Reducing the risks of cyclone storm surge inundation on the atolls of Tokelau:

An overview of cyclone-related coastal hazards

NIWA Client Report: HAM2005-120
July 2005

NIWA Project: UNS05201

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Doug Ramsay

Prepared for

United Nations Development Programme

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National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road, Hamilton
P O Box 11115, Hamilton, New Zealand
Phone +64-7-856 7026, Fax +64-7-856 0151
www.niwa.co.nz

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Reviewed by:

Dr Malcolm Green

Approved for release by:

Dr Rob Bell

Formatting checked

A. Bartley

Executive Summary

On 25 February 2005 Tropical Cyclone Percy affected the atolls of Tokelau. The cyclone was of category 3 intensity as it passed around 100 km to the south west of Tokelau, intensifying further as it past through the northern Cook Islands with sustained winds measuring from 178 to 249 km/hr. The cyclone resulted in widespread damage, particularly on Fakaofo and Nukunonu. On Nukunonu the storm surge and large waves resulted in overwashing of many parts of the motu. Inundation was also an issue on parts of Atafu and Fakaofo.

This report is one in a series prepared from on-atoll discussions and assessments of cyclone induced coastal hazards on each of the atolls of Tokelau. It provides a summary of known cyclone hazard and associated coastal hazard information to assist with future on-island decision making, education and awareness activities, and to provide potential design conditions for future coastal engineering works.

The review identified that:

1. Cyclone occurrence affecting the atolls of Tokelau is strongly influenced by interdecadal climate variability, with all cyclones that have significantly impacted on the three atolls occurring during El Niño periods.

2. There are few details of cyclones affecting Tokelau before the Great Cyclone (*Afa Lahi*) in 1914. Over the last century there have been approximately 10 cyclones that have caused significant damage to one or more of the Tokelau atolls, with the events of 1914 and 1966 most notable. A number of other cyclones have tracked within 300 km of the atolls but have caused less damage.

3. Of the cyclones that have affected Tokelau, three general patterns of tracks were identified:

   - The first set is characterised by Cyclones Tusi, Ofa, Val and Percy, which formed in southern Tuvalu and tracked eastwards before moving in a south easterly direction to the west of Tokelau. The inhabited motu are affected by high winds and high waves during this type of cyclone.

   - The second set is characterised by Cyclones Esau, Wini and the cyclone in 1966. This type tracks in an easterly direction well to the south of Tokelau close to Wallis and Futuna and Samoa. Winds tend not to reach hurricane force on Tokelau, but high swell waves emanating from the cyclone can affect the western coastlines of the atolls for prolonged periods.

- The final set is characterised by Cyclones Bob, Collette, Keli and Ron. This type either passes close to Tokelau but tracks in a south west direction, or forms to the south of Tokelau and hence does not appear to cause significant damage to the inhabited sections of the atolls.

4. Over the period 1969 to 2005 there was about a 15% chance of one or more cyclones in any one year causing significant damage on one or more of the atolls of Tokelau. This likelihood was higher than the average over the period 1914 to 2005 which was about a 10% chance of one or more cyclones in any one year.

5. The potential effect of future climate change on the occurrence, strength and movements of tropical cyclones close to Tokelau is uncertain with present studies suggesting that peak wind intensities may increase by 10-20%. However, over the next 20 or so years the Interdecadal Pacific Oscillation is expected to be in a negative phase. This would tend to increase the occurrence of neutral or La Niña conditions, which may decrease the occurrence of cyclones affecting Tokelau compared to the last 20 to 30 years. In the longer term, increased sea-surface temperatures may increase the number of cyclones forming and tracking close to Tokelau.

6. Of the ten most significant cyclones, five coincided within two days of a spring tide. However, significant damage can still occur when a cyclone coincides with lower tidal ranges, as occurred during the 1966 event.

7. Extreme water levels experienced during cyclones are a combination of a number of factors:

    - The astronomical tide with a spring range of 0.98 m and neap range of 0.59 m. Mean High Water Springs (MHWS) is exceeded by around 33% of all high tides and is approximately 1.15 m above the level of the reef flat, with the highest tide around 1.35 m above the reef flat level.

    - Long-period sea-level fluctuations, including annual (seasonal heating and cooling), interdecadal (El Niño Southern Oscillation), and decadal (IPO related). These can cause long term fluctuations in sea level of around ±0.25 m, with higher mean sea-levels occurring during late summer, a strong La Niña and –ve phase of IPO.

    - Storm surge, caused by the combination of low atmospheric pressure and strong winds. These typically cause a relatively low increase in water levels in the ocean <u>unless</u> the cyclone tracks relatively close (< 50 km) to any of the atolls. For example, the storm surge caused by Cyclone Percy would have been around 1 to 1.2 m close to the centre of the cyclone, but was only around 0.2 m to 0.3 m at Tokelau.

- The most significant influence on extreme water levels during cyclone events is typically due to wave set-up caused by waves breaking on the edge of the fringing reef. Wave set-up processes are extremely complex, varying both spatially along a section of coast, and temporally due to the particular wave spectrum and effects of wave grouping. Wave set-up during Cyclone Percy was estimated to have typically fluctuated between 1 to 2 m and up to 3 m during the largest wave grouping events.

- Mean sea levels in the Pacific region have risen about 0.16 m over the last century. This rate is expected to accelerate over the next century due to the effects of global climate change. Latest estimates give a “most likely” rise of 0.14-0.18 m by 2050 and 0.31-0.49 m by 2100. An important point to note is that this acceleration is unlikely to be discernible from the year-to-year variability in mean sea levels for at least another 20 to 30 years.

8. A design wave and water level condition has been derived based on estimates of conditions during Cyclone Percy, which is estimated to be around a 15-year return period event. This suggests:

    - An offshore significant wave height of 6 m and peak wave period of 12 s.

    - A design water level (astronomical tide + storm surge + wave set-up) of 3.05 m above reef flat level.

    - A depth limited significant wave height of 1.7 m on the reef flat.

9. Such design conditions should be satisfactory for the design of future coastal protection structures. However, it is recommended that a more rigorous assessment be conducted for larger capital investment projects requiring such information, e.g., any proposed wharf.

10. The effects of the small boat channels exacerbating localised damage during cyclone events are not well understood. However, it would appear that the channel at Nukunonu does have a detrimental influence.

11. A number of suggestions are provided that would aid ongoing activities relating to both this project and the UNDP funded Strengthening Disaster Management and Preparedness project. These include:

    - Recording recollections of past cyclones, particularly those that occurred longer than 20 – 25 years ago.

- Developing a methodology for each atoll community to systematically record the damage that occurs during a cyclone.

- More detailed numerical modelling of cyclone storm surge and wave conditions to improve both design conditions and aid forecasting and warning systems for future events.

1. Introduction

1.1 Background

On 25 February 2005 Tropical Cyclone Percy affected the atolls of Tokelau (Figure 1). The cyclone was of category 3 intensity as it passed around 100 km to the south west of Tokelau (the only wind measurement available was the 3 hourly recording at Nukunonu which recorded 59.3 km/hr at 03:00 NZST on the 27 February) with the cyclone going on to intensify as it past through the northern Cook Islands with sustained winds measuring from 178 to 249 km/hr. The cyclone resulted in widespread damage, particularly on Fakaofo and Nukunonu. On Nukunonu the storm surge and large waves resulted in overwashing of many parts of the motu[1]. Inundation was also an issue on parts of Atafu and Fakaofo.

