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Numerical modelling of extreme tropical cyclone winds

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Abstract

The paper addresses the issue of numerical and statistical modelling of extreme tropical cyclone winds in coastal regions, leading to the estimation of design return periods of gust wind speeds and the downstream application of risk models. The basic technique is outlined and examples shown of comparisons against anemometer records for the Queensland coast. A methodology is presented for the inclusion of varying surface terrain effects and an example is given of its application in estimating insurance losses across a complex suburban region.

Keywords: Simulation, tropical cyclone, return period, terrain, satellite, insurance loss.

1. Introduction

Traditional measured data extrapolation techniques for the estimation of extreme wind speeds, such as those generated by tropical cyclones (hurricanes or typhoons) are often inadequate for use in specialist engineering design. Firstly, the period of reliable data record at many sites is still relatively short (rarely exceeding 50 years). Secondly, the range of potential storm intensities can be high, their occurrence is typically very low and their area of influence relatively small. Even where reliable recorded data is available, extrapolation to long return periods is problematical and retention of an associated parameter such as direction or persistence to any level of accuracy is difficult. Also, the statistical wind record itself does not contain guidance on questions such as climate change, and is often not suitable for "downstream" design functions such as the determination of extreme wave heights and currents for offshore structural design. Knowledge of the wind generating *system* then becomes of paramount importance rather than the isolated analysis of specific, and sometimes inadequate, anemometer records. This paper presents an overview of techniques designed to overcome these types of difficulties.

2. Estimation Techniques Without Reliable Measured Data

In the absence of reliable measured environmental data in the 1960's the "design storm" approach arose as a useful technique for establishing some type of regional benchmark. This would be based on an assumed return period of a particular regional storm intensity, using nominal scales of storm influence. Aligning such a storm along the most unfavourable track relative to the site of interest then lead to a "worst case" scenario for a given storm intensity. This yielded a potentially very conservative estimate of the associated return period of the wind being experienced at a specific point. In some cases it may have been erroneously assumed that the return period of the resulting wind speed was similar to that of the return period of the regional storm intensity. Clearly, the joint probability of intensity and proximity to site is not considered by this method.

As computer modelling became more readily available through the 1970's, the "design storm" was replaced by the "hindcast" technique. This would involve selecting a number of extreme events from the record that would have been likely to have affected the site in question, but were not captured by a recording system at the time. Modelling of these events using historical track information then yielded a synthetic time series data set which, with sufficient samples, was amenable to traditional statistical extreme value extrapolation techniques. This technique is reasonable when an adequate historical track record is available but fails in cases where the record is sparse, and can be very site and data sensitive.

In the 1980s and 1990s, simulation techniques came to be developed to try and overcome the deficiencies of the other methods. Their attraction lay in an ability to represent the processes at work rather than just the outcomes and, specifically, the capacity to correctly consider joint probability. This shifted focus away from the strict mathematical art of statistical extrapolation of scalar data and towards a closer look at the possible underlying environmental mechanisms. There have been abuses of the technique, like any other, through a failure to adequately calibrate and verify where possible. It is the author's view however that simulation techniques offer not only the best way of estimating extreme wind speed climates but the only reasonable way of doing so out to the long return periods (in excess of 2000 years) increasingly being demanded by today's risk managers [1]. This paper presents some examples of a simulation technique for estimation of tropical cyclone extreme wind speeds applied to sites in tropical Australia.

