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Wind Hazard Modelling using Geoscience Australia's Tropical Risk Cyclone Model (TCRM)

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ABSTRACT

A probabilistic wind hazard assessment was undertaken, centred on Tongatapu, Kingdom of Tonga, in the South Pacific Ocean. The assessment was completed using an unaltered form of the open source software developed by Geoscience Australia (GA), the Tropical Cyclone Risk Model (TCRM). As part of the assessment, a sensitivity of several input parameters was conducted. Additional analysis was undertaken to assess directionality and preliminary findings indicated that design wind speeds could be reduced when designing for directionality. The results of the assessment were compared to a number of publications.

1. Introduction

A probabilistic wind hazard assessment was recently undertaken, which was centered on Tongatapu, Kingdom of Tonga, in the South Pacific Ocean. The aim of the assessment was to provide greater reliability of the ultimate exposure and risk assessments for cyclone and wind hazards and it formed part of a broader multi-hazard disaster risk assessment in the development of exposure maps for buildings on Tongatapu.

The assessment was completed using an unaltered form of the open source software developed by Geoscience Australia (GA), the Tropical Cyclone Risk Model (TCRM).

2. Methodology

The wind hazard assessment involved multiple stages:

- Undertake TCRM simulations
- Process simulated tropical cyclone tracks data for 50,000 years
- High level assessment of wind directionality at the site
- Perform extreme value analysis to determine return wind speeds for various return periods
- Calculate site multipliers to consider local topography, surface roughness, and shielding
- Combine extreme value analysis and site multipliers to determine wind speed estimate hazard maps

A couple of aspects of the methodology are discussed in further detail below.

2.1 TCRM

Developed by GA, TCRM is an open-source computational tool for estimating the wind hazard from tropical cyclones. A statistical model is developed based on input track data and a parametric wind field and boundary layer model to simulate the storm tracks and associated wind speeds. The model enables thousands of years' worth of storms to be modelled that are statistically similar to the historic track input data. An extreme value distribution is then fitted to the maximum winds at each location to estimate the wind hazard.

The wind hazard generated by TCRM represents the regional three-second gust wind speed at 10 m height in open country terrain. It does not take into account local influences on the wind caused by topography, terrain, and shielding. As the model is based on historic track data, it does not consider the effects of climate change.

An unaltered version of TCRM (version 3.1.3) was used for this assessment (Geoscience Australia, 2020).

2.2 Directionality analysis

TCRM does not provide any directional outputs, due to the large volume of spatial datasets and associated data constraints (Geoscience Australia, personal communication, November 2020). As part of the assessment, directionality at the site was determined by analysing the 50,000 years' worth of synthetically generated storm track data. This was completed using the storm position relative to the site and applying a radial wind speed profile to determine wind speed and direction at the site.

3. Modelling Inputs & Sensitivity Testing

The following sections outline the key inputs to the wind hazard assessment and TCRM modelling. The sensitivity testing that was undertaken is discussed.

3.1 Track data

TCRM generates random events for a nominated time period based on statistical properties of an input tropical cyclone track dataset. The International Best Track Archive for Climate Stewardship (IBTrACS) has been used for the assessment. Standard practice is to use post-1981 cyclone data to minimise data uncertainty. Version 4 (v04r00), which was originally released in March 2019, has been used for the assessment (National Centers for Environmental Information, 2020). The data are updated weekly. The data set used for this assessment was accessed in October 2020.

In February 2018, Cyclone Gita was the most intense tropical cyclone to impact Tonga since reliable records began and was a direct hit to Tongatapu. To understand the influence of a direct hit cyclone on the synthetically generated storms from the historical track data, a simulation based on track data from 1981 to 2017 was run to exclude the influence of Cyclone Gita and Cyclone Harold in April 2020.

3.2 Simulation domain

Tropical cyclones vary in size and are typically up to 500 km in diameter. To accurately capture the impacts of simulated storms moving through the region, a 20° latitude by 20° longitude simulation domain was chosen, which is larger than the size of a typical tropical cyclone. The domain was centred on Nuku'alofa, Tongatapu, located at 21.14°S and 175.2°W.

