Storm Tide Risk Assessment for the Cocos (Keeling) Islands

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Abstract

The Cocos (Keeling) Islands comprise an isolated group of islands in the eastern Indian Ocean administered as an external Australian territory by the Commonwealth Department of Transport and Regional Services. The islands are low lying and subject to tropical cyclone influences as well as southern ocean swell. The paper outlines a recent study undertaken into determining the risk of storm tide impacts at the islands under tropical cyclone conditions. The study concludes that storm tide levels will be dominated by reef-top breaking wave setup.

1. Introduction

The Cocos (Keeling) Islands are situated near 12°S 97°E (Figure 1). The major and populated South Keeling group of islands form a typical small to medium sized coral atoll system in which a large lagoon is surrounded by an enclosing intertidal reef on which the various islands are located (Figure 2).

The Cocos (Keeling) atoll is of considerable significance for scientific research on the geology and geomorphology of coral atolls. It was the only atoll which Charles Darwin actually visited and he sought evidence there for his theory that coral atolls were derived from the original fringing reefs formed around a volcanic island which had subsequently gradually subsided below sea level. It has only been during the latter half of the twentieth century that sufficient scientific evidence has been obtained to verify this theory.

The geological structure of the atoll is primarily the result of subsidence of an original volcanic island, although the present geomorphology is a consequence of the more recent sea level history, reef growth and sedimentation processes. This has resulted in a variety of coastal features that work together in delicate equilibrium to resist the incident ocean forcing from extreme weather conditions such as tropical cyclones.

The atoll is horseshoe shaped, with two major openings and numerous smaller passages, containing a lagoon about 12 km E-W and 15 km N-S. It consists of numerous islands that are fronted by a reef of varying width and a reef flat with a surface elevation less than 1 m below MSL. Much of the lagoon is very shallow, from 0 to 3 m, although the northern part extends to 10 to 20 m. The majority of the land is only 1 to 1.5 m above MSL, although the populated areas mostly exceed 3 m. Surrounding ocean depths exceed 2000 m.

Figure 1 Locality map.

2. Physical processes

Wave-action dominates the outer reef flats on the seaward sides of the islands but tidal action dominates the sheltered lagoon enclosed by the reef and islands. Twelve shallow inter-island passages connect the reef flat and shallow lagoon on the eastern and southern rim of the atoll. The depths in these passages are less than 1.5 m below mean sea level. Exchange of water between ocean and lagoon occurs along their total width of 4 km, as well as through the two deeper channels on the northern and northwestern sides of the atoll.

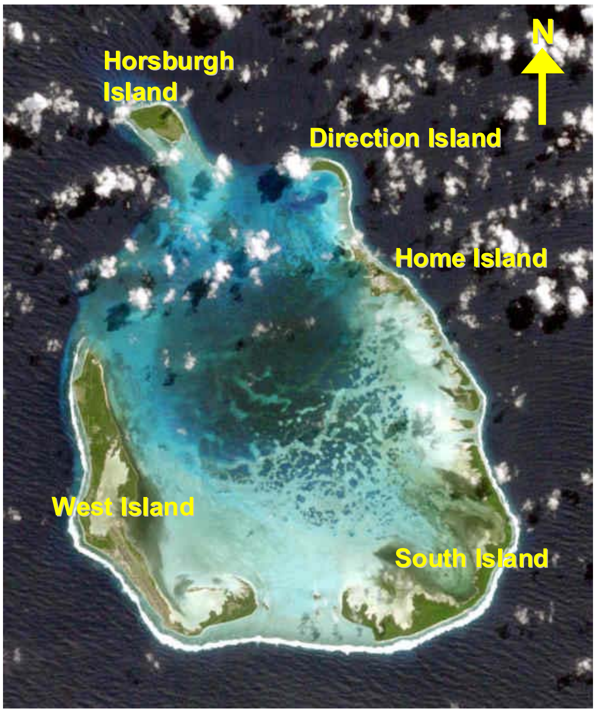

Figure 2 Landsat image of South Keeling atoll.

On the lagoonward side of the passages there are large sand deposits, formed where the lagoonward transporting energy of the waves is dissipated and/or counteracted by the tide within the lagoon. The shallow part of the lagoon variously contains mud flats and sea grass beds and there is a variable cover of coral, sand and algae. The northern lagoon region is covered generally with sand, dead coral, etc. The predominant SSE trade wind-driven swell breaks around the outer reef rim with breakers of the order of 2 m height and is diffracted and refracted around the atoll, entering the deeper northern passages with much reduced wave heights. Tides are mixed microtidal with a maximum range of 1.3 m.