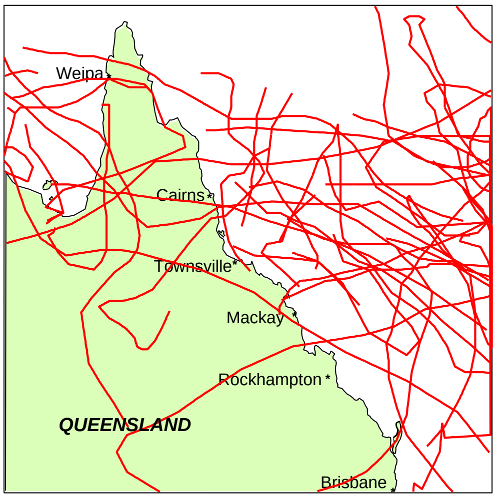

Figure 1. Example Tropical Cyclone Tracks in North Eastern Australia

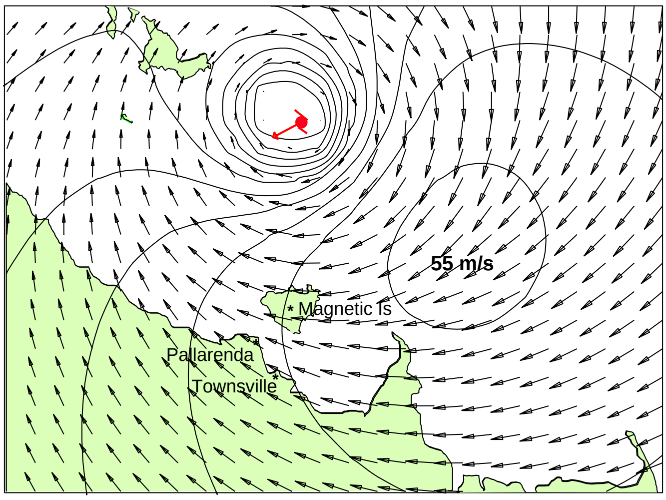

Figure 2. Deterministic Wind Field Modelling of Tropical Cyclone *Althea*

3. An Outline of the Simulation Method

The initial step is one of identifying the environment that leads to extreme winds. This entails a study of the regional climatology of severe storms, such as that shown in Figure 1, which presents historical tropical cyclone tracks in North Eastern Australia since 1959. It is essential that the climatological study adequately *identify* and *separate* the main statistical populations contributing to the risk. This leads to knowledge regarding variation in frequency, intensity, track, forward speed and spatial scale within a suitable control volume. Typically, the control volume (e.g. 500 km radius of site) must deliver an adequate sample size without exceeding the regional climatological scale. One should also be mindful of the accuracy of historical tropical cyclone data, much of which is inferred by satellite interpretation in many parts of the world. Physical limits to intensity are also known to exist based on sea surface temperature and regional atmospheric soundings [2]. This aspect of a study requires attention to detail and reasonably extensive experience in the interpretation of meteorological data sets.

The next step should be to reassure oneself that reasonable *deterministic* modelling of wind speeds is possible in the region, using a model of choice. In this case the Holland analytic model [3,4] has proved itself one of the most capable for representing the broad features of the tropical cyclone. An example of its use is given in Figure 2 for Cyclone *Althea* with an estimated central pressure of 952 hPa and 55 ms^{-1} measured wind gusts, which caused extensive damage to the North Queensland city of Townsville in 1971 [5,6]. Figure 3 shows the comparison between measured and modelled winds at the Townsville airport, based on +10m winds. In this case the model prediction of mean winds "over water" has been modified to include gust estimates over land [4]. For further comparison, an example of a much more intense storm is presented in Figure 4. This shows measured and modelled winds at an ocean site during the passage of the 905 hPa Cyclone *Orson* off the West Australian coast in 1989 [7]. The twin anemometers failed in their second passage through the eye wall. In this case the analytic vortex model has been enhanced by the addition of a broad scale geostrophic gradient that more effectively matches the early approach phase of the storm and can be critical for extreme wave development.