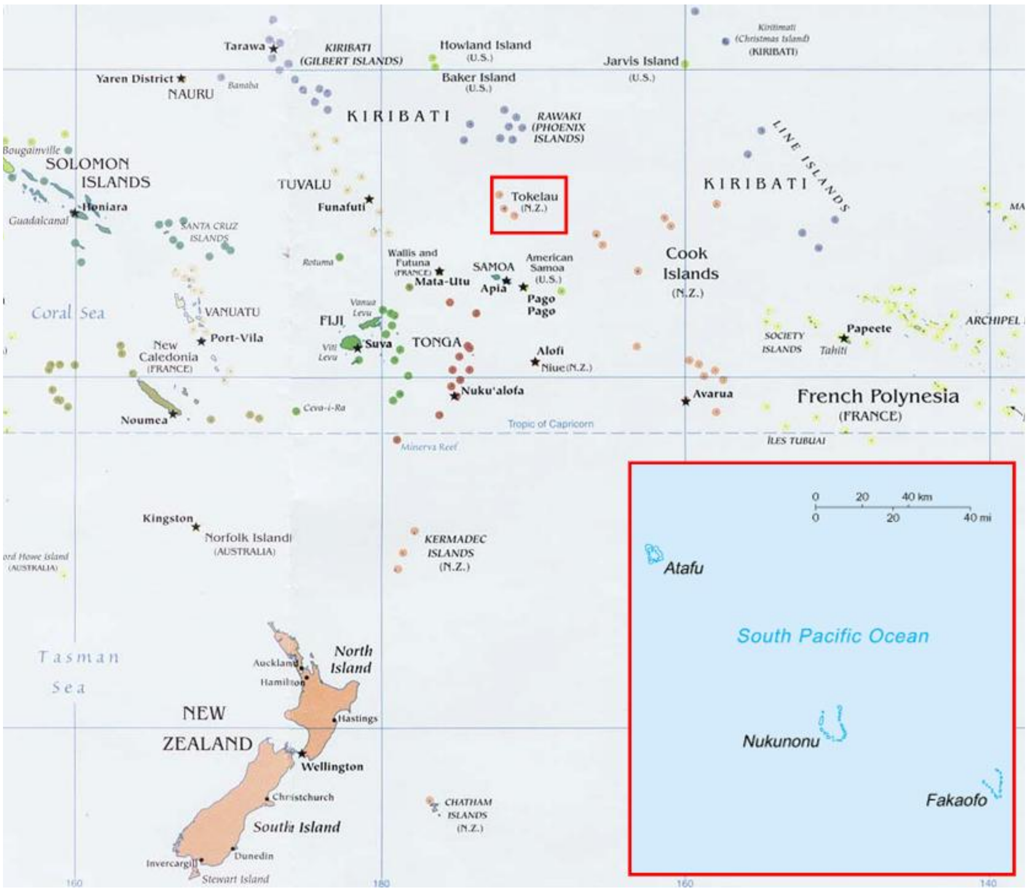

Figure 1: Location of the three atolls of Tokelau.

[1] Small islet on an atoll.

In the aftermath of Cyclone Percy, the United Nations Development Programme (UNDP) in Samoa commissioned NIWA to provide technical support to the Government and people of Tokelau to assist in the future reduction of coastal hazard risks, particularly those associated with cyclonic storm surge and wave overtopping and inundation (known as the Tokelau Seawall Project).

The objectives of the study were reviewed and discussed with the UNDP as part of the project inception assessment and subsequently the scope was widened with the primary goal *to reduce risk of loss of life, damage to coastal infrastructure and coastal environmental areas from the devastating impact of storm surge from cyclones* (UNDP, 2005). Rather than focus primarily on seawall structures, the project looked to identify a range of both short term and longer term objectives and activities for achieving effective risk mitigation of cyclone related inundation and other coastal hazards, over the long term which were technically, economically and environmentally sound and sustainable.

The in–country consultation and assessments were conducted between 05 July and 13 July 2005 by Mr Doug Ramsay, NIWA, assisted during the visit to Tokelau by Mr Heto Puka, Manager of Finance, Tokelau Apia Liaison Office. The scheduled passenger and cargo ferry MV Tokelau was used to transport the project team, with up to 2 days spent on each atoll. On each atoll an initial meeting was held with the Council of Elders (*Taupulega*), followed by discussions with the Women's Group (*Fatupaepae*), working or married men (*Aumaga* or *Taulelea* respectively) and a further, more detailed discussion, with the *Taupulega* at the end of the visit. A full walkover survey and collection of building and infrastructure information was also conducted. Details of the visit schedule and summary of the discussions are provided in the de-briefing report (Ramsay, 2005b).

1.2 Overview of the outputs of the study

This document is one in a series of reports prepared as part of the study. It provides a technical review of known cyclone and associated coastal hazard information for Tokelau. The report tries to fulfil a number of functions:

1. Provide a resource document summarising known information on tropical cyclones and coastal hazards to increase awareness on the occurrence and characteristics of such phenomena.

2. Be of sufficient technical detail to provide recommendations for wave / water level conditions for use in the development of future coastal engineering related designs. Note: the scope of this project does not permit detailed numerical modelling of cyclone wave and water level conditions.

3. To identify any gaps in our understanding of cyclone related coastal hazards which may need to be addressed as part of the Government of Tokelau's disaster management activities.

Other reports developed as part of this study include:

- An inception report completed prior to the trip to Tokelau (Ramsay, 2005a).
- A De-briefing report, summarising the visit and discussions held in Samoa and Tokelau (Ramsay, 2005b).
- A report for each of the three atolls detailing options and recommendations for reducing cyclone storm surge inundation risks for both the short and long term.

2. An overview of tropical cyclones affecting Tokelau

2.1 Tropical cyclone formation and occurrence in the south-west Pacific

Tropical cyclones require huge amounts of energy to survive, and will form only over specific regions of the globe's tropical oceans, where conditions are right for their formation and development. In the south-west Pacific these frequently develop within a trough of low pressure on the northern side of the South Pacific Convergence Zone (SPCZ), where cyclonic wind shear is greatest (Figure 2). The SPCZ is an area of wind convergence and enhanced rainfall between the low latitude easterly trade winds, and the higher latitude south-easterly trades. It is a semi-permanent feature of the southern hemisphere tropical circulation. From time to time troughs and depressions develop. During December – February the SPCZ lies from near Vanuatu to midway between Samoa and Northern Tonga to the South Cook Islands. As well as forming on the northern side of the SPCZ, favourable conditions for cyclones usually require sea-surface temperatures of at least 26-27°C. Once they form these systems typically move south west, before turning and moving south east. However, north of about 25°S, their tracks can be quite unpredictable apart from a general southward movement.

Classification of tropical cyclones differs according to the region. For the southwest Pacific a tropical cyclone is defined as a tropical low-pressure system with an organised wind circulation intense enough to produce sustained gale force winds (at least 34 knots or 63 km/hr) near its centre, (Table 1), with a severe tropical cyclone producing sustained hurricane force winds (at least 64 knots or 118km/hr), and which corresponds to the hurricanes or typhoons in other parts of the world.

Table 1: Tropical cyclone intensity classification for the South Pacific.

Classification	Windspeed (knots)	Windspeed (km / hr)	Windspeed (m/s)
Tropical depression	< 34	< 63	17
Tropical Cyclone (Gale)	34 – 47	63 – 87	17 – 24
Tropical Cyclone (Storm)	48 – 63	88 – 117	25 – 32
Severe Tropical Cyclone (Hurricane)	64 +	118 +	33 +

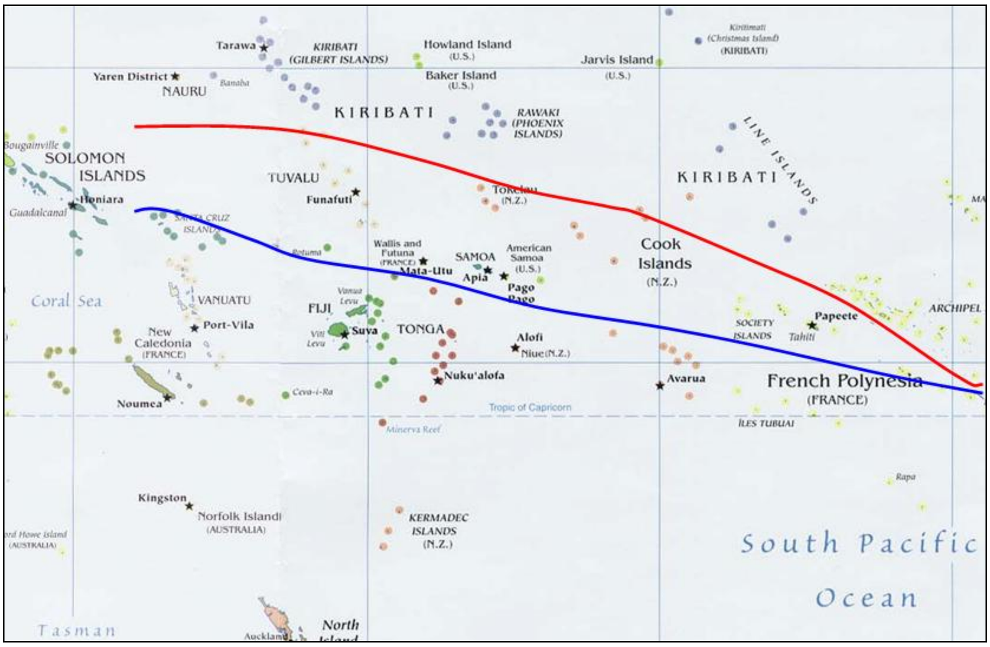

Figure 2: Approximate position of the South Pacific Convergence Zone in winter (June - August) – red, and in summer (December – February) – blue.

