IMPACT OF CLIMATE CHANGE, SEA-LEVEL RISE IN TONGATAPU, HA'APAI AND ITS EFFECT ON LIVELIHOOD.

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ABSTRACT[1]

This work will focus on Storm Surge in Tongatapu and Ha'apai island in the Kingdom of Tonga aiming on the impact of the climate change. Firstly, we simulated storm surge as well as inland flow caused by the cyclone Harold to evaluate Xbeach storm surge model for Tongatapu and Ha'apai and Rainfall-Runoff-Inundation model for Tongatapu only. The Xbeach model successfully simulated the storm surge in a part of the northern coast in Tongatapu, and in the west coast of Ha'apai island, consistent with disaster reports. Secondly, we simulated storm surge driven by climatological extreme wind in 50 year returning period in the past and future climate determined by d4PDF. We also consider the effect of sea level rise obtained from Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC). We found that the storm surge would decrease in the future due to decreasing extreme wind speed. 1.105-meter sea level rise in the future offset and caused 5cm increasing inundation by storm surge. This result suggests the increase of storm surge risk in the future.

Key words: Climate Change, Rainfall-runfall-inundation (RRI) Model, Moderate Resolution Imaging Spectroradiometer (MODIS), Coupled Model Intercomparison Project Phase 5 (CMIP5), Inundation.

INTRODUCTION

Climate change impact through sea level rise (SLR) and inundation due to prolong heavy rainfall and storm surge is a major threat to the Pacific Region including the Kingdom of Tonga (Ministry of Environment and Climate Change, 2010). Tongatapu and Ha'apai, both islands are flat low coral islands. Those islands are classified as tropical rainforest climate with a distinct warm period from December to April at a 32 degree celcius. However, this study will focus on a coastal protection measures for both islands, not only to overcome SLR and storm surge but also to balance vulnerability to climate risk for a safer country. Finally we would develop a long term sustainable actions for both islands. First, we predict how much climate change may affect the storm surge as well as SLR with affected sites according to wind directions and wind speed.

Tongatapu suffers from tropical cyclones and prolong heavy rainfall which causes the inundation and inland flooding. Tropical cyclone occurs ones during the wet seasons but as of now there are more than one cyclone that comes through the cyclone routine track for Tongatapu and Ha'apai. As for flooding situation, there are no river nor lake to cause this problem however, during cyclone and wet seasons (Ministry of Meteorology, 2020) flooding is witnessed thus due to prolong heavy rainfall. However, even though there are suggestions of implementations to monitor the impact of climate changes, they have been missing. Additionally, there are lack of funds to pursue further research for future preservations.

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THEORY AND METHODOLOGY

(i)STORM SURGE

To study the storm surge on the island coast, we employed a storm surge model, Xbeach (Roelvink et al., 2009, Deltares 2015). This model dynamically simulates water movement using a linear shallow water equations as follows

Equation 1-3: Momentum Equation

$$\frac{\partial n}{\partial t} + \frac{1}{Rcos\theta}\left[\frac{\partial P}{\partial \emptyset} + \frac{\partial Qcos(\theta)}{\partial \theta}\right] = 0,$$

$$\frac{\partial P}{\partial t} + \frac{1}{Rcos\theta}\frac{\partial n}{\partial \emptyset} = -fQ + \frac{\tau_s^{\emptyset} - \tau_b^{\emptyset}}{\rho_w} - \frac{h}{\rho_w Rcos\theta}\frac{\partial P}{\partial \emptyset},$$

$$\frac{\partial P}{\partial t} + \frac{gh}{R}\frac{\partial n}{\partial \emptyset} = -fP + \frac{\tau_s^{\emptyset} - \tau_b^{\emptyset}}{\rho_w} - \frac{h}{\rho_w R}\frac{\partial P}{\partial \emptyset},$$

Equation 4: Surface stress

$$\tau_s^i = \rho_a C_D |U| U_i$$

Equation 5: Wind drag coefficient

$$C_D = (1.29 - 0.024\, U_{10}) \times 10^{-3} \qquad U_{10} < \frac{8m}{s}$$

$$C_D = (0.581 + 0.063\, U_{10}) \times 10^{-3} \qquad U_{10} \geq \frac{8m}{s}$$