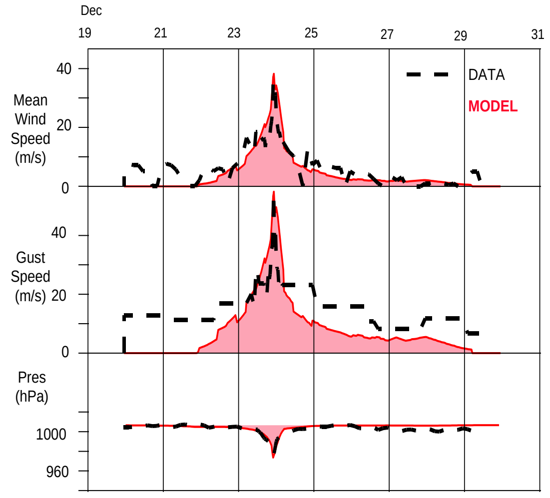

Figure 3. Wind Model Calibration for Cyclone *Althea*

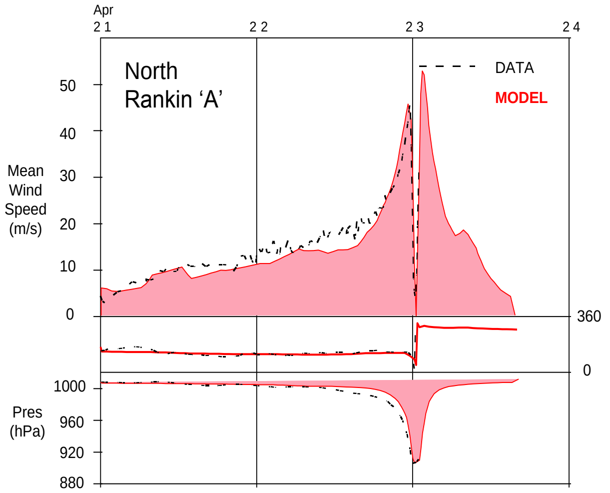

Figure 4. Wind Model Calibration for Cyclone *Orson*

Stochastic modelling of the assumed environment then follows, using a Monte Carlo or other sampling technique to allow the full range of environmental parameters to be explored. A numerical model is constructed which will allow the generation of synthetic storm tracks across the region of interest, with parameters such as intensity, angle of approach and scale radius being selected from the probability distributions derived earlier. Using the deterministic wind model, entire synthetic time histories of wind speed and direction may then be generated anywhere within the region, subject to the assumptions of the various model elements. A model "clock" is used to provide a base probability reference and the simulation proceeds, with typical durations in excess of 10,000 "years" being required to obtain stable exceedance statistics at return periods of interest (e.g. 1000 years). Accumulation of the synthetic exceedance statistics then directly yields an estimate of the long term wind speed risk at any point. Since all major wind generating parameters can be included in the simulation, their relative sensitivities can next be examined and verification tests can be undertaken. Where reasonable measured data exists, the model predictions should also be compared with that data.

4. Example Wind Speed Predictions

The first example is given in Figure 5 for the North Queensland city of Townsville, where 54 years of measured peak tropical cyclone only wind gust data from the airport is shown, together with the independently derived simulation result. For convenience, the partial data series has been plotted on a simple logarithmic scale according to Gringorten [8] with an applied Poisson scale shift. The highest recorded gust at Townsville is due to Cyclone *Althea*, being approximately 55 ms^{-1}. The current regional recommendation of the AS1170.2 wind loading code (Region C) is also shown [9]. It can be seen that the modelled wind speed is a very good match to the measured data set overall, allowing for the drift of the *Althea* result towards higher return periods as the data set grows. The AS1170.2 recommendation is shown here to be potentially more conservative.

What is of interest beyond the range of data verification of Figure 5 is the predicted wind speeds at longer return periods. The effect of the reducing parameter space results in the formation of a natural limit to regional gust speeds. Beyond the 1000 year return period, for example, increasing wind speeds result primarily due to differences in forward speeds of tropical cyclones alone, rather than an increase in intensity. This is because the maximum regional storm intensity will be limited [2] and in this case tends towards a return period less than the wind speed return period of interest. A purely statistical treatment of this data set would be unable to depict this type of potential behavior at long return periods.

Similar studies have been conducted for a number of coastal locations throughout Queensland. Figure 6 presents the equivalent prediction for Cairns, compared with 52 years of tropical cyclone gust data and Figure 7 presents Mackay against 35 years of measured tropical cyclone gusts. The Mackay anemometer location is subject to some local topographic effects and this is believed to account for the poorer match at low wind speeds, versus Townsville and Cairns, which are both on flat ground at standard height with Category 2 roughness. Each city prediction is based on a separate assessment of the regional tropical cyclone climatology, which slowly varies along the length of the Queensland coast.