Overtopping of the seaward beach ridge by waves at high tide occurs from time to time. The most recent event was recorded on 5 August 1999 in the vicinity of the sea wall protecting houses on West Island. Such overtopping is known to have occurred at least three times during the last 20 years. Significant overtopping also occurred in August 1980 during a period of low winds and extraordinary high tides. In contrast, cyclone *Doreen* (970 hPa) passed over the atoll in 1968 without causing any recorded storm tide damage. However, West Island was inundated four times by king tides and heavy swells during the previous six months. Significant movement of coral boulders, overwash of island foreshores and damage to houses and roads occurred during these last events.

3. Methodology

The atoll site is an open ocean location surrounded by deep water within a tropical cyclone environment, but with prevailing wind and sea influences from the southern ocean. The present study (SEA 2001) addresses only severe tropical cyclone conditions, the meteorological and oceanographic impacts being summarised as follows:

- Low tidal environment
- Exposed wind environment
- Exposed wave environment on the outer reef
- Protected wave environment within the lagoon but directionally sensitive to wind stress.

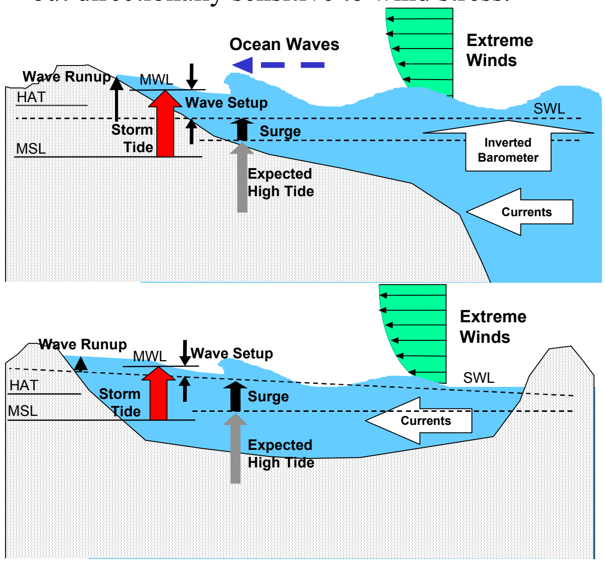

Figure 3 Factors influencing extreme water levels (top: outer reef; bottom: lagoon).

It was therefore expected that the principal threat of inundation due to extreme water levels on the outer reefs (Figure 3) would be due to the combined effects of (i) the pressure deficit component of a storm surge acting coincidentally with (ii) a high tidal level and (iii) high wave setup, caused by wave breaking on the outer reefs and reef entrances. Based on previous studies (e.g. Gourlay 1996) wave setup was expected to be the dominant water level controller, with pressure deficit (or inverted barometer effect - IBE) being a secondary component. The maximum potential inverted barometer effect is of the order of 1 m and would only be realised during a very close approach of a very intense storm (e.g. 900 hPa). Wave setup plus tide was therefore expected to largely control the statistics of outer reef water levels. Wind-stress induced storm surge setup was expected to be small because of the surrounding deep ocean environment but potentially more significant in some parts of the shallow lagoon.

Because of the complex non-linear interactions of storm surge, tide and breaking wave setup, a statistical simulation methodology was adopted. This firstly comprised a statistical analysis of the storm climatology to provide a complete range of potential storm parameters. These were then used to control a Monte Carlo simulation which invokes deterministic (parametric) models of each phenomenon (surge, waves, setup) and assembles a synthetic time history of extreme water levels from which return periods of water levels may then be derived. The technique is similar to Harper *et al.* (1989) and allows a fully objective assessment that accounts for the joint probability of all the necessary parameters. A complete return period estimation of water levels is obtained which does not directly rely on data fitting assumptions. The simulation can be easily altered to test the sensitivity to the controlling assumptions taken from the storm climatology and to any other assumptions such as reef geometry, wave setup response or enhanced-Greenhouse impacts.