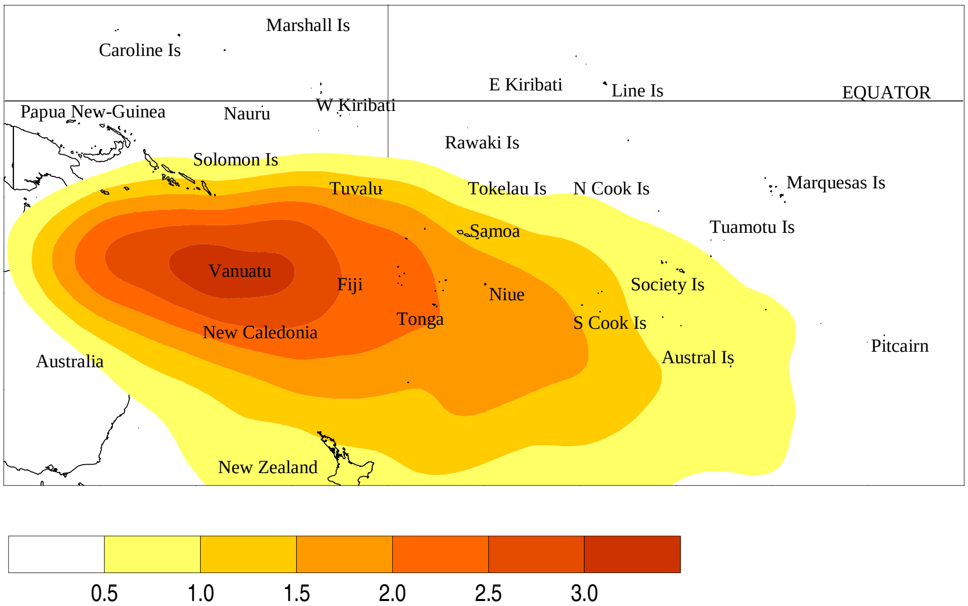

Figure 3: The average number of tropical cyclones per year passing within 555 km (a circle of radius equal to 5° of latitude) of the main island groups of the Southwest Pacific over the full cyclone season (November through May).

Figure 3 shows tropical cyclone occurrences for all years for the period 1970/71 to 2001/02, during the modern period of satellite records. Tropical cyclones develop in the South Pacific over the wet season, usually from November through April. Peak cyclone occurrence is usually during January, February and March. On average, nine tropical cyclones occur during the November to April season, but this can range from as few as four in 1994/95 to as many as seventeen in 1997/98 during the strong El Niño episode, largely due to the influence of climate variability on cyclone occurrence discussed next.

2.1.1 El Niño and La Niña

The El Niño Southern Oscillation (ENSO) is a primary cause of climate variability over a 2 to 7 year time period. It is normally defined by the Southern Oscillation Index, a measure of the atmospheric pressure gradient across the Pacific-Indian Ocean region. Atmospheric and oceanic conditions in the tropical Pacific vary considerably during ENSO, fluctuating somewhat irregularly between the El Niño phase and the opposite La Niña phase. Figure 4 shows the Southern Oscillation Index (SOI) since 1975 (the Tahiti minus Darwin normalized pressure index), which measures whether the climate system is in the El Niño or La Niña state. A negative index indicates the El Niño state, and a positive index the La Niña state. An SOI less than -1 defines a strong El Niño (and greater than + 1 a strong La Niña).

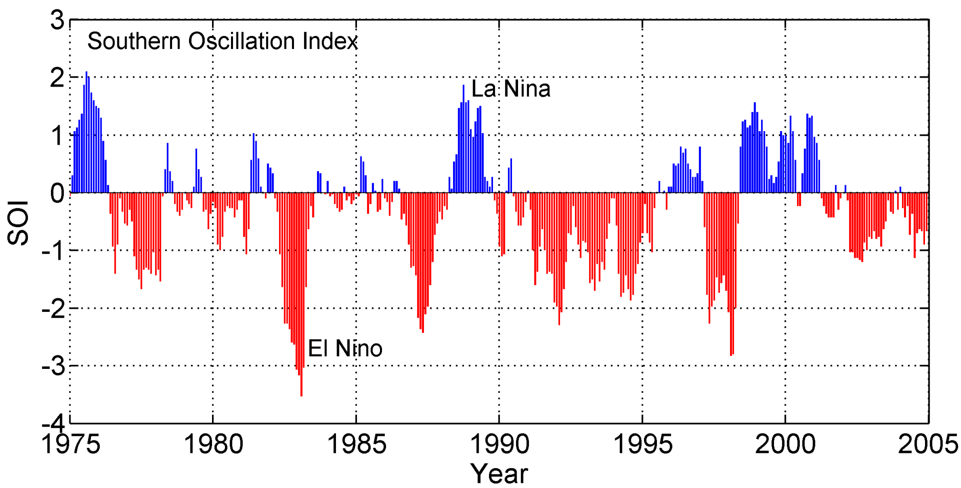

Figure 4: The Southern Oscillation Index (SOI) from 1975 – 2005 (based on the Tahiti – Darwin SOI). Low values represent El Niño and high values of this index La Niña conditions. A value less than -1 or greater than +1 represents a strong El Niño and strong La Niña state respectively.

El Niño phases typically become established around April or May and persist for about a year. As the El Niño develops, the trade winds weaken and warmer waters in the central and eastern Pacific occur, shifting the pattern of tropical rainstorms eastward. Higher than normal air pressures develop over northern Australia and Indonesia, with drier conditions or drought occurring. At the same time, lower than normal air pressures develop in the central and eastern Pacific with excessive rains in these areas and along the west coast of South America. Approximately reverse patterns occur during the La Niña phase of the ENSO phenomenon. The regions most affected are the sub-tropical regions of Indonesia, Australia, the Pacific Islands, the Americas and southern Africa, Figure 5.

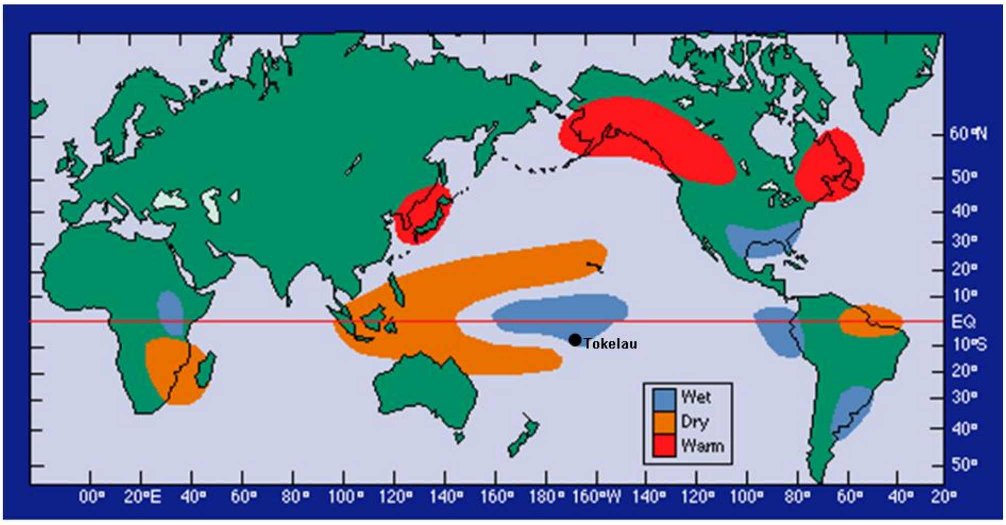

Figure 5: Some typical El Niño impacts, during Southern Hemisphere summer, when the event is at its peak. Image courtesy of the US NOAA Pacific Marine Environmental Laboratory, Seattle. Image available at URL: http://www.pmel.noaa.gov/tao/elnino/impacts.html

During El Niño phases the South Pacific Convergence Zone (SPCZ) is displaced north east (Folland et al. 2003). The general effects on Tokelau are summarised in Table 2.