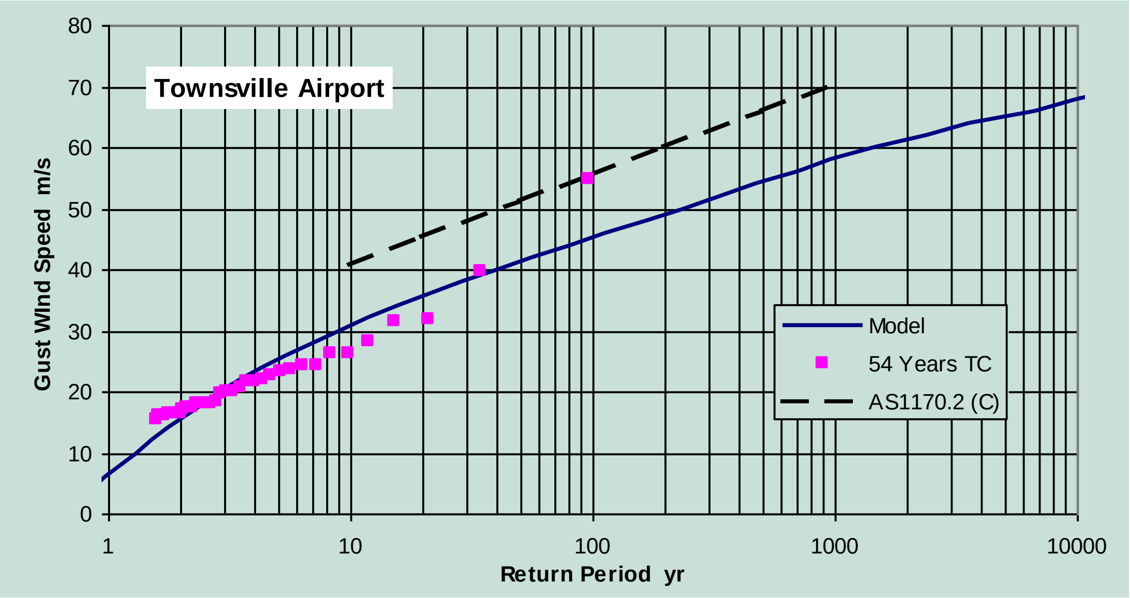

Figure 5. Example Modelled and Measured Extreme Winds Comparison - Townsville

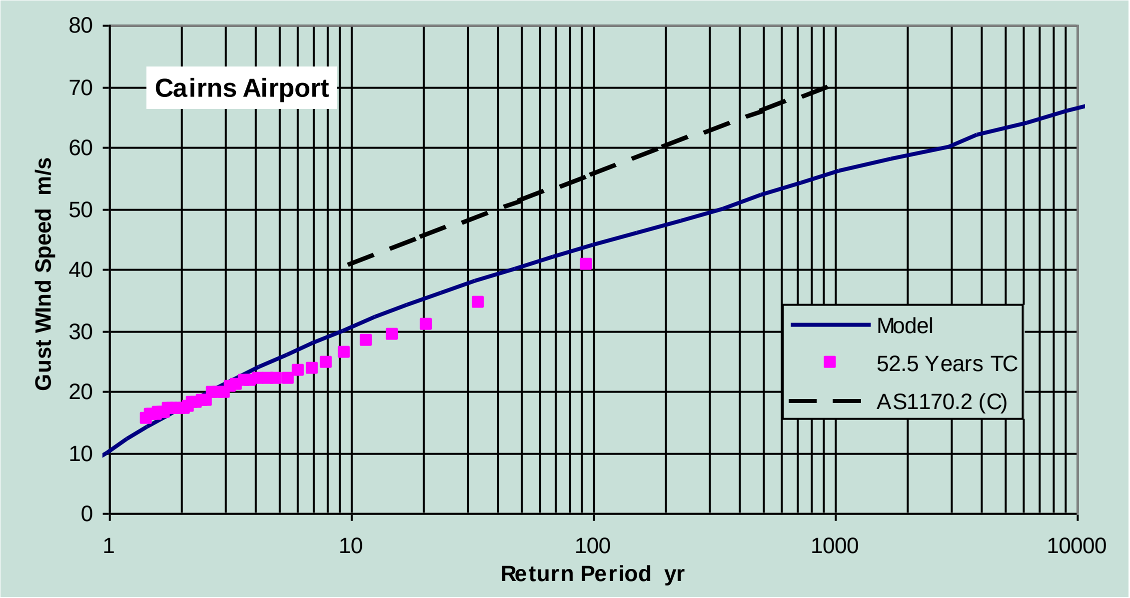

Figure 6. Example Modelled and Measured Extreme Winds Comparison - Cairns

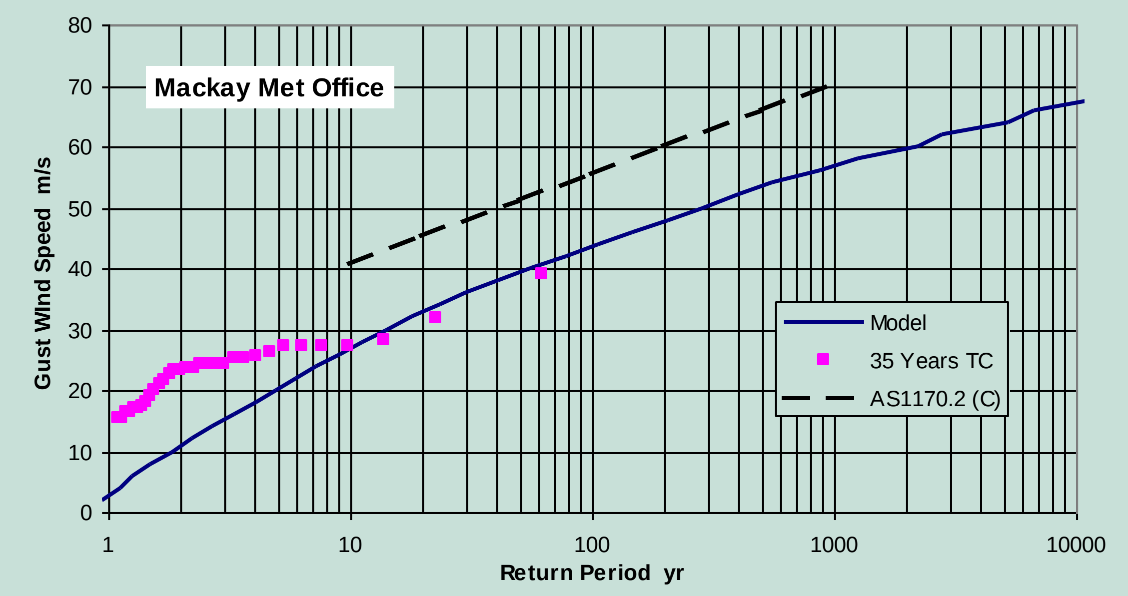

Figure 7. Example Modelled and Measured Extreme Winds Comparison - Mackay

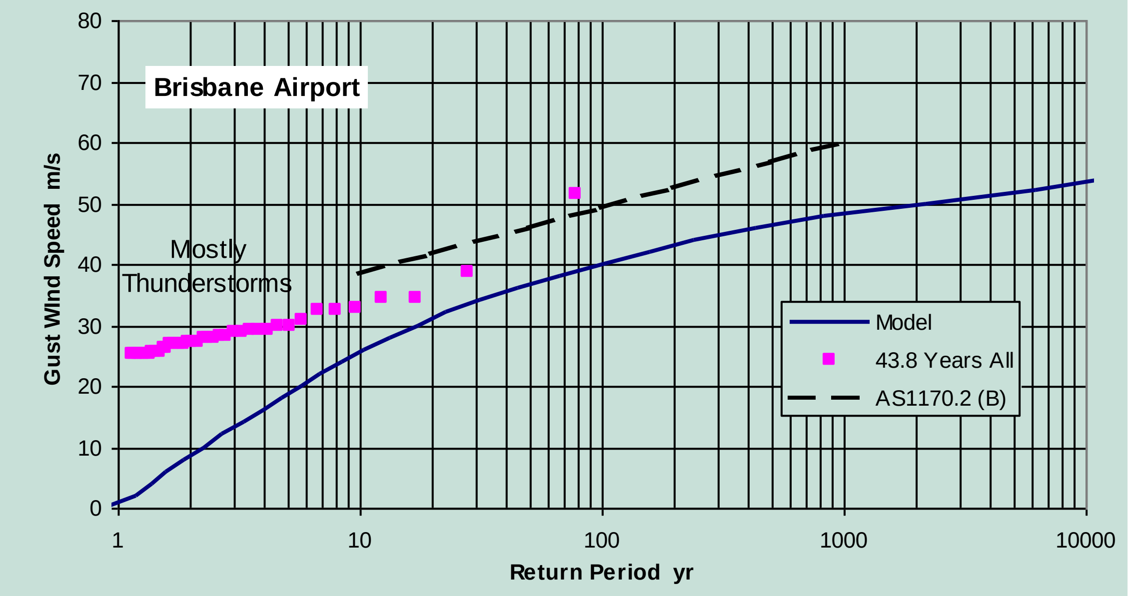

Figure 8. Example Modelled and Measured Extreme Winds Comparison - Brisbane

Figure 8 presents the comparison between measured and modelled data for the case of Brisbane, situated at the southern extremity of the state. This is an example of a situation where the record of significant tropical cyclone influence at a site is actually very low but nevertheless the potential exists for a severe event to occur. The graph shows summer half-year measured gust data for a period of some 44 years. During this time there were only nine occasions when peak gusts due to tropical cyclones exceeded 15 ms^{-1}, with the highest recorded gust being only 30 ms^{-1}. The remainder of the data is due to local severe thunderstorms. However, using the simulation approach, it has been possible to construct a continuous representation of the regional risk of extreme winds due to tropical cyclones and to develop the predicted curve as shown. This suggests that tropical cyclone-generated winds are significant only beyond a return period of about 10 years at Brisbane, with thunderstorm events predominating at all return periods. The AS1170.2 (Region B) recommendation brackets the peak thunderstorm data set. Although tropical cyclone wind risks are clearly lower than thunderstorms, the much increased scale of influence of tropical cyclones means that the total damage across the region will be much greater than for the equivalent thunderstorm wind speed, which is more localised. Later model developments which include severe thunderstorm events [10] have shown that a simulation model can also exactly match the recorded thunderstorm data series.

5. Extensions of the Basic Simulation Method

