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A Roadmap for Studying Extreme Winds in Pacific Islands: Statistics, Design Wind Speed Estimates, Challenges

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ABSTRACT

The study outlines a plan to develop an interactive product that will be embedded in an online platform, called CliDEsc (NIWA), to analyse gust and mean wind speed records of meteorological stations in the Pacific Islands (PI) countries. The primary aim of this project is to improve the resilience of PI to extreme weather through accurate estimates of design wind speeds and analyses of tropical cyclones (TC) records. Historical wind records from all PI are currently uploaded on a climate data base. The proposed open-source product acquires these data and conducts various analyses. Users can utilise the results of these analyses for various wind engineering and energy applications. The challenges associated with the short-term observed PI TC as well as possible effects of climate change on frequency and intensity of TC and consequently on design wind speeds are discussed here.

1. Introduction

"In the Pacific there are few places to hide from the extremes of nature. Almost everywhere in the Pacific is exposed to sea, weather and geology: where people live, and where their food, transport and businesses are located" (NIWA, 2015).

Out of the top 30 countries in the world with the highest average annual losses due to natural hazards as a percentage of gross domestic product (GDP), 10 countries are in the Pacific (World Bank, 2018). Seventy-five per cent of disasters are hydro-meteorological related, with tropical cyclones (TC) posing the highest threat and costs in the region (NIWA, 2015). Over US$3 billion of losses and damages due to TC and earthquakes have been estimated in Pacific Islands (PI) since 1950 (World Bank, 2018).

The magnitude of these losses is driven by high population increases and rapid urbanisation in all PI countries. The total population of the Pacific has tripled since 1960, and the urban population has increased more than five times (NIWA, 2015). In addition, geographical remoteness and isolation, dispersion across a vast ocean, and the degradation of natural resources further contribute to the vulnerability of PI to hazards and climate change impacts. Despite these challenges, it is possible to improve the resilience of PI to extreme winds and TC. Design of wind-resistant buildings is essential to minimise and mitigate the damage and losses of extreme winds. The first requirement for designing wind-resistant structures is the accurate assessment of the maximum wind speeds that a structure is likely to experience in its design lifetime.

NIWA is developing risk-based information to assist developing tools to provide information required for infrastructure design. CliDEsc, a web-based tool allowing end users to request data and products to be generated from a range of environmental observations and variables, was developed by NIWA in consultation with National Meteorological and Hydrological Services in the Pacific region. Currently, there are various analysis products on CliDEsc for different climate and environment variables, such as drought indices, rainfall accumulations, and fire weather indices among others. The current research aims to develop another CliDEsc product to comprehensively analyse extreme winds and TC and to estimate design wind speeds at each station location. Lastly, after analysing all PI stations, the possibility of publishing a wind-loading standard for this region will be considered.

2. Methodology and Data

The methodology and steps undertaken in this study are schematically shown in Figure 1. Data, mostly available after year 2000, from Automatic Weather Stations (AWS) across the PI countries are uploaded on CliDE, a climate database developed by the Australian Bureau of Meteorology. CliDEsc provides SQL access to CliDE, which enables the products to use the AWS data. The combined CliDE-CliDEsc web services platform is being further developed under the Australian Climate and Oceans Support Programme in the Pacific (COSPPac), a collaboration between the Australian and New Zealand Governments, the Secretariat of the Pacific Regional Environment Programme, (SPREP), and the National Meteorological and Hydrological Services of 14 Pacific programme partner countries.

