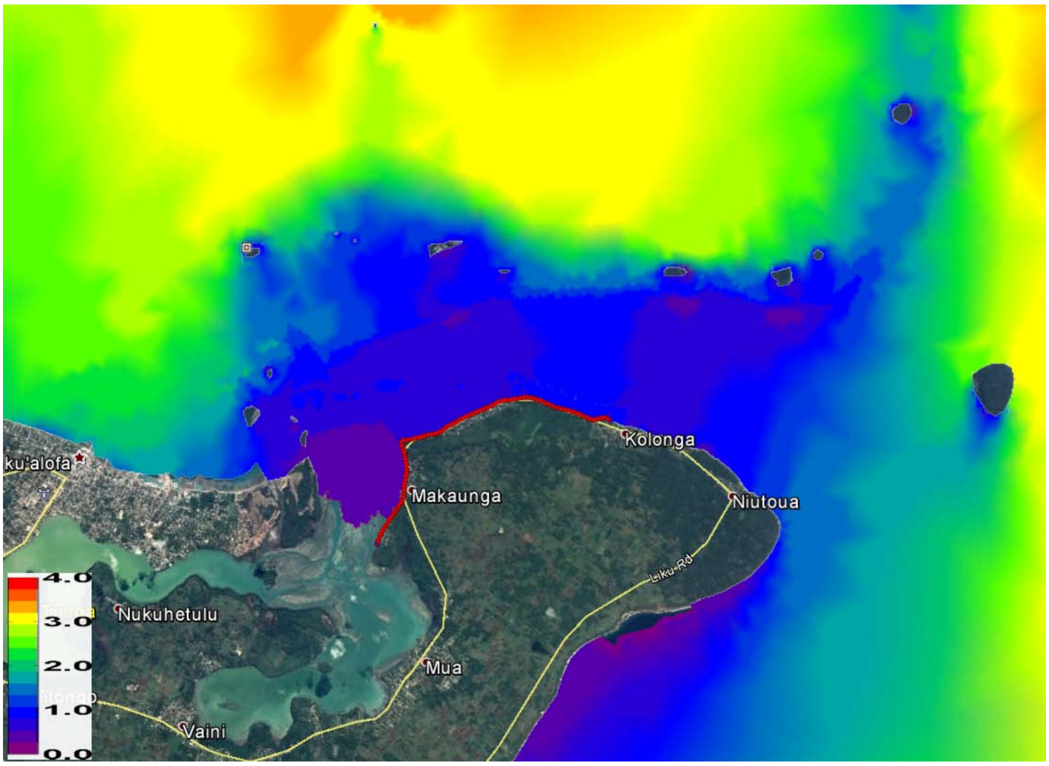
PROJECT RELATED

CLIMATE RESILIENT SECTOR PROJECT (CRSP) –MOI/PIU UNIT



REPORT

HAHAKE COASTAL PROTECTION SUBPROJECT
Coastal Process, Monitoring & Engineering Options Assessment: Wave Modelling Report

Civil Engineering Division of the Ministry of Infrastructure, Tonga

Client:	Asian Development Bank
Reference:	PIR : Grant No. 0378-TON
Revision:	01/Draft
Date:	16th December 2016

PROJECT RELATED

CLIMATE RESILIENT SECTOR PROJECT (CRSP) –MOI/PIU UNIT

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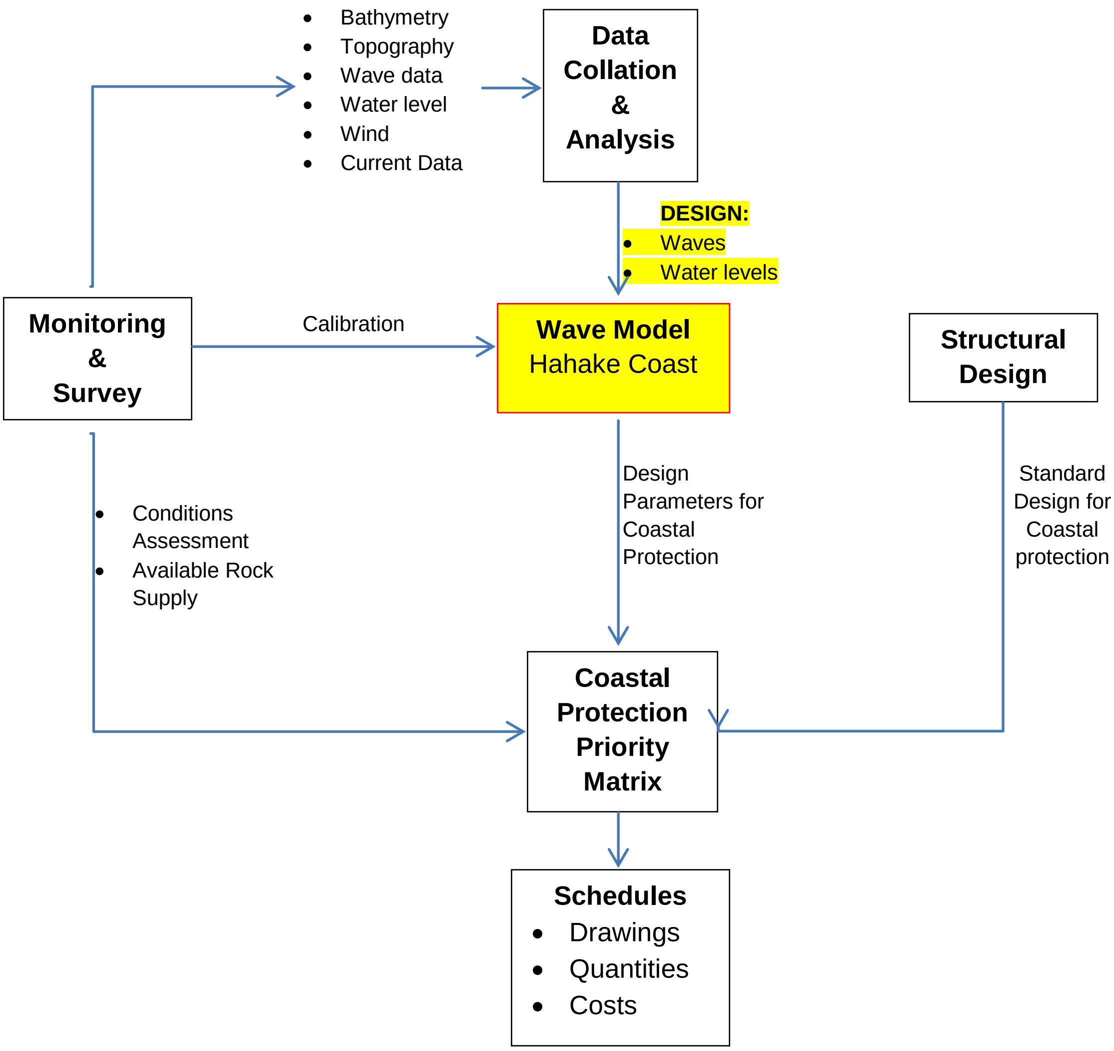
Table of Contents

1. Background

The Government of Tonga (GoT) have obtained a grant from the Asian Development Bank (ADB) to implement the Climate Resilience Sector Project (CSRP), which was prepared under Phase 2 of the Pilot Program for Climate Resilience (PPCR). The project will mainstream climate resilience into development planning and address country priorities focusing on the most vulnerable sectors and communities.

The Hahake (eastern) coastline has been identified as a vulnerable section of Tongatapu' s coast, as such the Hahake Coastal Protection Subproject (HCPS) was defined as being a critical task for implementation. The HCPS lies within the CRSP and is to be executed through a Project Implementation Unit (PIU). The implementation falls under Task3 of the CRSP: Design and Supervision consultants -PIU- Civil Engineering Division of the Ministry of Infrastructure (Grant No. 0378-TON). Task 3 is further defined as *Assessment Report and recommendations on Hahake coastal protection measures based on the review of previous study/reports*.

Two reports have been submitted defining the coastal processes of the study site, contextualising the problem as it relates to the wider CRSP and providing a detailed scope to be implemented in order to meet project objectives. As part of Report II: Scoping Document (Lewis, 2016), several recommendations were made as to the proposed scope of works to be undertaken in order to meet project objectives. A workflow diagram of the proposed works can be seen below.This report defines the approach taken during the wave modelling phase (highlighted below).



2. Objectives

The CRSP is designed to:

Mainstream climate resilience into government planning and address country priorities focusing on the most vulnerable sectors and communities. The Project is designed to increase resilience in economic, social, and natural eco-systems to climate variability and change and disaster risk in Tonga. The overall outcome of the Project is to strengthen the enabling environment for climate adaptation and disaster risk reduction at national and local levels.

A complete description of the CRSP can be found in the initial proposal document (SMEC/ITS, 2015) and further updated in the Inception Report (SMEC/ITS, 2016).

3. Scope

The scope of works of the Hahake Coastal Protection Subproject is defined as follows:

1. Review all existing data and reports and undertake site visitsto establish baseline conditions.
2. Develop a preliminary description of the coastal processes with special emphasis onhypotheses for the cause of the erosion.
3. Based on the preliminary understanding of the coastal processes, set up a numericalmodelling system covering wave conditions (offshore and nearshore), hydrodynamics(currents and water levels) and the resulting sediment transport.
4. Map the sediment budgets along the coast using historical LIDAR data and the numerical models
5. Based on all of the above, design a focused monitoring campaign covering: hydrodynamicforcing conditions and sediment transport (if possible) and shoreline evolution (as aminimum).
6. Use monitoring results to perform running calibrations of the numerical models,
7. Apply the calibrated models to design an effective and sustainable coastal protection strategy.
8. Develop a Coastal Protection Manual for Tonga using the data and experiences gatheredthrough this process.

The scope of this report is based upon point 3 (above) and the recommendations in Section 5.2 of the scoping Document (Lewis, 2016), summarised as follows:

1. Undertake a Spectral Wave (SW) modelling exercise order to understand wave transformation from offshore of Tongatapu into the Piha Passage and the study site.
2. The model will be used to determine maximum waves expected along the extent of the shoreline of Hahake
3. Investigate wave transformation from the dominant southerly source of swell as well as the semi-annual impact of large swells approaching the study site from the northern sectors due to cyclonic events.
4. The model will be driven by a matrix of the 1, 10, 20, 50, and 100 Annual Return Interval (ARI) *offshore* wave heights and water levels taken from a statistical analysis of available data.
5. The output will be a matrix of wave heights along the study site for the combination of ARI water levels and *offshore* wave heights taken from each directional sector where significant wave heights are seen to occur.
6. The acceptable design limit (combination of ARI *offshore* wave height/water level) will be determined in conjunction with Ministry of Infrastructure (MOI).

The output of the modelling exercise will be a short technical note (this report) detailing the methods and findings of the study. A table with design wave height, direction and period along the stretch of the Hahake shoreline will be produced and the values utilised for the future design phase of the project

4. Methodology

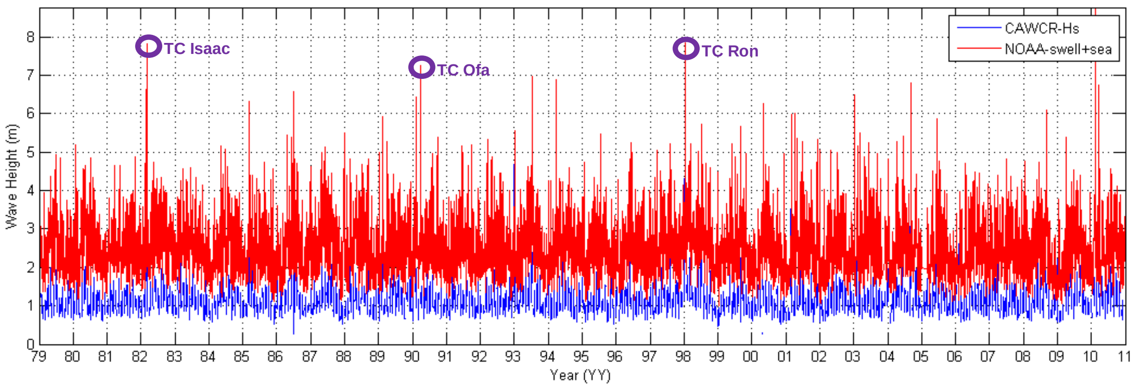
Following the review of the metocean conditions at the site detailed in the previous reports (Webb, 2016) and (Lewis, 2016), data was collated from a number of sources for use within the modelling phase. The available metocean data was quality assured (QA) and compared to other sources to find the most suitable for the study.

4.1 Data Collation and Analysis

4.1.1 Waves

A literature review of previous studies focussing on the wave climate of Tongatapu can be seen in (Lewis, 2016). A key finding of the review process was the need for a longer term wave record in order to appropriately calculate design return periods of significant wave events. As there are no direct wave measurements being taken in close proximity to Tongatapu, it was deemed necessary to source wave data from global hindcast models. Two wave models exist covering the study site with sufficient spatial resolution for an extended period of time that offer open source data; National Oceanic and Atmospheric Administration (NOAA)WaveWatch III (WWIII) Global Hindcast Model (NOAA) and the Collaboration for Australian Weather and Climate Research (CAWCR) Wave Hindcast . The NOAA data provided a much more detailed representation of the offshore wave climate of Tongatapu as it combines both wind and swell waves in its output in comparison to that of only swell waves for the CAWCR data. The NOAA data also seemed to capture larger (cyclonic) wave events (purple circles, Figure 1) whereas the CAWCR appeared to under-represent wave heights occurring during these times.

A comparison was made between the wave height outputs of the two models and can be seen in Figure 1. The top figure shows raw extracted values from the models at the same geographic location, it can be seen there is a clear offset in magnitude between the models. The mean percentage difference (42.7%) was applied to the CAWCR data set for comparison and can be seen in the bottom graph of Figure 1. The adjusted data seems to match the NOAA data better, however it can be seen that the data gaps at the beginning of each month in the CAWCR dataset (most probably caused by model initiation/warm-up) provide a reduced dataset in comparison to the NOAA data. In order to conduct a thorough Extreme Value Analysis of wave heights, it is best practise to maximise the dataset length to eliminate extrapolation error. As this study will be used to ascertain maximum wave heights for the purposes of design, it was deemed that the NOAA data would be most appropriate for further analysis.



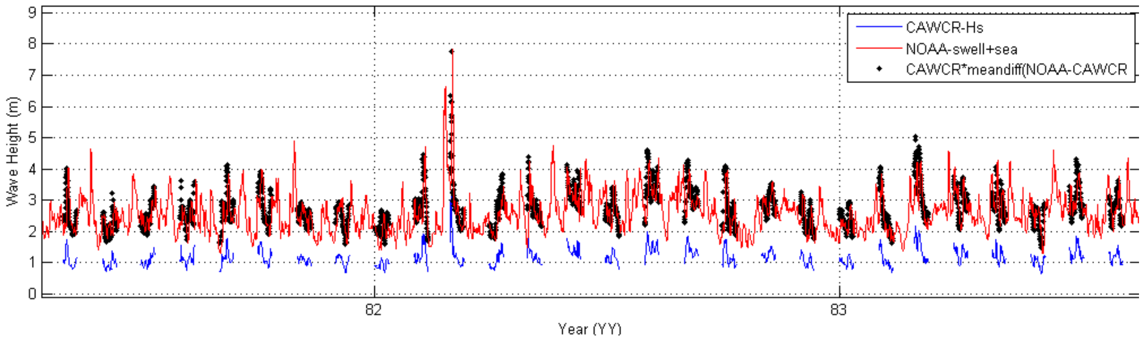


Figure 1Comparison of raw output wave height from the CAWCR and NOAA models (top). Adjusted CAWCR values (NOAA data x mean % difference NOAA/CAWCR) for the 1981-1984 period (bottom).

Three output locations were extracted from the NOAA 0.5° global wave hindcast grid for to be compared for use to drive a Tongatapu local wave model. The three locations as seen in Figure 2.have been extracted at strategic locations offshore of Tongatapu so that waves arriving at that point have not undergone significant transformation due to abrupt changes in bathymetry or are being blocked by nearby islands. The analysis of waves from each directional sector was performed on the dataset highlighted in Table 1.

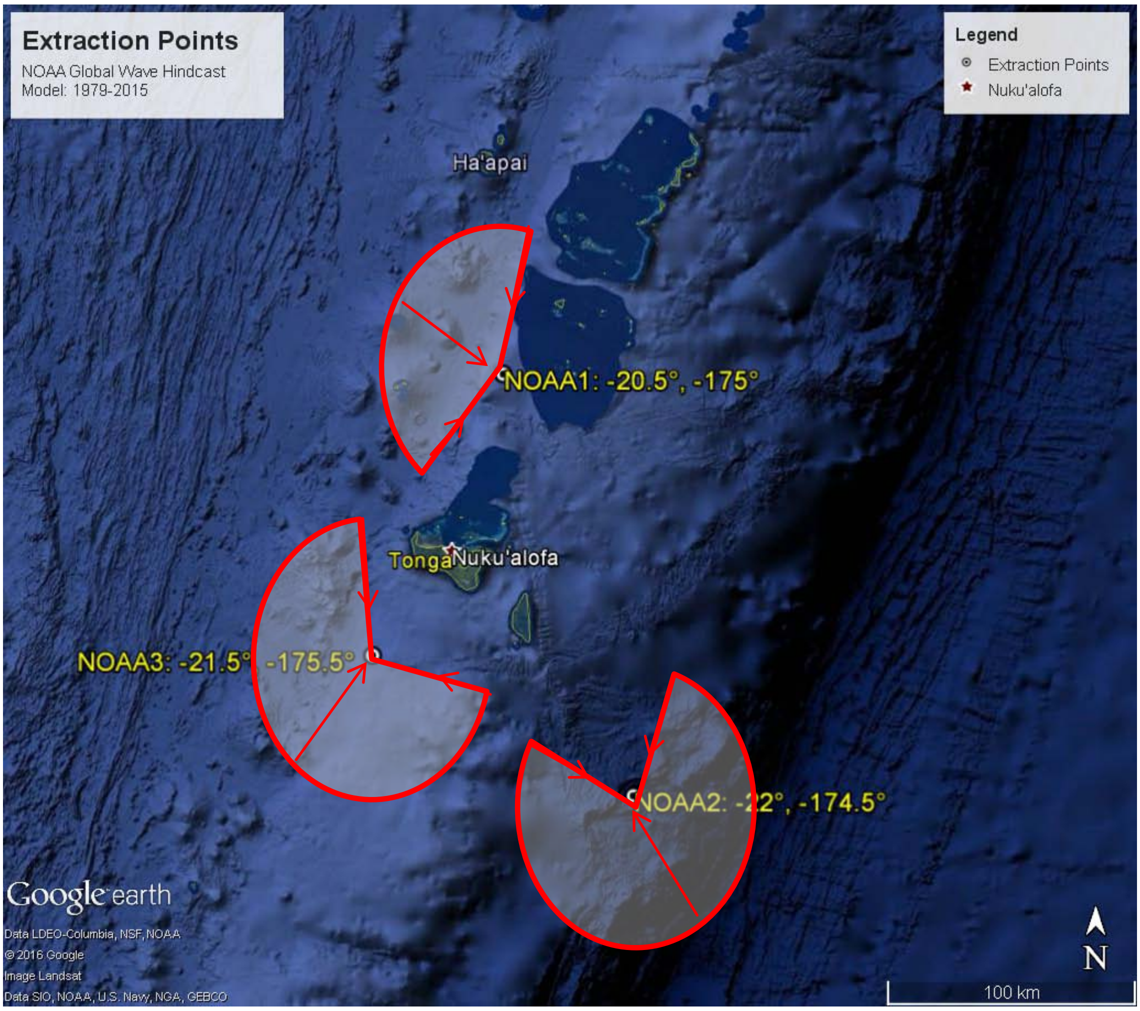
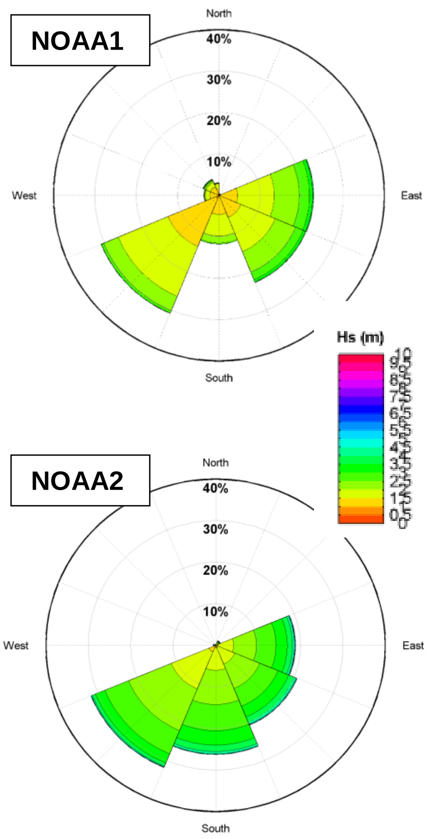


Figure 2Data extraction points taken from the NOAA Global Wave Hindcast Model: 1979-2015. The red pie chart and arrows represent directions of incoming waves to each extraction point that are unhindered by local bathymetric changes.

Table 1Extraction point data used for metocean analysis and Tongatapu Wave Model boundary conditions

Dataset	Unhindered direction range (from)	Directional Sector							
		N	NE	E	SE	S	SW	W	NW
		Dataset Used							
NOAA1	NNE - W - SW	x						x	x
NOAA2	NNE - E - WNW		x	x	x	x	x		
NOAA3	NNW - W – ESE								

An annual and seasonal Joint History Analysis (JHA) of wave height, period and direction was undertaken to validate the selection of each dataset for every directional sector, the results of which are summarised in Figure 2and supplied in detail in Appendix A. Due to the redundancy (or overlap) in wave directions covered by NOAA2 and NOAA3, the NOAA3 dataset has been excluded from the analysis. The difference in total percentage of recorded waves from the N, NW and W sectors between each extraction site validates the selection of the NOAA1 point to represent incoming wavesto the study site from these directions.



Joint Frequency Table (%) Showing Hs Against Direction for the Period 01–Jan–1979 to 01–Aug–2015

N=106889	N	NE	E	SE	S	SW	W	NW	Total	Cumul.
0–0.5	*	–	*	*	*	*	*	–	0.02	0.02
0.5–1	0.11	0.01	0.22	0.23	0.25	0.78	0.19	0.19	1.97	2.00
1–1.5	1.61	0.13	4.29	5.50	4.34	12.54	1.96	2.06	32.43	34.43
1.5–2	1.22	0.15	8.82	8.98	5.23	13.01	1.12	1.18	39.70	74.13
2–2.5	0.25	0.08	6.04	5.35	1.71	3.81	0.25	0.36	17.85	91.98
2.5–3	0.12	0.04	2.50	1.96	0.22	0.58	0.07	0.20	5.70	97.67
3–3.5	0.07	0.01	0.74	0.58	0.01	0.09	0.03	0.10	1.65	99.33
3.5–4	0.02	*	0.20	0.14	*	0.02	*	0.06	0.45	99.77
4–4.5	*	*	0.05	0.02	–	*	0.01	0.03	0.12	99.89
4.5–5	*	–	*	0.01	–	–	*	0.02	0.05	99.94
5–5.5	–	*	*	*	–	–	*	0.01	0.02	99.96
5.5–6	*	*	*	–	–	–	*	*	0.01	99.98
6–6.5	*	–	*	–	–	–	*	*	0.01	99.99
6.5–7	–	–	*	–	–	–	–	*	*	100.00
7–7.5	–	–	–	–	–	–	–	*	*	100.00
7.5–8	–	–	–	–	–	–	–	*	*	100.00
8–8.5	–	–	–	–	–	–	–	*	*	100.00
8.5–9	–	–	–	–	–	–	–	*	*	100.00
9–9.5	–	–	–	–	–	–	–	–	–	100.00
9.5–10	–	–	–	–	–	–	–	–	–	100.00
Total	3.40	0.45	22.88	22.77	11.76	30.85	3.66	4.23		
Cumul.	3.40	3.85	26.73	49.50	61.26	92.11	95.77	100.00		

* denotes values less than 0.01%   – denotes no records in bin

Joint Frequency Table (%) Showing Hs Against Direction for the Period 01–Jan–1979 to 01–Aug–2015

N=106889	N	NE	E	SE	S	SW	W	NW	Total	Cumul.
0–0.5	*	–	–	–	*	*	*	–	0.01	0.01
0.5–1	–	–	*	*	0.01	–	–	–	0.02	0.04
1–1.5	*	0.13	0.57	0.55	0.62	1.69	0.01	*	3.58	3.61
1.5–2	0.06	0.40	3.66	4.34	5.36	9.64	0.10	0.04	23.61	27.22
2–2.5	0.05	0.30	5.39	6.36	8.24	10.85	0.20	0.05	31.46	58.68
2.5–3	0.06	0.16	4.58	4.62	6.30	6.06	0.13	0.08	21.98	80.66
3–3.5	0.03	0.12	2.67	2.77	3.47	2.42	0.05	0.04	11.58	92.24
3.5–4	0.03	0.05	1.20	1.34	1.53	0.75	0.03	0.02	4.95	97.19
4–4.5	0.01	0.03	0.46	0.53	0.52	0.23	0.02	*	1.80	98.99
4.5–5	*	0.01	0.18	0.16	0.15	0.10	*	*	0.63	99.63
5–5.5	*	*	0.06	0.07	0.03	0.03	*	*	0.21	99.84
5.5–6	*	*	0.03	0.02	*	0.01	*	*	0.08	99.92
6–6.5	–	*	0.01	*	*	*	*	*	0.05	99.97
6.5–7	*	*	–	*	*	*	*	*	0.02	99.99
7–7.5	–	*	–	–	–	–	*	–	*	99.99
7.5–8	–	*	–	–	–	–	*	–	*	100.00
8–8.5	–	*	–	–	–	–	–	–	*	100.00
8.5–9	–	*	–	–	–	–	–	–	*	100.00
9–9.5	–	–	–	–	–	–	–	–	–	100.00
9.5–10	–	–	–	–	–	–	–	–	–	100.00
Total	0.25	1.22	18.83	20.79	26.26	31.81	0.58	0.27		
Cumul.	0.25	1.47	20.29	41.08	67.34	99.14	99.73	100.00		

* denotes values less than 0.01%   – denotes no records in bin

Figure 3Joint history analysis of wave height and direction at extraction points NOAA1 and NOAA2.

An Extreme Value Analysis (EVA)of wave height was undertaken for each directional sector from the extraction point data listed in Table 1. The EVA was undertaken to determine the Annual Recurrence Interval (ARI) wave height for the 1, 10, 20, 50 and 100 year return periods expected to occur from each directional sector. The results of the EVA analysis can be seen in Table 2 and detailed graphs in Appendix B.

An associated peak wave period, Tp (sec) was assigned to each of the offshore wave heights. The period was taken as the mean wave period determined for a given wave height (+/-0.5m) for each directional sector. The calculated Tp value was then cross-checked against the Wave Height and Period scatter plot (Figure 4) and the Wave Direction and Period Scatter plots (Figure 5) produced as part of the JHA. The Tp values associated with the each of the ARI wave heights can be seen in Table 2.

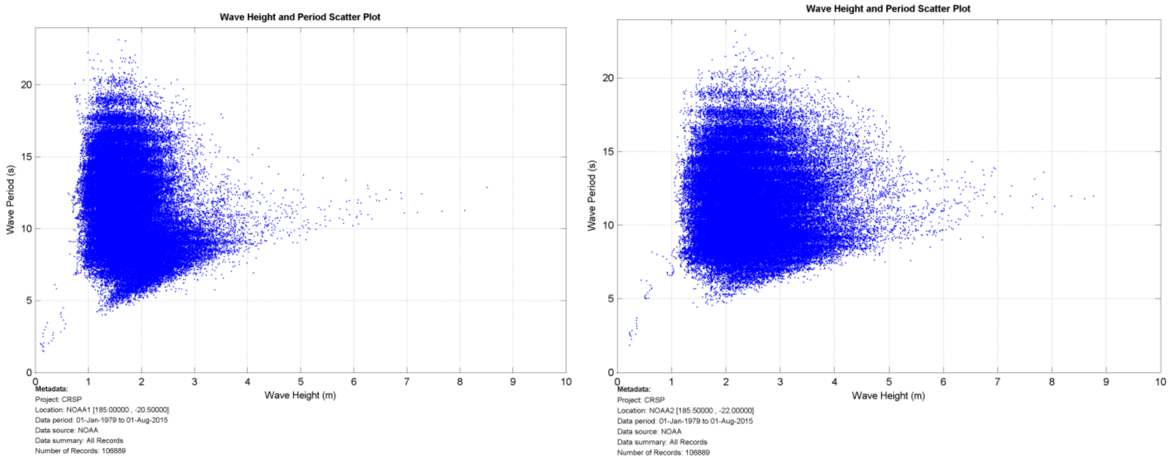


Figure 4 Wave Height and Period Scatter Plot for NOAA1 (left) and NOAA2 (right).