Over the past several years, the author has successfully applied the above techniques to the estimation of coastal and ocean environmental design criteria [1]. Integrated extreme wind, wave and current predictions can be formulated through simulation, with full joint probability information at very long return periods. This provides critical information for the dynamic design of structures subjected to multi-directional loadings at a range of applied frequencies. Lifetime directional fatigue loading data that is exactly consistent with the design extreme conditions can also be obtained directly from such a model.

More recently the technique has been applied to the problem of estimating insurance losses for domestic style construction [6,11,12] which are especially sensitive to the incident wind speed. In this case, extensive use was made of satellite imagery to provide the basis for estimating the regional variation in surface wind effects across large and complex metropolitan regions. Tropical cyclone winds, in the main, can be assumed to be well mixed and neutrally stable, allowing the development of a turbulent boundary layer structure. Satellite imagery was then combined with a digital elevation model at a base pixel resolution of 30 m. This provided a means of mapping several city areas in terms of simplified linear boundary layer multipliers, broadly using the provisions of AS1170.2 [9].

Firstly, the surface roughness was determined based on delineation of the actual surface features (both manmade and natural), and zoned using four Mz,cat levels in a stepped fashion inland from the coast. Assuming maximum structure heights (z) of 7 m for domestic housing, terrain categories typically assigned were Category 2 within 1 km of the sea; Category 2.5 between 1 km and 2 km from the sea; Category 3 for remaining suburban areas and Category 4 for CBD areas. Similar terrain adjustment sequences were applied at the land limits of each city where Category 2 or 2.5 boundary conditions were typically used. Allowance was also made for embedded changes in roughness within suburbs where, for example, golf courses, extensive sporting fields or water supply reservoirs provided opportunities for boundary layer adjustment. The technique used to date is omni-directional, which is conservative for a land-falling tropical cyclone where both on and offshore winds will exist, but the technique is readily extendable to a directional variation. Shielding of houses was also incorporated based on AS1170.2 recommendations for Ms.