Equation 6: Bottom stress

$$\tau_s^i \rho_w = k|U|U_i$$

To compute storm surge on the island, horizontal resolutions of hundreds of meters are required. To save the computer resources, Xbeach model simulates via shallow water equation (SWE) **(Equation 1-3)**. To determine free surfaces and the momentum flux on both the latitude and longitude directions. The surface and bottom stress are computed by **Equation 3-5** (Sabunas, 2020)**.**

(ii)RAINFALL-RUNOFF-INUNDATION Model

To study inland inundation by prolong rainfall, we employed RRI model. **RRI model** (Sayama, 2017) is a 2-dimensional distributed hydrological model that can be used to simulate two features which are the rainfall runoff and the flood inundation separately. GSMaP, a satellite observed rainfall were used due to data limitation. The RRI model simulated discharge, inundation, and water level.

(iii)SEA LEVEL RISE

The impact of SLR is considered in addition to the storm surge wave height in the future climate. SROCC data is used in this study. As for **SROCC** (Portner, et al., 2019) it was very useful for this paper for it can investigate the maximum height of the sea water level in RCP 8.5 scenario at 2100. However, RCP 8.5 scenario it will examine the larger increase of temperature yet at the end of this 21st century. In addition, the SLR value is not fixed yet it has variability of uncertainty due to how things are computed.

DATA

(i) STORM SURGE

The topography and the bathymetry are determined by **Shuttle Radar Topography Mission** (SRTM) (Becjer, 2019) and **General Bathymetric Chart of the Ocean** (GEBCO) and set 200m so resolve the storm surge in the island coast. The simulation of storm surge model was conducted with climatological extreme wind speed of 50 years returning period derived by the database for Policy decision making of future climate change (**d4PDF**) (Nobuhito Mori, Tomoya Shimura, Kohei Yoshida, Roy Mizuda, Mikiko Fujita, Temur Khujanazarov, Eiichi Nakakita, 2019). A homogenous wind field of 8 steady directions were used however, this study has recommended that the 8 directions can be best describe the vulnerability for Tongatapu.

(ii) RRI MODEL

As for the RRI model, rainfall data during cyclone Harold from the 6th April 2020 to 11th were used for simulations using the RRI model. **Digital Elevation Model** (DEM) ((Mission, 2019)which was made from SRTM data within 3 arc-sec with a distance grid of 90m thus determine land elevated part. The hydro shed for Tonga is not included however, the grid interval for RRI (rainfall-runoff-inundation) was 100m but since there is no river here in Tongatapu the river depth and width were zero thus no infiltration occurred. As according to (National Emergency Management Office, 2020) inundation occurred during TC Harold thus lots of damages to the Kingdom of Tonga.

RESULT AND DISCUSSION

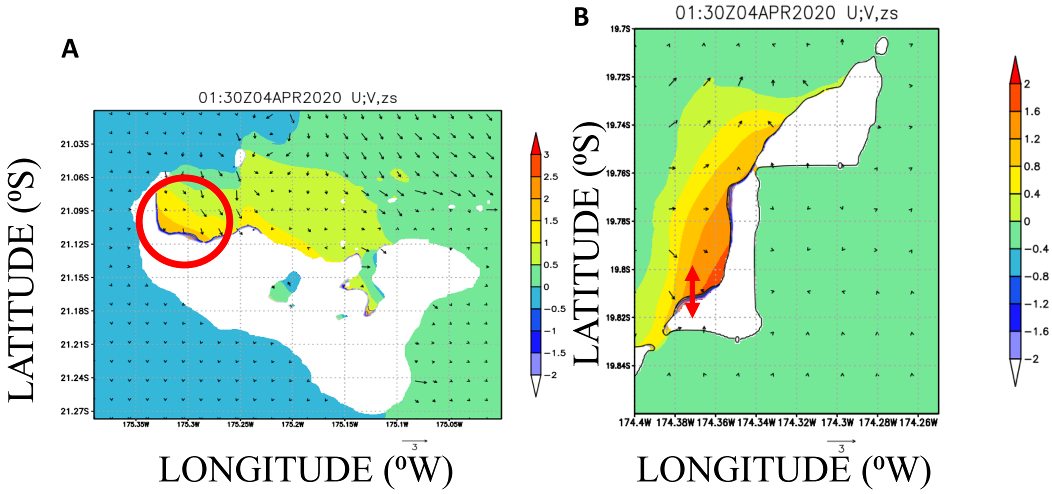

Figure 1: *In A, it describes a North-Westerly wind direction at 315º and B depict South-Westerly wind direction at 225º*