The method delivers sequences of time-varying water level components that would be generated during a severe tropical cyclone event, with breaking wave setup on the outer reef flats and local wind stress influencing the shallow lagoon regions. Both these effects are modulated in a non-linear fashion by the stage of the tide. Numerical hydrodynamic and spectral wave modelling of 10 close-approach historical tropical cyclones was undertaken to explore the range of likely responses. These results were incorporated into a statistical storm tide model and combined with an assessment of the regional tropical cyclone climatology to develop estimates of storm tide levels and their associated return periods at 20 sites around the atoll.

3.1. Available data sources

Principal recorded data sources for the study were limited to National Tidal Facility (NTF) hourly water level data from 1986 to 1999 and tidal harmonic analyses. While there has been a number of short term current and tide measurements made throughout the atoll, no long-term measurements were available for statistical analysis and no wave data is available. Long-term Bureau of Meteorology wind and pressure records were obtained for the airport site on West Island and have proved of critical value to the verification of the modelling process. Hindcast winds and waves were also available from the British Meteorological Office but were deemed unsuitable for the tropical cyclone risk assessment. Detailed information on water depths and reef slopes was limited to specific site surveys which mostly did not coincide exactly with the sites of interest. The relationship between the tidal plane and the reef topography was of particular interest, which lead to an estimate of the reef-top depth. All the available data was amalgamated as much as possible.

3.2. Tropical cyclone climatology

For the purpose of statistical analysis, a specific subset of the available tropical cyclone dataset from the National Climate Centre (NCC) was selected. Firstly, the data was limited to the period 1959 onwards when satellite observations started to become available, yielding a total of 41 seasons for analysis. Secondly, a statistical "control volume" was selected, taken as a 500 km radius of South Keeling atoll. The 500 km radius has been found adequate for these purposes in a number of previous analyses. This results in a total of 95 storms and an average of 2.3 storms per season within the radius. The greatest number in any season was six in 1974/75, although five occurrences in a single season have been recorded on several occasions.

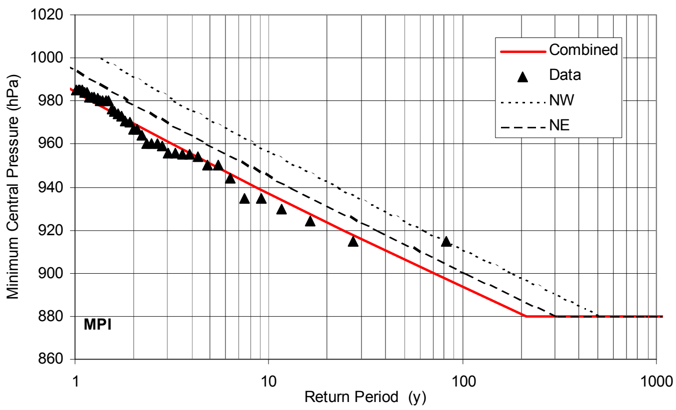

Figure 4 Extreme value analysis of regional tropical cyclone central pressure.

The analysis identified essentially two storm population sources in the region - a north-west source with storms moving typically south-eastward and a north-east source typically moving south-westward. Following separation of the tracks, extreme value statistical analysis was carried out on the estimated central pressure data. Figure 4 presents these results in terms of the best fit Extreme Value Type I (Gumbel) line for each origin class (NW and NE), the combined classes line and the combined dataset. The analysis shows that the NE origin class is the more intense storm population. In each case the continuous distributions are truncated at a nominal *Maximum Potential Intensity* (MPI) of 880 hPa based on a value consistent with the North West Shelf region of Western Australia. The MPI has an estimated return period of about 200 years for the NE origin class and about 500 years for the NW origin class. A variety of other storm parameters were also assembled to fully represent the cyclone climatology for the region.

As part of the overall model validation process, a "top 10" storm set was assembled comprising those storms which passed within 150 km of the Cocos Islands with central pressure below 990 hPa. Figure 5 shows their combined tracks. Wind speed and pressure data for each event was extracted from the NCC data record for the island airport.

3.3. Numerical Modelling

Several numerical models were developed to represent the tropical cyclone environment. The ADFA1 discrete spectral wave model (Young 1987) was applied to a system of four nested model domains (A thru D) of 60 km, 20 km, 4 km and 200 m resolution respectively. The outer A domain was 2000 km square to fully capture the regional wave generation area. Subsequent domain and resolution size were optimised to reflect the spatial variation in the cyclone forcing as well as geographic scales of the atoll. The SURGE numerical hydrodynamic model (Sobey and Harper 1977) was applied over the 200 m resolution wave grid (D) with the open sea boundaries driven by tidal levels.