The El Niño/Southern Oscillation (ENSO) has a significant impact on tropical cyclone risk within the Pacific region. Figure 6 shows tropical cyclone frequencies for El Niño (top) and La Niña (bottom) years. During El Niño years there is an eastward elongation of the average pattern (Figure 3), with the frequency over Tokelau increasing. In La Niña seasons more tropical cyclones occur in the Coral Sea with the risk of a cyclone affecting Tokelau decreasing. This is discussed further in Section 2.3.

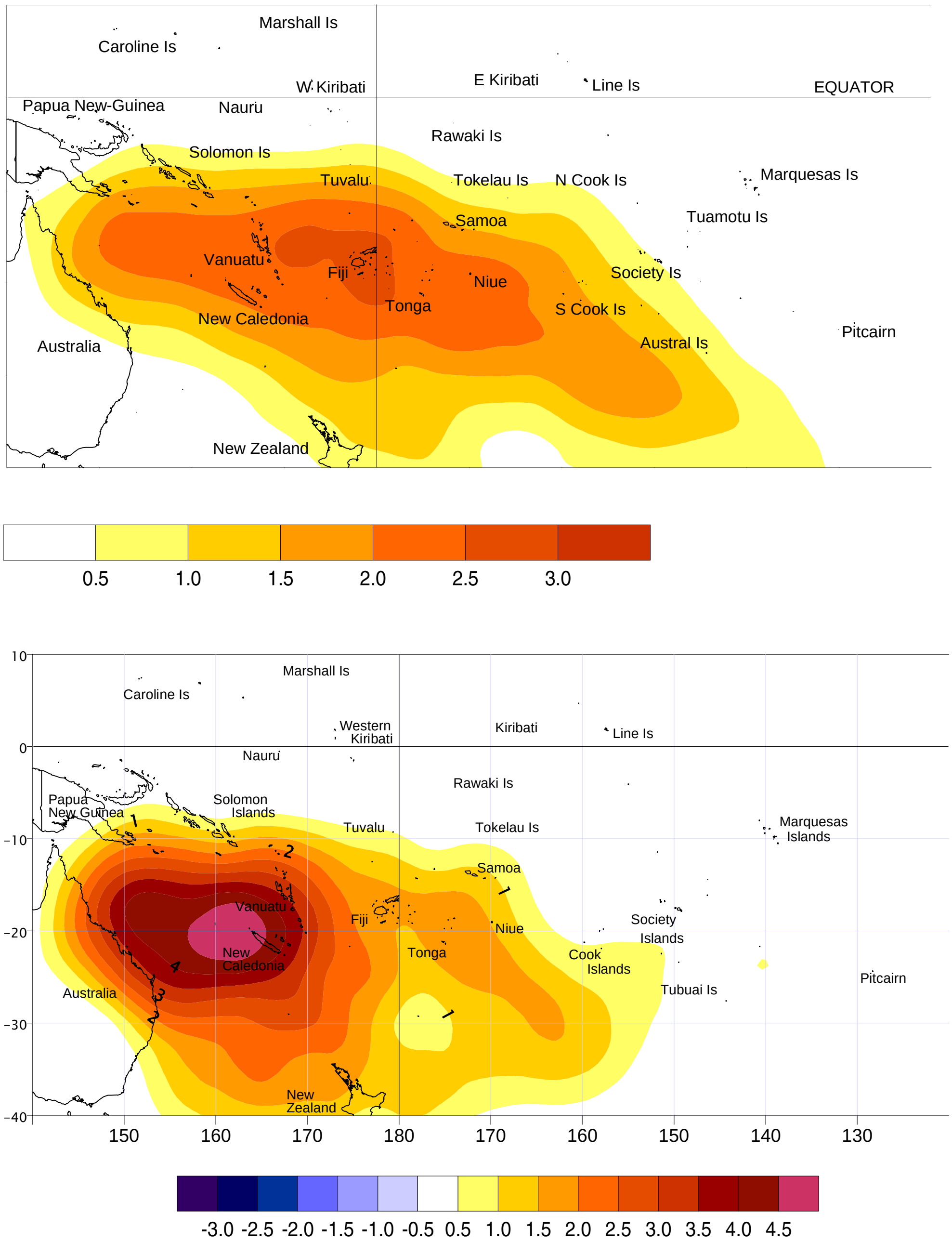

Figure 6: The average number of tropical cyclones passing within 555 km (a circle of radius equal to 5° of latitude) of the main island groups of the Southwest Pacific per year for (a) El Niño years – 1969, 1976, 1977, 1987, 1990, 1992, 1994 & 2002 (top) and (b) La Niña years (bottom).

Table 2: Summary of the influence of ENSO on general climatic patterns in the Tokelau region.

	During El Niño	During La Niña
Rainfall	Higher	Lower
Tradewinds	Weaker	Stronger
Atmospheric pressure	Lower	Higher
Sea levels	Lower	Higher
Risk of cyclones	Higher	Lower

2.1.2 Interdecadal Pacific Oscillation (IPO)

In recent years, researchers have found that the ENSO cycle is modulated by a longer-term cycle in the Pacific, the Interdecadal Pacific Oscillation (IPO), which causes shifts in climate regime every two to three decades (Salinger et al. 2002). This causes fluctuations in sea surface temperature primarily in the north Pacific centred near the dateline at 40°N, with an opposing area south of the equator in the eastern Pacific, north of Easter Island at 10 °S. There is also another weaker area, in the southwest Pacific centred near the Cook Islands at 20 °S, which is in the same phase as the north Pacific centre. The matching atmospheric sea level pressure pattern is one of an east/west seesaw at all latitudes, but again centred over the north Pacific, centred in the region of the Aleutian Islands.

Three phases, shown in Figure 7, of the IPO have been identified as having occurred during the 20th century: a positive phase (1922 – 1946), a negative phase (1947 – 1976) and the most recent positive phase (1977 - 1998). The IPO affects the strength and frequency of ENSO events, resulting in periods where El Niño conditions tend to be more frequent and stronger (e.g., during positive IPO phases such as during the 1980’s and 1990’s), and other periods where El Niño conditions are weak or absent, and where La Niña conditions are more prevalent (negative IPO phases) (Salinger, 2002).

During the positive phase of the IPO, the SPCZ is displaced north-east (Folland et al. 2003) resulting in higher rainfall over Tokelau during the latter part of the 20th century (Salinger et al. 2001). The reverse occurs in the negative phase, when rainfall was decreased over Tokelau.

ENSO and the IPO impinge on aspects of global climate, and are the dominant features of the tropical Pacific and oceanic Southern Hemisphere which effect climate variability in the Pacific basin. Monthly and longer-term climate predictions are made for all South Pacific islands and are summarised in a monthly newsletter, the *Island Climate Update*.[2]

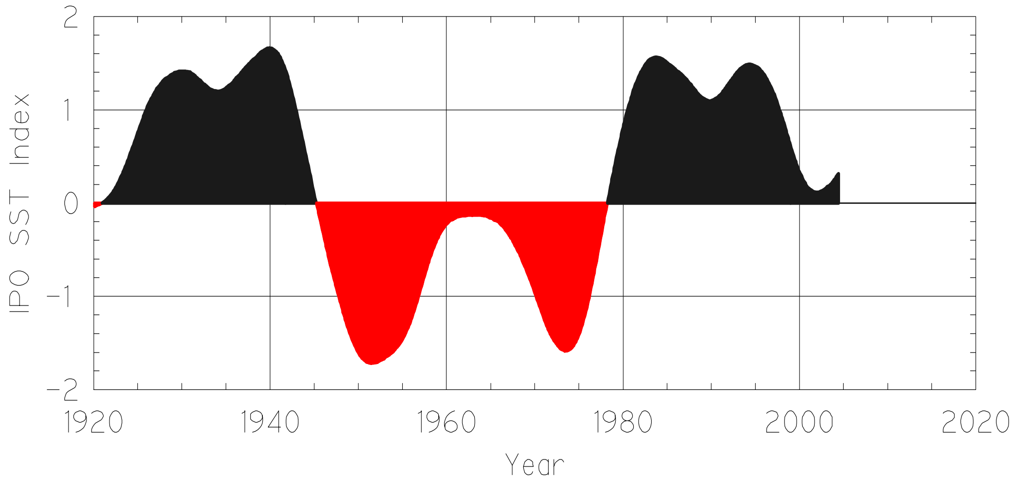

Figure 7 Phases of the Interdecadal Pacific Oscillation. During positive phases El Niño conditions are more likely to occur, with La Niña conditions more prevalent during negative phases.

