Influence of Seasonality and ENSO on Hydrodynamic Drivers for a Fringing Coral Reef and Lagoon System

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Abstract

On reef mediated coastlines, both waves and tides make an important contribution to the often-complex hydrodynamic processes. This is particularly the case for coral reef fringed islands and atolls, where wave driven flows heavily influence water quality, flushing, sediment transport and other ecological processes.

In a previous paper we explored the hydrodynamics of a fringing reef system at Muri Lagoon on the south-eastern coast of Rarotonga, Cook Islands. Muri Lagoon is a complex and shallow lagoon that contains a network of reef-top islands (motu) and drains through a natural passage in the fringing reef at Avana Harbour. The lagoon has a range of water quality issues, mostly the result of terrestrial inputs from the adjacent catchments including increasing nutrient and sediment loads. Within the current paper we now extend the previous work to investigate the influence of seasonality and ENSO on key hydrodynamic drivers of the lagoon, and the indirect relation to water quality and ecological health.

The hydrodynamics of the lagoon have previously been shown to be dominated by wave-driven currents that are modulated by tidal fluctuations in water level as freeboard over the fringing reef edge. We now combine this background knowledge with analysis of a down-scaled 40-year wave climate hindcast, to understand seasonality of wave energy, and the inter-annual influence of ENSO. An analysis is also undertaken for mean level of the sea to understand if there are also seasonal or inter-annual influences on this hydrodynamic driver. In considering Muri as a case study for other similar lagoons around the Pacific region, we discuss the learnings that can be drawn from the work in a broader context.

Keywords: Coral reef, lagoon, hydrodynamics, seasonality, ENSO.

1. Introduction

On reef-mediated coastlines, both waves and tides make an important contribution to the often-complex hydrodynamic processes of the coastal systems [1] [2] [3]. This is particularly the case for coral reef fringed islands and atolls of the tropical Pacific, where wave-driven flows heavily influence water quality and flushing, sediment transport and other ecological processes within lagoon systems.

In a previous paper [4] we introduced a field investigation site, Muri Lagoon, and explored the hydrodynamics of the lagoon through presentation and analysis of a range of field data sets. Within the current paper we now extend this work to investigate the influence of seasonality and the El Niño-Southern Oscillation (ENSO) on key hydrodynamic drivers of the lagoon, and the indirect relation to water quality and ecological health. Section 2 of the paper provides an overview of key findings from the previous analysis of lagoon hydrodynamics, while the new analysis of climate-related influences is presented in Sections 3 and 4.

2. Background

2.1 Location

Muri Lagoon is located on the south-eastern coast of Rarotonga, a volcanic island in the southern group of the Cook Islands. The lagoon is a complex and shallow system, with a length of approximately 2.5 km and typical water depths ranging from 2 m in the main lagoon basin down to 0.5 m through parts of the lagoon channels. The lagoon is sheltered from the open ocean swell by a fringing reef, and four motu (islands) are situated within the lagoon, creating a network of flow channels. The lagoon system drains through the Avana Passage at the northern end, which is a deep natural passage formed through the fringing reef (Figure 1).

2.2 Hydrodynamic Investigations

A detailed field investigation was undertaken in 2018 to develop a contemporary understanding of the coastal and hydrodynamic processes of the system. Full details of the investigation are reported in [4] and [5]. The main field investigation comprised a network of monitoring stations established for the collection of hydrodynamic data, and included continuous recording of water levels, currents and waves at key locations around the lagoon (Table 1, Figure 1). Each monitoring station comprised a range of logging instruments as detailed in [4] and summarised in Table 1. Data sets were collected over a 16-week period from February to May 2018. Synchronous ocean water level data from the SeaFRAME tide gauge at Avatiu Port (Figure 1) on the north coast of Rarotonga was also obtained from the Bureau of Meteorology, as well as hindcast deepwater wave conditions from CAWCR's wave hindcast for the Pacific region [6].