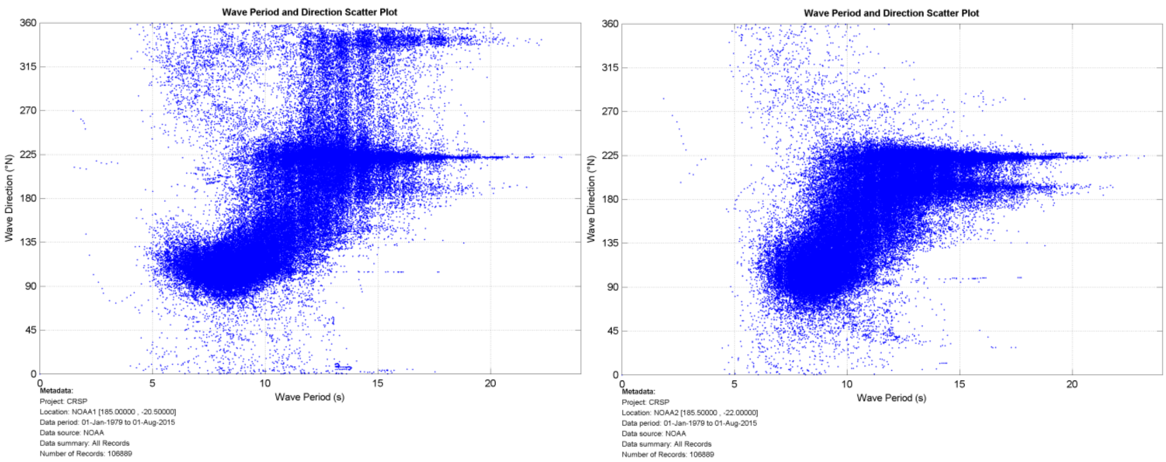


Figure 5 Wave Direction and Period Scatter Plot for NOAA1 (left) and NOAA2 (right).

Table 2Extreme Value Analysis of extracted wave height (m) data from the NOAA global Wave Hindcast Model for the period 1979-2015 for each directional sector

Directional Sector		**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
EVA Distribution Method		GPD*	GPD*	Weibull	GPD*	Weibull	Weibull	Weibull	Weibull
Wave Height Threshold (m)		2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
Extraction Point		NOAA1	NOAA2	NOAA2	NOAA2	NOAA2	NOAA2	NOAA1	NOAA1
Annual Recurrence Interval (years)		**Wave Height (m) / Wave Period (sec)**							
	1	**2.8 / 10.2**	**3.3 / 8.7**	**4.7 / 9.9**	**4.7 / 10.3**	**4.7 / 13.8**	**4.8 / 13.7**	**2.6 / 9.9**	**3.4 / 8.9**
	10	**4.6 / 10.7**	**6.1 / 10.3**	**6 / 10.4**	**5.6 / 10.7**	**5.8 / 12.4**	**5.4 / 13.1**	**4.8 / 10.8**	**6.2 / 11.6**
	20	**5.2 / 11.1**	**7.2 / 11.5**	**6.4 / 10.6**	**5.8 / 10.6**	**6.3 / 12.4**	**5.8 / 12.7**	**5.5 / 10.6**	**7.2 / 11.7**
	50	**5.9 / 12**	**8.7 / 11.9**	**6.9 / 11**	**6.1 / 10.9**	**6.6 / 12.5**	**6.1 / 12.4**	**6.5 / 11.3**	**8.4 / 12.1**
	100	**6.3 / 12**	**10 / 12**	**7.2/ 11**	**6.3 / 11**	**6.9 / 13.3**	**6.4 / 12.8**	**7.3 / 12.4**	**9.3 / 12.9**

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4.1.2 Water Levels

Tidal data has been collected at the Queen Salote Wharf in the Nuku'alofa Harbour since 1993, Figure 6The tide gauge is maintained by Ministry of Meteorology, Energy, Information, Disaster Management, Environment, Climate Change and Communication (MEIDECC) and the data managed in collaboration with the Australian Bureau of Meteorology (BoM). As this gauge is located in close proximity to the study site and the adjacent coastline faces a similar direction, it is considered a suitable proxy for water levels experienced at the study site.

Figure 6Nuku'alofa tide gauge location, (BoM, 2016).

A 23.6 year dataset of recorded water levels at the Nuku'alofa Tide Gauge was supplied by BoM. Tidal harmonic analysis was undertaken on the water level data and a predicted tidal signal was reconstructed for the period based upon 68 harmonic constituents. The tidal plane (and tidal range) for the Nuku'alofa tide gauge determined from the harmonic reconstruction of the datacan be seen in Table 3**.**The difference between the predicted signal and the recorded water level was used to determine the level of surge recorded in the water level data. The reconstruction of the predicted water level, the recorded water level and the calculated surge component can be seen in Figure 7.

Table 3Tidal Plane and Tidal Range for the Nuku'alofa Tide Gauge based on harmonic analysis of 68 constituents calculated from 23.6 years of recorded water level data.

Tidal Plane Identifier	Height (mMSL)	Tidal Range	Height (mMSL)
Highest Astronomical Tide (HAT)	0.93	Range	1.87
High High Water Spring (HHWS)	0.71	Spring Range	1.14
Mean High Water Springs (MHWS)	0.57	Neap Range	0.91
Mean High Water (MHW)	0.51	Mean Range	1.03
Mean High Water Neap (MHWN)	0.46		
Mean Sea Level (MSL)	0.00		
Mean Low Water Neap (MLWN)	-0.46		
Mean Low Water (MLW)	-0.51		
Mean Low Water Spring (MLWS)	-0.57		
Indian Spring Low Water (ISLW)	-0.67		
Lowest Astronomical Tide (LAT)	-0.94		

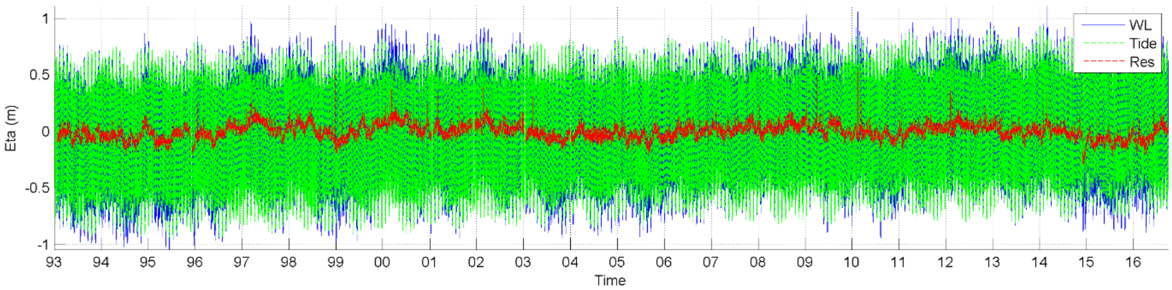
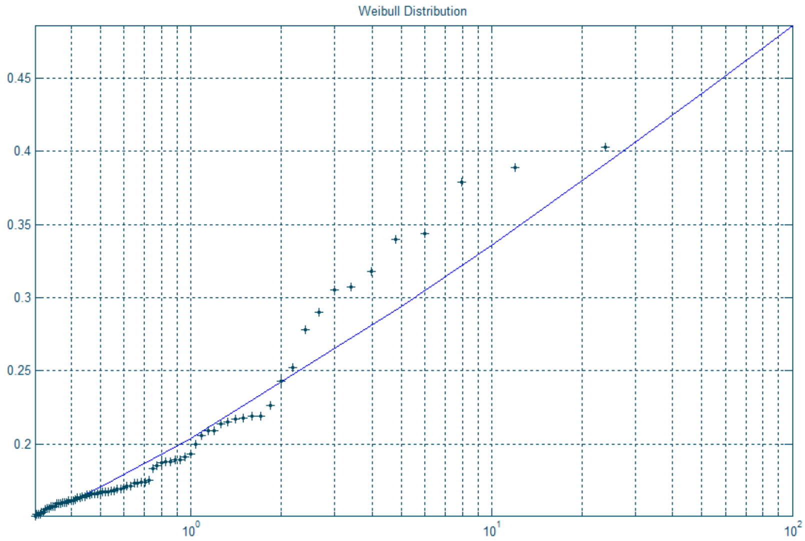


Figure 7Water level data recorded at the Nuku'alofa Tide Gauge (blue), predicted water level based on harmonic analysis of 23.6 years of data (green), calculated tidal residual (red).

The calculated tidal residual (surge) was then corrected for the barometric effect to give an adjusted surge component. Inundation at the study site is seen to occur as a direct result of increased water levels (in addition to wave overtopping). As such, only the positive recordings of surgewere used in subsequent EVA calculations. The positive residual (adjusted surge) component of the Nuku'alofa Tide Gauge was used to determine ARI surge events as seen in Figure 7.

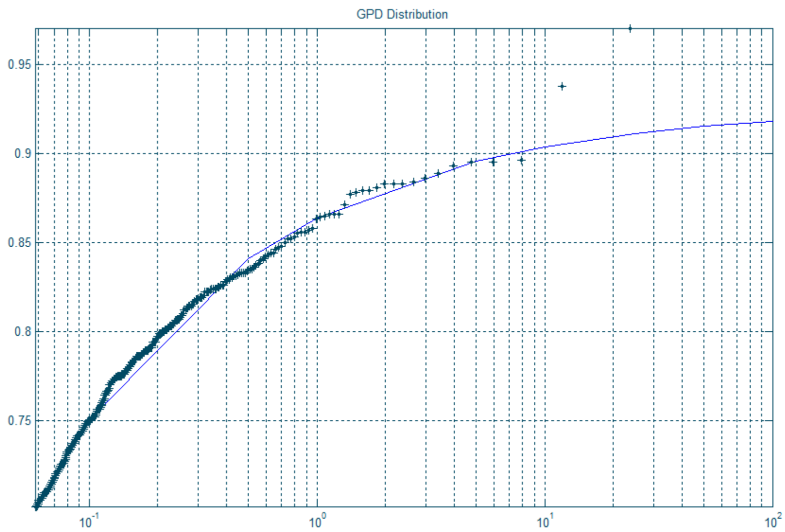


Dataset	Positive Surge
Threshold	0.15
Distribution Method	Weibull
ARI (years)	Water Level (m)
1	0.21
10	0.33
20	0.38
50	0.44
100	0.47

Figure 8Annual Return Interval (ARI, years) of water level (m) calculated on the positive residual (adjusted surge) component of the Nuku'alofa Tide Gauge

In order to calculate return periods for total water level, it is integral that a realistic value of the tidal signal is combined with the surge component calculated previously. Storm-induced surge can occur at any time within the tidal signal depending on the tracking of the particular storm in relation to the recording site. To undertake a complete statistical EVA on water levels to include the effects of storm-induced surge, a comprehensive numerical modelling approach would need to be undertaken that incorporates thousands of synthetic storms approaching the study site at different locations/intensities at varying points in the tidal cycle. The large dataset produced through this exercise would then undergo statistical analysis to determine ARI water level events. An undertaking of this magnitude is beyond the scope of this study, however is recommended as a future scope of works to investigate storm-surge (and inundation) for the Tongatapu coast.

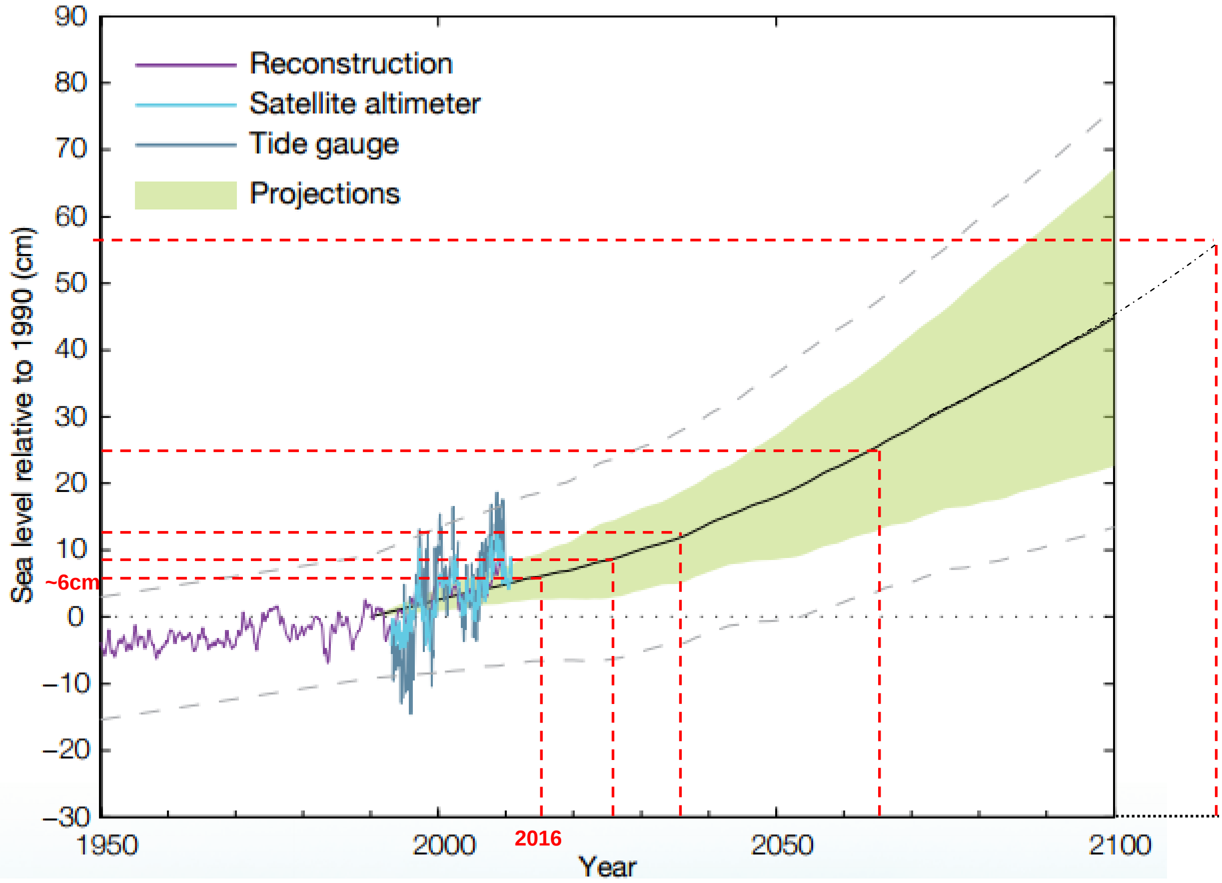
To reasonablyincorporate a surge component into the water level conditions of our wave model, the adjusted residual calculated through the harmonic analysis was added to the predicted water level for the 23.6 year dataset. The positive component of the resultant water level (i.e. WL above MSL) was then used in an EVA, the results of which can be seen in Figure 7.



Dataset	Adjusted Surge + Predicted WL
Threshold	0.7
Distribution Method	GPD
ARI (years)	Water Level (m)
1	0.86
10	0.91
20	0.92
50	0.925
100	0.93

Figure 9Annual Return Interval (ARI, years) of water level (m) calculated on the positive predicted water level + adjusted surge component of the Nuku'alofa Tide Gauge

When projecting design water levels past a 20year horizon, it is necessary to also include a component of sea level rise to the level. The International Climate Change Adaption Initiative (ICCAI) paper *Current and Future Climate of Tonga* (PCCSP, 2014) provides low, medium and high Sea Level Rise (SLR) projections to 2090, as seen in Figure 10



Scenario \ Year	2030 (cm)(median)	2055 (cm)(median)	2090 (cm)(median)
Low Emissions	5 – 16 **(10.5)**	10 – 27 **(18.5)**	16 – 47 **(31.5)**
Medium Emissions	4 – 16 **(10)**	10 – 31 **(20.5)**	20 – 59 **(39.5)**
High Emissions	3 – 17 **(10)**	9 – 31 **(20)**	21 – 62 **(41.5)**

Figure 10 Observed and projected relative sea-level change near Tonga. The observed sea-level records are indicated in dark blue (relative tide gauge observations) and light blue (the satellite record since 1993). Reconstructed estimates of sea level near Tonga (since 1950) are shown in purple. The projections for the medium emissions scenario (representing 90% of the range of models) are shown by the shaded green region from 1990 to 2100. The dashed lines are an estimate of 90% of the range of natural year-to-year variability in sea level. The red-dotted lines have been used to inter/extrapolate values out the design horizon of this study (PCCSP, 2014).

The ARI water levels determined in Figure 9were then combined with the median Medium Emissions Projections (baselined to 2016 data) inter/extrapolated from the graph inFigure 8. The final calculated Design ARI Water Levels can be seen inTable 4.

Table 4 Design ARI water Levels for Nuku'alofa tide Gauge

Dataset		Adjusted Surge + Predicted WL	Median Medium Emissions SLR Projection	Design Water Level
ARI (years)	ARI (year)	Water Level (m)	Water Level (m)	Water Level (m)
1	2016	0.86	0	0.86
10	2026	0.91	0.03	0.94
20	2036	0.92	0.06	0.98
50	2066	0.925	0.19	1.12
100	2116	0.93	0.52	1.45

4.1.1 Wind and Tropical Cyclones

The development of tropical cyclones (TC) occurs on an annual basis from November 1 to April 30 in the South Pacific basin between 160°E and 120°W. Most tropical cyclones have their origins within the South Pacific Convergence Zone or within the Northern Australian monsoon trough, both of which form an extensive area of cloudiness and are dominant features of the season. Within this region a tropical disturbance is classified as a tropical cyclone, when it has 10-minute sustained wind speeds of more than 65 km/h, that wrap halfway around the low level circulation centre, while a severe tropical cyclone is classified when the maximum 10-minute sustained wind speeds are greater than 120 km/h. There were 82 TCs which crossed within500km of the coast of Tongatapu between1969-2010 as seen in Figure 9.

Figure 11 Historic tropical cyclones tracking within 500km of the Tongatapu coast between 1969-2010. (BoM, 2016).

Understanding the effects of TCs on the study site is important in order to define the necessary boundary conditions for the numerical wave model. TC's have the ability to produce extreme wave events (purple circles,

Figure 1) depending on the nature of their track and their intensity. The transformation of these large waves into the study site will be investigated within the numerical model.

The pressure effects of tropical cyclones will cause the water level in the open ocean to rise in regions of low atmospheric pressure and fall in regions of high atmospheric pressure. The rising water level will counteract the low atmospheric pressure such that the total pressure at some plane beneath the water surface remains constant. This effect is estimated at a 10 mm increase in sea level for every millibar (hPa) drop in atmospheric pressure. Associated strong surface winds cause "wind set-up", increasing water levels of the downwind shore, and to decrease upwind. The pressure effect and the wind set-up on an open coast will be driven into coastal lagoons in the same way as the astronomical tide.

Due to the location of the Nuku'alofa tide gauge at the southern end of the Tongatapu Lagoon, the water level analysis undertaken in the previous section (4.1.2) has incorporated readings which include the effects of storm surge and wind-setup. As such, additional hydrodynamic modelling will not be required to produce these influences on the study site.

As outlined in Section 4.1.1, waves will enter the model domain along each of the North, South, East and West boundaries (Figure 12, Figure 15) based upon the EVA of the NOAA1 and NOAA2 data extraction points. Once these waves have entered the domain there will still be a propensity for further wave growth due to wind over water along each of the fetch lengths leading to the study site. As such, a further EVA of wind speeds along each of the modelled fetch directions (0°:45°:360°) is required in order to determine the amount of wave growth that may occur due to sustained wind speeds.

Hourly sustained wind speed data was analysed from the Fua'amotu International Airport Meteorological Station over the period 1993-2016. The data was separated into each directional sector and an EVA was undertaken on average hourly wind speeds. Although also available, wind-gust and 10minute-average wind speed data as expected was much higher than the analysed time period. However the minimum temporal resolution of one hour was considered acceptable for use in the determination of wind-wave growth over each of the fetch-lengths defined in the model domain. The results of the EVA Wind Speed analysis can be seen in Table 5and detailed graphs in Appendix C.

Table 5Extreme Value Analysis of wind speeds (m/s) data from the Fua'amotu International Airport Meteorological Station for the period 1993-2016 for each directional sector

Directional Sector		**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
EVA Distribution Method		Weibull	GPD*	GPD*	GPD*	GEV**	GEV**	GPD*	GPD*
Wind Speed Threshold (m/s)		10	10	10	10	6	7	6	10
Annual Recurrence Interval (years)		**Wind Speed (m/s)**							
	1	14.2	12.6	8	10.5	7.5	7.6	11	15
	10	22.2	17.5	18	15	13.5	9.2	18.4	21.5
	20	25	18.9	23	17.7	17.5	9.8	21	23.5
	50	28.2	20.7	28	22.5	25	10.7	24.2	26
	100	30.5	21.5	36	28.2	34	11.7	26.5	27

*****_Generalised Pareto Division_

**Generalised Extreme Value Distribution

4.1.2 Bathymetry

Bathymetry data has been obtained from three (3) key sources to represent both the nearshore inter-tidal zone and the deeper offshore bathymetry governing the transformation of waves into the study site. Offshore of Tongatapu, bathymetric data was sourced from the 2014 GEBCO 30 arc-second global grid of elevations. The grid has been largely generated by combining quality-controlled ship depth soundings with interpolation between sounding points guided by satellite-derived gravity data to create a continuous terrain model for ocean and land. The extracted grid for this study can be seen in Figure 12. The northern border of the extracted grid lies on the latitude of the NOAA1 extraction point. The eastern and southern borders were selected to intersect the NOAA2 extraction point. The western boundary was selected due to its relatively uniform bathymetry.

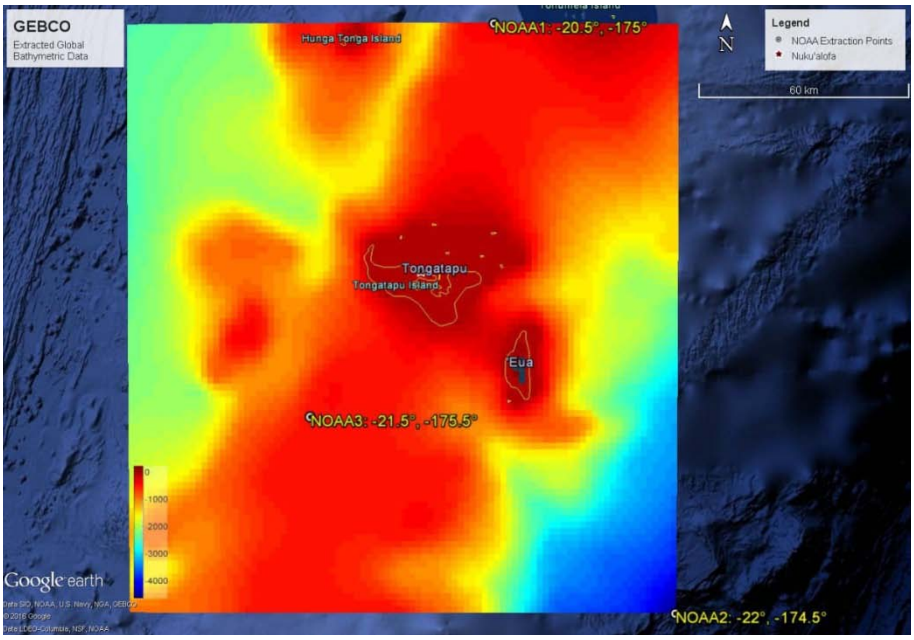


Figure 12 Extracted bathymetric data from the GEBCO Global Bathymetric Dataset

Higher resolution bathymetry in close proximity to Tongatapu has been sourced from several navigational charts supplied by the Hydrographic Office of the Royal New Zealand Navy (RNZN, 1996). The bathymetric data varies in horizontal resolution of between 500m–3km and has been digitized from the hard copy charts. The dataset was used to 'fill the gaps' between the low resolution GEBCO data in proximity to Tongatapu and the high resolution 2011 LiDAR survey which is only applicable to an approximate 40m depth. The charts were geo-rectified into GIS software and the bathymetric soundings were digitised for use in domain generation for the modelling, Figure 13.

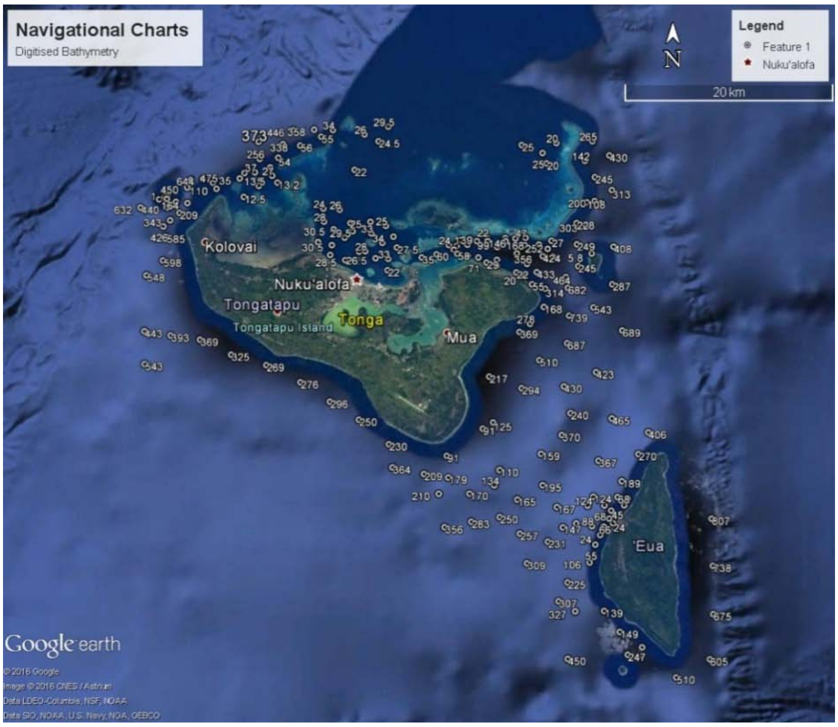


Figure 13 Digitised bathymetric data from the Tongatapu Navigational Chart, (RNZN, 1996)

A comprehensive LiDAR (land + marine) survey was undertaken in 2011 as part of the Australian Government's International Climate Change Adaptation Initiative (ICCAI), the Pacific Adaptation Strategies Assistance Program (PASAP) and it's continuation the Pacific Australia Climate Change Science and Adaptation Planning (PACCSAP), (AusAid, 2011). The dataset has been reduced to 5m horizontal resolution to match the resolution of the modelling domain, this data can be seen in Figure 14.

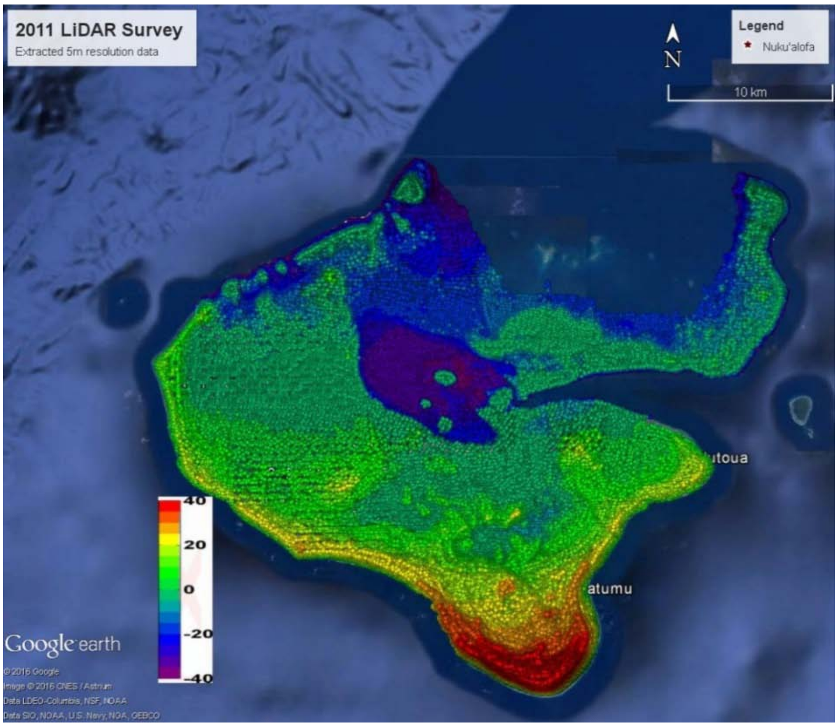


Figure 14 Extracted bathymetric data from the 2011 Tongatapu LiDAR survey. The data has been reduced to 5m resolution.