2.2 Tropical cyclone climatology within the Tokelau region

2.2.1 Cyclone occurrence

There are few records of cyclones affecting Tokelau prior to the 20th century. Richards (1990) notes a severe event in 1908, an event in 1846, and based on Tokelauan tradition, early in the 19th century. Visher (1925) only notes only the Great Cyclone in 1914. The NZ Meteorological Service began collating cyclone information, including approximate cyclone tracks, from around 1940. Summaries of cyclones that affected Tokelau between 1940 and 1969 are provided by Kerr (1976), between 1969 and 1979 by Revell (1981), and between 1979 and 1989 by Thompson et al. (1992). A list of known cyclones to have passed within 150 km and 300 km, along with other cyclones that have significantly affected Tokelau are summarised in Table 3. Cyclones that have caused significant damage are highlighted in red. This confirms the influence that El Niño conditions have on cyclone occurrence in the region surrounding Tokelau.

Cyclone tracks within approximately a 600 km radius of each of the three atolls of Tokelau were extracted from a database of SW Pacific cyclone tracks and

[2] The *Island Climate Update* is available from: http://www.niwa.co.nz/ncc/icu/archive

characteristics compiled since 1940 by the NZ Meteorological Service and held by NIWA. It should be noted that prior to 1969-70 (when satellite records began to be used) the number of cyclones is under-represented by possibly as much as 30-50% and cyclone track positions are much less accurate.

Tropical cyclone tracks were input into GIS and overlain on a base map of the Pacific region around Tokelau downloaded from the SOPAC Mapserver[3]. All the cyclone tracks since 1940 that have passed within 300 km of any of the three atolls are shown in Figure 8. Tracks of cyclones that have caused significant damage on any of the three atolls are shown in Figure 9.

[3] http://www.sopac.org/tiki/tiki-index.php?page=Maps

Table 3: Summary of main cyclones to have affected the atolls of Tokelau. Cyclones that resulted in significant damage are highlighted in red. The IPO +ve phase is shaded in grey. Note: A = Atafu, N = Nukunonu, and F = Fakaofo.

Year	Date Tokelau affected	Name	ENSO	IPO	Within 300 km of	Within 150 km of
Early 1800s					?	?
1846					?	?
1908					?	?
1914	**7 Jan**	**Great Cyclone (Afa Lahi)**	**El Niño**	**- ve**		**A N F**
1925	?? Dec		El Niño	+ ve	?	?
1936	14-15 Jan		El Niño	+ ve	?	?
1941	**26-27 Feb**		**Strong El Niño**	**+ ve**	**A N F**	
1941	**24 Nov**		**El Niño**	**+ ve**	**A N F**	
1957	14 Dec		El Niño	- ve	F	A N
1966	**29-30 Jan**		**Strong El Niño**	**- ve**		
1967	14-15 Dec		El Niño	- ve	A	N F
1972	27 Feb	Isaac	La Niña	- ve	N F	
1972	01-02 Nov	Collette	El Niño	- ve	F	A N
1978	31 Jan	Bob	Strong El Niño	+ ve		A N F
1981	**1-3 Mar**	**Esau**	**Strong El Niño**	**+ ve**		
1987	**15 Jan**	**Tusi**	**El Niño**	**+ ve**		**A N F**
1987	**28 Feb**	**Wini**	**Strong El Niño**	**+ ve**		
1990	**30 Jan - 02 Feb**	**Ofa**	**Strong El Niño**	**+ ve**		
1991	**6 Dec**	**Val**	**Strong El Niño**	**+ ve**	**A**	
1997	8-10 June	Keli	Strong El Niño	+ ve	N F	A
1998	2-3 Jan	Ron	Strong El Niño	+ ve	N F	
1998	24-25 Jan	Tui	Strong El Niño	+ ve	N	
2004	01-03 Jan	Heta	Strong El Niño	+ ve	A N F	
2005	**25-26 Feb**	**Percy**	**Strong El Niño**	**- ve**		**A N F**

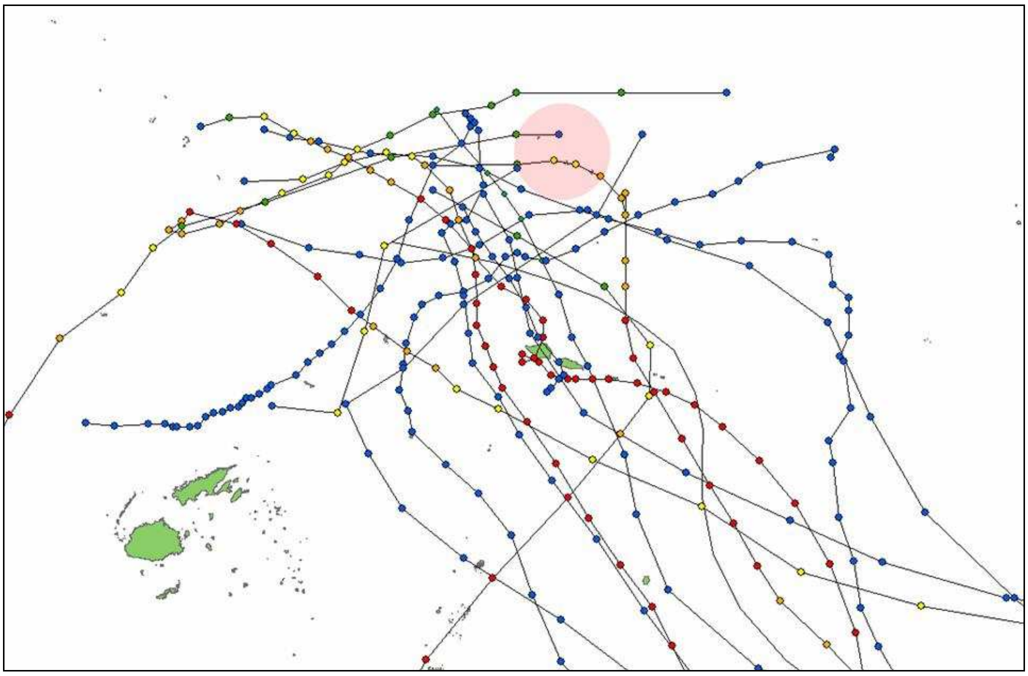

Figure 8: Tracks of all cyclones passing within 300 km of the three Tokelau atolls. The coloured dots represent the position every 12 hours, with red: severe tropical cyclone intensity, yellow and orange: tropical cyclone intensity, and green: tropical disturbance, and blue: no record.

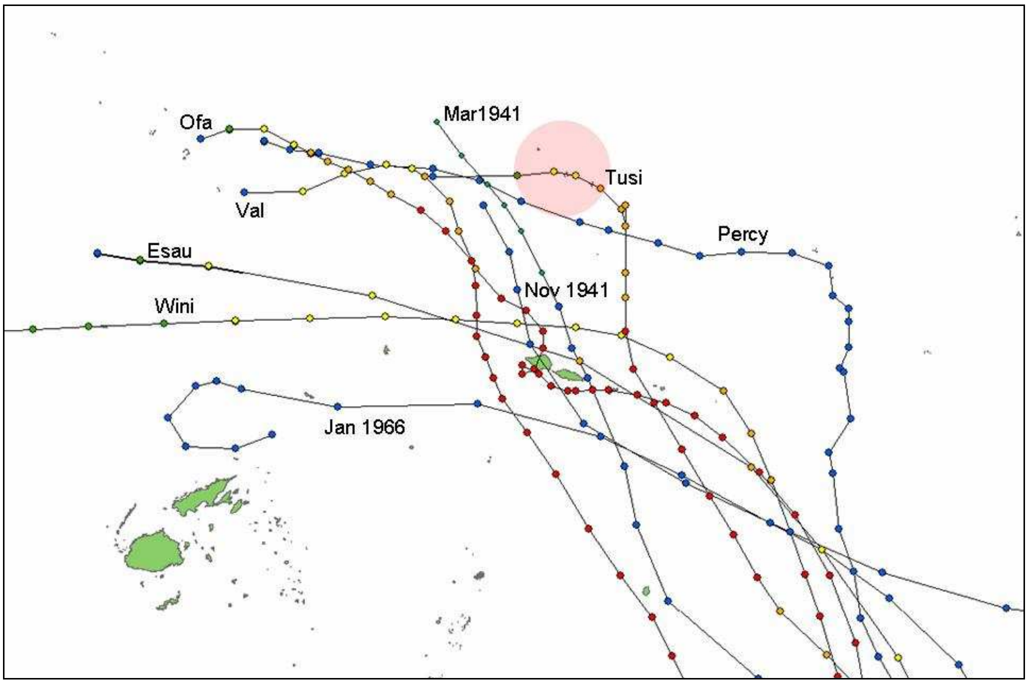

Figure 9: Tracks of cyclones (since 1940) that have caused significant damage on the inhabited motu of any or all of the three atolls.