Simulation domain directly influences simulation times. As part of the assessment, a number of different domain sizes were tested to understand the sensitivity to the results: including 2° by 2°, 10° by 10° and 10° by 15°.

3.3 Simulation years

As part of the assessment, 50,000 years' worth of storms were simulated. A higher number of simulations results in a more robust wind hazard estimate as more data points are available to fit the extreme value distributions. 1,000 and 10,000 year simulations were also run to understand the sensitivity of the results.

3.4 Boundary layer profile

TCRM has three different boundary layer models that users can apply: McConochie et al. (2004), Hubbert et al. (1991), and Kepert (2001). These boundary layer models take into account the asymmetry induced by the forward motion of the tropical cyclone and the surface friction effects and relate the winds at the gradient level to those near the surface.

A comparison of boundary layer profiles was undertaken. The boundary layer profile of AS1170.2:2020 (Standards Australia, 2020) was compared to that of ESDU (normalised to 200 m), with good agreement found. The McConochie et al. (2004) profile was reviewed, which is based on the work of Harper et al. (2001). For a fast-moving storm at gradient, the factor at 10 m height is 0.66. When normalised to a gradient height of 600 m, the ESDU profile results in a factor of 0.65 at 10 m height. It was not possible to compare the boundary layer profiles of Hubbert et al. (1991) and Kepert (2001) based on the information available.

A parametric analysis was undertaken to compare the boundary layer models and their influence on the results. Kepert (2001) was found to be the most conservative and was used for this assessment. The Kepert (2001) model is a linear analytical model and is considered to provide a more realistic representation of the boundary layer flow with minimal computational cost. It is the model that is commonly used by GA for their published data/assessments so allows for ready benchmarking.

3.5 Radial wind speed profile

TCRM calculates the wind field around each tropical cyclone at high spatial resolution to ensure the peak wind speeds near the eye wall are estimated. A radial profile is used to estimate the gradient level wind associated with the circulation. A number of different profiles are implemented in TCRM, Figure 1. The Powell et al. (2005) model is commonly applied and has been used for this assessment. The Powell et al. (2005) model represents an average wind speed at a greater radius from the eye of the storm in the area of most interest.

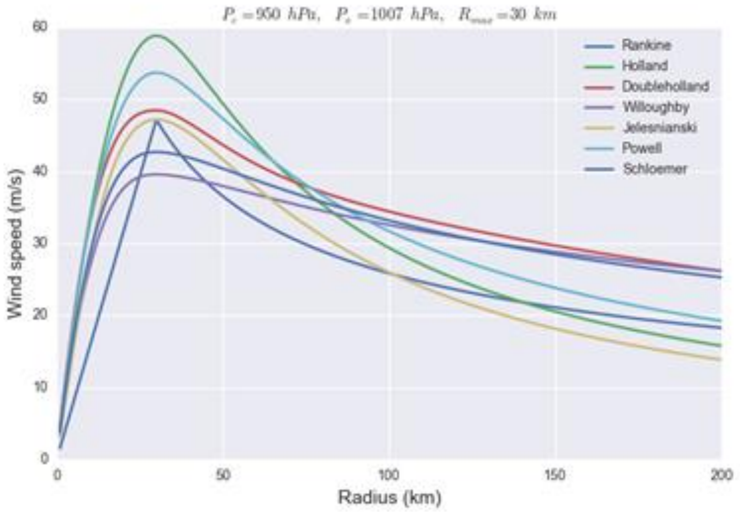

Figure 1. Comparison of radial wind speed profiles available in TCRM (Geoscience Australia, 2015).

4. Sensitivity Testing Outcomes

A summary of the sensitivity testing and the raw results from the TCRM simulations are presented in Table 1. The results presented are for Nuku'alofa, Tongatapu, for ease of comparison. Run 1 is considered to be the base case, having been simulated for 50,000 years and on a 20° x 20° simulation domain.

