Wave data is collected in a variety of forms but, due to the statistical nature of the sea state and its near-linear characteristics, is normally used in directional spectral energy format, with the most common scalar parameters being the (equivalent) significant wave height Hs and peak spectral period Tp. Much of the global wave observation network has been established for commercial purposes (marine operations, oil and gas etc) but these also typically feed into the meteorological networks, together with atmospheric and ocean parameters. National wave data buoy systems have become increasingly established since the 1980s (e.g. NOAA NDBC, UK WaveNet, Australian State Governments etc) with the majority now offering directional information derived from pitch-roll-buoys, the latest using GPS rather than the more fragile accelerometer sensors.

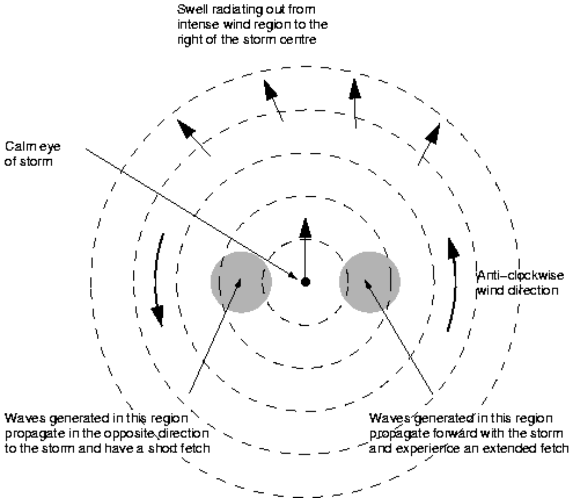

Figure 3 Schematic showing the generation of waves in a translating hurricane (after Young 1999).

Some of the first insights into the complex wave fields in tropical cyclone conditions were obtained by aircraft mounted side-scan radars in 1978 and the NASA/SRA instrument is widely used in the USA (e.g. Walsh et al. 2002). Several countries also operate HF radar facilities (e.g. NOAA, UK/OSCR, AUS/COSRAD) that can provide spatial wave height information in addition to surface winds and currents, typically out to about 300km offshore. Wave staffs and pressure gauges are also utilised for non-directional measurements and velocity-pressure instruments for directional data. Satellite altimetry (e.g. Topex /Poseidon) can also provide wave height and derived wind speeds on polar orbiting transects that can be useful for model verification. Drifting wave buoys are also increasingly used for targeted deployments.

Issues:

- Wave height, period and direction observations in deep water are relatively routine and reliable, with well-established processing standards. Data are available around a variety of developed nations but the networks are still relatively sparse
- Point-measured wave data often differs from spatially derived (e.g. remotely sensed) data due to sampling and averaging techniques.

- Shallow water wave measurements in specific locations are relatively limited.
- Measurements of breaking wave properties (setup, runup and swash) are exceedingly rare and normally only obtained from brief periods of experimentation at specific sites.
- Post-storm surveys of beach debris levels are significantly affected by localised wave setup, runup and wind stress components.

Forecasting and Modelling

Numerical wave models used for generation and propagation are spectrally based and consider the evolution of the directional energy spectrum in time and space propagating under the action of a variety of source and dissipation terms. To select the most appropriate model requires an understanding of the relative importance of the various physical processes active in each domain. A modified form of classification presented by Battjes (1994) appears in Table 1, which divides wave prediction into four physical process domains.

Models can then be divided into two general classes: *phase resolving*, which predict both the amplitude and phase of individual waves, and *phase averaging* models which predict average quantities such as the spectrum or its integral properties. Should phase averaged properties vary rapidly (order of a few wavelengths) then a phase resolving model, with significant computational overheads, may be required. If not, then phase averaging models are adequate. These are then described by their treatment of the complex source terms into 1st, 2nd or 3rd generation models, each requiring increased computational effort.