Figure 1: (Left) Location of the Cook Islands, Rarotonga and Muri Lagoon; (Right) Arrangement of Monitoring Stations

Table 1 Measurements at each Monitoring Station

Measurement	**Monitoring Station ID**						
	A	B	C	D	E	F	G
Water Level	✓	✓	✓	✓	✓	✓	✓
Currents	✓	✓	✓	✓	✓	✓	
Water Temp.	✓	✓	✓	✓	✓	✓	✓
Waves		✓					✓

2.3 Summary of Lagoon Hydrodynamics

Data collected during the 16-week monitoring program was analysed to develop a robust understanding of the hydrodynamics of the lagoon. Only the key processes identified from the analysis are explained here for context, firstly related to water levels, and secondly related to currents and flows within the lagoon.

2.3.1 Lagoon Water Levels

Compared to the open ocean tides, water levels within the lagoon were found to:

- Have a superelevated mean water level, varying between 0.1 and 0.5 m above the ocean sea level.
- Have a slight phase lag in tides (15 – 25 mins), in particular at low tide;
- Have a reduced tidal amplitude (60-80% of full amplitude).

Further analysis determined that the lagoon water levels were strongly influenced by the ocean wave climate breaking on the fringing reef, such that wave energy was the primary driver for the lagoon water level setup or “pumping”. Figure 2 (top panel) shows a plot of nearshore wave energy flux and the recorded lagoon water level in the main lagoon basin (Monitoring Station B), covering a one-month subset of the recorded data. It can be seen in this figure that, in addition to tidal fluctuations, the lagoon water level has a non-tidal setup component (dark blue line) that is closely correlated to the wave energy on the fringing reef (orange line).

2.3.2 Lagoon Currents and Flushing

Currents within the lagoon were found to move from the south toward the north during most conditions, with flows eventually draining back to the open ocean through Avana passage. Analysis of lagoon water levels showed that a corresponding south-to-north hydraulic gradient through the system was the driver of these flows and was generated by the wave-driven pumping/setup of lagoon water level. As such, waves are considered to, indirectly, be the key driver of lagoon flows. The correlation between wave energy flux on the fringing reef, and the speed of currents discharging from the lagoon at Monitoring Station F is shown in Figure 2 (bottom).

Currents flowing through the system were found to be greater at high tide when ocean water levels create a greater freeboard over the fringing reef, compared with low tide when the ocean water level is below the crest of the fringing reef (see light blue line in Figure 2). When averaged across a complete tide cycle, the tidally-averaged currents (dark blue line) can be seen to be closely correlated to the wave energy flux on the fringing reef (orange line).