While delineation of “hills” within the definitions of AS1170.2 were extensively trialed, these remained impractical in the majority of real terrain situations examined over large areas. Accordingly, only the variation in terrain *slope* was considered as representing areas of accelerating flow. A total of seven separate Mt slope multipliers was developed based on recommendations in Part 2 of AS1170.2. Overall, this approach is deemed to be conservative since it accounts for upslope and downslope areas in all cases. It also ascribes the highest multiplier applicable to each slope category without regard to transitional effects, proximity to crest or the “height” of the “hill”.

Finally, a separate information code was attributed on the basis of whether or not the image pixel was judged to be a part of the natural or the built environment. This ensured that the wind analyses were constrained to areas of infrastructure interest. This is particularly relevant along the coastal fringe where typically large areas of swampy ground might exist next to estuaries, river mouths and the like. The combination of the chosen terrain and topographic zoning at the 30 m resolution allows for a very comprehensive representation of the regional variability of wind speeds across a city. This is depicted visually in Figure 10 where each colour level represents a separate wind multiplying factor M to be applied relative to the local "over water" modelled wind speed at any instant. These are made up from up to 56 combinations of built/non-built Mz,cat, Mt and Ms. The proportion of any *built* area exposed to a particular wind multiplier (such as a postal code region) is then obtained directly by the summing of coded pixels in that area and can be assigned to the insured value at risk in the same area. The base topographic model was then incorporated into a Monte Carlo risk model of tropical cyclone winds of the type already described.