Wave models should be selected on the basis of their suitability to a specific region rather than their absolute complexity, as there are many factors affecting their practical use. For example, 1st generation models can still be well suited to some enclosed or directionally limited near-shore regions (SWAMP Group 1985). Likewise many 2nd generation models (e.g. Sobey and Young 1988) continue to prove particularly accurate in many tropical cyclone situations. Where highly accurate wave height estimates are required close to the region of maximum winds, 3rd generation models (e.g. WAM, WAMDI (1988); WAVEWATCH, Tolman (1991); SWAN, Booij et al.(1996)) are recommended due to their ability to better cope with the rapidly changing wind directions and high stress regions (e.g. Jensen et al. 2006). Importantly though there are different variants for deep and shallow water situations or especially targeted versions for reef regions (e.g. Hardy et al. 2003).

Notwithstanding the capabilities of the available complex numerical wave models there is reliance on empiricism in regard to near-shore wave impacts, and analytical wave setup and runup formula (e.g. Nielsen and Hanslow 1991, Gourlay 1996, Stockdon et al 2006) are essential adjuncts to full model solutions. Also, for some open ocean forecasting purposes there is good skill and utility in simpler parametric models (e.g. Young and Burchell 1996, Bowyer and McAfee 2005).

Table 1 Relative importance of various physical processes in numerical wave modelling

Physical Process	**Deep Oceans**	**Shelf Seas**	**Shoaling Zone**	**Harbours**
Diffraction	⊗	⊗	°	∗
Depth refract./shoaling	⊗	•	∗	•
Current refraction	⊗	°	•	⊗
4 wave interactions	∗	∗	°	⊗
3 wave interactions	⊗	°	•	°
Atmospheric input	∗	∗	°	⊗
White-capping	∗	∗	°	⊗
Depth breaking	⊗	°	∗	⊗
Bottom friction	⊗	∗	•	⊗

⊗ - negligible; ° - minor importance; • - significant; ∗ - dominant (after Battjes 1994).

Issues:

- Spectral wave models have over time been empirically calibrated against specific and limited sets of wind and wave data.
- Recent measurements of drag coefficients in high winds suggesting saturation around 30 m/s are conceptualised in some models but not others (e.g. Moon et al. 2008).
- Wind averaging assumptions are of a similar order of magnitude effect to possible drag coefficient changes.
- Accurate wave modelling requires good wind structure representation up to 10 times *Rmax*
- Observed values of wave setup can vary greatly over short distance and in different environments
- Numerically modelled wave setup tends to significantly underpredict observed values
- Wave runup is a very localised phenomenon that requires knowledge of beach slope, dune elevations, vegetation and strata etc
- There is very little information on wave effects on domestic structures during storm tide inundation events (e.g. Kraus and Lin 2009)

Possible Initiatives:

While numerical wave modelling has proven quite accurate in deepwater situations, and propagation within shallow areas is well developed, the following issues remain of research and operational interest for landfalling tropical cyclones:

- The influence of the drag coefficient as it relates to relative wave age (steepness), wind-wave angle and wind speed
- Wind-wave and wave-current coupling effects

- Increasing the density of wave buoy networks
- Accurate bathymetry in coastal waters
- Accurate wind structure out to *Rgales*
- Overland dissipation due to vegetation and effects by and on the built environment
- Assimilation of future higher resolution satellite wind and wave data

4. STORM TIDE

The term *storm tide* is used here in preference to the generic *storm surge* when describing the impact of a land-falling tropical cyclone. Importantly, surge is the *long wave* component magnitude related to the energetics of the storm, its size, track and speed and the specific coastal interactions. Then storm tide is the combination of that with the pre-existing astronomical tide and localised breaking wave setup component. Accordingly, storm tide refers to an absolute sea level elevation that can be related to land elevation and hence is applicable to assessing impacts (Figure 4).