Run 2 tested the influence of removing Cyclone Gita from the historical track data and compared to Run 1, the results were similar.

Run 3 was conducted for 1,000 years and on a medium size simulation domain. The return wind speeds for 100 and 200 year return periods were the highest of all the runs, which is not surprising given the reduced number of data points. However, given the significant reduction in computational resources to run the simulation, it was of interest to note that the results were reasonable, if a little high.

Run 4 was run for 50,000 years on a medium size simulation domain and the results were very similar to that of Run 1, indicating that in the case of this region and the historical tracks data, a large simulation domain is not required necessarily to achieve reasonably accurate results. Similarly, Run 5 was simulated on a small simulation domain and still achieved very similar results to Runs 1 and 4, confirming that the simulation domain is not a major influence for this region.

Runs 6 and 7 can be compared to Run 5, with the only changes being the boundary layer models. Kepert (2001) was seen to be the most conservative with the highest return wind speeds, while the McConochie et al. (2004) model gave the lowest return wind speeds.

Table 1. Results comparison – input sensitivity testing

	Simulations						
	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**
Sensitivity testing parameter	Base case	Removing Influence of direct hit cyclone (Gita)	Simulated years & domain	Simulation domain	Simulation domain & boundary layer model	Simulation domain & boundary layer model	Simulation domain & boundary layer model
Number of years	50,000	10,000	1,000	50,000	50,000	50,000	50,000
Track data years	1981-2020	1981-2017	1981-2020	1981-2020	1981-2020	1981-2020	1981-2020
Simulation domain (°)	20 x 20	10 x 10	10 x 15	10 x 10	2 x 2	2 x 2	2 x 2
Boundary layer model	Kepert	Kepert	Kepert	Kepert	Kepert	Hubbert	McConochie
Windfield model	Powell	Powell	Powell	Powell	Powell	Powell	Powell
Point location results for comparison (Nuku'alofa, Tongatapu; 3 s gust)							
1:50 years	63.0	59.0	56.7	63.2	62.6	48.0	45.0
1:100 years	71.6	69.6	77.5	72.1	71.4	59.0	54.4
1:200 years	79.3	78.0	85.3	79.8	79.3	68.0	62.2

5. Benchmarking / Validation

The outputs of the assessment were benchmarked against a range of published data, Figure 2. 3 s gust wind speeds were converted to a 0.2 s gust wind speed using a factor of 1.08. The referenced data sources are:

- Evaluation of severe wind hazard from tropical cyclones - current and future climate simulations, PACCSAP, Siqueira *et al.* (2014).

- AIR Worldwide Data from the PCRAFI project, AIR Worldwide (2013).
- Data from the PacSAFE project (‘GA2018’ data), Geoscience Australia (2018).