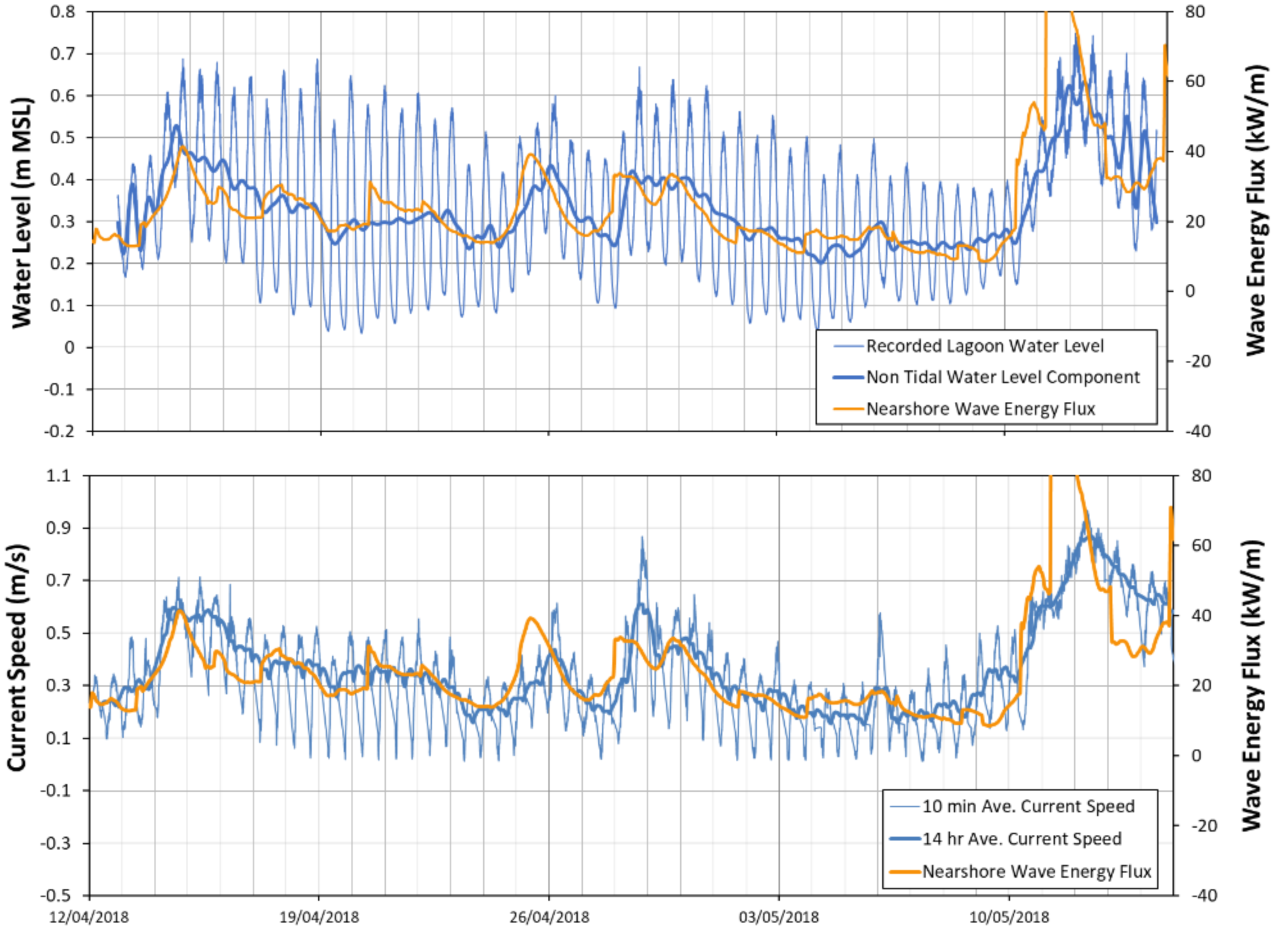

Figure 2: Example of Lagoon Water Level Fluctuations (Top) and Currents (Bottom) in Muri Lagoon

2.3.3 Discussion on Hydrodynamic Processes

The key conclusion from the analysis of lagoon hydrodynamics is that currents and flushing of the lagoon are driven by wave energy on the fringing reef, but modulated by ocean tide level. This finding is consistent with the “wave pump” theory published in [1], where analysis of a similar hydrodynamic data set for a reef-fringed atoll in the northern group of the Cook Islands is presented. [1] identifies an empirical model for the wave pump theory (Figure 3; Equation 1), whereby flows into the lagoon are shown as being proportional to:

1. wave energy flux;
2. ocean water level freeboard over the fringing reef.

$$Q_i = C_{pump}\frac{E_f}{\rho g(n_{max}-n_{tide})} \qquad (1)$$

where Q_i = inflow to the lagoon; E_f = wave energy flux; n_{max} = peak lagoon water level near reef edge; n_{tide} = ocean tide level; C_{pump} = energy conversion coefficient

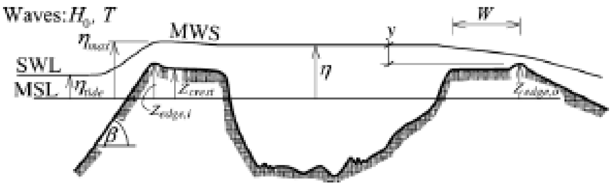

Figure 3: Wave pump model for an atoll fringing reef [1]

It is, therefore, plausible to also conclude that seasonal or inter-decadal shifts in wave energy or mean level of the sea (MLoS), may have a corresponding shift in lagoon currents and flushing rates, ultimately impacting the water quality of the lagoon. This is now explored in the following sections of the paper.

