

Application of a Synthetic Cyclone Method for Assessment of Tropical Cyclone Storm Tides in Samoa

Kathleen L. McInnes¹, Ron K. Hoeke¹, Kevin J.E. Walsh², and Julian G. O'Grady¹ and Graeme D. Hubbert³

¹CAWCR Centre for Australian Weather and Climate Research,
CSIRO Marine and Atmospheric Research,
Aspendale, 3195, Australia
kathleen.mcinnes@csiro.au
julian.ogrady@csiro.au
ron.hoeke@csiro.au

²School of Earth Sciences
University of Melbourne,
Melbourne, Australia, 3010
kevin.walsh@unimelb.edu.au

³Global Environmental Modelling Systems,
Warrandyte, Vic, Australia, 3113
graeme.hubbert@gems-aus.com
Corresponding author email: kathleen.mcinnes@csiro.au

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Abstract

Tropical cyclone-induced storm surges cause damaging impacts in coastal regions. The present study uses a stochastic cyclone modelling approach to evaluate the likelihoods of storm tides, the combination of storm surges and astronomical tides, for Samoa. Cyclones that occurred in the vicinity of Samoa from 1969-2009 are used to build a stochastic tropical cyclone data set and an analytic cyclone model and hydrodynamic model are used to model storm tides under average, La Niña and El Niño cyclone and sea level conditions for present climate conditions as well as cyclone and sea level conditions relevant for 2055 and storm tide return periods are estimated. We find that extreme storm tides exhibit relatively modest variation around the coastline of Samoa owing to the uniform width of the shelf surrounding the coastlines of two main islands of Savai'i and Upolu. The frequency of cyclones and hence storm tides during El Niño conditions is similar to the frequency for all seasons, but is considerably lower in La Niña conditions. For the future, tropical cyclones are assumed to undergo decreased frequency and increased intensity. This is found to lower the storm tide height for return periods less than 100 years and increase it for return periods greater than about 200 years. Sea-level rise is shown to have a larger influence on storm tides than future changes to tropical cyclones. Considering the aggregated probabilities of storm tides occurring at the national scale we find that the likelihood of a storm tide occurring that locally exceeds a 1-in-100 year level (i.e. an event with a 1% annual exceedence probability) has a 6% probability of occurring somewhere along the entire coastline of Samoa. Such information may be useful for those involved in coastal management and disaster response for which there may be a need to consider the overall likelihood that a nation may have to respond to such a disaster.

Introduction

Tropical cyclone-induced storm surges are responsible for the most damaging impacts of tropical cyclones (TC)s in coastal regions (Knutson et al., 2010). Knowing the return periods of these events is therefore important to facilitate disaster planning and preparedness. While tide gauges potentially provide a fundamental data source for evaluating these return periods, the reality is that for many coastlines, including those of Pacific nations, the low density of tide gauges in a spatial sense (typically one per nation), together with the often short length of records, and relative infrequency of TCs prevents a reliable estimate of extreme sea level return periods (Walsh et al, 2012, McInnes et al, 2014). Therefore in this study we extend the use of statistical and numerical modelling techniques applied to Fiji in McInnes et al (2014) to evaluate storm tide likelihoods for Samoa. We select Samoa because it has experienced significant impacts from a number of TCs over recent decades.

Storm surges are caused by severe storms such as TCs whose low-pressure centres elevate the ocean surface (the inverse barometer effect) and whose winds drive the seas onshore (wind setup). Tide gauges measure the storm surge together with the astronomical tide levels. The combination of these two processes is referred to here as a storm tide. Breaking wave-induced contributions to extreme sea levels are considered in a companion study (Hoeke et al, 2015) using the stochastic cyclones from the present study.

Notable TCs to have affected Samoa in recent decades include TC Ofa in 1990, TC Val in 1991, TC Tui in 1998, TC Heta in 2004 and most recently TC Evan in 2012. In February 1990, TC Ofa killed seven people and caused damages estimated at US\$130 million (Ready and Woodcock, 1992). Anecdotal observations suggest it produced deep-water wave heights of around 7.5 m and a maximum water level of 1.6 m, which partially submerged the Apia Observatory to 0.5 m (Rearic, 1990; Carter, 1991). TC Val, in December of the following year, was more destructive due to the slow movement of the cyclone and caused 15 deaths, the loss of 95% of homes in Samoa and approximately US\$200 million damage (Gill, 1994; Solomon, 1994). More recently, cyclone Evan in December 2012 caused 14 deaths and around US\$207 million damages (Nelson, 2013).

Despite these significant historical TC impacts, little quantitative, spatially discrete, information on storm surges associated with TCs is currently available to Samoan agencies. Such current climate information (referred to as baseline conditions in this study) is essential to build the resilience of coastal communities to the impacts of storm tides. Also of relevance is the influence of climate variability such as the El Niño Southern Oscillation (ENSO) as well as future changes to cyclone frequency and intensity and sea level rise (SLR).