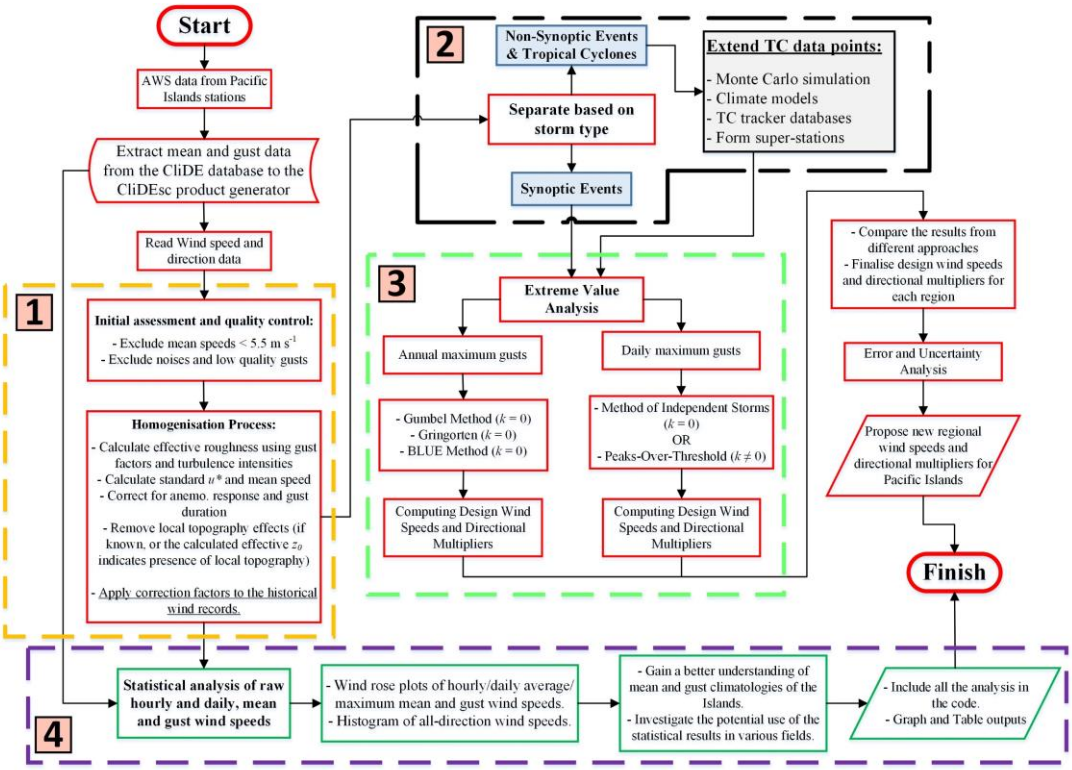


Figure 1. Schematic diagram of the steps undertaken in this study

Following extraction from CliDE, the data are subjected to a robust homogenisation algorithm (more details see (Safaei Pirooz et al, 2020; Turner et al, 2019)) to ensure all the data are converted to a common standard, i.e. 3-s gust duration, equivalent wind over open-country terrain (z_0 = 0.02 m), 10-m measurement height, and free of any local topography effect.

After that, the homogenised data are separated based on the storm-type, using the method recently proposed by Holmes et al. (2018), and employed by Safaei Pirooz et al. (2020) for New Zealand's historical wind records. A minimum of 20 – 30 years of data is required to conduct extreme value analysis (EVA) using maximum annual gust speeds (Cook, 1985). Having access to AWS data since 2000 provides the minimum required data point for synoptic events. However, over the last 20 years a few TC have been recorded at each single station, which makes the TC time series at a station location not suitable for EVA. The issues associated with the short-term TC records and possible solutions are discussed in Section 4.1.

Having homogenised and separated the wind data, EVA is performed on each type of the extreme events separately. Annual maximum gusts are used in Gumbel, Gringorten and Best Linear Unbiased Estimators (BLUE) (Lieblein, 1974) methods, assuming Type I extreme value distribution (i.e. $k = 0$). To increase the number of extreme events, the method of independent storms (MIS) (Cook, 1982) and/or peaks-over-thresholds (POT) (Holmes and Moriarty, 1999) are also used. Lastly, the results from all the EVA methods are assessed to obtain suitable design wind speeds and directional multipliers.

Lastly, in Stage 4 (Figure 1), to gain a better understanding of the wind climatology of each area, wind rose plots and histograms are computed. Generalised extreme value (GEV) and Weibull distributions are fitted to gust and mean wind speed data, respectively, and the parameters of distributions are also calculated, which are important for wind energy (mean wind speed), and several wind-engineering applications, such as environmental studies including pedestrian safety and comfort criteria.

3. Preliminary Results

This section presents only sample outputs of the product using data from an AWS station. Initially, the outputs of the homogenisation process (Figure 2) are average directional gust factor (GF), turbulence intensity (I_u), effective roughness (z_0), and mean and gust speed correction factors. The correction factors are used to convert the data to a common standard. GF, I_u and z_0 can be used in other applications, such as setting up wind tunnel experiments, etc. A tabularised version of Figure 2 is also an output of the product. Figure 3 shows wind rose plots and probability densities of maximum daily mean and gust wind speeds. GEV and Weibull fits and the distribution parameters are also shown in the figure. Lastly, the annual maximum gust and mean wind speeds along with the directions are shown in Figure 4, which will be used for EVA.