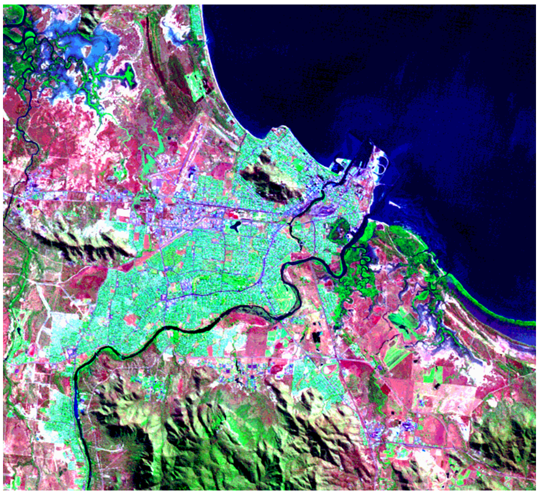

Figure 9. Landsat Image of Townsville

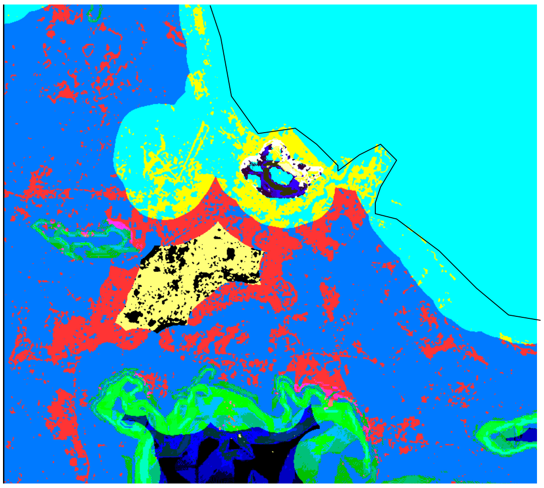

Figure 10. Composite Terrain and Topographic Zoning of Townsville

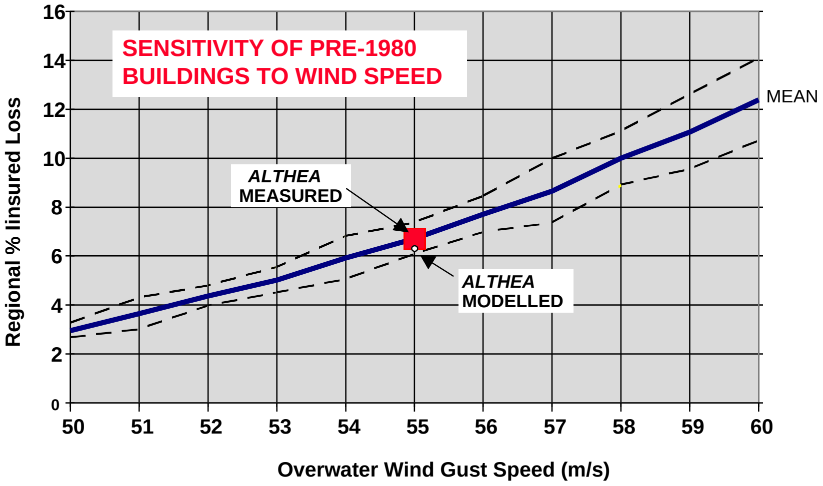

Figure 11. Insurance Loss Model Verification

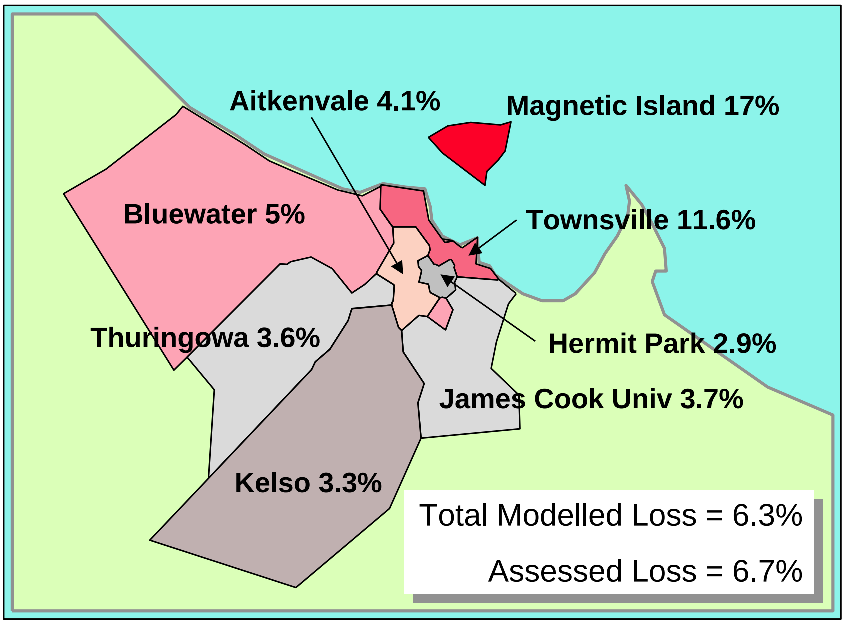

Figure 12. Spatial Loss Variation in *Althea* Derived from Regional Topographic Zoning