Efforts to evaluate return periods of TC-induced extreme sea levels in the South Pacific in general are hampered by a lack of observational data, which is necessary for a comprehensive analysis of extreme sea levels as well as for setting up and calibrating coastal ocean models. For example, in Samoa the single available tide gauge has been in operation since 1993. About nine TCs occur in the western tropical Pacific region each year, with far fewer impacting any particular island in this region such as Samoa (see next section). This means that a statistically robust analysis of TC-induced extreme sea levels based on the tide gauge observations is not possible.

This problem is overcome by using a technique that involves the stochastic modelling of synthetic cyclones together with hydrodynamic modelling of the sea level, similar to previous studies (McInnes et al. 2003, 2014; Haigh et al. 2013) to develop information on storm tide return periods at the scale of Samoa under average climate (baseline) conditions. The spatial resolution of the modelling performed in this study is too coarse to include the effects of wind-waves, an additional important contributor to extreme sea levels particularly in island settings (Hoeke et al, 2013). The inclusion of waves would require high resolution bathymetric data (at least two orders of magnitude higher than that currently available for the entire model region studied here) to underpin higher resolution model grids. Not only is the bathymetric data unavailable for the region studied here, the computing requirements would be prohibitive. However, the approach used here provides not only an important basis for understanding the storm tide contribution to extreme sea levels, it sets the foundation for more localized studies that incorporate the additional influence of waves (Hoeke et al, 2014; 2015). It also enables an investigation of the likelihood of extreme sea levels under La Niña, El Niño and future climate conditions that factor in changes to cyclone frequency, intensity and sea level rise.

The goal of this study is to develop spatial maps of sea levels associated with specific return periods. These spatial maps provide the storm tide level associated with a particular probability or return period. In addition to this, a novel aspect of this study is to also use the generated data to investigate the probability that such a level will be experienced in anywhere along the coast of Samoa. This information would be relevant where agencies are required to manage risk at the national rather than the local scale.

The remainder of the paper is organised as follows. Section 2 describes the statistical representation of TCs under present climate, La Niña, El Niño and future climate conditions. Section 3 describes the models and methods and discusses the model performance. Section 4 assesses the large-scale variability of mean sea level due to ENSO and summarises future projections of sea level rise in the Samoa region. Section 5 presents the main results of the study, followed in section 6 by a discussion and conclusions.

2 Tropical Cyclones

2.1 Cyclones under Baseline conditions

Regional TC 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 1969-2010. These data contain the coordinates and central pressures of each cyclone throughout its life at 6-hourly intervals. From this was derived information about each cyclone's direction and speed of movement. 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 Samoa region, all cyclone tracks were considered that passed within an 8° radius of the coordinate (13.5°S, 187.5°E) located midway between the two main islands of Samoa. The cyclone track data were linearly interpolated to hourly intervals to increase the temporal representation of the cyclone positions throughout their lifetime and ensure that cyclones that passed through the area of interest were not missed in the selection process.

For the hydrodynamic modelling the stochastically-generated cyclone paths were constrained to travel within 2° of the coordinate (13.5°S 187.5°E). This is because cyclones whose paths fall outside this radius were found to not produce a storm surge along the coastlines of the two main islands (see next section). Over the 42-cyclone seasons for which cyclone track information was available, six cyclones with central pressure less than 885 hPa travelled within the 2° radius of Samoa yielding an approximate rate of cyclone occurrence of 1 every 7 years. La Niña and El Niño seasons were defined by the state of the Oceanic Niño Index (i.e. warm and cold episodes are defined when 3-month running means of SST anomalies are +/- 0.5°C over the Niño 3.4 region that spans 5°N-5°S, 120°-170°W; see also Chand and Walsh, 2009). The rates of occurrence of cyclones during La Niña and El Niño seasons were found to be approximately once every 14 and 7 years respectively.

A characteristic of a TC that is needed to model its wind and pressure field is its size as measured by the radius of maximum winds (RMW). Since the available cyclone data sets in this region do not contain information on RMW, we used a bivariate log-linear regression based on Kossin et al. (2007) to estimate RMW:

$$\text{RMW} = \exp(a_0 + a_1x_1 + a_2x_2) \quad (1)$$

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 RMW 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).

Distributions of cyclone forward speed (Figure 2a), direction of movement (Figure 2b) and month of occurrence were developed for cyclones during all years, as well as for La Niña years and El Niño years. The cyclone direction and speed distributions indicate that cyclones approach Samoa most commonly from the northwest with a smaller number originating from the northeast (Figures 2a and b). During El Niño (La Niña) seasons, cyclones originate more from the north (west). Cyclone speeds also show interannual variability with lower speeds during El Niño and larger speeds during La Niña. Distributions for cyclone latitude and longitude (Figures 2c and d) reveal that cyclones during La Niña seasons tend to occur further south and west than those during El Niño seasons. The cyclone monthly occurrence was used to randomly select a cyclone month to which a random day of commencement of the cyclone track could be assigned so that astronomical tide forcing could be applied to the hydrodynamic simulations.

