THIRD INTERNATIONAL WORKSHOP ON TROPICAL CYCLONE LANDFALLING PROCESSES

7. : Storm Surge

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Abstract: This brief overview report re-states the storm surge hazard condition, and reflects on global experience in recent years of our ability to successfully understand, predict, warn and avoid the impacts of tropical cyclone storm surge. As well, it provides some guidance for future research, implementation and operations. Likely road blocks to these necessary advances are also discussed. The reader is encouraged to also revisit the previous IWTC VI statement on the subject of storm surge forecasting (Dube et al. 2006) for context and continuity.

7.0.1. Introduction

Storm surge remains the most dangerous and deadly manifestation of the impact from a tropical cyclone (TC). In spite of gradual and significant improvements over recent years into many facets of TC knowledge, modelling and forecasting it is regrettable that storm surge disasters remain a clear and present danger to vulnerable communities throughout the world (e.g. Katrina 2005, Nargis 2008, Haiyan 2013). Why is this so and is it acceptable?

Damaging winds alone can create significant destruction and also loss of life, but those impacts pale into insignificance when combined with the power of water and mere humans who are defenceless to its passage. In many ways, storm surge represents the ultimate malevolent impact of the TC, focusing our accumulated uncertainty of track, size, speed and intensity into an especially deadly amalgam. When combined with the physical susceptibility of a particular coastal region to enable the generation of a significant storm surge, the exposure of people and assets and their vulnerability to the threat, it often reduces to a simple game of chance in the last few hours before storm passage. Without adequate emergency planning and action, the relative phasing of TC passage with the peak of the local astronomical tide often becomes the simple difference between disaster and providence. Although not all regions have the added statistical diffuser of a significant astronomical tide range (e.g. Gulf of Mexico), the typical lack of acknowledgement of the “tide” in concert with “surge”, which are of comparable magnitude and wavelength, is a major hindrance to appreciation of the true threat and the communication of that in warnings. Accordingly, this report and review favours what has been a traditionally sole Australian view that the term “storm tide” should replace “storm surge” in respect of warning products to reflect the complex combination and timing of tide, surge and also potentially dangerous breaking wave setup and coincident coastal river fluvial flooding. Wave runup also remains a destructive additional component in certain locations and situations.

Figure 1 below summarises schematically the TC storm tide risk interactions, separating the challenges of climate, forcing, impacts and human responses required to mitigate its potentially deadly outcomes. Each of these elements must be addressed in order to effectively counter storm tide risks and prevent loss of life.