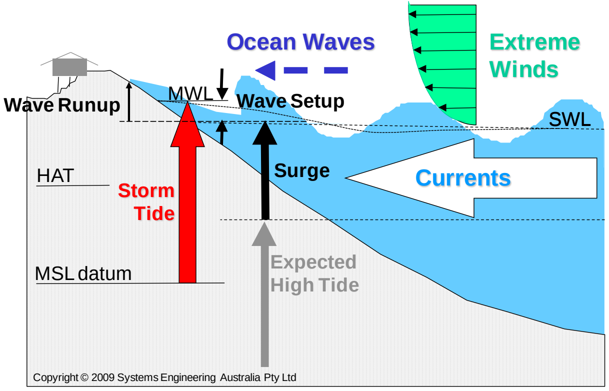

Figure 4 Schematic diagram of the components of storm tide. (after Harper 2001); MSL is the mean sea level, HAT is the highest astronomical tide level, SWL is the still-water level in the absence of surface waves, MWL is the beach-face mean water level due to breaking wave setup influence, wave runup elevation is normally referenced to the SWL.

The storm surge (or meteorological tide), is an atmospherically forced transient long wave ocean response caused by the extreme surface winds and low surface pressures. Severe tropical cyclones (<980 hPa) on or near the coast are capable of producing a dangerous storm surge (>3m), which can increase coastal water levels for periods of several hours and significantly affect over 100 km of coastline (Harper 2001, Dube et al. 2009). In regions with a significant tidal range, the phasing of the peak of the surge with the astronomical tide on the day normally dictates the degree of likely impact. Close to the position of the peak surge level, which is normally close to the region of maximum winds, the rate of increase in water height can at times be quite rapid, e.g. several metres in one hour and bores are possible.

Storms that are more remote from a coast but with large circulations may also generate synoptic scale responses of generally low magnitude (<1m) but that can persist for several days and likely interact with many high tide sequences. Depending on the specific environment these may manifest as coastally-trapped edge-waves (e.g. Kelvin-like, Yankovsky 2009), or basin-wide responses and seiching. These situations can readily cause widespread beach erosion and encroachment, and in conjunction with heavy rainfall may raise river tail-water levels and exacerbate near-coastal flooding.

The potential magnitude of the surge is affected by many factors - principally the intensity of the tropical cyclone, its size and forward speed. In deep water far from the coast the main contribution comes from the so-called *inverted barometer* effect - which is broadly a mirror image of the cyclone's own surface pressure profile in the underlying ocean. The local magnitude is about 10 mm per hPa of pressure deficit, relative to the ambient surface pressure far removed from the storm centre. Consequently, a Category 5 cyclone (e.g. 910 hPa) would produce a maximum pressure-induced surge component of about 1m directly below the eye in deep water. Islands with narrow continental shelves and in deep water away from the coast normally only experience the static effects of the pressure-induced surge. In such situations, breaking wave setup may represent the greater component of increased water levels. In shallow waters, the pressure surge component interacts with the bathymetry and coastal forms, and may become dynamically amplified at the coastline to levels approximately twice the offshore levels.

By contrast, the influence of the severe surface wind shear on surge levels is confined largely to the shallower waters of the continental shelf. The wind-induced surge component is depth dependent, increasing with decreasing water depth and normally responsible for the greater proportion of surge height at the coastline. Flat, shallow and wide continental shelf regions are therefore much more effective in assisting the generation of large storm surges than are narrow, steep shelf regions. Storm surge magnitude can often be regarded as linearly proportional to the intensity for a given coastal site but can be highly site specific due to local factors. The relative horizontal scale (e.g. *Rmax*) of the cyclone is also important in determining the length of affected coastline.

When normally dry land becomes inundated during a severe storm tide episode, the sea begins to quickly flood inland as an intermittent wave front, driven by the initial momentum of the surge, products of wave setup and runup and the local surface wind stress. This flow then reacts to the local ground contours and the encountered hydraulic roughness due to either natural vegetation or housing and other infrastructure. It will continue inland until a dynamic balance is reached between the applied hydraulic gradients, wind stress and the land surface resistance or until it becomes constrained by elevation. As the storm abates or the tide reduces, an ebb flow is created that is often responsible for observed coastline scouring after such events.