3. Methodology and Results

The updated analysis completed for this paper has focussed on the wave climatology and water levels for the Muri coastline, including long term averages, seasonality, and the influence of ENSO. Section 3.1 presents the analysis of wave climate, while Section 3.2 presents the analysis for water levels.

3.1 Wave Climate Analysis

Analysis of the wave climate for the Muri coastline was based on a 40-year hindcast of nearshore wave conditions, covering the period 1/1/1980 to 31/12/2020. Firstly, a deepwater wave hindcast for the open ocean offshore of Rarotonga was obtained from the CAWCR Wave Hindcast for the Pacific region [6]. This regional hindcast was developed under the Pacific-Australia Climate Change Science and Adaptation Planning Program and was based on a global Wavewatch III model with higher resolution nested grids in the vicinity of major island nations (Figure 4). Within the vicinity of Rarotonga, the hindcast model had a resolution of 4 arcminutes.

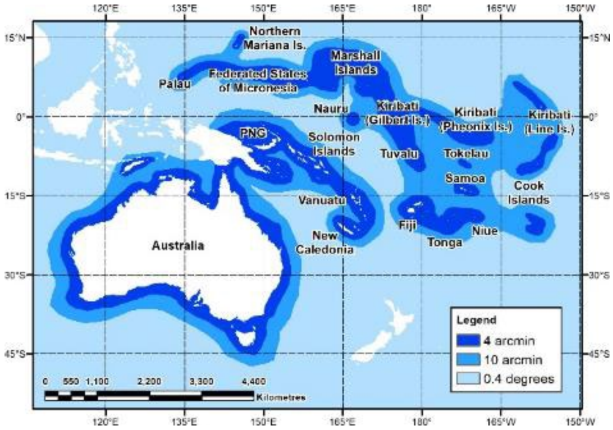

Figure 4: CAWCR Hindcast model grid resolutions [6]

The 40-year deepwater wave hindcast was downscaled to create a nearshore wave hindcast around the complete coastline of Rarotonga, including Muri. Downscaling was completed using the numerical model SWAN, established with a series of nested model grids including a nearshore grid of 30 m resolution covering the region from ~1000 m depth up to the edge of the fringing reef (Figure 5). The open-ocean hourly wave timeseries from the CAWCR Wave Hindcast was input as a boundary condition for the SWAN model, allowing for the development of the 40-year hindcast of nearshore wave conditions. The nearshore hindcast was subsequently verified against 4 months of recorded nearshore wave data collected by UNSW in 2019, as well as several other historical large-wave events that were captured during prior wave buoy deployments. Under most conditions the nearshore hindcast was found to provide a relatively robust estimate of the main wave energy components.

Figure 5: High resolution nearshore SWAN model grid

Nearshore wave conditions were extracted from the hindcast along the 15 m depth contour for the Muri coastline. The 40-year timeseries was subsequently analysed using Python to develop an understanding of the wave climatology for Muri.

Figure 6a shows the 40-year hindcast of wave energy flux for Muri. Also shown is the seasonal average wave energy flux, colour coded for simplicity, with red dots indicating a summer average (Dec, Jan, Feb), orange dots indicating an autumn average (Mar, Apr, May), green dots indicating a winter average (Jun, Jul, Aug) and blue dots indicating a spring average (Sep, Oct, Nov). Also shown in Figure 6b is the multivariate ENSO index for the corresponding 40-year period.

Immediately apparent from the seasonal wave time series, is that the average wave energy flux for summer periods (red dots) is typically lower compared with the other three seasons. This is further explored in Figure 7 (left) which shows the seasonal variation in wave energy flux from the long-term mean value. The long-term annual average wave energy flux for Muri was determined to be 22 kW/m. For summer seasons this drops by an average of 4.7 kW/m, corresponding to a reduction of 21%. In contrast, for winter seasons wave energy flux was 3.3 kW/m higher than the long-term average, an increase of 15%. Key drivers for this seasonality are the exposure to easterly trade winds and southerly swells which both have strong seasonality.