For TC intensity, the Generalised Pareto Distribution (GPD) (e.g. Coles, 2001) was employed. As an extreme value distribution, the GPD is appropriate for representing TC intensity, either as measured by central pressure or wind speed. The GPD is bounded in the sense that at extreme values the cumulative probability distribution asymptotes to 1. This has particular advantages for the representation of TC intensities, as theory suggests that there is a maximum TC intensity that could occur in a particular climate, beyond which there would be insufficient energy in the climate system to produce stronger storms (e.g. Emanuel, 1987). Therefore, the ability of the GPD to represent an upper bound of intensity as an intrinsic part of the distribution makes it more appropriate for this work than other extreme value distributions that have been employed to represent the observed distribution of TC intensities, such as the Gumbel distribution (Coles, 2001; McInnes et al. 2003). The cumulative distribution function (cdf) of the GPD is given by:

$$F(y) = 1 - \left(\frac{1 + \xi(y - u)}{\sigma} \right)^{-\frac{1}{\xi}} \quad (2)$$

where y is the central pressure deficit in hPa; ξ and σ are the shape and scale parameters and u is the threshold representing the pressure deficit. To model the cyclone intensity, cyclone central pressures that attained a pressure deficit of $u=25$ hPa compared to a climatological pressure of 1010 hPa while within an 8° radius of Samoa were selected and fitted to the GPD. The data were best described by a distribution with $\xi = -0.60 \pm 0.8$ and $\sigma = 46 \pm 40$. The resultant cyclone intensity cumulative probability curve is shown in Figure 3.

2.2 Future Climate Cyclones

Future changes to TC behaviour have been incorporated into the statistical models through changes to the parameters that describe the distribution of TC intensity. Based on the cdf of the GPD in Eq (2), the exceedance level (the probability E that an event will exceed magnitude y) is given by

$$E(y) = 1 - F(y) = \left(1 + \frac{\xi(y - u)}{\sigma}\right)^{-\frac{1}{\xi}} \quad (3)$$

Here y is defined as the central storm pressure deficit less than 1010 hPa, and u is the pressure deficit threshold below which TCs are detected. As discussed in the previous section we choose u to be 25 hPa here, so only cyclones with central pressures of less than 985 hPa are analysed. As described above, σ and ξ are shape and scale parameters of the GPD distribution. The return period in years is given by

$$R(y) = \frac{1}{n} \left(1 + \frac{\xi(y - u)}{\sigma}\right)^{\frac{1}{\xi}} \quad (4)$$

where n is the number of cyclones per year. This was determined from observations to be 0.43 for cyclones with central pressures less than 985 hPa that have travelled within 8° radius of Samoa, over the period 1969-2007. To construct similar curves for a changed climate, we first note that the upper bound of pressure deficit below 1010 hPa of the GPD distribution (e.g. Coles 2001) is given by

$$pd_{max} = u - \sigma_0 / \xi_0 \quad (5)$$

where the subscript zero refers to current climate conditions. For the values of the shape parameters used in Figure 4, we have $pd_{max} = 25 + 76.72 = 101.7$ hPa pressure deficit for the maximum intensity in the current climate. This corresponds to a storm central pressure of about 910 hPa.

In a warmer world, here taken to be the climate the second half of this century, an increase in intensity of cyclones in the South Pacific as measured by an increase in maximum wind speeds of 10% is here assumed, based on theory and numerical simulation results (Walsh et al., 2012). To convert this to a pressure deficit increase, we use the wind-pressure relationship of Courtney and Knaff (2009). Thus the new maximum pressure deficit in a warmer climate becomes

$$pd_{max\ cc} = u - \sigma_{cc}/\xi_{cc} = 20 + 90.69 + p_{inc} \quad (6)$$

where p_{inc} is the increase in maximum pressure deficit due to climate change and the “cc” subscript refers to changed GPD parameters under a changed climate. We also assume the same percentage increase in the mean intensity of the storm as in the maximum intensity. This assumption is supported by Emanuel (2000), who found that due to the linearity of the cumulative distribution functions of observed TC intensities, any increase in percentage maximum tropical cyclone intensity in a warmer world would be matched by a similar percentage increase in mean TC intensity.