4.2 Numerical Model

A MIKE21 Spectral Wave (SW) Flexible Mesh (FM) model was setup for the study site. The MIKE21FM SW model is a third generation spectral wind-wave model based on unstructured meshes, giving the opportunity to vary resolution around complex bathymetric and topographic features. The FM module was selected due to the complexity of the offshore bathymetry of the study site. The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas.
MIKE 21 SW includes the following physical phenomena:

- wave growth by action of wind;
- non-linear wave-wave interaction;
- dissipation due to white capping;
- dissipation due to bottom friction;
- dissipation due to depth-induced wave breaking; and
- refraction and shoaling due to depth variations.

4.2.1 Domain

An unstructured flexible mesh was created to encompass a regional domain of Tongatapu Island covering almost 26,000km^2 stretching 1.5° in latitude and 0.5° in longitude. The domain was setup to include the NOAA2 extraction point on its southern and eastern boundaries and the NOAA1 point along it northern edge, as seen in Figure 12. The domain for the SW model can be seen inFigure 13. Unstructured flexible mesh resolution varies from approximately 1km offshore to 10m in the nearshore areas around the Hahake coastline, with varying resolution in areas of numerical interest; i.e. abrupt changes in bathymetry around islands, channels and coral cays.

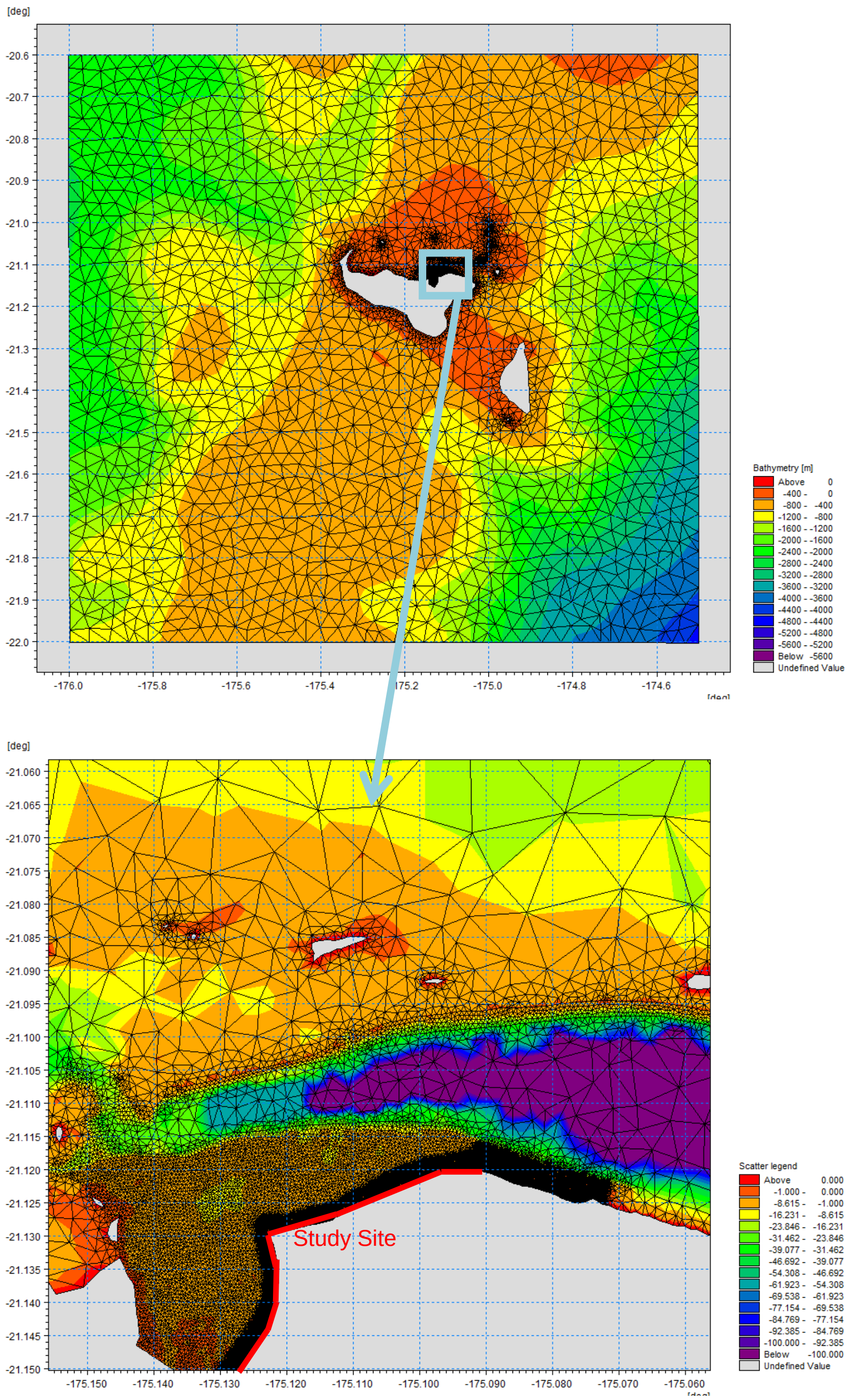


Figure 15 Regional and local views of the unstructured mesh resolution of the MIKE21 SW model domain

4.2.2 Model Forcing and Parameterisation

A matrix of model runs was defined based on the combination of (5) Design ARI water levels and (5) Design ARI offshore wave heights from each (8) directional sector. Five (5) different simulations of the model domain specified in Figure 14 were run based upon the five water levels determined in the ARI analysis (Figure 8). The wave model was simulated using the following model forcing:

- Spatially uniform wind field using the ARI wind speeds and directions provided in Table 4
- Steady state solution, providing a fully developed sea state for each condition.

This matrix approach was used to simulate all five (5) ARI water levels for each of the five (5) ARI offshore wave heights for each directional sector. These 25 model simulations were completed for each wave direction (on a8-point compass). A total of 200 simulations were completed.

The SW model was run using a quasi-stationary time formulation, meaning the time is removed as an independent variable and a steady state solution is calculated at each time step. The model used a fully spectral formulation, based on the wave action conservation equation, where the directional-frequency wave action spectrum is the dependant variable. These selections were made to ensure efficiency of model run times and to correctly resolve wind-wave growth through the selected domain.

4 Results

Wave parameters were extracted at 100 evenly-spaced locations from Nukuleka to Kolonga a short distance seaward of the existing foreshore. These locations can be seen in Figure 16.

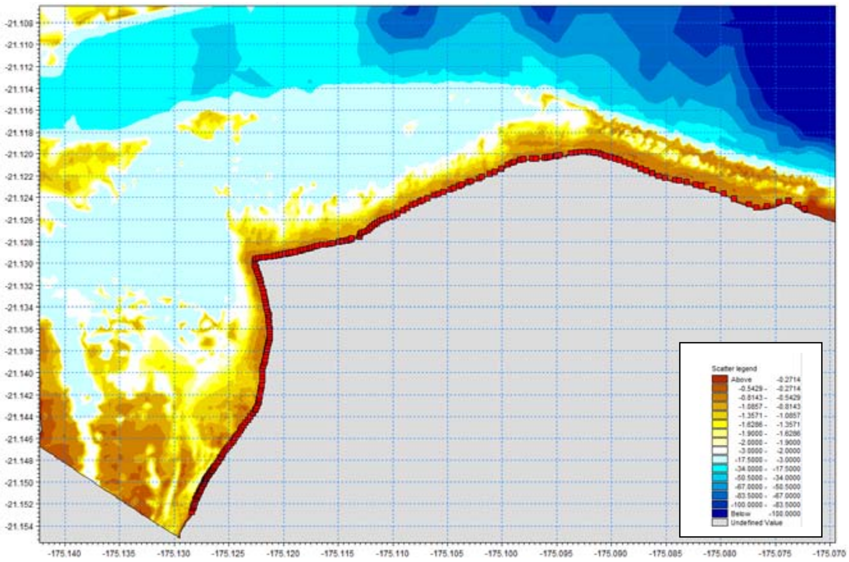
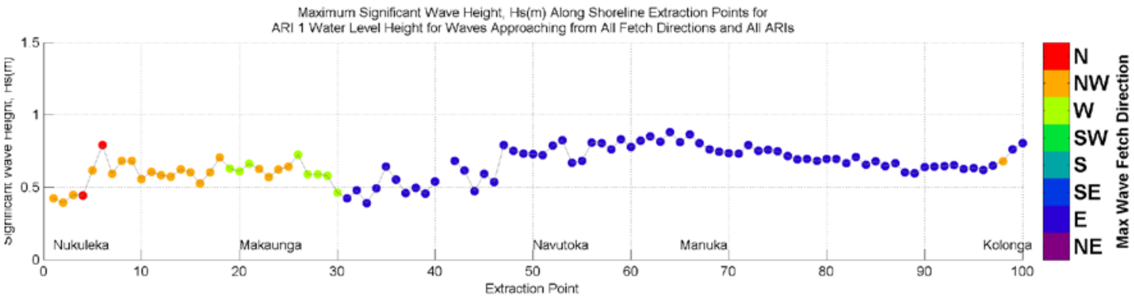
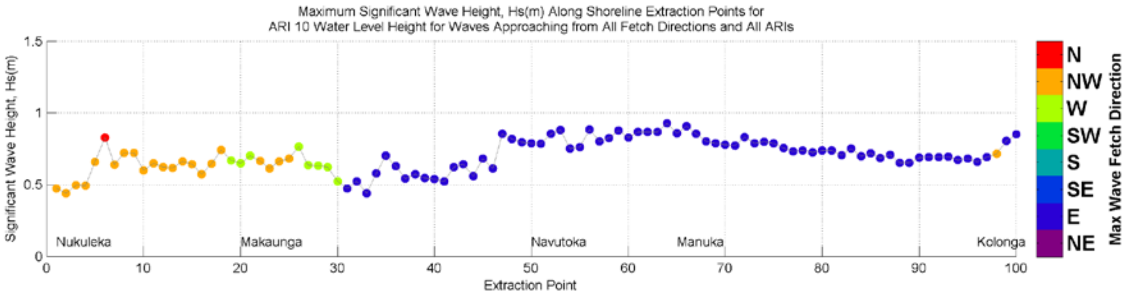


Figure 16MIKE21FM SW wave data extraction points.

Plots of combined 1, 10, 20, 50 and 100 year ARI water level (+ storm surge) and offshore wave height (Hoff) + wind speed (and direction) and resultant significant wave heights (Hs), peak wave period (Tp) and peak wave direction (Dp) at each of the extraction points are provided in Appendix D.

From the model results (Appendix D) it can be seen that each section of the Hahake coastline is affected by waves generated from different fetches in different manners. The maximum significant wave height (Hs) was extracted at all points over all modelled scenarios to gain an understanding of which coastline sections are most affected by the differing fetch directions, the results of this analysis can be seen in Figure 17.





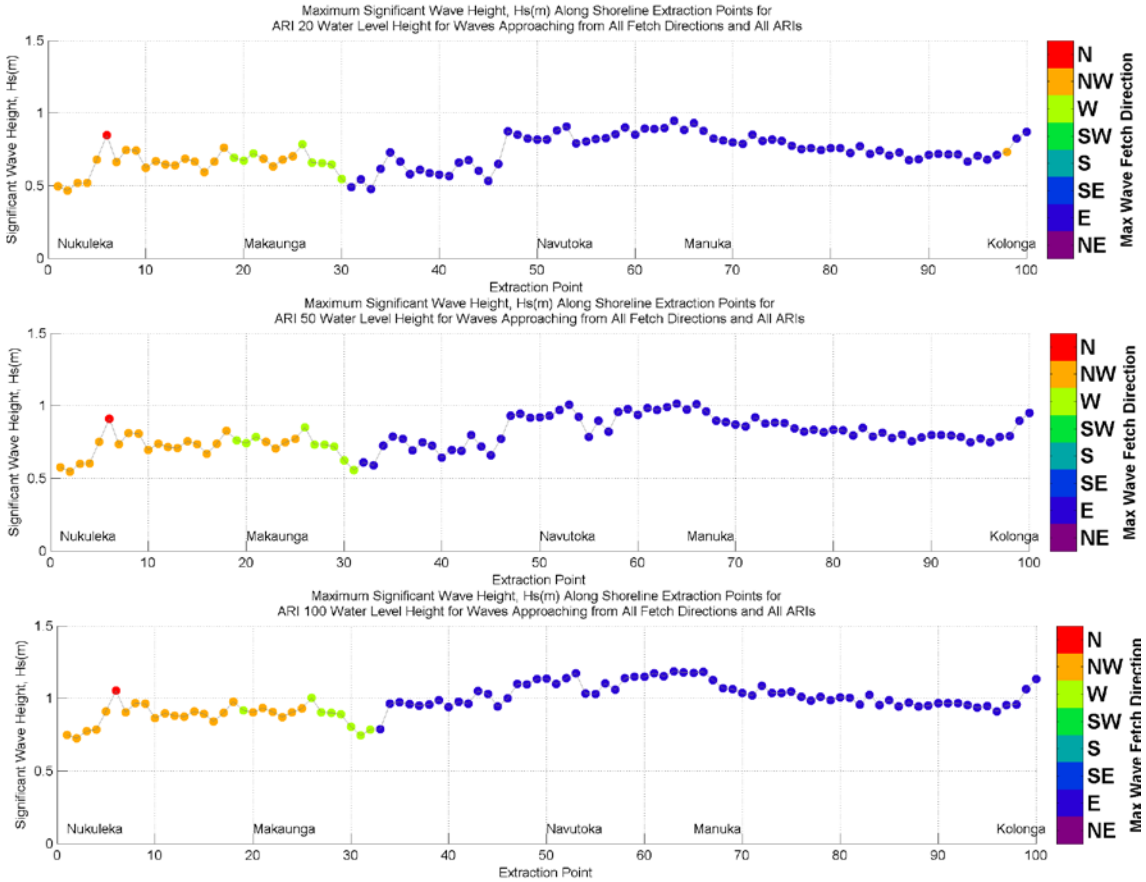


Figure 17Maximum Significant Wave Height, Hs(m) along Hahake shoreline extraction points for ARI 1, 10, 20, 50, 100 year water level for waves approaching from all fetch directions under all ARI conditions

From this analysis, it can be seen that there is a clear link between wave height and water level. Increased water level over the model domain leads to increased wave height at the extraction points. This is due to less energy being dissipated offshore of the study site (at the reef platform edge) due to wave breaking. Some fetch lengths are also increased due to the increased water depth over shallow reef sections now being submerged. This leads to greater wind wave growth over these directions. This is most evident in the west-facing Makaunga section where fetch lengths are increased as the water level increase submerges sections of “The Narrows” adjacent to the intersection of the Piha Passage and the Tongatapu Lagoon.

Moving east from Makaunga (~Point 25) a clear separation between the incoming direction of the offshore waves and their impact on different sections of the coast is evident. The coastline to the west of this section (Sandy Point) is impacted more heavily by waves from the North through to the west whereas the coastline to the east is impacted by waves from the east through to the south. This is to be expected due to the orientation of the coastline in each section being open to each of these fetch directions.

It can also be seen that the maximum Hs extracted from the model varies by about 50cm from the far west (Nukuleka) to the far east (Kolonga). As such it was deemed necessary to separate each section of the coast based upon orientation and maximum modelled wave heights experienced. The seven coastal segments can be seen in Figure 18.

Figure 18 Hahake coastal segments and corresponding data extraction points.

The three predominant fetch directions impacting the Hahake Coastline as seen in Figure 17 are offshore wave (Hoff) + wind (Wspd) approaching the study site from the; North West (NW), West (W), and the East (E). 2D Significant wave height (Hs) plots offshore of the study site can be seen in Figure 19 and Figure 20for each of the above offshore wave directions at ARI 100year Hoff at the ARI 100year water level (largest wave condition).

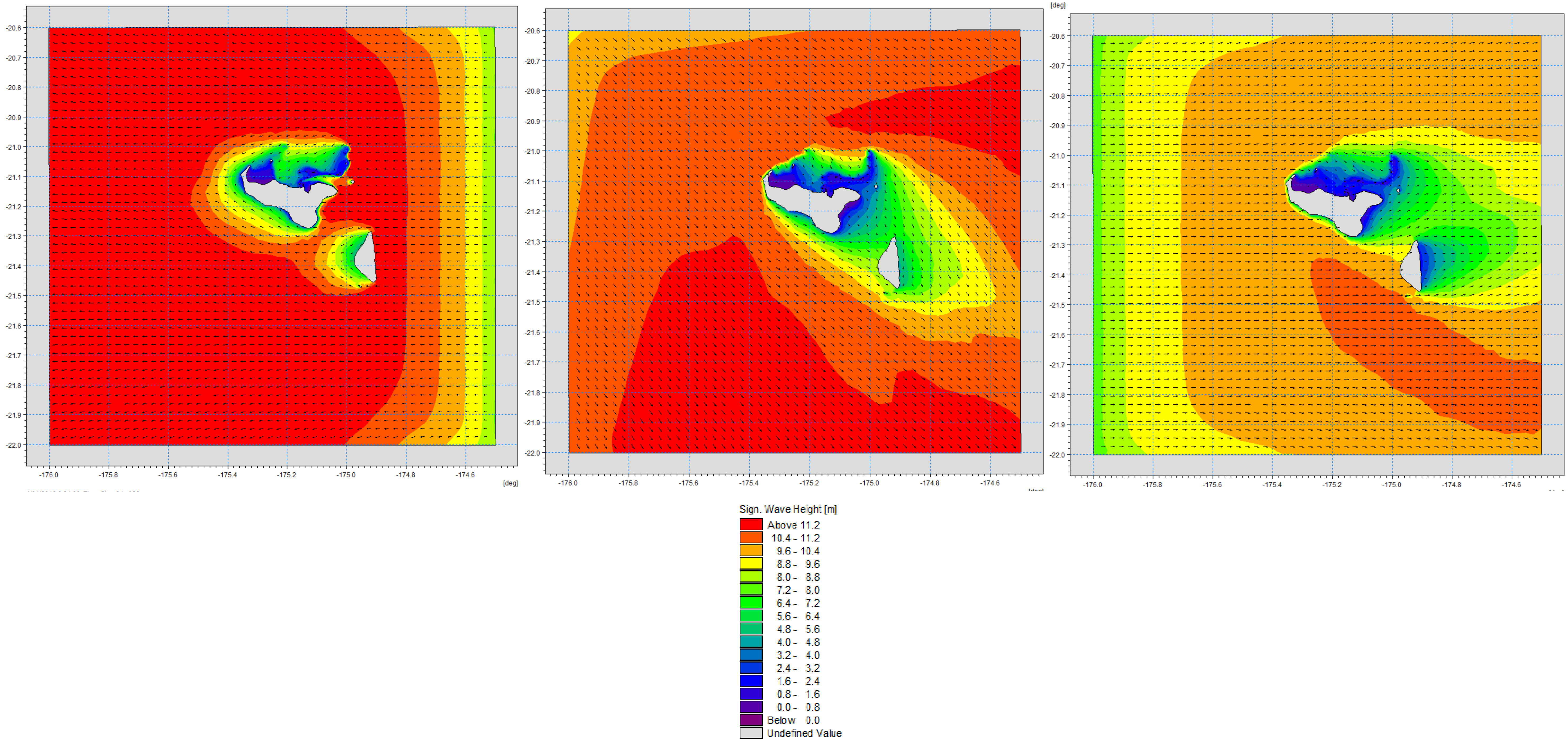


Figure 19 2D spatial plot of Significant Wave Height Hs(m) from a MIKE 21SW modelled ARI 100year Offshore Wave Height (Hoff) + ARI 100 year wind speed (Wspd) + ARI 100 year water level for East (left), North West (middle) and West (right) fetch directions across regional model domain, note legend extent

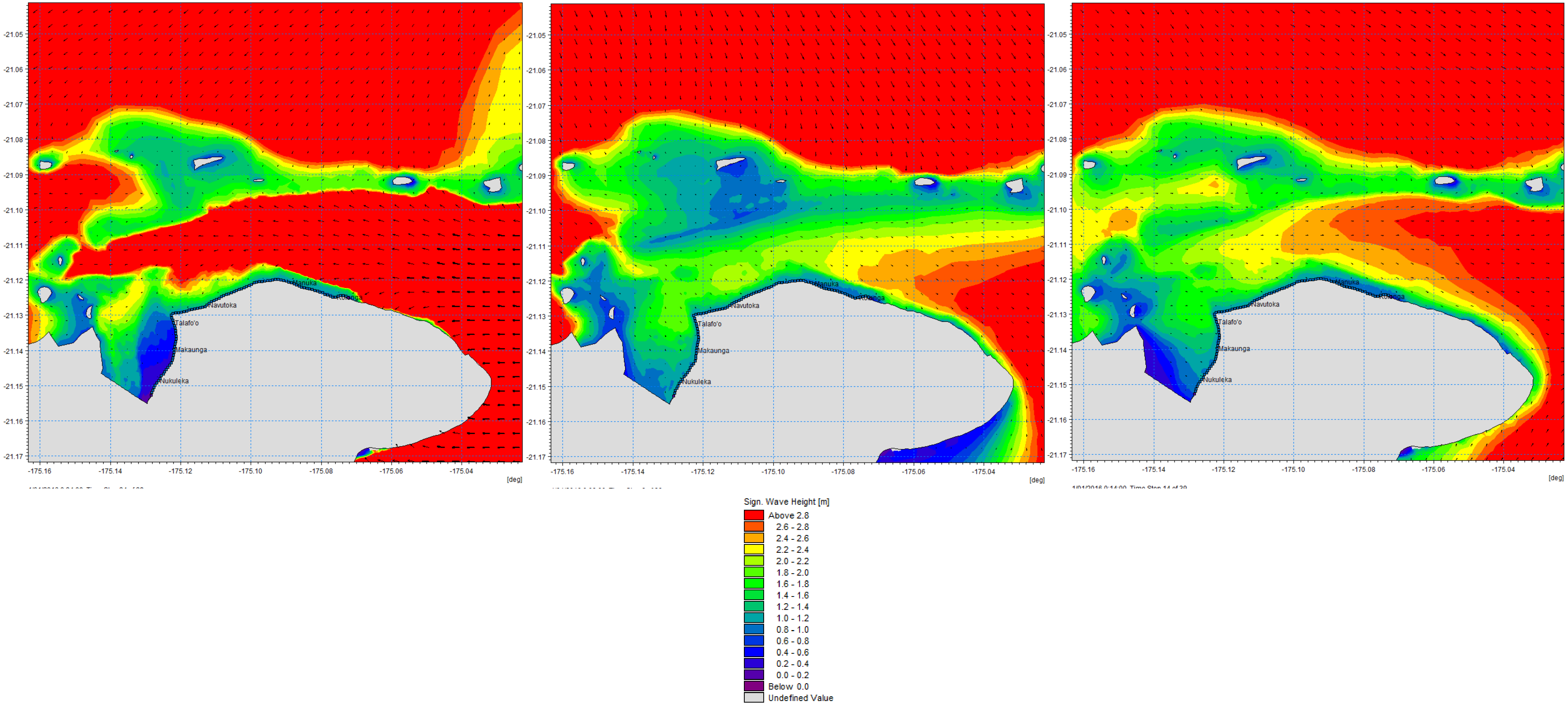
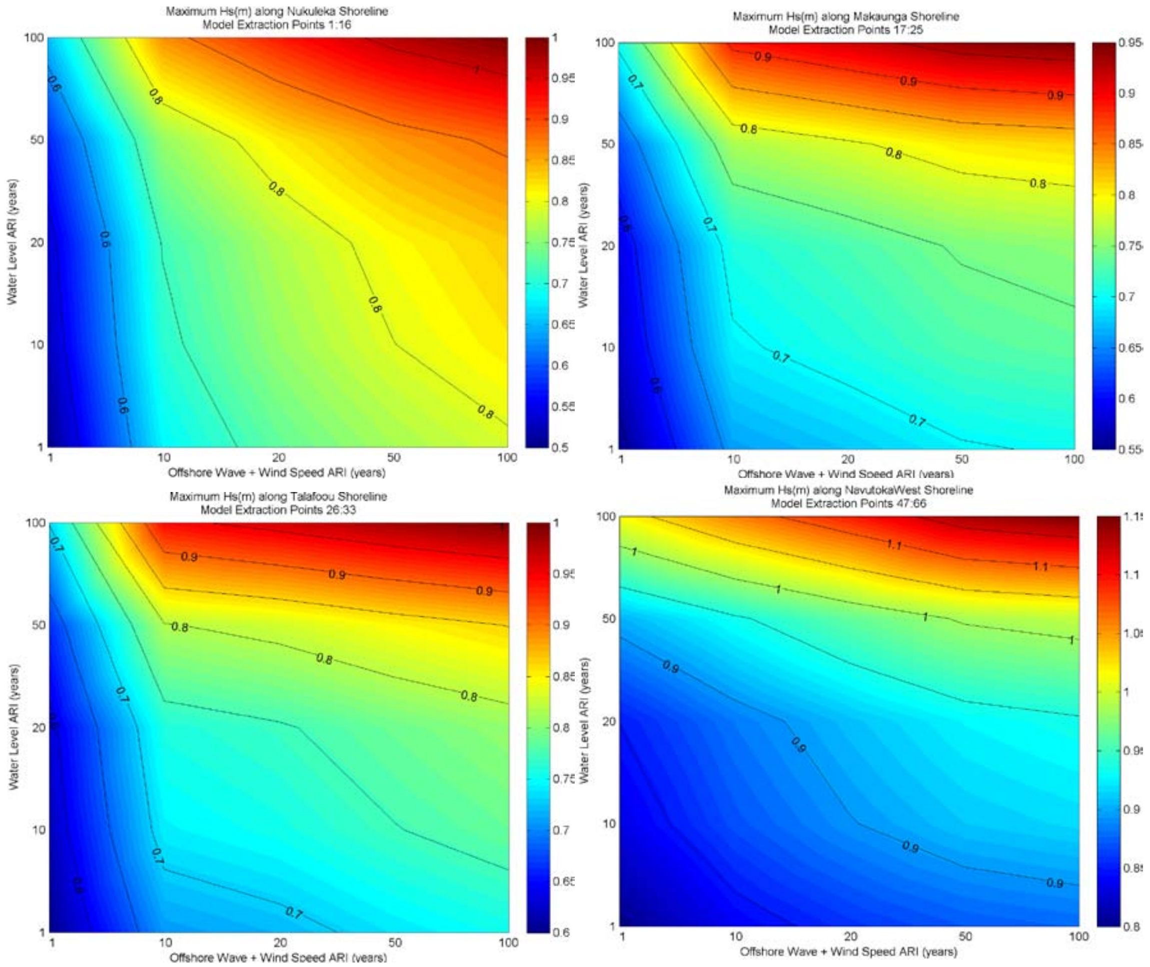


Figure 20 2D spatial plot of Significant Wave Height Hs(m) from a MIKE 21SW modelled ARI 100year Offshore Wave Height (Hoff) + ARI 100 year wind speed (Wspd) + ARI 100 year water level for East (left), North West (middle) and West (right) fetch directions offshore of the study site, note legend extent.

The complex transformation processes occurring offshore of the study site are clearly seen in the representations in Figure 20. An interesting finding of the modelling was the maximum wave heights occurring along the Makaunga section of the study site. This section of coastline (although facing west) appears to have a very small physical fetch length. However due to the severity of the ARI 100 year westerly wind condition (26.5m/s) sustaining growth of westerly waves into the site combining with the residual wave energy travelling through The Narrows (deepened by the ARI 100yr water level), the westerly boundary condition proved to be the determining wave height at this section of the coastline.

The resulting Hs(m) at each of the coastal sections outlined in Figure 18 as a matrix of water level ARI and Hoff + Wspd ARI can be seen inFigure 21. The associated Tp(sec) and Dp(deg) values for each coastal section can be seen in Appendix E.