Figure 7 (right) plots the variation in wave energy flux for summer seasons only, separated into all summers, El Niño summers and La Niña summers. From this plot we can again see that the wave energy flux averaged across all summer seasons was 4.7 kW/m lower (-21%) than the long-term annual average. Of greater significance, we can also see a stark difference in wave energy flux for La Niña summers versus El Niño summers. During La Niña summers, average wave energy flux was 7.8 kW/m lower than the long-term average, corresponding to an additional 14% reduction below the average summer value, and a total decrease of 35% from the long-term average. For some La Niña summers, the reduction in wave energy flux was up to 50% lower than the long-term annual average.

While El Niño summers also had slightly lower wave energy flux compared to the long-term average value (0.9 kW/m reduction, -4%), this was still higher than the average summer value, and notably higher than the average La Niña summer value. A similar analysis to consider ENSO influences on wave energy flux for the other seasons was also undertaken (Figure 8), with only minor influence of ENSO identified.

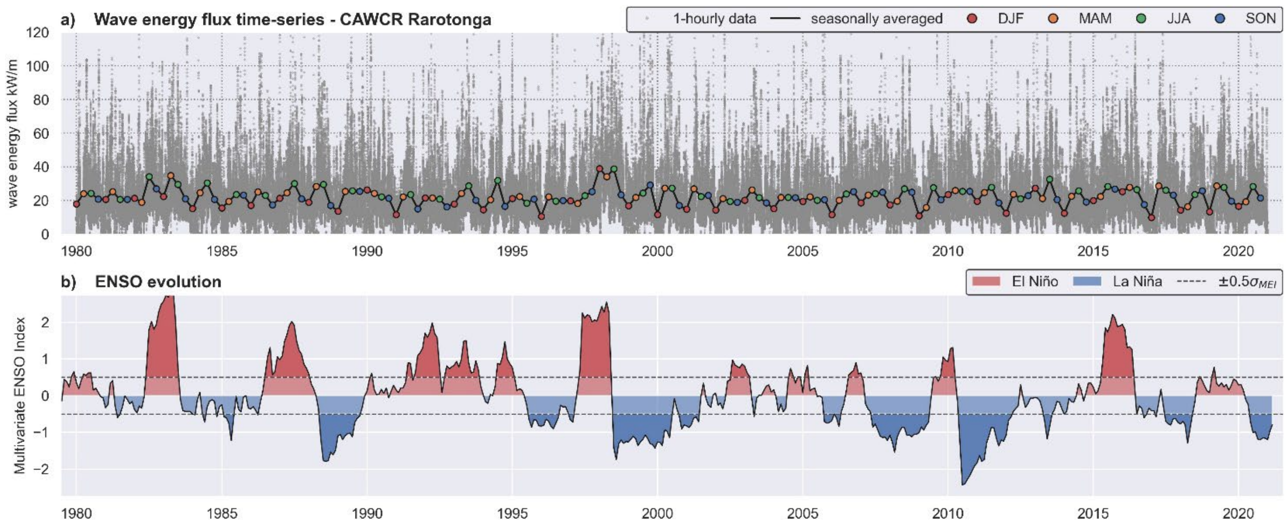

Figure 6: 40-year time series of wave conditions at Muri (top); Evolution of ENSO index (bottom)