Both the ADFA1 and SURGE models obtained surface wind forcing from the Harper and Holland (1999) model, the SURGE model additionally using the pressure gradient information. The analytical wave setup method after Gourlay (1997) was then applied to the wave model output for off-reef conditions using incident water levels from the storm surge/tide model. These models were coupled to investigate the likely storm tide behaviour during each of the "top 10" extreme events.

Tropical cyclone *Alison* (967 hPa) in 1998 was the most recent storm to affect the region that was available to the study. *Alison* passed about 90 km to the south east of the island on a SW track (shown dashed in Figure 5), generating peak 10 minute wind speeds at the airport of 20 m.s^{-1}. Figure 6 shows the modelled time history of wind speed, direction and pressure during *Alison* compared with the measured data from the airport on West Island. Also shown is the modelled time history of significant wave height and peak spectral period off-reef of the southern entrance to the lagoon (no data for comparison). Finally, the modelled and measured time history of storm surge magnitude at the Home Island tide gauge is also indicated. Agreement between the modelled and measured data is quite good in all cases.

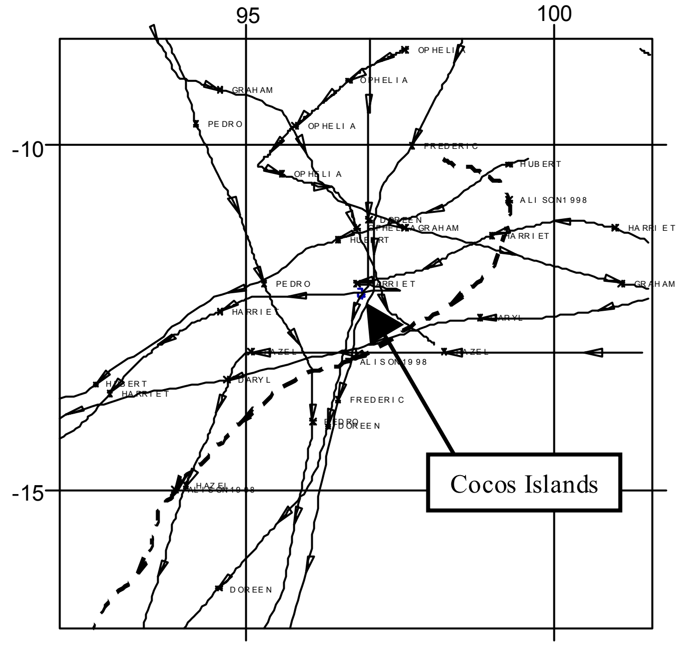

Figure 5 Tracks of the "top 10" hindcast set.

Figure 7 shows the wind speed and storm surge magnitude patterns over the atoll region (D grid) at time 24 h when the storm centre is approximately due south of the atoll. The winds are from the NW at about 17 m.s^{-1} at this time, creating a wind stress induced surface setup across the shallow lagoon. The predicted wave pattern at this time was combined local wind sea from the NW and swell emanating from the storm centre to the south.

4. Statistical Modelling

The "top 10" hindcast studies demonstrated the ability to individually model wind, wave, setup, tides and storm surge throughout the atoll. Each of these physical processes was then parameterised into a format suitable for inclusion in a statistical model to allow estimation of return periods for water level exceedance. The SATSIM model (Harper and McMonagle 1985) was specially modified to simultaneously represent coupled time series of each of the parameters of interest at all the island sites. The model enabled the reproduction of non-linear tide and surge in the lagoon via a directionally sensitive Bathystrophic Storm Tide module.

