Woja Causeway Project: Coastal Processes and Feasibility Study

Prepared for:

SPC – GCCA:PSIS

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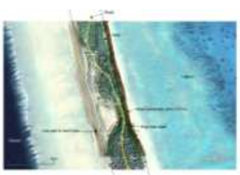
: **Cover page: Height contours of the causeway area overlaid on a satellite image.**

Executive Summary

This report provides the first output for SPC contract CC/13/357, which has been developed to provide engineering design and costing for coastal protection works for Woja Island, Ailinglaplap Atoll, in the Republic of the Marshall Islands specifically:

1. Review of past studies, assessments and documents relating to the project site, and liaise with RMI authorities and SPC Applied Geoscience and Technology Division regarding their archived data and knowledge relating to the project site.
2. Undertake an assessment visit to Ailinglaplap and Woja Island in particular. Hold consultations with the local community and collect the necessary data for assessment and design.
3. Prepare an assessment of coastal changes at Woja Island over the past 30 years within the context of coastal changes in Ailinglaplap Atoll, and based on the scientific studies, assessment visit and community consultation.
4. Prepare a feasibility and costing study of coastal protection measures required for Woja Island for the next 30 years, taking into account projected climate change and including hard and soft engineering measures.

A site visit on Woja Island was undertaken between 4th and 6th November 2013. The investigations included visual inspection and topographic survey of the existing causeway area, coastal inspection along both coasts of southern Woja Island, inspection of the north western coast of the island to determine suitable sources of construction material (i.e. large rocks), and ecological surveys (both marine and terrestrial) of the project site and the site of potential construction material (the latter is not reported here).

The site investigations indicated that there are two areas of concern at the causeway; the southern and most vulnerable part of the causeway, some 70 m in length which is exposed to on-going erosion on the eastern/lagoon side (Priority 1 site), and a less vulnerable part of the causeway to the north that is some 150 m

long and is flooded and impassable with vehicular traffic 1-2 hours either side of high tide (Priority 2 site).

Without intervention, continued erosion of the lagoon side beach and degradation of the beachrock reef on the western side will very likely lead to a permanent breach dividing the island through this area on every high tide. Lifting and armouring the 2 vulnerable sections of the causeway is required to prevent this from occurring.

A source of armour rock for remediating the access issues at Woja Causeway was identified some 4 km to the north on the north western exposed coast of the island. This area has abundant rock of 1.0 m diameter and larger, is accessible with vehicles and due to the very large number of rocks and the natural beach armouring with rocks and boulders, extraction of the relatively small volume of rocks for causeway remediation will have an insignificant impact on coastal processes.

Literature and data sources were reviewed for an overall assessment of environmental conditions at Woja Island and the determination of extreme water levels. It is notable that there are no studies specific to Woja Island, other than the scoping study that led to this project. Even so, general metocean data is available for the area from a variety of sources, which is relevant to development of design parameters for the remediation of Woja Causeway.

Literature and data reviewed includes general climate, tidal range, wave climate, wind climate, atmospheric pressure, historical aerial imagery and historical events (floods, typhoons and tsunami). The results of these investigations in conjunction with the information collected during the site survey has been used to develop estimates of super-elevated water levels at Woja Island in order to determine a suitable design height for the causeway.

Coastal hazard assessment and consideration of design factors for the Woja causeway project were undertaken for the eastern and western sides of the island using different methods due to the different physical settings (i.e. lagoon and open-ocean, respectively).

Long-term wind, wave and pressure data was used to determine extreme water levels for a variety of factors that are combined to determine maximum water elevations during extreme events (i.e. wind set-up, wave set-up, inverse barometric pressure, wave run-up and sea level variation) using both empirical and numerical models. In addition, typhoon and tsunami impacts were also investigated using historic records and tsunami modelling.

Total coastal hazard extreme water levels were calculated by combining all the various parameters with 100 year return periodicity, with the additional incorporation of 0.3 m of sea level rise over the next 30 years (the life-expectancy of the causeway structures), which produces 30 year extreme water levels of:

- 4.29 m on the west coast, and;
- 4.67 m on the east coast.

These levels are similar to those found in a comparable assessment for Beran Island, which is located north east of Woja Island on Ailinglaplap Atoll.

When these levels are related to the topographical survey of the site, it obvious that the highest land areas beyond the causeway are less than 3 m – this elevation is common for many of the Marshall Island Atolls. Therefore adopting design levels to avoid coastal hazards that are almost 2 m above the level of the island is impractical.

In the first instance, wave run-up was disregarded – the infrastructure planned is armoured roading, and so does not have to consider intermittent inundation by seawater. This leads to extreme water level values of:

- 3.79 m on the west coast, and;
- 3.07 m on the east coast.

Considering both the practicality of construction and the height of the surrounding island, a 3.0 m finished causeway height is recommended. This is an ‘Irish-

Crossing' type structure, i.e., rather than a primary piece of infrastructure for a densely populated coastal area, a robust structure that is designed to allow over-topping in the rarest and most extreme cases.

In considering the eastern side of the causeway, and the Priority 1 site, at an extreme water level of 3.07 m in 30 years time, there will be over-topping of this structure in the most extreme cases during high tide. Similar over-topping would occur along the finger of land adjacent to the northern area (Priority 2 site), where there is presently a footpath.

With respect to extreme water levels on the western side of the project site, disregarding run-up is warranted since the crest of the beachrock reef is some 35-80 m from the road, at an elevation of some 1.5-2.0 m above LAT and there is no beach beyond it for waves to run-up (the level drops away behind the crest to the low area of Priority 2 in the north and the tidal lagoon west of the Priority 1 area). However, the potentially significant wave set-up of 0.81 m during a 100 year return period wave event leads to a potential extreme water level of 3.79 m, i.e. 0.79 m above the finished causeway road level in 30 years time.

Based on the local topography, it is expected that during an extreme water level event with extreme wave set-up, over-topping will occur with an infra-gravity wave type period, i.e. surges occurring in relation to the arrival of wave groups (sets) across the reef flat, which are usually several minutes apart.

At the Priority 1 southern site, the new causeway road will be set some 15-20 m to the west of the existing causeway road to provide an additional erosion buffer on the eroding eastern side of the causeway. The new elevated road in the northern Priority 2 area will run along its existing route. In addition to elevating and armouring the causeway road, planting out of the existing road in the Priority 1 area (which will be replaced by the new causeway 15-20 m to the west) should be undertaken to provide additional buffering from erosion, preventing wind-blown loss of sand and providing added natural erosion resistance. Additional soft-engineering in the form planting around the site should also be applied, with mangrove in the low wet areas along the western side of the footpath, and additional Kone trees all around lower areas of the site. The exception to planting may be around the tidal lagoon area on the south western side of the causeway, since this area is known as Diamond Kan and is a popular picnic area for the villagers. This will be discussed during the next phase of consultation in the project.

The extreme wave heights calculated from long-term wave data and empirical and numerical modelling were used in the calculations of rock sizes. The results of applying these maximum wave heights to the Hudson formula led to a Dn_{50} (median rock diameter) of 0.71 m for the Priority 1 new causeway road, with ~10% safety factor resulting in the specified 0.6-0.9 m limestone rocks at a gradient of 1.5:1 (H:V), which are reduced to 0.3-0.5 m diameter for the elevated road section (Priority 2).

Contractors in Majuro were requested to provide cost estimates based on a project brief. The brief included preliminary plans and cross-sections of the proposed works for the Priority 1 and 2 areas, location photographs and maps, and a basic construction plan. Based on this information, the following cost estimates were developed for the project:

- Priority 1 cost estimate total: USD467,000
- Priority 2 cost estimate total: USD359,650
- Mobilization/Demobilization: USD60,00
- Total estimated cost: USD886,650

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1 Background

SPC, specifically the Global Climate Change Alliance: Pacific Small Island States (GCCA:PSIS) project in the Strategic Engagement Policy and Planning Facility, has commissioned eCoast Marine Consulting and Research to provide engineering design and costing for coastal protection works for Woja Island, Ailinglaplap Atoll, in the Republic of the Marshall Islands (Figure 1.1).

This report provides the first output for SPC contract CC/13/357, specifically:

1. Review of past studies, assessments and documents relating to the project site, and liaise with the Republic of Marshall Islands (RMI) authorities and SPC Applied Geoscience and Technology Division regarding their archived data and knowledge relating to the project site.
2. Undertake an assessment visit to Ailinglaplap Atoll and Woja Island in particular. Hold consultations with the local community and collect the necessary data for assessment and design.
3. Prepare an assessment of coastal changes at Woja Island over the past 30 years within the context of coastal changes in Ailinglaplap Atoll, and based on the scientific studies, assessment visit and community consultation.
4. Prepare a feasibility and costing study of coastal protection measures required for Woja Island for the next 30 years, taking into account projected climate change and including hard and soft engineering measures.

This report considers the feasibility of developing a causeway on Woja Island capable of meeting the future needs of the inhabitants while addressing issues related with climate change (i.e. developing climate change resilience). Understanding of the existing coastal processes and consideration of coastal hazards are implicit to determining the feasibility of the project. Therefore, this report considered these aspects within the context of a coastal hazard assessment, along with appropriate design levels and determination of appropriate structural intervention for the study site.

The next stages of the project include:

1. Participate in a consultation in Majuro, RMI, to present this feasibility study and assist in the selection of priority coastal protection measures for Woja Island within the context of the project budget (the project has a €0.5M cap). It is anticipated that community representatives from Woja Island and other islands in Ailinglaplap Atoll will come to Majuro to participate in this meeting in early March 2014.
2. Prepare a detailed design, costing and engineering drawings for the selected coastal protection measure(s), which should combine hard and soft engineering measures where possible.
3. Design a monitoring and evaluation framework for the selected coastal protection measure(s).

In order to consider the efficacy of each component of the project, the monitoring and evaluation framework is critical, and will cover the construction of the coastal protection works and monitoring over at least a 3 year post-construction period. A thorough and quantified understanding of the efficacy of the project at Woja will lead to the development of sustainable and effective methods for these types of environments in other parts of the Marshall Islands and in the Pacific.

Figure 1.1. Location map of the project site on Woja Island, Ailinglaplap Atoll in the Republic of the Marshall Islands. (Source Google Earth 2014)

2 Site Description/Visit and Data Collection

A site visit on Woja Island was undertaken between 4th and 6th November 2013. The investigations included visual inspection and topographic survey of the existing causeway area, coastal inspection along both coasts of southern Woja Island, inspection of the northwestern coast of the island to determine suitable sources of construction material (i.e. large rocks), and ecological surveys (both marine and terrestrial) of the project site and the site of potential construction material (the marine ecological survey is presented in a separate report, Fellenius, 2013).

2.1 The Project Site

Figure 2.1 shows satellite images of the project site and the potential source for construction materials some 4 km to the north of the site.

Figure 2.1. Location of the project site and potential construction material area. (Source: Google Earth, 2014)

The project site is some 400 m from north to south, with a low beachrock reef on the western open ocean side and low limestone rock flats (near the low tide level) below a sandy beach on the eastern lagoon side (Figure 2.2). The area of low and friable beachrock reef on the western side of the site is the only part of the island's surrounding reef flat that is comprised of this type of rock and is distinctly lower than the reef platforms to the north and south of the area – the length of beachrock on the reef flat adjacent to the causeway area is clearly visible in Figure 2.1.

Figure 2.2. Left: The low-crested, friable, beach rock reef on the western side of the project site. Right: the flat limestone reef flat near low tide on the eastern lagoon side of the project site.

There are two parts of the causeway that require protection and elevation to allow all weather access (presented in Figure 2.3):

1. The southern part is some 70 m long and located close to the eroding eastern lagoon side of the island – this site is considered the most vulnerable, and is located on a strip of land only 10 m wide between the lagoon-side beach and the small tidal lagoon inside the beach reef on the western side (Figure 2.4). This stretch is considered the first priority for the project.
2. The northern part is separated by a ~90 m long high area of the road (it is over 3 m above chart datum along much of this stretch), and is comprised of a low area of road some 150 m long that is flooded 1-2 hours either side of low-tide (Figure 2.5). However, while access is restricted during higher tidal

levels, this section of the road is not vulnerable to erosion or wave attack. Thus, this section is considered the second priority for the project.

Figure 2.3. The project site is divided into 3 distinct areas – the first priority most vulnerable 70 m length of road in the south; the high central section of the site, and the second priority 150 m low stretch of road to the north.

Figure 2.4. The 70 m long Priority 1 southern part of the vulnerable road adjacent to the lagoon – to the left of the photograph (out of view) is the tidal lagoon that floods each high tide; only 10 m separates the east and west sides of the island at high water.

Figure 2.5. The 150 m long Priority 2 section of low road at the north of the project site during high tide (left) and low tide (right).

During high tides, the sea over-tops the low beachrock crest (Figure 2.6) and floods the northern part of the causeway over a ~150 m stretch of road, making it inaccessible to vehicles for 1-2 hours either side of high tide. There is a narrow footpath access on the eastern side of the site. However, it is not suitable for development into a road since it is very close to the lagoon beach and vulnerable to erosion, as is the southern part of the existing causeway.

Figure 2.6. Over-topping of the beachrock reef on the western side of the project area; during high tide, the northern 150 m of low road and the tidal lagoon adjacent to the Priority 1 area floods.

On the southern part of the project site, at the Priority 1 site, the high tide fills a tidal lagoon (Figure 2.3), which results in this stretch of the island being only some 10 m wide at high tide (Figure 2.7). Discussions with locals indicate this area, and the area to the north where the Priority 2 stretch of road is submerged at high tide, have gotten lower over time (i.e. the water is deeper today over the road and in the lagoon than it was previously).

Figure 2.7. Looking north from the tidal lagoon on the western side of the Priority 1 site at mid-tide – the road is directly behind the trees on the right of the photograph, with the width of the island being only some 10 m along this stretch at high tide.

From the site inspection, it is likely that the loss of sand from this area has been caused by currents generated by the over-topping of the low beach-rock reef crest. When water is pushed over the reef crest by wave action and into the low road and tidal lagoon area (Figure 2.6), it wants to flow back seawards, i.e. a water level gradient is set-up inside the reef crest which drives a current seawards. There are two low areas in the beach rock reef, a large breach (~9 m wide – Figure 2.3) and a smaller secondary breach. It is likely that sand has been periodically washed out through these gaps during large wave events that both lift the sand into suspension and set-up a strong water level gradient and consequent strong currents that remove the sand.

Ribbons of sand on the reef flat below the beach rock reef were observed below both the breaches in the beach rock reef, which supports this method leading to the lowering of the areas of the northern low road and lagoon. However, it is not expected that the road or lagoon will continue to deepen. There is little loose sand in the lagoon (only around the beach on the eastern side, distant from the breaches, the rest is beachrock), and much of the road area is a compact layer of gravel and beachrock reef – Kone trees with their exposed roots are the also abundant in the northern area (Figure 2.8). Even so, simple measures to reduce the potential further loss of sand in these areas could be undertaken during construction, which would entail plugging the 9 m wide gap with 0.9-1.1 m diameter rock.

Figure 2.8. The compact gravel and beach rock northern section of road and Kone trees growing on exposed rock.

Over 10 km of coast was also surveyed on the east and west coasts to the north and south of the project site. On the western coast of Woja Island, apart from the lower beachrock reef area adjacent to the project site, limestone reef rises to near the high tide mark and is topped with sand and/or over-hanging coconut palms (Figure 2.9). There was little evidence of active erosion on the western coast.

In contrast, the whole south eastern coast of Woja Island from the southern tip to 300-400 m north of the project site has been experiencing aggressive on-going erosion (Figure 2.9). There is little data available to determine the cause of the erosion. However, the strong La Nina conditions of the past few years or so may be accountable. Stronger and more persistent winds from the east or southeast (rather than the usual north of east winds Figure 3.11) would result in the loss of sand on the south eastern coast of Woja Island, since there is no sediment source to the south, beyond the end of the island to replenish sand that is moved northward by this wind.

Figure 2.9. Left: the western coast of Woja Island is typified by limestone reef rising to near the high tide mark and is topped with sand and/or over-hanging coconut palms, except at the project site where friable beach reef is located adjacent to the project site. Right: Aggressive erosion on the south eastern coast of Woja Island has left bare rock and fallen trees along much of this part of the coast.

To consider whether or not the La Nina may have led to the erosion of the southeastern coast of Woja Island, annual wind roses for 2011, 2012 and 2013 were extracted from the eCoast-MDI (long term met-ocean data base). Analysis of the wind for these 3 years indicates a significant difference in wind direction for 2011 and 2012 in comparison to 2013 (Figure 2.10), which is similar to the average winds from the 14 year record (Figure 3.11). Winds during 2011 and 2012 are offset to the south compared to average conditions, which may account for, or have contributed to, the erosion of the south eastern beaches of Woja Island.

Ford (2013) considered the shoreline using aerial photography and satellite images from 1945 to 2012 at Wotje Atoll in the RMI. Ford concluded that up until 2010 shoreline accretion was more prevalent than erosion, which fits with the recent La Nina phase. However, there was some indication of a shift towards erosion from 2004, which he suggests may be due to sea level rise (Ford, 2013). Recent research has also indicated that winds in the Pacific Ocean have been significantly stronger since early this century (Newman, 2013), which may also impact on the eastern coast of atoll islands in the Marshall Islands.

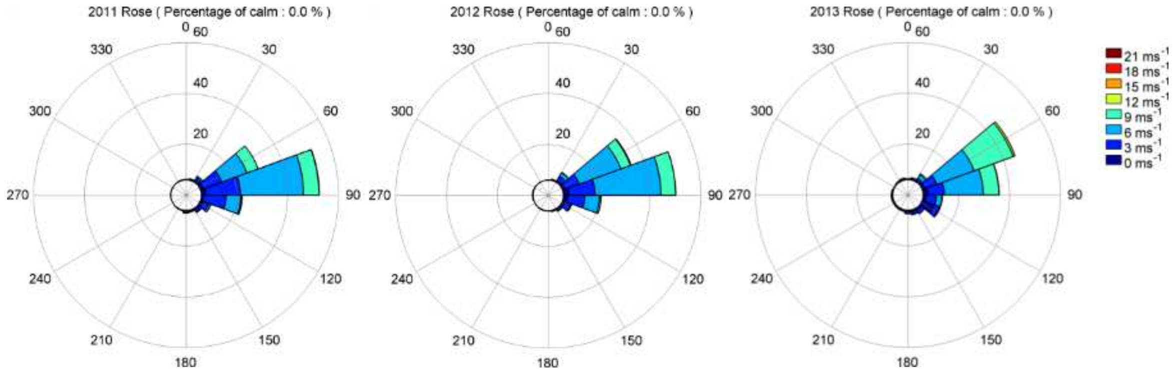

Figure 2.10. Annual wind roses for 2011 (Left), 2012 (Centre) and 2013 (Right). The 2013 wind conditions are similar to the average wind conditions determined from long term wind records (Figure 3.11). Winds during 2011 and 2012 are offset more to the south than during average wind conditions.

Along most parts of the island, the reef platform rises to beyond the high tide mark (e.g. right hand image in Figure 2.9). However, the lack of reef platform above the lower tidal level on the lagoon side of the Priority 1 site (Figure 2.2), the lower level of the island in this area (Figure 2.3), as well as the gap in the offshore reef on the lagoon side[1], exacerbate erosion along this stretch of the lagoon beach, and so make this section of the causeway very vulnerable.

Thus, without intervention, continued erosion of the lagoon side beach and degradation of the beachrock reef on the western side will very likely lead to a permanent breach dividing the island on every high tide. Lifting and armouring the 2 vulnerable sections of the causeway will prevent this from occurring.

2.2 Topographic Survey

During the site visit, personnel from RMI Lands and Survey undertook a topography survey of the project site using a total station (Figure 2.11). Since there were no

[1] It was observed during low tides that the reef on the lagoon side of the project site is both close to the shore and lower than adjacent reef areas.

existing benchmarks for the survey to be tied into, temporary benchmarks were developed for the survey, and the height of the tide was used to reduce all levels to Lowest Astronomical Tide (LAT), which is also Chart Datum (CD). By matching the predicted level of the tide at the time the survey marks of water level were taken (Figure 2.12), and offsetting the predicted level with the air pressure at the time of the survey (using the NCEP/NCAR Reanalysis – http://www.esrl.noaa.gov), the whole dataset could be reduced to heights relative to LAT. Further analysis of the tidal and water level data is presented in later parts of this report.

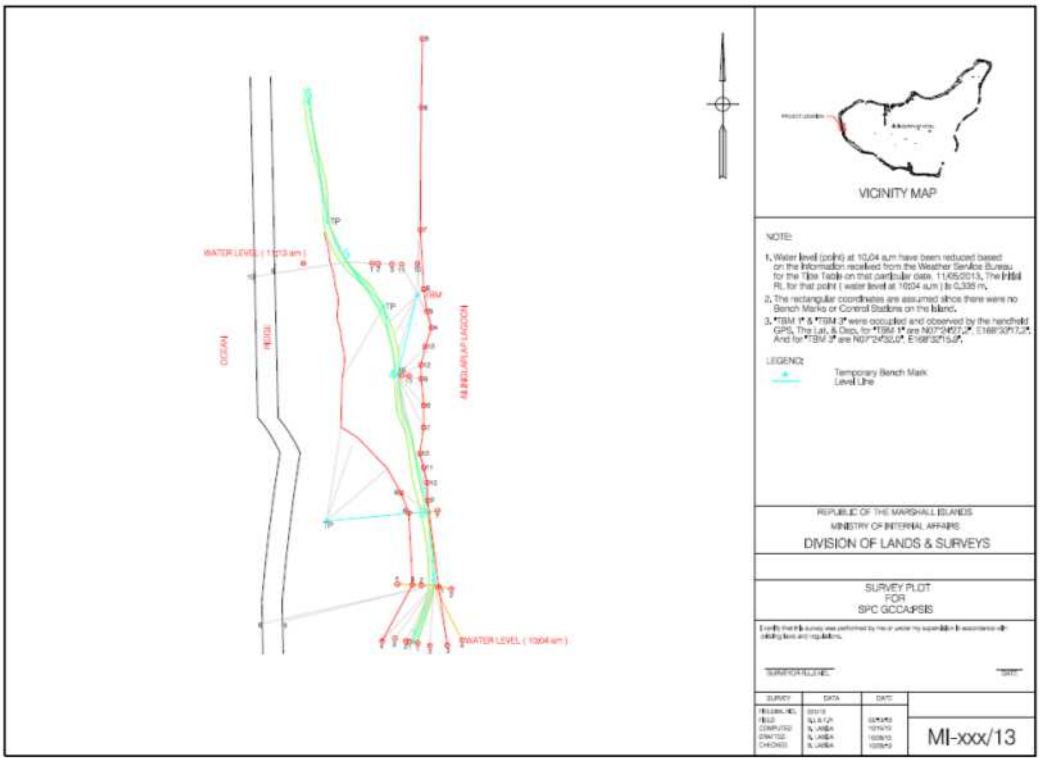

Figure 2.11. The survey undertaken of the causeway site by Lands and Survey, RMI.

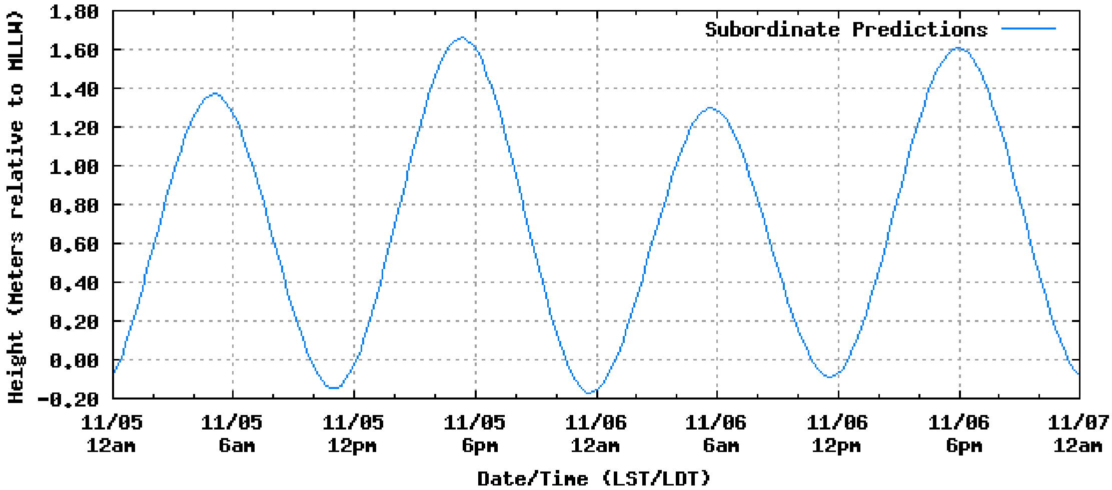

Figure 2.12. The predicted tidal levels during the survey period.

These corrected data were next supplemented with data captured at the site using a handheld GPS to further add detail with respect to both elevations (e.g. the location of the high-tide mark around the site) and site layout. The resulting data set was then used to develop a digital terrain model (DTM) of the site, as presented in Figure 2.13. From the DTM a series of cross-sections and long-sections (Appendix 1) were extracted to assist in the estimation of distances and volumes for the development of the causeway.

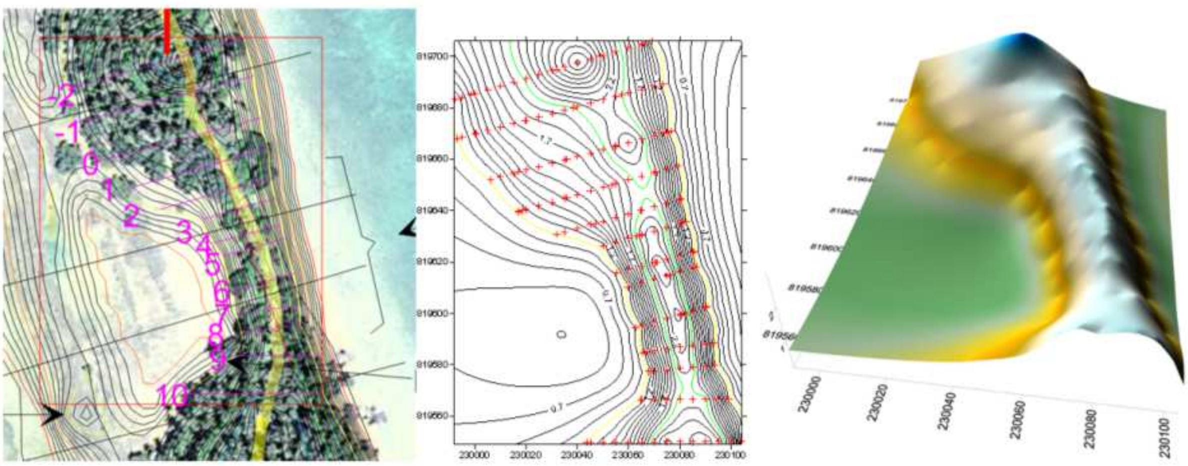

Figure 2.13. The height corrected and supplemented survey dataset was used to develop a digital terrain model (DTM), which was then used to develop cross-sections and long-sections and hence estimates of distances and volumes required for causeway development.

2.3 Potential Source of Construction Material

Due to the isolation of the atoll, part of the site visit was directed to identifying suitable construction material on the island, mainly large rocks for armouring the causeway. Some suitably sized rock was identified at the landing site, which is on the northwestern coast of the island. Investigation further north of the landing site led to an extensive area of large rocks (many >1.0 m in diameter) which were considered suitable for construction units – calculation of maximum wave heights and consequent rock sizes required for armouring are presented in Section 5.2 below. During the site visit it was assumed that rock over 1 m in diameter would be suitable for armouring based on a) the fetch-limited extent of the lagoon on the eastern side, b) the height-limited wave exposure due to the platform reef on the western side (e.g. Gourlay, 1997), and c) experience with similar coral island sites around the Pacific.

The source of construction rocks (Figure 2.1) is some 4 km north of the project site, and access is available via a coastal road adjacent to the school. There are extensive volumes of rocks that are located on a flat reef platform, which make access to them relatively easy during lower tidal phases (Figure 2.14). These rocks have been broken off the outer edge of the platform reef during large wave events and thrown up onto the flats. Over time they are worked shoreward and slowly reduced to smaller and smaller boulders over time. An additional advantage of this source site is the abundance of smaller boulders armouring the beach (Figure 2.14), i.e. removal of a relatively low number of large rocks on the platform reef is unlikely to have any significant impact on coastal process (e.g. lead to erosion).

Figure 2.14. A very large supply of rock is available on the northwestern coast of Woja Atoll. The GPS on the rock in the righthand photo is 15 cm long (i.e. the rock it is sitting on is approximately 1.1 m diameter).

2.4 Summary

A site visit on Woja Island was undertaken between 4th and 6th November 2013. The investigations included the visual inspection and topographic survey of the existing causeway area, coastal inspection along both coasts of southern Woja Island, inspection of the northwestern coast of the island to determine suitable sources of construction material (i.e. large rocks), and marine and terrestrial ecological survey of the project site and the site of potential construction material.

The site investigations indicated that there are two areas of concern at the causeway; a southern and most vulnerable part of the causeway of some 70 m length which is exposed to on-going erosion on the eastern/lagoon side (Priority 1 site), and a less vulnerable part of the causeway to the north that is some 150 m long and is flooded and un-passable with vehicular traffic 1-2 hours either side of high tide (Priority 2 site).

Without intervention, continued erosion of the lagoon side beach and degradation of the beachrock reef on the western side will very likely lead to a permanent breach dividing the island through this area on every high tide. Lifting and armouring the 2 vulnerable sections of the causeway is required to prevent this from occurring.

A source of armour rock for remediating the access issues at Woja Causeway was identified some 4 km to the north on the north western exposed coast of the island. This area has abundant rock of 1.0 m diameter and larger, is accessible with vehicles and due to the very large number of rocks and the natural beach armouring with rocks and boulders, extraction of the relatively small volume of rocks for causeway remediation will have an insignificant impact on coastal processes.

3 Review of Available Data and Literature

3.1 Data Sources

This section details the literature and data sources reviewed for overall assessment of environmental conditions at Woja Island and the determination of extreme water levels. It is notable that there are no studies specific to Woja Island, other than the scoping study that led to this project – "Ailinglaplap Coastal and Climate Change Vulnerability Study" (Why et al., 2013). Even so, general metocean data is available for the area from a variety of sources.

Literature and data sources included an extensive internet search of electronically available publications and websites. This included news sites, university research sites (i.e. University of Hawaii) and governmental data repositories (i.e: NOAA, Australian Bureau of Meteorology). In addition, a set of historical aerial photographs of Ailinglaplap Atoll were available for comparison to recent satellite images.

Wind and wave data were sourced from the eCoast Marine Data Interface (MDI). The eCoast MDI is an in-house database of global marine data. The MDI is a user-friendly software aid to allow ready access to global tide, wind, wave, and sea level data stored on in-house computers. The database contains over 14 years of information from various sources. Available datasets include QuikSCAT satellite-observed wind from NASA's Jet Propulsion Laboratory, NOAA Wavewatch III outputs from a global forecast/hindcast system for wind and waves, global bathymetry, satellite observed sea surface temperature and sea surface height anomalies.

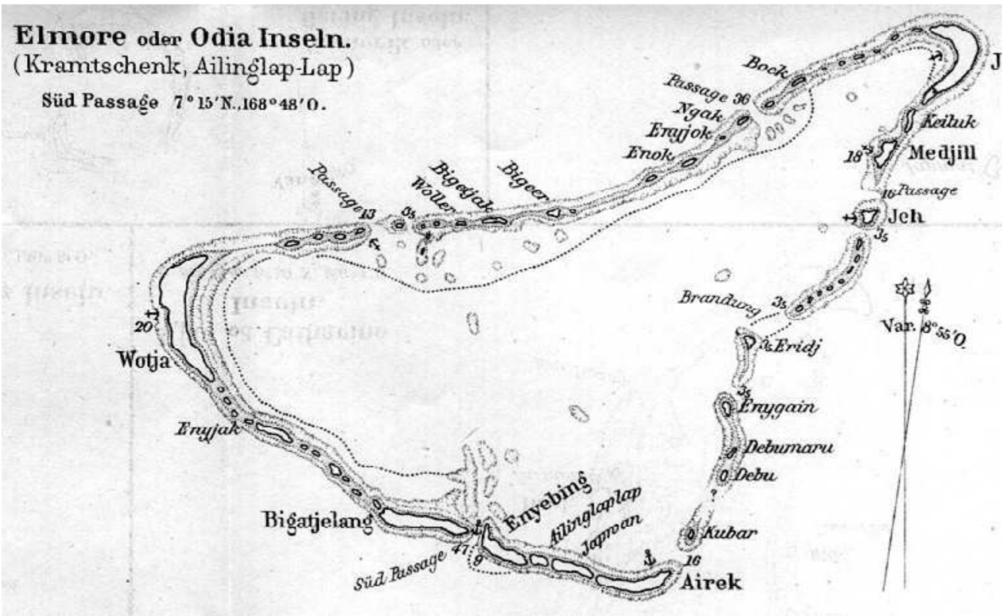

Figure 3.1. A historical map of Ailinglaplap Atoll found during the search. Note the presence of an anchorage noted at the location off Woja Island where the Police Patrol Boat was stationed during the site visit.

3.2 RMI Climate

The Embassy of the Republic of the Marshall Islands provides a climate overview on their website (http://www.rmiembassyus.org/Geography.htm). The climate is hot and humid, tempered by prevalent trade winds. The average temperature is 27 °C with the average monthly temperatures varying less than 0.5 °C. Rainfall varies significantly throughout the Marshall Islands, with the southern atolls being wetter and the northern atolls drier. Rainfall averages between the north and south vary from 500 to 4,000 mm per annum. Rainfall at Majuro situated 300 km to the east of Alinglaplap Atoll has monthly rainfall averages of 175 - 350 mm and an average annual rainfall of 3,350 mm.

However, periods of drought are not unknown.On 20th March 1998 March 21st 2007 and again on 19th April 2013, the government of the Marshall Islands declared a state of emergency due to severe and prolonged droughts.

3.3 Tides

There are several factors that contribute to the water level at any coastal site. In the present case, water levels are very important to consider, with spring tide events meaning that the causeway cannot be crossed 1-2 hours either side of high tide.

The most basic component of water level is tidal fluctuations. The largest variability in the magnitude of tidally driven water levels is over monthly time scales with the well-known ‘spring-neap’ tide cycle where tides are higher during new and full moons (spring tides) and not as extreme during quarter phases of the moon (neap tides). This effect is caused by the relative phase difference between the position of the moon and the sun relative to the earth (spring tide interval ~15 days) and by the relative distance of the earth from the moon (anomalistic month effect ~28 days).

In addition to this fluctuation, water levels are also affected by the declination of the suns orbit relative to the earth (solar semi-annual ~183 days) and the proximity of the earth to the sun (anomalistic year ~ 365 days). A final factor contributing to the magnitude of the tide is the regression of the moon’s nodes, this effect controls the declination of the moons orbit relative to the earth and operates over a period of 18.6 years.

While these effects are all secondary to the basic driver of the tidal water level – the rotation of the earth relative to the moon (~12.4 hours) and the influence of the lunar and solar declination caused by the earth’s rotation on its axis (~24 hours), they can become very important when they occur concurrently. Such an occurrence is called a ‘king tide’ and occurs twice per year at any particular location. King tides can of course be exacerbated if they occur in phase with other factors such as the 18.6 year lunar nodal regression, climatological events or atmospheric conditions.

As mentioned above meteorological and climatological factors are important drivers of the overall water level. These fluctuations are caused by wave conditions, wind conditions and local pressure fluctuations and can collectively be referred to as the ‘storm surge’. Typhoons, strong trade winds or very large long period swells can cause this effect. Longer term climate effects such as El Niño-Southern Oscillation

(ENSO), the Inter-decadal Pacific Oscillation (IPO) and the Madden Julien Oscillation (MJO) can also have an impact on water levels. While somewhat less severe in most parts of the world, these events have a particularly strong effect on low lying atolls such as the Marshall Islands. A final water level factor considered in this report is tsunamis caused by tectonic events around the Pacific Rim, which may also have an effect on water level.