In general, the spatial distribution of cyclones is fairly even between each of the main island groups (Table 4), with a slightly lower risk for Atafu than Fakaofo (although based on cyclone tracks over the last 36 years the risk of a cyclone passing within 150 km is greater for Atafa than Nukunonu or Fakaofo).

Table 4: Number of cyclones tracking within 150 km, 300 km and 600 km (based on the period between 1969 and 2005), and causing significant damage (based on the 1914 – 2005 and 1969 – 2005 periods).

Atoll	Within			Damaging cyclones	
	150 km	300 km	600 km	1914 – 1969	1969-2005
Atafu	5	7	29		
Nukunonu	4	9	32	4	6
Fakaofo	3	8	33		

Based on the average number of cyclones per year calculated using the information in Table 4, the Poisson distribution can be used to define the probability of one or more cyclones occurring in the region in any one year (Oliver, 2004):

$$\Pr(n\,storms) = \frac{m^n e^{-m}}{n!}$$

where *n* is the number of cyclones and *m*, the average number of storms per year. Figure 10 shows the probability (expressed as a percentage) of one or more cyclones tracking within various distances of the three atolls in any one year (based on cyclone tracks since 1969 when more accurate recording of cyclone tracks commenced). Also shown is the corresponding probability of damaging cyclones occurring (using both the average number of damaging cyclones per year over the period 1914 to 2005 and also between 1969 to 2005).

For example, for Fakaofo this suggests that, on average, there is an 80% chance in any one year of no cyclone passing within 300 km (and hence a 20% chance of one or more cyclones occurring in any one year within 300 km; specifically a near 18% chance that only one cyclone will occur and a 2% chance that 2 cyclones will occur in any one year). Expressed a different way, a cyclone will pass within 300 km of Fakaofo about once every 5 years (1/(1.0-0.8)), with 2 or more cyclones passing within 300km in any one year only likely to occur about once every 50 years (1/(1.0-0.02)). However, it should be borne in mind that these are averages and that the likelihood of a cyclone occurring during El Niño conditions is much higher than when El Niño conditions are not occurring.

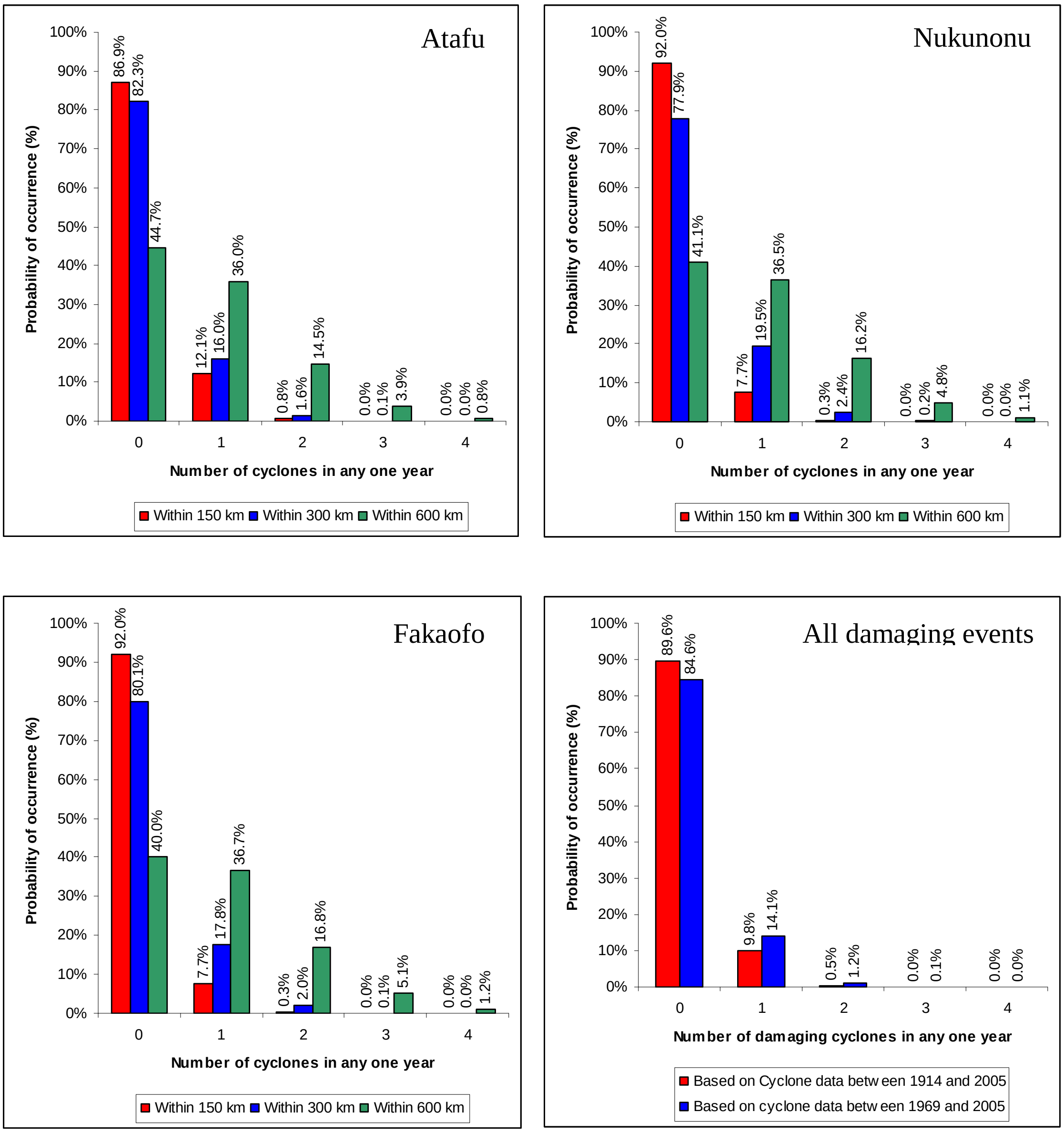

Figure 10: Probability of occurrence of one or more cyclones occurring in any one year within various distances of each atoll.

Whether significant impact occurs on the inhabited motu of each atoll depends on the particular track of the cyclone (discussed below). Based on historic accounts of cyclone events that have significantly impacted on the human population of each atoll, Figure 10 (bottom right) suggests that, based on the period between 1914 and 2005, the likelihood of a damaging event occurring in any one year is about 10.4%, (or will occur on average about once every 9 to 10 years). However, based on the occurrence of damaging cyclones since 1969, the probability of a damaging event occurring in any one year is around 15.4% (or once every 6 to 7 years). This higher occurrence is likely to be primarily related to the +ve phase of the IPO over much of this period resulting in a prevalence of El Niño conditions which has increased the occurrence of cyclone events affecting Tokelau over this period.

2.2.2 Cyclone characteristics

A tropical cyclone is an intense low pressure weather system with, in the southern hemisphere, winds circulating around the eye of the cyclone in a clockwise direction. The eye is the area at the centre of the cyclone with the lowest atmospheric pressure at sea level. Typically it is 20 to 50 km in diameter with often light winds and clear skies. Surrounding the eye is the eye wall and outer rain bands. This is the area of strongest winds and highest rainfall with rain bands that can extend over 1000 km or more in diameter, spiralling inwards towards the eye. In the early stages of the cyclone, the lateral extent may only be between 100 and 200 km in diameter. If conditions are favourable, the cyclone can continue to intensify with the lateral extent varying significantly for any given central pressure.

In the southern hemisphere, the strongest winds are experienced to the left of the direction of movement (track) of the cyclone system. This is due to the combined influence of the forward speed of the cyclone system (which is generally less than 30 km/hr with 10 to 20 km/hr typical) acting with the clockwise wind circulation. On the right hand side of the cyclone system the forward speed and wind circulations are opposing each other. Likewise the storm surge and wave heights also tend to be greatest in the left forward quadrant where the surface winds are greatest.