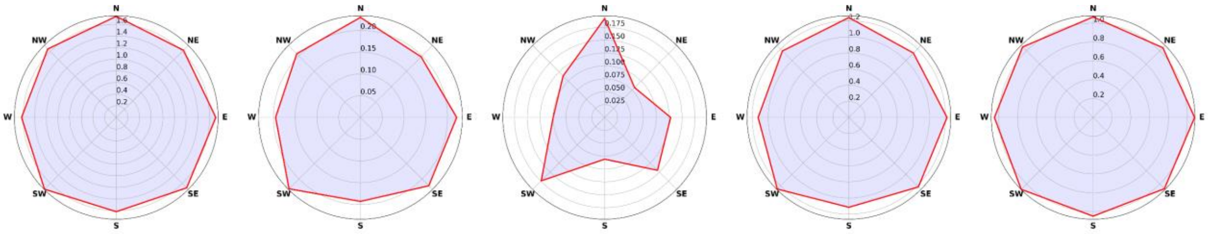
4. Challenges

4.1 Short Record of Tropical Cyclone Events

As mentioned above, unlike non-TC winds, TC have a small occurrence rate at a specific location. Thus, the number of TC recorded at each station after year 2000 is not sufficient for EVA. Therefore, to address this issue we consider a few different approaches to extend the TC time series.

Monte Carlo simulation is one approach to stochastically generate a large number of wind speed samples utilising probability distributions of several key parameters based on historical records. Several researchers and wind-loading standards (Batts et al, 1980; Fang et al, 2020) have used this approach to extend the wind speed data series and estimate design wind speeds. To collect historical TC, apart from the station records, some other databases that track TC, such as the Asia-Pacific Data-Research Centre (http://apdrc.soest.hawaii.edu/), or climate models can be used.

An alternative approach is to combine the wind data recorded at several stations and form “superstations” (Peterka and Shahid, 1998; Simiu, 2011). This approach increases the sizes of the samples, which consequently provides better estimations of extreme values. However, in forming superstations, it is crucial to consider the following points (Simiu, 2011): (1) its component stations must be located in a comparable wind climate zone in meteorological and micrometeorological terms; (2) the data of stations should be independent; (3) a station can only be part of one superstation.



(a) **(b)** **(c)** **(d)** **(e)**

Figure 2. Average directional: a) gust factor; b) turbulence intensity; c) effective roughness, d) mean and e) gust correction factors, for the considered station.

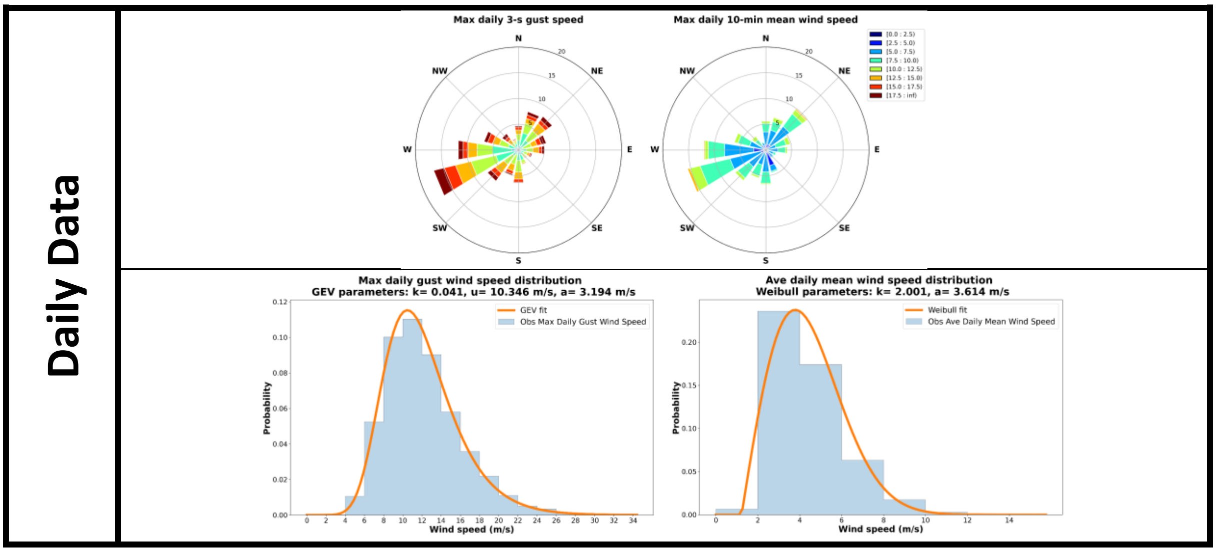


Figure 3. Wind rose plots and probability densities of maximum daily gust and mean wind speeds. GEV and Weibull fits to gust and mean speeds, respectively, are also shown.

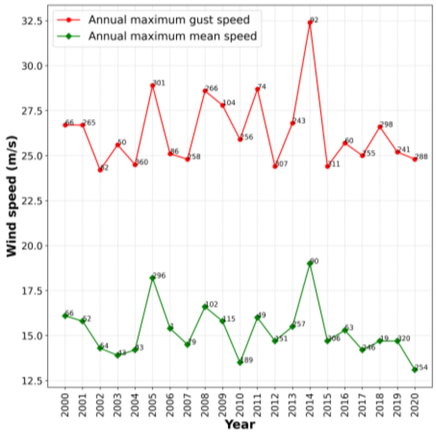


Figure 4. Annual maximum gust and mean wind speeds along with the directions of the maxima (labels next to the data points).