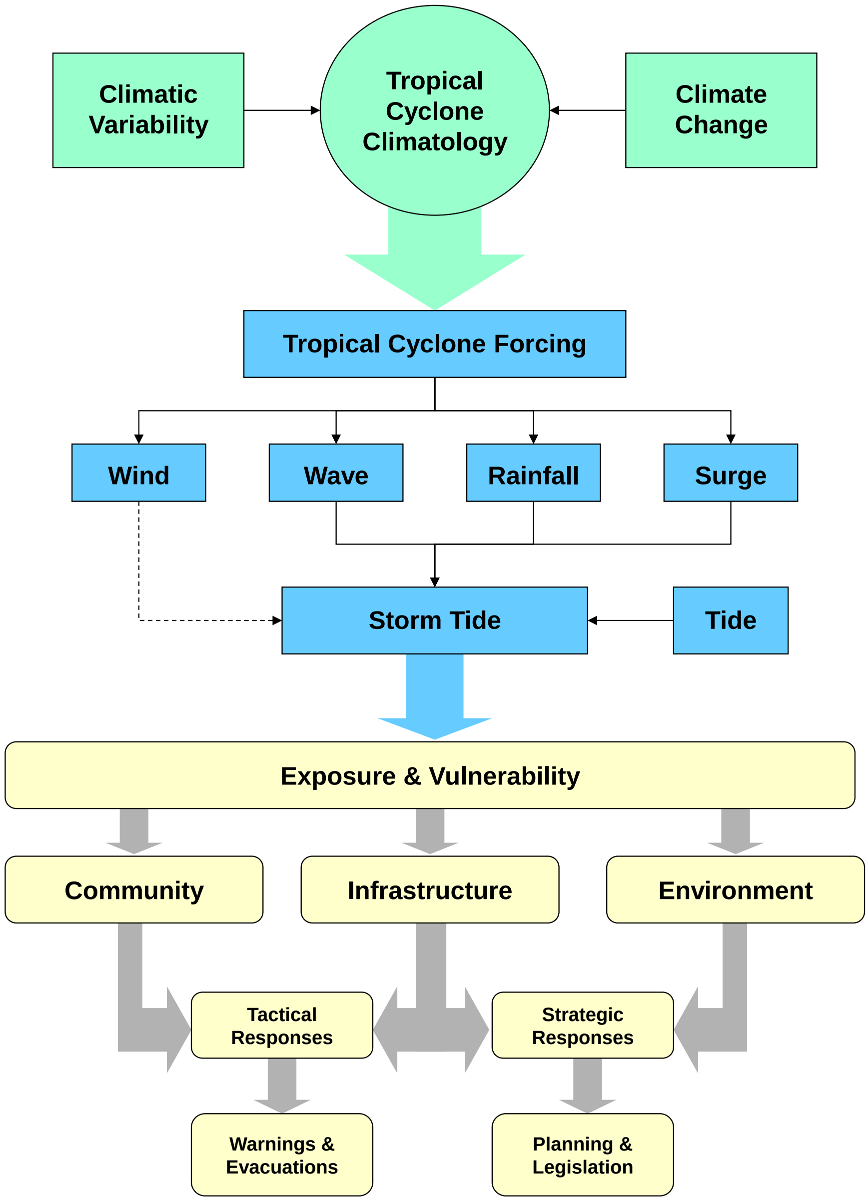

Figure 1. Tropical cyclone storm tide risk interactions (after Harper 2001)

7.0.2. Understanding Storm Tide Hazard

Figure 2 provides a schematic snapshot of the principal wind and pressure forcing and water level components of the storm tide hazard at a typical sandy coastline.

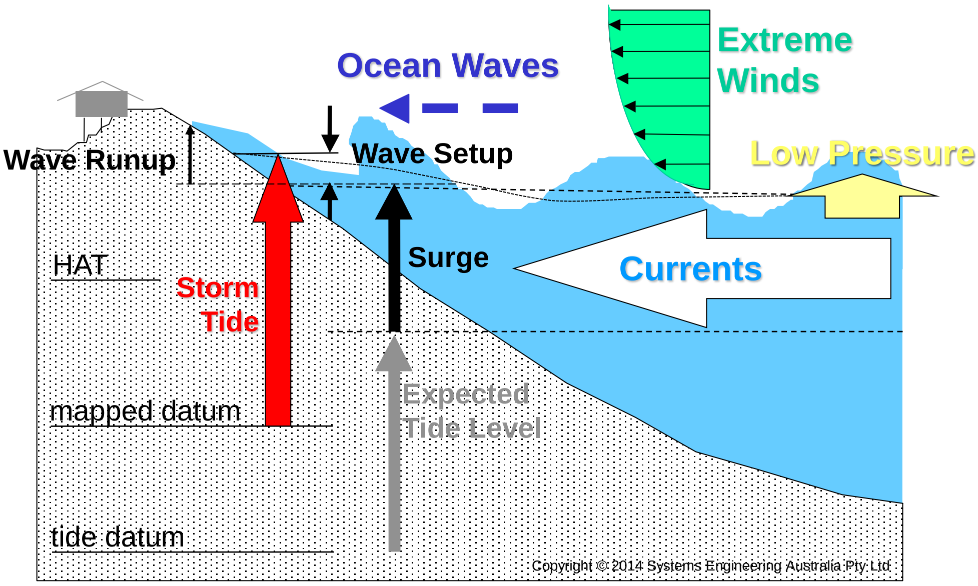

Figure 2. Schematic snapshot of storm tide forcing and water level components (after Harper 2001)

Without diverging into the various complexities of well-established approaches to storm surge prediction (e.g. Dube et al. 2009), the above schematic highlights basic but often overlooked technical elements, such as:

a) Expected ocean daily tide level variations are typically and most readily available in the form of water levels relative to a low-water datum specifically designed to inform navigation activities and marine safety (i.e. minimum depth under keel), and for a fishing-dominated coastal community this will likely be the commonly understood local water level metric;

b) Mapping of land elevations are typically (and sensibly) related to a Mean Sea Level (MSL) datum reflecting the self-evident boundary between land and sea, and are often not commonly known by residents even in highly-developed nations;

c) The Highest Astronomical Tide (HAT) level defines the eventual highest expected ocean still-water level over approximately a 20 year solar-dominated period (notwithstanding commonly occurring more benign weather-related influences and long-term sea level rise). It is a level typically experienced by near-coastal residents because ocean levels close to HAT can often occur biennially. Any incursion of ocean levels beyond this observable experiential point will therefore be outside of common expectations and will represent the threshold of danger to residents and damage to facilities. It may be sensible therefore to contrast forecast storm tide impacts with the known flooding extent of HAT, for emphasis at least;

d) *Storm tide*, defined here as the combination of expected tide, incoming uncertain TC-generated storm surge superelevation and accompanying localised breaking wave setup must be reported to the same elevation datum as the readily available and promulgated land surface mapping datum in use by planning and emergency services, whatever that may be;

e) Wave runup, which is especially locally-sensitive to foreshore depth, slope and surface, remains the most likely publically-visible and threatening interface with an incoming storm tide. It can initiate serious erosion, close beaches and possibly damage infrastructure well ahead of an incoming inundation episode. However, it is the reckless and adventurous who are likely most prone to the direct impacts of wave runup[1].