Tide levels were obtained for the area using two sources, measured data from the Kwajalein tide gauge maintained by NOAA and from a world tidal model. To obtain accurate tidal information for the Ailinglaplap Atoll, data was extracted from the global tidal model which provides the amplitudes and phases of the 8 most dominant tidal constituents.

The global model was developed by Oregon State University and is based on data collected from the TOPEX/Poseidon (T/P) satellite overpasses. The T/P satellite altimeter was in service from 1992 to the end of 2005 and throughout its life, continuously observed global ocean topography which has been measured to within 5 cm accuracy between the latitudes of 66°N and 66°S.

This data was used by Egbert *et al* (1994) to create a global tidal model from which the phases and amplitudes of 8 tidal constituents (Table 3.1) can be extracted from any location, to quarter degree resolution, within the flight path of the T/P satellite.

Tidal prediction was undertaken considering the full 18.6 year tidal cycle (Figure 3.2). Predicted maximum and minimum tide levels during this period are +1.005 m above MSL, and -0.92 m below MSL respectively. The maximum level of +1.0 m above MSL is included in the calculation of extreme water levels detailed later in the report. Thus, the maximum tidal range for Woja is 1.925 m.

Table 3.1. Tidal constituents used for the creation of the tidal record.

	Symbol	Period (Solar Hrs)	Description
Semidiurnal tides (approximately two tides per day)	M_2	12.42	Main lunar semidiurnal constituent
	S_2	12.00	Main solar semidiurnal constituent
	N_2	12.66	Lunar constituent due to monthly variation in the Moon's distance
	K_2	11.97	Solar-lunar constituent due to changes in declination of the sun and the moon throughout their orbital cycle
Diurnal tides (approximately one tide per day)	K_1	23.93	Solar-lunar constituent
	O_1	25.82	Main lunar diurnal constituent
	P_1	24.07	Main solar diurnal constituent
	Q_1	26.8684	Larger lunar elliptic diurnal constituent

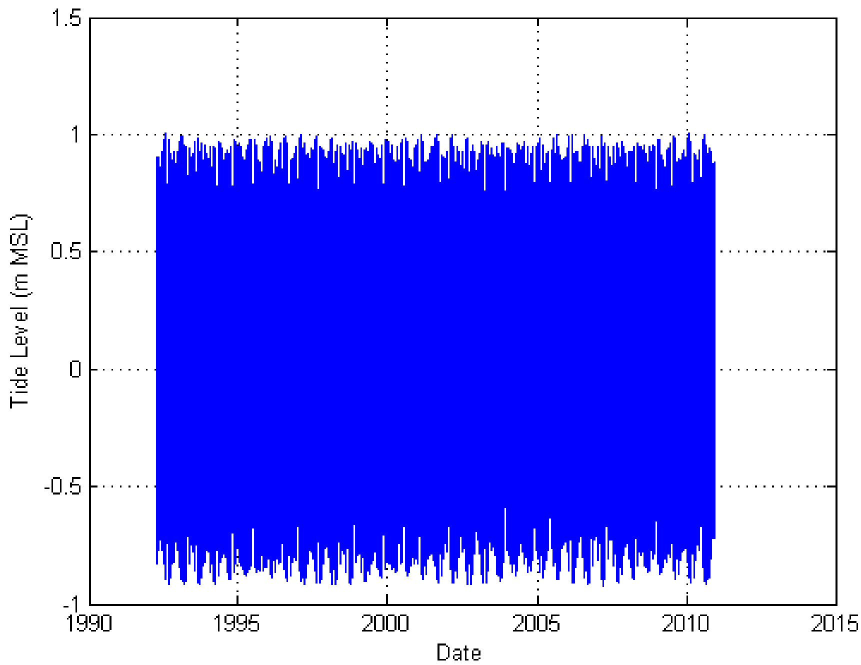

Figure 3.2 Predicted tidal levels considering the full tidal cycle over the past 18.6 years.

Section 4 of this report details the computation of each of the factors contributing to a super-elevation of the water level at Woja Island in order to determine a suitable design height for the causeway.

3.4 Wave-Climate

Wave data was extracted from eCoast's MDI from February 1997 to August 2010 for two nodes to the north and south of Ailinglaplap Atoll. The two nodes are described as 'north' and 'south' and are located at 8°N / 168.75°E and 7°N / 168.75°E, respectively (Figure 3.3).

The 14 year wave records for the two sites are shown in Figure 3.4 and Figure 3.5. Records for both sites indicate that wave heights over 3 m occur frequently during the windy season / northern hemisphere winter. Wave events over 3.5 m are less common with 8 and 5 events occurring within the past 14 years for the north and south sites, respectively. These events had peak periods of 7 to 14 s. Wave statistics for the two sites are shown in Table 3.2.

Wave records for the two sites have been decomposed into months to show seasonal variation in significant wave height (H_s) and peak wave period (T_p) from the 14 year record (Figure 3.6). These are included in Appendix 2 and show greater wave heights from November to April from the northeast owing to trade winds. Long period swell from the northwest also occurs from December through March owing to the northern hemisphere winter wave climate.

A verification of the MDI data with buoy data (as per the wind analysis) is problematic owing to the availability of proximal wave buoy data. NDBC buoy records proximal to Ailinglaplap include Kwajalein Island and Kalo (Figure 3.7). Both buoys measure meteorological data but only the Kalo buoy includes wave data. The Kalo wave data covers the period May to December 2010. The Kalo buoy is also located 300 km east and is subject to a different wave climate due to various bathymetric and topographic features. Nonetheless the Kalo data has been compared to the MDI record for the available overlap period of May to August 2010 (Figure 3.7). The two data sets compare well for the wave height, but the Kalo data set shows much more variability in direction and period.

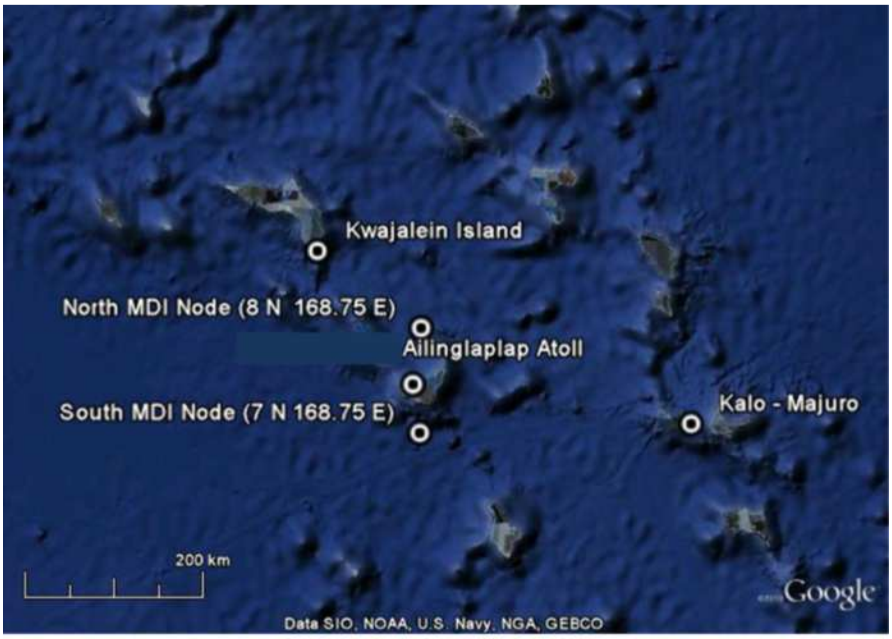

Figure 3.3. Location of MDI nodes north and south of Ailinglaplap Atoll, Kwajalein Island and Kalo NDBC buoys.

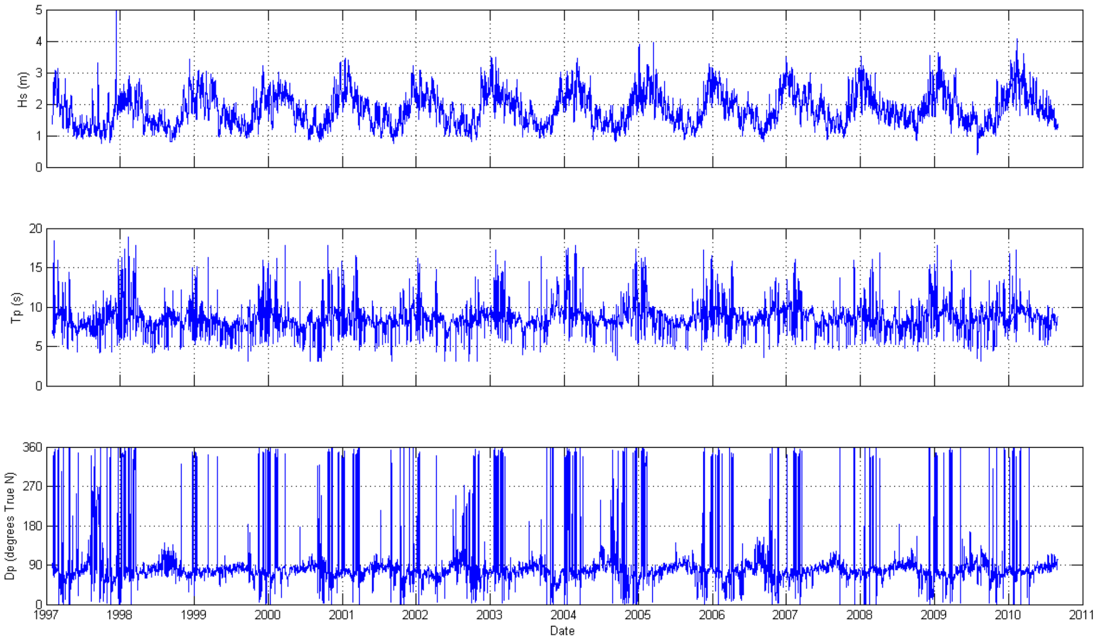

Figure 3.4. MDI wave record for site north of Ailinglaplap Atoll at 8°N 168.75°E.

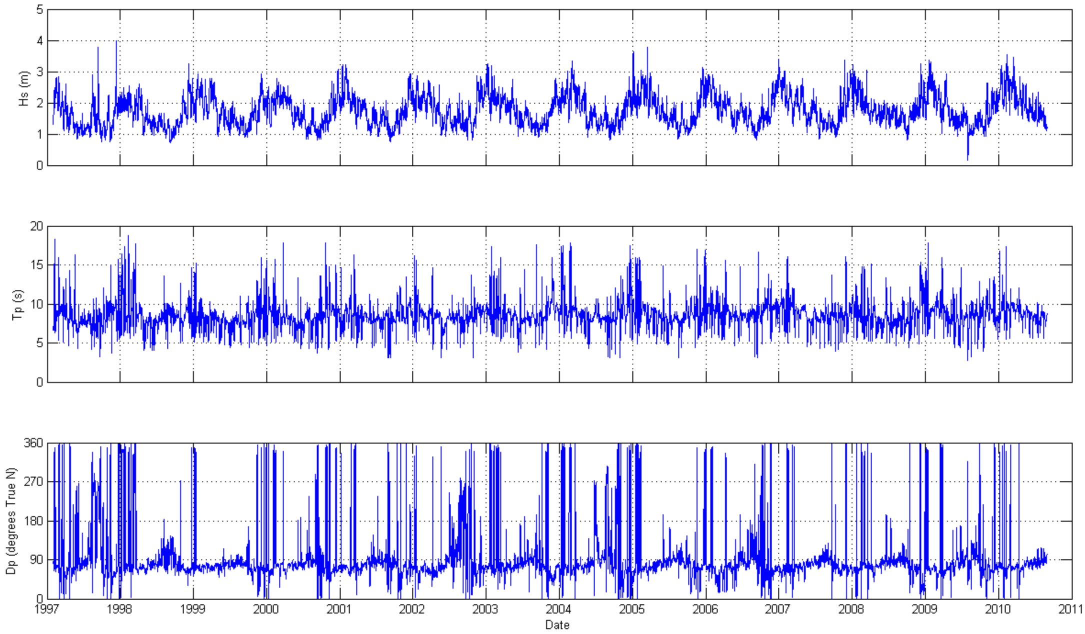

Figure 3.5. MDI wave record for site south of Ailinglaplap Atoll at 7°N 168.75°E.

Table 3.2. Wave statistics for two sites north and south of Ailinglaplap Atoll.

	North (8°N	South (7°N
Max H_s	5.04 m	4.00 m
Mean	1.81 m	1.74 m
Mean	9 s	9 s
Mean	93°	92°

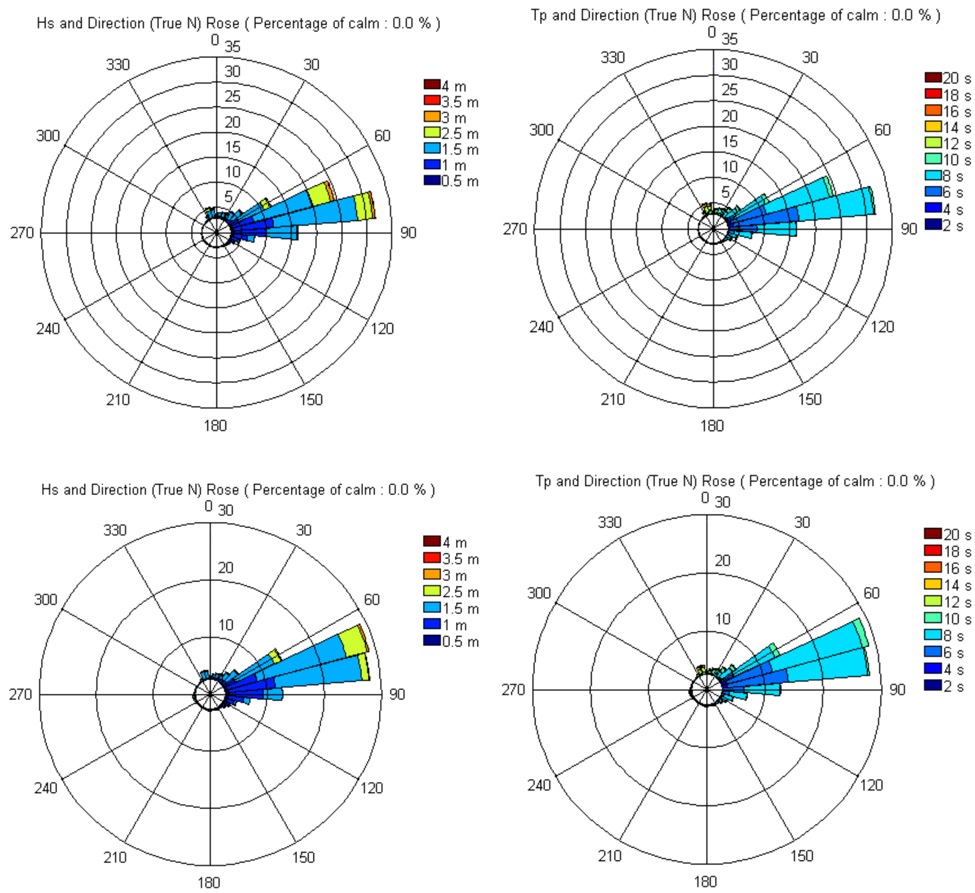

Figure 3.6. Wave roses for significant wave height (H_s - left) and peak wave period (T_p - right) extracted from the MDI wave record for the north (top) and south (bottom) sites of Ailinglaplap Atoll at 7°N 1/ 68.75°E.

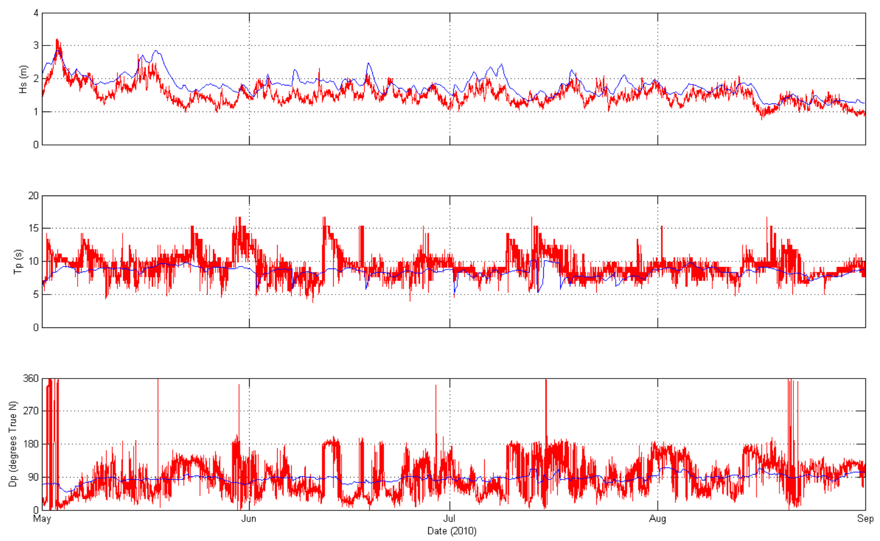

Figure 3.7. MDI wave record for site north of Ailinglaplap Atoll at 8°N / 168.75°E (blue) compared to NDBC Station 52201 – Kalo, Majuro 7.092°N / 171.395°E (red).

3.5 Wind-Climate

A 14 year time series of 3-hourly wind speeds from the eCoast-MDI were used in the analysis. Data from two model nodes north and south of Ainglaplap were extracted and compared to 4 years of wind records from the Kwajalein Island wave buoy. The locations of the data points and the Kwajalein Buoy are shown in Figure 3.8. An extreme wind analysis has then been undertaken on the 14 year MDI wind record.

The 14 year wind records for the two sites are shown in Figure 3.9 and Figure 3.10. Wind roses for the same period are shown in Figure 3.11 and clearly show the dominant trade winds from the northeast. The wind record for the two sites have been decomposed into months to show seasonal variation (Appendix 3). Trade winds are apparent in the record with speeds increasing from November through April.

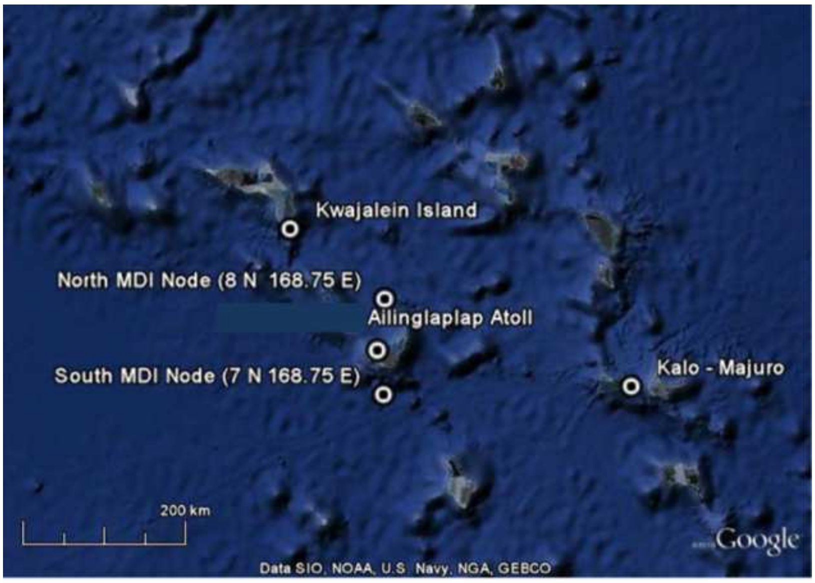

Figure 3.8. Location of MDI nodes north and south of Ailinglaplap Atoll, and Kwajalein Island NDBC buoy.

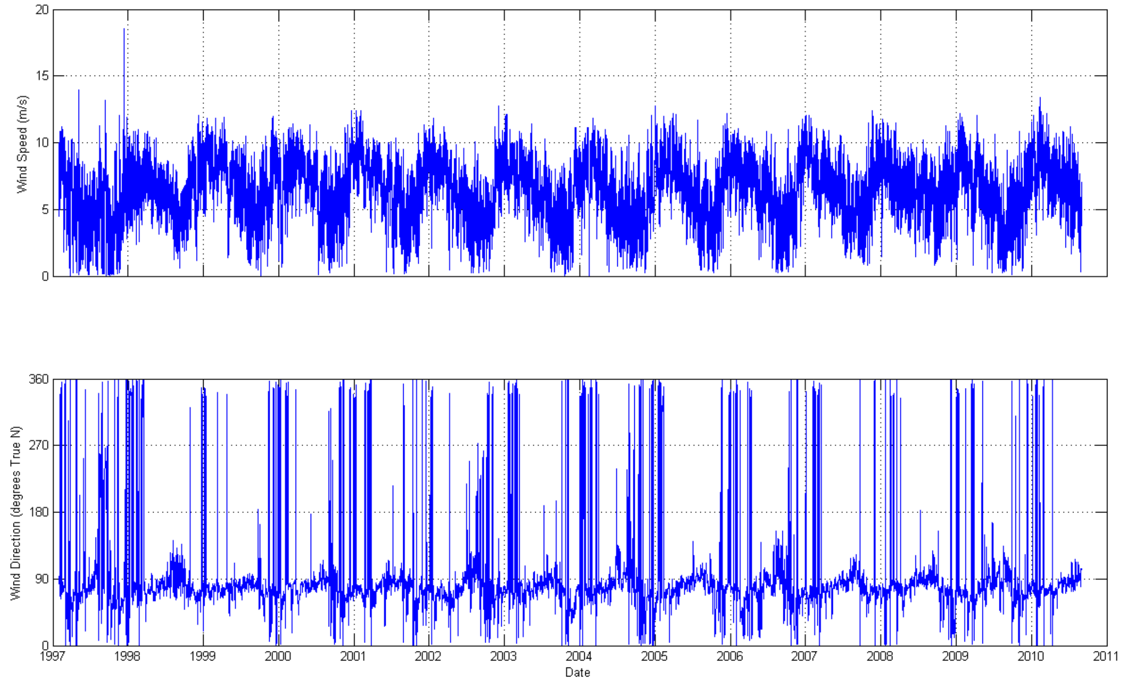

Figure 3.9. MDI wind record for site north of Ailinglaplap Atoll at 8°N / 168.75°E.

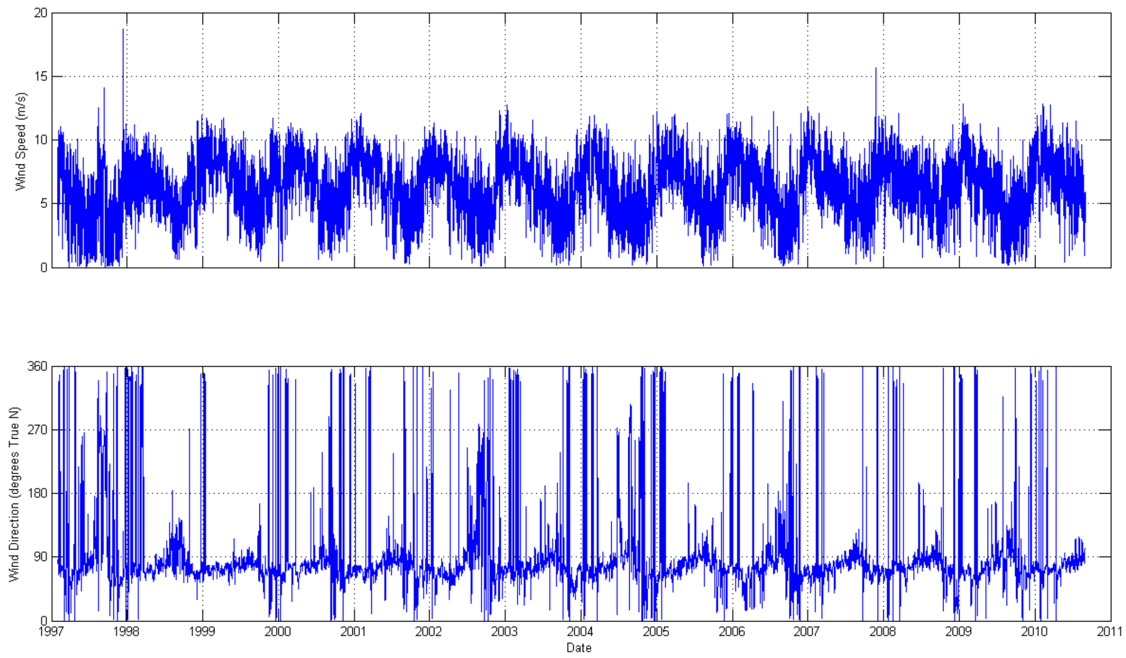

Figure 3.10. MDI wind record for site south of Ailinglaplap Atoll at 7°N / 168.75°E.

Kwajalein buoy (NDBC buoy KWJP8 8.737 N / 167.737 E) wind data has been compared to that from the MDI in Figure 3.12. The Kwajalein record is at 8 minute averaging intervals whilst the MDI is 3 hourly, hence the buoy record shows more variability but trends in speed and direction correspond. The wind speed from Kwajalein is recorded from the buoy gauge near sea level, whilst that from MDI is for 10 m above sea level, therefore the MDI record shows consistently faster wind speeds on the order of 2 m/s. Regression of the speed records between MDI and Kwajalein (averaged to MDI 3 hour intervals) gives $r^2 = 0.61$ (Figure 3.13).

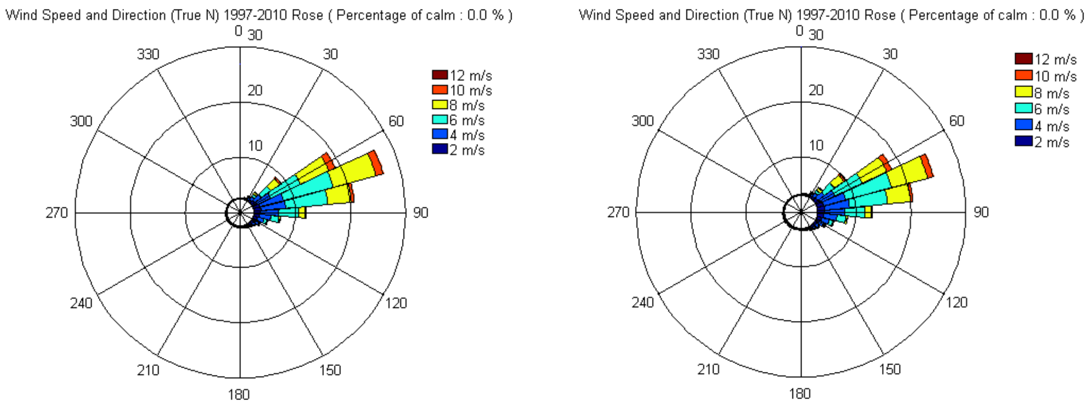

Figure 3.11. Wind roses extracted from the MDI record (1997-2010) for sites north (left, 8°N 168.75°E) and south (right, 7°N 168.75°E) of Ailinglaplap Atoll.

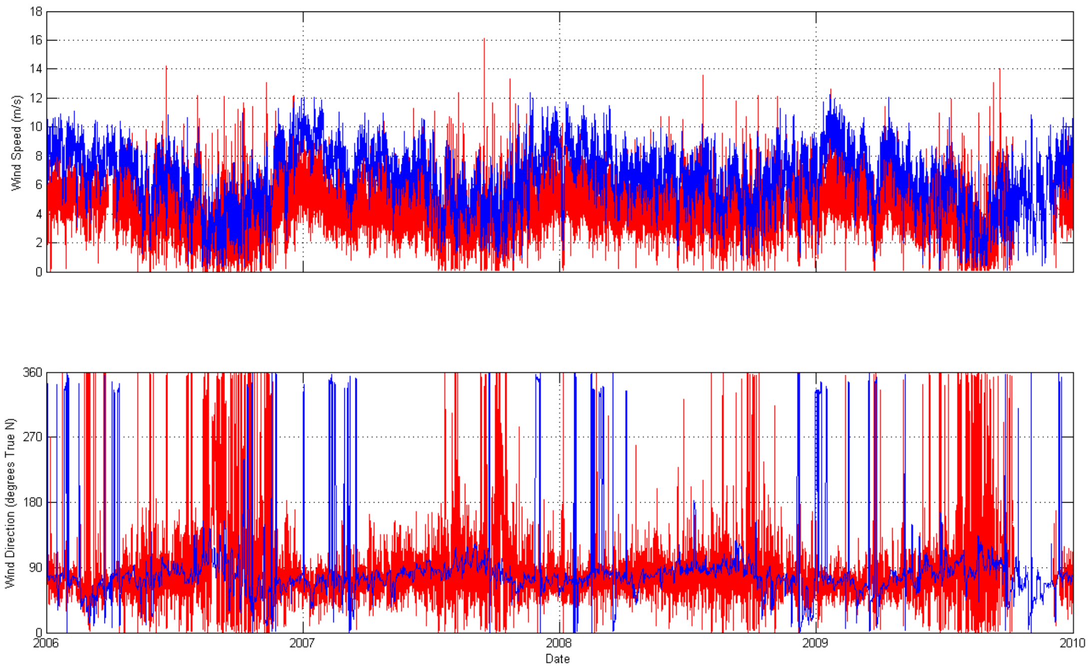

Figure 3.12. MDI wind record for site north of Ailinglaplap Atoll at 8°N / 168.75°E (blue) compared to NDBC Station KWJP8 Kwajalein Island 8.737°N / 167.737°E (red).

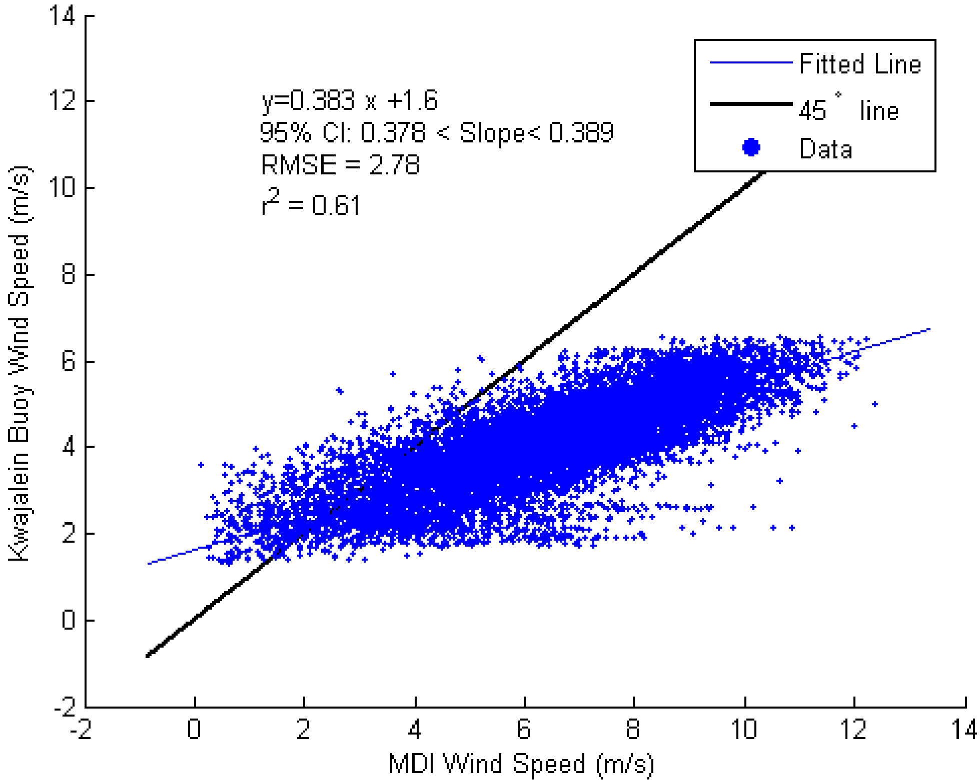

Figure 3.13. Regression plot of wind speed for MDI site north of Ailinglaplap Atoll (8°N / 168.75°E) and NDBC Station KWJP8 Kwajalein Island (8.737°N / 167.737°E).

3.6 Atmospheric Pressure

Barometric pressure has the effect of raising sea levels during low pressure events and lowering sea level during high pressure events. A 1 mbar change in barometric pressure roughly corresponds to a 1 cm change in sea level. The longest barometric pressure record available was obtained from the National Centre for Environmental Prediction (NCEP) for the closest node to the Ailinglaplap Atoll for the period 1947 to 2012 at 6 hour intervals (Figure 3.14). The records were compared against atmospheric pressure records for the Kwajalein buoy and showed good agreement (Figure 3.15). Mean atmospheric pressure from the 62 year record is 1010 mbar, and the mean minimum is 999.5 mbar.

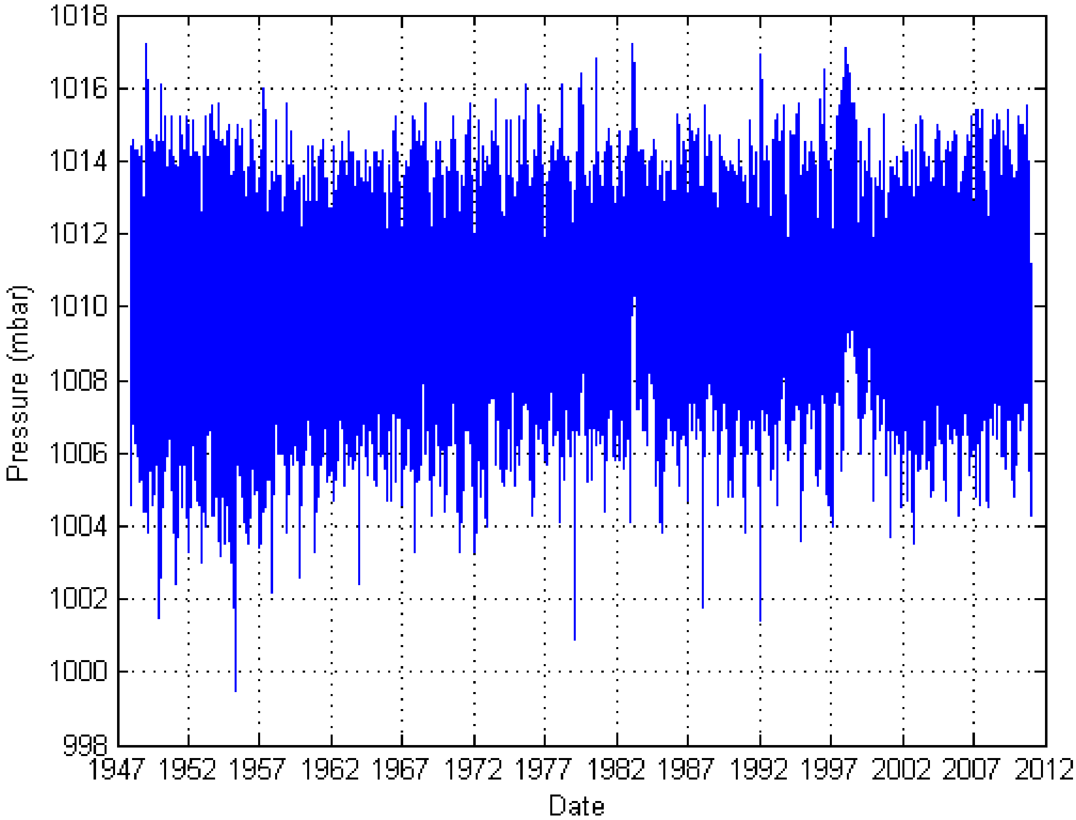

Figure 3.14. NCEP atmospheric pressure records for most proximal node to Ailinglaplap Atoll for the period 1948 to 2011.

