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# Quantifying storm tide risk in Fiji due to climate variability and change

Kathleen L. McInnes [a,*], Kevin J.E. Walsh [b], Ron K. Hoeke [a], Julian G. O'Grady [a], Frank Colberg [a], Graeme D. Hubbert [c]

[a] CAWCR Centre for Australian Weather and Climate Research, CSIRO Marine and Atmospheric Research, Aspendale 3195, Australia
[b] School of Earth Sciences, University of Melbourne, Melbourne 3010, Australia
[c] Global Environmental Modelling Systems, Warrandyte, Vic 3113, Australia

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ABSTRACT

Extreme sea level events due to tropical cyclone storm surge combined with astronomical tide (storm tides) severely impact Pacific Island communities and these impacts are expected to increase with projected sea level rise. However, these sea level extremes are not well characterised by available tide gauge records owing to the low frequency of occurrence of tropical cyclones, the sparse array of tide gauges and the short time frame over which many gauges in this region have been operating. In this study, a combined statistical/dynamical method for estimating storm tide risk is presented. Tropical cyclones in the Fiji region over the period 1969–2007 are characterised in a statistical model that represents cyclone frequency, intensity and movement. The statistical model is then used to develop a population of "synthetic" cyclones that provide boundary conditions to a hydrodynamic storm surge and tidal model. This Monte-Carlo method is applied to the coasts of the Fiji archipelago. It is found that storm tide risk is higher on the northwest coasts of both the southern and northern main islands Viti Levu and Vanua Levu, respectively. Modelling suggests that there is a greater tendency for higher storm surges to occur on southwest Viti Levu under El Niño and La Niña years compared with average years, but elsewhere on Viti Levu and Vanua Levu, there is a tendency for slightly lower storm surges in La Niña years. Imposing perturbations to the cyclone statistical model that represent projected tropical cyclone changes in intensity and frequency for mid to late 21st Century, leads to storm tide return period curves that are steeper such that sea levels associated with return periods of 200 years or more become higher, those with return periods of 50 years and less become lower and the 1-in-100 year heights are little changed. Projected changes in sea level are found to make the largest contribution to increased extreme sea level risk.

## 1. Introduction

Extreme sea levels brought about by tropical cyclone storm surges pose a major threat for many South Pacific islands. For example, in Fiji, Cyclone Gavin in 1997 caused 18 deaths and a damage bill estimated at F$33.4 million 1997 dollars (FMS, 1998) (around $20.9 million US 1997 dollars) and caused extensive flooding of Labasa town, on the north coast of Vanua Levu island, after the storm surge breached sea walls (Terry, 2007).

Storm surges are caused by the inverse barometer effect (IBE) together with surface wind stresses acting over coastal seas, which produces wind setup (see for example, Pugh, 2004). The severity of the extreme sea levels arising from storm surges is also influenced by other variations in sea level that operate on time scales that vary from hours to years. These include wave breaking processes that lead to wave setup and run-up (Walsh et al., 2012) and sea level variations due to modes of climate variability (e.g. Church et al., 2006). Bathymetric depths over the adjacent coastal shelves also influence the severity of storm surges (Kennedy et al., 2012; Hoeke et al., 2013).

The extreme sea levels arising from storm surges are further modulated by astronomical tides, the combination of the two often referred to as a storm tide. A storm surge generally has significantly greater impact if it coincides with high astronomical tide. Astronomical tides vary not only on semi-diurnal or diurnal time-scales, but large variations in maximum tide height also can occur monthly (due to the spring-neap and lunar declination cycles) as well as annually due to semi-annual modulations in tide-producing forces (e.g. Merrifield et al., 2007, 2013). These variations are location-specific, but generally locations where diurnal tidal constituents are larger relative to semi-diurnal constituents, i.e. mixed semidiurnal (as at Fiji) and diurnal tidal locations, the highest tides are experienced around the solstices, while locations

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[*] Corresponding author.
*E-mail addresses:* kathleen.mcinnes@csiro.au (K.L. McInnes), kevin.walsh@unimelb.edu.au (K.J.E. Walsh), ron.hoeke@csiro.au (R.K. Hoeke), julian.ogrady@csiro.au (J.G. O'Grady), frank.colberg@csiro.au (F. Colberg), graeme.hubbert@gems-aus.com (G.D. Hubbert).

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with more strictly semidiurnal tides tend to produce the highest spring tides around the equinoxes (Chowdhury et al., 2007; Merrifield et al., 2013). These semi-annual tidal variations may be on the order of 10 cm. Clearly, for locations where large semi-annual variations in tides occur, there is potential for tides to make larger contributions to extreme sea levels at certain times of the year. Longer term tidal variations (e.g. lunar nodal and perigee cycles; see for example Haigh et al., 2011) are an order of magnitude smaller and not considered in the context of this study.

On longer time scales, the most dominant mode of climate variability in the Pacific is the El Niño Southern Oscillation (ENSO) phenomenon. The phases of ENSO may be characterised by the Southern Oscillation Index (SOI), which is a measure of MSL pressure at Tahiti minus that at Darwin. During an El Niño event (SOI negative) sea levels are low in the western tropical Pacific and higher to the east while the opposite situation occurs in La Niña conditions (SOI positive) (Collins et al., 2010). Finally, global sea level rise, driven primarily by the thermal expansion of the oceans and a net decrease in terrestrial ice storage, both associated with anthropogenic global warming, will worsen the impacts of severe storm tide events in the future. While there is high confidence that globally averaged sea levels will increase, there is less certainty regarding the regional patterns of change. Global warming-induced changes to other factors such as the frequency and intensity of tropical cyclones and ENSO may also occur, although precisely how these factors will change is less certain than the prediction of future sea level rise (Walsh et al., 2012). Another less explored issue is the effect of climate variability as well as projected changes in tropical cyclone behaviour on storm surge risk. It is likely that the relatively short and sparsely located network of tide gauge records along many tropical cyclone-prone coastlines, which limits the direct observation of historical cyclone storm surges, has contributed to the limited analysis of tropical cyclone storm surge risk (e.g.Walsh et al., 2012; Hoeke et al., 2013).