Figure 8 shows the tracks of all cyclones passing within 300 km of Tokelau, and Figure 9 shows the tracks of cyclones that have caused significant damage on the inhabited motu on each atoll. This suggests three general types of cyclone tracks, schematised in Figure 11.

The first type is characterised by Cyclones, Tusi, Ofa, Val, Percy and the two cyclones that affected Tokelau in 1941. These tend to form to the west of Tokelau, between Tokelau and the southern Tuvalu atolls, and start tracking in an easterly direction towards Tokelau before turning and moving in a south easterly direction passing, up to 500 km, to the west of Tokelau. This results in the western (inhabited) side of the Tokelau atolls being in the region of the strongest winds rotating around the cyclone eye, the magnitude of which depends on how close the cyclone tracks to the west of Tokelau. Such tracks typically result in winds from the north (*Laki*) or northwest

(*Lakilua*). It also results in the largest storm surge and wave conditions on the north-western side of the atoll. Cyclone Tusi is the only cyclone since 1940 to have passed directly over Tokelau (Nukunonu and Fakaofo); it was fortuitous that the cyclone did not develop fully until well south of Fakaofo. Reports of the Great Cyclone in 1914, which described winds on Atafu and Fakaofo from the north and northwest, also suggest that this cyclone tracked in a south easterly direction to the west of Tokelau.

The second type is characterised by the cyclone in January 1966, Cyclone Esau in 1981, and Cyclone Wini in 1987. These cyclones track in an easterly direction well to the south of Tokelau (around the same latitude as Wallis and Futuna and Samoa). Large swell waves generated by the extreme winds radiate out in a fan-shaped pattern away from the centre of the storm, propagating in a north easterly direction towards Tokelau (i.e., arriving from the south west). Depending on the forward speed of the cyclone, such swell can continue to occur for a considerable period of time (days) with the relative impact on the atolls on Tokelau dependent on the tide conditions. This is discussed further in Section 3.

Figure 11: General cyclone track patterns affecting Tokelau.

Other cyclones that have tracked close to Tokelau (e.g., Cyclones Bob, Collette, Keli and Ron) but that have caused less damage on the inhabited motu on the atolls, have tended to form in the region to the south of Fakaofo and track away from Tokelau, or have tended to track in a south-westerly direction, resulting in the most damaging impacts occurring on the uninhabited sides of the atolls. However, if any track were to pass close to any of the atolls, significant wind damage could be expected on the inhabited motu. An example from Fakaofo called "The Omen of Fakamalu" is described in *Matagi Tokelau* (Anon, 1991) where the winds blew from the direction of *Tufa* (East) with evidence of past cyclone events affecting the eastern coastline of Fakaofo due to the coral block and rubble deposits on the reef flat between Matagi and Fenuatapu to Atu Hakea (eastern coast).

2.3 Potential effects of climate change on tropical cyclone characteristics

There is still plenty of work to do on changes in the tropical cyclone hazard due to global warming. However, the IPCC (2001) concluded that despite no clear trends in observations, a series of theoretical and model-based studies, including the use of a high-resolution tropical cyclone model, indicates that peak wind intensities will increase by 5 to 10% and mean and peak rainfall intensities by 20 to 30%. This is primarily because of warming of the ocean surface. The IPCC notes that there is no direct evidence of changes in cyclone frequency or areas of their formation.

There is insufficient data for assessment to provide conclusive results for the south Pacific. However, there is confidence in projections that an increase in severity (peak wind intensities and peak precipitation intensities) is likely over some areas during the 21st century. Notwithstanding the foregoing conclusions, individual studies have reported the likelihood of a possible increase of approximately 10 to 20% in intensity of tropical cyclones, which is supported by modelling for the South Pacific region, under enhanced carbon dioxide concentrations.

In Tokelau the occurrence of cyclone events affecting the atolls is closely linked to the occurrence of periods of El Niño. Current projections show little change or a small increase in magnitude for such events over the next 100 years. However, current confidence in projections of changes in future magnitude and spatial patterns of ENSO events in the tropical Pacific is tempered by some short-comings in how well El Niño is simulated in the complex climate-ocean models. However, recent trends for surface temperature to become more El Niño like in the tropical Pacific, with the eastern tropical Pacific warming more than the western tropical Pacific may well increase the likelihood of tropical cyclones affecting Tokelau over the next 100 years.

3. Cyclone effects on coastal inundation

3.1 Sea levels

The elevated water level experienced at the coastline during a cyclone is a combination of a number of processes including:

- The level of the astronomical (daily) tide (which can be influenced by longer period sea-level fluctuations at seasonal (annual), El Niño–Southern Oscillation (2–5 year), and Interdecadal Pacific Oscillation (20–30 year) timescales, which can cause higher (or lower) background sea levels in some years or seasons than others.

- Storm surge: the increase in sea level due to the reduction in atmospheric pressure close to the cyclone (inverse barometer effect) and influence of wind stress on the ocean's surface.

- Wave set-up: the increase in sea level over the reef flat due to waves breaking on the seaward edge of the reef.

- Further wave set-up at the shoreline due to waves translating over the reef flat and breaking close to the beach.

- Wave run-up and overtopping of the shoreline.

These processes are shown in Figure 12 and discussed in more detail in the next sections.

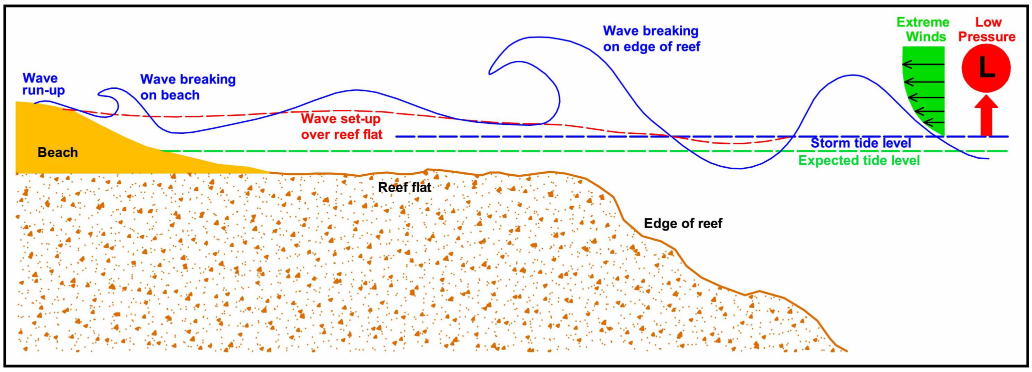

Figure 12: Effects of a cyclone on sea levels over a fringing reef.

3.1.1 Tides

Astronomical tides are an important factor in determining the potential impact of inundation during a cyclone or when large swell wave conditions are affecting the western shorelines of the atolls. On the ocean side the size of the waves translating over the fringing reef systems and reaching the shoreline are highly dependent on the tide level. For example, the overwashing and inundation during Cyclone Percy would not have been as severe on Nukunonu if the cyclone hadn't coincided with high water on a spring tide.

Little tide data has previously been collected on Tokelau, with it being one of the few nations in the world where there are no tide predictions available (e.g., from organisations such as the UK Hydrographic Office). As part of this study, tide data collected over a 30 day period (19:30 UTM, 18 June 1994 to 03:30 UTM, 19 July 1994) by the Royal New Zealand Navy (1994) from one of the two tide gauges installed in the boat channel at Nukunonu were analysed to establish the main tidal constituents[4]. Using these constituents, approximate tidal predictions can be made for any time in the past (e.g., to look at tide conditions during known past cyclone events) and future. More accurate tide predictions would require identifying more of the minor tidal constituents, which requires a longer period of tide measurement (in this case at least 206 days). The comparison between the measured and predicted tide for the 30 day period in 1994 is shown in Figure 13.

Figure 13 shows the tide in Tokelau as being a mixed, dominant semi-diurnal type with high water levels alternately higher and lower than the average (high water level)

[4] Individual components which compose the tides. Each constituent arises either from a specific astronomical feature or from the interaction between two or more constituents. For example, N_2, the elliptic semi-diurnal constituent (N_2 is its Darwin symbol), arises from the elliptic orbit of the Moon around Earth. Each constituent has a unique period.

with the difference being most pronounced when the angular distance of the moon north or south of the equator is greatest. Mean spring tide range is around 0.98 m and mean neap range around 0.59 m. Figure 14 shows the predicted highest tide levels between 2000 and 2021. This shows cycles of higher tide levels (relative to the mean level of the sea[5] (MLOS) during the 30 days that tide data was collected in 1994), with a series of higher tides occurring between 2001 to 2003, 2009 to 2011, and 2018 to 2020. Figure 15 shows, over the next 100 years, the percentage of high tides exceeding certain levels. This suggests that the mean spring tide level is exceeded around 31% of the time.