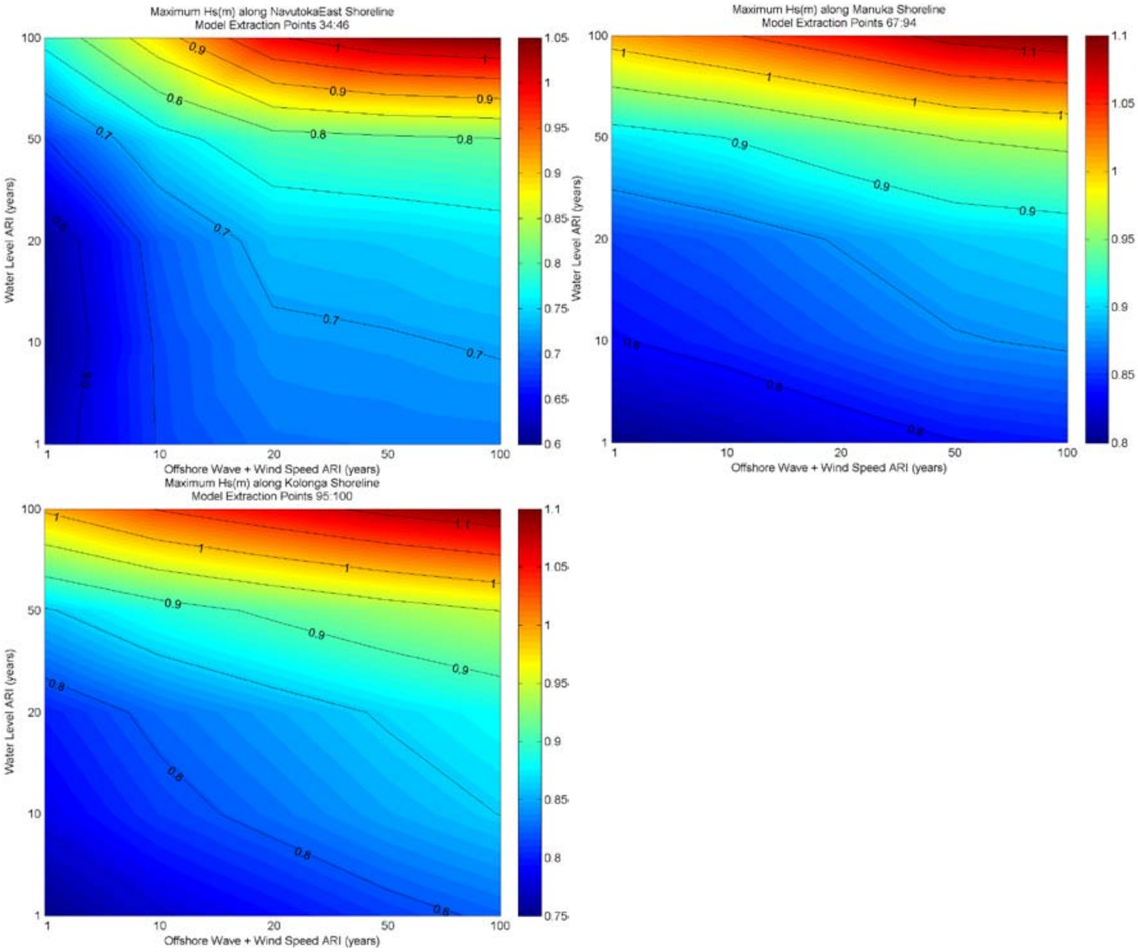


Figure 21Hs(m) at each Hahake coastal section as a matrix of water level ARI and Hoff + Wspd ARI

5 Discussion

The design wave heights given for each of the Hahake coastal sections (Figure 21) have been provided as a function of return period offshore wave height + wind speed and water level. Moving forward with the design process, a determination will need to be made by the project team as to the accepted level of protection the proposed coastal structures will be designed to withstand. A combination of an ARI 100year Hoff + Wspd and 100yr ARI water level, does not necessarily result in an ARI 100 year design, however would be more closer to an ARI 1000 year design. In reality it will most probably be a combination of ARI events (i.e. ARI 10yr Hoff + Wspd with an ARI 50 year Water level or some combination of each) that is used for the design calculations.

It is recommended that the decision as to which ARI design combination is used should be based upon the influence the design wave height will have on structure size and ultimately total project budget. These options will be specified in a subsequent engineering options assessment report, which will be finally followed by the Coastal Protection Priority Matrix and the detailed structure design.

It needs to be reiterated that no matter what coastal protection measure is put in place, it should only be viewed as a temporary solution to the inundation problems at the project site. More specifically, that the structure to be designed in the following reports should be viewed as an upgrade to the existing (failing) seawall in response to the advancement (and rising) of the coastal road. Ultimately as per the recommendation of (Webb, 2016) and (Lewis, 2016) the only long-term coastal protection solution for the study site is a planned retreat of both private (houses, etc) and public (road) infrastructure out of the active coastal zone.

4.3 Limitations

In general the approach described herein provides a conservative approach to the representation of design wave conditions at the Hahake coastline. However, as noted in the report, the lack of wave and water level measurements in close proximity to the site means that verification of the model and the correct use of model parameters is left to the experience of the modeller. The following limitations to the modelling approach have been noted below to ensure transparency in the design process.

- Recent studies have found that there is an increased wave setup over coral reef platforms in comparison to homogenous sandy coastlines. In order to correctly account for this additional water level it was found that non-linear (Boussinesq-type) models have shown a good representation of these phenomena. The location of the Nuku'alofa tide gauge has been used as a proxy to water levels at the site and although its location is in proximity to a coral platform the extent of this effect will certainly be different to that obtained at the study site. The use of non-linear models to investigate this effect (if any) could be undertaken in the future but at this stage is considered out of scope.
- Wave runup increases for lower bed roughness (coral degradation), creating a 'smoother' platform for the waves to travel across. Uniform bed roughness has been applied in this model due to lack of data relating to this factor. Wave runup and overtopping will be determined in the proceeding design options assessment report using empirical methods.
- The combination of offshore wave and wind speed in the approach above can be considered overly conservative. Although the larger wave heights used for the analysis are most certainly the result of cyclonic activity and the corresponding largest wind speeds will also be due to the same cyclone, a specific joint frequency analysis needs to be undertaken to determine if the combination of each design event occur in concurrence. For example the design ARI 100year offshore wave height that occurred across a NE fetch may not have occurred in combination with ARI 100year wind speed from the same direction. Instead this wind speed may have occurred in concurrence with this wave

condition from a N or an E sector or vice versa. Modelling of these combinations will nevertheless produce smaller Hs at the study site. As such the approach taken to combine these events can be considered a 'worst case scenario' and as conservative.

- As this is purely a numerical wave (SW) modelling exercise, the effects of hydrodynamics on wave transformation have not been accounted for. As such, wave-current interaction offshore of the study site due to tidal exchange between the lagoons and the ocean has not been accounted for. However due to the deep bathymetry of the Piha Passage offshore of the site it is envisaged that the only areas where wave-current interaction may (if at all) occur would be the shallower sections adjacent to 'The Narrows' where current speeds are high. As recommended in (Lewis, 2016) a subsequent hydrodynamic (HD) modelling exercise incorporating Tongatapu should be undertaken in the future.

References

AusAid, 2011.*Tonga LiDAR Factsheet.*Prepared by Australian Aid for the Australian Government, 2011.

Barstow, S., Haug, O. (Barstow & Haug, 1994a) *The Wave Climate Of The Kingdom of Tonga.* SOPAC Technical Report 201.OCEANOR, June 1994.

Barstow, S., Haug, O. (Barstow & Haug, 1994b) *The Wave Climate Of The Southwest Pacific.* SOPAC Technical Report 206.OCEANOR, December 1994.

Lewis, J. 2016. *HAHAKE COASTAL PROTECTON SUBPROJECT Coastal Process, Monitoring & Engineering Options Assessment: Scoping Document.* Produced for the Government of Tonga Ministry of Infrastructure by SMEC-ITS, 30th October 2016.

Mead, 2013.*Review of Historical and Recent Studies Pertaining to Erosion of Eastern Tongatapu, Tonga.*Prepared for SPC – GCCA: PSIS.eCoasts. May, 2013.

PCCSP, 2014.*Current and future climate of Tonga*. International Climate Change Adaption Initiative, Pacific Climate Change Science Program, 2014.

RHDHV, 2016.*Cooktown Waterfront Wave Modelling.* Technical Note prepared for Cook Shire Council, 19th September, 2016.

RNZN, 1996.*Tongatapu Navigational Chart.*Hydrographic Office of the Royal New Zealand Navy.

SMEC/ITS, 2015.*Grant No. 0378-TON – Climate Resilience Sector Project Design and Supervision consultants – Project Implementation Unit - Civil Engineering Division of the Ministry of Infrastructure: Technical Proposal.16 October 2015*

SMEC/ITS, 2016.*Climate Resilience Sector Project (CSRP) Detailed Design and Construction Supervision PIU - Ministry of Infrastructure: Inception Report.*July 2016.

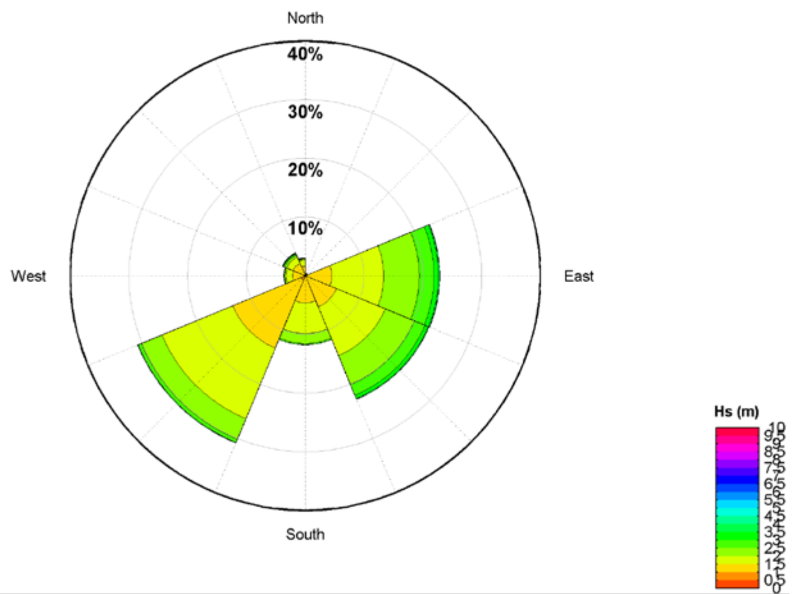
SOPAC, 1995.*Coastal Protection inthe South Pacific*.SOPAC Technical Report 190. March, 1994.

Webb, A., 2016. *Coastal Processes, Monitoring & Engineering Options Assessment: Nukuleka to Kolonga shorelines, west Tongatapu.* Grant No. 0378-TON – Climate Resilience Sector Project –PIU_ Civil Engineering Division of the Ministry of Infrastructure, Tonga. September, 2016.

Appendix A: Annual and Seasonal Joint History Analysis of NOAA Global Hindcast Wave Model Extraction Points

NOAA1:

Wave Height and Direction Rose, 106889 Records, 01-Jan-1979 to 01-Aug-2015



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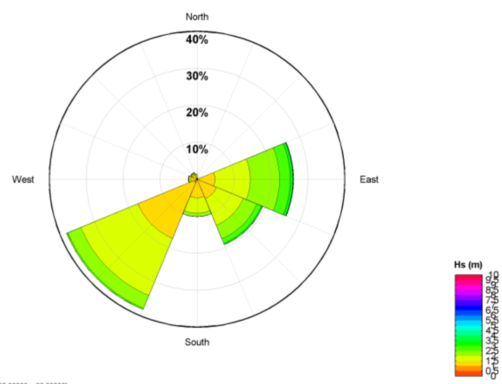

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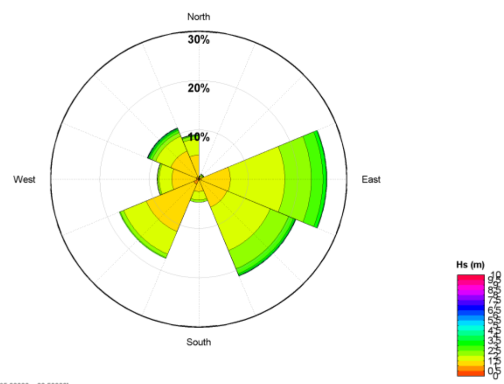
Wave Height and Direction Rose, 26464 Records, Summer



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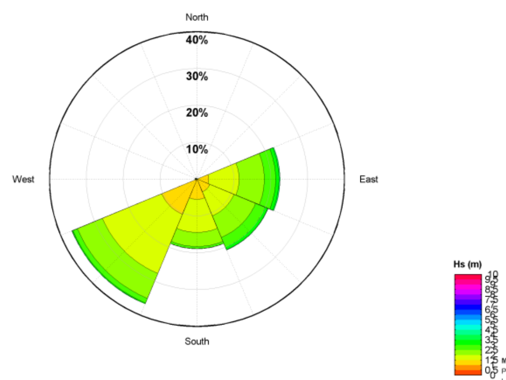
Number of Records: 26464

Wave Height and Direction Rose, 26985 Records, Winter



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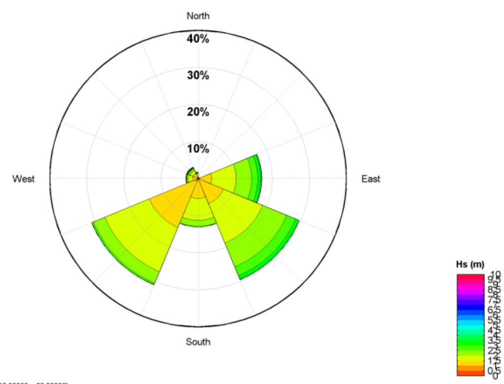
Wave Height and Direction Rose, 27232 Records, Autumn



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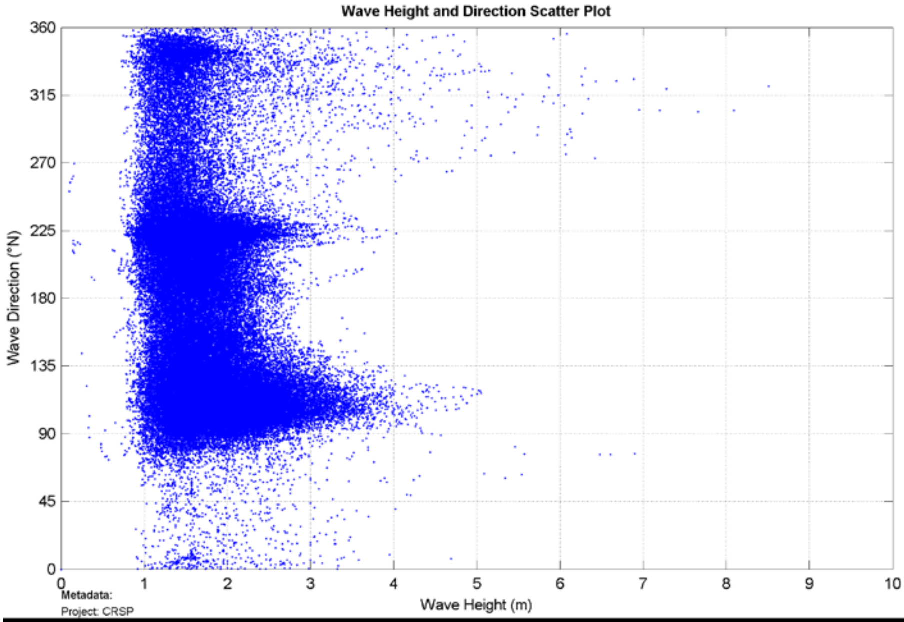
Wave Height and Direction Scatter Plot
Wave Direction (°N)
Wave Height (m)
Metadata:
Project: CRSP

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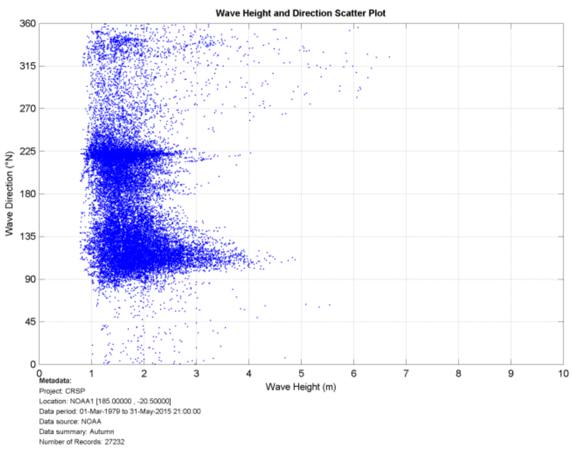
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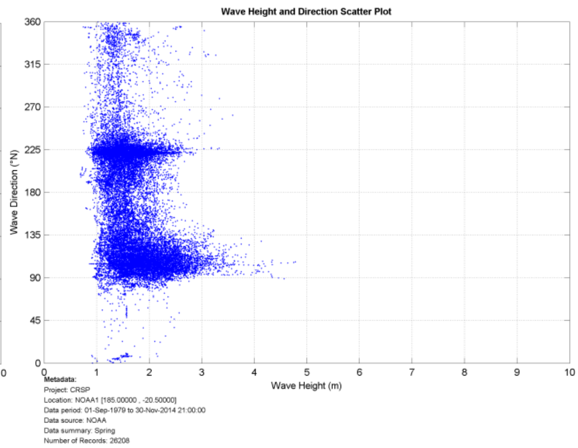
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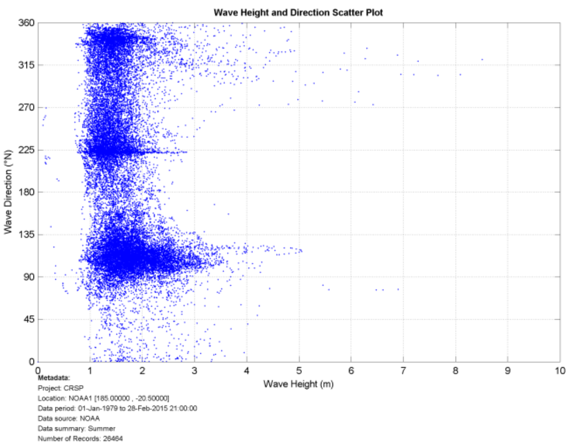
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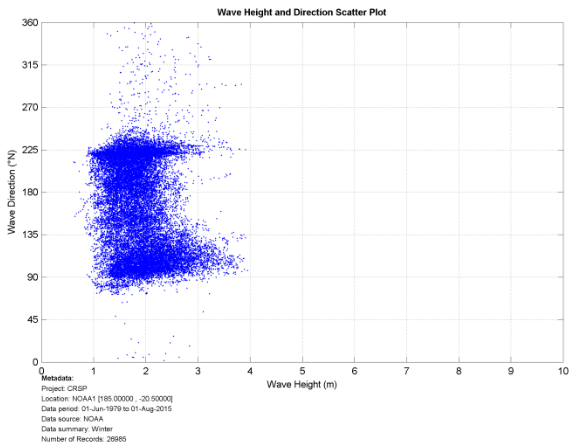
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Wave Height (m)
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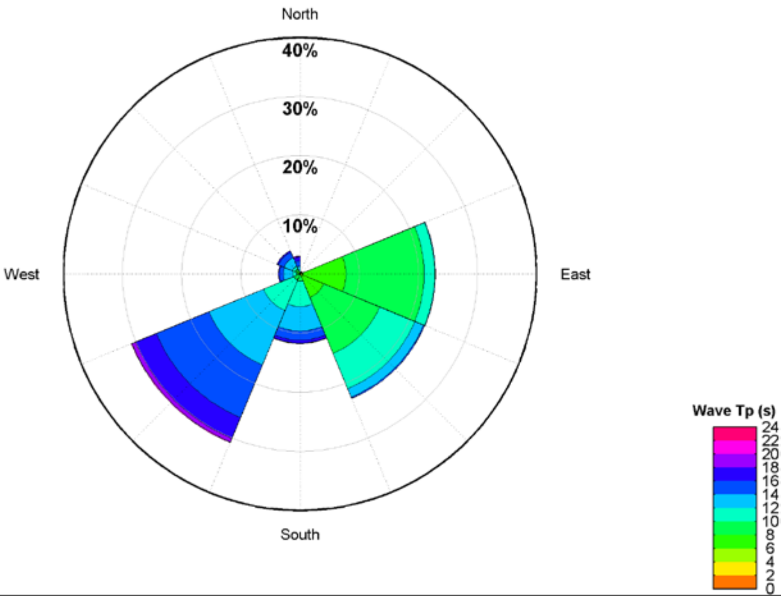
Data source: NOAA
Data summary: Winter
Number of Records: 26985

Wave Period and Direction Rose, 106889 Records, 01-Jan-1979 to 01-Aug-2015



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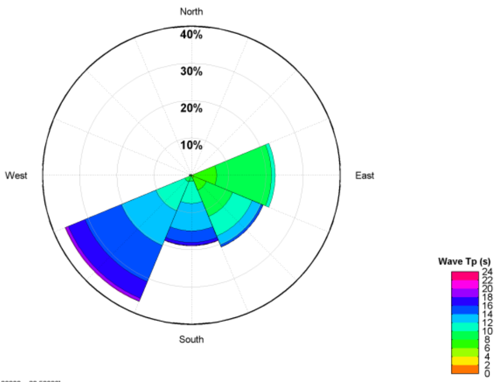
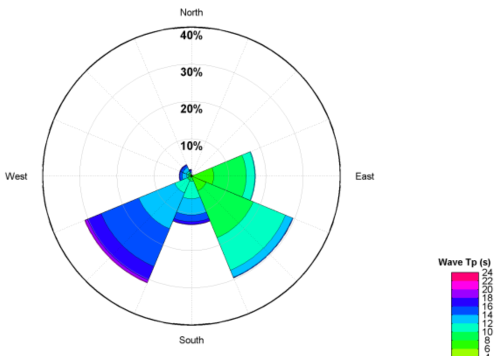
Project: CRSP
[redacted]

Wave Period and Direction Rose, 26985 Records, Winter



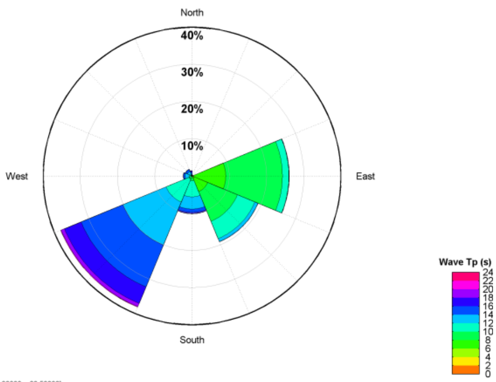
Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Jun-1979 to 01-Aug-2015
Data source: NOAA
Data summary: Winter
Number of Records: 26985

Wave Period and Direction Rose, 27232 Records, Autumn



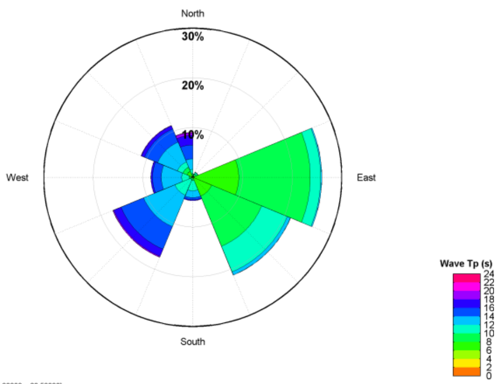
Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Mar-1979 to 31-May-2015 21:00:00
Data source: NOAA
Data summary: Autumn
Number of Records: 27232

Wave Period and Direction Rose, 26208 Records, Spring

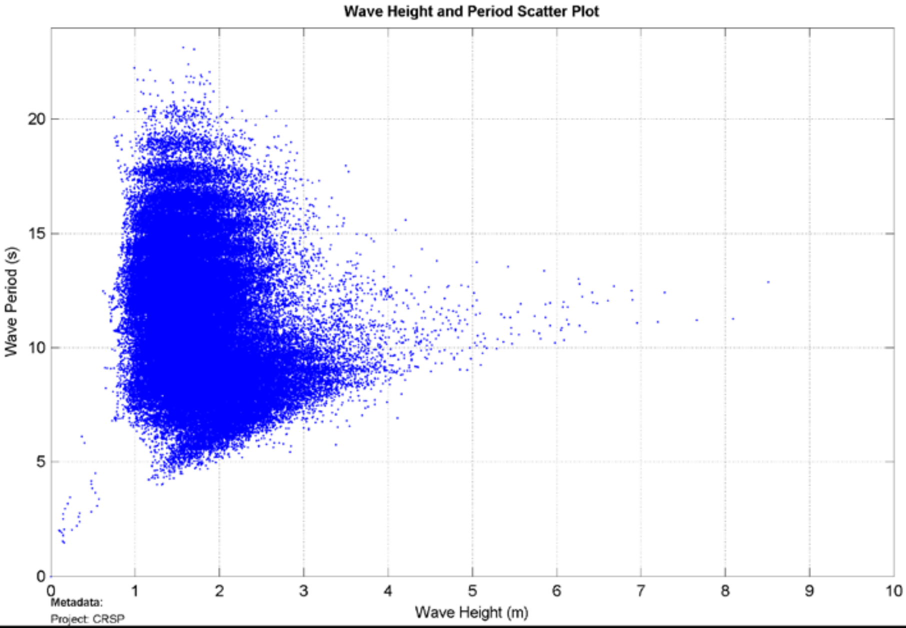


Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Sep-1979 to 30-Nov-2014 21:00:00
Data source: NOAA
Data summary: Spring
Number of Records: 26208

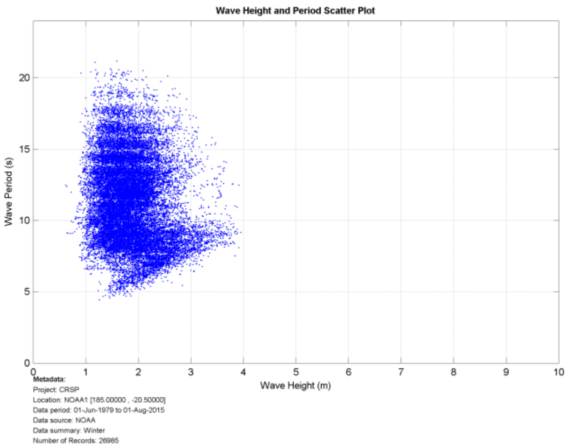
Wave Period and Direction Rose, 26464 Records, Summer

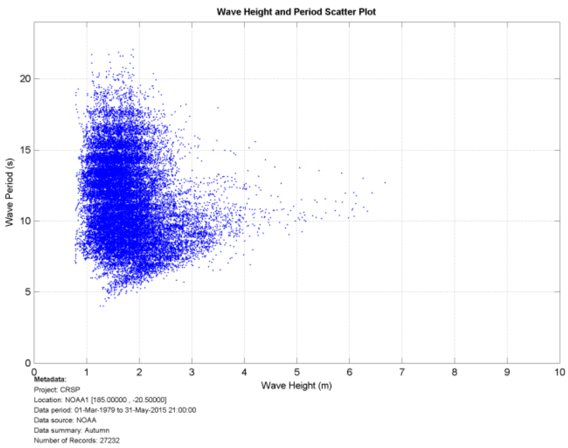


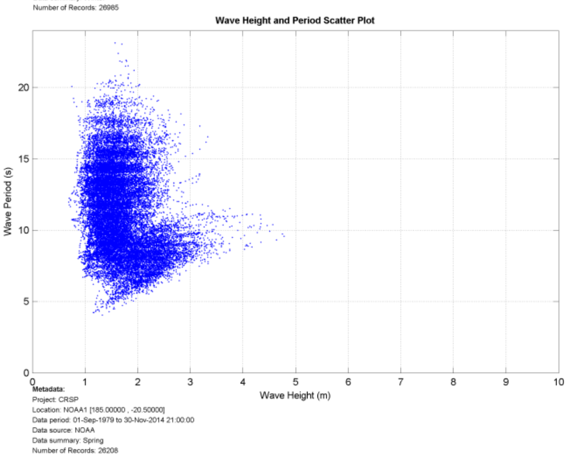
Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Jan-1979 to 28-Feb-2015 21:00:00
Data source: NOAA
Data summary: Summer
Number of Records: 26464