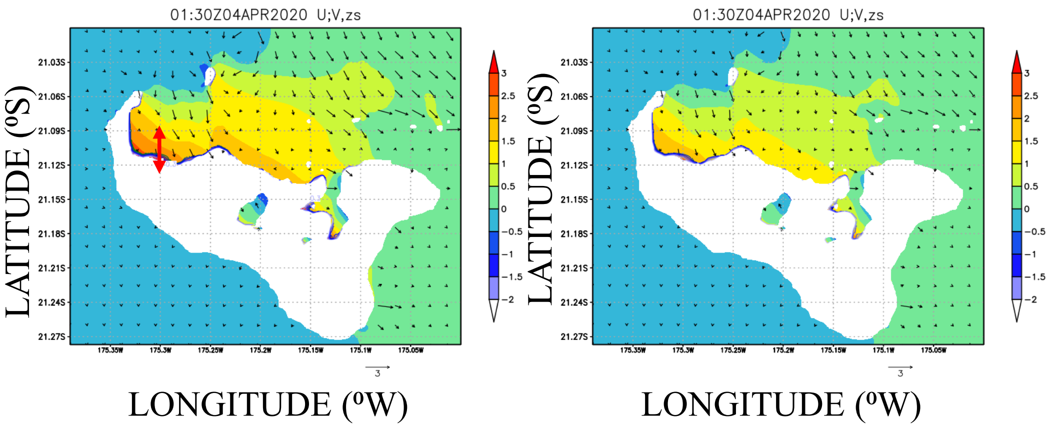

Figure 2: Past and Future Climate for Tongatapu.

During cyclone Harold, the GSMaP rainfall data within the 6th -11th of April were used to input and run RRI model to simulate the maximum inundation. In figure 1 A, it was obtained from a wind speed of

35m/s and a wind direction from the North-Westerly side which was the most severe storm surge damages compared to the other 7 wind direction analysis. In this finding, the storm surge area can be determined in a part of the northern side is the shallow area however, the blue contour lines indicated the area of storm surge occurred and Western side of Tongatapu indicated by the red circle. Color shading symbolize the water level accordingly to the parameter shown above. In **Figure 1 B,** the arrow indicated the cross-section of bed level according to **Figure 2** above as well as that in Tongatapu.

The red arrow shows the cross section shown in Figure.

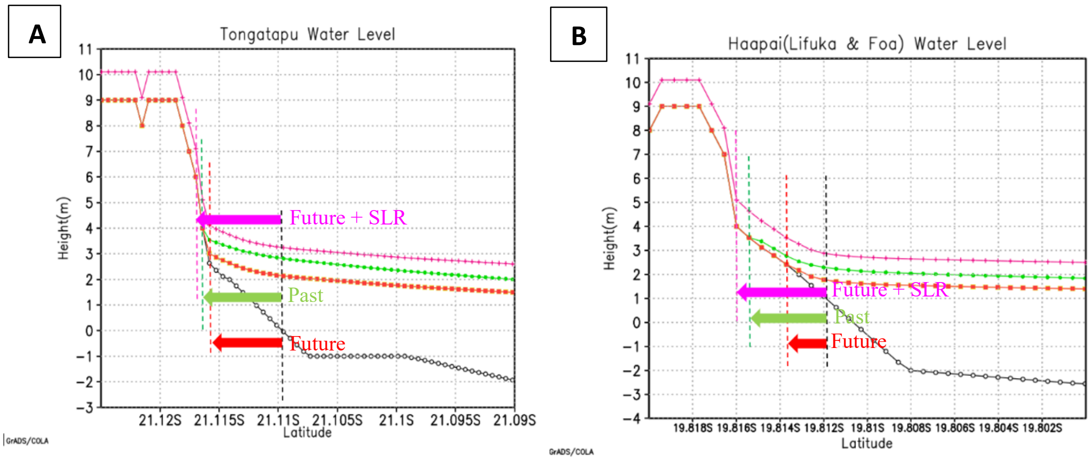

Figure 3: Water level analysis for Tongatapu and Ha'apai.