7.0.3 Researching Storm Tide Hazard

Khono (2014) provides a companion summary of recent and current research-related activities by universities, government research organizations and agencies responsible for storm tide prediction.

As last noted at the IWTC-VI (Dube 2006) numerical hydrodynamic storm surge models have become widespread and reliable over recent decades, in hindcast mode at least, and the basic model numerics have changed little since the 1970s. Recent improvements have been mainly in the application of higher resolution models, integration of various formerly separate models and a shift towards integrated and practical information rather than only storm surge magnitude information.

Recent progress in model integration includes coupled model systems or the combination of many forecasted elements. It is clear that storm surge risk should not be interpreted solely based on estimated storm surge magnitude, but rather together with other critically important factors such as tides and waves and their relative magnitude and phasing. Such integrated forecasting systems developed in the research fields are gradually being applied in operations.

Besides system-level developments, improvement in information of direct practical use by emergency management is being advanced. Storm surge is an oceanographic phenomenon but its potential magnitude alone does not directly indicate the emergency risk because disasters are caused by coastal inundation. The importance of inundation risk information, rather than storm surge magnitude alone, is highlighted. Many efforts are now increasingly dedicated to the creation of and issuing of inundation risk information based on exposure and vulnerability, thus moving away from the strict physics of storm tide prediction.

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[1] Tropical Cyclone *Heta's* impacts on the remote island of Niue in 2003 included a graphic example of direct and damaging wave runup impacts at an elevated yet exposed community.

7.0.4. Forecasting and Communicating Storm Tide Hazard

Harper (2014) provides a companion summary addressing this context in more detail.

Many agencies now have established operational numerical storm surge modelling capabilities, but these have largely emerged directly from research environments rather than having been designed for and/or by forecast and warning specialists. This can create gaps of practical significance that might interfere with operational constraints, may result in insufficient detail of the threat and could lead to mis-information when applied by emergency managers.

Notwithstanding the widespread basic capability that exists it is not clear whether all products are sufficiently detailed to provide reliable advice at a local scale, either because the model resolutions are too coarse, or there is simply a lack of essential data or coverage, or not all the necessary components of water level and their relative phasing are being addressed and reported.

Importantly, all storm surge forecast tools should, as a minimum, explicitly include the uncertainty of the storm forcing parameters (track, intensity, structure and speed) and the phasing with the local tide. It would appear that many operational models do not explicitly include tide magnitude and timing and that it becomes an additional analysis step prone to misinterpretation and confusion of datums.

Secondly, the impact of extreme waves needs special attention in exposed areas, in the context of both shallow water coastal and deep water island communities. In addition to the possibility of dangerous wave setup there is also the potential for non-linear interactions with the incoming surge that may trigger bore-like responses with very damaging consequences.

While noting the research interest and initiatives in producing “integrated” modelling systems for areas of concentrated exposure and vulnerability, the vast majority of widely scattered yet highly-vulnerable regions will better benefit from pragmatic improvements in basic forecast skill and warning effectiveness.

7.0.5. Avoiding Storm Tide Hazard through Risk Reduction and Planning

This is the ultimate humanitarian goal, which requires a multi-disciplinary approach and political will to achieve. Even the most precise or ultimately *perfect* forecast of a deadly and destructive storm tide event will <u>never</u> by itself avoid disaster. When combined with windborne debris, any necessary but delayed evacuation until the onset of an inundating storm tide event becomes perilous at best and likely non-survivable by those threatened. Accordingly it remains essential (refer Figure 1) that there is <u>palpable investment</u> in strategic efforts and approaches to reduce storm tide threat through multi-agency coordinated long-term activities, such as:

- Basic data collection (retrieve or plan to obtain and maintain)
    - Tide, wave and historical storm surge data and impacts