The mean pressure deficit under climate change for the GPD is

$$\bar{y}_{cc} = \mu + \frac{\sigma_{cc}}{(1-\xi_{cc})} = u + \frac{\sigma_o}{(1-\xi_o)} + p_{incmean} \quad (7)$$

where $p_{incmean}$ is the change in mean cyclone central pressures. Using this equation and the above equation for $pd_{max\ cc}$, we can calculate values of the shape and scale parameters under climate change conditions. For a 10% increase in wind speed, the mean and maximum pressure deficit change is 8 and 12 hPa respectively and the modified parameters σ_{cc} and ξ_{cc} are 63.147 and -0.7117 respectively.

In addition to increased wind speeds, climate models suggest a substantial decrease in the total number of storms in this region. Following the summary contained in Walsh et al (2012), we here assume a decrease in numbers of 25%. This is incorporated into the return period estimates simply by decreasing the value of n , the number of events per year, to a climate change value n_{cc} :

$$R_{yr\ cc}(y) = \frac{1}{n_{cc}} \left(1 + \frac{\xi(y-u)}{\sigma} \right)^{1/\xi} \quad (8)$$

Assuming a decrease in total storm numbers of 25%, then $n_{cc} = n/1.25$.

Other factors that may act to change TC return periods include changes in regions of formation or changes in the characteristics of ENSO, which affect TC numbers in this region. At present however, there is insufficient information to quantify these changes (Walsh et al. 2012) and so we elect to keep the cyclone tracks unchanged. The probability curves for cyclone intensity calculated for a warmer world are shown in Figure 3 and represent conditions towards the end of the century.

2.3 Synthetic Cyclone Construction

A population of synthetic cyclones was developed for Samoa based on the smoothed empirical distributions for cyclone direction, speed of movement and cyclone position for all cyclone seasons and also for La Niña and El Niño seasons, as shown in Figure 2. Cyclone intensity for present climate conditions (including La Niña and El Niño) was sampled from the GPD distribution for current climate conditions while those for the two future scenarios considered were sampled from the distributions representing a 10% increase in cyclone intensity. TC numbers were assumed to decrease by 25%. As it was desirable to investigate storm tide return periods up to 1000 years, and cyclones were found to occur around once every seven years within a 2° radius of Samoa, 3000 events (representing nine to twelve thousand years) ensured that the ranked levels at the 1000-year period varied smoothly and were well modelled by extreme value distributions.

To generate a time varying spatial field of 10-m wind and mean sea level pressure to provide forcing for the hydrodynamic model, the analytical cyclone model of Holland et al. (1980) using the improved wind-pressure relationship from Holland (2008) was implemented in a similar manner as described in Hubbert et al. (1991). Cyclone intensity is represented by the cyclone's central pressure relative to the background atmospheric pressure, while the size of the cyclone is given by the radius of maximum winds. The initial positions were constrained to fall within 2° radius of Samoa and the sampled speed and bearing were used to construct a cyclone track by calculating the cyclone's position both forward and back in time across the computational grid of the hydrodynamic model.

3 Model Setup and Performance

3.1 Hydrodynamic Model

The hydrodynamic model used in this study is the depth-averaged shallow water equations model GCOM2D, the mathematical formulation of which is described in Hubbert and McInnes (1999). The model was set up over the region shown in Figure 1 at 1 km resolution. Topographic and bathymetric data defining the region were obtained from General Bathymetric Chart of the Oceans (GEBCO) data on a global 30 arc-second grid available at <http://www.gebco.net>, which uses the 90 m Shuttle Radar Topography Mission data (available at <http://srtm.csi.cgiar.org/>) over land. Tide heights on the lateral boundaries of the hydrodynamic model were predicted using the tidal amplitudes and phases of the eight major tidal constituents (M2, N2, S2, K2, O1, K1, P1, Q1) obtained from a global tidal model (Le Provost et al., 1995).

Meteorological forcing is provided through the application of 10 m winds and mean sea level pressure. To assess hydrodynamic model performance and the use of the Holland vortex model, meteorological data is obtained from the National Centre for Atmospheric Research (NCEP) Climate Forecast System Reanalyses (CFSR; Saha et al., 2010), which are available globally at a horizontal resolution of ~38 km and hourly temporal resolution for selected historical cyclone events. For the purposes of establishing storm tide return periods under current and future climate conditions, wind and pressure fields are generated under TC conditions using the Holland vortex model as described in section 2.

3.2 Model Performance

The performance of the models selected for use in this study has been discussed in detail in McInnes et al. (2014). For Samoa the tracks of historical cyclones since 1990 that have travelled close to Samoa are shown in Figure 4. The two most significant cyclones in terms of coastal impacts were TCs Ofa and Val. However, both of these occurred prior to the installation of the tide gauge in Apia Harbour in 1993 and so no direct observations are available. TC Heta, similar to TC Ofa travelled on a north to south path well to the west of Savai'i. Because of its distance from the coastline of Apia it is less appropriate for modelling with a Holland vortex as the winds that would have affected Apia would have been in the far field of the cyclone centre, in a region not well captured by the cyclone model used in the present study. On the other hand TC Tui, although a relatively weak cyclone, travelled from the northwest to southeast on a path that passed between Upolo and Savai'i thus producing onshore winds at Apia as the cyclone approached the islands. The official TC Evan track was not available at the time the modelling was undertaken for this study and so although its track is shown in Figure 4 it was not modelled in this study. The impacts of this cyclone were reported to be large, but mainly due to wind damage and rainfall flooding. This was supported by inspection of the de-tided sea level observations, which show non-tidal residuals to be small (not shown). The performance of the models used in this study is therefore investigated using TC Tui although the reader is referred to a more detailed investigation of model performance in the Fiji region in McInnes et al. (2014).