Observations

Storm tides are most reliably recorded by permanently located and continuously operated water level gauges optimised for recording tides and not subject to breaking wave influences. While this ensures accurate detection of the broadscale tide+surge component it does not measure the wave setup that may be significant elsewhere. As previously mentioned, measuring of wave setup is extremely difficult because of its localised effects. Remote sensing (aerial and satellite imagery) is especially useful in mapping impacts and debris lines after an event and may become of increasing use in forecasting where significant aerial monitoring capability exists (e.g. NASA/SRA).

Issues:

- Tide gauge network density is often inadequate to detect the peak of a coast-crossing storm.
- Gauges not designed for the likely storm surge magnitudes may be damaged and data lost.
- Real-time gauges provide important feedback to forecasters of pre-cursor water levels that may not be fully represented in a model.
- Beach debris levels will include locally complex influences of wave setup and runup.
- Inland inundation heights may include local wind stress effects that can raise water levels above oceanic levels.

Forecasting and Modelling

Numerical modelling of storm surge over large spatial domains has been successfully undertaken for the past 30 years (Bode and Hardy 1993, Harper 2001, Dube et al. 2009) and is well established. The most common approach is to numerically solve the 2D depth-integrated shallow water equations (i.e. barotropic) at scales appropriate to the applied forcing and the coastal features. Normally Coriolis, bed friction (with some empiricism) and advective components are included. While 3D barotropic and baroclinic models are also widely available, they are more complex to initialize, more expensive to operate, and normally only applied in response to specifically identified regional sensitivities. The choice of numerics (FD or FE, implicit, explicit), discretisation (regular, spherical, or triangular), and transition (nested or coupled) vary according to needs and preferences. Many models implement wetting and drying (although this can be problematical in terms of numerical stability) and “constant volume” models are becoming more popular in this context.

Tides are increasingly fully modelled due to the availability of global constituents but this can prove difficult in some complex areas where bathymetric data is poor and if measured constituents are available for specific high impact sites they may be preferable. In such cases linear addition is often acceptable but should be verified by numerical experimentation and a non-linear interaction factor can be devised for operational purposes if necessary. This will often be <10% effect and will likely attenuate peak levels relative to the assumption of independence.

In regions of significant coastal waterways and riverine environments with good data and potentially high impacts, very sophisticated models can now be developed that show high levels of accuracy (e.g. < 0.3m, Westerink et al. 2008). However, in most areas of the world, and especially the high-risk developing nations, suitably good data is typically unavailable. Nevertheless, with careful consideration of the environments, accuracy of the order of 0.5<1.0m for forecasting are not necessarily unrealistic aims.

Coupled surge-wave models have become more popular, incorporating consideration of the wave radiation stress (responsible for wave setup) in the momentum flux. However, the correct coupling extends to bottom stress and surface stress to make the models especially complex. When properly calibrated, this results in a new balance of still empirically-dependent assumptions.

In spite of the ready availability of numerical ocean models for storm surge prediction, many agencies appear not to have fully embraced their use, and empirical (e.g. Nickerson 1971) are apparently still widely used. This likely reflects the level of resources available to implement operational products and the traditional separation of numerical atmospheric and ocean expertise. However it may also reflect forecaster preferences for simplified hands-on approaches of similar utility to the Dvorak method for intensity estimation. Accordingly there remains a place for parametric or hybrid approaches to storm tide forecasting that provide a significant increase in warning capability with relatively low overhead and can incorporate powerful Monte Carlo ensembles. Australia, for example, with its extensive and complex tropical coastline, has adopted such techniques with benefit (Harper 2001, Harper et al. 2009).