    - Adequate land and seabed mapping at storm and site-relevant vertical and horizontal scales
    - Current and planned future exposure of residents and community infrastructure (numbers, values, floor levels, resistance metrics)
- Model building (numerical and statistical)
    - Assessment of the regional TC threat climatology (present and potential uncertainty)
    - Determine appropriate forcing scales (spatial and temporal) and necessary precision
    - Address the principal threats (surge, waves, setup, runup, and/or coincident rainfall)
    - Tidal calibration and verification to prove basic long-wave hydrodynamics
    - Hindcasting of past events, calibration, verification and parameter sensitivity studies
- Risk assessment studies
    - Hazard encounter and exceedance statistics
    - Initial high-level screening to identify susceptibility, exposure and rank risk
    - Local detailed assessments of hazard, exposure and vulnerability for high risks
- Adaptation strategies
    - Defence, if practical and economically feasible, through the use of structural options like levees or accommodation of hazards by strengthening and/or raising
    - Long term planning and/or retreat away from threatened areas
    - Increasing resilience through guidelines, standards and education
- Emergency response planning
    - Education and training
    - Risk communication
    - Scenario planning and simulation
    - Escape routes and/or vertical shelters

7.0.6. Recommendations and Potential Road Blocks

Notwithstanding the above listed institutional items that require certainty in investment, resourcing and support, the following focuses on a number of specifically relevant sub-areas that if pursued, will likely lead to improved storm tide prediction outcomes.

(a) Research-related

Boundary layer momentum transfer

This remains an especially relevant topic for hydrodynamic model enhancement that can significantly alter the choice of associated empirical coefficients and should lead to reduced scatter and reduction of bias in storm surge predictions. For example, the role of wave age and effective roughness at high winds requires further investigation and verification, as well as the correct specification of the windspeed height and averaging period adopted by modellers.

During inundation modelling there are additional atmospheric boundary layer roughness aspects such as the effect of vegetation (e.g. mangroves) and shielding from buildings etc.

Storm structure (wind, pressure, scale, equilibrium, and asymmetry)

Storm surge and associated wave growth and propagation is an integrated ocean response over large and intermediate time and space scales dictated not by the traditional simplistic “Vmax” TC intensity measure but by the combined interactions of the applied forcing, coastal interactions and significant inertial responses. Many existing operational storm surge models will likely embody parametric representations of the essential aspects of the wind and pressure fields that may not reflect current best practice. Some will directly inherit operationally imperfect NWP representations. Transparency by model builders as to the physical parameterisations and assumptions being adopted is essential to allow comparison and rating of performance. Studies need extensive validation and verification of the wind field to demonstrate skill and simply stating that the model uses a particular generic approach is not sufficient

Tide, surge and wave coupling

A more complex numerical model does not necessarily result in greater accuracy of prediction and it is important to assess whether and when dynamic tide, surge and/or wave coupling will be of significant import, rather than simply leading to increased computing resources with potentially lessened reliability. Importantly, researchers and forecasters need to jointly consider the balance of empirical interactions in established models that have been verified on the basis of linear superposition before committing to such changes. An investigation into the physical characteristics of those types of coastal environments that would benefit most from such enhancements would be a useful assessment tool.

Perhaps the most pressing need would be to help identify the susceptibility for rapid and damaging bore-like surge transitions in certain topographies and in certain spatial and temporal settings.

Breaking wave setup

This remains a complex and rarely studied phenomenon that requires increased experimental research in both idealised and natural environments. While the concept of wave radiation stress is well-founded, the complex dissipation mechanisms in natural environments potentially diminish its influence and its exact role in the inundation process remains largely unexplored. While many numerical models provide for estimation of wave setup, some are known to produce it in situations where it is observed from direct measurements not to occur. It is likely that many models fail to represent the correct scales of interaction and dissipation of breaking wave setup.

Although long-recognised and experienced, the process of reef-top wave setup has received even less attention, yet it is a significant threat to many low-lying oceanic islands having fringing reefs and lagoons. Indeed, it is likely to be the only significant storm tide component in such situations and is known to be highly sensitive to the tide-modulated incident ocean level relative to the reef top height. Very significant infra-gravity wave motions are possible and can present as damaging tidal bores.

Baroclinic interactions

While rarely life-threatening, associated baroclinic interactions can be significant for lower intensity or remote events in certain environments and reduce reliability of barotropic model predictions that leads to a lessening of confidence in forecasts. Identifying regions where this is possibly of significance is desirable so that its effects can be gauged and if necessary included.

(b) Forecast-related

Terminology

It is the "total water level" (recommending to be named *storm tide* here as the preferred terminology) comprised of the various sub-components, together with their timing, magnitude and interactions that must be reliably forecast and communicated. The continued use of "surge" terminology in warnings should ideally be replaced to reflect these complexities and to ensure that absolute height references are forecast and clearly communicated, so that the expected timing, extents of flooding and depths can be determined by emergency managers.