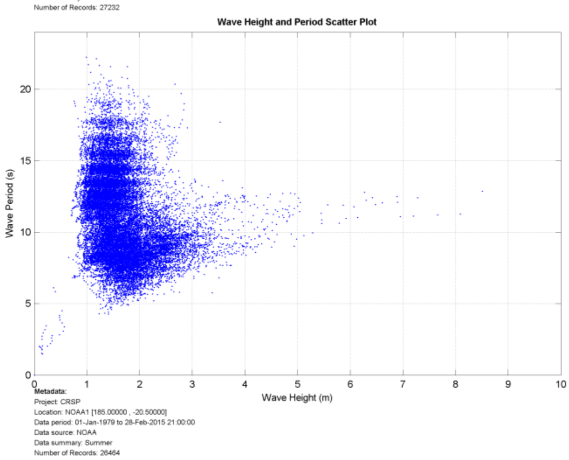

Wave Height and Period Scatter Plot
Wave Period (s)
Wave Height (m)
Metadata:
Project: CRSP

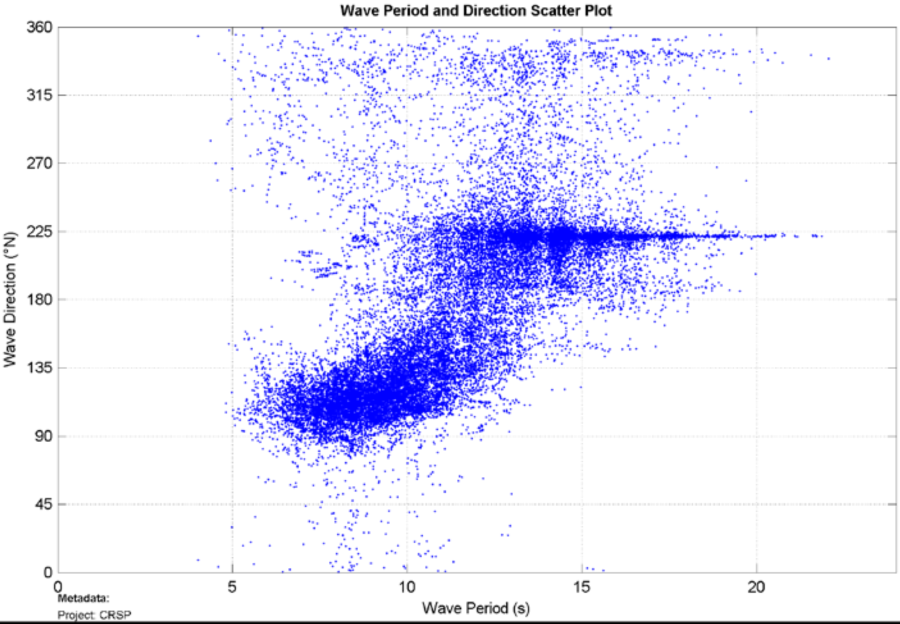
[redacted]


Wave Height and Period Scatter Plot
Wave Period (s)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Jun-1979 to 01-Aug-2015
Data source: NOAA
Data summary: Winter
Number of Records: 26965

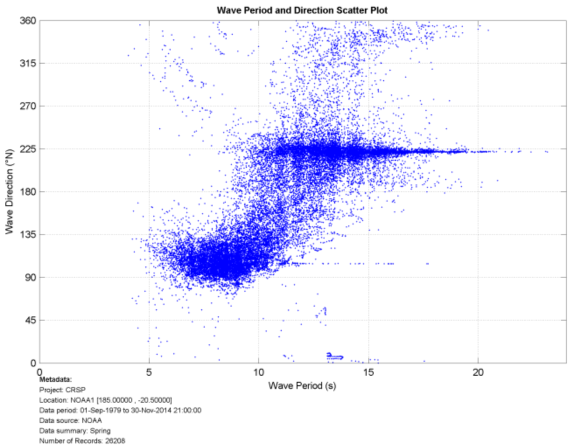

Wave Height and Period Scatter Plot
Wave Period (s)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Mar-1979 to 31-May-2015 21:00:00
Data source: NOAA
Data summary: Autumn
Number of Records: 27232

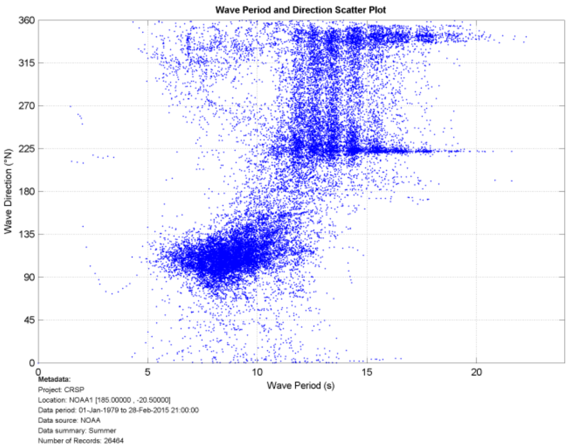

Wave Height and Period Scatter Plot
Wave Period (s)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Sep-1979 to 30-Nov-2014 21:00:00
Data source: NOAA
Data summary: Spring
Number of Records: 26208

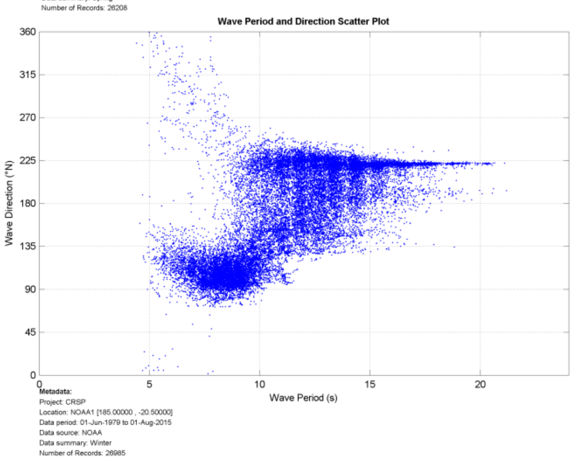

Wave Height and Period Scatter Plot
Wave Period (s)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Jan-1979 to 28-Feb-2015 21:00:00
Data source: NOAA
Data summary: Summer
Number of Records: 26464

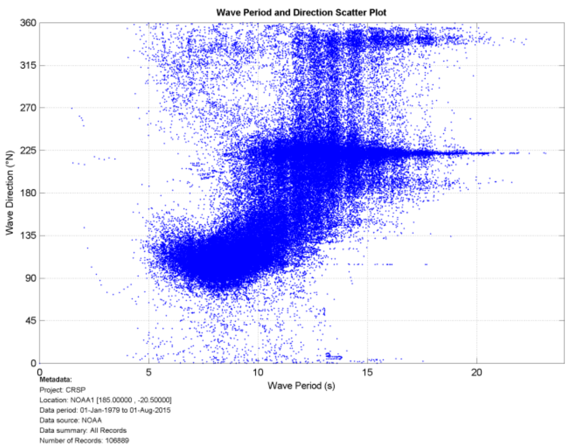

Wave Period and Direction Scatter Plot
Wave Direction (°N)
Wave Period (s)
Metadata:
Project: CRSP

[redacted]


Wave Period and Direction Scatter Plot
Wave Direction (°N)
Wave Period (s)
Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Sep-1979 to 30-Nov-2014 21:00:00
Data source: NOAA
Data summary: Spring
Number of Records: 26208

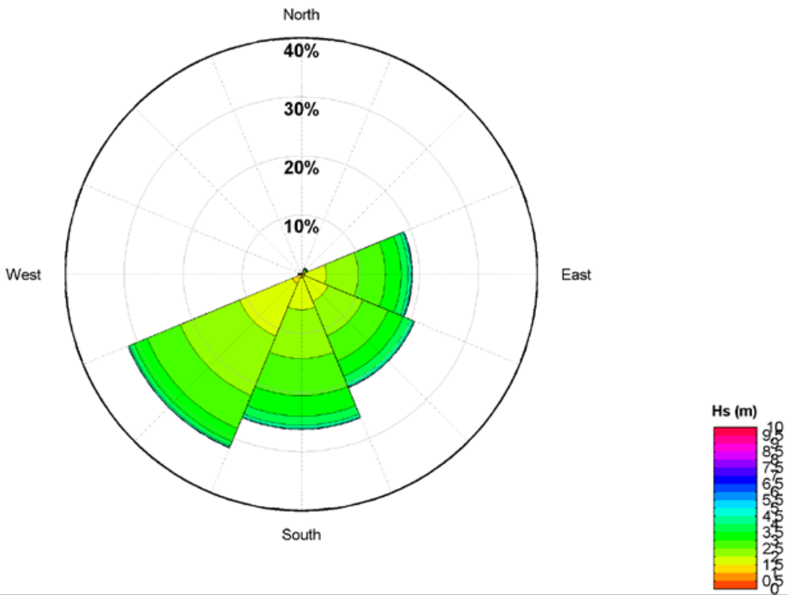

Wave Period and Direction Scatter Plot
Wave Direction (°N)
Wave Period (s)
Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Jan-1979 to 28-Feb-2015 21:00:00
Data source: NOAA
Data summary: Summer
Number of Records: 26464


Wave Period and Direction Scatter Plot
Wave Direction (°N)
Wave Period (s)
Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Jun-1979 to 01-Aug-2015
Data source: NOAA
Data summary: Winter
Number of Records: 26985


Wave Period and Direction Scatter Plot
Wave Direction (°N)
Wave Period (s)
Metadata:
Project: CRSP
Location: NOAA1 [185.00000 , -20.50000]
Data period: 01-Jan-1979 to 01-Aug-2015
Data source: NOAA
Data summary: All Records
Number of Records: 106889

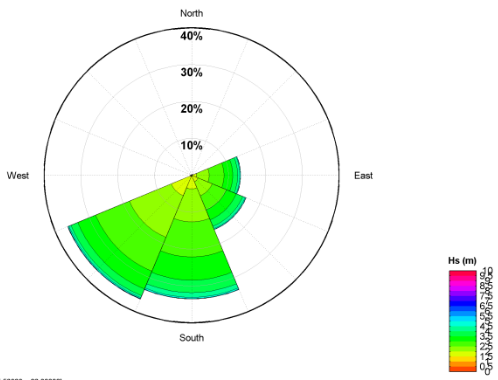
NOAA2:

Wave Height and Direction Rose, 106889 Records, 01-Jan-1979 to 01-Aug-2015



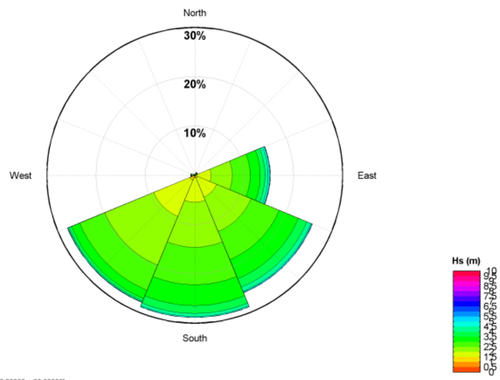
Metadata:
Project: CRSP
[redacted]

Wave Height and Direction Rose, 26985 Records, Winter



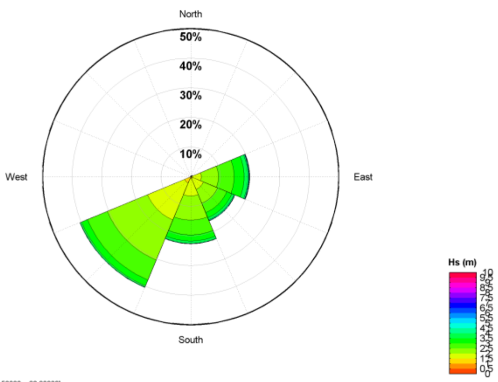
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Jun-1979 to 01-Aug-2015
Data source: NOAA
Data summary: Winter
Number of Records: 26985

Wave Height and Direction Rose, 27232 Records, Autumn



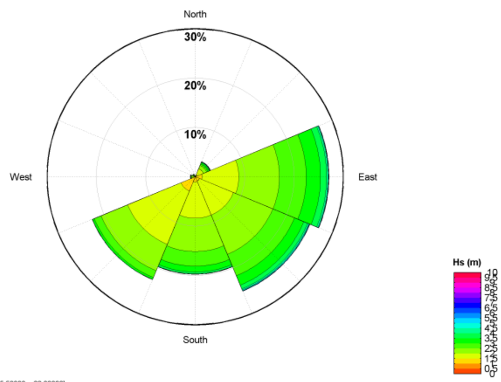
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Mar-1979 to 31-May-2015 21:00:00
Data source: NOAA
Data summary: Autumn
Number of Records: 27232

Wave Height and Direction Rose, 26208 Records, Spring

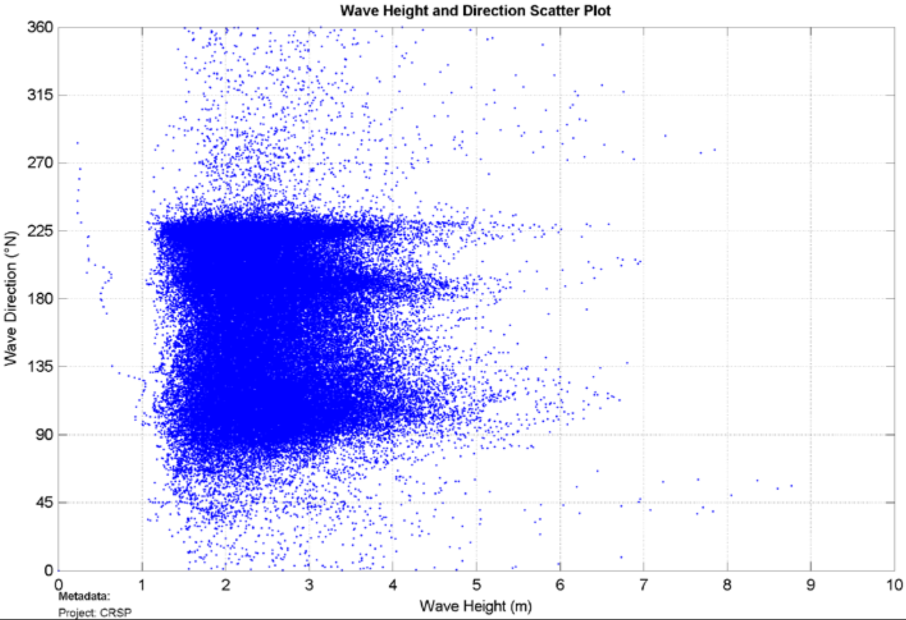


Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Sep-1979 to 30-Nov-2014 21:00:00
Data source: NOAA
Data summary: Spring
Number of Records: 26208

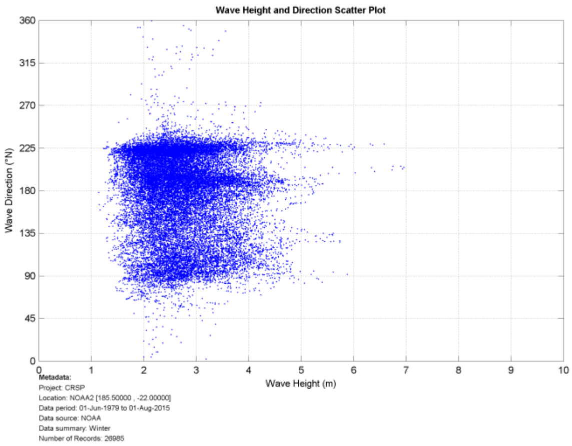
Wave Height and Direction Rose, 26464 Records, Summer

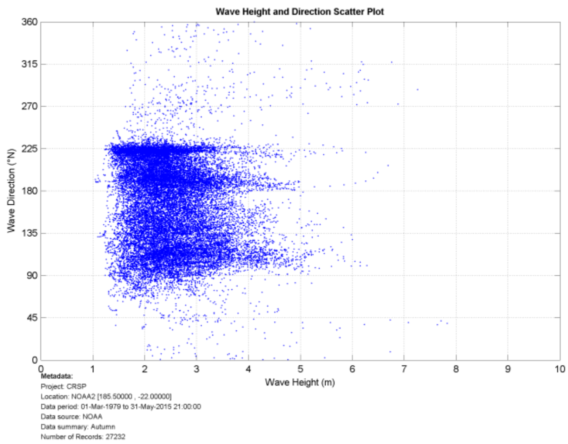


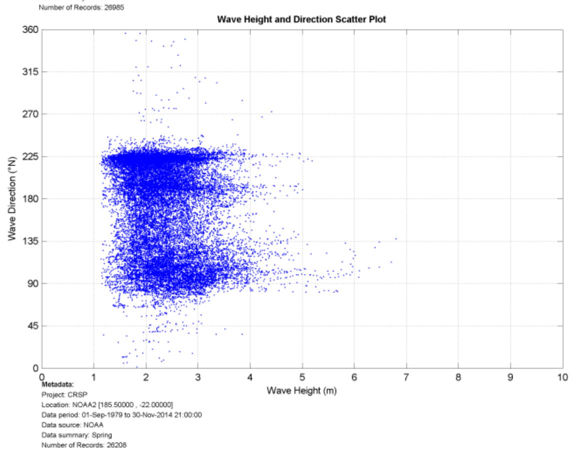
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Jan-1979 to 28-Feb-2015 21:00:00
Data source: NOAA
Data summary: Summer
Number of Records: 26464

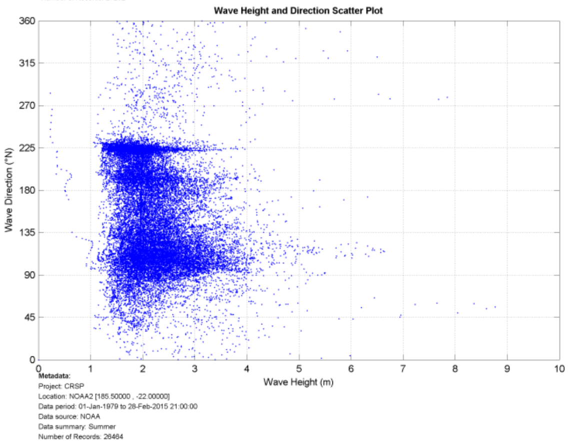

Wave Height and Direction Scatter Plot
Wave Direction (°N)
Wave Height (m)
Metadata:
Project: CRSP

[redacted]


Wave Height and Direction Scatter Plot
Wave Direction (°N)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Jun-1979 to 01-Aug-2015
Data source: NOAA
Data summary: Winter
Number of Records: 26985


Wave Height and Direction Scatter Plot
Wave Direction (°N)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Mar-1979 to 31-May-2015 21:00:00
Data source: NOAA
Data summary: Autumn
Number of Records: 27232

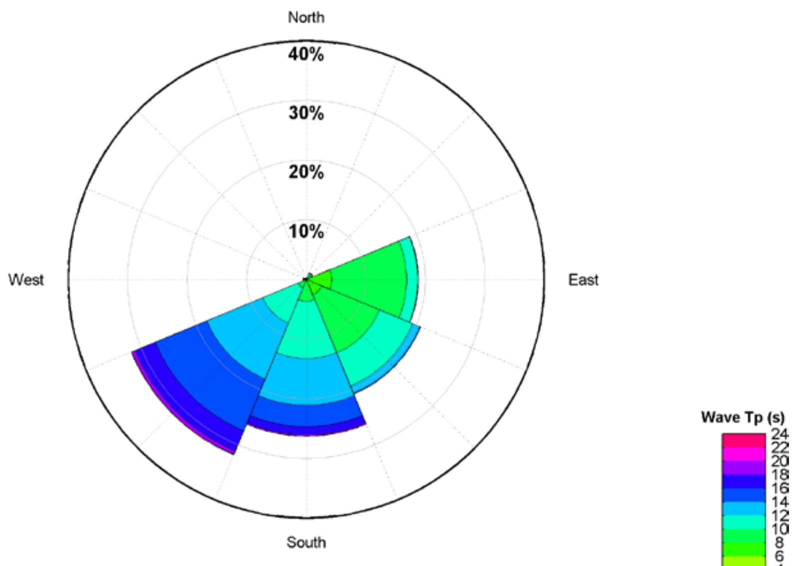

Wave Height and Direction Scatter Plot
Wave Direction (°N)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Sep-1979 to 30-Nov-2014 21:00:00
Data source: NOAA
Data summary: Spring
Number of Records: 26208


Wave Height and Direction Scatter Plot
Wave Direction (°N)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Jan-1979 to 28-Feb-2015 21:00:00
Data source: NOAA
Data summary: Summer
Number of Records: 26464

PROJECT RELATED

CLIMATE RESILIENT SECTOR PROJECT (CRSP) – MOI/PIU UNIT

Wave Period and Direction Rose, 106889 Records, 01-Jan-1979 to 01-Aug-2015



Metadata:
Project: CRSP
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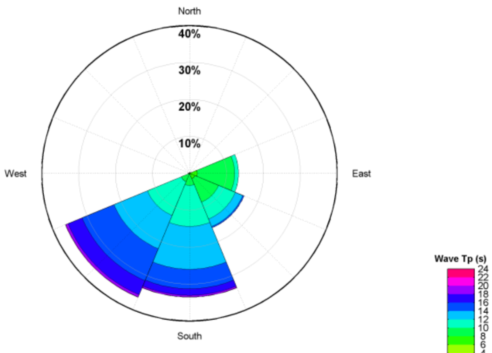
Wave Period and Direction Rose, 26985 Records, Winter



Metadata:
Project: CRSP
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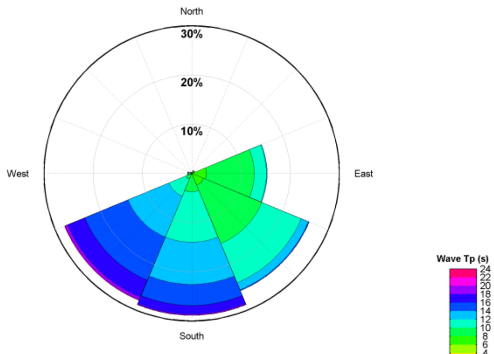
Data source: NOAA
Data summary: Winter
Number of Records: 26985

Wave Period and Direction Rose, 27232 Records, Autumn



Metadata:
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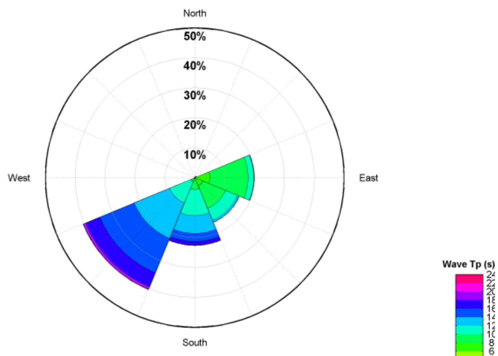
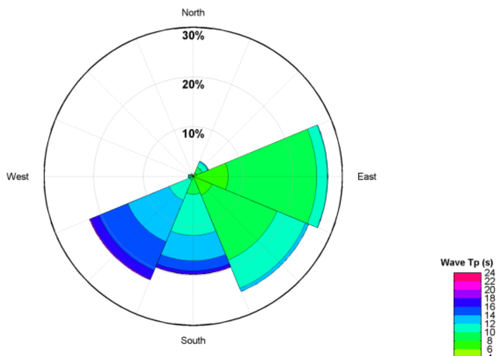
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Mar-1979 to 31-May-2015 21:00:00
Data source: NOAA
Data summary: Autumn
Number of Records: 27232

Wave Period and Direction Rose, 26208 Records, Spring



Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Sep-1979 to 30-Nov-2014 21:00:00
Data source: NOAA
Data summary: Spring
Number of Records: 26208

Wave Period and Direction Rose, 26464 Records, Summer



Metadata:
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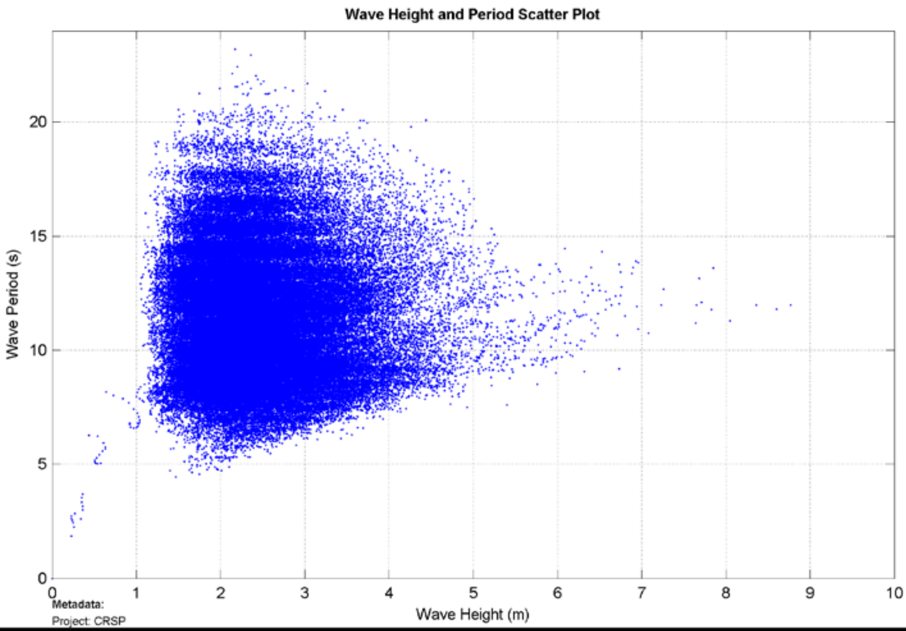
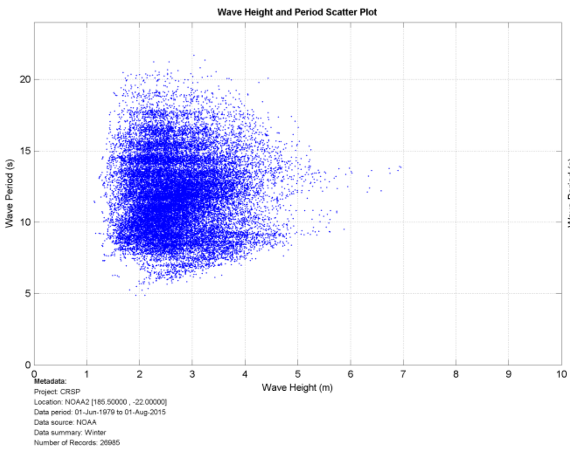
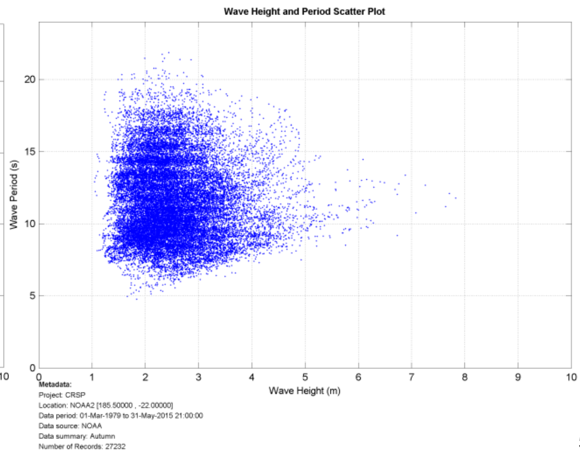
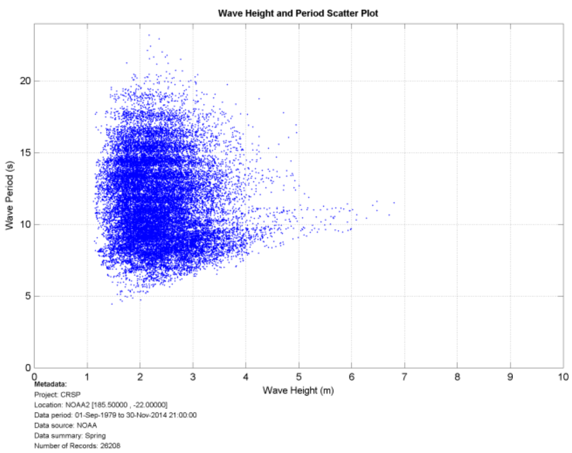
Data source: NOAA
Data summary: Summer
Number of Records: 26464

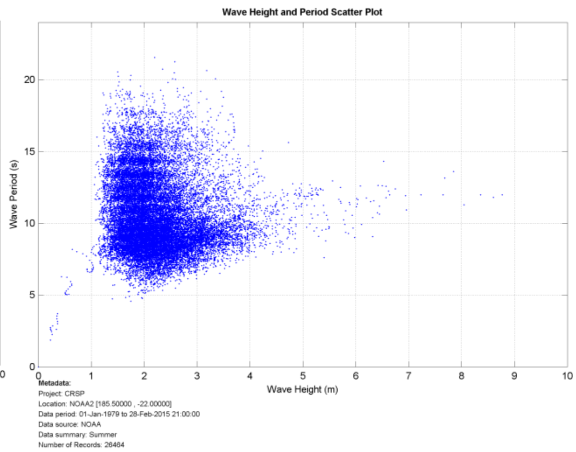

Wave Height and Period Scatter Plot
Wave Period (s)
Wave Height (m)
0
5
10
15
20
1
2
3
4
5
6
7
8
9
10
Metadata:
Project: CRSP