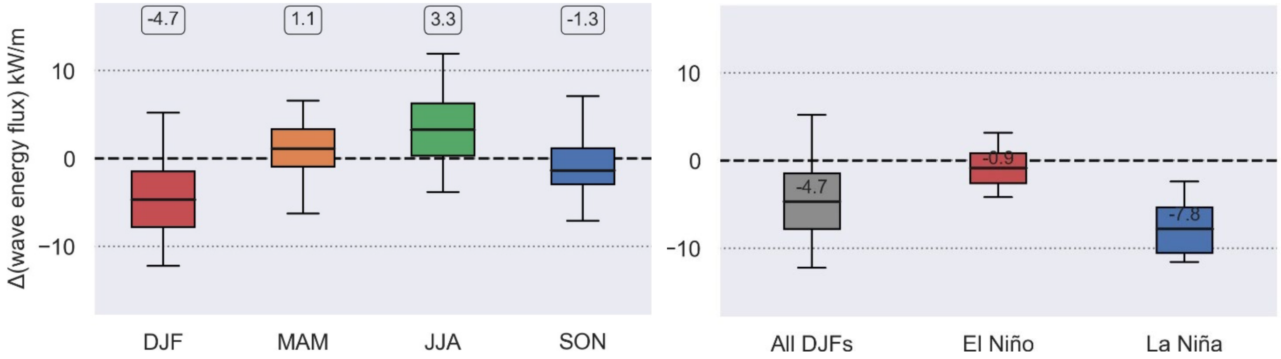

Figure 7: Seasonal variation in wave energy flux (left); Influence of ENSO on wave energy flux for summer (right)

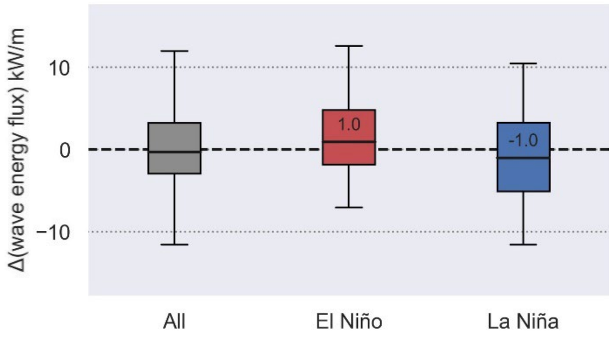

Figure 8: Influence of ENSO on wave energy flux for all seasons

3.2 Ocean Water Level Analysis

Analysis of ocean water levels was based on 41 years of daily sea level measurements from tide gauges located at Avarua harbour (1977-1997) and Avatiu harbour (1993-2018) on the north coast of Rarotonga. Both tide data sets are quality-controlled records obtained from the University of Hawaii Sea Level Centre. The gauged data was also compared with gridded daily sea level estimates from satellite altimetry, sourced from the Copernicus Marine Environment Monitoring Service for the period 1993-2018, and found to show good agreement.

The tide gauge sea level data was first de-trended to remove the underlying sea level rise signature, and analysed to develop a seasonal water level timeseries. An analysis of seasonality and ENSO influences was subsequently completed for this data set. The 41-year daily and seasonal sea level time series are shown in Figure 9a, and the analysis for seasonality is presented in Figure 10. It can be seen here that there is no significant seasonality in the variation of MLoS, with the greatest seasonal deviation being -2.3 cm in winter (-3.4% of the spring tide range).