Three model simulations were performed with different combinations of forcing fields applied. The first incorporated tidal forcing only; the second and third used tide forcing together with two different sources of hourly surface pressure and wind forcing and the residual sea level was determined by subtracting the tide-only time series from that which also included meteorological forcing. The two sources of meteorological forcing that were used were those from CFSR and those generated by the Holland vortex. Figure 5 shows that prior to and following the peak of the cyclone when meteorological forcing is minimal, the modelled tides agree well with those measured. During the cyclone, however, the CFSR analyses do not resolve the detailed structure of the cyclone which leads

to an absence of positive sea level anomaly in the hydrodynamic model simulation during the time of minimum pressure and maximum winds. The Holland vortex, on the other hand, is better able to represent this detail leading to a modelled sea level response of 0.18 m, which is closer to the observed residual peak of 0.22m (Figure 5c). The peak is still underestimated however and possible reasons for the underestimation may be the absence of waves in the modelling, which could contribute to a further increase in sea levels at the tide gauge due to wave setup. This aspect is addressed in companion studies in which high resolution wave and hydrodynamic models are run over Apia (Hoeke et al. 2014, 2015).

3.3 Stochastically-modelled cyclones

Four sets of hydrodynamic simulations were undertaken, each set using wind and pressure fields generated by the Holland model for each member of the population of 3000 synthetic cyclone tracks. A date and time, weighted to the months of observed cyclone occurrence for Samoa and lying within the period 1980-2000 is assigned to the commencement of the cyclone so that time-varying tidal forcing could be applied to each simulation.

The first set of simulations represents cyclones over the observation period and therefore constitutes the ‘baseline’. The second and third sets use the cyclone paths and frequencies observed in El Niño and La Niña years respectively. The fourth set assumes a 10% increase to cyclone intensity and a 25% reduction to the overall frequency of cyclones, to represent the effect of future climate change.

The peak sea levels attained during each simulation are stored for later analysis. At each model grid point the set of ensemble peaks are ranked from highest to lowest and assigned a return period according to $R = N_{\text{yrs}}/r$, where R is the return period, $N_{\text{yrs}} = n$ is the total number of years represented by the ensemble of synthetic cyclones, given by the product of the number of ensemble members (i.e. 3000) and the average number of years between cyclone occurrences and r is the rank of the event. Finally, values are fitted to a GPD to facilitate comparison of results. A threshold (u) value of 0.59 m is used; this corresponding to the mean spring high tide level calculated from a harmonic analysis of hourly water level observations of the Apia tide gauge over the period 1997-2012. This value yields a stable shape parameter (ξ) relative to neighbouring values and retains on the order of 1700 modelled extremes for GPD fitting from the set of synthetic runs for all locations in this study.

Spatial storm tide maps provide information about the sea level height for a given return period at discrete locations across a domain of interest. By definition, the probability of a sea level height being exceeded in a particular year is the inverse of the return period, so the annual probability of a 1-in-100 year storm tide is 0.01. Another quantity that can be derived from the modelled events is the

probability, P_{ag} , that a particular return level event (e.g. a 1-in-100 year event) may be experienced at any point along the Samoan coastline. This is simply given by the number of synthetic events, N_c , that produced levels that exceeded the local return level of interest (e.g. the 1-in-100 year level) at a minimum of one point along the coastline, divided by the total number of years that are represented by the synthetic events. In other words, $P_{ag} = N_c/N_{yrs}$. To estimate these probabilities, a coastline dataset for Samoa was defined from the model grid containing 513 model grid points.

4 Sea-Level Variability and Change

In addition to variations in cyclone forcing, regional sea levels are also expected to vary due to ENSO variability (e.g. Zhang and Church, 2012) and future climate change (e.g. Yin et al. 2010; Timmerman et al. 2010; Church et al., 2014) and this will contribute to the total sea levels during storm tides. This section describes the characteristics of sea level variability on annual and interannual time-scales in Samoa and also provides recent projections of sea level rise for the region. The results presented in this section are combined with results from the synthetic cyclone modelling in section 5 to explore relative contributions to extreme sea levels from different sources.