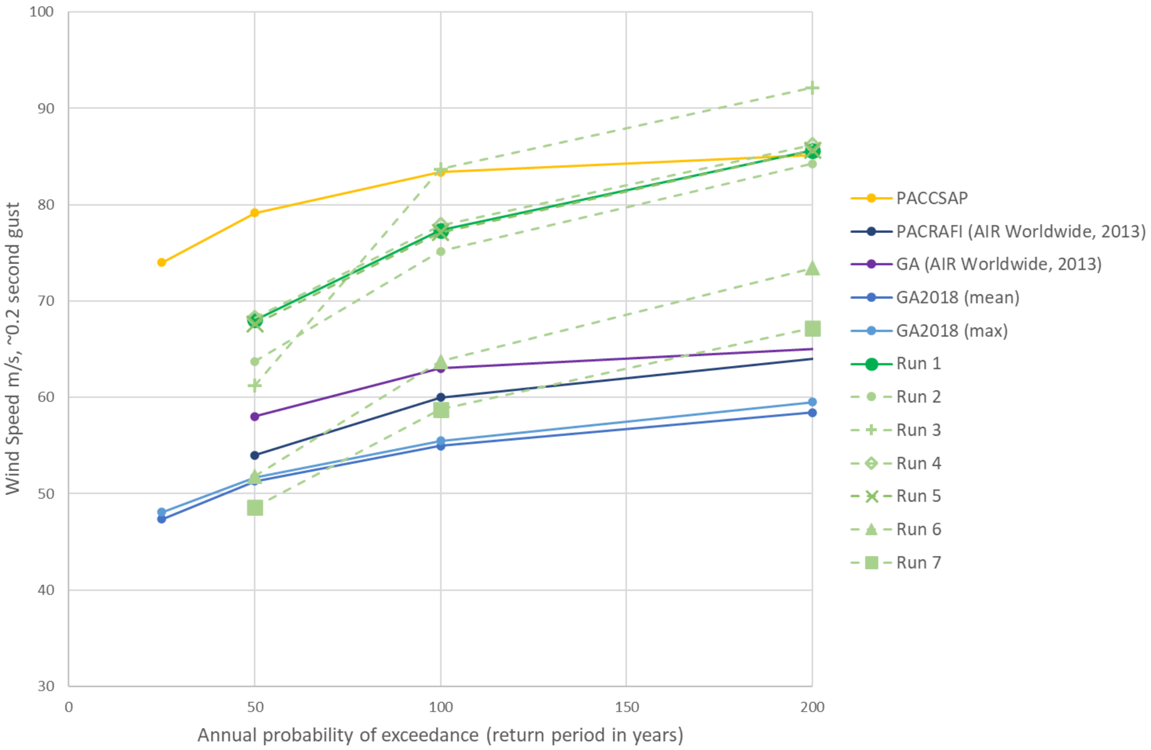

Figure 2. Return wind speeds comparison

The calculated return period design wind speeds using TCRM are presented in Figure 2 (Run 1 – Run 7). The results cover a range, but tend to fall in the upper range of the benchmarked sources.

Through comparing with published GA data and direct conversations with GA (Geoscience Australia, personal communication, November 2020), there are no apparent reasons for the differences between the ‘GA2018’ and ‘GA PACCSAP’ return wind speeds and the outcomes of this assessment. There are no discernible differences in TCRM inputs. The only apparent differences are that the TCRM has been updated since the GA work was completed, and this wind hazard assessment is based on the most recent IBTrACS data. Rigorous sensitivity testing of TCRM inputs was conducted, included suggestions by GA. As discussed in Sections 3 and 4, these parameters included domain size, number of simulated years, and the influence of Cyclone Gita and Harold in 2018 and 2020, in the event that it skewed the storm statistics in recent years. None of these parameters had a significant influence on the consistency of results.

6. Directionality

The local directionality was found to be relatively consistent for all incident wind directions with a slight bias to the south-west quadrant. Preliminary findings indicate that the directional design gust wind speed would be reduced compared with the omni-directional value by about a factor of at least 0.8 for a 100-year return period event. Considering the directional results for a 500-year return period event, the preliminary findings indicated that the directional design gust wind speed could be reduced by factor of at least 0.9. This agrees with the discussion by Holmes (2020) in regard to the derivation of the probabilistic basis for the directional multipliers of AS/NZS 1170.2 for cyclonic regions.

For a reduction factor of approximately 0.8, this would result in about a 35% reduction in wind loading and the associated benefit to the storm surge estimate if designing to account for directionality.

7. Conclusions

A probabilistic wind hazard assessment was undertaken using an unaltered version of TCRM. Rigorous sensitivity testing of input parameters was conducted, with key insights being that simulations should be run for a minimum of 10,000 years, simulation domain size for the South Pacific Ocean region did not have a major influence and that the Kepert (2001) boundary layer model is the most conservative.

Using extreme value analysis and combining the site multipliers, return wind gust speeds were determined for various return periods. The outcomes of the wind hazard assessment were benchmarked against published data by GA and through direct discussions with GA. A significant variation in return wind speed is evident between various publications for the region.

A high-level review of wind directionality was undertaken. Preliminary findings indicated that design wind speeds could be reduced by a significant factor when designing for directionality, particularly for the lower return periods.

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