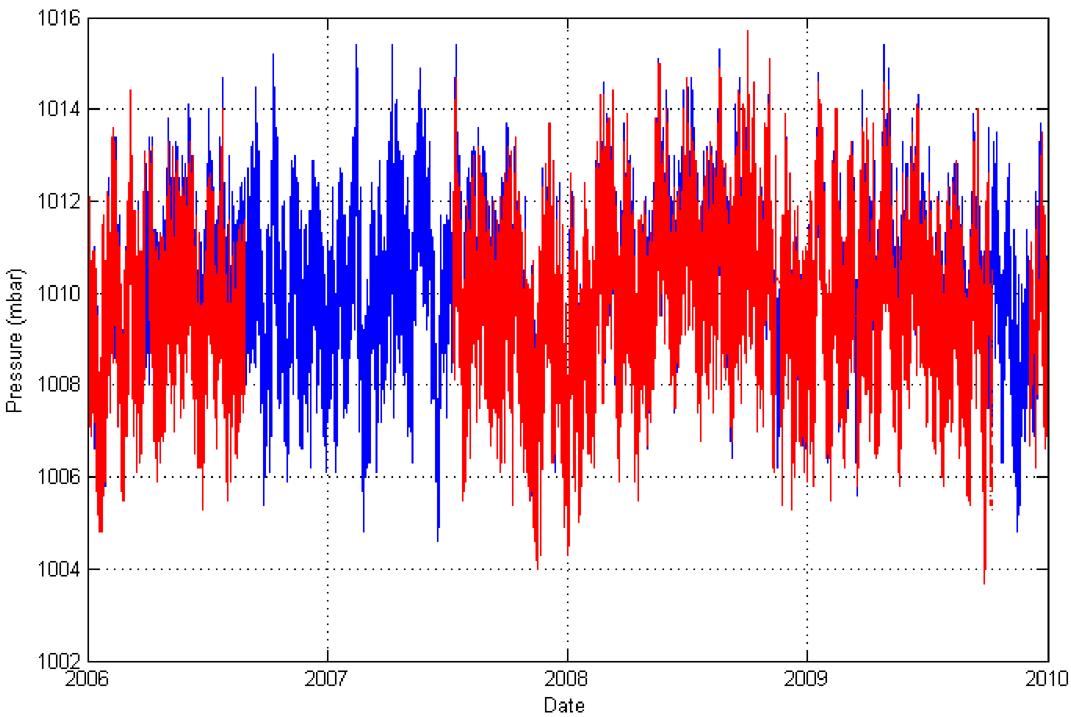

Figure 3.15. NCEP atmospheric pressure records for most proximal node to Ailinglaplap Atoll (blue) compared to the Kwajalein buoy records (red) for the period 2006 to 2010.

3.7 Historical Aerial Photographs of Woja Island

Apart from 2 satellite images available from Google Earth from March 2006 and November 2011, no aerial imagery of Woja Island has been found. These two images are not sufficient to even consider the changes between 2006 and 2011 due to the poor contrast in the images. As can be seen from Figure 3.16, the contrast in both images is such that it is difficult to determine the high-tide mark at the time the images were recorded.

12/3/2006

13/11/2011

Figure 3.16. Satellite images of the site for 2006 (top) and 2011 (bottom).

One set of historical aerial photographs from xx were available for islands along the southern part of Ailinglaplap Atoll. Comparison of these aerial photographs and the satellite images from 2003 to 2011 indicated little change, and possibly accretion, in some parts of the islands. This is consistent with Ford (2013), who concluded that accretion was more prevalent than erosion up to 2010 when aerial photographs from another atoll in the Marshall Islands (Wotja Atoll) was analysed using photographs back to 1945.

19xx

2003

Figure 3.17. An aerial image from 19xx (top) and a satellite image from 2003 (bottom) of Japroan along the southern part of Ailinglaplap Atoll.

3.8 Historical Events

This section describes significant events in recent history relevant to extreme water levels in the Marshall Islands. A number of events encountered during the literature review which had the potential to impact design causeway water levels at Woja are briefly described. There are no direct records of the effect these events had on Woja itself, however, it is assumed that the effects on other parts of the Marshall Islands could have occurred at Woja given the appropriate set of environmental conditions.

3.8.1 Flooding Events

There have been several instances of flooding on the Marshall Islands that were not directly related to a storm or weather event directly over the islands. These events are generally associated with the coincidence of higher than normal tides (king tides) with strong swells from storms several hundred kilometres away.

November 27 and December 3, 1979, Majuro (Figure 3.18): According to Bryant (2008):

> *"On a clear calm day, a single 6 m high wave appeared from the northeast at low tide, crossed the reefs protecting the shoreline, and crashed through the residential and business districts of the town of Rita, washing away 144 homes. The next day at high tide, the same thing happened again. After this second wave hit, the island was declared a natural disaster area by the US government, which was administering the islands. Six days later, another series of waves up to 8 m high again swept the east coast of the island, destroying the hospital, communications center and, more houses. The waves cost $20 million and affected the livelihood of two-thirds of the island's 12,000 people."*

Bryant does not attribute these waves to any particular source, nor offer an explanation for the event.

Another website[2] also mentions this event, but does not provide any references. They call the series of waves a 'tsunami' but do not relate it to a tectonic event. They simply state:

> *"Two series of tsunami, occurring one week apart, almost destroyed the capital city of Majuro in the Marshall Islands. The city's major districts were destroyed, but no lives were lost. President Jimmy Carter declared the area a disaster area after the first 20-foot-high waves hit. The tsunami* [sic] *were most likely caused by undersea seismic activity."*

According to Graham (2007):

> *"The high wave action in* [sic] *1979, for instance, displaced over 5,000 people in the DUD area of Majuro, many of whom were unable to rebuild their homes for several years. If the same high wave action were to occur today, the equivalent affected population would now be 20,000".*

Figure 3.18. Flooding on Majuro in 1979.

[2] http://library.thinkquest.org/C003603/english/tsunamis/casestudies.shtml#19

Despite the ambiguity of the causative mechanism, the net result was the flooding of a significant portion of Majuro. The suggestion of an impulsive flooding event (the sudden appearance of large waves) is intriguing, but the lack of relevant seismicity discounts a tectonic tsunami as the source. It is possible these were rogue waves from a distant storm, or some sort of coupling or resonance between astronomical high tide, a super-elevated sea level caused by atmospheric effects and large swells from either a strong storm in the north pacific or a tropical cyclone nearby. These events may be somewhat comparable to the 'Loka' events that occur in Fiji due to large, long period, swells generated in the Tasman Sea.

December 15, 2008, Majuro: According to a BBC report (2008):

> *"In December 2008 the Islands were pounded several times in quick succession by long period swell waves generated by an extra tropical storm. These extreme waves combined with high tides, causing widespread flooding in the capital city of Majuro and other urban centres, located at just one meter above sea level. On Christmas morning, the government declared a state of emergency".*

See also: http://www.yokwe.net/index.php?module=News&func=display&sid=2328
This story was also reported on a number of other news web sites.

There is a little more clarity in reporting the details of this event and it appears to be caused by the coincident occurrence of high tides and large swells. This is also a likely mechanism of the 1979 event described above.

January and February 2011: A recent event was described in a number of news outlets:

> *"Kili Island in the Marshall Islands was hit by a wave during a high tide on January 21, 2011. […] No one was hurt during the January flood, but some houses and public buildings were damaged. On Friday, February 11, 2011, Bikini Atoll Mayor Alson Kelen and Bikini Atoll Senator Tomaki Juda accompanied a delegation comprised of a USAID official from the US Embassy, an official from the RMI EPA, an engineer from the Ministry of Public Works, and an oceanographer from the College of the Marshall Islands to assess the situation."*

> *"Ejit Island of Majuro Atoll, home to the people of Bikini Atoll in the Marshall Islands who were evacuated from Bikini Atoll in 1979 due to high*

levels of cesium 137 in the soil, was overcome by waves during the highest tide of 2011 on Saturday, February 19, 2011. The high tide measured 6.23 feet (1.9 meters) at about 5 PM local time. While no one was hurt by the waves washing over the island, many of the local food crops such as breadfruit, pandanus, bananas, papaya and coconuts were damaged."

Source:

- http://bikiniatoll.wordpress.com/2011/02/13/kili-island-gets-hit-by-wave-at-high-tide/
- http://bikiniatoll.wordpress.com/2011/02/20/ejit-island-gets-hit-by-waves-during-highest-tide-of-2011/

A short video on this event was produced by the University of Hawaii SeaGrant Program and can be seen at the following link:

- http://www.youtube.com/watch?v=B4abshci7rY

These three events show the vulnerability of the Marshall Islands, and Majuro in particular, to flooding from the combination of elevated sea level and large swells. It is not known if any of those events directly affected the Ailinglaplap Atoll or Woja Island in particular.

3.8.2 Typhoons

While the Marshall Islands are located southeast of the main typhoon generation and tracking areas, they are however, intermittently affected directly by typhoons, or indirectly through distant effects (i.e. long period swell generation or oceanic wind/wave/pressure set-ups). Appendix 4 shows annual storm tracks for 1994 - 2010 and monthly storm tracks for 1956 - 2006.

Spennemann and Marschner (1994) and Spennemann (1998) include a comprehensive list of historic typhoons affecting the Marshall Islands dating back to the 1840's. Events prior to 1994 noted to have directly affected the Ailinglaplap Atoll occurred in 1874, 1905, 1952, 1957, 1990, 1991 and 1992.

The event of 1874 is reported to have reduced the population on Ailinglaplap Atoll from 500-600 to 220. Indeed significant losses of life and property damage are recorded on numerous other Marshall Islands. Other typhoons with effects reported on Ailinglaplap Atoll include events between October and December 1979, December 1997 and December 2008.

3.8.2.1 Typhoon Tip - October 1979

Typhoon Tip developed out of an active monsoon trough between the Philippines and the Marshall Islands in early October 1979. The trough developed into one of the largest and most intense tropical cyclones ever recorded. The typhoon had a minimum pressure of 870 mbar, maximum wind speeds of approximately 300 km/h, and grew to a maximum diameter of 2200 km across. Typhoon Tip made landfall in Japan. The effects in the Marshalls were limited but it is noteworthy because of its size and severity.

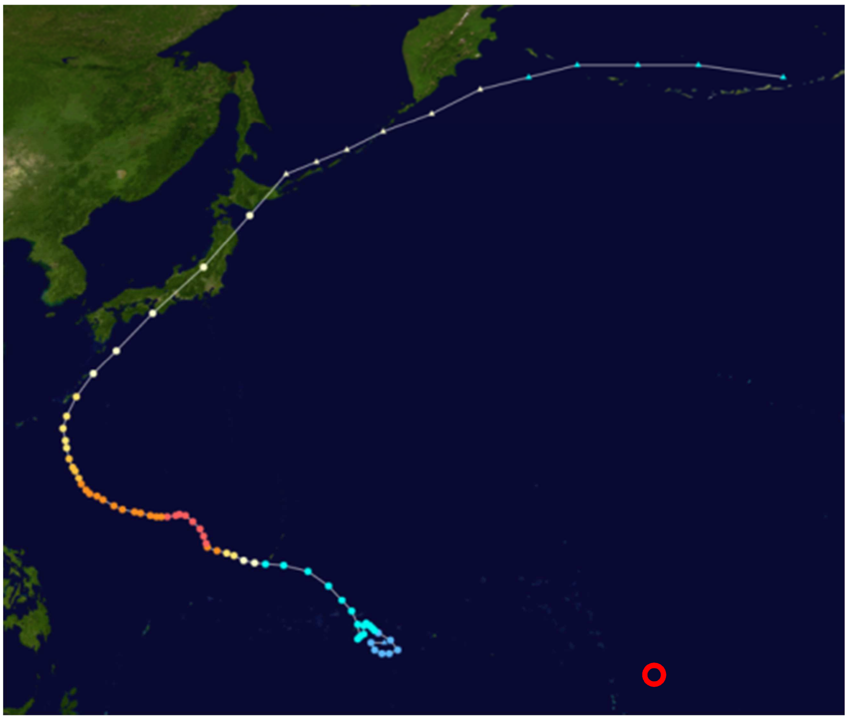

Figure 3.19 Path of Typhoon Tip – Oct 1979. Red circle is approximate location of Woja.

3.8.2.2 November/December 1979

Spennemann (1998) describes a subtropical high pressure system in late November 1979:

> *"some 2000 miles east of the Marshall Islands, creating higher than normal sea-level at its perimeter, as well as creating a storm surge, sent out as a swell with a wave amplitude of over 6 m".*

This is reported to have caused flooding on the Majuro Atoll 26-28 November 1979. Further flooding on Majuro Atoll occurred on 4 December 1979 with high winds and seas. This is most likely to be the effects of Typhoon Abbey, a Category 3 event occurring from December 1-14 with 205 km/h winds.

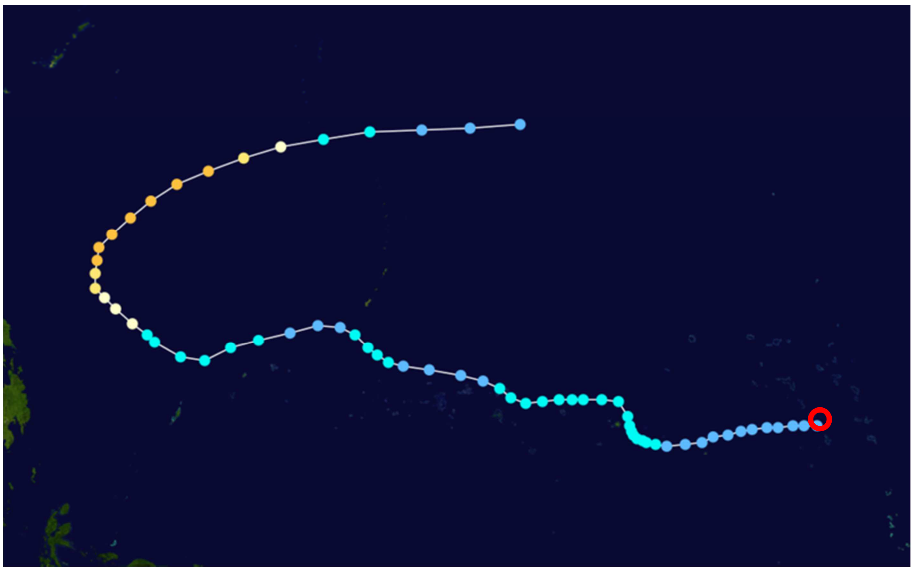

Figure 3.20 Path of Typhoon Abbey – Dec 1979. Red circle is approximate location of Woja.

3.8.2.3 Typhoon Paka - December 1997

Severe damage was caused by waves, wind and heavy rainfall during Typhoon Paka (10-14 December 1997). 70% of houses on Ailinglaplap Atoll were left damaged with cost estimates at 80 million USD (US National Climate Data Center).

From the eCoast MDI node north of Ailinglaplap Atoll, maximum wind speeds were recorded of 18.6 m/s and records over 10 m/s occur for 60 hours between 10-12

December. The maximum wind speed was the greatest on record since the MDI record commenced in 1997 (Figure 3.10).

Wave heights recorded were also the greatest on record since 1997 with a maximum significant wave height of 5.04 m, and exceeded 4 m for 30 hours. The maximum wave height exceeds the 100 year return period calculated from the 14 year MDI record. Peak periods were typically 8-10 s from the easterly quarter (65-85°).

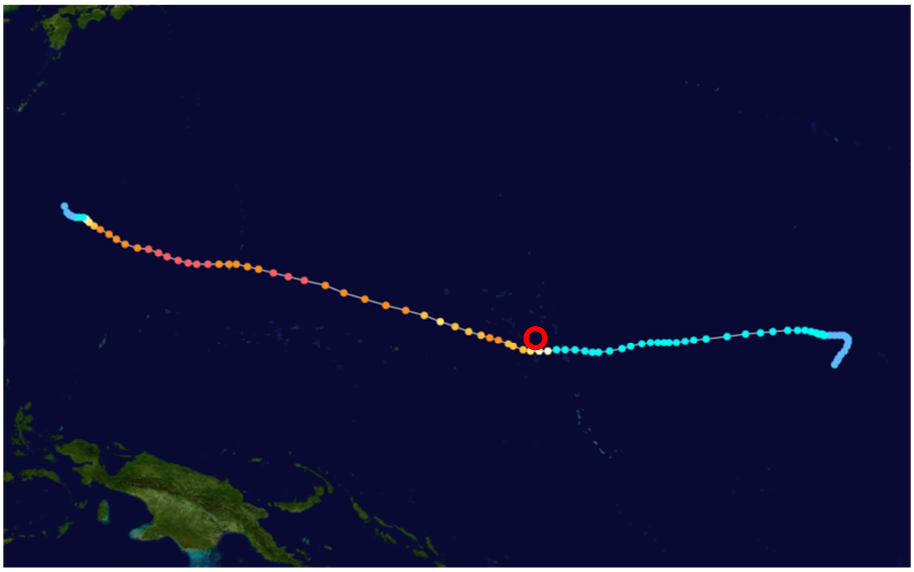

Figure 3.21 Path of Typhoon Paka – Dec 1997. Red circle is approximate location of Woja.

3.8.2.4 December 2008 – Tropical Depression 27W and Tropical Storm Dolphin/Ulysses

A state of emergency was declared in the Marshall Islands in December 2008 when long period swell waves generated by an extra tropical storm and high tides caused flooding in many areas including Majuro. This storm was initially classified as Tropical Depression 27W from which the swell waves were generated and later formed into Tropical Storm Dolphin/Ulysses.

Flooding was reported in Majuro on 9 December 2008 due to a combination of the large long period swell and high tides. The eCoast MDI for the node north of Ailinglaplap records a peak significant wave height of 3.54 m with at peak wave period of 14 s from the north (Figure 3.22). The peak significant wave height is between a 1 and 5 year event for a north swell with predicted high tides of 0.60 m to 0.95 m above MSL occurring over the following days. The storm was distance significant distance away and local atmospheric pressure and winds were not a significant issue on sea levels.

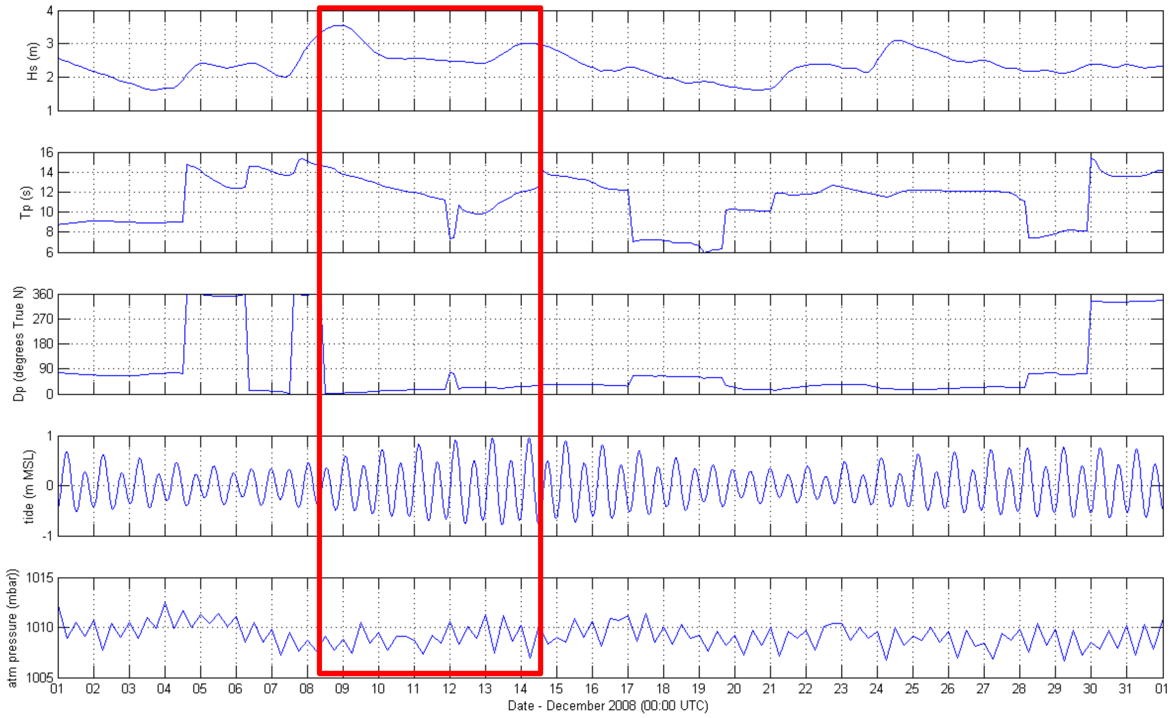

Figure 3.22. MDI wave record for site north of Ainglaplap Atoll at 8°N / 168.75°E with predicted tide and NCEP atmospheric pressure.

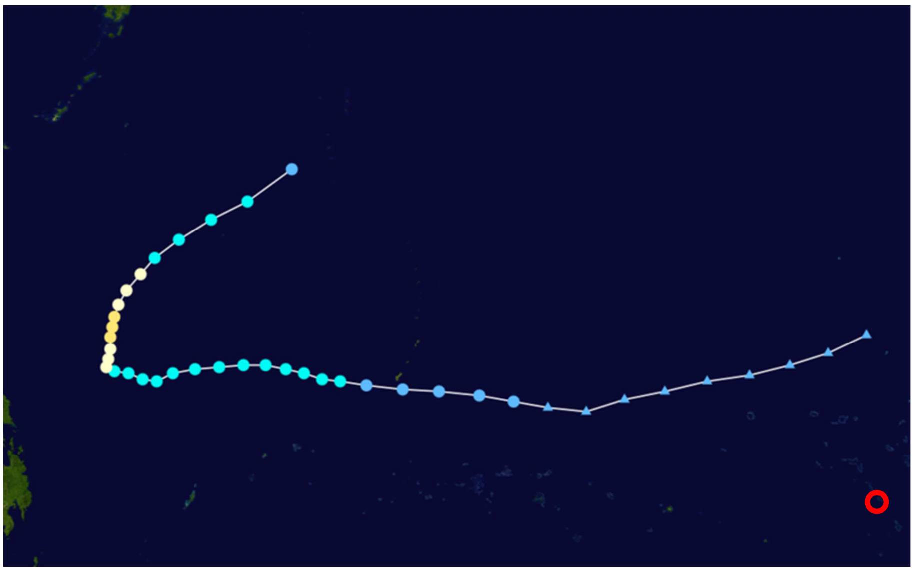

Figure 3.23 Typhoon Dolphin (Ulysses) - Dec 2008. Red circle is approximate location of Woja.

3.9 Other Causes of Elevated Sea Levels

In February 2011 the capital of Majuro was also flooded due to high tides and the coinciding effects of La Nina which is attributed to a periodic 150 mm rise in local sea levels. The impacts at Ailinglaplap Atoll during this event are unknown. Some historic events are described in the following sections.

Spennemann (1998) also describes exceptionally high tides due to high pressure systems:

> "*Stable high pressure systems north-east of Wake Island or east of the Marshall Islands can create higher-than-normal sea levels which will cause flooding of low-lying areas if they coincide with a spring tide, or with higher wave action. Such high pressure systems are common and have affected the atolls of the Marshall Islands on numerous occasions (the 1979, 1989, 1990 and 1991 floods on Majuro Atoll for example)"*.

3.10 Tsunamis

Sitting in the Middle of the Pacific Ocean, the Marshall Islands have the potential to be affected by tsunamis emanating from sources around the entire Pacific Rim (Figure 3.24). Despite the occurrence of numerous large earthquakes on the pacific rim creating transpacific tsunamis (i.e. 1868 Chile/Peru, 1877 Chile, 1946 Aleutian Islands, 1952 Kamchatka, 1957 Aleutians, 1960 Chile, 1964 Alaska, 2010 Chile and 2011 Japan), there are no reports of damage in the Marshall Islands from any of these events.

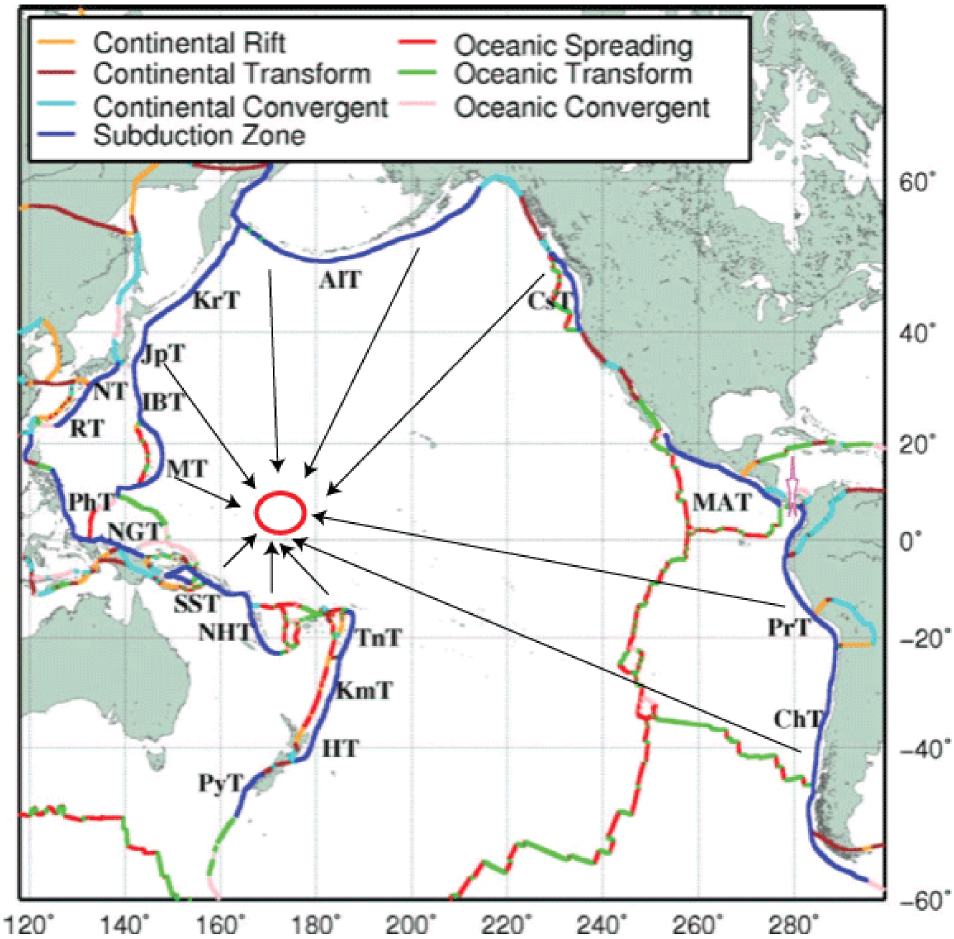

Figure 3.24 Pacific Rim tectonic tsunami sources for the Marshall Islands

Indeed, a search of tsunami catalogues provides very little data on tsunami run-up on Pacific atolls in general. This is presumably because there have been so few observations, despite the five great ocean-crossing tsunamis of the 20th century. The highest reported value is at Midway in 1952, when run-up reached 1.9 meters. However, that event was for an exceptionally large earthquake with Midway Island located only 3000 km away from the source and squarely in the centre of the radiated beam of wave energy. It is also possible that this run-up value was enhanced by human modifications to the barrier reef, allowing more wave energy to enter the lagoon.

The only other island with measurements approaching Midway's is Johnston Atoll---another atoll extensively modified by dredging---where the Chile tsunami of 1960 had a run-up of 0.7 meters. Of atolls not extensively modified to handle shipping, the highest run-up we are aware of is at Kiritimati in 1960, which recorded a run-up of 0.3 meters.

Because Pacific atolls have very steep upper slopes and rise to the ocean surface from very large depths, they are virtually invisible to an approaching tsunami. The tsunami does not interact with the island much. In general, tsunami run-up on atolls seems to be little more than a factor of two from the height of the tsunami on the open ocean as compared to a factor of five or six for open coasts on high islands. Even high islands have a tremendously reduced hazard if they have reefs. For example, the greatest run-up in Tahiti in 1960 was approximately 1 m and that occurred opposite a reef pass. In contrast, during the 1960 tsunami in Hawaii, there was approximately 3 m run-up on open coasts without focussing, where focussing or harbours were involved there were numerous locations where run-up approached 10 meters, and in Hilo run-up reached 11 meters and caused 61 fatalities.

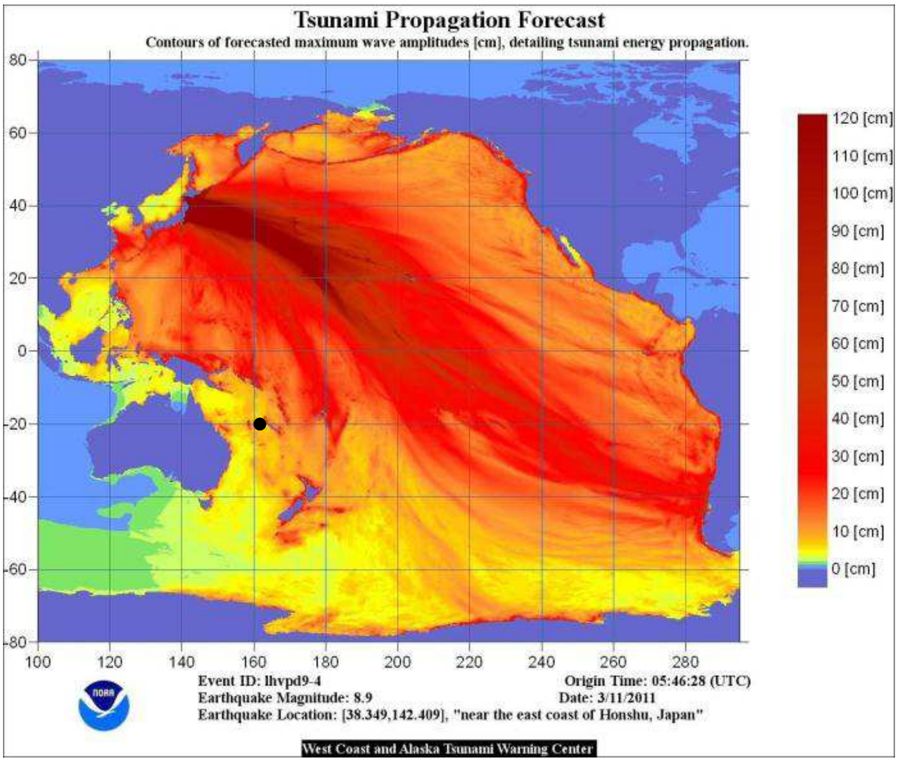

Figure 3.25 Energy propagation pattern from the March 11, 2011 Tohoku tsunami. The black dot indicates the location of the Marshall Islands.

The most recent example is the great Tohoku Earthquake of March 11, 2011. This earthquake had a magnitude of 9.0 and was centred approximately 4000 km from the Marshall Islands. The main beam of wave energy radiated from this tsunami passed to the north of the Marshall Islands as indicated in Figure 3.25. Nevertheless the tsunami caused approximately 1.2 m of water level fluctuation on the tide gauge at Kwajalien (Figure 3.26). It is evident that the tsunami arrived at low tide, and the resulting surges only reached a level 0.6 m above local mean sea level. If instead this tsunami has arrived at high tide, the surges would have reached up to 1.4 m above local mean sea level.

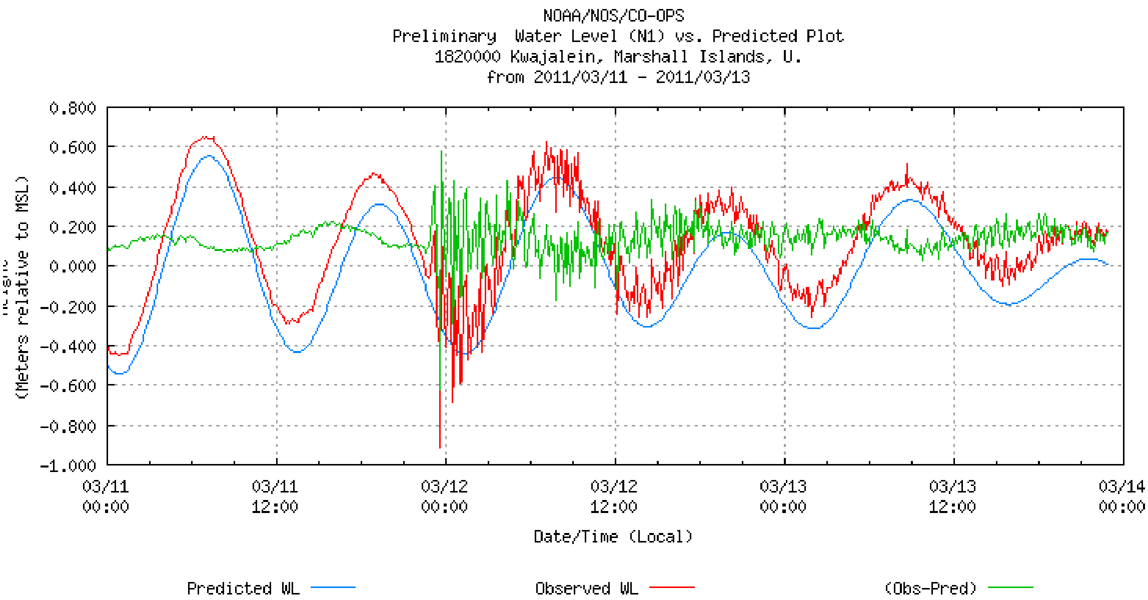

Figure 3.26 Tide gauge recording of the 2011 Tohoku tsunami at Kwajalien in the Marshall Islands.

3.11 Summary

Literature and data sources were reviewed for an overall assessment of environmental conditions at Woja Island and the determination of extreme water levels. It is notable that there are no studies specific to Woja Island, other than the scoping study that led to this project. Even so, general metocean data is available for the area from a variety of sources, which is relevant to development of design parameters for the remediation of Woja Causeway.

Literature and data reviewed includes general climate, tidal range, wave climate, wind climate, atmospheric pressure, historical aerial imagery and historical events (floods, typhoons and tsunami). The results of these investigations in conjunction with the information collected during the site survey are used in the following section to develop estimates of super-elevated water levels at Woja Island in order to determine a suitable design height for the causeway.

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4 Coastal Hazard Assessment and Design Considerations

Several factors contribute to sea level fluctuations, short and long term, which need to be considered for design purposes. In this section, the factors that affect the total sea level are described and quantified. The western and eastern coasts of Woja Island are considered separately. This is due to the fact that each side of the island has a different relationship with the wind and wave climate and can be expected to behave differently (Figure 4.1).

The west coast of Woja is exposed to large swells coming from the North Pacific. The beach itself is situated approximately 400 m from the reef edge. Large swells coming from the western quarter will break on the reef, and then lose energy and thus do not affect the beach directly. However, the transport of water across the reef causes a set up in water level at the beach. Wind set up is not considered for the north coast because it is assumed that any set up caused by wind is still not sufficient to allow waves to pass over the reef without breaking, thus the mechanism described above will dominate – wind set up is very small on the open coasts of ocean atolls. Also, since the deep ocean waves have broken on the outer reef, and the beach is set only 400 m from the reef edge, there is not sufficient distance for significant waves to form. Therefore direct wave run-up is also not considered for the west coast.

The east coast on the other hand is not exposed to large swell waves, but it is exposed to wind set up caused as wind blows across the lagoon. It is also vulnerable to wind-waves generated in the fetch across the entire lagoon width, which is 10’s of kilometres. These waves and their associated set up and run up are accounted for on the east facing beach at the site. Pressure set up, sea level rise and tsunami effects are assumed to affect both coasts equally.

In the following sections, each of these parameters is considered individually, and following each set of computations a range of values based on different assumptions is provided. Values highlighted in red are used for the final water level calculation.

The additional values provided are generally quite conservative and are included to indicate potential worst-case scenarios for that particular component.

Figure 4.1 Woja Island west and east coasts are treated differently for computing water levels due to their different exposure to water level forcing mechanism, i.e. open ocean versus lagoon.