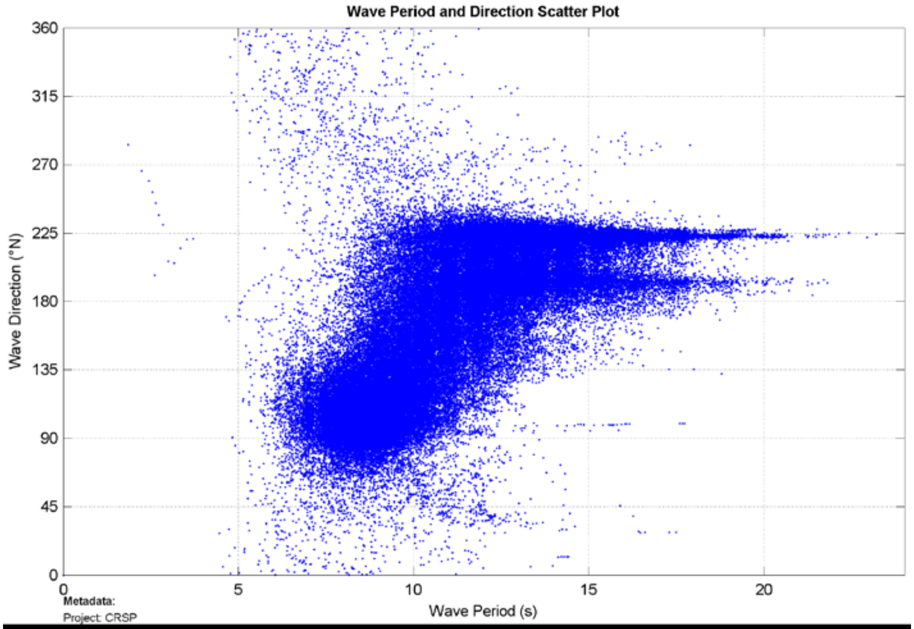
[redacted]


Wave Height and Period Scatter Plot
Wave Period (s)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Jun-1979 to 01-Aug-2015
Data source: NOAA
Data summary: Winter
Number of Records: 26985

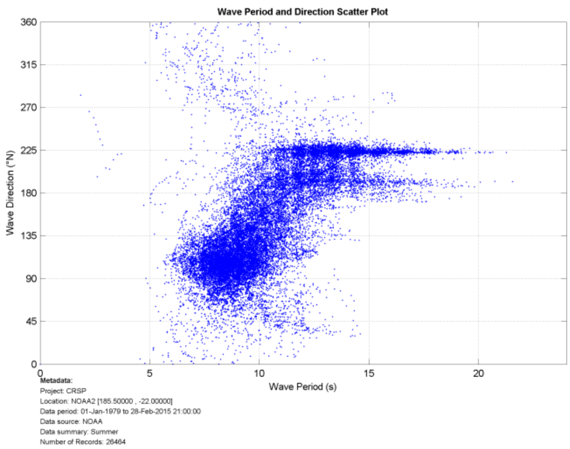

Wave Height and Period Scatter Plot
Wave Period (s)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Mar-1979 to 31-May-2015 21:00:00
Data source: NOAA
Data summary: Autumn
Number of Records: 27232

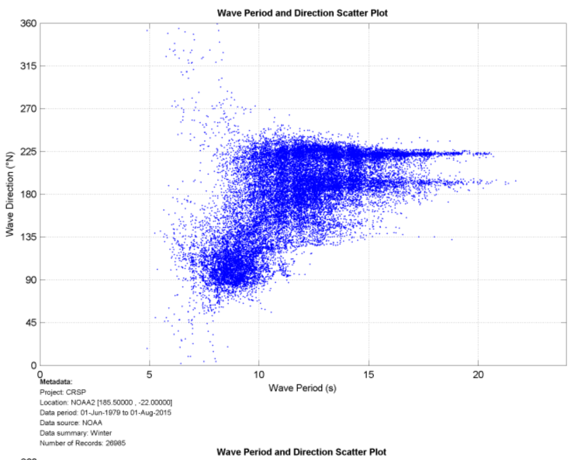

Wave Height and Period Scatter Plot
Wave Period (s)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Sep-1979 to 30-Nov-2014 21:00:00
Data source: NOAA
Data summary: Spring
Number of Records: 26208

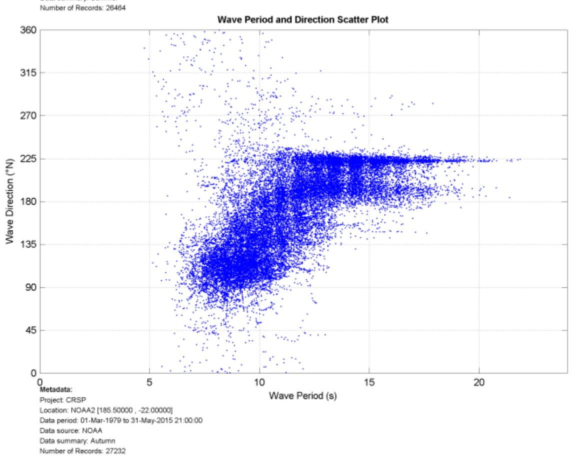

Wave Height and Period Scatter Plot
Wave Period (s)
Wave Height (m)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Jan-1979 to 28-Feb-2015 21:00:00
Data source: NOAA
Data summary: Summer
Number of Records: 26464

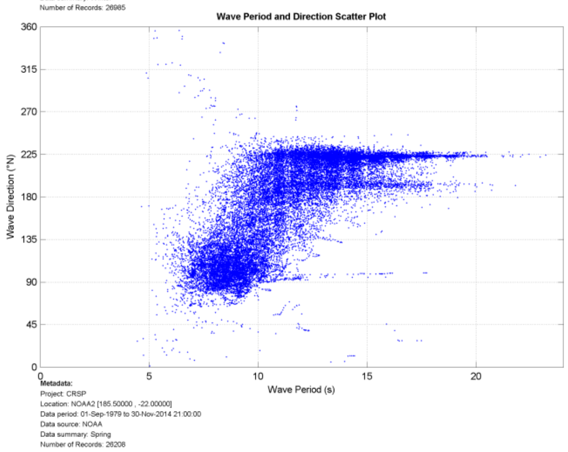

Wave Period and Direction Scatter Plot
Wave Direction (°N)
Wave Period (s)
Metadata:
Project: CRSP

[redacted]


Wave Period and Direction Scatter Plot
Wave Direction (°N)
Wave Period (s)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Jan-1979 to 28-Feb-2015 21:00:00
Data source: NOAA
Data summary: Summer
Number of Records: 26464

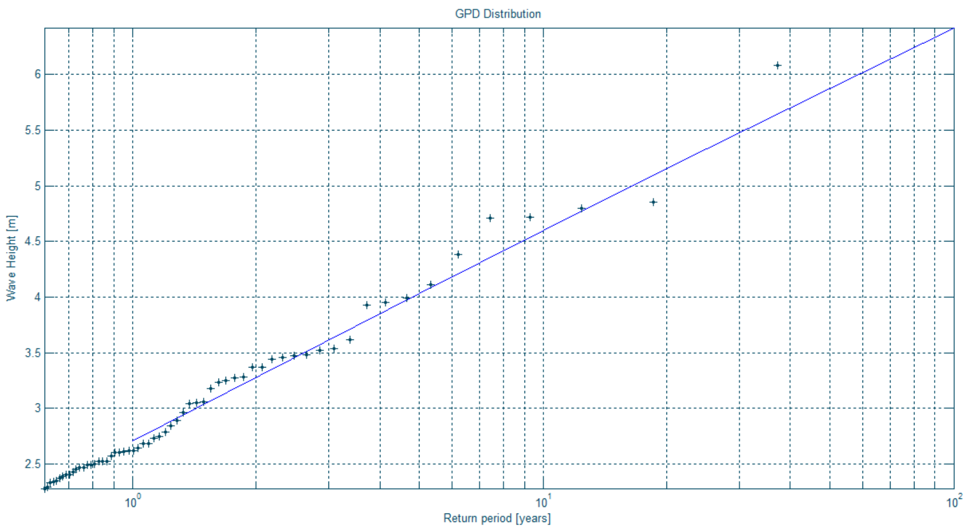

Wave Period and Direction Scatter Plot
Wave Direction (°N)
Wave Period (s)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Jun-1979 to 01-Aug-2015
Data source: NOAA
Data summary: Winter
Number of Records: 26985


Wave Period and Direction Scatter Plot
Wave Direction (°N)
Wave Period (s)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Mar-1979 to 31-May-2015 21:00:00
Data source: NOAA
Data summary: Autumn
Number of Records: 27232

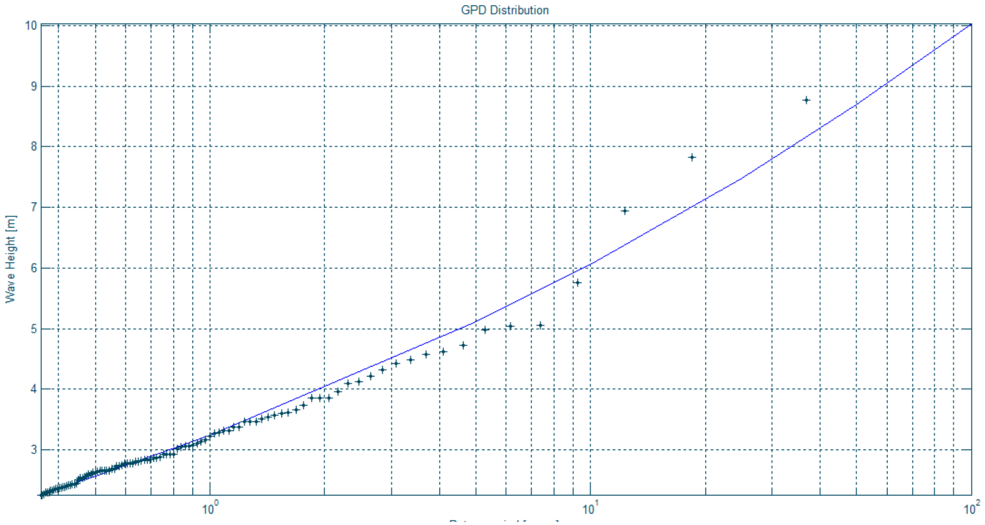

Wave Period and Direction Scatter Plot
Wave Direction (°N)
Wave Period (s)
Metadata:
Project: CRSP
Location: NOAA2 [185.50000 , -22.00000]
Data period: 01-Sep-1979 to 30-Nov-2014 21:00:00
Data source: NOAA
Data summary: Spring
Number of Records: 26208

Appendix B: Extreme Value Analysis of extracted wave height (m) data from the NOAA Global Wave Hindcast Model for the period 1979-2015 for each directional sector

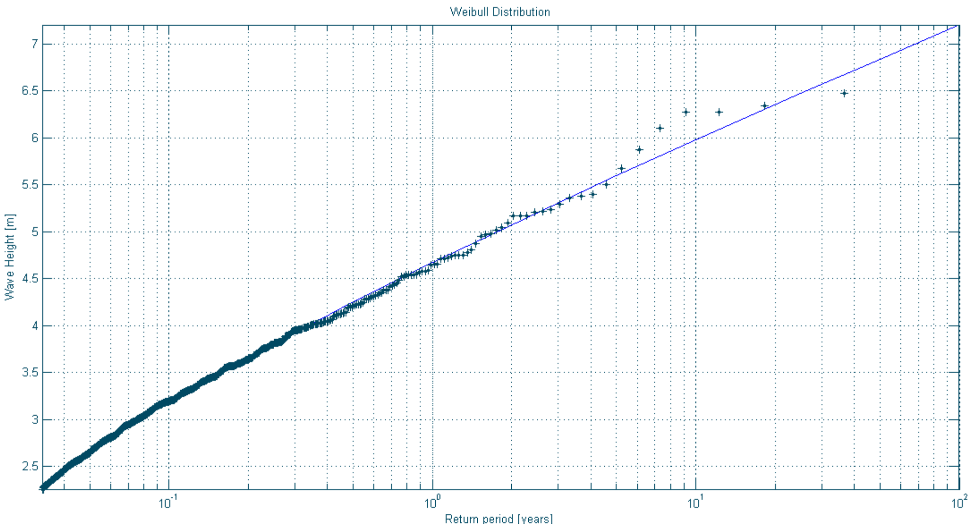
Direction	**North**
Dataset	NOAA1
Threshold	2.25
Distribution Method	GPD
ARI (years)	Wave Height (m)
1	2.75
10	4.6
20	5.2
50	5.85
100	6.3



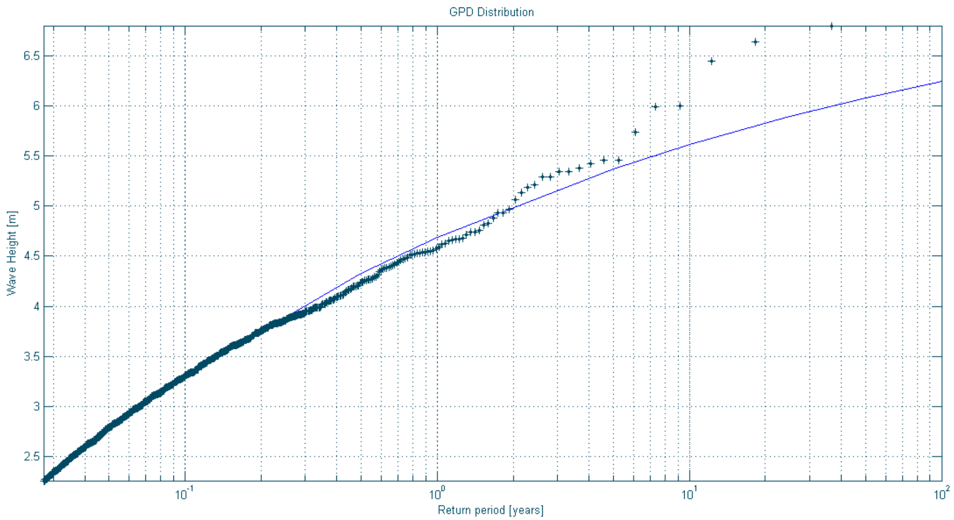
Direction	**North East**
Dataset	NOAA2
Threshold	2.25
Distribution Method	GPD
ARI (years)	Wave Height (m)
1	3.3
10	6.1
20	7.2
50	8.7
100	10



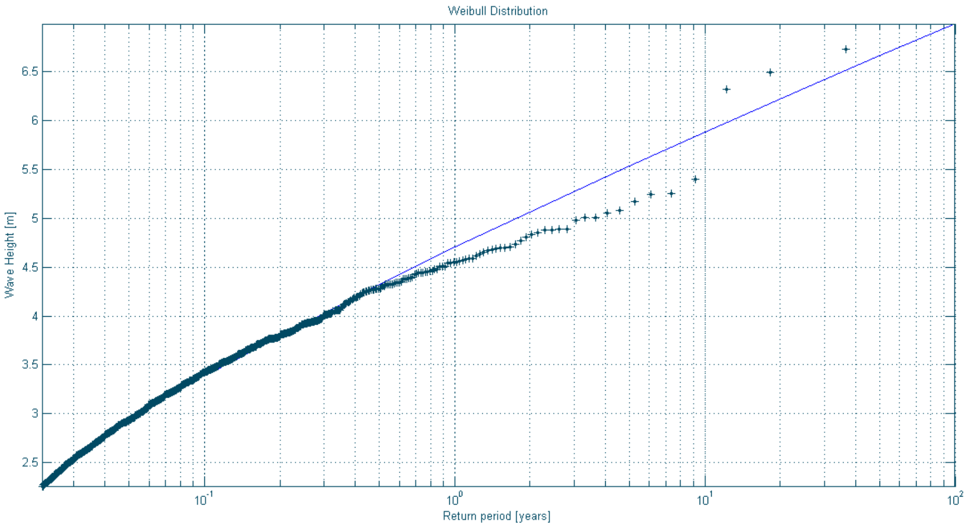
Direction	**East**
Dataset	NOAA2
Threshold	2.25
Distribution Method	Weibull
ARI (years)	Wave Height (m)
1	4.7
10	6
20	6.4
50	6.85
100	7.15



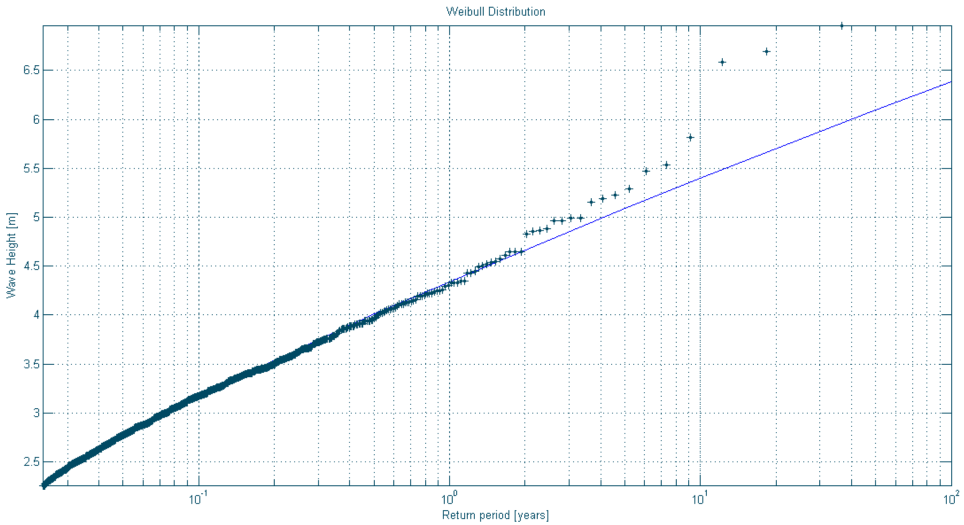
Direction	**South East**
Dataset	NOAA2
Threshold	2.25
Distribution Method	GPD
ARI (years)	Wave Height (m)
1	4.7
10	5.6
20	5.8
50	6.1
100	6.25



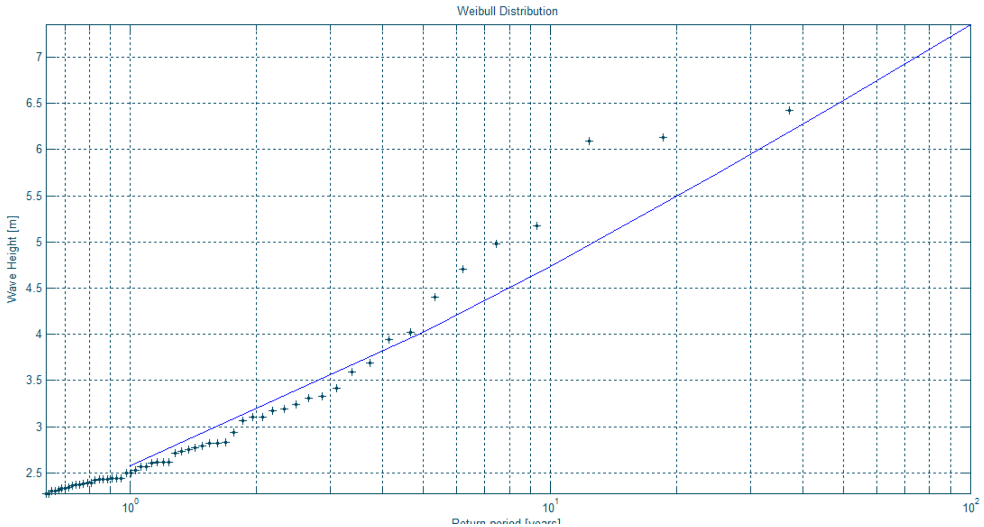
Direction	**South**
Dataset	NOAA2
Threshold	2.25
Distribution Method	Weibull
ARI (years)	Wave Height (m)
1	4.7
10	5.8
20	6.25
50	6.6
100	6.9



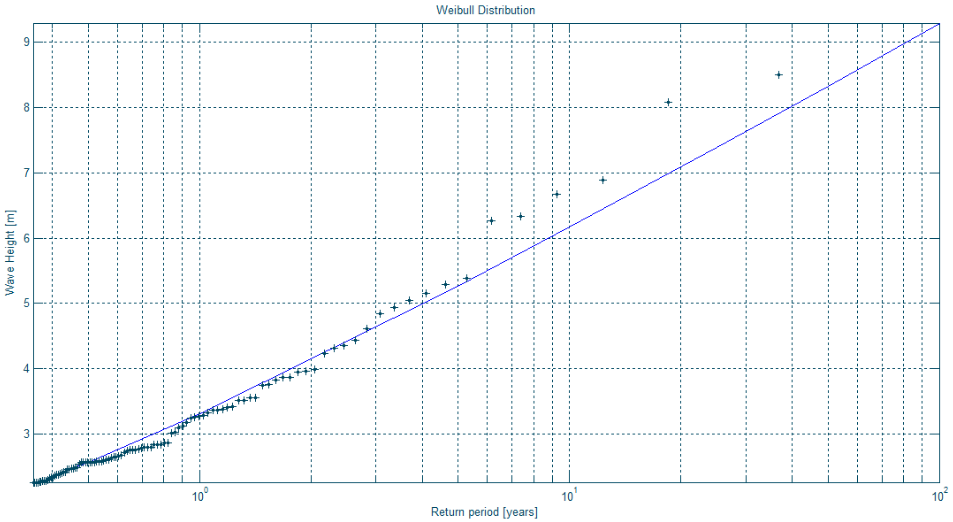
Direction	**South West**
Dataset	NOAA2
Threshold	2.25
Distribution Method	Weibull
ARI (years)	Wave Height (m)
1	4.7
10	5.8
20	6.25
50	6.6
100	6.9



Direction	**West**
Dataset	NOAA1
Threshold	2.25
Distribution Method	Weibull
ARI (years)	Wave Height (m)
1	2.6
10	4.75
20	5.5
50	6.5
100	7.3

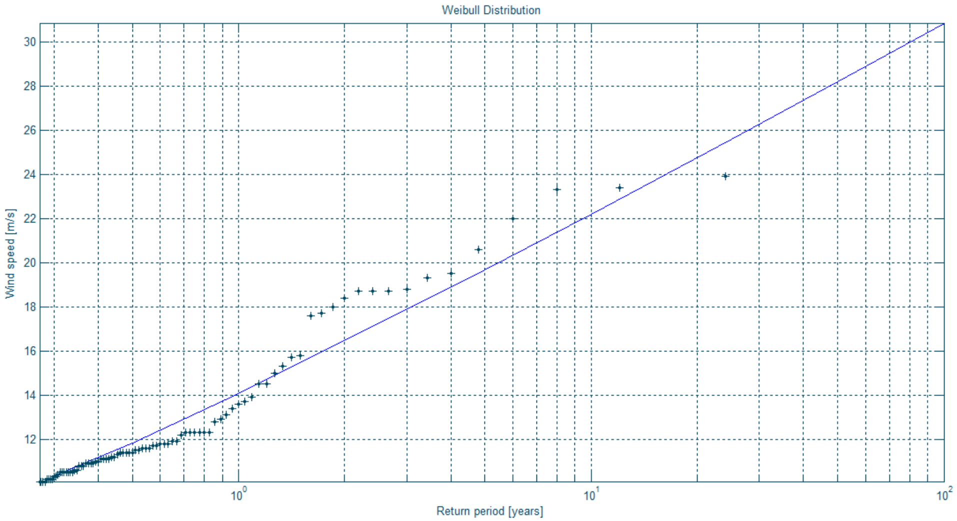


Direction	**North West**
Dataset	NOAA1
Threshold	2.25
Distribution Method	Weibull
ARI (years)	Wave Height (m)
1	3.4
10	6.2
20	7.2
50	8.4
100	9.3

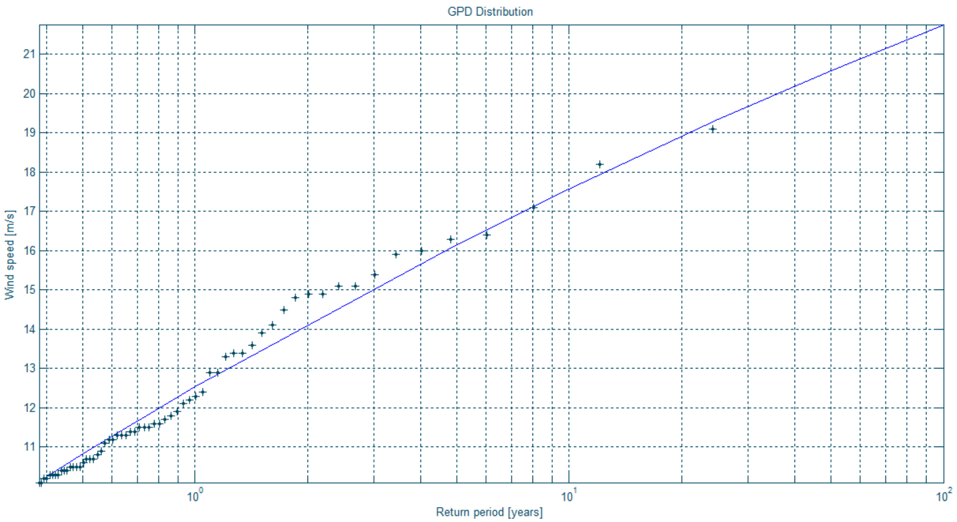


Appendix C: Extreme Value Analysis of wind speeds (m/s) data from the Fua'amotu International Airport Meteorological Station for the period 1993-2016 for each directional sector

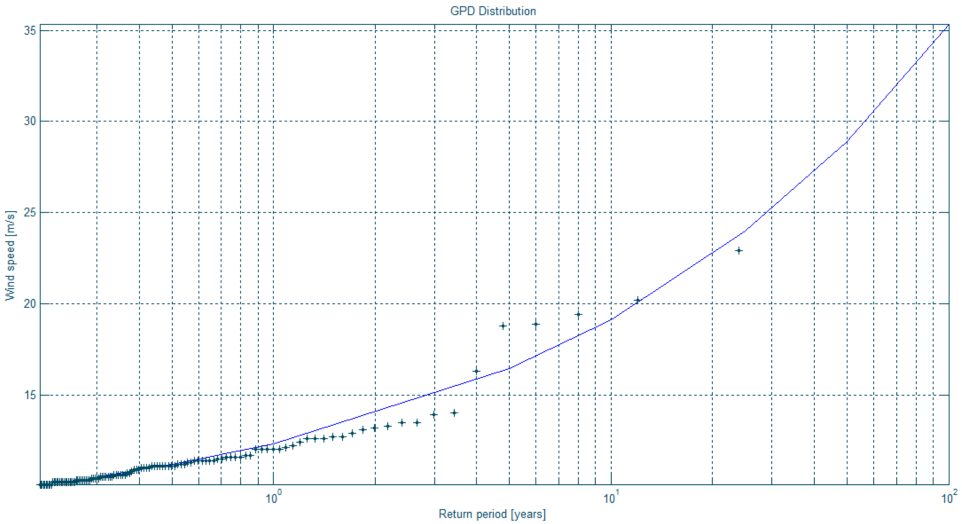
Direction	**North**
Dataset	FIA
Threshold	10
Distribution Method	Weibull
ARI (years)	Wind Speed (m/s)
1	14.2
10	22.2
20	25
50	28.2
100	30.5



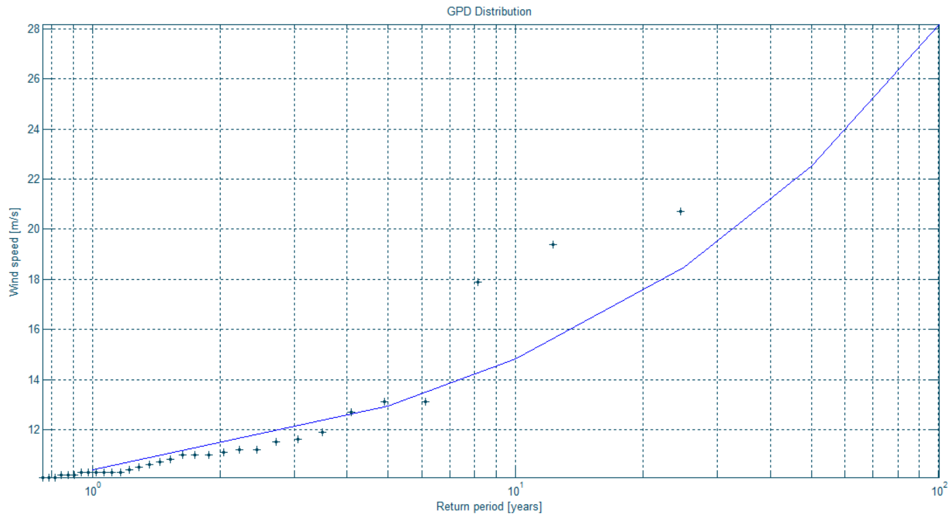
Direction	**North East**
Dataset	FIA
Threshold	10
Distribution Method	GPD
ARI (years)	Wind Speed (m/s)
1	12.6
10	17.5
20	18.9
50	20.7
100	21.5