4.1 Annual and Interannual Influences on Sea Level Extremes

As well as the short term contribution to extreme sea levels arising from TCs, regional sea levels also vary on seasonal and interannual time-scales due to variations in the ocean and atmospheric circulation. These contributions were evaluated from the sea level data from the Apia tide gauge, which has been in operation since 1993, using a method based on Merrifield et al. (2013), also described in McInnes et al. (2014). In this method, the hourly sea level data is detrended and astronomical tides are removed leaving tidal anomalies as a residual. These are low-pass filtered to remove high frequency variations in the sea levels and the resulting year-days (e.g. all firsts of July and so on) averaged across the record for all years, as well as separately for El Niño and La Niña periods defined as previously ($\pm 0.5^\circ\text{C}$ SST anomaly in the Niño-3.4 region).

The annual climatologies for highest daily tide at Apia show that highest annual water levels due to astronomical tides tend to occur near the summer equinox, near the end of December/beginning of January (Figure 6), when high tides of around 23 cm above mean higher high tide are likely to occur. In addition, there is a (non-tidal) seasonal variation, with mean sea-level approximately 3 cm higher in July than December. Annual variation in sea surface temperature is very small in the Samoa Islands (Australian Bureau of Meteorology and CSIRO, 2011), thus steric effects are likely very small and so this relatively small mean seasonal difference is most likely due to seasonal changes in Pacific (trade) wind fields. Other processes, such as ENSO, result in relatively much larger variations in sea level

with higher (lower) water levels at the Apia tide gauge during La Niña (El Niño) periods, particularly during the months of March to June, when ENSO associated deviations of ± 10 cm occurred (Figure 6), consistent with other studies (e.g. Becker et al . 2012). To contrast the differences in seasonal sea levels between the TC season and the remainder of the year, the historical average deviation of the seasonal variations from mean sea level for all years (“baseline”) and for La Niña and El Niño years during the periods November to April and May to October are summarised in Table 1.

4.2 Future Sea Level Rise

Regional projections of SLR for Samoa presented here were obtained from Australian Bureau of Meteorology and CSIRO (2011), which developed spatially varying SLR projections for the Pacific. These projections are available for the greenhouse gas emission scenarios B1, A1B and A2 for three time horizons centred on 2030, 2055 and 2090. To illustrate the effect of sea level rise versus future cyclone change on extreme sea levels, it is relatively arbitrary which SLR scenario is selected. We selected 2055 as the time horizon since this matched that for which the TC scenarios were valid and we used the upper (i.e. 95th percentile) SLR for the A1B scenario. The A1B scenario is a mid-range emissions scenario but we note that for 2055 there was little difference between it and the higher A2 scenario for the location of Samoa. The resulting value assumed for SLR was 0.3 m.

5 Results

5.1 Current Climate

Figure 7 presents the sea level heights associated with a 1-in-100 year and a 1-in-1000 year event. For the 1-in-100 year levels (Figure 7a) the heights vary around the coastline from about 0.7 to 1.1 m with the highest sea levels occurring at the western end of the island of Upolu. Storm tide heights for selected return periods and coastal locations are provided in Table 2. It is noteworthy that an earlier study by Carter (1987) also estimated the level of the 1-in-100 year storm tide at Apia to be 0.92 m, as also found in this study (see also Hoeke et al, 2014). A spatial pattern similar to the 1-in-100 year pattern is evident for the 1-in-1000 year heights that are shown in Figure 7b but the values are higher by 0.2-0.3 m.

Return period curves for selected locations are shown in Figure 8. The differences in height for a given return period for locations around the Samoan archipelago are relatively small. This is in contrast to the results shown in McInnes et al. (2014) for Fiji in which sea levels for a given return period on the northwest coast were approximately twice as high as those at other locations. The reason for the difference is likely due to the narrow and relatively uniform shelf width surrounding the coastline of Samoa compared to Fiji, which has a considerably wider shelf on its northwest side. It

should be noted that the curves relate to TC-induced storm tides only and due to the low frequency of TCs the storm tide values for shorter return periods (i.e. less than about 20 years) may be lower than water level return values due to the combination of tides with other weather phenomena unrelated to TCs. The combination of cyclone-induced storm surges with other causes of elevated sea levels will be the topic of a subsequent study.

We also examine the probability that a storm tide of a particular return period will be experienced somewhere along the Samoa coastline. Results for baseline conditions for Samoa are shown in Table 3. The results indicate, as expected, that the aggregated probability of a particular return period event occurring somewhere along the Samoan coastline is considerably higher than the probability of the return level being exceeded at any particular location. For a 1-in-100 year event, which by definition has a 1% probability of annual exceedence at any one location, there is a 6% chance of being exceeded somewhere along Samoa's coastline in any one year. Similarly, for a 1-in-1000 year event with local annual exceedence probability 0.1% by definition, the chance that a 1000-year extreme water level may occur somewhere along the Samoan coastline in any one year increases 10-fold. The increasing ratio of aggregated to local probability with return period likely reflects the larger footprint in terms of storm tide made by the lower probability, more severe TCs. The aggregated probability of exceedence may be relevant for those involved in planning or emergency response activities at the national scale rather than at a particular location along the coast.