4.1 Design Winds

Design wind conditions have been determined from analysis of the 14 year MDI record for the point north of Ailinglaplap Atoll at 8°N / 168.75°E. Table 4.1 lists directional and non-directional wind speed values for various percentage annual exceedance probabilities (%AEP), commonly referred to as return periods. In addition, higher wind speeds associated with typhoons have been tested and used in the analyses.

Table 4.1. Directional and non-directional annual exceedance probabilities (%AEP) / return periods (years) for 10 m wind speed (given in m/s and km/h) based on 14 year MDI record for node north of Ailinglaplap Atoll at 8°N / 168.75°E during normal conditions (top) and typhoons (bottom)

RP (y)	Prob % AEP	Wind Speeds (m/s)								
		Direction (45° centred binning)								Non Direct-ional
		N	NE	E	SE	S	SW	W	NW	
1	**100**	7.4	13.1	13.0	10.3	8.4	10.1	9.5	7.4	13.5
5	**20**	9.1	14.1	13.9	12.6	10.2	12.5	11.9	9.3	14.4
10	**10**	9.8	14.5	14.3	13.6	11.0	13.5	12.9	10.0	14.7
25	**4**	10.7	15.0	14.8	14.9	11.9	14.8	14.2	10.9	15.2
50	**2**	11.4	15.4	15.2	15.8	12.6	15.7	15.1	11.6	15.5
100	**1**	12.0	15.8	15.6	**16.8**	**13.3**	16.6	16.0	12.3	15.9

RP (y)	Prob % AEP	Wind Speeds (km/h)								
		Direction (45° centred binning)								Non Direct-ional
		N	NE	E	SE	S	SW	W	NW	
1	**100**	27	47	47	37	30	36	34	27	49
5	**20**	33	51	50	45	37	45	43	33	52
10	**10**	35	52	51	49	40	49	46	36	53
25	**4**	39	54	53	54	43	53	51	39	55
50	**2**	41	55	55	57	45	57	54	42	56
100	**1**	43	57	56	60	48	60	58	44	57

4.2 Wind Induced Set-Up

Wind stress over open water causes a net transport of water mass in the direction of the prevailing wind. Wind induced set-up has only been considered for the east side of Woja Island within the Ailinglaplap lagoon, which has a maximum fetch of approximately 44 km (Figure 4.2). It was assumed that wind set up on the west side of Woja would be damped out by the presence of the offshore reef – wind-induced set-up is relatively insignificant on atoll islands. Because the east side of the island faces the semi enclosed lagoon, it is more susceptible to direct wind induced set up.

The water elevation due to the wind stress was calculated using the approach of Dean and Dalrymple (1991). A profile south of Woja Island across the Ailingalaplap Atoll was considered with a south wind of 16.8 m/s taken from Section 3.5. The calculation of set-up η_w is given by :

$$\eta_w(x) = -h_0 + \sqrt{h_0^2 + \frac{2n\tau_w x}{\rho g}}$$

Where h_0 is the water depth, x is the fetch length, ρ is the water density (1030 kg/m^3), n is a constant with typical values ranging 1.15-1.30, 1.15 was used in this case, and τ_w is given by:

$$\tau_w = \rho k W^2$$

Where W is the sustained wind speed, and k the friction factor is given by:

$$k = 1.2x10^{-6} + 2.25x10^{-6}\left(1 - \frac{w_c}{W}\right)^2$$

Where w_c is 5.6 m/s.

For the case of a 16.8 m/s sustained south wind a wind set-up of 0.04 m was calculated. Higher sustained wind speeds of 30 m/s and 40 m/s were also calculated with set-ups of 0.14 m and 0.25 m respectively. Typhoon force being sustained wind speeds over 32.7 m/s.

Table 4.2. Computed wind induced water level set up for three different wind speeds.

Wind Speed	Set-up (m)
16.8 m/s	**0.09**
30 m/s	0.31
40 m/s	0.55

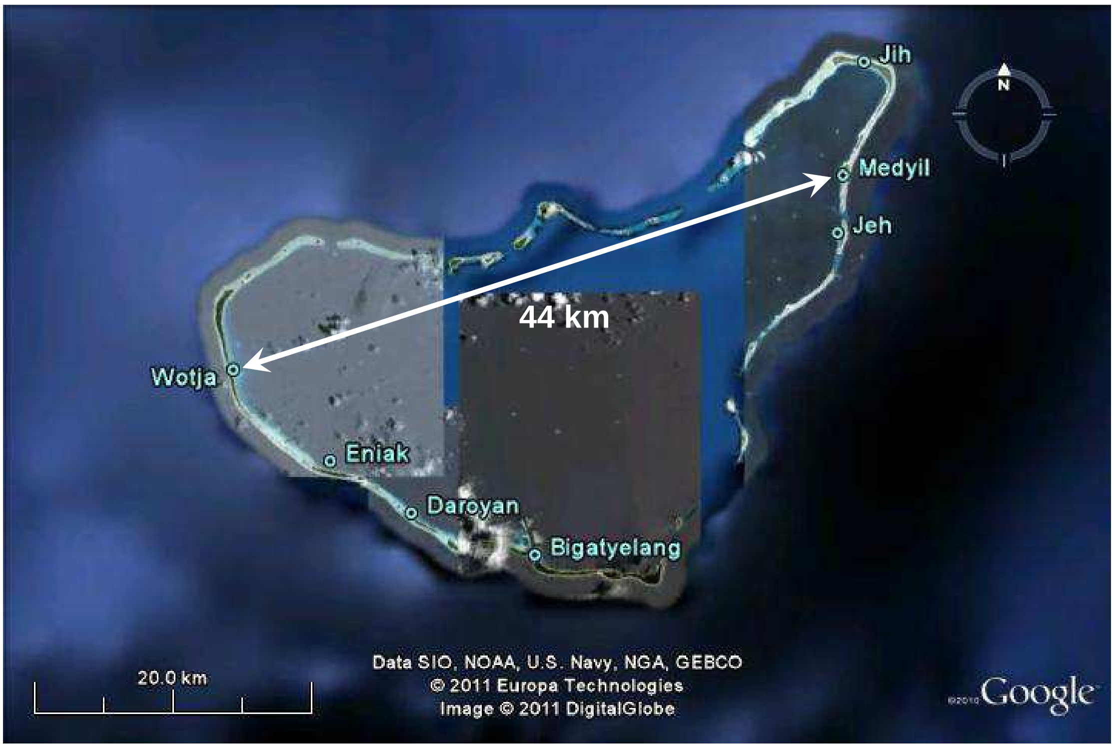

Figure 4.2. Available fetch within the Ailinglaplap Atoll lagoon.

4.3 Design Waves for the West Coast

Design wave conditions were determined from analysis of the 14 year MDI record for a point north of Ailinglaplap Atoll at 8°N / 168.75°E. Table 4.3 and Table 4.4 detail directional and non-directional significant wave height (H_s) and peak wave period (T_p) values for various percentage annual exceedance probabilities (%AEP), commonly referred to as return periods.

The extreme waves determined in this analysis were used for calculations of wave induced set up on the west side of Woja Island, which is exposed to the open ocean. On the east side of the island, the coast is exposed to the limited fetch within the Ailinglaplap Atoll lagoon (Figure 4.1). To determine extreme waves within the lagoon, wave generation modelling has been undertaken as described in Section 4.4.

Table 4.3. Directional and non-directional annual exceedance probabilities (%) for significant wave height (H_s) based on 14 year MDI record for node north of Ailinglaplap Atoll at 8°N / 168.75°E.

RP (y)	Prob (%)	Direction (45° centred binning)								Non Direct-ional
		N	NE	E	SE	S	SW	W	NW	
1	**100**	3.4	3.9	4.0	2.3	1.8	2.0	2.5	3.0	4.0
5	**20**	3.7	4.3	4.3	2.7	2.1	2.4	3.2	3.4	4.3
10	**10**	3.9	4.4	4.5	2.9	2.2	2.5	3.5	3.5	4.4
25	**4**	4.1	4.6	4.6	3.2	2.4	2.7	3.9	3.7	4.6
50	**2**	4.2	4.8	4.8	3.2	2.5	2.9	4.1	3.9	4.7
100	**1**	4.3	**4.9**	4.9	3.5	2.6	3.0	4.4	4.0	4.8

Table 4.4. Directional and non-directional annual exceedance probabilities (%) for peak period (T_p) based on 14 year MDI record for node north of Ailinglaplap Atoll at 8°N / 168.75°E.

RP (y)	Prob (%)	Direction (45° centred binning)								Non Direct-ional
		N	NE	E	SE	S	SW	W	NW	
1	**100**	18	14	11	12	16	10	11	17	19
5	**20**	20	15	12	12	18	12	12	18	21
10	**10**	20	16	12	13	20	12	13	19	22
25	**4**	21	17	12	13	21	13	14	20	23
50	**2**	21	17	12	14	22	13	14	20	24
100	**1**	22	**18**	13	14	23	14	15	21	25

4.4 Wave Generation Modelling Within Lagoon for the East Coast

In order to predict wave heights and periods on the east side of Woja Island within the Ailinglaplap Atoll lagoon, the relationships found in the Coastal Engineering manual for fetch and duration limited wind speeds were applied. For extreme (typhoon strength) winds the numerical model WGEN was used. Based on the return period analysis presented in Section 4.3, the 50 and 100 year wind speed from any direction is on the order of 15-17 m/s. We therefore use a wind speed of 16 m/s to determine the wave height and period. Using the relationships found in the Coastal Engineering Manual (CEM), the resultant wave conditions are approximately:

1.1 m at 4.8 seconds.

In addition stronger wind speeds were considered of 20, 30 and 40 m/s, typhoon force being sustained wind speeds over 32.7 m/s. For these cases, the modelling was undertaken using eCoast's in-house 3DD suite software WGEN component and the results of the wave generation modelling are shown in Table 4.5.

For the results the wave height values are considered 'duration unlimited', that is assumes the particular wind strength lasts for an infinite time period. For the wave speeds considered, the fetch limited wave heights are exceeded with wind duration of 3 hours, thus it is reasonable to use the fetch limited, infinite duration predictions for the resulting wave height.

Table 4.5. Results of wave generation modelling to predict wave height and period within Ailinglaplap lagoon at Woja under various sustained wind speeds and directions. We used both the CEM tables assuming a 44 km fetch and WGEN numerical modelling.

Bearing	Wind Dir	Wind Speed	Predicted H_s	Predicted T
Extremes associated with typhoons (from WGEN				
ENE	75	20	1.25	5.0
ENE	75	30	2.23	5.5
ENE	75	40	3.38	6.2

4.5 Wave Setup and Runup – West Coast

Wave induced set-up is the super-elevation of mean water level caused by wave action inside the surf zone. Once waves break and lose height, the radiation stress drives water shoreward which leads to a set-up in water level at the coast. The magnitude of set-up and subsequent flows are dictated largely by the coastal geometry and incident wave conditions. Mechanisms over coral reefs are similar to those on open coast beaches for which most research exists, however calculation of set-up has been addressed specifically for coral reefs by Gourlay (1997) (Figure 4.3). The Gourlay method was recently compared to the outputs of numerical model simulations using both a boussinesq (3DD) and a third generation wave (SWAN) model and was found to produce very similar results as the models (Mead *et al*., 2012).

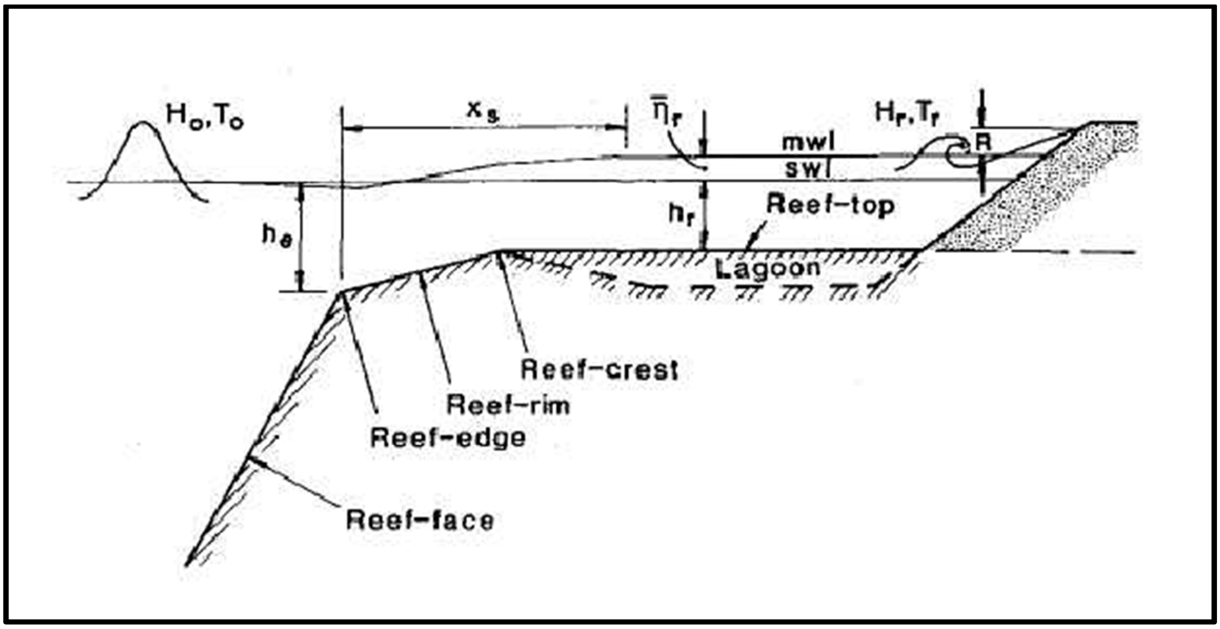

Figure 4.3. Definition sketch for the method of Gourlay (1997). This closely resembles the situation on the west coast of Woja.

The method of Gourlay (1997) was used to determine the wave set-up for the western coast of Woja Island for the estimated 100 year return period significant wave height of 4.9 m with varying peak wave periods and tide conditions (Table 4.6). For calculation of the design water levels a peak period of 18 s was used with a

Highest Astronomical Tide (HAT) water level giving a setup of 0.65 m (shown in blue bold in Table 4.6).

In addition to this case, the set up was evaluated in association with these same wave conditions occurring at water levels above high tide. Values of 0.5 and 1.0 m above high tide were applied to correspond to the case where wind, wave or pressure setup contribution to the total water level. Note, that using these values results in a lower amount of setup, but will result in a higher total water level due to the elevated sea level.

A further complicating factor is the steepness of the offshore reef slope. This value is a critical component to calculating the reef top setup. Gourlay's method was used for the two end members for the K_p parameter which is controlled by the offshore reef steepness (0.3 and 0.8). The results show that setup increases with the steeper offshore slope.

Thus, the final value for the setup and runup computation is governed by the case with the elevated water level due to wave and pressure set up and a steep offshore slope (as measured for Beran Island, the next island north of Woja – Borrero and Grant (2011). This value of 0.81 m is highlighted in red bold in Table 4.7.

In addition to the setup value calculated, wave runup on the shoreline is added. Gourlay (1997) suggests using a standard runup formula, i.e.:

$$R = 0.64 \tan \alpha T_r \sqrt{g H_{rs}}$$

For H_{rs} it is assume a maximum value of 1.25 m based on an H_{rs} value calculated from

$$H_{rs} = 0.4(\overline{\eta_r} + h_r)$$

and allowance for wave height decay across the ~400 m wide reef flat.

For n_r we use 0.81, for h_r we use 2.9 to yield an H_{rs} value of 1.5 m. This wave height will however, be subject to wave height decay due to friction over the reef top. Gourlay (1997) provides an expression for the rate of wave height decay with distance across the reef; however it tends to overstate the wave decay and yield nonsensical results. Thus, a decay of 0.25 m is assumed.

Period (T_r) in the runup formula is assumed to be 4 seconds based on guidance from Gourlay (1997). Thus the resulting runup is **0.8 m** which is added to the computed setup.

These values are reflected in the final calculation listed in Section 4.12.

Table 4.6. Estimated wave set-up on the west coast of Woja Island using the method of Gourlay (1997). K_p = 0.3 – low offshore slope.

Tide	Data for Calculations				Calculated Quantities	
	Tide LAT Datum (m)	Offshore RMS wave height (m)	Offshore wave period (s)	Reef top water depth (m)	Trans-mission para-meter	Set-up (m)
	z_0	H_{orms}	T_o	h_r	P_T	n_r
H_o 4.9 m (H_{orms} 3.46 m) T_o 25 s						
HAT	1.92	3.46	25	1.92	0.90	0.80
MSL	0.92	3.46	25	0.92	0.95	1.08
LAT	0.00	3.46	25	0.00	0.96	1.70
H_o 4.9 m (H_{orms} 3.46 m) T_o 18 s						
HAT	1.92	3.46	18	1.92	0.91	**0.65**
MSL	0.92	3.46	18	0.92	0.95	1.02
LAT	0.00	3.46	18	0.00	0.97	1.50
H_o 4.9 m (H_{orms} 3.46 m) T_o 10 s						
HAT	1.92	3.46	10	1.92	0.93	0.42
MSL	0.92	3.46	10	0.92	0.96	0.74
LAT	0.00	3.46	10	0.00	0.98	1.20
H_o 4.9 m (H_{orms} 3.46 m) T_o 18 s						
H_{ex1}	2.40	3.46	18.00	2.40	0.89	**0.52**
H_{ex2}	2.90	3.46	18.00	2.90	0.85	**0.40**

Note: assumes K_p = 0.3

Table 4.7. Estimated wave set-up on the west coast of Woja Island using the method of Gourlay (1997). K_p = 0.8 – high offshore slope

Tide	Data for Calculations				Calculated Quantities	
	Tide LAT Datum (m)	Offshore RMS wave height (m)	Offshore wave period (s)	Reef top water depth (m)	Trans-mission para-meter	Set-up (m)
	z_0	H_{orms}	T_o	h_r	P_T	n_r
H_o 4.9 m (H_{orms} 3.46 m) T_o 25 s						
HAT	1.92	3.46	25.00	1.92	0.85	1.41
MSL	0.92	3.46	25.00	0.92	0.89	1.89
LAT	0.00	3.46	25.00	0.00	0.92	2.42
H_o 4.9 m (H_{orms} 3.46 m) T_o 18 s						
HAT	1.92	3.46	18.00	1.92	0.87	**1.18**
MSL	0.92	3.46	18.00	0.92	0.91	1.64
LAT	0.00	3.46	18.00	0.00	0.94	2.16
H_o 4.9 m (H_{orms} 3.46 m) T_o 10 s						
HAT	1.92	3.46	10.00	1.92	0.90	0.84
MSL	0.92	3.46	10.00	0.92	0.94	1.25
LAT	0.00	3.46	10.00	0.00	0.96	1.75
H_o 4.9 m (H_{orms} 3.46 m) T_o 18 s						
H_{ex1}	2.40	3.46	18.00	2.40	0.85	**1.00**
H_{ex2}	2.90	3.46	18.00	2.90	0.81	**0.81**

Note: assumes K_p = 0.8

4.6 Wave Setup – East Coast

Wave induced setup is the super-elevation of mean water level caused by wave action inside the surf zone. Once waves break and lose height, the radiation stress drives water shoreward which leads to a setup in level at the coast.

To calculate the wave induced set-up, we use the method described in the Coastal Engineering Manual (CEM, 2002).

For wave data following a Rayleigh distribution, the relationship is:

$$H_{rms} = 0.707.\ H_s \qquad \text{(Longuet-Higgins, 1952)} \qquad [1]$$

Assuming a planar beach, set-up at the still-water shoreline is determined from the RMS wave height as:

$$\overline{\eta}_s = \overline{\eta}_b + \left[\frac{1}{1+\frac{8}{3\gamma_b^{\ 2}}} \right] h_b \qquad [2]$$

where $\overline{\eta}_s$ is the water level due to wave set-up about MSL at the mean shoreline position, $\overline{\eta}_b$ is taken as MSL and h_b is the depth at the breakpoint.

The height to depth ratio at breaking is taken as:

$$\gamma_b = a - bH_b/(gT^2) \qquad [3]$$

With $a = 43.8(1-e^{-19\tan\beta})$ and $b = 1.56/(1+e^{-19.5\tan\beta})$

The depth at breaking is,

$$h_b = H_b/\gamma_b \qquad [4]$$

We assume a 1:10 slope at the beach based on the bathymetry transects collected on the lagoon side of Beran Island to the north (Borrero and Grant, 2011).

Using the wave height values determined above for a 15.9 m/s south wind (1.5 m, 4.6 sec) and for extreme cases with typhoon wind speeds of 30 and 40 m/s (Hs = 2.3 m, 3.1 m, T_p = 5.4 s, 6.0 s respectively) we calculate the resultant wave set up values (Table 4.8).

Table 4.8 Computed wave set up for three different wave heights.

Wind (m/s)	Wave H_s (m)	Wave Period (s)	Wave Setup (m)
15.9	1.15	4.8	0.38
30.0	1.23	5.5	0.43
40.0	1.28	6.2	0.47

4.7 Wave Runup – East Coast

Wave run-up is the fluctuation in elevation above the wave set-up caused by individual waves. The USACE (2002) Coastal Engineering Manual determines the maximum run-up, $R_{max,}$ by:

$$R_{max} = 2.32\xi^{0.77}H_s$$

Where ξ is the surf similarity parameter given by:

$$\xi = tan\beta(H_0/L_0)^{-1/2}$$

where tanβ is the slope of the beach face.

Similarly the highest 2% wave runup can be calculated by:

$$R_{2\%} = 1.86\xi^{0.71}H_s$$

Wave run-up has been calculated for the east coast of Woja from significant wave heights estimated using wave generation modelling (WGEN) considering only the available fetch within the Ailinglaplap lagoon (Section 4.4) and design winds (Section 4.1).

Beach slopes were calculated from the average of 5 shore-normal transects on the lagoon side of Beran Island to the north (Borrero and Grant, 2011), these ranged from 1:7.5 to 1:11.5, the average being ≈1:10 which was used in the analysis.

The estimated 100 year non-directional wind speed of 15.9 m/s applied to the ENE (WGEN H_s = 1.15 m, T_p = 4.8 s) gives a wave run-up of 1.59 m above MSL. Testing was also undertaken on stronger winds of 30 m/s and 40 m/s (WGEN Hs = 1.23 m, 1.38 m, T_p = 5.5 s, 6.2 s respectively). The results are presented in Table 4.9.

Table 4.9 Computed wave runup for different wind speeds and associated wind generated wave heights. Runup values are given for the max, highest 2% and highest 1/3 conditions.

Wind (m/s)	Wave H_s (m)	Runup Max (m)	Runup 2% (m)	Runup 1/3 (m)
16.0	1.15	**1.6**	1.35	1.01
30.0	1.23	2.86	2.41	1.80
40.0	1.38	3.73	3.14	2.35

4.8 Extreme Atmospheric Pressure

The minimum pressure from the 62 year NCEP Reanalysis record for Ailinglaplap is 999.5 mbar. However, passage of a typhoon directly over the region would result in considerably lower barometric pressures. As described above, Typhoon Tip produced one of the lowest pressure measurements on record at 870 mbar; but most typhoons have a typical central pressure on the order of 950 mbar, and so this value has been used as the design atmospheric pressure.

For every mbar fall in atmospheric pressure there is a corresponding 10 mm rise in sea level. The difference between the average atmospheric pressure (1010 mbar) and the typical typhoon pressure (950 mbar) is 60 mbar equating to a 600 mm rise in sea level.

4.9 Periodic Sea Level Variations Due to Atmospheric and Climatological Effects

Periodic fluctuations in local sea levels occur due to the effects of the El Nino Southern Oscillation (ENSO). The Australian Bureau of Meteorology (ABoM) includes analysis of sea levels as part of their South Pacific Sea Level and Climate Monitoring Project.

The ABoM (2009) data shows variations of approximately 300 mm below and 150mm above the Marshall Islands tide gauge zero since 1993. 1997-1998 is the largest fall in sea level of 300 mm and relates to the strong El Nino event of this period as measured by the Southern Oscillation Index (SOI, Figure 4.4). Presently sea levels are reported to be approximately 150 mm higher than normal and this coincides with the current La Nina episode or positive SOI Index values. SOI index trends from 1993-2011 are shown in Figure 4.5 reproduced from ABoM (http://www.bom.gov.au).

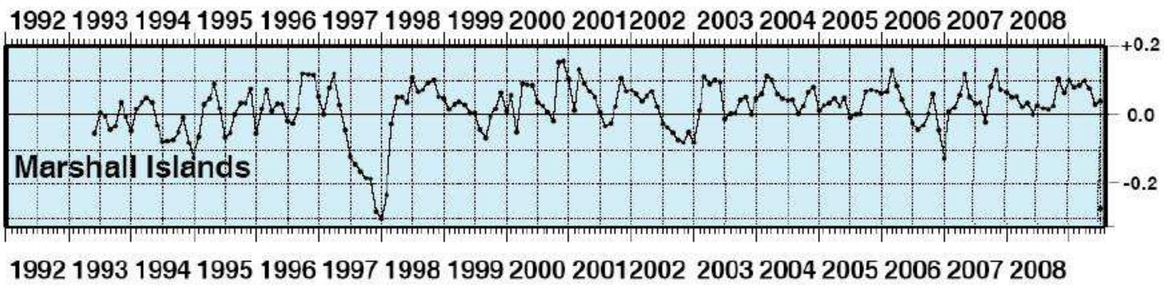

Figure 4.4. Variations in sea level in the Marshall Islands. The range of the graph is +/- 0.2 m. A large depression in sea level is seen to correspond with the 1997 – 1998 El Nino and again in 2002/2003 (Source: Tiempo, 2003)

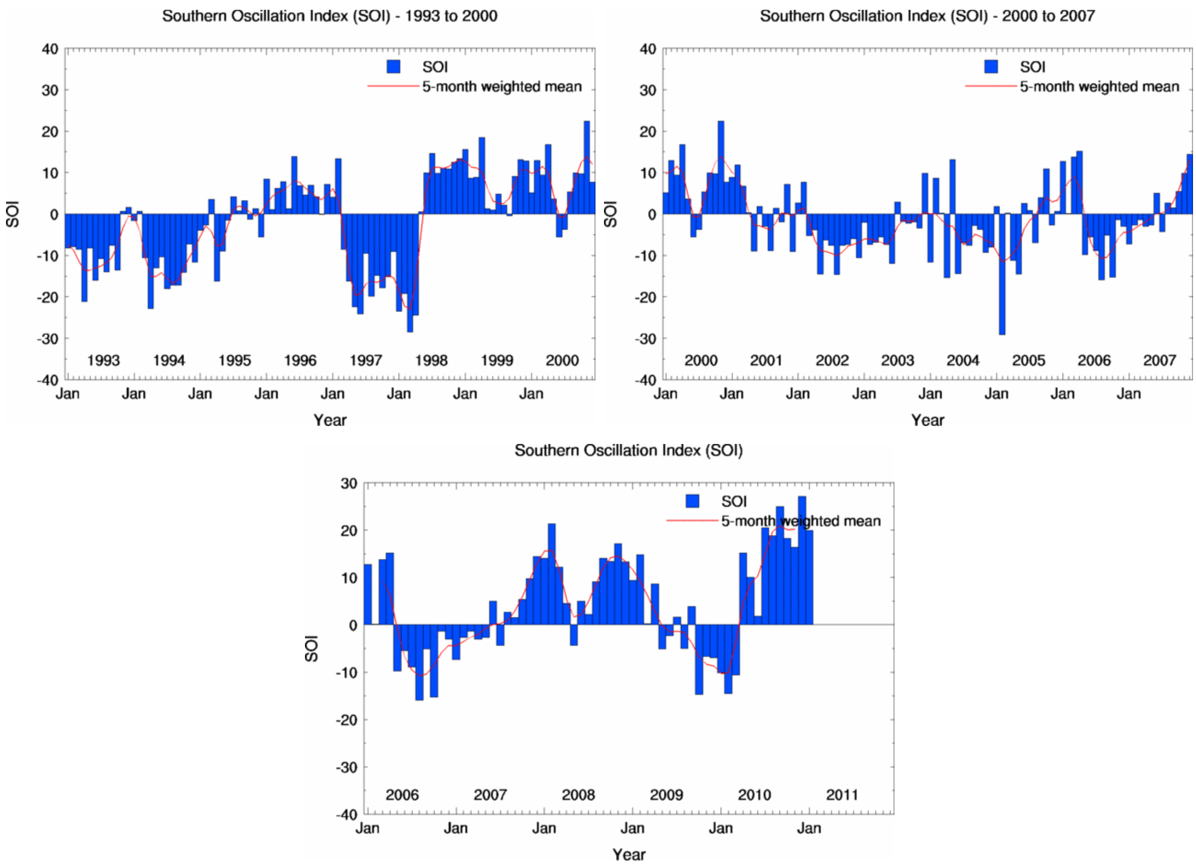

Figure 4.5. Southern Oscillation Index (SOI) from 1993 to 2011 (Source: Australian Bureau of Meteorology).

Spennemann and Marschner (1994) also suggested a relationship between the occurrence of typhoons and ENSO events, suggesting that typhoons are 2.6 times more likely to occur during El Niño years (negative SOI), with a 71% chance of a typhoon striking, and only a 26% chance of one happening during a non-ENSO year (positive SOI). This is a positive effect in that sea level rises caused by the low central pressure of a typhoon would occur when sea levels are already lower due to the ENSO effect.

4.10 Long Term Sea level Rise

While most researchers agree that global sea level rise is occurring, the exact rate at which it is occurring is subject to considerable debate. However, the Intergovernmental Panel on Climate Change is considered the most comprehensive reference to consider likely sealevel rise to 2100. Last year the 5th IPCC Assessment Report (IPCC, 2013) was release, which provided the following predictions on sea level rise (Figure 4.6):

- Sea levels will likely rise between 0.28 to 0.98 m by the year 2100 (3.2-11.4 mm/year);
- These values represent the extremes of all scenarios tested, which consider the amount of reduction in greenhouse gas emissions going forwards (e.g. 0.28 m is the low end of predictions that consider aggressive reduction in emissions with zero emissions by 2070; 0.98 m is the high end of predictions with unmitigated future rise in emissions);
- Should sectors of marine-based ice sheets of Antarctic collapse during this period, sea level could rise by an additional several tenths of a meter during the 21st century; this provides an upper likely range of 1.2 to 1.5 m of sea level rise by 2100.

Church *et al*. (2008) provide a comprehensive review of a range of sea level rise values, which emphasize the global variability of the rate of sea level rise (Figure 4.7). This Figure (Figure 4.7) puts the Marshall Islands in a zone that is experiencing higher than average rates of sea level rise (9-10 mm/year).

Based on the available information a rate of 10 mm/yr has been adopted for Ailinglaplap Atoll for a 30 year planning horizon (i.e. the design-life of the causeway). This is shown in Figure 4.6 and represents the mean estimate of the current IPCC estimates which include the effect of accelerated glacial melting. Thus, on a 30 year planning horizon, the causeway at Woja should accommodate approximate ~30 cm rise in water level.

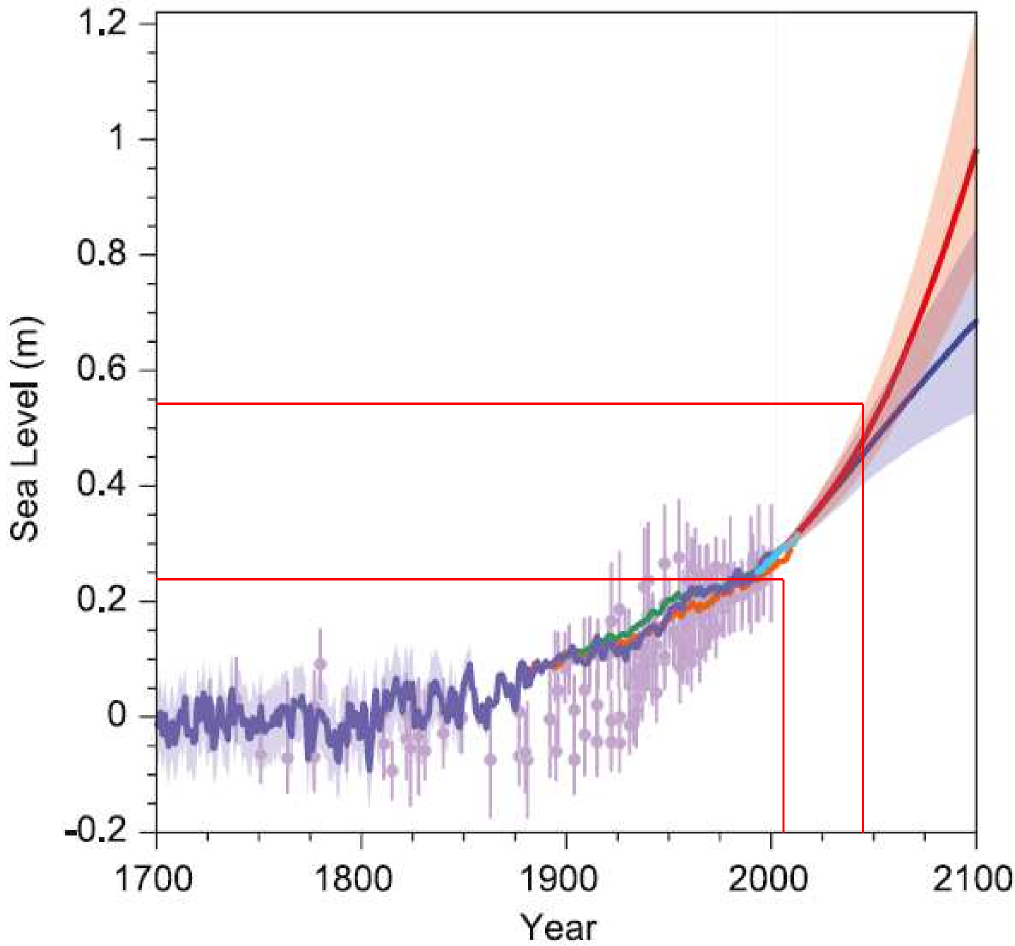

Figure 4.6 Summary of sea level rise predictions through to 2100. The red vertical/horizontal reference lines indicate the 30 year sea level change in value used for the water level calculations for Woja causeway, i.e. 0.3 m in the next 30 years . (Source, http://www.realclimate.org/index.php/archives/2013/10/sea-level-in-the-5th-ipcc-report/).

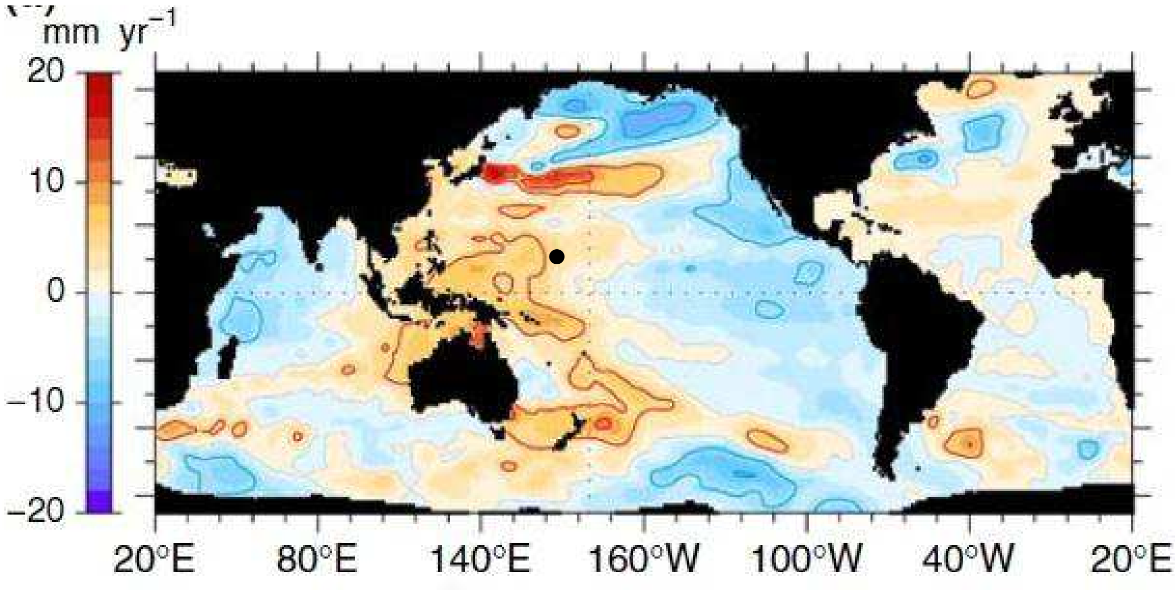

Figure 4.7 Variability in the rates of sea level rise (From Church et al., 2008). The black dot is the approximate location of the Marshall Islands. It is located very close to the 10 mm/yr contour.