Issues:

- Model domains and physics must be constructed to address the regional coastal scales, oceanic and meteorological influences.
- Accurate bathymetry in shallow water (<50m) or reef areas where bed friction is important.
- Tide plus surge in conjunction with accurate land elevations are required to estimate impacts.
- Storm surge model accuracy is a function of the supplied wind forcing and its inherent uncertainty, which should be transferred into the storm tide prediction via ensemble simulations.
- In the face of data limitations (tide, bathymetry, land elevation, wind structure and air/sea observations) overly complex models will likely be counter-productive.
- Accurate winds within 12 hr of landfall and within 5 to 7 *Rmax* are essential for surge modelling.
- Calibration and verification of storm tide models remains an essential factor in their development.

Possible Initiatives

Lack of quality data (atmospheric, bathymetric and topographic) is the principal barrier to accurate storm tide forecasting, combined with limited agency resources. Some possible initiatives in this area are:

- Capacity building in developing nations at highest risk, especially increased understanding of the regional contributions to storm tide risk and emergency management options.

- Risk studies could be done as a first-pass assessment of impacts allowing concentration on identification of the primary storm tide components in specific regions and targeting of data to address those needs.
- Development of simplified forecasting tools suited to local needs. While these might involve numerical modelling in various ways, the operational tool need not be complex or onerous.
- The availability of forecast gridded wind fields (as previously discussed) would greatly facilitate improved forecasting of storm tide impacts.

5. REFERENCES

Battjes J.A. 1994: Shallow water wave modelling. Proc. Int. Symp.: Waves - Physical and Numerical Modelling, Vancouver, 1-23.

Bode L. and Hardy T.A., 1997: Progress and recent developments in storm surge modelling. *J Hyd Engin*, 123, 315–331.

Bowyer P.J., and A.W. MacAfee, 2005: The Theory of Trapped-Fetch Waves with Tropical Cyclones—An Operational Perspective. *Weather and Forecasting*, 20, 229–244.

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

Dube S.K, Murty T.S., Feyen J.C., Cabrera R., Harper B.A., Bales J.D. and Amer S. (2009) Storm surge modeling and applications in coastal areas. In Chan J. (Ed.) Global Perspectives on Tropical Cyclones, *World Scientific*, (in press).

Gourlay M.R. 1996: Wave setup on coral reefs. 1. Set-up and wave-generated flow on an idealised two dimensional horizontal reef. *Coastal Engineering*, 27,161-193.

Hanslow D.J. and Nielsen P. 1993: Shoreline setup on natural beaches. *J Coastal Res*, Special Issue 15, 1-10.

Hardy T.A., McConochie J.D. and Mason L.B., 2001: A wave model for the Great Barrier Reef. *Ocean Eng*, 28 (1), 45-70.

Harper B.A. and Holland G.J. 1999: An updated parametric model of the tropical cyclone. Proc. 23rd Conf. Hurricanes and Tropl Met, *AMS*, 10-15 Jan.

Harper B.A. (ed.), 2001: Queensland climate change and community vulnerability to tropical cyclones - ocean hazards assessment - stage 1, Systems Engineering Australia Pty Ltd in association with James Cook University Marine Modelling Unit, *Queensland Government*, March, 375pp.

Harper B.A., Kepert J. and Ginger J., 2008: Wind speed time averaging conversions for tropical cyclone conditions. 28th Conf Hurricanes and Trop Met, *AMS*, Orlando, 4B.1, April.

Harper B.A., Hardy T.A. and Mason L.B. 2009: Developments in storm tide modelling and risk assessment in the Australian region. Proc. WMO/IOC JCOMM 1st Scientific and Technical Symposium on Storm Surges, Seoul, Korea, 2-6 Oct, 2007. *Natural Hazards*, Vol 51, 1, Oct, 225-238.

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, *ASCE*, Sept 25-29.

Kaplan J. and DeMaria M., 1995: A simple empirical model for predicting the decay of tropical cyclone winds after landfall. *J. App. Meteor.,* 34, No. 11, 2499-2512.

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. 2002: The impact of landfall on tropical cyclone boundary layer winds. Proc. 25th Conf Hurricanes and Tropical Meteorology, *AMS*, San Diego, 335-336.