5.2 The Role of ENSO

Figure 8 also shows the return period curves evaluated for El Niño and La Niña seasons. The curves evaluated for El Niño seasons suggest that there is little difference from the baseline in the likelihood of a storm tide during El Niño seasons; the return period curves lie within the 95% confidence intervals of the statistical fit evaluated for the baseline case. The likelihood of a storm tide is considerably lower during La Niña years and this relates to the much lower frequency of cyclones in the Samoa region during these years. For example, considering the storm tide height associated with the 1-in-100 year event under baseline conditions, the probability that this sea level height would be experienced in a La Niña year drops from 0.01 to about 0.005. Storm tide heights for selected return periods and coastal locations are provided in Table 2.

5.3 Future Climate

The effect of the changes in cyclone intensity and frequency are also illustrated in Figure 8 and Table 2 for the scenario of a 10% increase in TC intensity. Note that these curves have also had the SLR scenario added to them, which has the effect of displacing the baseline curve vertically along the axis thereby making the effect of the change more clearly visible with respect to the SLR-only scenario.

The impact of the changes in cyclones (i.e. increased intensity and reduced frequency) is to increase the steepness of the return period curves, leading to a slight lowering of storm tide heights at return periods less than about 50 years and increasing storm tide heights for return periods beyond about 200 years. There is little discernible difference in storm tide heights around the 100-year level and the differences between the future climate scenarios and the baseline values mostly lie within the 95% confidence limits of the statistical fit to the baseline values. This result was also found in McInnes et al. (2014) for Fiji. For return periods most commonly considered for planning purposes (i.e. 100 years or less), the effect of an increase in mean sea level will cause the largest changes to these levels.

6 Summary and Conclusions

This study has employed hydrodynamic modelling forced by stochastically-generated cyclones to estimate storm tide return periods around the coastlines of Upolu and Savai'i in Samoa. This approach allows for statistically meaningful investigation of spatially discrete storm tide likelihoods and provides insight into how storm tides are affected by changes in TC tracks associated with La Niña and El Niño, and how climate change may further modify storm tide levels.

Under baseline conditions, the main findings are that the storm tides for a particular return period shows some variation around the coastline, with the highest sea levels occurring at the western end of Upolu. This is somewhat different to the previously undertaken study for Fiji in which sea levels for a given return period exhibited much greater variation around the coast. The smaller variation around the Samoan coastline compared to Fiji is partially related to the relatively narrow but uniform shelf width in Samoa compared to the more variable shelf width around Fiji.

The influence of ENSO on storm tides was also investigated, through changes in the paths and frequencies of TCs and in terms of variations in ambient sea levels. It was found that the storm tides in El Niño seasons were similar to baseline conditions, due mainly to the similar rate of occurrence of cyclones between El Niño and baseline conditions. However, there was a marked reduction in the number of cyclones during La Niña and this led to lower sea levels associated with given return periods.

Under future climate conditions, the combination of an increase in intensity and a reduction of frequency of TCs was found to produce a steeper return period curve for storm tides with sea levels becoming several centimetres lower for return periods of around 50 years or less, little difference in heights for return periods of up to 200 years and increasingly larger storm tide values for return periods longer than 200 years. On the other hand SLR had a much larger overall effect by reducing the recurrence interval for all storm tides heights. The relatively modest change to return periods

arising from cyclone intensity and frequency changes compared to SLR found in this study is qualitatively similar to results reported in other studies (e.g. for the east coast of Queensland in Australia, Hardy et al, 2004), in which changes to modelled TC storm tides were discernible only for return periods considerably longer than 100 years.

This study has focussed on TC-induced storm tides which undoubtedly are the primary cause of severe storm tides and therefore influence the tail of the storm tide distribution curve. However, other factors influence storm tides particularly over shorter return periods, typically 20 years or less. These include the effects of regional sea level variations, astronomical tides and other meteorological influences such as tropical depressions and trade winds. Efforts to combine the effects of these contributions with the synthetically modelled TC storm tides are planned in future work.