4.11 Tsunami Wave Heights

To assess the effect of distant tsunamis, we used guidance based on the recent Tohoku earthquake and tsunami. As discussed in Section 3.10, this earthquake produced a tsunami that caused 1.2 m of sea level fluctuation at the Kwajalein tide station in the Marshall Islands. However, this earthquake was on a section of the Japan subduction zone that is oriented facing to the east, and subsequently the main beam of radiated tsunami energy passed to the north of the Marshall Islands.

Given that there have been several major trans-pacific tsunamis in the past 60 years and that there are virtually no reports of significant inundation on any of the small pacific atolls or islands, a simple sensitivity study was performed rather than a detailed inundation analysis.

For this sensitivity study, a data base of pre-computed tsunami scenarios to simulate three different tsunami sources was applied. The first is the recent, March 11, 2011 Tohoku tsunami. The other two are a hypothetical magnitude 9 earthquake in the central Aleutian islands and the third is a hypothetical magnitude 9 earthquake on the Cascadia subduction zone offshore of North-western North America. Because there is an element of directivity to tsunami propagation, scenarios which would likely have the most impact at the Marshall Islands were simulated. Also, since the Tohoku earthquake was a Magnitude 9 event and major transpacific tsunami are generally of that order of magnitude, only magnitude 9 events were used. These are listed as A, B and C respectively in Figure 4.8

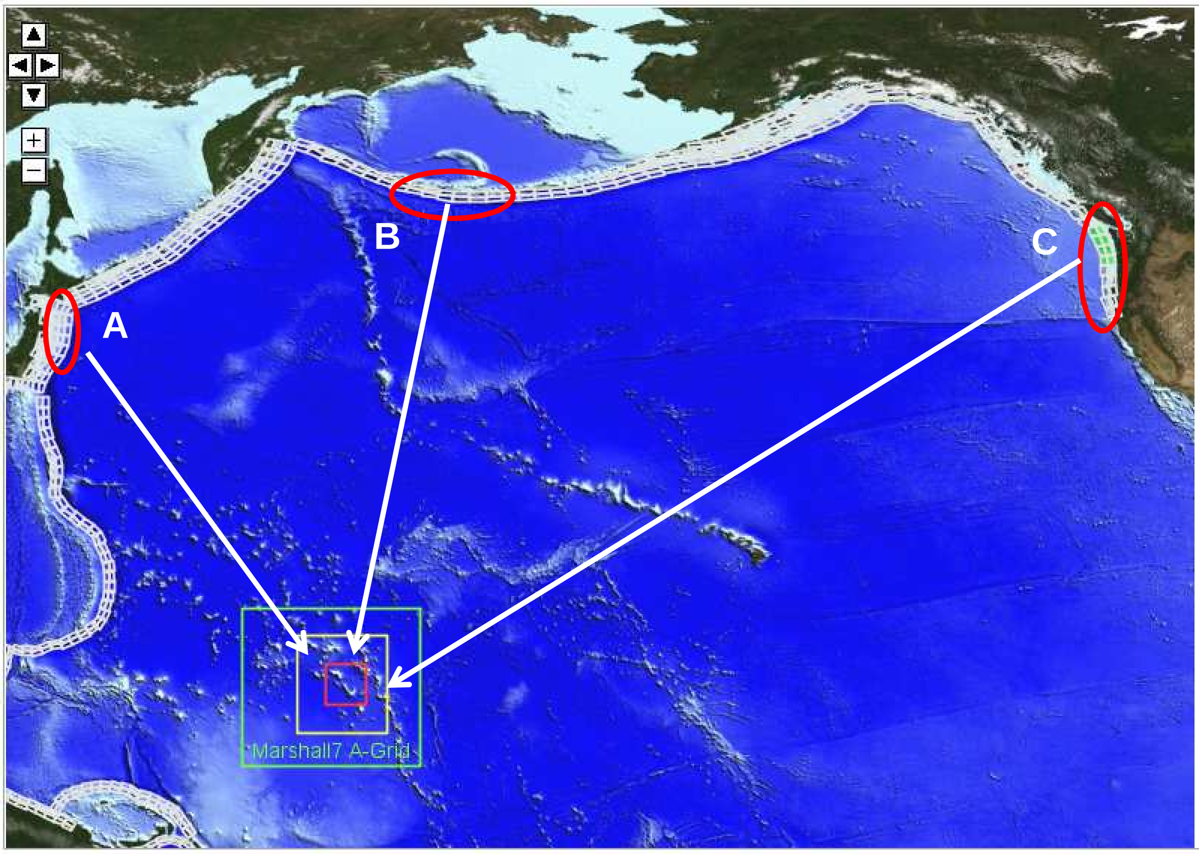

Figure 4.8. Locations of the three magnitude 9 tsunami source used for the Marshall Islands.

Note that these simulations are performed on a very coarse bathymetric grid and are expected to under predict the measured tsunami effects. A comparison between the Kwajalein tide gauge data and the modelled tsunami is shown in Figure 4.9. The model accurately predicts the timing of the wave arrival, but somewhat under predicts the amplitude of the initial wave. The model also under predicts the subsequent negative wave. Later waves are not resolved well, but this is to be expected since the data comes from a tide gauge located in the Kwajalein Lagoon, while the model data is extracted from a model grid node that does not resolve these features at all, i.e. the tsunami is reinforced in the lagoon. Nevertheless, we can use this result as guidance when assessing the potential impact from other tsunami sources.

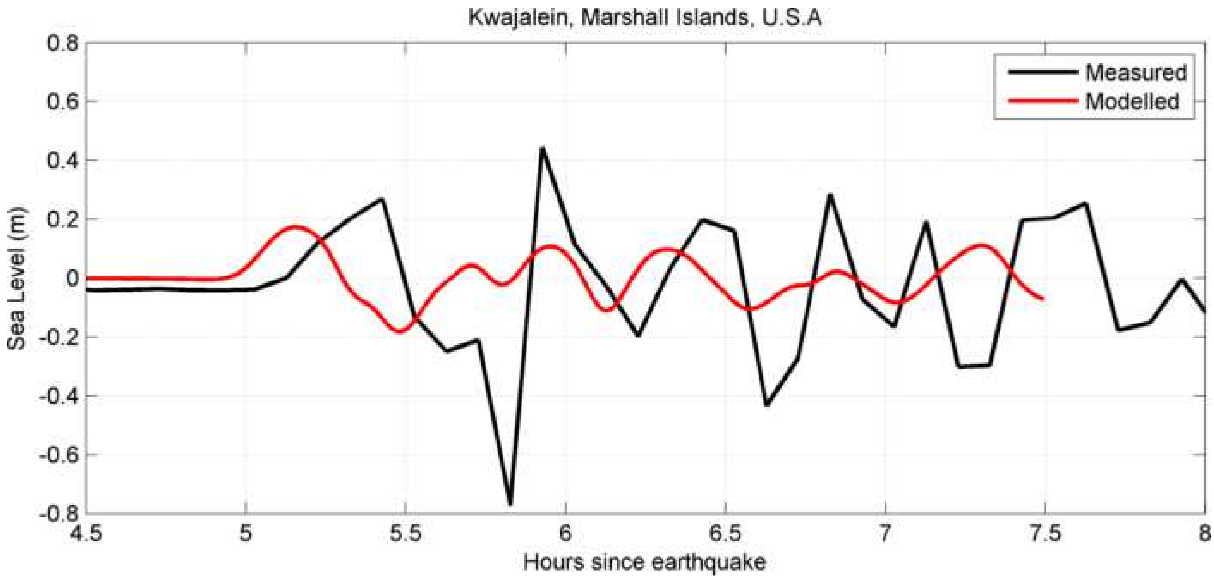

Figure 4.9. Comparison between measured and modelled tsunami wave heights at Kwajalein for the March 11, 2011, Tohoku Japan earthquake and tsunami.

The model results from the Aleutian Islands source (B) are shown in Figure 4.10 and compared to the results previously presented from source A (Tohoku). From this plot it is apparent that despite the improved directivity, the Aleutian source produces waves of similar size to the Japan source. However the wave arrival is approximately 1 hour later. Also this source produces slightly larger waves later in the simulation that are slightly larger than the initial wave.

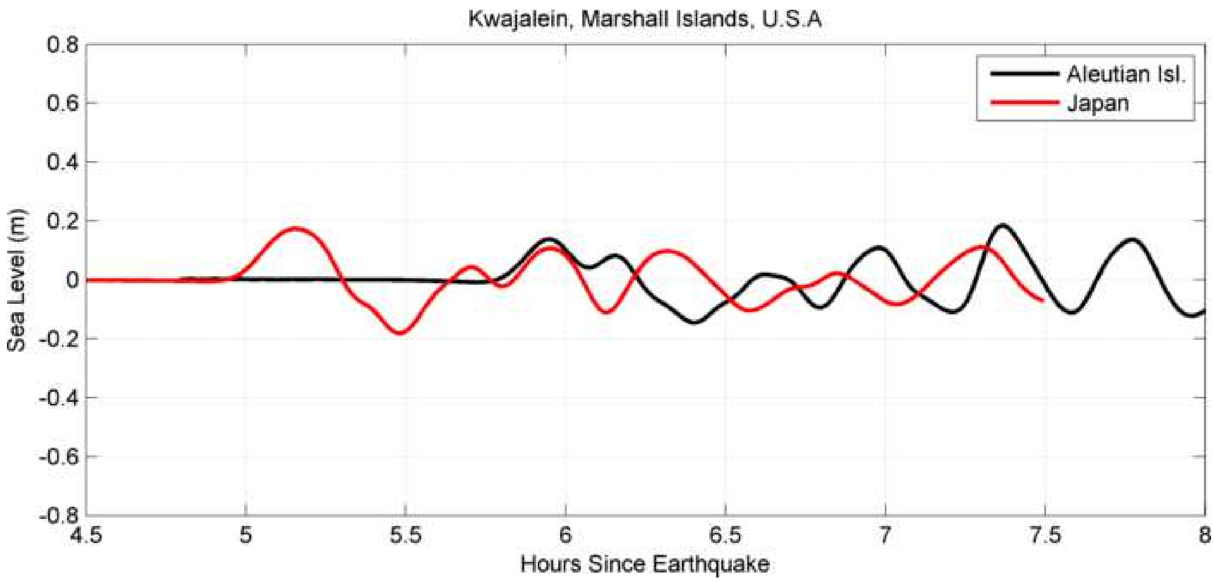

Figure 4.10 Predicted wave height from the Aleutian source compared to the predicted wave height from the Tohoku, Japan source.

Finally, the results from Source C (The Cascadia subduction zone) are shown in Figure 4.11 and compared to sources A and B. While the waves from this source arrive several hours later than the previous two sources, the leading wave is 50% larger than the other two sources. This suggests that there is the potential for slightly larger tsunami waves to affect Woja.

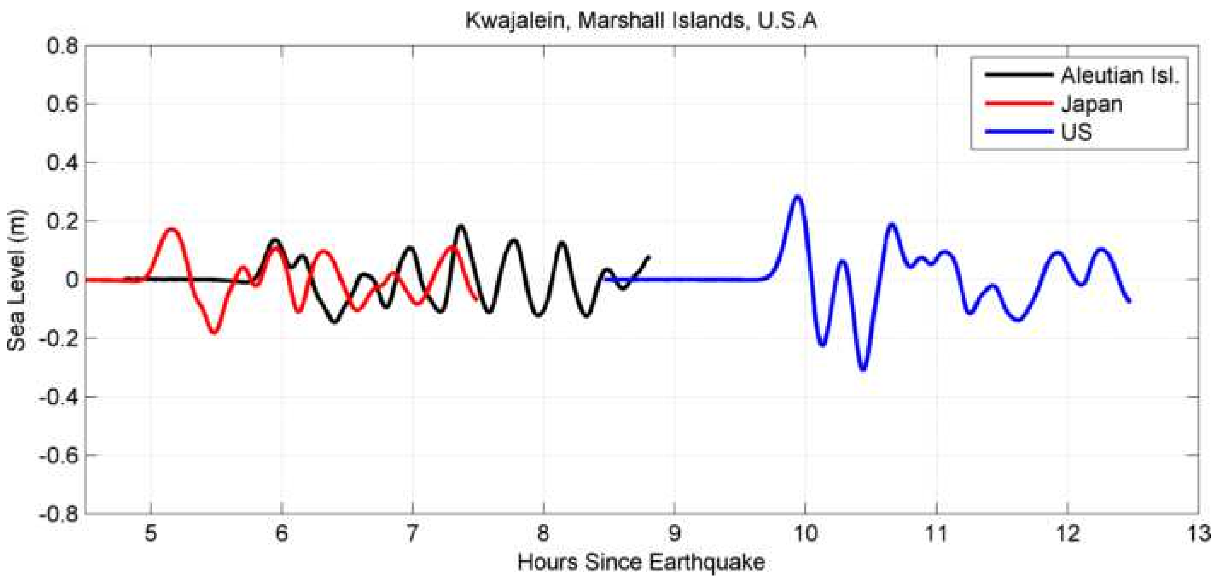

Figure 4.11 Predicted wave heights from the three tsunami source models at Kwajalein in the Marshall Islands.

Based on the analysis above, the Marshall Islands were affected by a maximum positive surge of 0.45 m during the March 11, 2011 Tohoku Japan tsunami. Our model simulations suggest that a similar sized earthquake on the Aleutian Islands would produce similar sized surges. However, a similar sized earthquake on the Cascadsia Subduction Zone could produce waves 50% larger, i.e 0.7 m.

In terms of tsunami planning and preparedness, approximately 1 m of sea level rise could occur during a major tsunami event that will be superimposed on the water level at the time of tsunami arrival. Sources from Japan would arrive approximately 5 hours after the earthquake, 6 hours from the Aleutian Islands and 9.5 hours for the Cascadia subduction zone.

4.12 Coastal Hazard Extreme Water Level Calculations.

Final design water levels have been derived from the summation of the various components assessed within this document. Below we provide summations for the 100-year recurrence interval for the various components, with 50-years of sea level rise for the design-life of the structure. Design water levels have been assessed from the 0 m LAT/CD datum calculated from the site survey and adding the various components. Whilst this does not account for the joint probability of all these events occurring simultaneously, most of the effects are derived during storm and typhoon-like conditions when low atmospheric pressure, storm surge, high winds and waves will occur simultaneously. Tsunami inundation is considered as a separate event since it is not dependent on metocean conditions.

Rises and falls in sea level due to long term climatological effects are not added to the total either. This is because there is insufficient data available on the periodicity of these fluctuations.

The design water levels and the various components for the west and east coasts are detailed in Table 4.10 and Table 4.11, respectively.

Table 4.10. Woja west coast extreme water levels.

Component	Datum (0 m LAT)
Still water level (MSL)	0.92
Mean High Water Spring Tide above MSL	0.68
Effect of pressure and wave set up	0.98
Sea Level Variability	0.10
Wave Set-up 100 y (H_s=4.9 m, T_p 18 s)	0.81
Wave run-up	0.80
Woja west coast extreme water level:	**4.29 LAT**
Disregarding wave run-up	3.49

Table 4.11. Woja east coast extreme water levels.

Component	Datum (0 m LAT)
Still water level (MSL)	0.92
Mean High Water Spring Tide above MSL	0.68
Wind Set-up (16 m/s south east wind)	0.09
Sea Level Variability	0.10
Wave Set-up	0.38
Wave Run-up – calculated from wave generation modelling of 15.9 m/s wind over longest fetch (SE) giving H_s = 1.1 m, T_p = 4.5 s.	1.60
Effects of typical typhoon pressure (950mbar) on sea level.	0.60
Woja east coast extreme water level:	**4.37 LAT**
Disregarding wave run-up	2.77 m

The total values computed for the north and south coasts are quite similar. The values presented here are based on separate 100-year recurrence interval events occurring simultaneously, for present day conditions (i.e. excluding sea level rise). In a strict mathematical sense, this represents a recurrence interval that is much higher than 100-years, i.e. the likelihood of all occurring at the same time is less than 1 in 100. However, in a practical sense this may not be the case since a very strong typhoon will have strong winds in conjunction with low pressures and higher waves, which is why this method is the standard method used for determining coastal hazard levels.

In addition to these extreme water levels, 0.3 m of sea level rise over the next 30 years must be incorporated, which produces 30 year extreme water levels of:

- 4.59 m on the west coast, and;
- 4.67 m on the east coast.

These levels are similar to those found with a similar assessment for Beran Island, which is, north east of Woja Island on Ailinglaplap Atoll (Borrero and Grant, 2011).

4.13 Selection of Causeway Construction Level

When these levels are related to the topographical survey of the site (Section 2.2 and Appendix 1), it can be seen that the highest land areas beyond the causeway are less than 3 m – this elevation is common for many of the Marshall Island Atolls (e.g. Sea Grant's (2011) rapid assessment indicates that the main habited areas of Kili Island are between 2.0 and 3.0 m above MLLW). Therefore adopting design levels to avoid coastal hazards that are almost 2 m above the level of the island is impractical.

In the first instance, wave run-up can be disregarded – the infrastructure planned is armoured roading, and so does not have to consider intermittent inundation by seawater. This leads to extreme water level values of:

- 3.79 m on the west coast, and;
- 3.07 m on the east coast.

Therefore, for practically of construction and considering the height of the surrounding island, a 3.0 m finished causeway height is recommended. This is an 'Irish-Crossing' type structure, i.e., rather than a primary piece of infrastructure for a densely populated coastal area, a robust structure that is designed to allow over-topping in the rarest and most extreme cases.

In considering the eastern side of the causeway, and the Priority 1 site, at an extreme water level of 3.07 m in 30 years time, there will be over-topping of this structure in the most extreme cases during high tide. Similar over-topping would occur along the finger of land adjacent to the northern area (Priority 2 site), where there is presently a footpath (Figure 2.3).

With respect to extreme water levels on the western side of the project site, disregarding run-up is warranted since the crest of the beachrock reef is at an elevation of some 1.5-2.0 m above LAT and there is no beach beyond it for waves to run-up (the level drops away behind the crest to the low area of Priority 2 in the north and the tidal lagoon west of the Priority 1 area (Figure 2.3)). The causeway road is some 35-80 m from the crest of the beachrock reef (north to south), which will also reduce wave over-topping impacts. However, the potentially significant wave set-up of 0.81 m during a 100 year return period wave event leads to a potential extreme water level of 3.79 m, i.e. 0.79 m above the finished causeway road level in 30 years time.

Based on the local topography (i.e. the beachrock reef crest dropping to lower land levels that are some 35-80 m from the causeway), it is expected that during an extreme water level event with extreme wave set-up, over-topping will occurring with an infra-gravity wave type period, i.e. surges occurring in relation to the arrival of wave groups (sets) across the reef flat. Figure 4.12 is an example of a similar situation where extreme elevated water levels known as loka (caused by long period large waves from the Tasman Sea) result in infra-gravity waves over-topping the Irish-Crossing at Shangri-La Resort on the Coral Coast of Fiji (Mead *et al.*, 2013).

Figure 4.12. Infra-gravity waves over-topping the Irish-Crossing at Shangri-La Resort on the Coral Coast in Fiji (Mead *et al.*, 2013). Similar over-topping is likely during extreme events at high tide on the Woja causeway with a level of 3.0 m above LAT.

4.14 Summary

Coastal hazard assessment and consideration of design factors for the Woja causeway project were undertaken for the eastern and western sides of the island using different methods due to the different physical settings (i.e. lagoon and open-ocean, respectively).

Long-term wind, wave and pressure data was used to determine extreme water levels for a variety of factors that are combined to determine maximum water elevations during extreme events (i.e. wind set-up, wave set-up, inverse barometric pressure, wave run-up and sea level variation) using both empirical and numerical models. In addition, typhoon and tsunami impacts were also investigated using historic records and tsunami modelling.

Total coastal hazard extreme water levels were calculated by combining all the various parameters with 100 year return periodicity, with the additional incorporation of 0.3 m of sea level rise over the next 30 years (the life-expectancy of the causeway structures), which produces 30 year extreme water levels of:

- 4.59 m on the west coast, and;
- 4.67 m on the east coast.

These levels are similar to those found with a similar assessment for Beran Island, which is, north east of Woja Island on Ailinglaplap Atoll.

When these levels are related to the topographical survey of the site, it obvious that the highest land areas beyond the causeway are less than 3 m – this elevation is common for many of the Marshall Island Atolls. Therefore adopting design levels to avoid coastal hazards that are almost 2 m above the level of the island is impractical.

In the first instance, wave run-up was disregarded – the infrastructure planned is armoured roading, and so does not have to consider intermittent inundation by seawater. This leads to extreme water level values of:

- 3.79 m on the west coast, and;
- 3.07 m on the east coast.

For practically of construction and considering the height of the surrounding island, a 3.0 m finished causeway height is recommended. This is an ‘Irish-Crossing’ type structure, i.e., rather than a primary piece of infrastructure for a densely populated coastal area, a robust structure that is designed to allow over-topping in the rarest and most extreme cases.

In considering the eastern side of the causeway, and the Priority 1 site, at an extreme water level of 3.07 m in 30 years time, there will be over-topping of this structure in the most extreme cases during high tide. Similar over-topping would occur along the finger of land adjacent to the northern area (Priority 2 site), where there is presently a footpath.

With respect to extreme water levels on the western side of the project site, disregarding run-up is warranted since the crest of the beachrock reef is some 35-80 m from the road, at an elevation of some 1.5-2.0 m above LAT and there is no beach beyond it for waves to run-up (the level drops away behind the crest to the low area of Priority 2 in the north and the tidal lagoon west of the Priority 1 area). However, the potentially significant wave set-up of 0.81 m during a 100 year return period wave event leads to a potential extreme water level of 3.79 m, i.e. 0.79 m above the finished causeway road level in 30 years time.

Based on the local topography, it is expected that during an extreme water level event with extreme wave set-up, over-topping will occurring with an infra-gravity wave type period, i.e. surges occurring in relation to the arrival of wave groups (sets) across the reef flat, which are usually several minutes apart.

5 Preliminary Design and Costing

Based on the investigations described above, an 'Irish crossing' type causeway, i.e. a robust structure that is designed to allow over-topping in the rarest and most extreme cases, with a finished road level of 3.0 m above LAT is the most practical solution for the site. This approach is considered appropriate relative to the height of the surrounding land, the position of the causeway road in relation to the beachrock reef crest on the western side of the site, and population and traffic pressure that the causeway road will experience. A higher road (i.e. above the total coastal hazard level) is not considered to provide additional benefits at the site in terms of accessibility, since if the causeway at 3.0 m above LAT is being over-topped, other areas of the island and stretches of the road will also be experiencing over-topping (e.g. there are 2 stretches of road north of the site (100 and 300 m long) which are within 10-20 of the beach). In addition, there is significant cost savings due to reduced volume at 3.0 m compared to higher levels, i.e. because the level of the road is not set higher than the rare and most extreme events.

5.1 Causeway Road Position and Planting

The existing causeway road position needs to be considered, since it has had to be moved in the recent past and any resilience remediation should attempt to ensure that future movement is not required. The northern low section of the road was previously located along the narrow strip of land to the east on the margin of the lagoon that is today the foot path (Figure 5.1). It was abandoned due to erosion and over-topping making it impassable during higher tides and large wave events. At present, the Priority 1 southern area is vulnerable to on-going erosion and over-topping and so moving it away from the eastern coast will provide further future protection for this section of causeway.

At the Priority 1 southern site, the new causeway road will be set some 15-20 m to the west of the existing causeway road to provide an additional erosion buffer on the eroding eastern side of the causeway (Figure 5.1). The new elevated road in the northern Priority 2 area will run along its existing route (Figure 5.1). In addition to elevating and armouring the causeway road, planting out of the existing road in the

Priority 1 area (which will be replaced by the new causeway 15-20 m to the west) should be undertaken to provide additional buffering from erosion, preventing wind-blown loss of sand and providing added natural erosion resistance. Additional soft-engineering in the form planting around the site should also be applied, with mangrove in the low wet areas along the western side of the footpath, and additional Kone trees all around lower areas of the site. The exception to planting may be the area around the tidal lagoon area on the southwestern side of the causeway, since this area is known as Diamond Kan and is a popular picnic area for the villagers. This will be discussed during the next phase of consultation in the project.

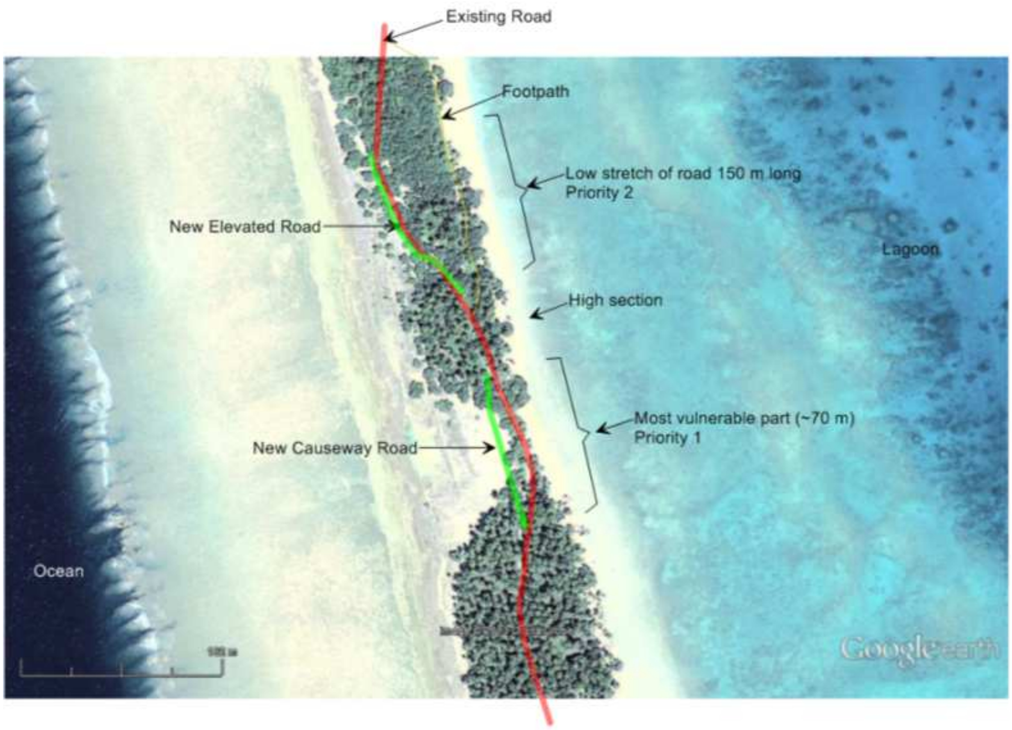

Figure 5.1. The existing road is shown in red – the northern section previously ran along the eastern edge adjacent to the lagoon, where there is now a footpath; it was abandoned due to erosion and over-topping making it impassable during higher tides and large wave events. In the Priority 1 southern areas, the new causeway road will be set some 15-20 to the west of the existing causeway road (shown with the green line) to provide an additional erosion buffer on the eroding eastern side of the causeway. The new elevated road in the northern Priority 2 area will run along its existing route (also shown with a green line).

5.2 Rock Armour Sizing

Limestone rock (i.e. reef blocks located on the north western coast of the island - Figure 2.14) of 0.75 m diameter (i.e. nominally 0.6-0.9 m in diameter) has been specified for the Priority 1 southern causeway road based on the application of the Hudson formula. Smaller diameter rock is required for the elevated road (i.e. nominally 0.3-0.5 m diameter) at the northern Priority 2 site, since it is protected from direct wave attack by the beachrock reef to the west and is 40-80 m away from the eastern coast of the island.

The US Army Corps of Engineers' method for determining proper rock sizing relies on the Hudson formula which is expressed as:

$$W = \gamma_r H^3 / K_D (\gamma_r/\gamma_w - 1)^3 \cot\theta$$

Where,

W = weight of the outer layer armour unit
γ_r = unit weight of armour unit
H = design wave height
K_D = stability coefficient from armour size, shape and material
γ_w = unit weight of water
θ = angle of structure slope

Where K_D is a stability coefficient taking onto account all the other variables. K_D values in the literature are for "no damage" conditions defined so that up to 5% of the armour rock may be displaced. H in the equation being taken as $H_{1/10}$ i.e., the highest 1/10th of all waves.

The extreme wave heights calculated in Section 4.4 were used in the calculations of rock sizes. The results of applying these maximum wave heights to the Hudson formula led to a Dn_{50} (median rock diameter) of 0.71 m for the Priority 1 new causeway road, with ~10% safety factor resulting in the specified 0.6-0.9 m limestone rocks at a gradient of 1.5:1 (H:V), which are reduced to 0.3-0.5 m diameter for the elevated road section (Priority 2).

5.3 New Causeway Road – Priority 1

Figure 5.2 shows the location and a generic cross-section of the new causeway for the southern Priority 1 area. The new causeway is located 15-20 m west of the existing road and has a finished road level of 3.0 m. The existing road should be planted out to provide additional buffering from erosion, preventing wind-blown loss of sand and providing added natural erosion resistance.

5.4 Elevated Road – Priority 2

Figure 5.3 shows the location and a generic cross-section of the new elevated road for the northern Priority 2 area. The new elevated road is to be located in the same position as the existing road and has a finished road level of 3.0 m. Additional planting around the site should also be applied, with mangrove in the low wet areas along the western side of the footpath (i.e. between the elevated road and the eastern side of the causeway area), and additional Kone trees all around lower areas of the site.

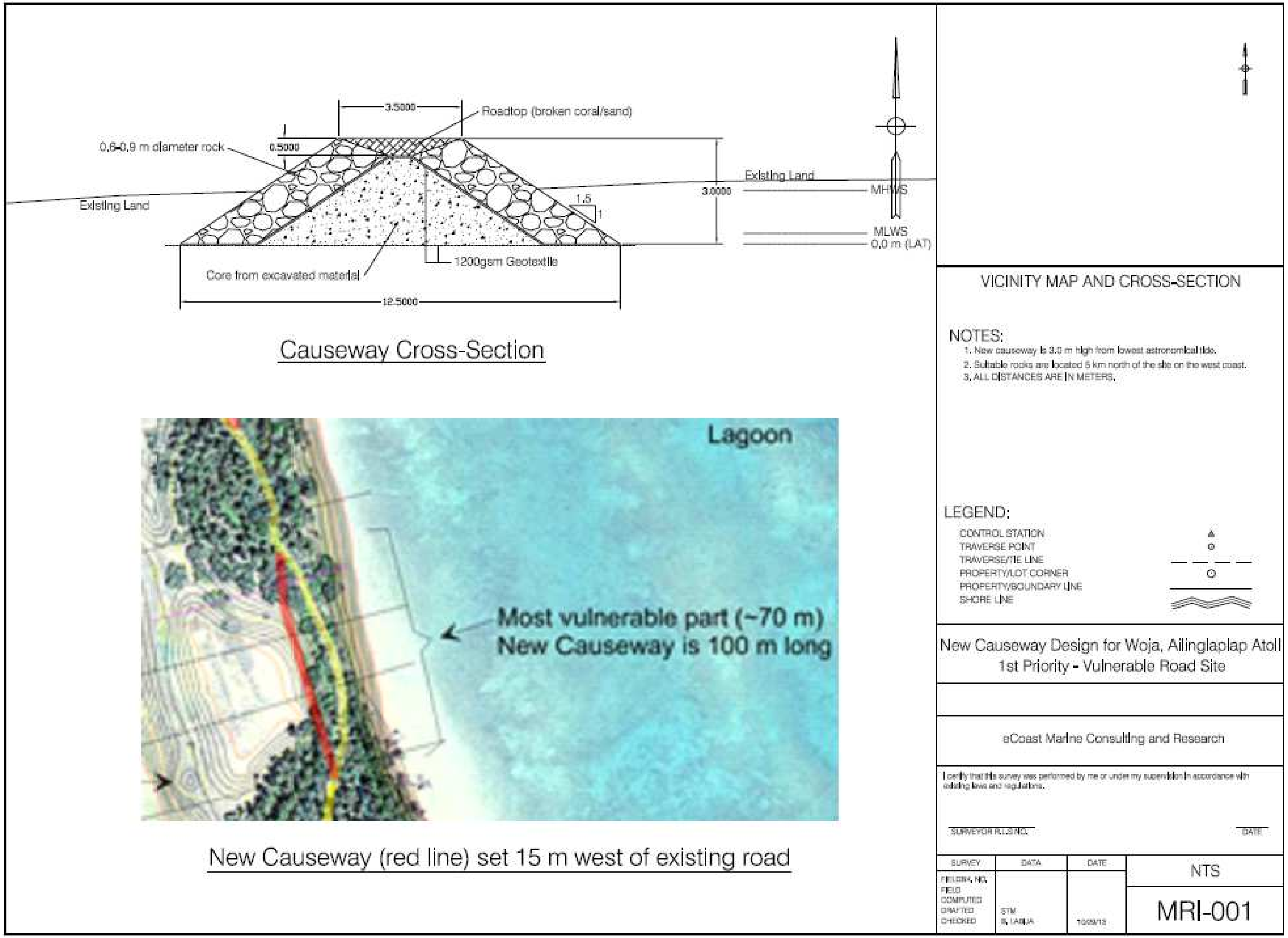

Figure 5.2. Location and cross-section for Priority 1 southern causeway road.