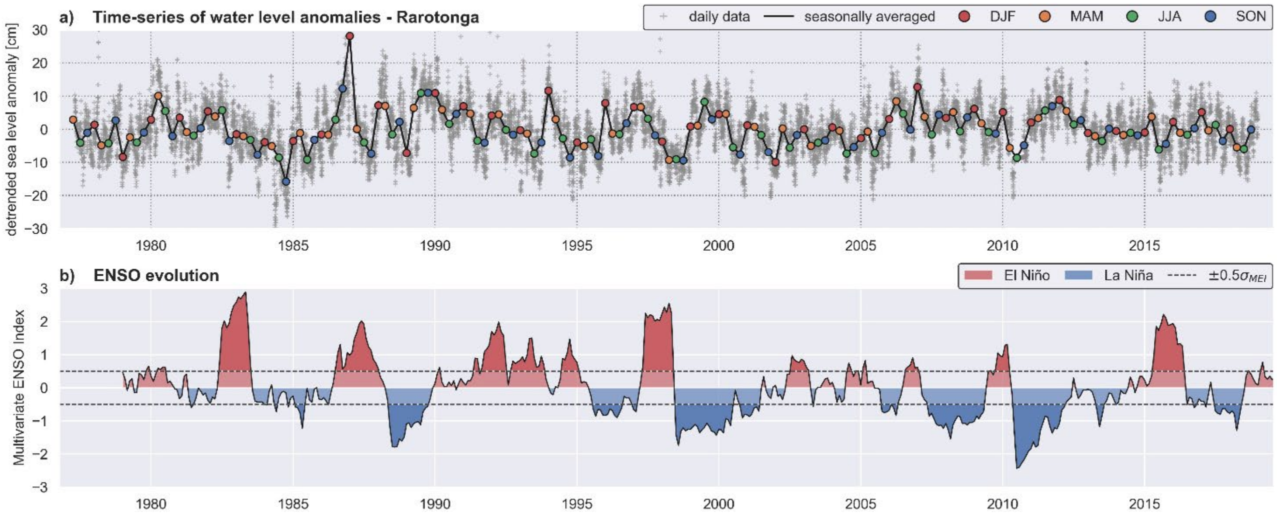

Figure 9: 41-year time series of ocean water levels at Muri (top); Evolution of ENSO index (bottom)

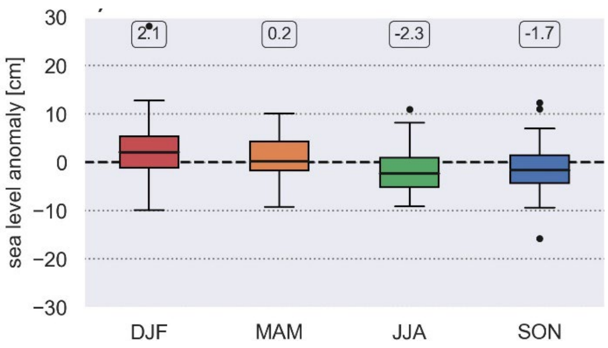

Figure 10: Seasonal variation in Mean Level of the Sea

The results of the analysis to consider the influence of ENSO on MLoS across all seasons is shown in Figure 11. It can be seen here that during El Niño periods, MLoS had a very slight 1.5 cm deviation lower than the long-term mean position (-2.2% of the spring tide range), whereas during La Niña periods sea level tended to deviate very slightly higher than the long-term mean (1.2 cm, 1.8% of the spring tide range). Both of these values were assessed to be statistically non-significant (within the error of the analysis).

The analysis also considered the influence of ENSO on sea levels on a season-by-season basis. The largest influence was noted for the summer season, with the results shown in Figure 12. For El Niño summer periods MLoS varied 2.2 cm higher than the long-term mean (3.2% of spring tide range), whereas for La Niña summers it varied 3.1 cm higher (4.6% of spring tide range). Both values were assessed to be statistically non-significant.

4. Discussion

Wave energy on the fringing reef has been shown to be the dominant driver for flushing of Muri Lagoon, consistent with a “wave pump” theory. Flows through the lagoon are also modulated by the level of the sea relative to the fringing reef and elevated lagoon water levels.