4.2 Possible Effects of Climate Change

The evaluation of the future effects of climate change on extreme weather, particularly TC and gust wind speeds, is challenging, due to the uncertainties associated with prediction of the speed and direction of climate change, and especially at local scales. We will need to assess the trends in both synoptic (i.e. convective) maximum gust wind speeds and TC, and how they might influence design wind speeds values for different return periods to ensure the safety and reliability of future structures.

Several recent studies have studied the trends in near-surface mean and gust wind speeds. Comprehensive reviews on mean and gust wind speeds trends are provided in (McVicar et al, 2012) and (Azorin-Molina et al, 2016; Safaei Pirooz et al, 2019b), respectively. Several of these studies have shown a declining or insignificant trend in the frequency and magnitude of mean and gust wind speeds, the phenomenon was called "stilling". However, there are some countries in which positive trends have been observed. Considering the dependency of trends on the location, it is essential to analyse the trends in PI extremes to gain a better understanding of the gust climatology of the region.

In the case of TC, there are several parameters that need to be considered, including frequency, magnitude and location/track of TC. Some studies have demonstrated that hurricanes and TC are getting stronger (Emanuel, 2020; Kossin et al, 2020) and climate change has already affected the global spatial distribution of TC (Murakami et al, 2020). Limited length of observed TC data, and often poor quality of the available data, along with the influence of multidecadal internal variability have made the detection of trends in TC challenging (Emanuel, 2020; Murakami et al, 2020). As can be seen in Figure 5a (Knutson et al, 2020), the TC trends depend on the location. Figure 5b (Rafter et al, 2019) also depicts that all the climate models have predicted reducing trend in the frequency of TC in the southern hemisphere. It is noteworthy that besides frequency and magnitude of TC, some studies (Knutson et al, 2020; Wang and Toumi, 2021) demonstrated poleward migrations of TC. All these changes and uncertainties in the location, magnitude and frequency of TC highlight a need for accurate evaluation of TC records and climate data to improve the potential for these changes to be implemented in the estimations of design wind speeds.

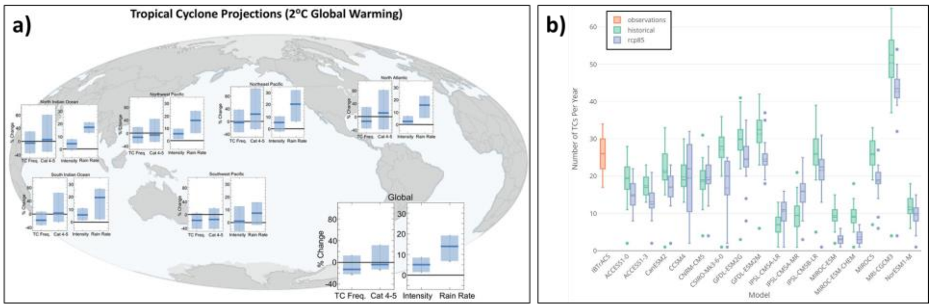


Figure 5. a) TC projections for a 2°C global warming (Knutson et al, 2020); b) number pf TC per year in the southern hemisphere detected from observation (orange) and different climate models (green: historical 1970-2000; blue: future 2070-2100) (Rafter et al, 2019).

4.3 Topography Effects on Wind Speed

Most PI countries have complex terrain, which not only influence the historical records but also can significantly increase the effects of extreme winds and TC by increasing near-surface wind speeds that consequently result in larger wind loads on structures. If the local topography is a simple, isolated two- or three-dimensional hill, wind-loading standards, such as (AS/NZS 1170.2, 2011), can be used to estimate the wind speed-ups. However, it has been demonstrated (Flay et al, 2019; Safaei Pirooz and Flay, 2018) that standards perform poorly in the prediction of speed-ups in real complex terrain and multiple-hill situations. Therefore, in this study, where the wind records are affected by complex terrain, numerical simulations can be employed to estimate accurate wind speed-up effects.

4. Conclusions

The paper summarised the structure of an interactive online product being developed at NIWA to analyse extreme winds and TC as well as mean wind speeds across the Pacific Island countries. The product takes AWS data as inputs and produces homogenised time series, separates storm types, estimates design wind speeds and generates probability density and wind rose plots. The outputs are essential to support various wind engineering and infrastructure design requirements, and wind energy resource assessment. So far, the homogenisation and probability plot components of the code have been prepared, and more work in underway to complete the other sections of the product. Some challenges to this work, including limited length of observational TC, and climate change effects have been outlined, and will be investigated in more detail in subsequent work to find the best solutions.

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