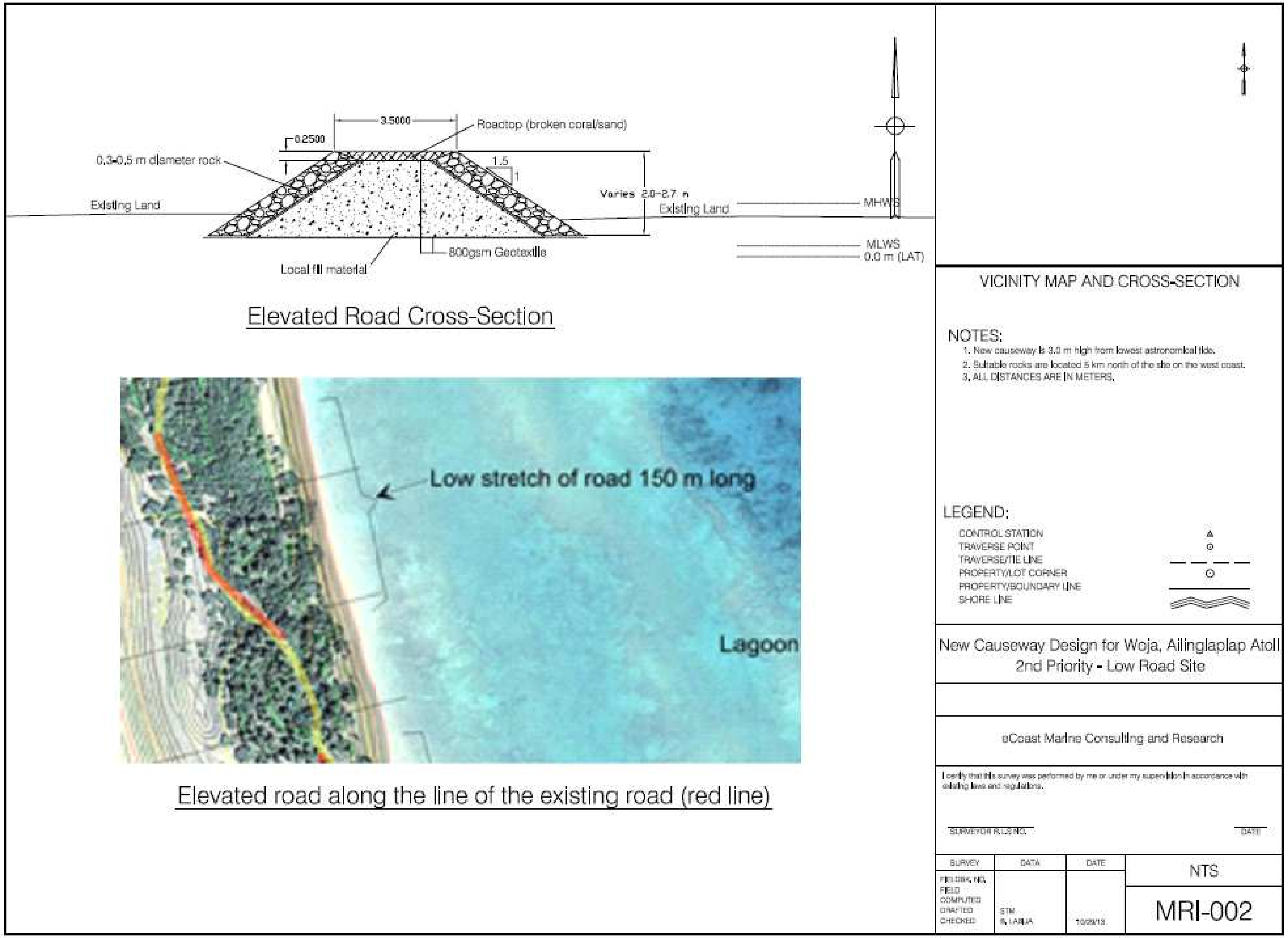

Figure 5.3. Location and cross-section for Priority 2 northern elevated road.

5.5 Cost Estimate

Contractors in the Majuro were requested to provide cost estimates based on the brief presented in Appendix 5. The brief included preliminary plans and cross-sections of the proposed works for the Priority 1 and 2 areas, location photographs and maps, and a basic construction plan (Appendix 4). Based on this information, the following cost estimates were developed (Table 5.1 and Table 5.2):

Table 5.1. Priority 1 cost estimate.

Item	Quantity	Cost (USD)
Armour rock acquisition/placement	700 m^3	300,450
Excavation	1,100 m^3	43,650
Core Fill	1,200 m^3	74,700
Road Top	175 m^3	11,700
Geofabric	2,250 m^2	36,500
Total		467,000

Table 5.2. Priority 2 cost estimate.

Item	Quantity	Cost (USD)
Armour rock acquisition/placement	450 m^3	193,150
Excavation	800 m^3	31,700
Core Fill	1,300 m^3	80,950
Road Top	150 m^3	10,000
Geofabric	2,700 m^2	43,850
Total		359,650

Mobilization/Demobilization	60,000
Grand Total	886,650

5.6 Summary

At the Priority 1 southern site, the new causeway road will be set some 15-20 m to the west of the existing causeway road to provide an additional erosion buffer on the eroding eastern side of the causeway. The new elevated road in the northern Priority 2 area will run along its existing route. In addition to elevating and armouring the causeway road, planting out of the existing road in the Priority 1 area (which will be replaced by the new causeway 15-20 m to the west) should be undertaken to provide additional buffering from erosion, preventing wind-blown loss of sand and providing added natural erosion resistance. Additional soft-engineering in the form planting around the site should also be applied, with mangrove in the low wet areas along the western side of the footpath, and additional Kone trees all around lower areas of the site. The exception to planting may be the around the tidal lagoon area on the southwestern side of the causeway, since this area is known as Diamond Kan and is a popular picnic area for the villagers. This will be discussed during the next phase of consultation in the project.

The extreme wave heights calculated from long-term wave data and empirical and numerical modelling were used in the calculations of rock sizes. The results of applying these maximum wave heights to the Hudson formula led to a Dn_{50} (median rock diameter) of 0.71 m for the Priority 1 new causeway road, with ~10% safety factor resulting in the specified 0.6-0.9 m limestone rocks at a gradient of 1.5:1 (H:V), which are reduced to 0.3-0.5 m diameter for the elevated road section (Priority 2).

Contractors in the Majuro were requested to provide cost estimates based on a brief which included preliminary plans and cross-sections of the proposed works for the Priority 1 and 2 areas, location photographs and maps, and a basic construction plan. Based on this information, the following cost estimates were developed for the project:

- Priority 1 cost estimate total: USD467,000
- Priority 2 cost estimate total: USD359,650
- Mobilization/Demobilization: USD60,00
- Total estimated cost: USD886,650

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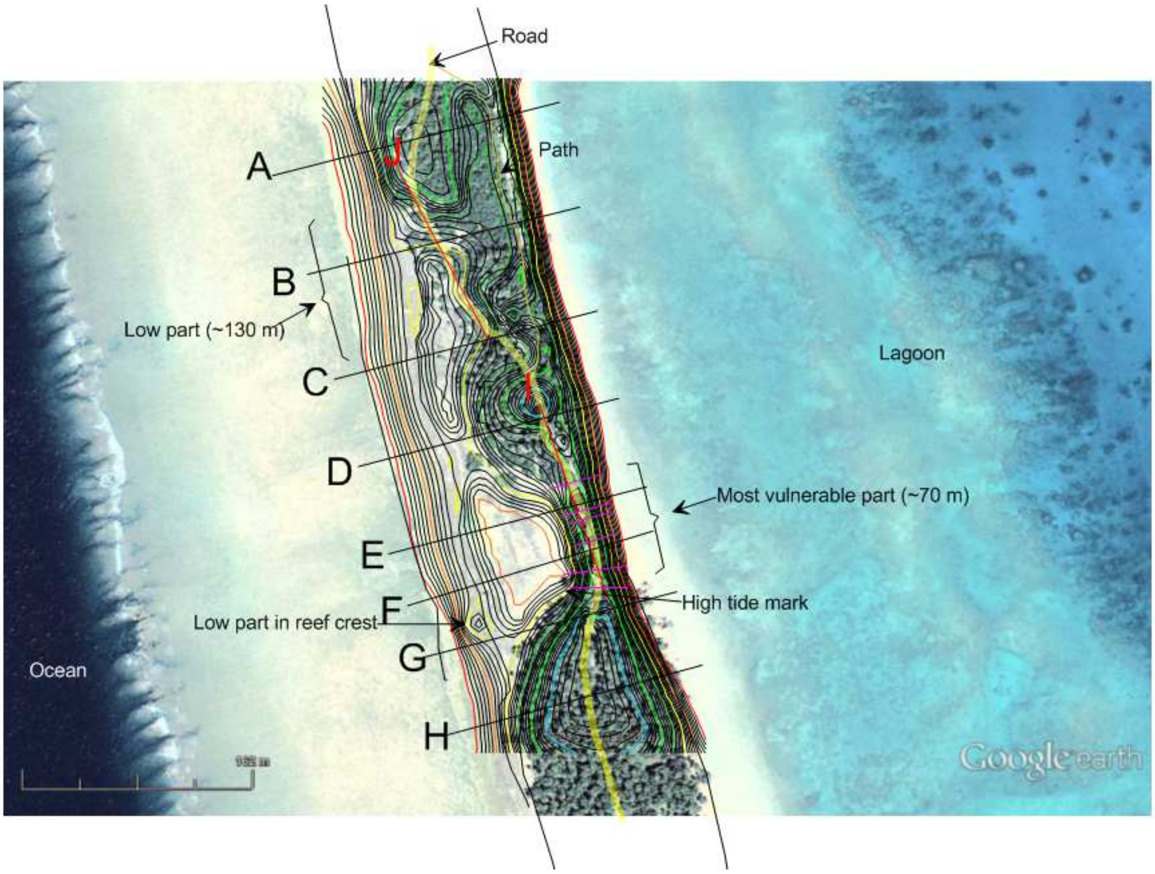
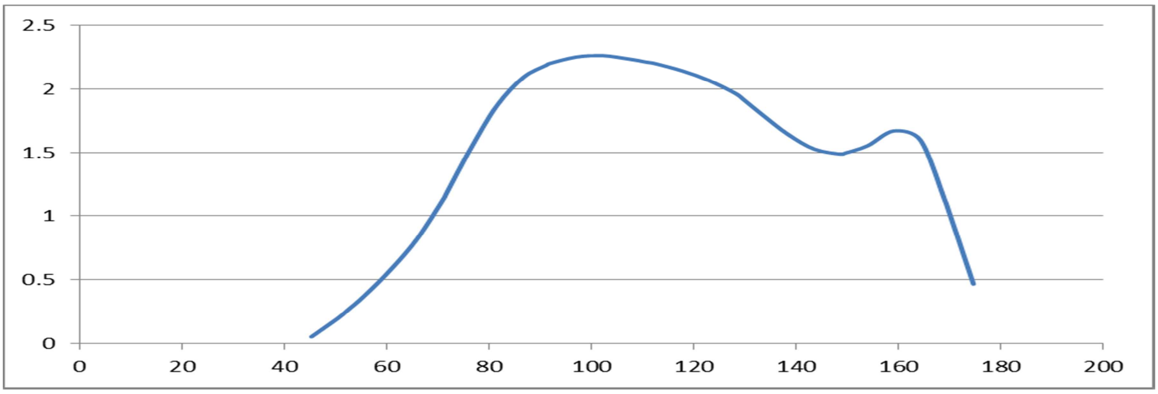
Appendix 1 – Profiles extracted from the DTM



Location Key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80
100
120
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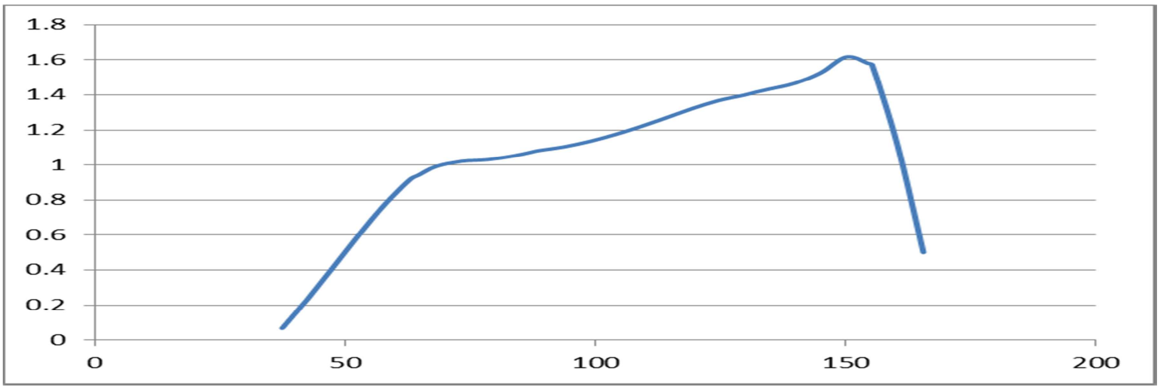
160
180
200

A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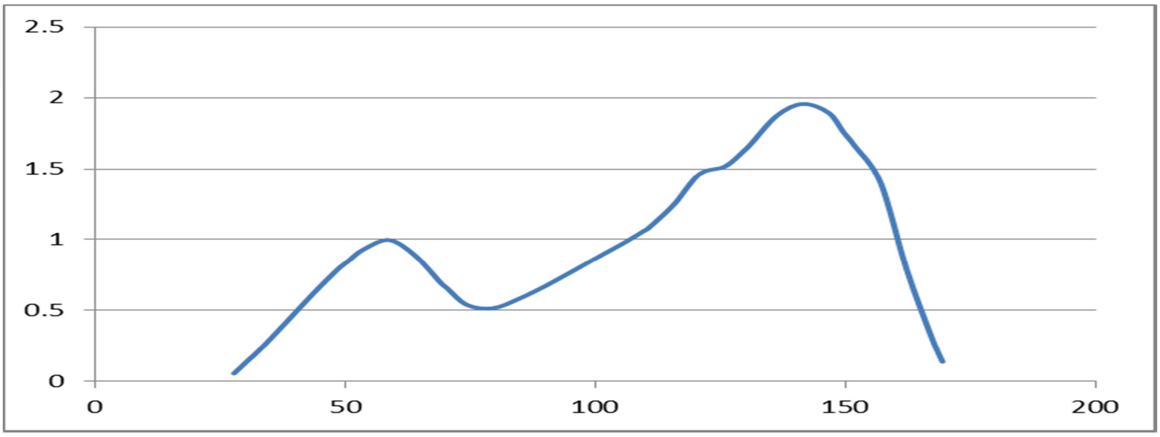
200

B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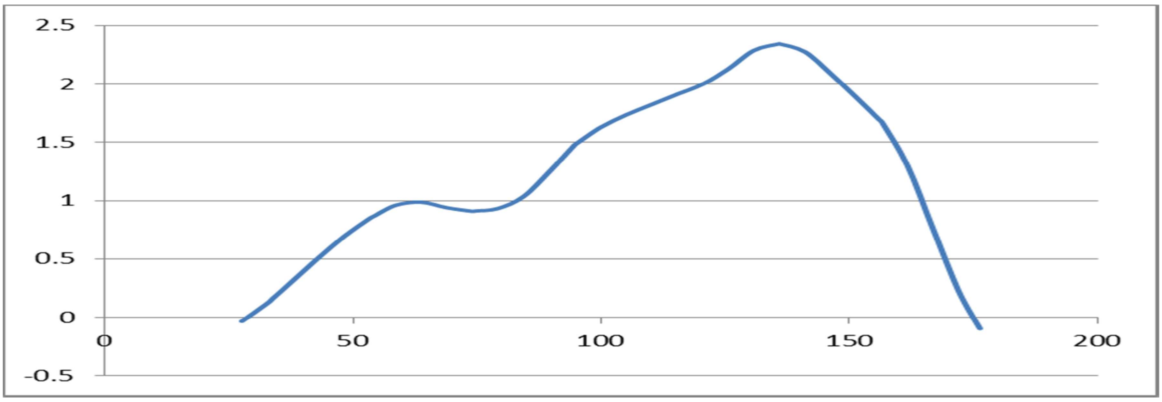
200

C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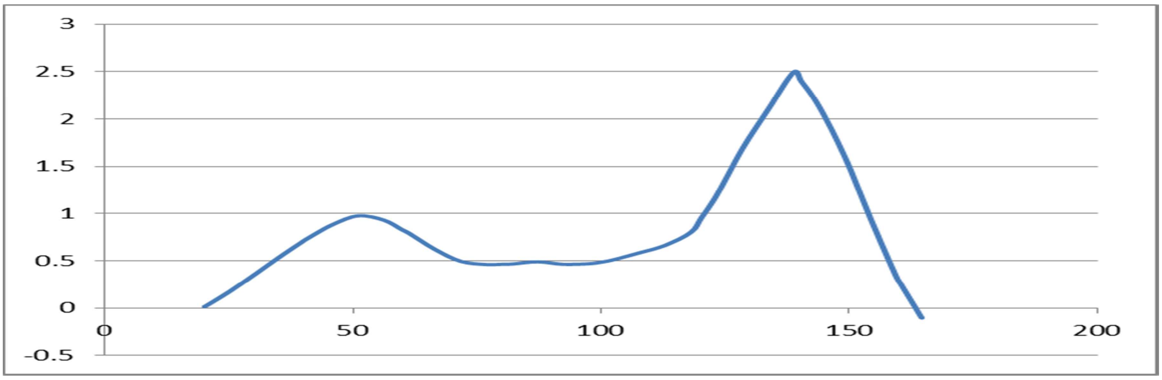
-0.5
0
50
100
150
200

D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1
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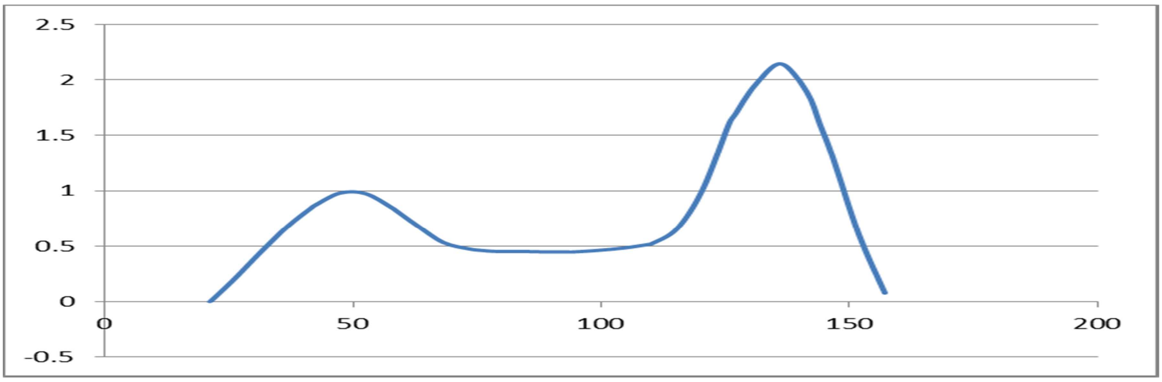
-0.5
0
50
100
150
200

E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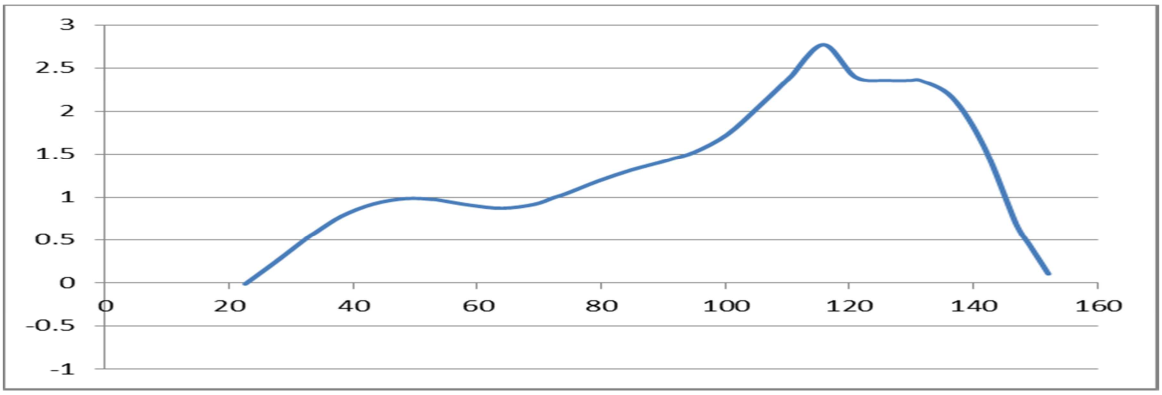
100
150
200

F


3
2.5
2
1.5
1
0.5
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-1
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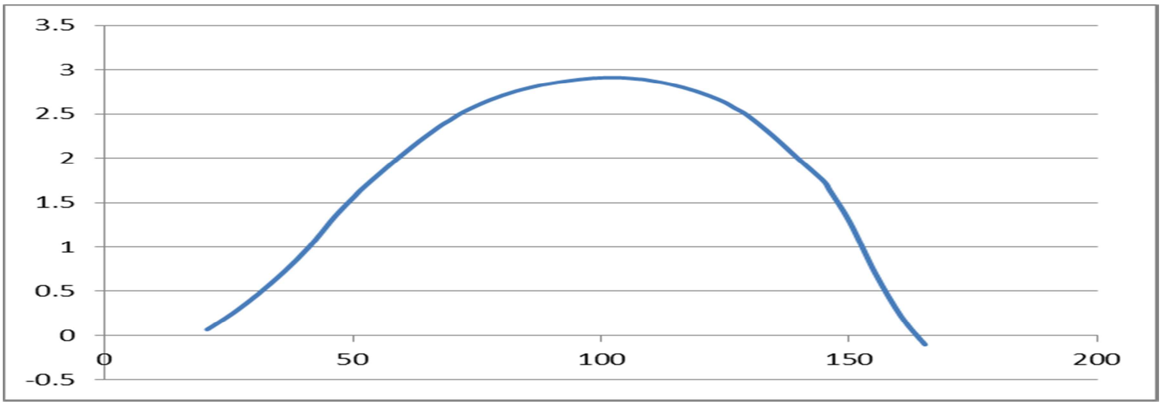
20
40
60
80
100
120
140
160

G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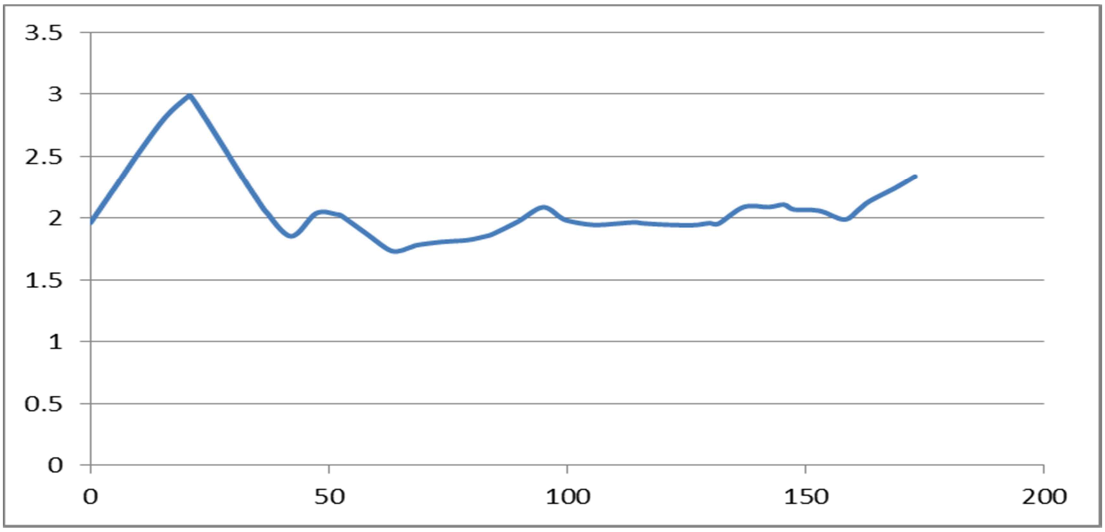
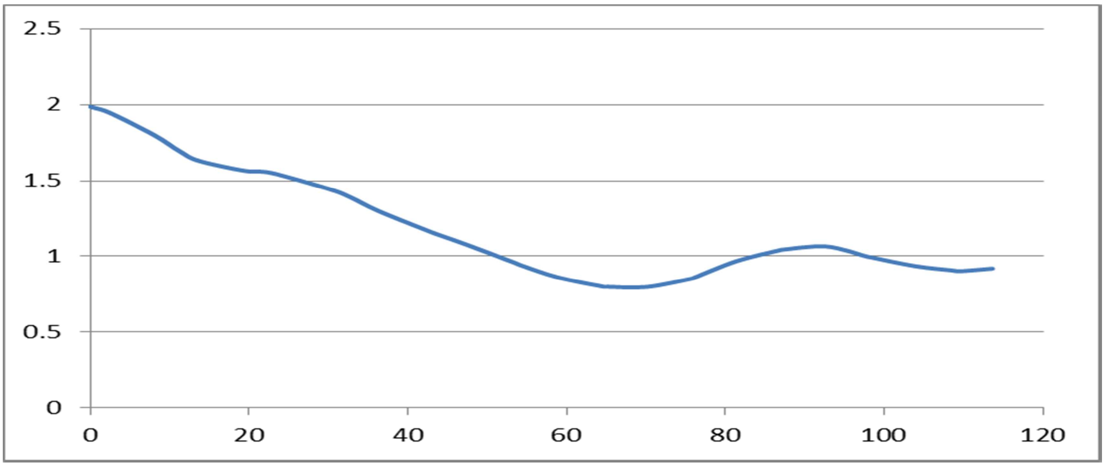
1
0.5
0
-0.5
0
50
100
150
200

H



I – Along low road northern area.



J – Along vulnerable road southern area.

APPENDIX 2 – SEASONAL WAVE CLIMATE ANALSIS

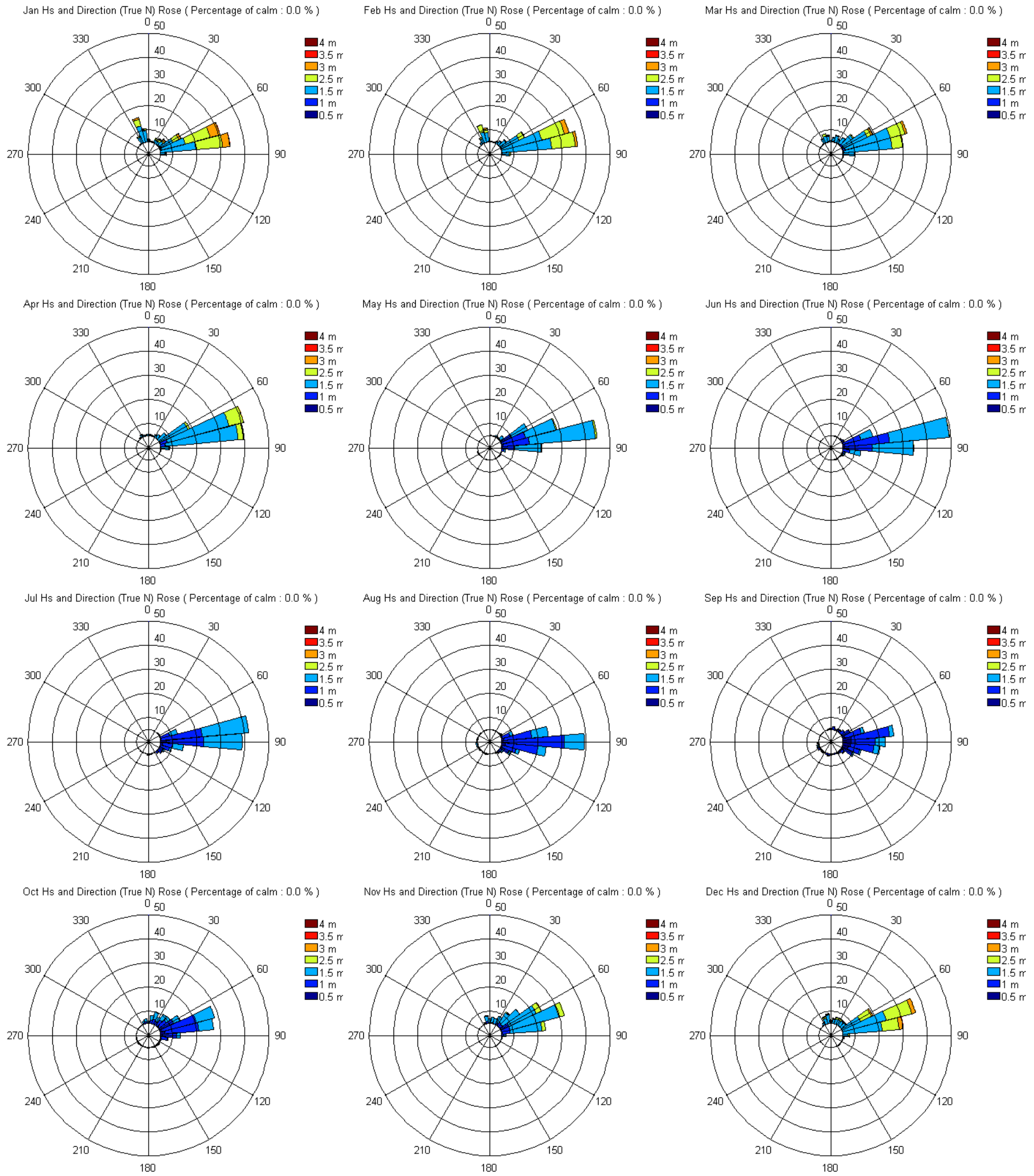


Figure A2.1 – Significant wave height (H_s) roses from monthly decomposition of MDI wave record from 1997-2010 for location north of Ailinglaplap Atoll (8°N 168.75°E).

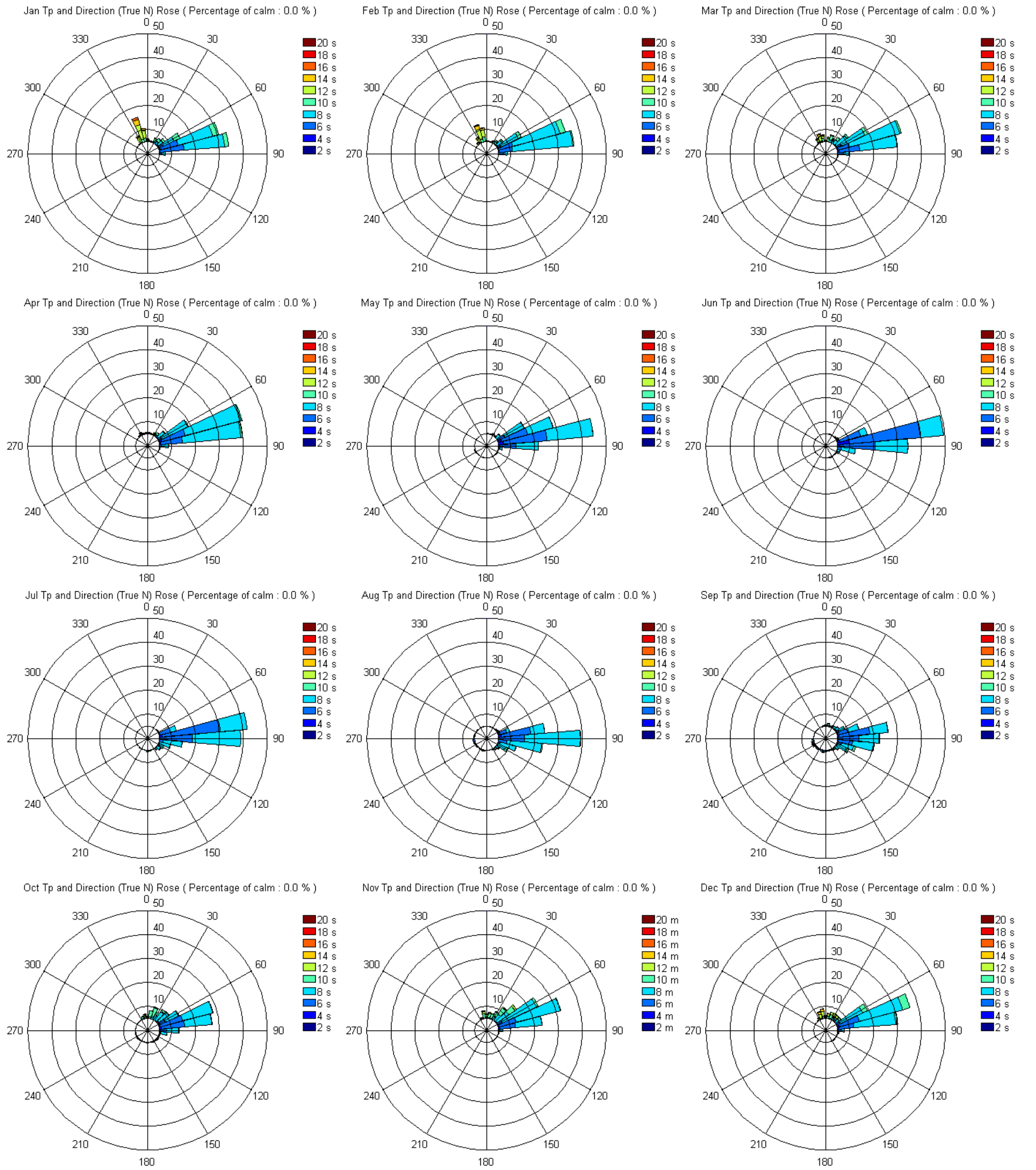


Figure A2.2 – Peak wave period (T_p) roses from monthly decomposition of MDI wave record from 1997-2010 for location north of Ailinglaplap Atoll (8°N 168.75°E).

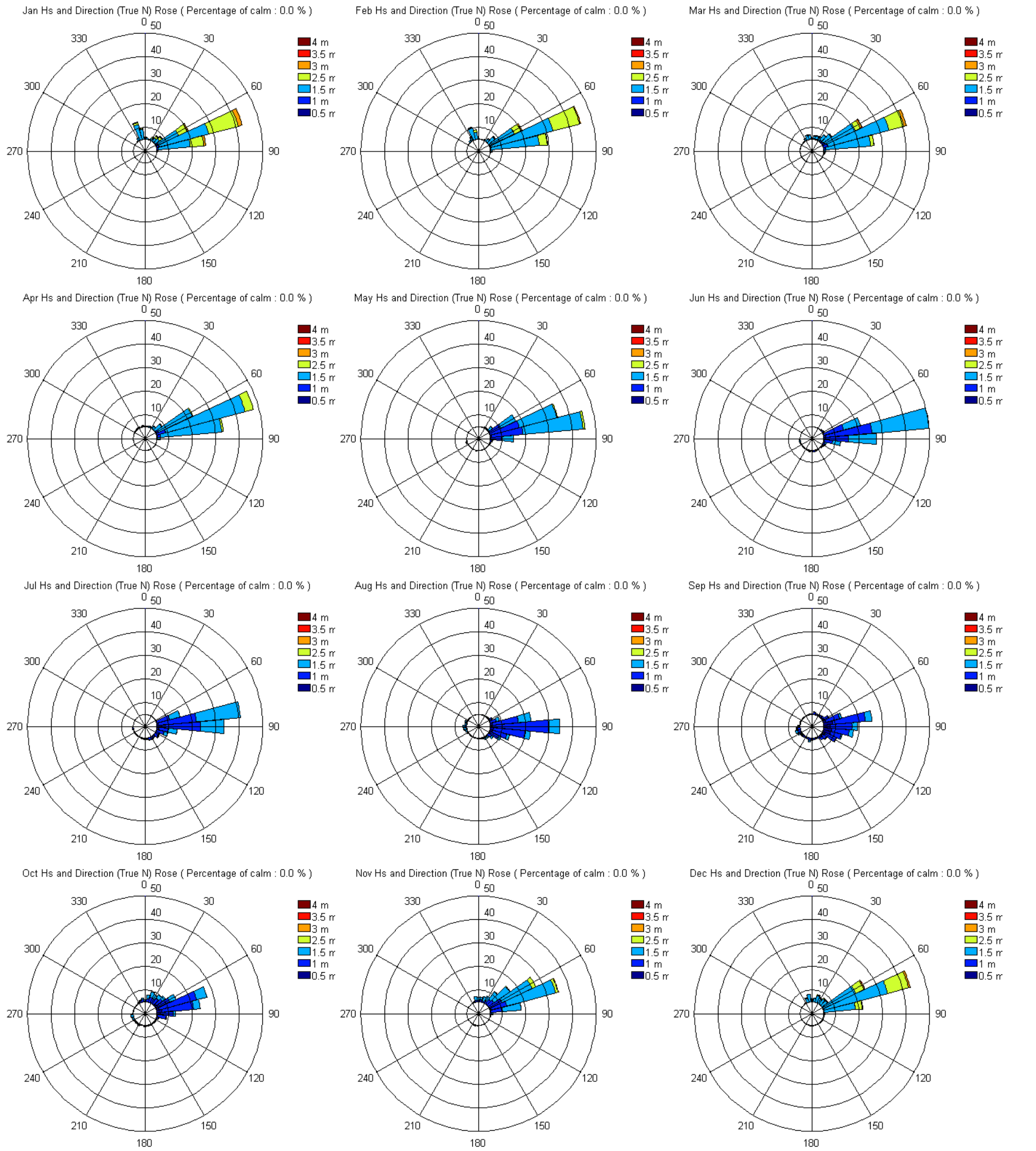


Figure A2.3 – Significant wave height (H_s) roses from monthly decomposition of MDI wave record from 1997-2010 for location south of Ailinglaplap Atoll (7°N 168.75°E).