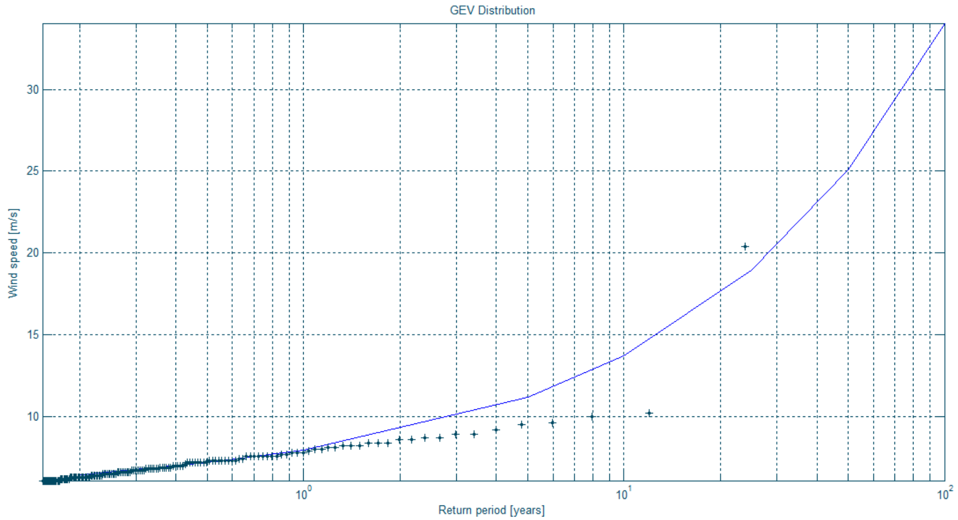
Direction	**East**
Dataset	FIA
Threshold	10
Distribution Method	GPD
ARI (years)	Wind Speed (m/s)
1	8
10	18
20	23
50	28
100	36



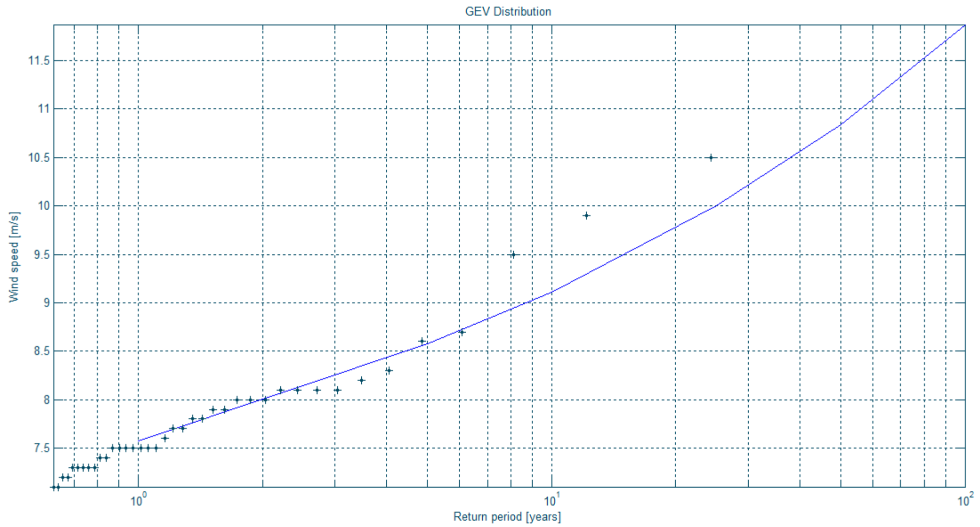
Direction	**South East**
Dataset	FIA
Threshold	10
Distribution Method	GPD
ARI (years)	Wind Speed (m/s)
1	10.5
10	15
20	17.7
50	22.5
100	28.2



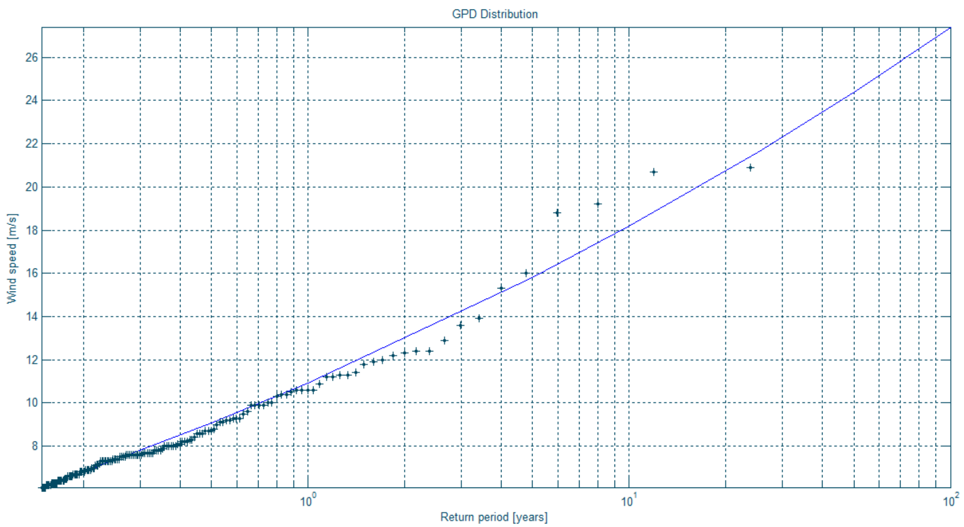
Direction	**South**
Dataset	FIA
Threshold	6
Distribution Method	GEV
ARI (years)	Wind Speed (m/s)
1	7.5
10	13.5
20	17.5
50	25
100	34



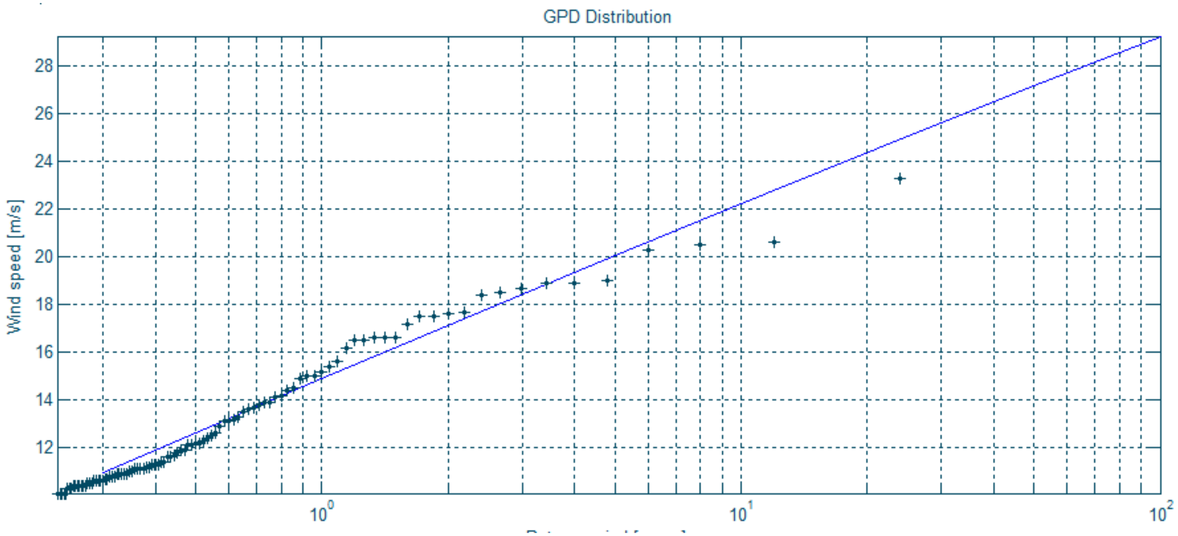
Direction	**South West**
Dataset	FIA
Threshold	7
Distribution Method	GEV
ARI (years)	Wind Speed (m/s)
1	7.6
10	9.2
20	9.8
50	10.7
100	11.7



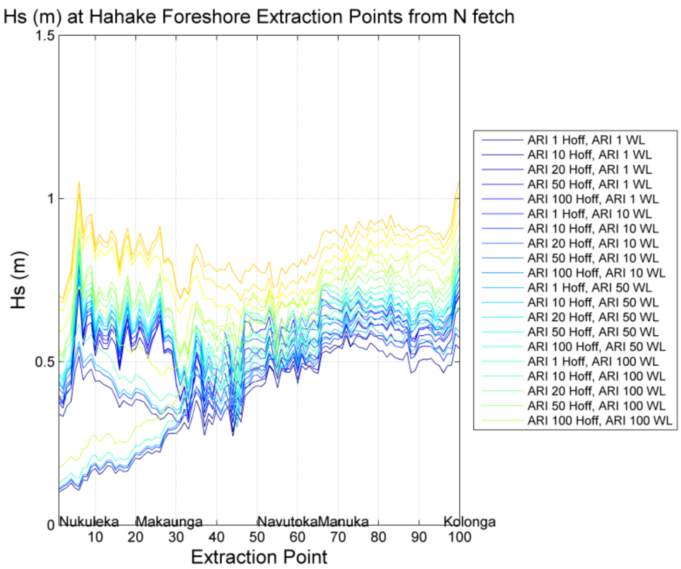
Direction	**West**
Dataset	FIA
Threshold	6
Distribution Method	GPD
ARI (years)	Wind Speed (m/s)
1	11
10	18.4
20	21
50	24.2
100	26.5

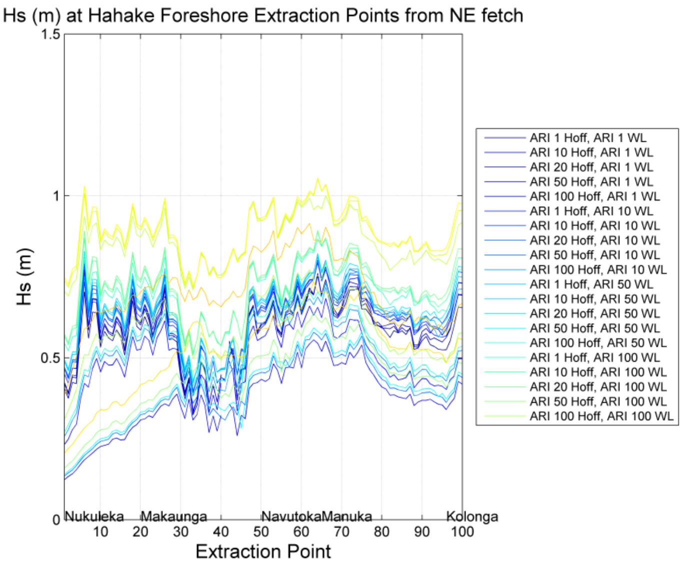


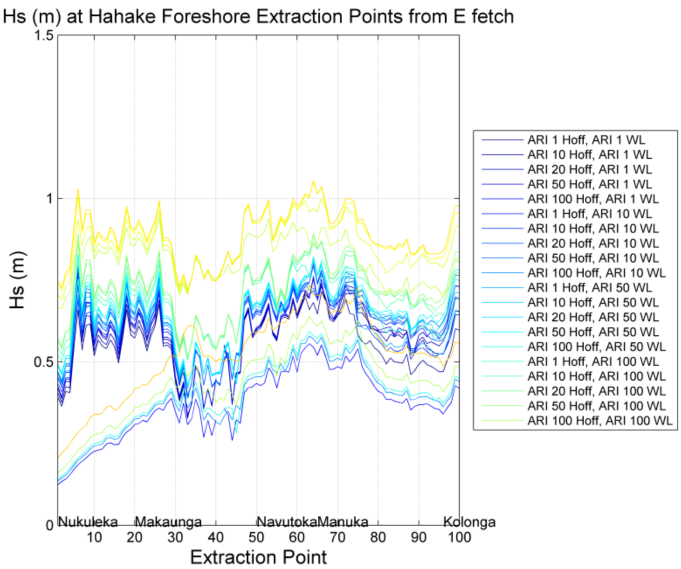
Direction	**North West**
Dataset	FIA
Threshold	10
Distribution Method	GPD
ARI (years)	Wind Speed (m/s)
1	15
10	22
20	24.5
50	27
100	28.5

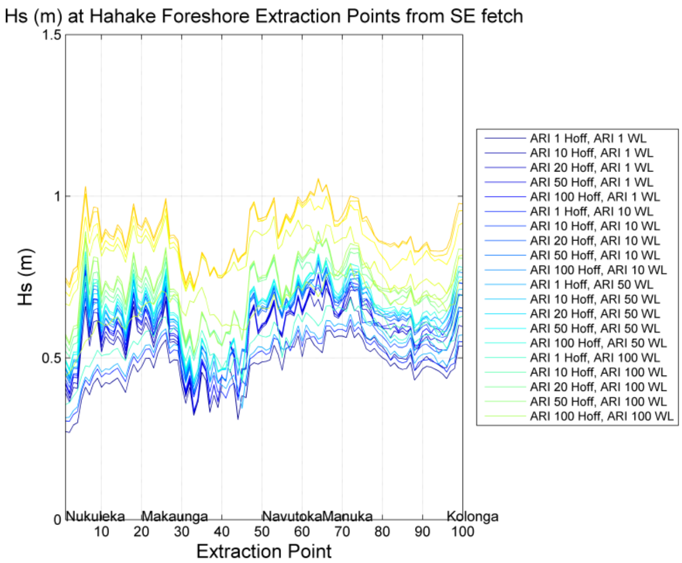


Appendix D: Combined ARI Wave Parameters

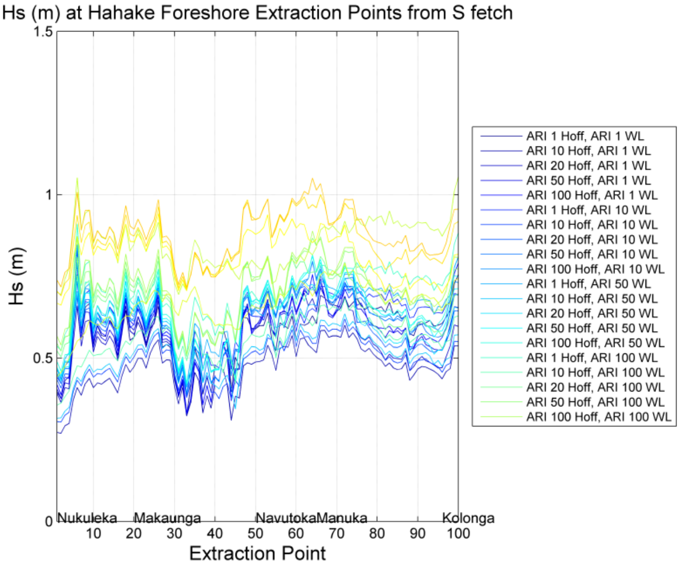




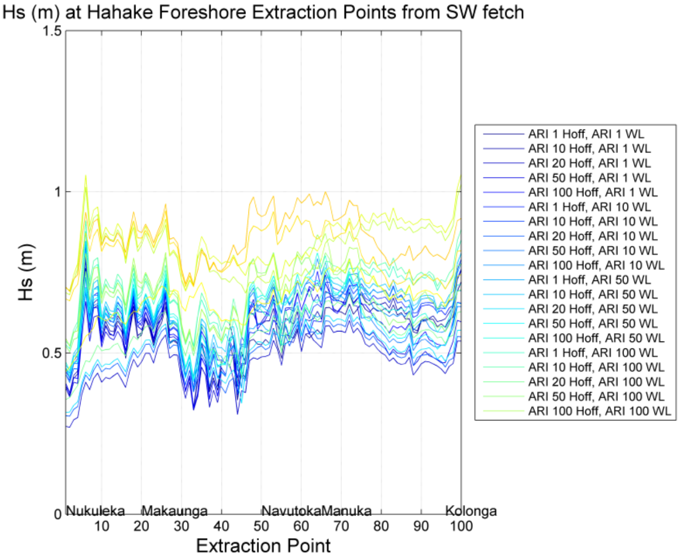




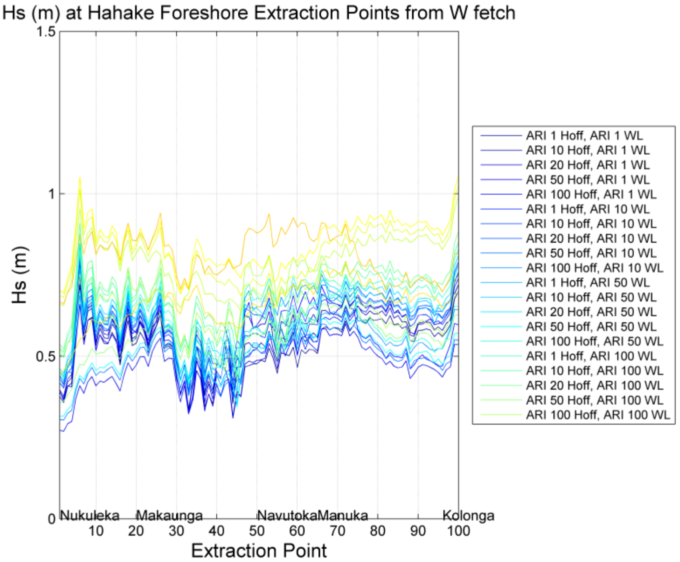
Hs (m) at Hahake Foreshore Extraction Points from S fetch



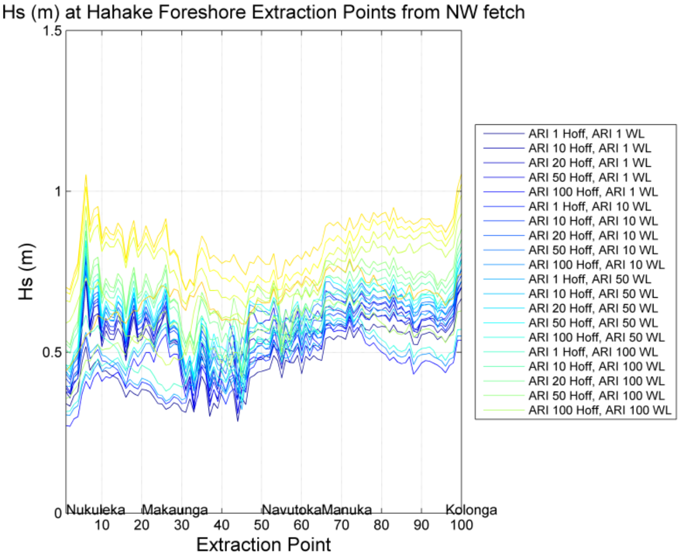
Hs (m) at Hahake Foreshore Extraction Points from SW fetch



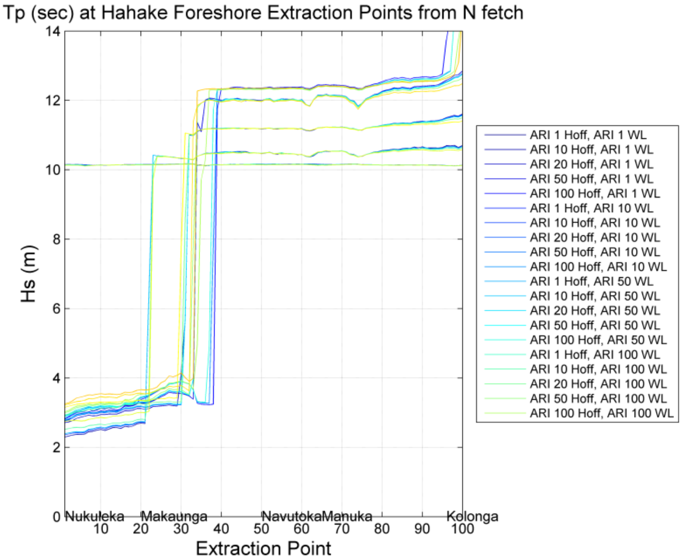
Hs (m) at Hahake Foreshore Extraction Points from W fetch



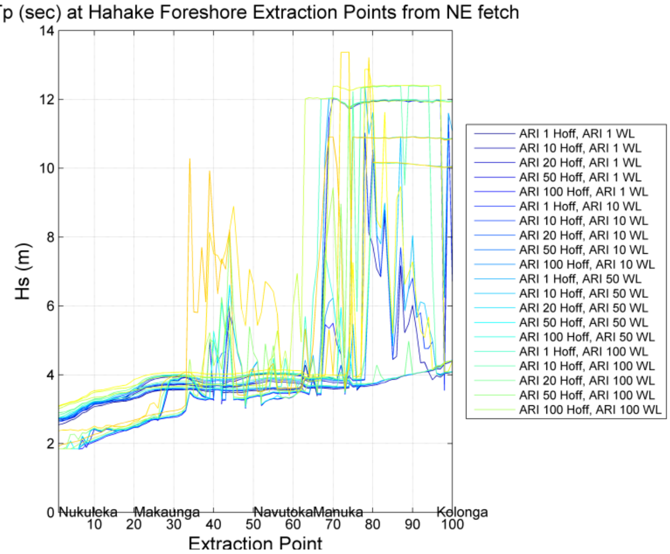
Hs (m) at Hahake Foreshore Extraction Points from NW fetch



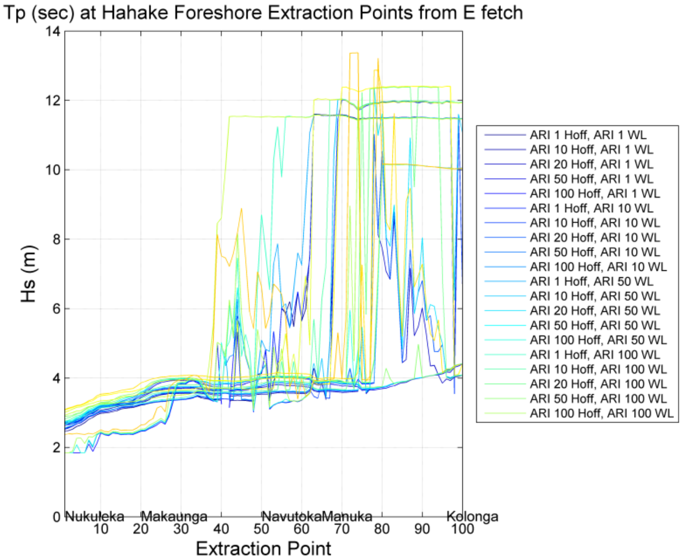
Tp (sec) at Hahake Foreshore Extraction Points from N fetch



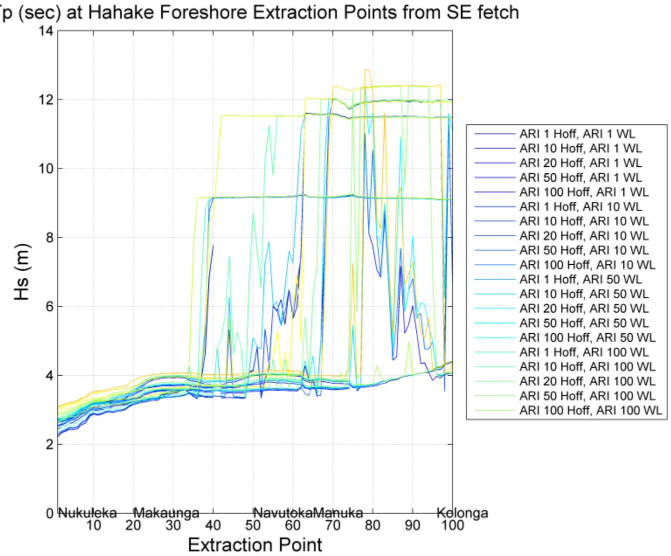
Tp (sec) at Hahake Foreshore Extraction Points from NE fetch



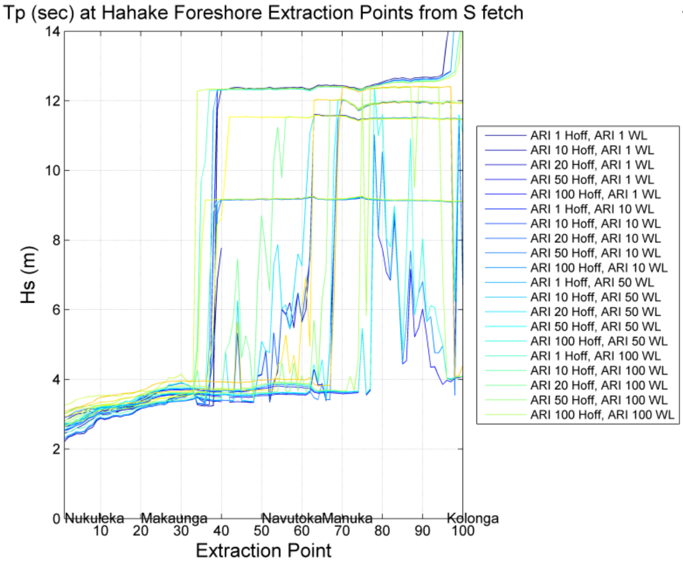
Tp (sec) at Hahake Foreshore Extraction Points from E fetch



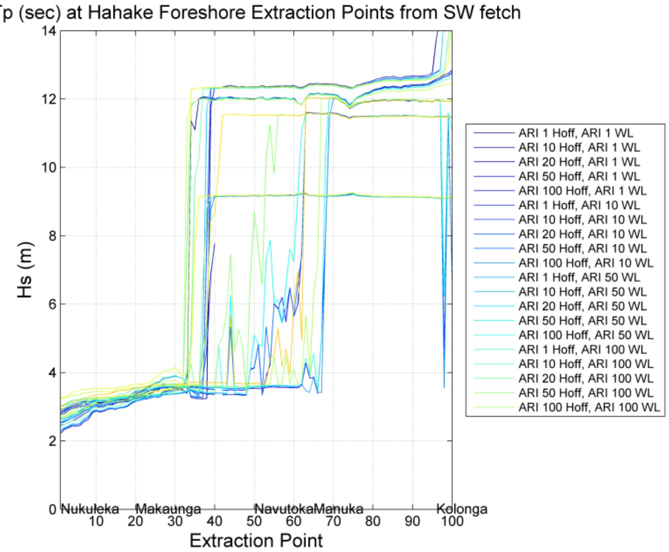
Tp (sec) at Hahake Foreshore Extraction Points from SE fetch



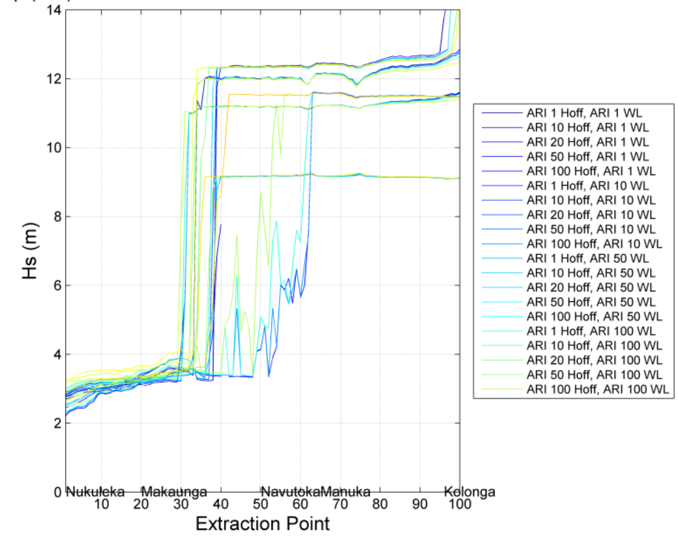
Tp (sec) at Hahake Foreshore Extraction Points from S fetch