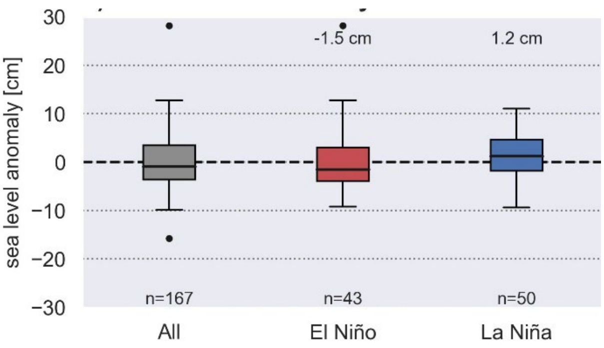

Figure 11: Influence of ENSO on Mean Level of the Sea across all seasons

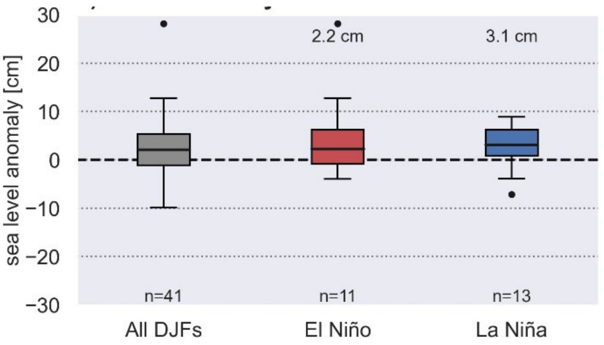

Figure 12: Influence of ENSO on Mean Level of the Sea for summer seasons

The results of the analysis presented in this paper indicate that there is very little to no seasonal influence on ocean sea level variations for Muri. Likewise, ENSO has no significant influence on sea levels. However, wave energy on the fringing reef was determined to be significantly lower during summer periods compared with other seasons. La Niña summers were found to have even greater reduction in wave energy, with wave energy flux being some 35% lower, and up to 50% lower for some La Niña summers, compared with the long-term mean wave energy flux. This large decrease in wave energy will also translate directly into a large reduction in lagoon flows and flushing during La Niña summer seasons.

[7] identifies that La Niña periods bring warmer and wetter conditions to Rarotonga. This is postulated in [8] to result in greater sediment and nutrient runoff from the catchment, and reduced salinity of lagoon water; both creating preferential conditions for excessive growth of algae within the lagoon. As demonstrated in the current paper, significantly reduced lagoon flushing over La Niña summers will compound with these conditions to also result in further water quality issues and stress on the marine ecosystem of the lagoon.

During the La Niña summer of 2020/21 these climatological factors aligned, and algae growth proliferated at Muri. As lagoon water temperatures proceeded to climb due to elevated air/sea temperatures and a near-complete lack of lagoon flushing, algae began to die-off in the lagoon, rapidly reducing dissolved oxygen levels and resulting in localised areas with near-anoxic conditions [9]. Subsequent kills of various marine organisms were observed, along with anoxic sub-surface lagoon sediments. The impacts on the lagoon were significant and translated to impacts on the local community with regards to recreation and aquaculture activities in the lagoon. Tourism impacts would also have been significant had the country not been in the midst of the Covid-19 pandemic.

By having a good understanding that La Niña summer conditions result in significantly higher risk of lagoon health issues compared with other seasons or even El Niño summers, we are now able to forecast the high-risk conditions weeks or months ahead of impacts occurring. Several organisations already produce climate forecasts in the Pacific that include seasonal and ENSO impacts on key climate parameters such as rainfall and Tropical Cyclone likelihood. These forecasts could easily be adapted to also consider lagoon health (similar to coral bleaching forecasts).

5. Conclusions

Wave energy is widely recognised as a key driver of hydrodynamics for fringing reef and lagoon systems typical of many islands in the tropical Pacific. This paper has demonstrated the potential for significant influence of both seasonality and ENSO on wave-generated flows and flushing of these systems, using Muri Lagoon as a case study. This finding is of high relevance to many similar coastal lagoons across both the Cook Islands and broader Pacific region, with importance for water quality, ecology, subsistence and commercial aquaculture and tourism as a minimum. Further investigation of similar trends in other areas of the Pacific would be highly valuable in this regard.

6. Acknowledgements

The hydrodynamic investigations in this paper were undertaken as part of the Mei te vai ki te vai project, in partnership with GHD and the Cook Islands Government. The National Tidal Centre, CSIRO and Cook Islands Meteorological Service are acknowledged for provision of various data sets. Several community members from Muri are acknowledged for their review of paper drafts and contribution of their personal observations of the lagoon and climate processes.

7. Acronyms

ENSO: El Niño-Southern Oscillation

DJF: December, January, February

MAM: March, April, May

JJA: June, July, August

SON: September, October, November

MLoS: Mean level of the sea

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