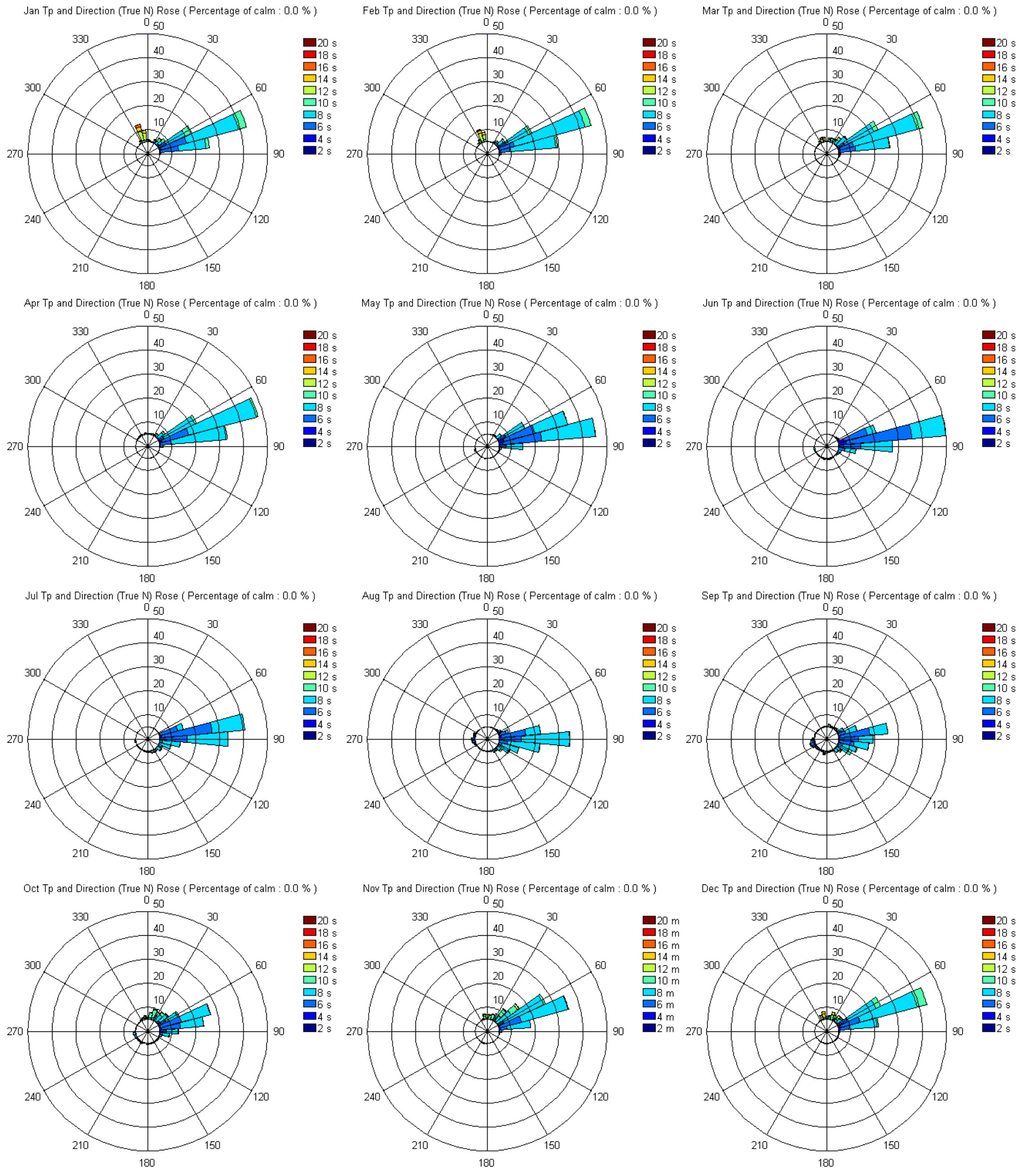


Figure A2.4 – Peak wave period (T_p) roses from monthly decomposition of MDI wave record from 1997-2010 for location south of Ailinglaplap Atoll (7°N 168.75°E).

APPENDIX 3 – SEASONAL WIND CLIMATE ANALSIS

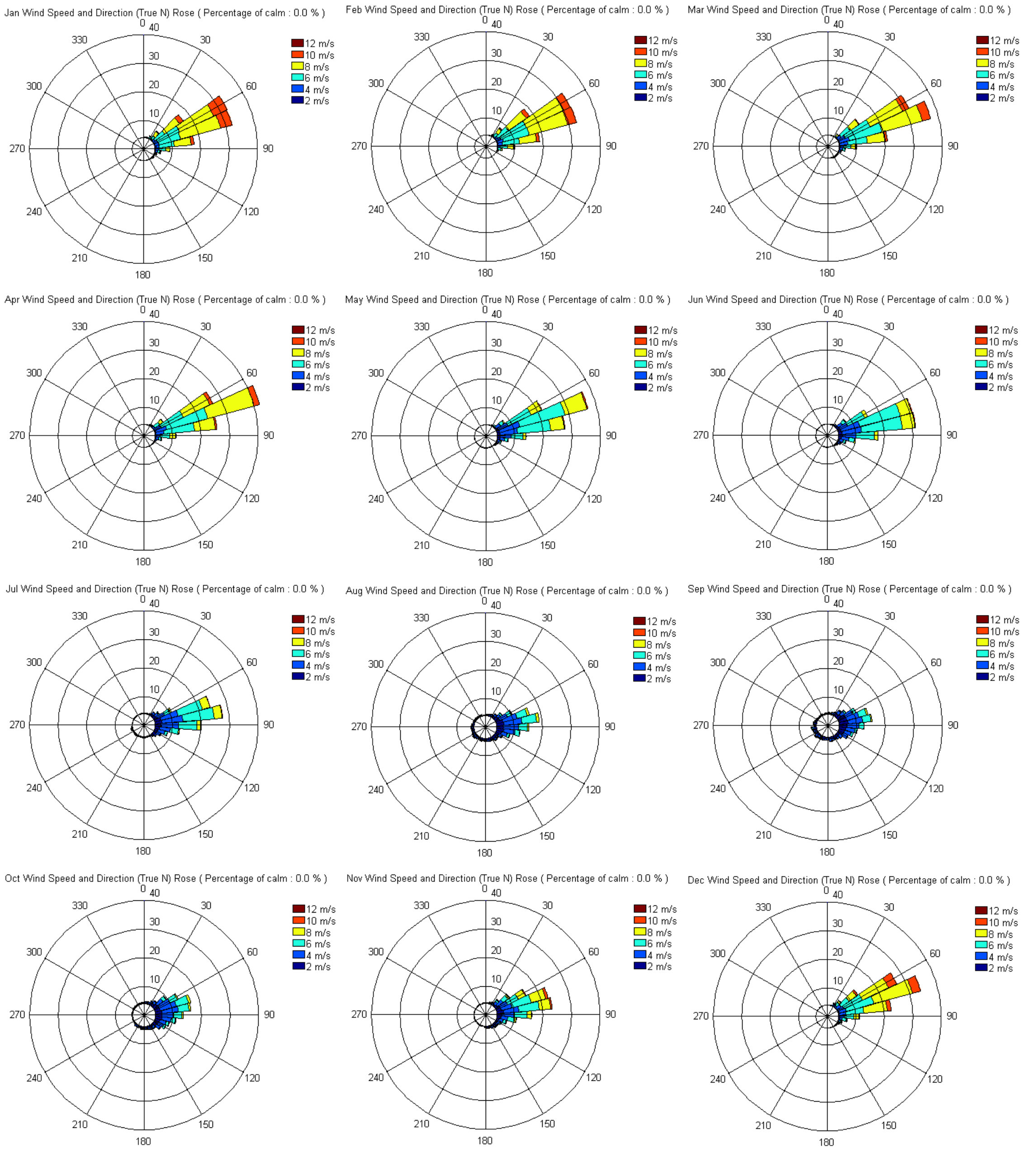


Figure A3.1 – Wind roses from monthly decomposition of MDI wave record from 1997-2010 for location north of Ailinglaplap Atoll (8°N 168.75°E).

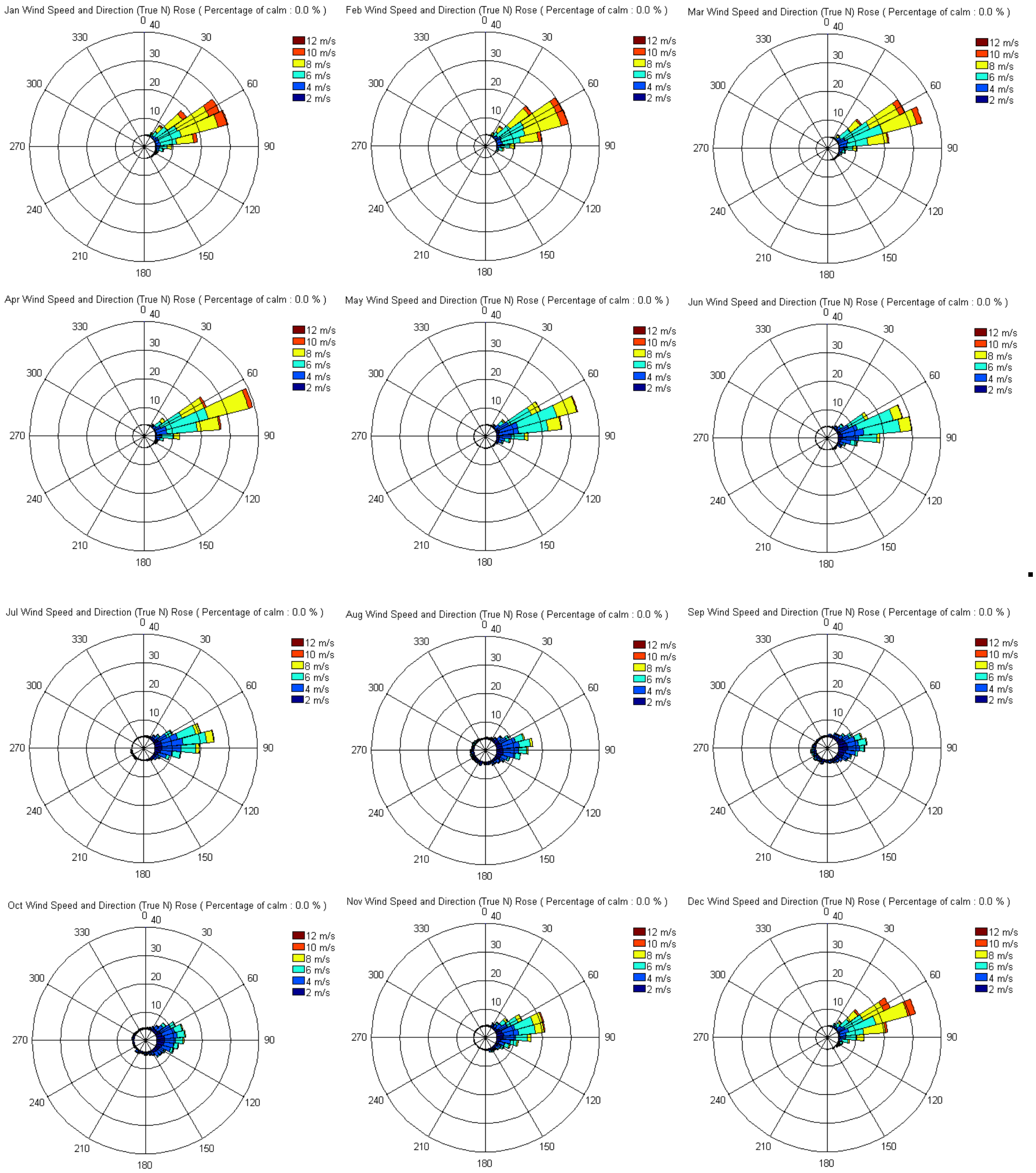
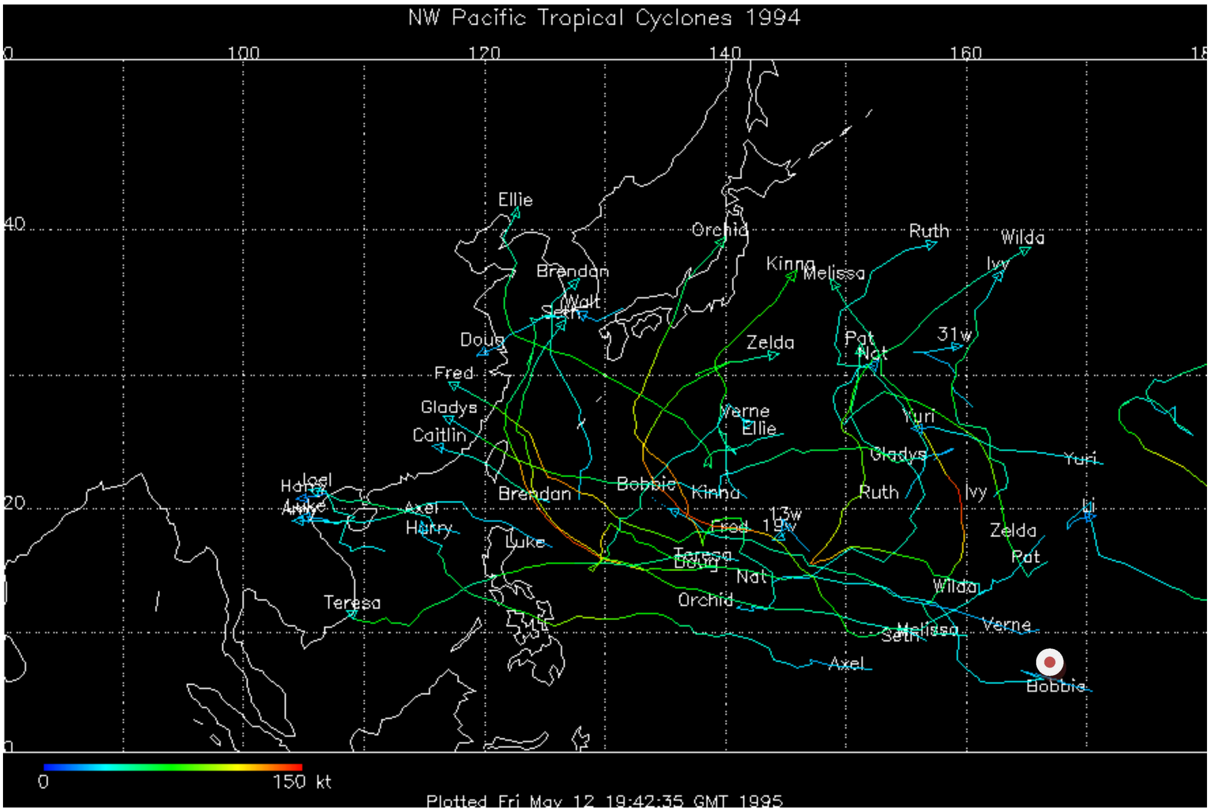
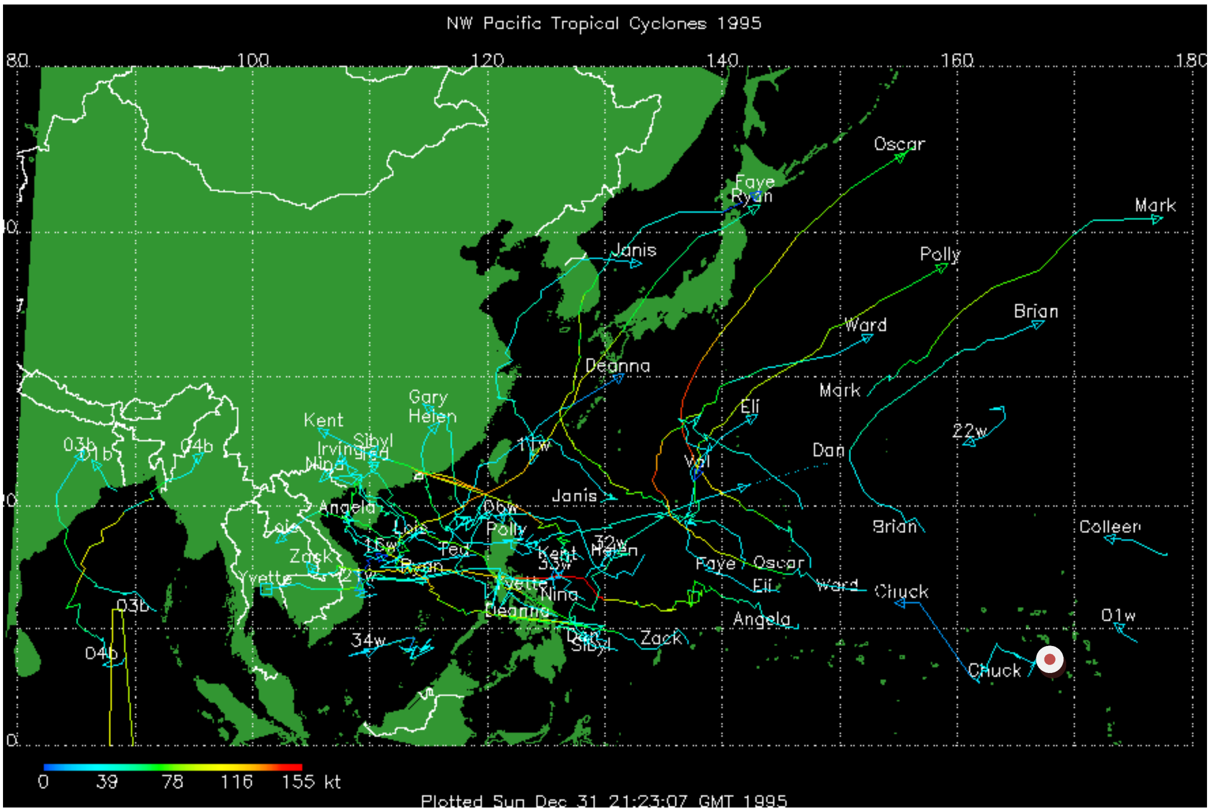


Figure A3.2 – Wind roses from monthly decomposition of MDI wave record from 1997-2010 for location south of Ailinglaplap Atoll (7°N 168.75°E).

APPENDIX 4 – ANNUAL STORM TRACKS 1994-2010 AND MONTHLY STORM TRACKS 1956-2006

The location of the Ailinglaplap Atoll is indicated with a red/white dot.




NW Pacific Tropical Cyclones 1995
0 39 78 116 155 kt
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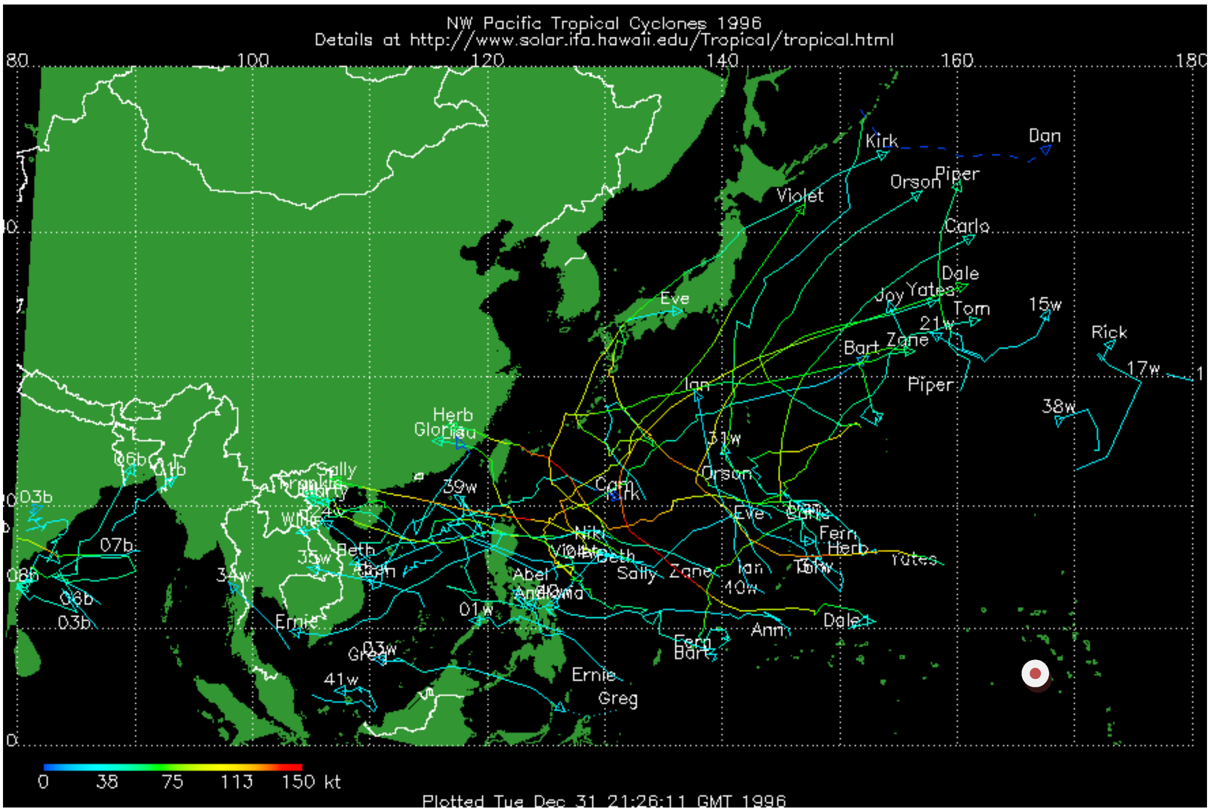
NW Pacific Tropical Cyclones 1996
Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
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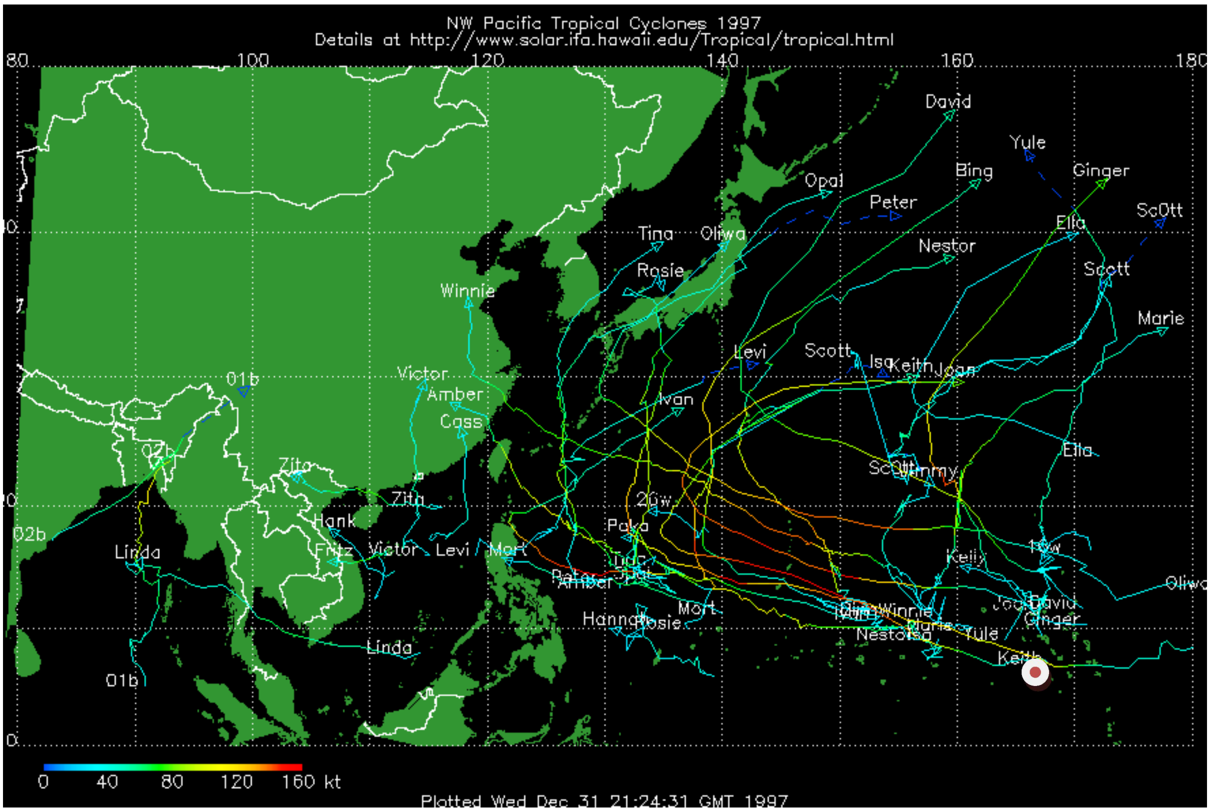
Plotted Tue Dec 31 21:26:11 GMT 1996


NW Pacific Tropical Cyclones 1997
Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
80
100
120
140
160
180
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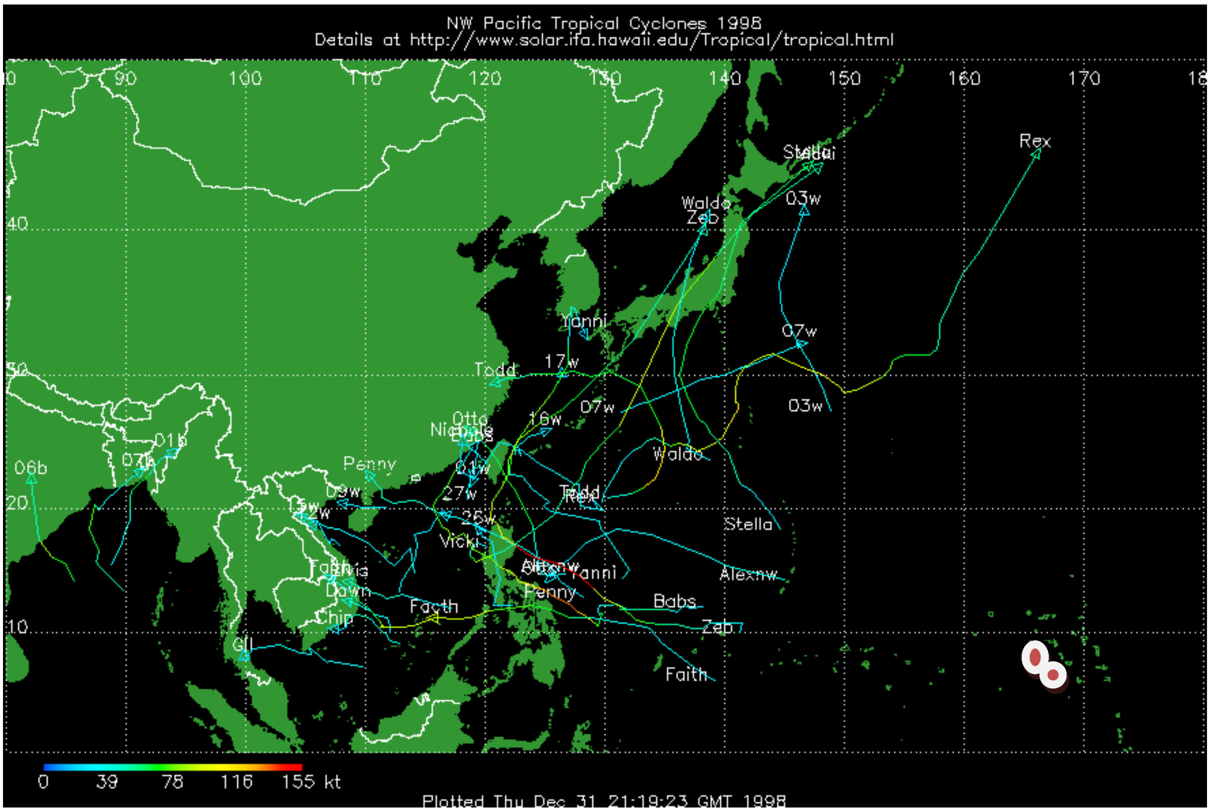
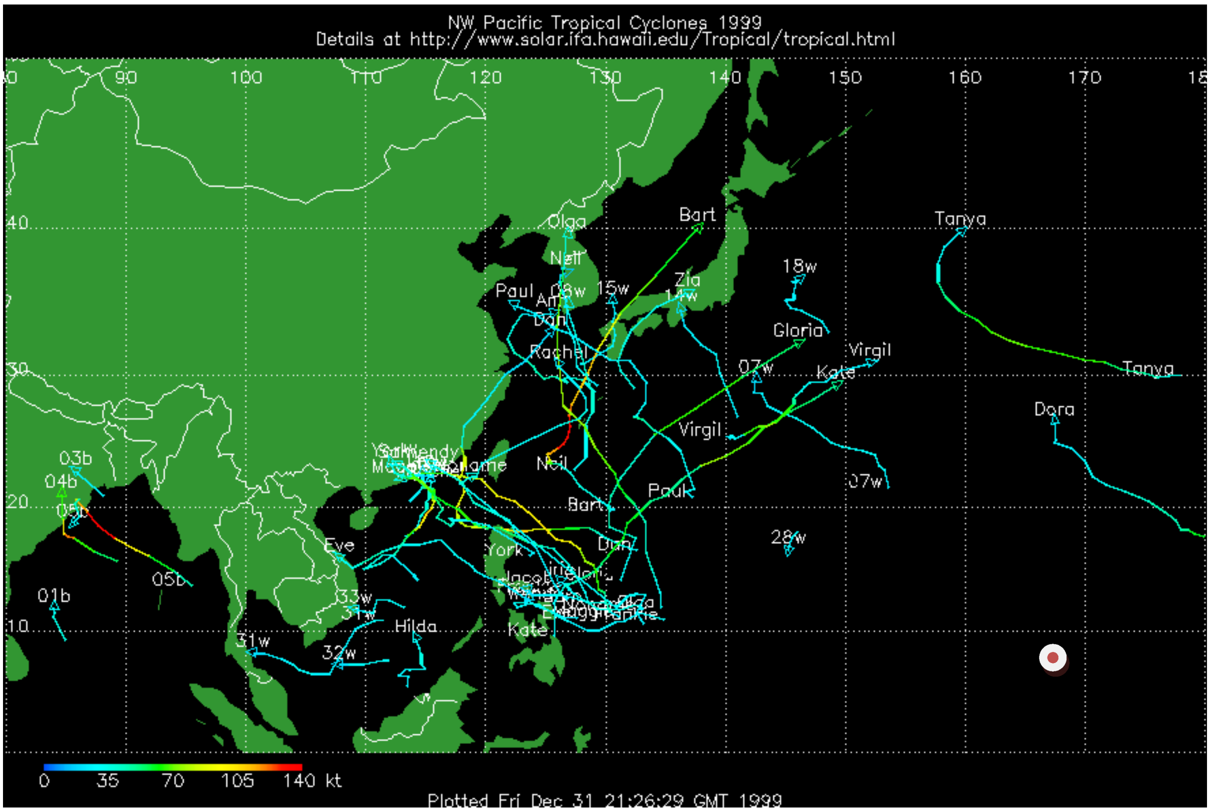
Plotted Wed Dec 31 21:24:31 GMT 1997


NW Pacific Tropical Cyclones 1998
Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
90
100
110
120
130
140
150
160
170
40
30
20
10
0 39 78 116 155 kt
Plotted Thu Dec 31 21:19:23 GMT 1998