Dissipation of storm waves (e.g. wave breaking) can lead to considerably larger coastal sea levels and inundation through wave setup and runup, particularly along coasts bordered by narrow fringing reefs, where wave setup may be up to 30% of incident wave height (e.g. Vetter et al. 2010, Hoeke et al. 2013). Although the contribution to waves was not investigated in this study, it should be noted that the synthetic cyclone method presented here can be readily extended to investigate the wave contribution to sea levels. In companion studies, Hoeke et al. (2014, 2015) used high resolution wave and hydrodynamic models to investigate the additional contribution made by wave breaking to storm tide levels determined here for a small region surrounding the capitol, Apia. They find that for a selection of synthetic cyclones that produce 1-in -50 and 1-in-100 year storm tide levels, the additional contribution from wave setup varies from almost zero at sheltered parts of the coast, such as the deep water harbour where the tide gauge is located, to approximately 1 m on top of the 50 and 100 year levels of 0.80 and 0.92 m respectively due to the storm tide component alone. It should also be noted that waves from sources other than TCs may also pose a significant threat for some coastlines (Hoeke et al, 2013).

This study can support adaptation planning where information about extreme sea levels from TC storm tides is required. The study also provides guidance about the relative importance of ENSO variability, sea level rise and TC intensity and frequency change to storm tides.

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Table and Figure Captions

Table 1 The average deviation of low-pass filtered sea-level from annual mean sea level for the half year intervals indicated for all, El Niño and La Niña conditions, respectively. The range indicated in parenthesis is one standard deviation for the same respective period.

Table 2 Columns 1 and 2 are the return periods and associated probabilities of annual exceedance of the particular level. Column 3 represents the number of synthetic events from the 3000 member ensemble for which modelled maximum levels at any point that defined the coastline exceeded the respective return level height. Column 4 gives the associated annual probability that exceedance of the given return level will occur somewhere in Samoa and Column 5 represents the ratio of the two probabilities.

Table 3: Selected return period storm tide levels for 6 locations; column headers indicate 20, 50, 100, 200 and 500-year return period levels, respectively; row headers indicate scenarios discussed in the text.

Figure 1 Samoa region over which hydrodynamic simulations are carried out. Bathymetric contours are shown for depths of 100 m and 1000 m and relevant locations are marked.

Figure 2 Distributions of (a) cyclone direction (b) translation speed (c) crossing longitude (d) crossing latitude of observed cyclones in the Samoa region as well as those occurring during El Niño and La Niña years.

Figure 3 Cumulative probability distribution for cyclone central pressure for present climate (black line) and future decreases in storm numbers of 25% combined with future increases in maximum intensity of 10% (dashed line).

Figure 4 Cyclone tracks of TCs Ofa, Val, Tui, Heta and Evan, also showing the RMW as calculated using the Kossin model.

Figure 5 Time series for 15 days centred on TC Tui comparing observations and CFSR (a) pressure (b) wind speed and direction and (c) measured and modelled sea levels and sea level residuals.

Figure 6 The annual cycle of the highest daily water levels relative to the Mean Higher High Water (MHHW) due to tides and seasonal variations derived from the Apia tide gauge. The highest daily tides are smoothed with a 16-day low-pass filter; seasonal variations are smoothed with a 60-day low-pass filter. Smoothing is applied for easier interpretation. Dashed and dotted lines indicate values during La Niña and El Niño years respectively.

Figure 7 Modelled storm tide heights (m) corresponding with the 1-in-100 and 1-in-1000 year return period. (Note that only results are shown only for bathymetric depths shallower than 1000 m).

Figure 8 Return period curves for selected locations under the scenarios indicated in Table 3 with 95% confidence intervals for the baseline scenario indicated with dashed lines. The shaded band represents range of SLR scenarios for 2050 added to the storm tide return levels with the heavy red line representing the upper SLR scenario (0.3m). The dark red line represents the return levels from the combination of changes to tropical cyclones and upper SLR scenario.

Table 1: The average deviation of low-pass filtered sea-level from annual mean sea level for the half year intervals indicated for all, El Niño and La Niña conditions, respectively. The range indicated in parenthesis is one standard deviation for the same respective period.

	November – April	May - October
All	-0.009 (± 0.070)	0.006 (± 0.065)
La Niña	0.018 (± 0.054)	0.031 (± 0.031)
El Niño	-0.054 (± 0.074)	-0.028 (± 0.079)

Table 2: Columns 1 and 2 are the return periods and associated probabilities of annual exceedance of the particular level. Column 3 represents the number of synthetic events from the 3000 member ensemble in which the modelled maximum levels exceeded the respective return level height for at least one point along the coastline. Column 4 gives the associated annual probability that exceedance of the given return level will occur somewhere in Samoa and Column 5 represents the ratio of the two probabilities.

Return period	P	N_c	P_{ag}	P_{ag}/P
5000	0.0002	121	0.0058	29.0
2000	0.0005	184	0.0088	17.6
1000	0.0010	291	0.0139	13.9
500	0.0020	472	0.0225	11.3
400	0.0025	554	0.0264	10.6
300	0.0033	658	0.0313	9.4
200	0.0050	865	0.0412	8.2
100	0.0100	1299	0.0619	6.2
70	0.0143	1505	0.0717	5.0
50	0.0200	1660	0.0790	4.0