In regions such as the Pacific, where a statistically robust analysis of storm tide risk from observations is not possible due to the limited spatial coverage and length of tide gauge observations, modelling approaches that simulate the storm tide response from a large population of plausible tropical cyclones over a coastline of interest provide an alternative method for estimating storm tide risk (e.g. Haigh et al., 2013). Such approaches have also been used to investigate scenarios of future tropical cyclone change (e.g. McInnes et al., 2003; Harper et al., 2009; Lin et al., 2012). For example, along the tropical east coast of Australia, Harper et al. (2009) showed that a 10% increase in tropical cyclone intensity, assumed to represent tropical cyclone intensity change in 2050, led to an increase in the 1-in-100 year storm tide level that was considerably smaller than the assumed 0.3 m sea level rise scenario considered. A recent study on hurricane storm surge change for New York City finds that changes in cyclones from two out of four global climate models (GCMs), scaled-up to realistic cyclone numbers via a synthetic cyclone approach, yields storm surge changes that are comparable to the projected change in sea level rise (Lin et al., 2012), while the remaining two show storm surge changes that are considerably smaller. To our knowledge, application of these and similar techniques in the South Pacific region has not been undertaken to date.

The purpose of this study is to use a combination of dynamical and statistical modelling to evaluate the storm tide risk in Fiji and investigate how climate variability and change influence storm surges. Preliminary results of this study were presented in McInnes et al. (2011). Over 90% of Fiji's population are coastal dwellers (Govt. of the Fiji Islands, 2005). In addition, there is considerable sugar cane industry centred around Lautoka and coastal tourism around Nadi on the northwest coast of Viti Levu island, all of which are potentially vulnerable to the coastal hazards arising from tropical cyclones.

The remainder of the paper is organised as follows. Section 2 describes the statistical representation of tropical cyclones under average present climate conditions as well as those associated with La Niña and El Niño. Modification of these relationships to represent future climate conditions is also discussed. Section 3 introduces the models and methods used to evaluate storm tide risk and discusses model performance. Section 4 assesses the variation in sea level in Fiji due to ENSO and summarises future projections for sea level rise in the Fiji region. Section 5 presents the main results of the study, followed in Section 6 by a discussion and conclusions.

## 2. Tropical cyclones

This section analyses observed tropical cyclone data over Fiji to provide the basis for stochastic sampling to generate a synthetic cyclone record. The basis for the perturbations to tropical cyclone intensity and frequency used here to represent future climate conditions is also discussed.

### 2.1. Cyclones under baseline conditions

Regional tropical cyclone information for the Southern Hemisphere, available for the post-satellite period from 1969 onwards, was obtained from the National Climate Centre of the Australian Bureau of Meteorology for the period 1969–2009. Tropical cyclones that feature in multiple agency areas (e.g. Fiji, New Zealand and Australia) have been manually combined in this dataset to provide a “best track”. These data contain the coordinates and central pressures of each cyclone throughout its life at mostly 6-hourly intervals. Using these, information about each cyclone's direction and speed of movement was derived. To maximize the number of cyclones considered for the statistical fitting of cyclone intensity, while still obtaining a cyclone record that is representative of the Fiji region, all cyclone tracks were considered that passed within a 6° radius of the coordinate (17°S 178.5°E), located midway between the two main islands of Fiji.

The frequency of occurrence of cyclones is needed to assign a representative time frame over which the synthetic cyclones could have been expected to occur. For the cyclone frequency estimates for the storm surge model, a radial limit of 1.5° is set (calculated as an area-weighted fraction of the incidence at 6° radius specified above) since cyclones whose paths fall outside this radius are not found to produce a storm surge along the coastlines of the two main islands (see next section). The cyclone track data were first linearly interpolated to hourly intervals to increase the temporal representation of the cyclone positions throughout their lifetime. Over the 39 cyclone seasons for which cyclone track information was available, ten cyclones with central pressure less than 990 hPa travelled within the 1.5° radius yielding an approximate rate of cyclone occurrence of 1 every 3.9 years. We also evaluated the rate of occurrence of cyclones during La Niña and El Niño seasons as defined by the state of the Niño-3.4 region as reported in Chand and Walsh (2009). In La Niña and El Niño seasons, these were found to be approximately once every 4.8 and 3.6 years respectively.

A characteristic of a tropical cyclone that is needed to model its wind and pressure field is its size as measured by the radius of maximum winds (RMW). As available cyclone data sets do not contain information on RMW, in this study this parameter was modelled using a bivariate log-linear regression based on Kossin et al. (2007):

$$\mathrm{RMW} = \exp(a_0 + a_1 x_1 + a_2 x_2) \tag{1}$$

where $x_1$ = latitude (in degrees and absolute value), $x_2$ = minimum central pressure (in hPa) and the coefficients $(a_0, a_1, a_2) = (-3.5115, 0.0264, 0.0068)$ (Kossin, pers. comm. October, 2010). Even though there is a large scatter in the RMW around the central estimate in the observations, this parameterization of RMW is appropriate for use in the stochastic model used here as it represents a central estimate of this quantity as a function of latitude and intensity, thus incorporating the observed tendency of more intense and lower latitude storms to have a smaller RMW (Vickery et al., 2000; Kimball and Mulekar, 2004).