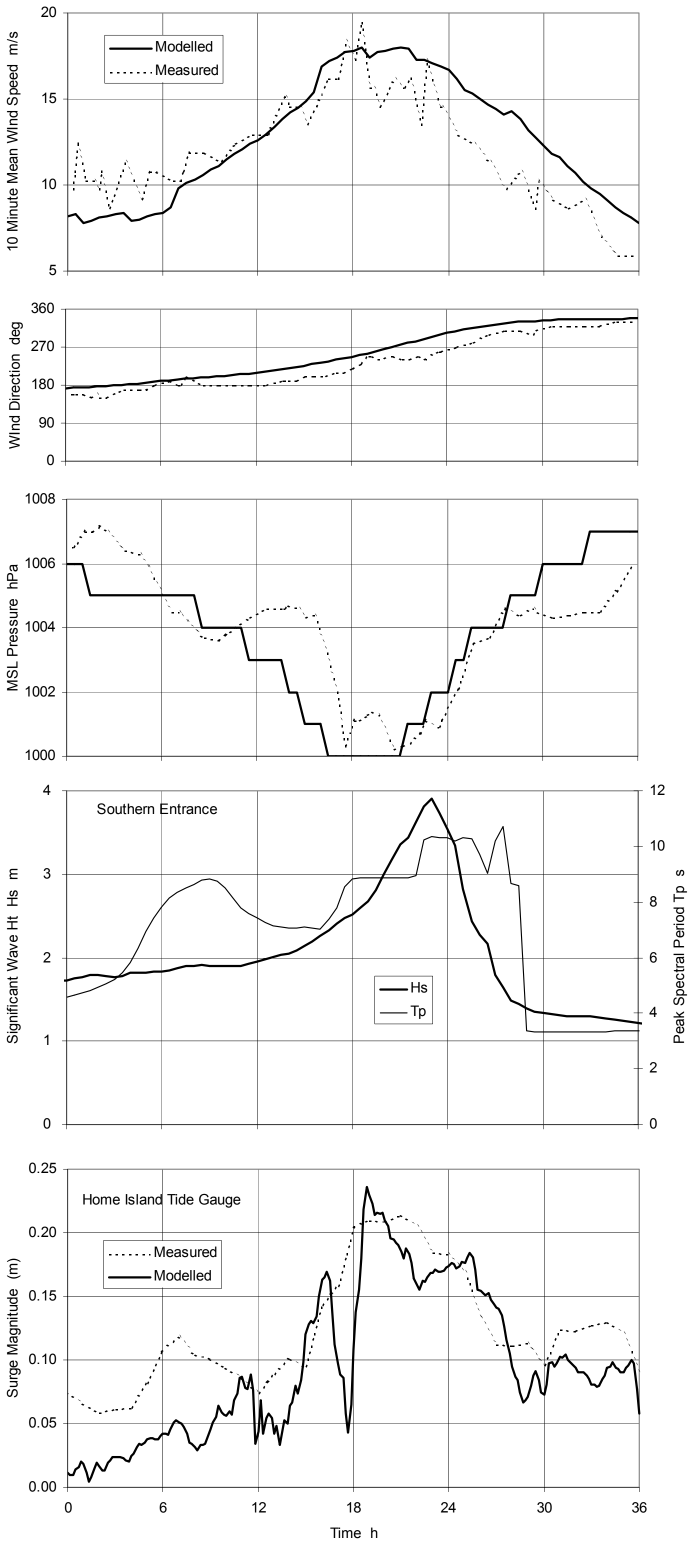

Figure 6 Simultaneous time histories of wind speed, direction, wave height and period and storm surge for *Alison.*

Open sea levels were based on tide plus inverted barometer effect with wave height, period and direction provided by a parametric wave module. Wave setup time histories were then calculated as a function of the incident wave and tide conditions and the site specific reef parameters.

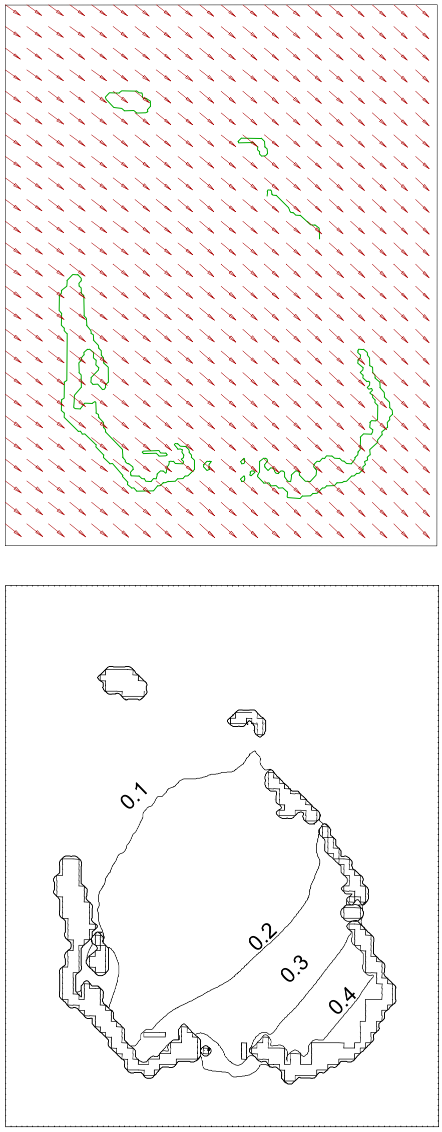

Figure 7 Patterns of wind speed (top) and storm surge (bottom) at time 24 h for *Alison.*