As for cyclone frequency, some argument agreed with the fact that the TC frequency will be decreasing such as, Dowdy (2014) referring to what he found in eastern Australia during satellite era, removing substantial effects of ENSO variation on TC incidence there will be a decrease in TC numbers. Tory et al., (2013) suggested that TC frequency will decrease globally according to the simulation on climate model warming scenarios (CMIP5) in which support the finding in d4PDF. Nash et al., (2015) stated in the 19th century record TC number will be decreasing. However, TC number will be decreasing as according to Merlis et al., (2016) with the use of global uniform-SST simulation stated that there will be an increase in TC intensity but decreasing in TC number. Moreover, Holland et al., (2014) has argued that TC intensity will be increasing in a proportion of category 4 and category 5 recently thus most increasing TC's are determined to be poleward migrate away from the equator. This TC trend shift will possibly decrease the number of TC occurrence in the Pacific region. However, the intensity of the cyclone won't decrease. Therefore, it is consistent that there will be a decrease in the number of tropical cyclone as well as the wind speed according to the d4PDF analysis done in this research with much support from previous studies mentioned above.

Where the bed level indicated it is the coastline (19.811^{o}). In **figure 3** above, red line indicates the future water level to be 19.81^{o} with a maximum height of 4m, green line is the past water level which is within 19.816^{o}-19.814^{o} with a maximum height of 3.5m. As for the pink line, it is the future sea level rise plus storm surge in the future generated from the Ha'apai Water Level graph. SLR is determined to be at a maximum height of 5m thus plotted at 19.816^{o}. As for Tongatapu, future water level 2.9m, past water level 3.8m and for SLR it will be 4m however, longitudinal ranges within 21.125^{o}.

Focusing on Ha'apai for it is considered worse case than Tongatapu according to **Figure 3 B,** according to the coastline which is 0m. As according to the arrow indicated with green it is with approximately 400m from the coastline towards the land it is where storm surge occurred. In the future water level, it is approximately 250m of inland storm surge towards the coastline. As for the Sea level rise and storm surge from the coastline it's with an aggregate of 530m entering the land area of Ha'apai. In the determination of heights for each water level, future with an aggregate of 2.5, past is approximately 3.5 and as for the SLR + Future Storm Surge it's an aggregate of 5m.

RECOMMENDATION & CONCLUSION

In this research, since things are new such as the idea of proposing storm surge investigation for Tongatapu and Ha'apai it is ***"highly recommended"*** that this study should consider by the Government of Tonga thus endorse a continuation process on this matter as according to the finding towards this study the government of Tonga should extremely take into account for storm surge did not occurred in the past thus experience storm surge recently and who knows that it will progressively deteriorated . Storm surge is an ongoing issue thus process occur in quite a long period of time. This needs to be addressed for it causes a lot of problem. In a way to tackle this concern, strengthening the knowledge on this issue is needed to put the best solution into it. There are models used to determine important information that contribute to the establishing of storm surge. At this state, there should be training endorse by the government in a way that related ministries can be aware of what is going on yet allow them to work together in compromising things for the better future for Tongatapu and Ha'apai. Enforcement of the government's bond with the communities that are vulnerable to storm surge especially those that are near coastal areas. Strengthening their knowledge on the characteristics of storm surge and implementing ways for them to minimize storm surge from occurring. However, the government should enforce this issue to save the future generation. To implement ways to overcome storm surge problem or to establish a long-term plan or a policy to address this issue. Finally, this should familiarize appropriate people who are practicing related field such as climate change however, scientifically this problem cannot be completely stop yet there may be ways to medicate this issue such as proposing an infrastructure such as levee, foreshore, or seawall to withstand the impact of storm surge.