Kraus N.C. and Lin L., 2009: Hurricane Ike along the upper Texas coast: an introduction. *Shore & Beach*, Vol 77, 2, 3-8.

Masters F., Reinhold T., Gurley K. and Powell M. 2005: Gust factors observed in tropical cyclone landfalls. Tenth Americas Conference on Wind Engineering, *ASCE*, Baton Rouge.

Miller C. 2007: Defining the effective duration of a gust. Proc. 12th Intl. Conf. Wind Engin., ICWE12, Intl. Asoc. for Wind Engin., *IAWE*, July 2-6, Cairns, 759-766.

Moon I.J., I. Ginis, and T. Hara, 2008: Impact of the reduced drag coefficient on ocean wave modeling under hurricane conditions. *Mon. Wea. Rev.*, 136, 1217–1223.

Nickerson J.W. 1971: Storm surge forecasting. Navy Weather Research Facility, Tech Report 10-71.

Nielsen P. and Hanslow D.J. 1991: Wave runup distributions on natural beaches. *J Coastal Res*, Vol 7, No 4, 1139-1152.

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. *Weather and Forecasting*, 11, 304–328.

Powell M.D. 2009: Near-surface-based observations of tropical cyclones. In: Chan J. (Ed.) Global Perspectives of Tropical Cyclones, *World Scientific* (in press).

Schroeder J.L., Edwards B.P and Glammanco I.M., 2009: Observed tropical cyclone wind flow characteristics. *Wind and Structures*, Vol 12, 4, 349-381.

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

Sobey R.J. and Young I.R. 1986: Hurricane wind waves -- A discrete spectral model. *J. Waterways Port Costal Ocean Eng.*, 112, 370-389.

Stockdon H.F., Holman R.A., Howd P.A. and Sallenger A.H. Jr., 2006: Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, Vol 53, 7, May, 573-588.

SWAMP Group, 1985: Ocean wave modeling. *Plenum Press*, New York, 256pp.

Thompson E.F. and Cardone V.J. 1996: Practical modeling of hurricane surface winds. *J. Waterway, Port, Coastal and Ocean Eng.,* 122: 195–204.

Vickery P.J., Skerjl P.F., Steckley A.C., Twisdale L.A. 2000: Hurricane wind field model for use in hurricane simulations. *J. Engineering Structures,* 126, 1203–1221.

Velden C., Harper B., Wells F., Beven J.L., Zehr R., Olander T., Mayfield M., Guard C., Lander M., Edson R., Avila L., Burton A., Turk M., Kikuchi A., Christian A., Caroff P. and McCrone P. 2006: The Dvorak tropical cyclone intensity estimation technique: a satellite-based method that has endured for over 30 years. *Bulletin American Meteorological Society*, Vol 87, Sept, 1195-1210.

Walsh E.J. et al, 2002: Hurricane Directional Wave Spectrum Spatial Variation at Landfall. *J. Phys. Ocn*., 32, 1667–1684.

Westerink J.J., R.A. Luettich, J.C. Feyen, J.H. Atkinson, C. Dawson, H.J. Roberts, M.D. Powell, J.P. Dunion, E.J. Kubatko, and H. Pourtaheri, , 2008: A basin- to channel-scale unstructured grid hurricane storm surge model applied to Southern Louisiana. *Mon. Wea. Rev.*, 136, 833–864.

Wieringa J. 1996: Does representative wind information exist? *J. Wind Engineering and Industrial Aerodynamics*, 65, 1-12.

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

WMO 2008: Guide to meteorological instruments and methods of observation. WMO-No. 8, 7th Ed, 681pp.

Yankovsky A.E. 2009: Large-scale edge waves generated by hurricane landfall, *J Geophys Res*, 114, C03014.

Young I.R. and Burchell G.P. 1996: Hurricane generated waves as observed by satellite. *Ocean Eng,* 23, 761-776.

Young I.R. 1999: Wind generated ocean waves. *Elsevier Sciences Ltd.*, 306pp.