Choice of Modelling System

There is a wide variety of deterministic numerical hydrodynamic models known to be capable of reproducing past storm surge events to a high accuracy when given reliable wind and pressure forcing data. Although forecasters should seek the evidence of that capability, the focus should then be on the probabilistic component of the forecast tool to ensure that it provides the necessary stochastic uncertainty to explore the range of damaging possibilities, that it has a practical interface that enables forecast efficiency and that it provides output that facilitates clear communication of risks.

Predicted Tides

Since almost every area of the world is now served by reliable and reasonably precise (by TC forecasting standards) predictions of the variation in the local astronomical tide, it seems there is no excuse for storm surge forecasting tools not to explicitly include tide phasing and magnitude when constructing warnings.

Waves

The impact of extreme waves needs special attention in exposed areas, both in the context of coastal and island (especially reef-fringed) communities. In addition to the possibility of dangerous wave setup there is also the potential for non-linear interactions with the incoming surge that may trigger bore-like responses with very damaging consequences.

Observations

It is important that forecasters have access to real time observations of wind, waves and storm tide from reliable gauges throughout an event to enable corroboration of modelled parameters. Areas of specific vulnerability should have long-term monitoring stations and data archiving standards. Satellite data alone cannot be relied upon to provide this feedback.

Datums

Confusion over simple ocean elevation and land datums likely remains a principal impediment to effective communication of storm tide threats and hazards throughout the world. As a minimum, for inundation prediction, any model must have a reasonably accurate estimate of the ground elevation in the threatened areas. Also, the tidal planes and their associated datum must be reliable else the forecast may be worthless at best and deadly at worst.

Precision vs Accuracy

There remains a significant challenge to simultaneously model large scale oceanic forcing at the same time as localized hydraulic processes such as wave runup and overtopping or hydraulic structures such as levees or weirs in rivers and also flow between buildings. This adds considerably to the computational effort required, places extreme demands on data requirements and requires expert consideration of the relative precision of the various inputs. Given that the greatest uncertainty in storm surge prediction currently lies in the estimation of intensity, size and track at landfall, it is important that all vulnerable regions have basic reliable storm surge forecasting capabilities before considering the need for “high precision” deterministic modelling that cannot be practically calibrated or verified.

Strategic Planning

All forecast Agencies are encouraged to continue their efforts in promoting the clear advantages of avoiding deadly storm tide risks through strategic planning, which should be based on quantitative risk studies that include hazard, exposure and vulnerability. It simply makes sense that forecast and planning models always have a common scientific base.

Recommendations

The following draft recommendations are for consideration at the Workshop:

1. The term “storm tide” should operationally replace the use of the term “surge” when considering the total water level hazard that is comprised of tide, surge and breaking wave setup, and where applicable, coincident coastal river flooding, so that there is no confusion as to forecast and disseminated mapped extents and depths.
2. Probabilistic storm tide forecasting systems should be adopted that include allowance for the uncertainty of the TC parameters, including both track, timing, intensity and structure.
3. Storm tide forecasts should explicitly include the astronomical tide prediction and the relative phasing with the time of TC closest approach, which in turn is affected by the uncertainty in the TC track and speed.
4. Storm tide models for forecasting and warning should have adequate spatial and temporal resolution to resolve coastal features capable of locally amplifying incoming surges.
5. Where inundation forecasts are required there must be adequate land elevation data available and mapping and tidal datums must be verified with the emergency service organizations.
6. Storm tide model wind and pressure forcing assumptions should be transparent and developers should provide verification studies that include both the hydrodynamic performance versus measured water level data (instrumented, debris-surveyed or anecdotal) and also the wind and pressure performance versus measured data.
7. Wave forecasts should be included in storm tide forecasts where coastal or island communities are likely at risk due to breaking wave setup (especially isolated low lying islands).
8. Coastal river forecasts should be integrated with storm tide where it is evident that the interaction is likely significant and there is associated exposure and vulnerability.
9. Model developers should ensure that there is adequate and reliable data available to formulate the model and seek to verify the model performance in all the regions where it is to be applied.
10. Due to the possibility of rapid changes in threats over the final 12 h of a landfall event as the result of track and intensity changes, storm tide forecast models should be efficient, flexible and practical to meet the operational constraints for timely issuing of warnings.
11. Forecast agencies should work with emergency service and strategic planning organizations to identify exposed and vulnerable communities so that long-term mitigation planning can be implemented and interim emergency response plans can be enacted.

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Acronyms used in the report

NWP: Numerical Weather Prediction
TC: Tropical Cyclone

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