The statistical operation of the model was verified by comparing generated tide level statistics and the estimated wind speed exceedance with the long-term island records. Figure 8 shows the comparison of the modelled mean wind speed exceedance and an extreme value analysis of the measured winds at the airport.

Figure 9 presents an example of the model results for an outer atoll location at the northern tip of West Island. A series of water level exceedance curves are produced for each of the water level components of inverted barometer effect, local bathystrophic storm tide (here small), and breaking wave setup. The highest plotted solid line is the predicted total water level relative to MSL. The off-reef wave height exceedance is also indicated on the RH axis and by the upper dashed line. Due to its exposure to the west, this site is dominated by the influence of breaking wave setup, which is taken here as the 1% upper limit (Gourlay 1997). Other measures of the statistical variation in setup were also explored.

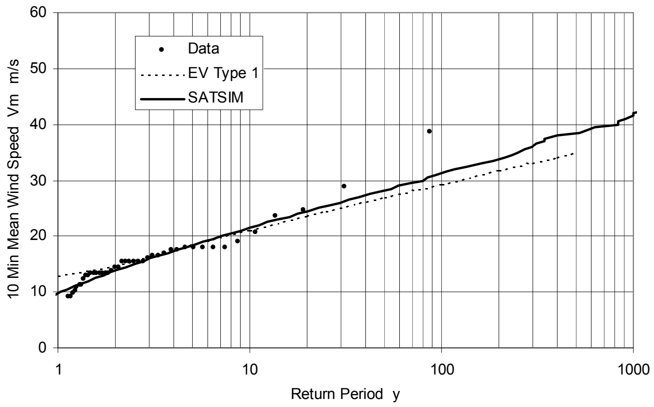

Figure 8 Comparison of modelled and measured wind speed records.

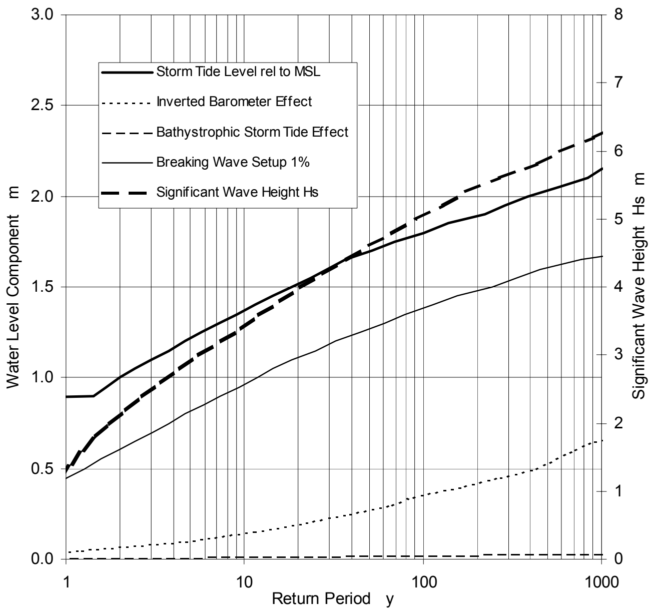

Figure 9 An example of the modelled water level and wave height exceedance for an outer reef site.

5. Conclusions

The Cocos (Keeling) Island atoll is a very complex physical environment that has evolved over thousands of years to a delicate equilibrium between tide, wind, sea, subsidence and coral growth. While the present study has not attempted to fully explore the many subtle relationships between prevailing weather and tide it has identified the principal water level components during the close approach of a tropical cyclone. A combination of deterministic hydrodynamic modelling validated by hindcast combined with statistical simulation has provided a firm basis for establishing the exceedance of water levels. A number of sophisticated models has been combined to ensure the best technical representation of the various non-linear interactions between tide, surge and wave setup.

6. Acknowledgements

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