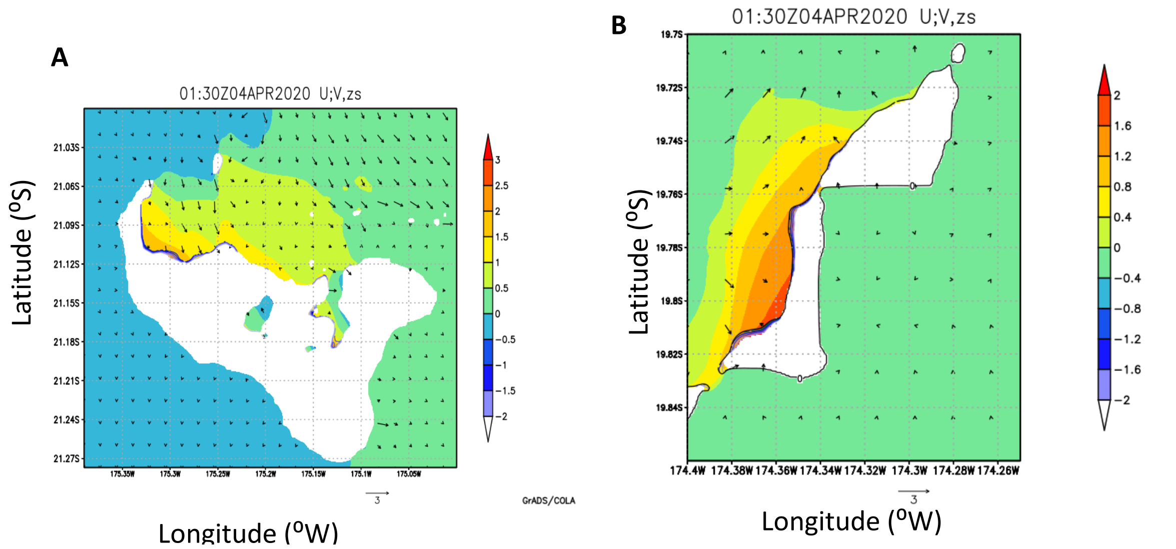

Figure 4: A is North-Westerly wind direction for Tonga (315⁰) B is the South-Westerly wind direction for Ha'apai (225⁰)

In conclusion, this study believed that if storm surge issue does not address it will seriously affect Tongatapu and Ha'apai in the future. As for Tonga the sever storm surge occur when the wind direction is from the North-Westerly wind (315⁰) and as for Ha'apai when the wind direction of a cyclone is from the South-Westerly direction (225⁰) storm surge occurred.

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REFERENCES

Becker, J. J., Sandwell, D. T., Smith, W. H. F., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls, S., Kim, S-H., Ladner, R., Marks, K., Nelson, S., Pharaoh, A., Trimmer, R., Von Rosenberg, J., Wallace, G. and Weatherall, P. (2009) Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS, *Marine Geodesy*,32:4,355 — 371

Deltares: XBeach Technical Reference, *Kingsday Release*, 139p, 2015.

Ministry of environment and climate change, National emergency management office, 2010. *Joint National Action Plan On Climate Change Adaptation and Disaster Risk Management,* Nuku'alofa:p. 88.

Ministry of Meteorological, E. I. D. M. E. C. C. a. C., 2016. *Tonga Climate Change Policy, A Resilient Tonga by 2035, p.30,* Nuku'alofa: SPREP.

Ministry of Meteorology, E. I. D. M. E. C. C. a. C., 2020. *Tonga's Second Nationally Determined Contribution, p. 101,* Nuku'alofa: Regional Pacific NDC HUB.

Nobuhito Mori, Tomoya Shimura, Kohei Yoshida, Roy Mizuda, Mikiko Fujita, Temur Khujanazarov, Eiichi Nakakita, 2019. Future changes in extreme storm surges based on meg-ensemble projection using 60-km resolution atmospheric global circulation model.. *COASTAL ENGINEERING JOURNAL,* Volume VOL 61, NO.3, 295-307, p. 14.

Roelvink, D. Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R. and Lescinski, J.: Modelling storm impacts on beaches, dunes and barrier islands, *Coastal Eng.*, 56(11-12), pp.1133–1152, 2009.

Sabunas, A., 2020. *Impact Assessment of Climate Change on Storm Surge and Sea Level Rise Around Viti Levu, Fiji,* p.14.: Frontiers in Climate.

Sayama, T., 2017. *Rainfall-Runoff-Inundation (RRI) Model, p.1.*

SROCC(2019). *Special Report on the Ocean and Cryosphere in a Changing Climate,* editors H. O. Portner, D. C. Roberts, V.Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. M. Weyer. SROCC.

Tonga, T. K. o., 2019. Third National Communication to the united nation framework convention on climate change, p.252 .

K.J.E. Walsh, S.J. Camargo, T.R Knutson, J. Kossin, T.-C. Lee, H. Murakami, C. Patricola. (2019). *Tropical Cyclone and Climate Change,* p. 11