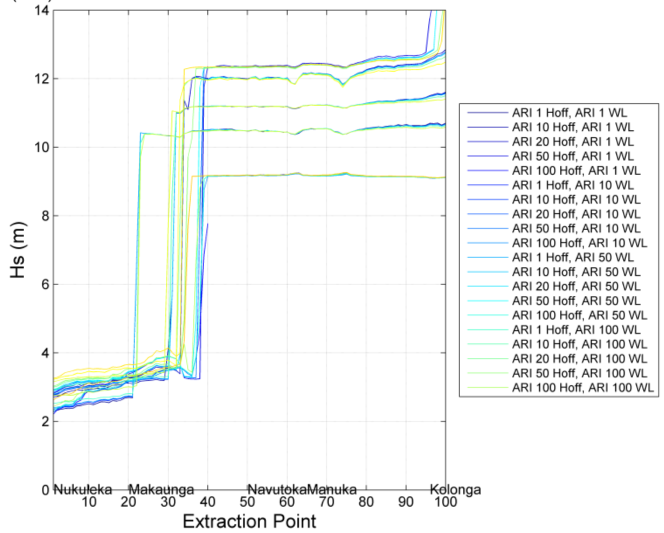
Tp (sec) at Hahake Foreshore Extraction Points from SW fetch



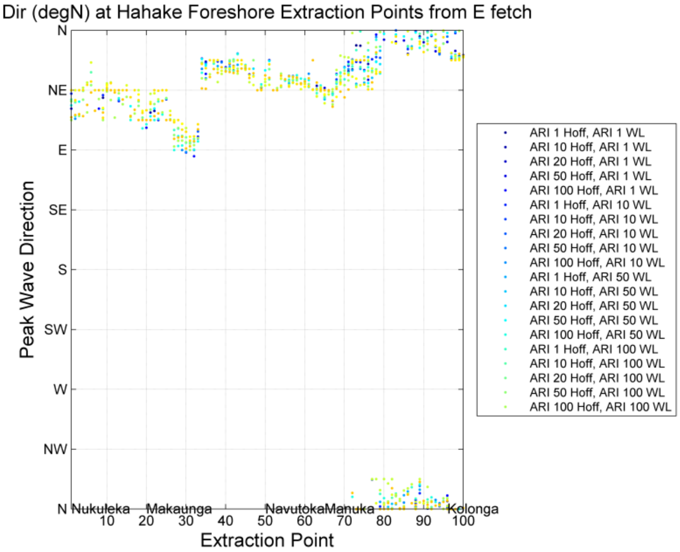
Tp (sec) at Hahake Foreshore Extraction Points from W fetch



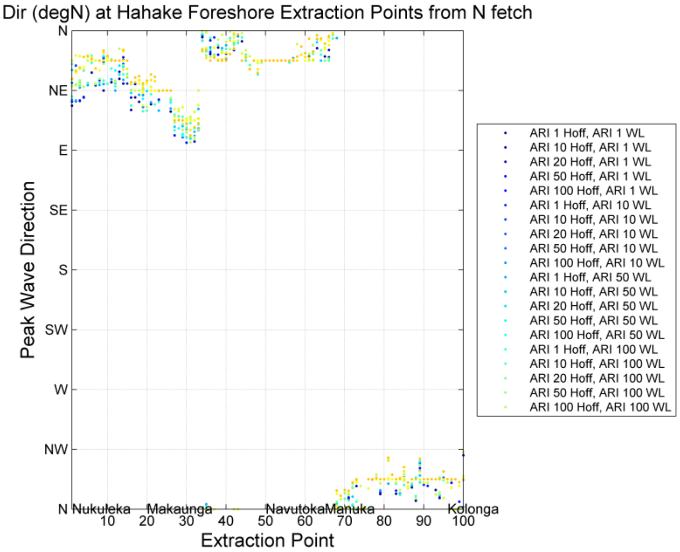
Tp (sec) at Hahake Foreshore Extraction Points from NW fetch



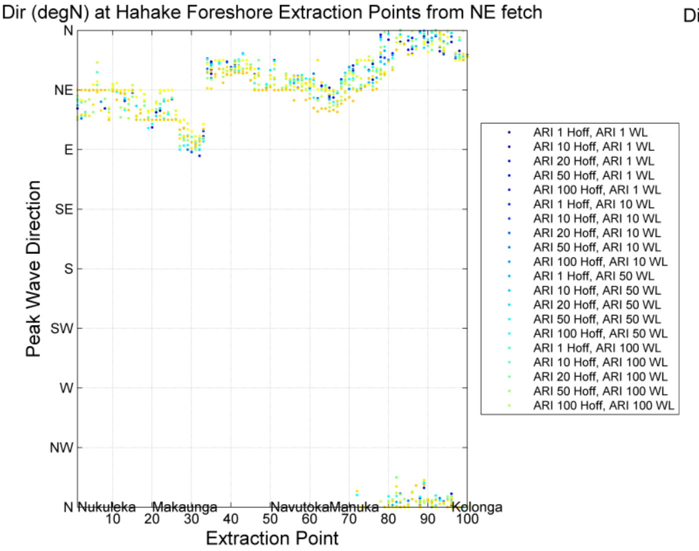
Dir (degN) at Hahake Foreshore Extraction Points from E fetch



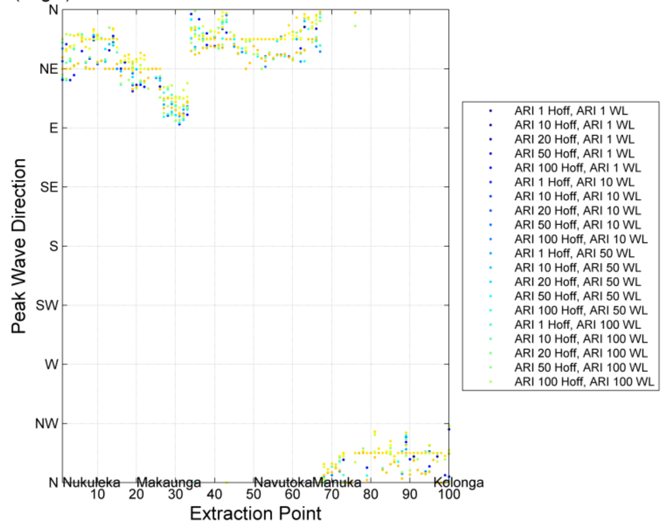
Dir (degN) at Hahake Foreshore Extraction Points from N fetch



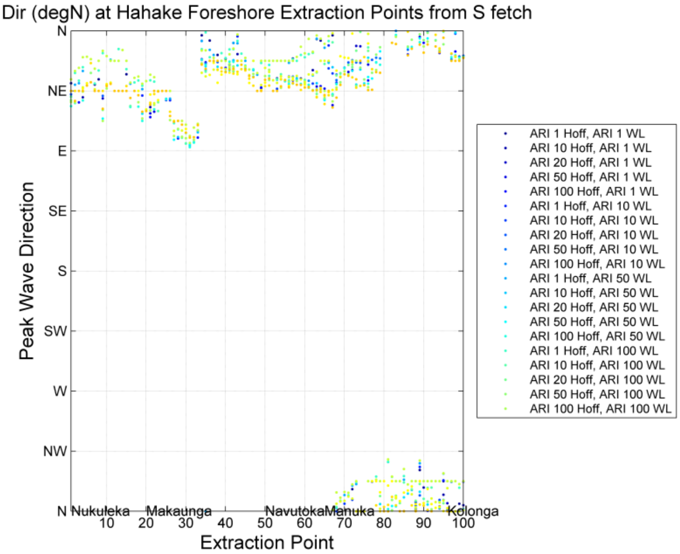
Dir (degN) at Hahake Foreshore Extraction Points from NE fetch



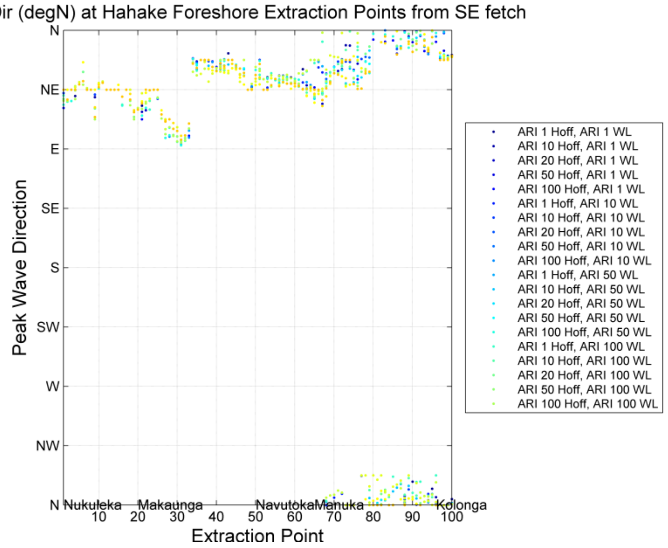
Dir (degN) at Hahake Foreshore Extraction Points from NW fetch



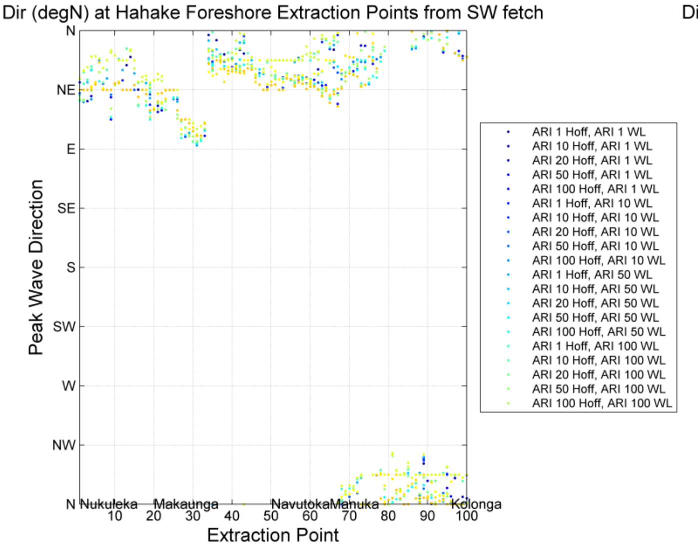
Dir (degN) at Hahake Foreshore Extraction Points from S fetch



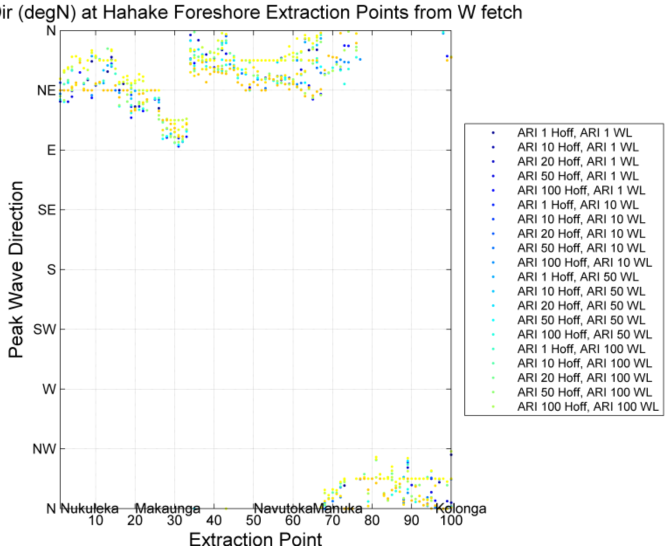
Dir (degN) at Hahake Foreshore Extraction Points from SE fetch



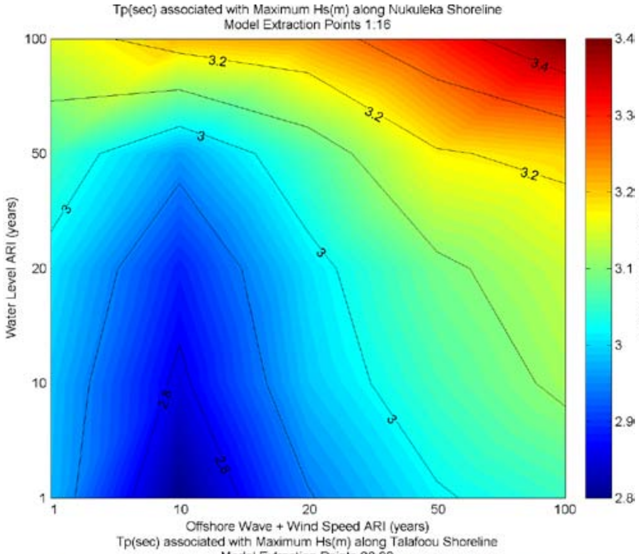
Dir (degN) at Hahake Foreshore Extraction Points from SW fetch

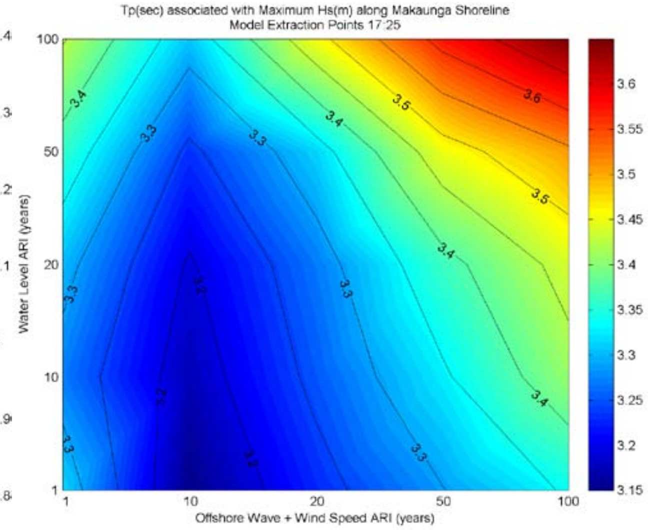


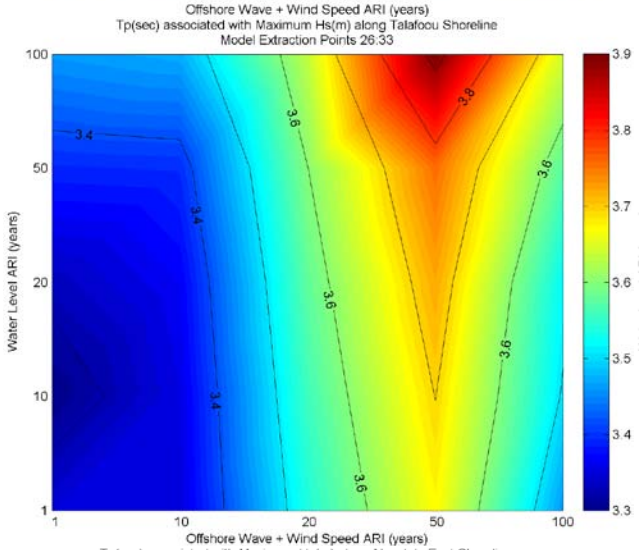
Dir (degN) at Hahake Foreshore Extraction Points from W fetch

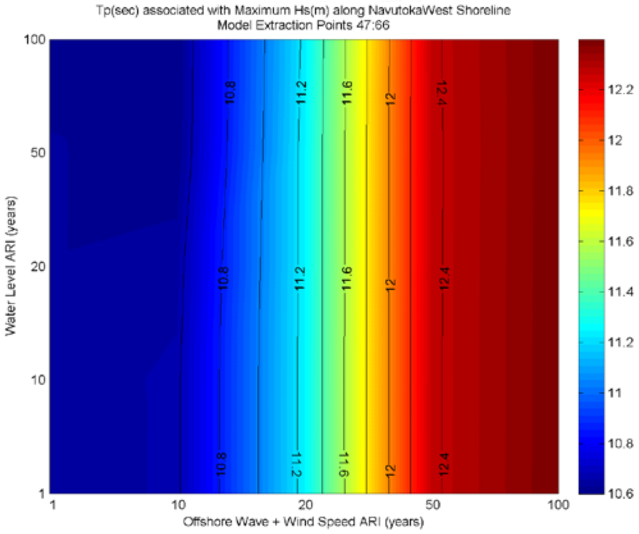


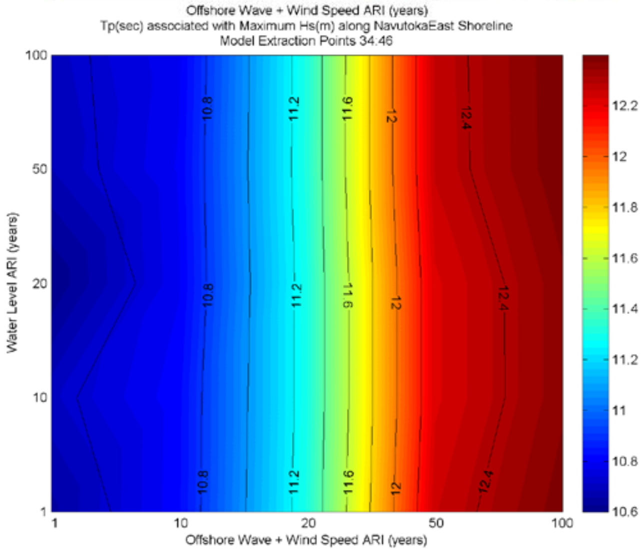
Appendix E: Tp(sec) and Dp(deg) at each Hahake coastal section as a matrix of water level ARI and Hoff + Wspd ARI

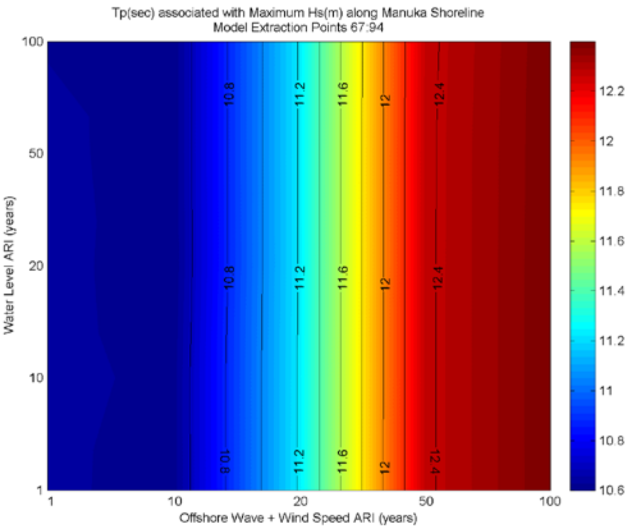


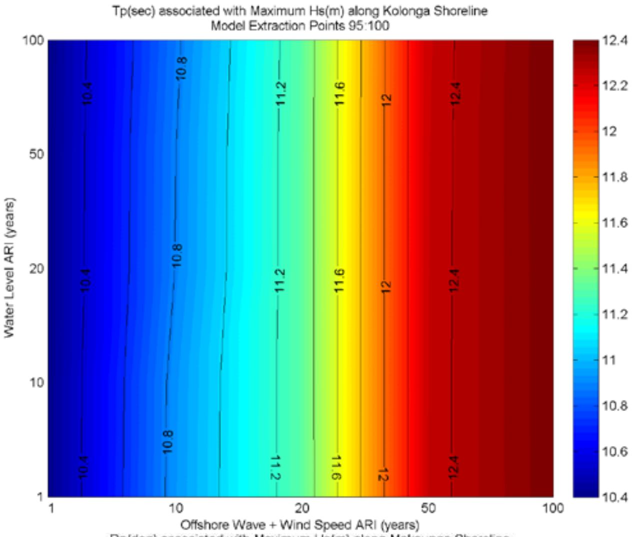


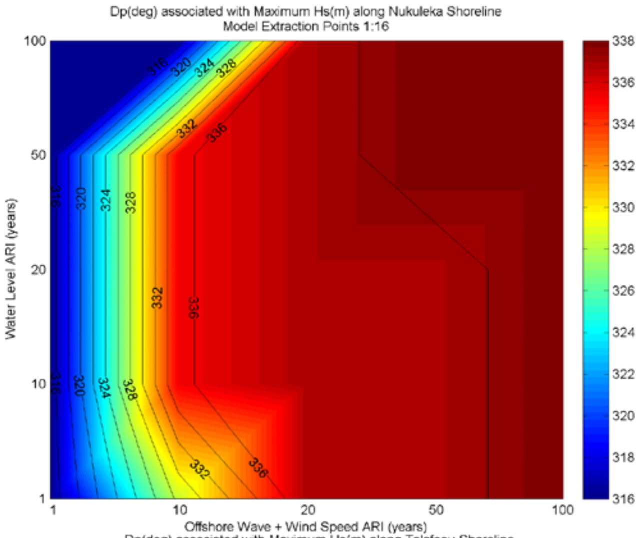


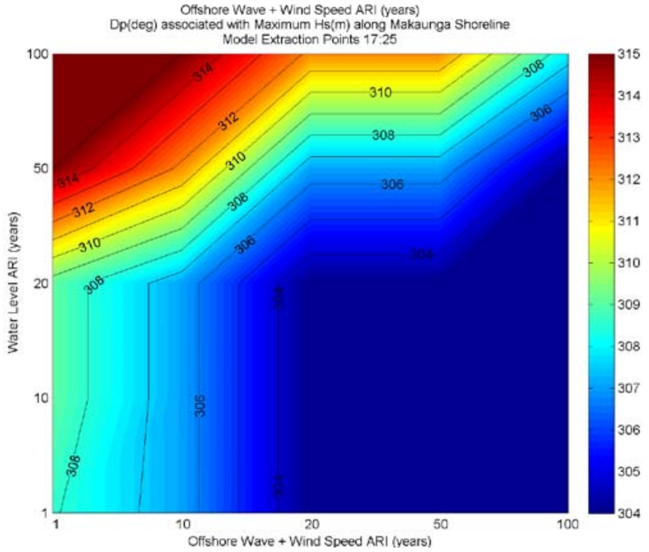


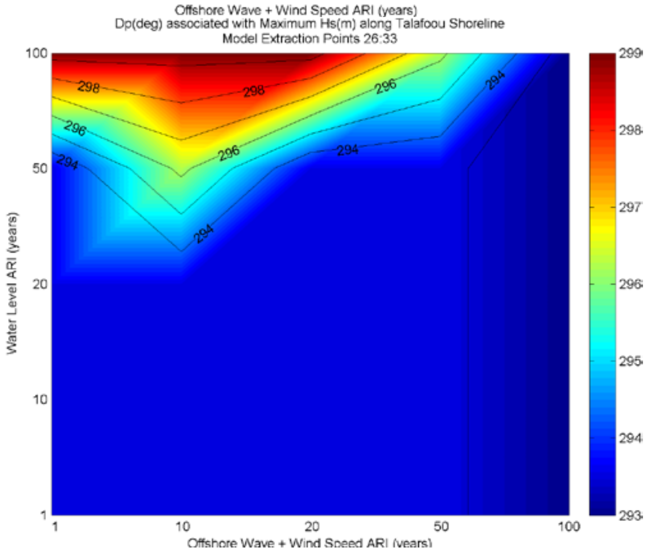


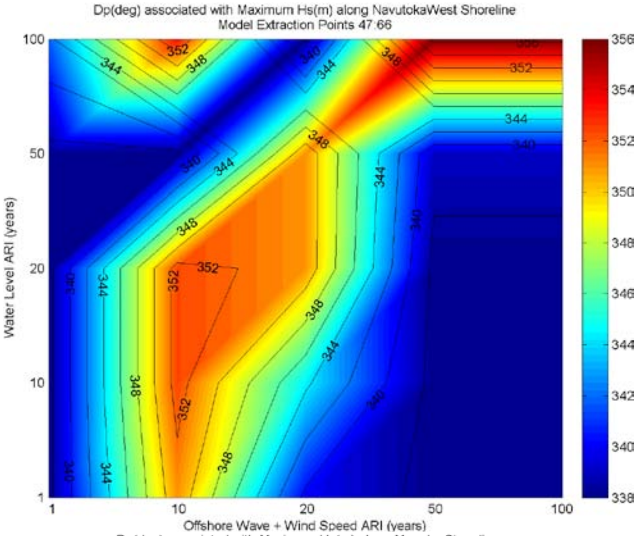


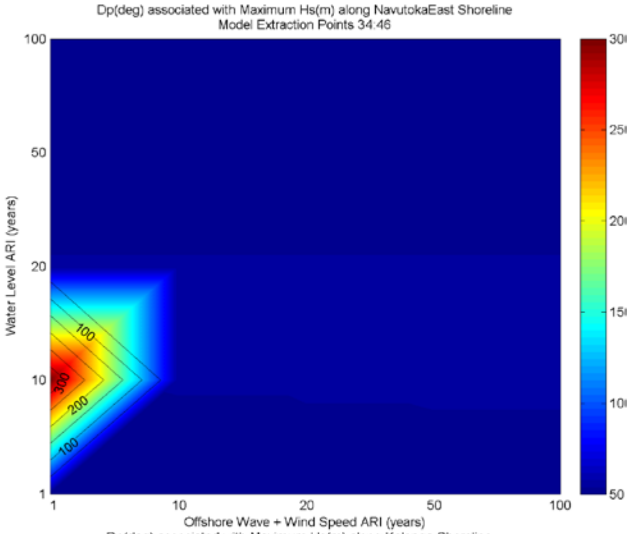

Tp(sec) associated with Maximum Hs(m) along Kolonga Shoreline
Model Extraction Points 95:100
Water Level ARI (years)
Offshore Wave + Wind Speed ARI (years)

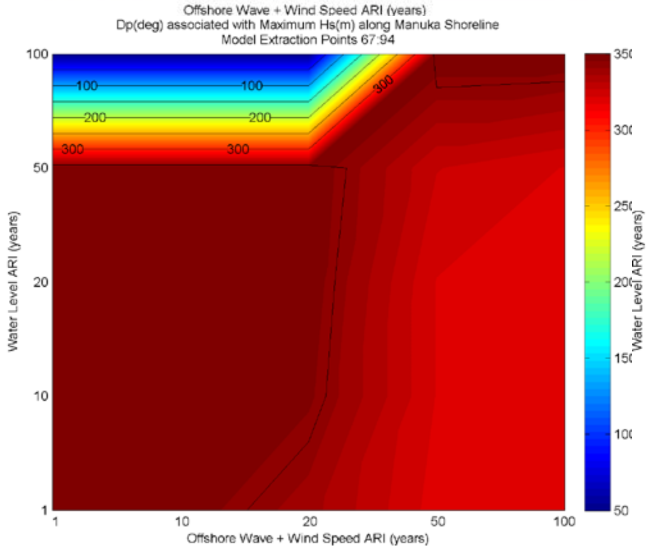

Dp(deg) associated with Maximum Hs(m) along Nukuleka Shoreline
Model Extraction Points 1:16
Water Level ARI (years)
Offshore Wave + Wind Speed ARI (years)

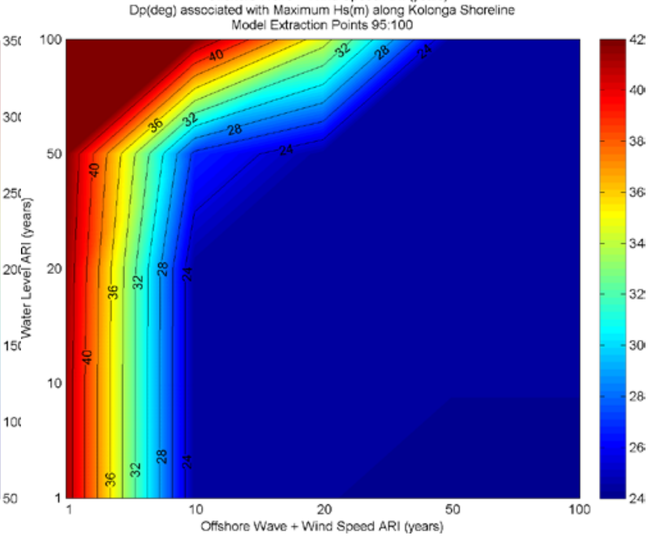

Dp(deg) associated with Maximum Hs(m) along Makaunga Shoreline
Model Extraction Points 17:25
Water Level ARI (years)
Offshore Wave + Wind Speed ARI (years)


Dp(deg) associated with Maximum Hs(m) along Talafoou Shoreline
Model Extraction Points 26:33
Water Level ARI (years)
Offshore Wave + Wind Speed ARI (years)


Dp(deg) associated with Maximum Hs(m) along NavutokaWest Shoreline
Model Extraction Points 47:66
Water Level ARI (years)
Offshore Wave + Wind Speed ARI (years)


Dp(deg) associated with Maximum Hs(m) along NavutokaEast Shoreline
Model Extraction Points 34:46
Water Level ARI (years)
Offshore Wave + Wind Speed ARI (years)


Dp(deg) associated with Maximum Hs(m) along Manuka Shoreline
Model Extraction Points 67:94
Water Level ARI (years)
Offshore Wave + Wind Speed ARI (years)


Dp(deg) associated with Maximum Hs(m) along Kolonga Shoreline
Model Extraction Points 95:100
Water Level ARI (years)
Offshore Wave + Wind Speed ARI (years)