An example of the outcome of such an analysis is given in Figure 11 where wind speed has been successfully converted to expected regional insured loss through the use of empirical wind-damage transfer functions [13]. The graph shows the verification of the damage loss model for Townsville based on estimated construction quality in the city at the time of cyclone *Althea*. The modelled prediction of the variation of loss with wind speed (mean and standard deviations) is compared with the specific hindcast of *Althea* and the industry recorded gross insured loss figure. The agreement for this specific event is excellent, due in part to *Althea* being one of the historical cyclones used to formulate the empirical damage functions. However, the model prediction can be seen to be well behaved across this range of wind speeds. Furthermore, Figure 12 illustrates that the total loss prediction for any wind speed is the weighted average loss from a number of postcodes in the region. Heaviest damage is indicated by the model to occur along the coastal fringes. The general spatial variation in predicted damage appears to be broadly consistent with experience at the time (D. Lloyd, personal communication). A storm surge inundation model also forms part of the overall risk model for this region.

6. Conclusions

Simulation techniques, when carefully constructed, can provide essential insight into the complex mechanisms that underscore extreme winds in a region and may provide the only reasonable basis for extrapolation to very long return periods. They provide an excellent framework for extension to other allied fields of analysis such as offshore design criteria, insurance loss and even emergency planning. Climate change scenarios can be tested and wind directionality and duration can be readily included to permit true joint probability estimates to be made at very long return periods. The cooperation of SUNCORP General Insurance for the use of some illustrations is gratefully acknowledged.

7. References

1. B.A. Harper, K.F. Lovell, B.D. Chandler and D.J. Todd, The Derivation of Environmental Design Criteria for Goodwyn 'A' Platform, Proc 9th Aust Conf Coastal and Ocean Engin, IEAust, Dec, 1989.
2. G.J. Holland, The Maximum Potential Intensity of Tropical Cyclones, J. Atmospheric Science., 54, Nov, 2519-2541, 1997.
3. G.J. Holland, An Analytic Model of the Wind and Pressure Profiles in Hurricanes, Monthly Weather Review, 108 (8), Aug, 1212-1218, 1980.
4. B.A. Harper and G.J. Holland, An Updated Parametric Model of the Tropical Cyclone. Proc. 23rd Conf. Hurricanes and Tropical Meteorology, American Meteorological Society, Dallas, Texas, 10-15 Jan, 1999.
5. James Cook University, Cyclone Althea - Part I: Effects on Buildings, Dept of Civil and Systems Engineering, 1972.
6. B.A. Harper, Tropical Cyclone Risk Model Study for North Queensland, SUNCORP Insurance and Finance, Mar, 400pp, 1995.
7. B.A. Harper, L.B. Mason and L. Bode, Tropical Cyclone Orson - A Severe Test for Modelling, Proc 11th Australian Conference on Coastal and Ocean Engineering, IEAust, Townsville, Aug, 59-64, 1993.
8. I. I. Gringorten, A Plotting Rule for Extreme Probability Paper, J. Geophysical Research, 68 (3), 813-814, 1963.
9. Standards Australia, AS1170.2 - 1989 SAA Loading Code. Part 2: Wind Loads, 96pp.
10. B.A. Harper and J. Callaghan, Modelling of Severe Thunderstorms in South East Queensland. Proc. Sixth Australian Severe Storms Conference, Bureau of Meteorology, Brisbane, Aug, 1998.
11. B.A. Harper, Risk Modelling of Cyclone Losses, Proc. Annual Engin Conf, IEAust, Darwin, Apr, 1996.
12. B.A. Harper, The Application of Numerical Modelling in Natural Disaster Risk Management, Proc. Conf. Natural Disaster Reduction NDR’96, Gold Coast, Sep, 1996.
13. G.R. Walker, Personal Communication, 1994.