NW Pacific Tropical Cyclones 1999
Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
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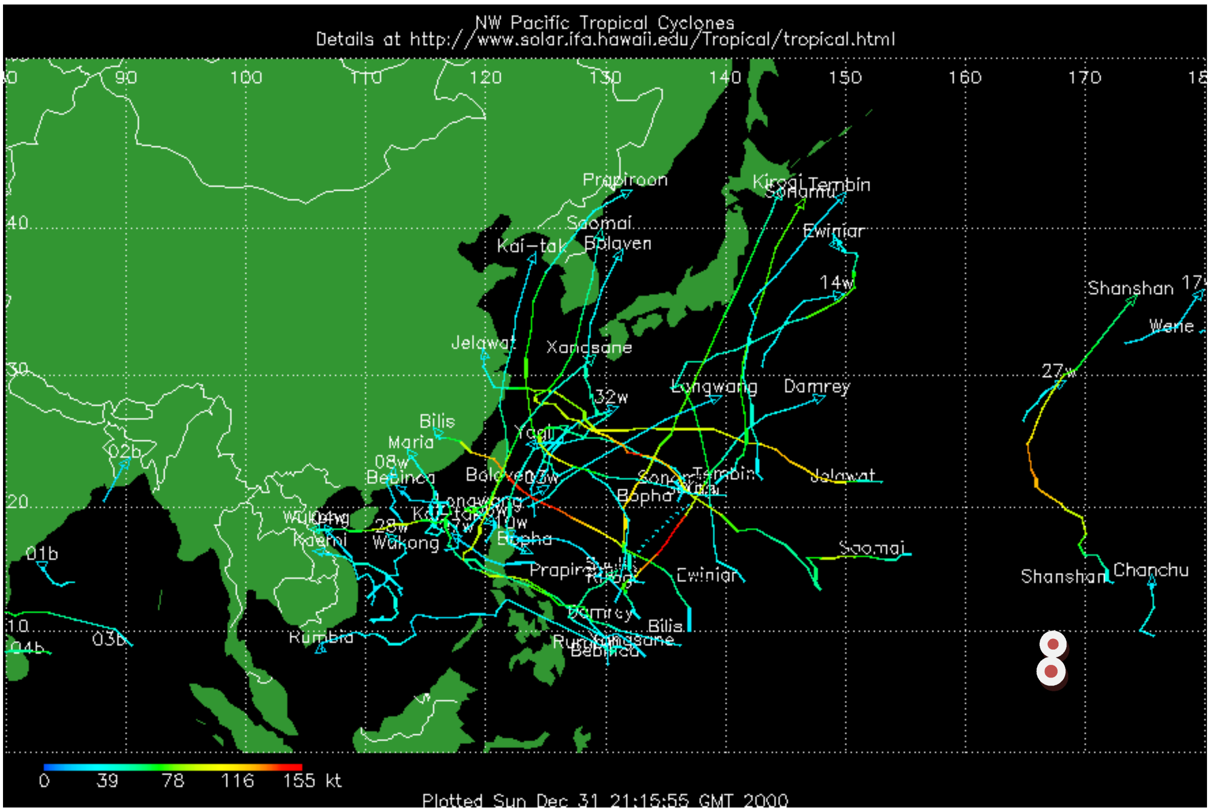
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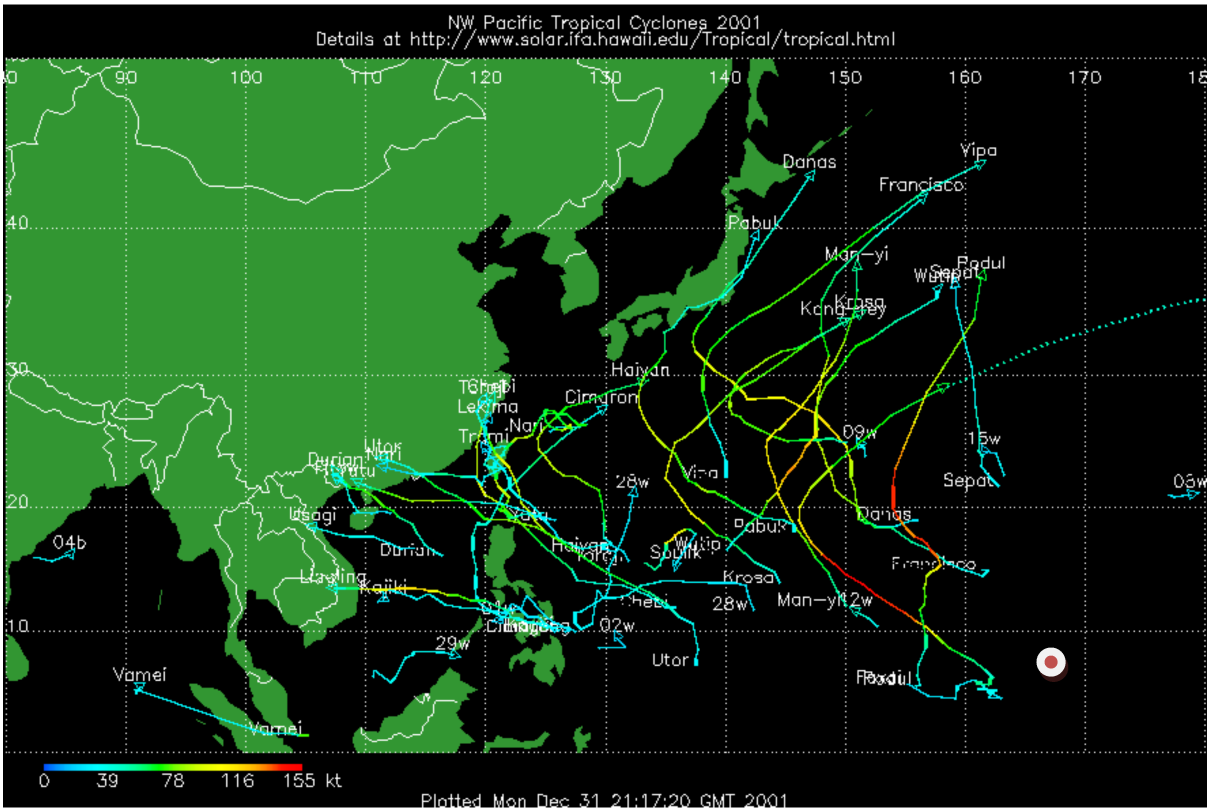
NW Pacific Tropical Cyclones 2001
Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
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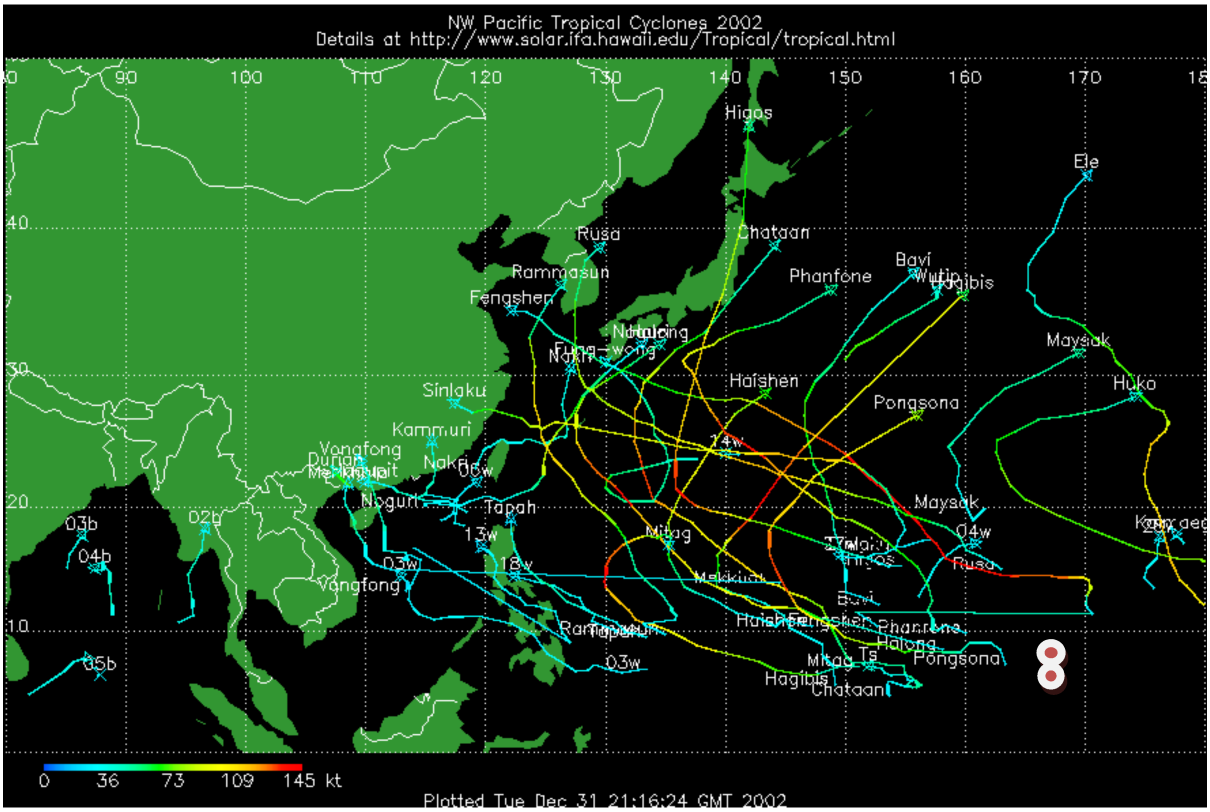
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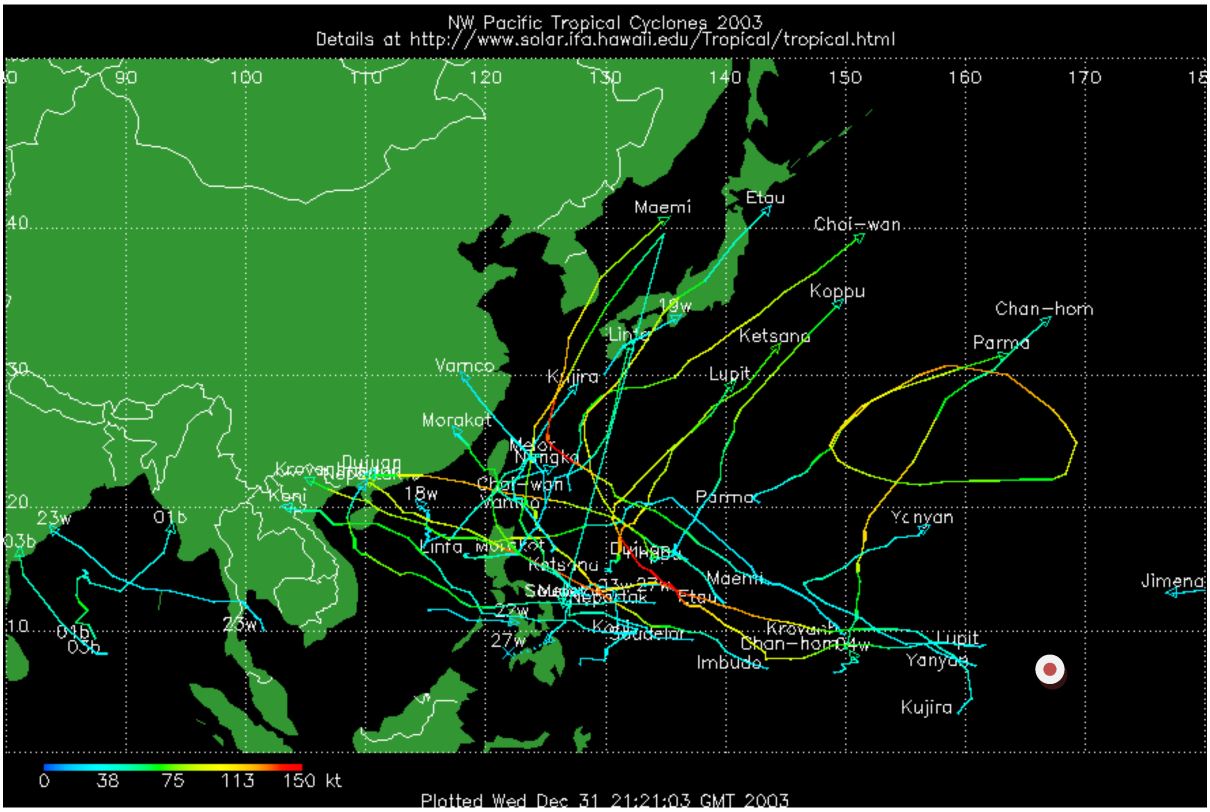
NW Pacific Tropical Cyclones 2003
Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
Maemi
Etau
Choi-wan
Koppu
Chan-hom
Parma
Ketsana
Lupit
Vamco
Kujira
Morakot
Parma
Yanyan
Jimena
Lupit
Yanyan
Kujira
Imbudo
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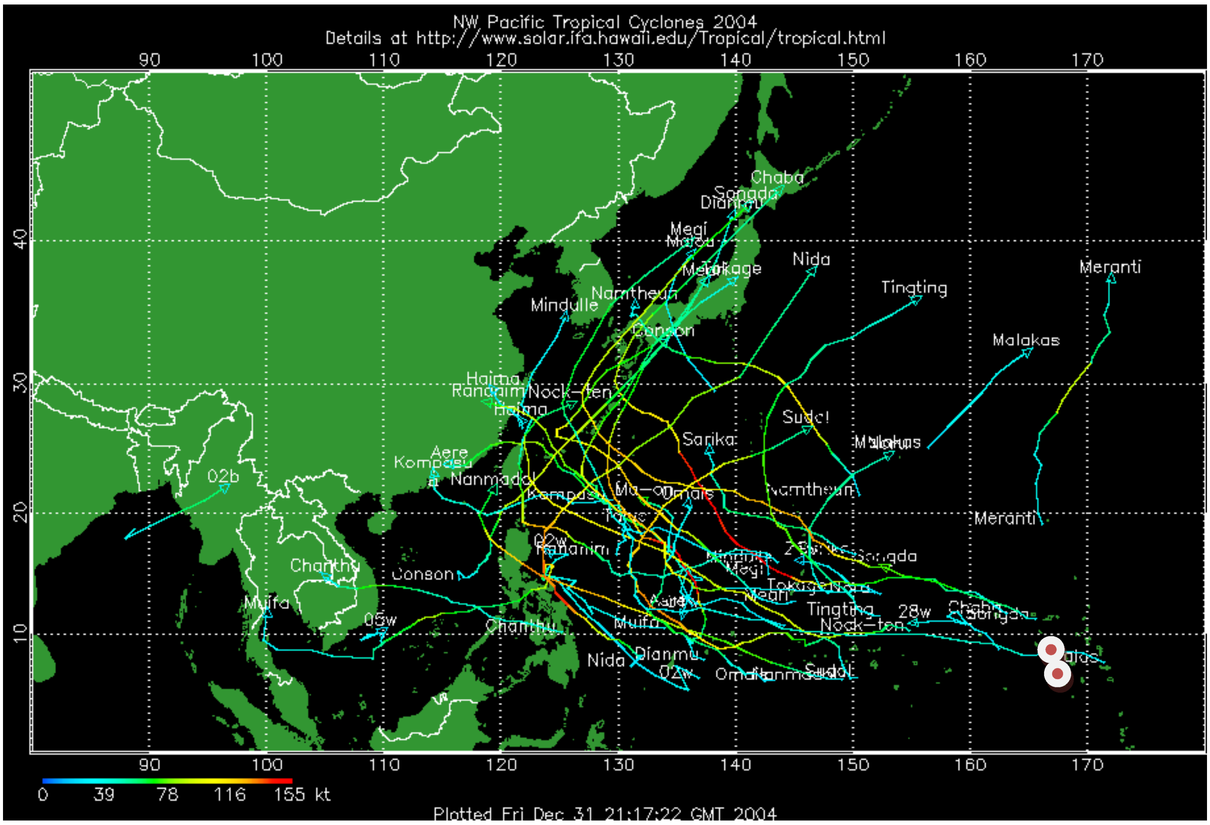
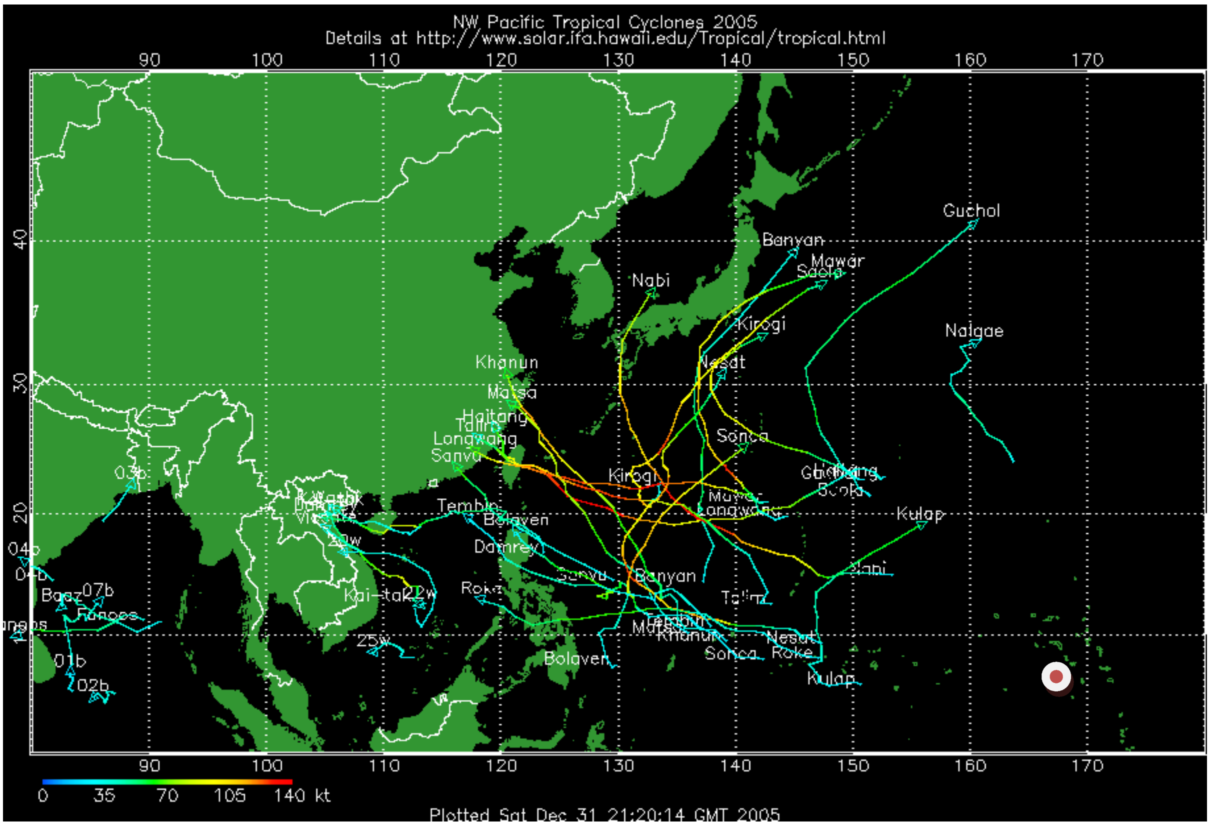
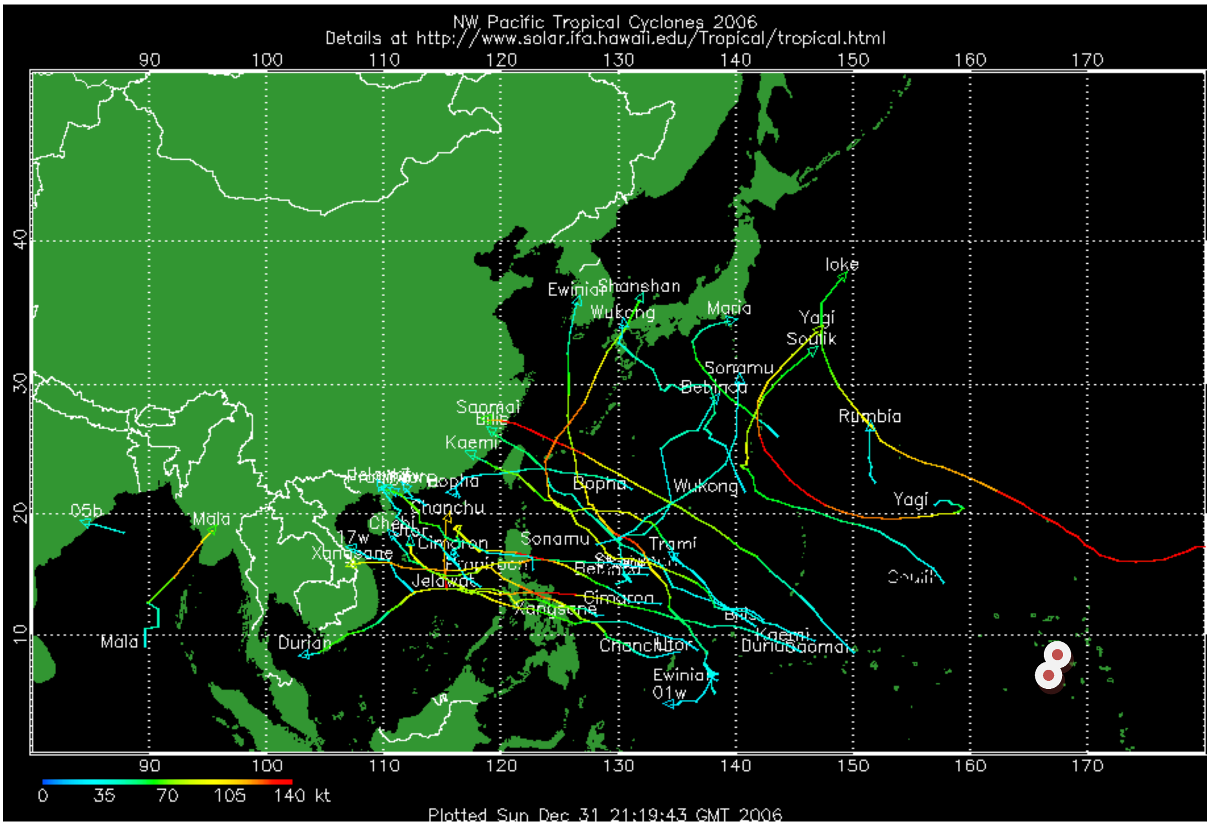
Plotted Wed Dec 31 21:21:03 GMT 2003


NW Pacific Tropical Cyclones 2004
Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
Chaba
Songda
Megi
Nida
Tingting
Meranti
Mindulle
Namtheun
Conson
Malakas
Sudal
Sarika
Chanthu
Conson
Muifa
Meranti
Nida
0 39 78 116 155 kt
Plotted Fri Dec 31 21:17:22 GMT 2004


NW Pacific Tropical Cyclones 2005
Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
90 100 110 120 130 140 150 160 170
40
30
20
0 35 70 105 140 kt
Plotted Sat Dec 31 21:20:14 GMT 2005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Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
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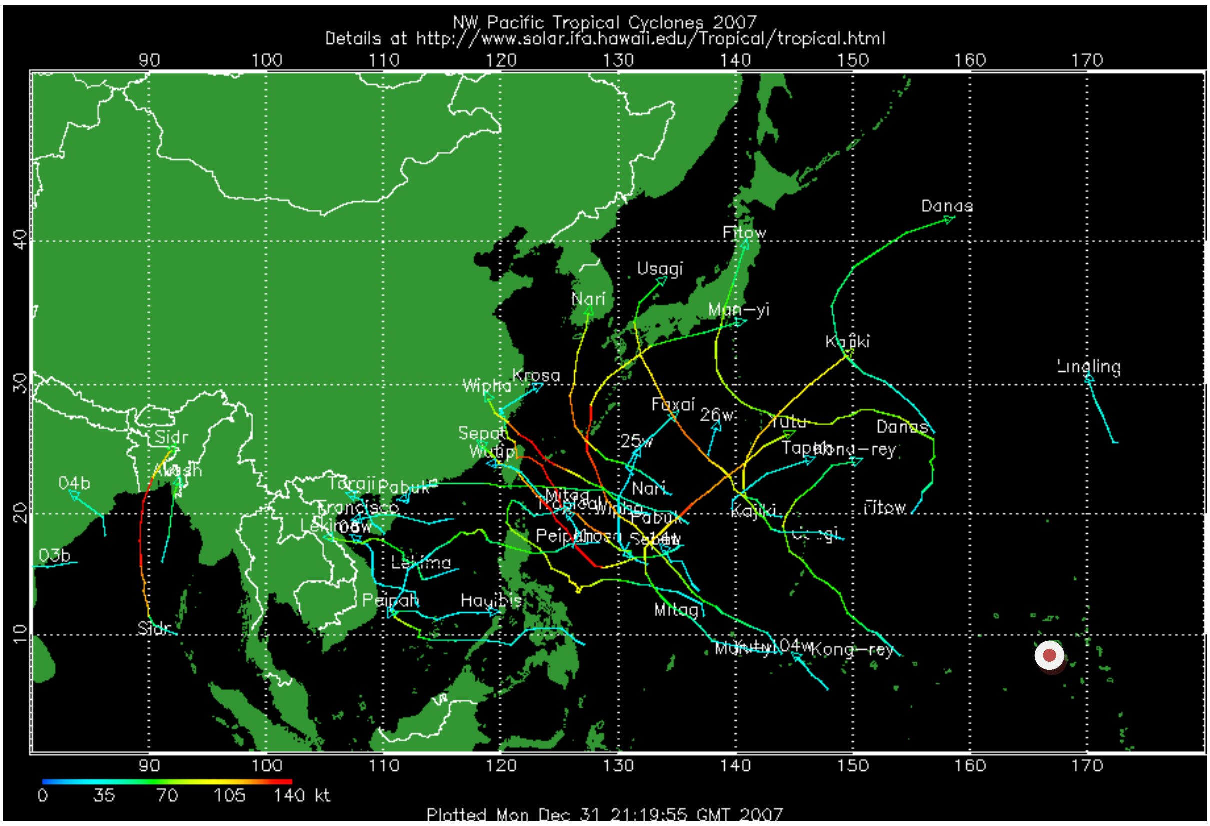
40
30
20
10
0 35 70 105 140 kt
Plotted Sun Dec 31 21:19:43 GMT 2006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Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
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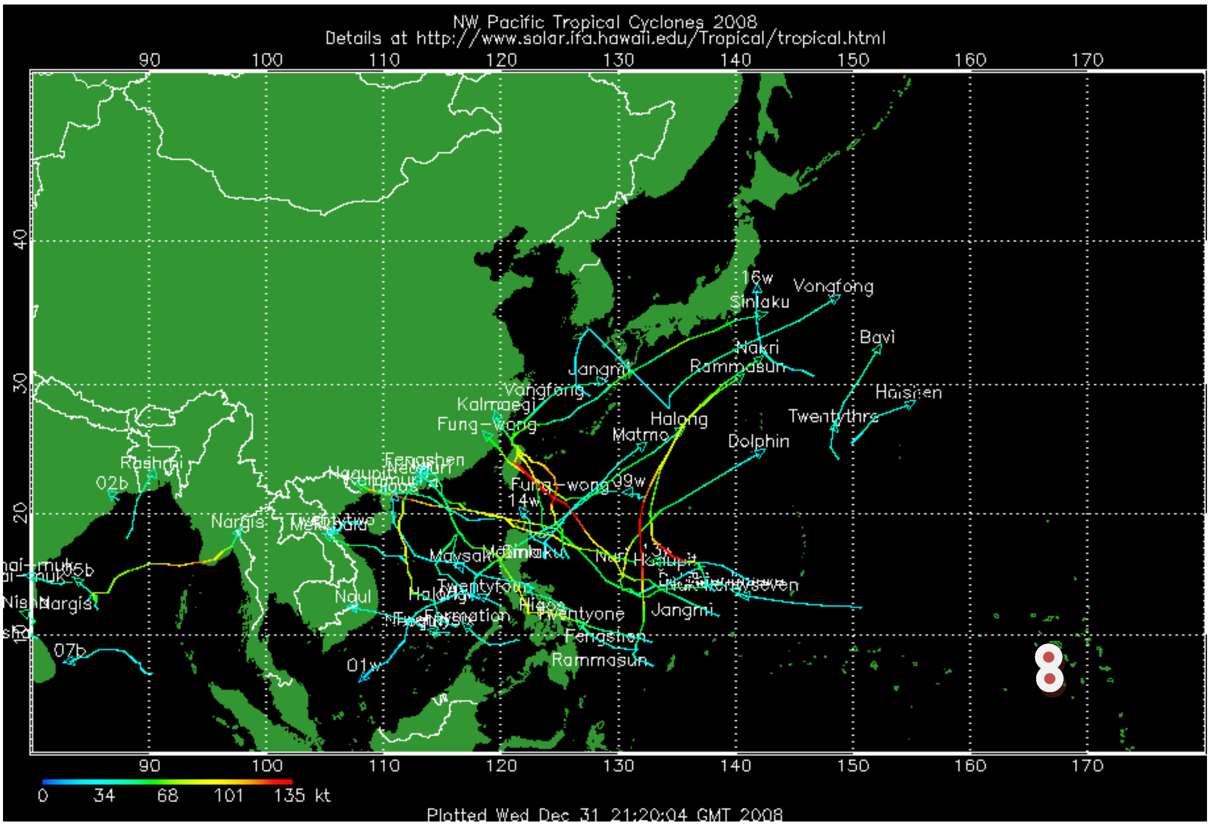
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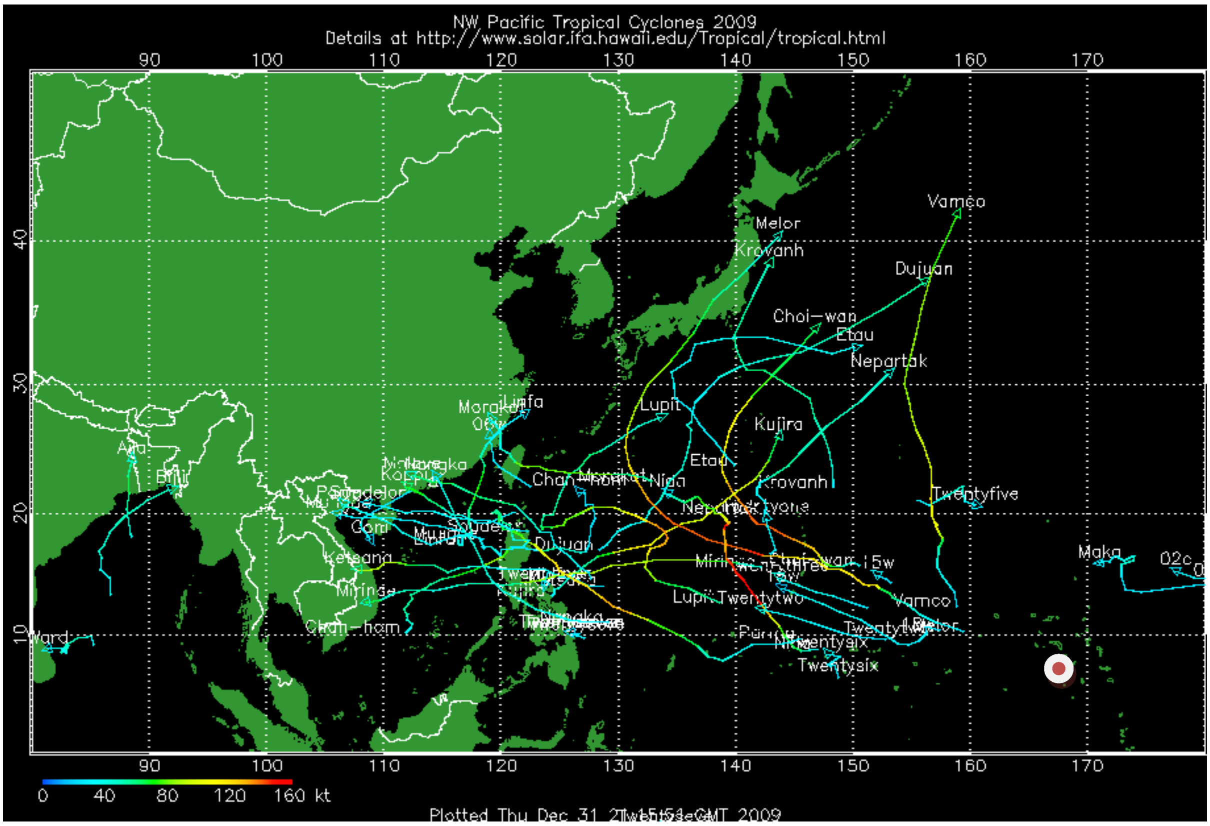
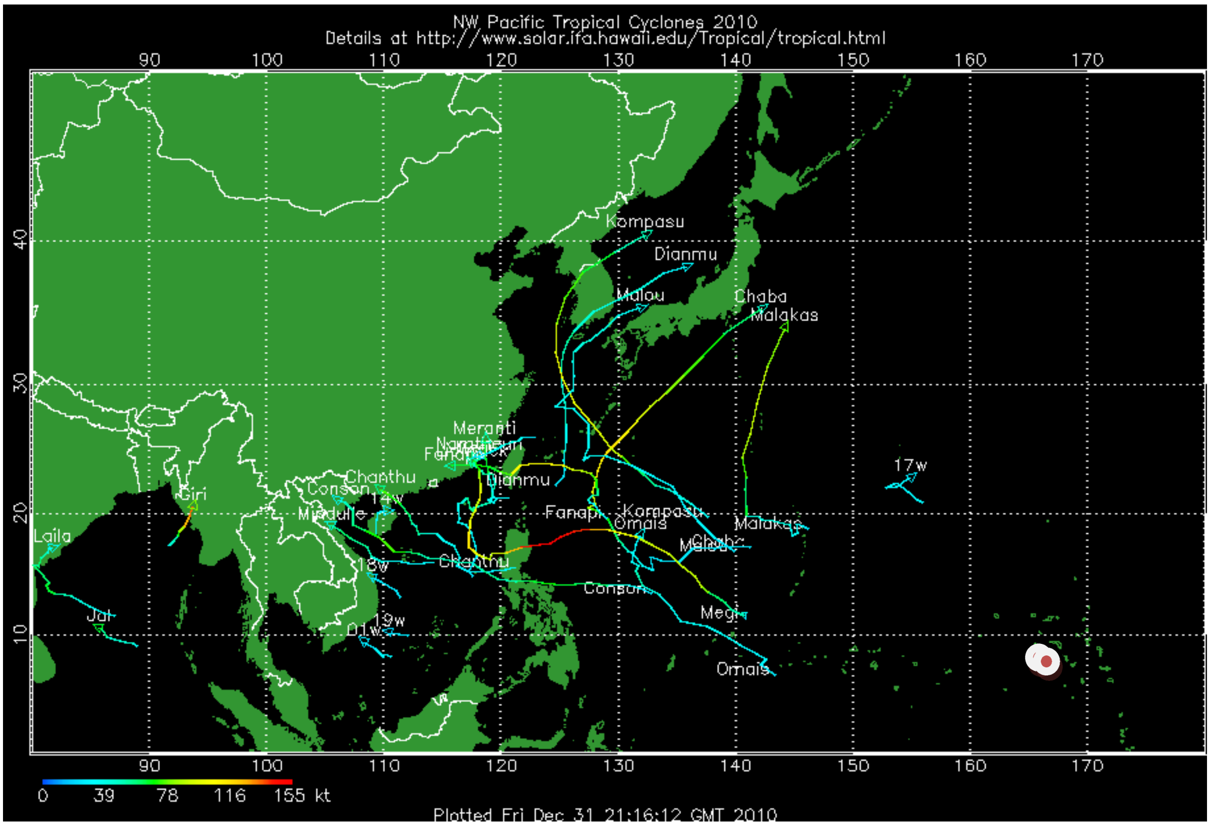

NW Pacific Tropical Cyclones 2009
Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
Vamco
Melor
Krovanh
Dujuan
Choi-wan
Etau
Nepartak
Lupit
Kujira
Linfa
Twentyfive
Maka
Lupit Twentytwo
Twentysix
Chan-hom
Ketsana
Mirinae
Ward
Aila
Bijli
0 40 80 120 160 kt
Plotted Thu Dec 31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Details at http://www.solar.ifa.hawaii.edu/Tropical/tropical.html
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Dianmu
Malou
Chaba
Malakas
Meranti
Chanthu
Conson
Mindulle
Giri
Laila
Jal
14w
18w
19w
01w
17w
Dianmu
Fanapi
Omais
Kompasu
Malakas
Chanthu
Conson
Megi
Omais
0 39 78 116 155 kt
Plotted Fri Dec 31 21:16:12 GMT 2010

APPENDIX 5 – BREIF TO CONTRACTORS FOR COST ESTIMATES

eCoast Marine Consulting and Research
PO Box 151
Raglan,
New Zealand.
Ph. +64 21 423 224
www.ecoast.co.nz
info@ecoast.co.nz

22 December 2013

Pacific International Inc.
PO Box 6
Majuro
Marshall Islands 96960

Dear Sir,

Re: Cost Estimate for the Construction of Woja Causeway, Ailinglaplap Atoll, RMI.

The following description of the construction project is supplied along with attached drawings for your company to kindly provide us with a cost estimate. The project was selected as a main priority for rehabilitation under the Global Climate Change Alliance: Pacific Small Island States project (GCCA: PSIS), and is currently in the detailed design stage and will be finalised early next year – a visit to RMI is planned in early February to finalise, which will swiftly be followed by construction to meet our time constraints.

There are 3 attachments:

1. Location photographs and maps. This document provides maps and photographs of the site and the location of suitable rock for construction.
2. 1st Priority Causeway construction drawing. This drawing provides a construction cross-section of first priority of the two parts of the causeway, which is a 100 m long causeway designed at 3.0 m above lowest astronomical tide. This part of the causeway is vulnerable to erosion from the lagoon side, as has already occurred to the north. At this height (3 m) the causeway will be over-topped by waves during only very extreme events (an Irish crossing design). The new causeway is to be located 15 m west of the existing vulnerable road.
3. 2nd Priority low road area. This drawing provides a construction cross-section of second priority of the two parts of the causeway, which is a 150 m long elevated road designed at 3.0 m above lowest astronomical tide. This part of the causeway is currently flooded by the tide during high tides, although is not vulnerable to erosion or large wave attack, and as a result the rock armour is significantly smaller than for the priority 1 site. The elevated road will follow the path of the existing road.

The basic construction components for the 1st Priority site are considered as follows:

1. Mobilization of equipment and transport to Woja at Ailinglaplap Atoll.
2. Site survey and set out.
3. Construction working from the north to the south, completing parts of the new causeway a piece at time, which will incorporate:
    a) Excavation down to 0.0 m (lowest astronomical tide, or rock pavement (it is likely that rock will be encountered at a higher elevation that 0.0 m in many areas).
    b) Laying of geotextile foundation (1200 gsm).
    c) Construction of the causeway core using the excavated material (sand/gravel), which has 1.5:1 (H:V) sloping sides.
    d) Laying of geotextile material over the core (1200 gsm) to prevent chronic winnowing of fine material and subsequent failure of the structure.

e) Collection and placement of 0.6-0.9 m diameter rock at a thickness of 1200 mm on either side of the core. An abundant supply of easily accessible rock is located 5 km to the north of the site on the west coast of Woja.
f) Placement of road surface on top of the 3.5 m wide causeway (broken coral, as is used for roading all around the island).

4. Transportation back to Majuro and demobilisation.

If funds are sufficient to undertaken construction of the 2nd Priority site – elevated road – then it would be undertaken before the 1st Priority site since it is north of the 1st Priority site and so would provide better construction access (all tide).

The tide level is a consideration for the construction project:

1. Construction will likely to be possible over a 6 hr period each day because of the site will be underwater from mid tide.
2. Rocks will only be able to be removed from the north western site for 2-3 hours each low tide.

To assist with your costing, the following volumes have been calculated:

	Rock volume (m^3)	Excavation Volume (m^3)	Core Volume (m^3)	Roadtop volume (m^3)	Geofabric (m^2)
Priority 1	700[a]	1,100	1,200	175	2,250[c]
Priority 2	450[b]	800	1,300	150	2,700[d]

a) 0.6-0.9 m diameter
b) 0.3-0.5 m diameter
c) 1,200 gsm
d) 800 gsm

A simple breakdown of all costs with any contingencies will provide the necessary input to determine what components of the project can be constructed with in the available budget and allow for further funds to be sought if necessary.

Thank you in advance for your assistance. If you require any further information, please contact me via email.

Kind regards

Dr. Shaw Mead s.mead@ecoast.co.nz
Managing Director