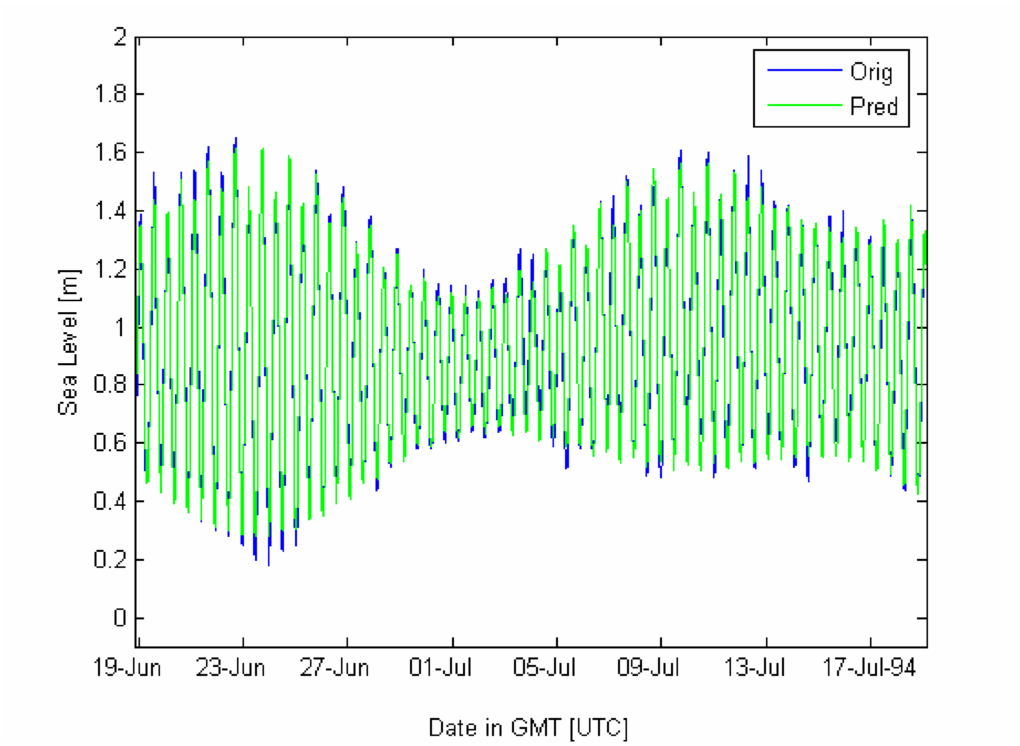

Figure 13: Comparison between measured and predicted tides between 18 June and 19 July 1994. The figure also shows the typical Spring-Neap tidal cycle experienced on Tokelau.

[5] Mean Level of the Sea was 0.9321 m above zero on the tide pole. Zero on the tide pole was 2.374 m below Trig N 00 Fundamental (a standard RNZN Trig plate set in concrete with stones inset in front of Matiti school) and 4.530 m below Benchmark Nukunonu Church (a brass RNZN benchmark set in concrete at the base of the steps at the main entrance to the church).

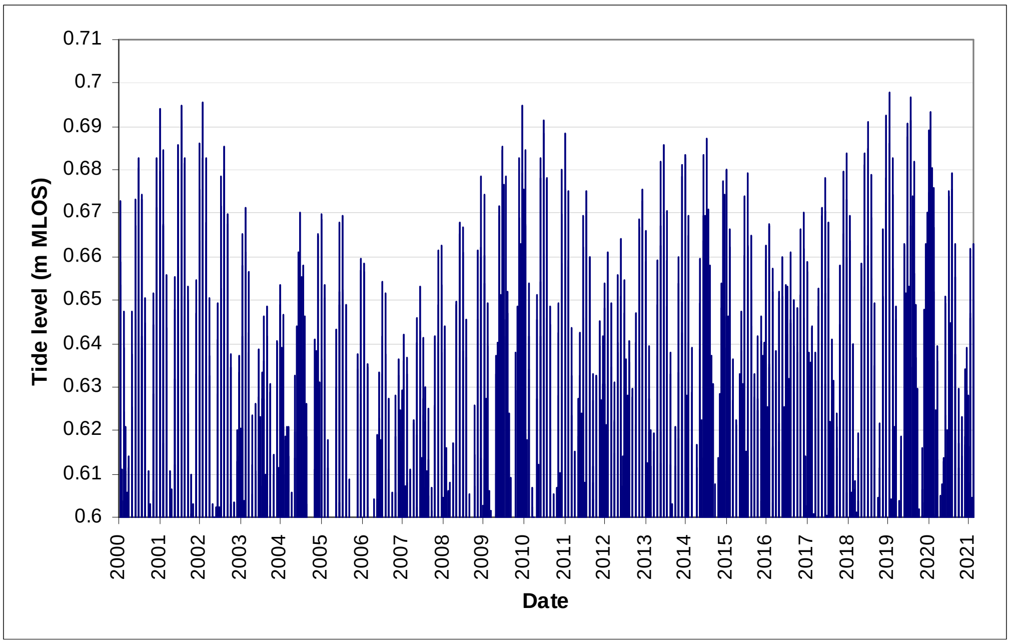

Figure 14: Highest high tide levels (relative to mean level of the sea) between 2000 and 2021.

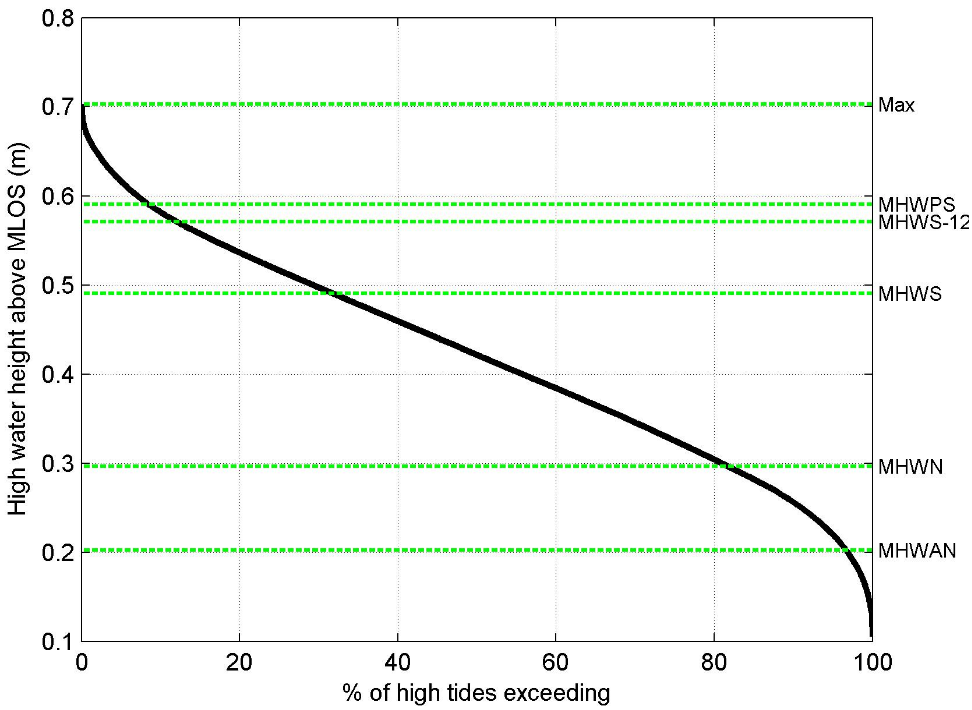

Figure 15: Percentage of high tides exceeding certain levels (relative to mean level of the sea) over the next 100 years.

The tide predictions have also been used to assess tide levels during past cyclone events. Figure 16 summarises the highest tide level during the day(s) that the cyclone impacted on the atolls. Approximately half the cyclones that have significantly affected Tokelau have coincided within a couple of days of a Spring tide, with the peak swell waves from Cyclone Wini in February 1987, and the passage of Cyclone Percy in February 2005 both coinciding with high tide. However, the event in 1966 demonstrates that significant inundation can still occur when tide conditions are lower, in this case a Neap tide.

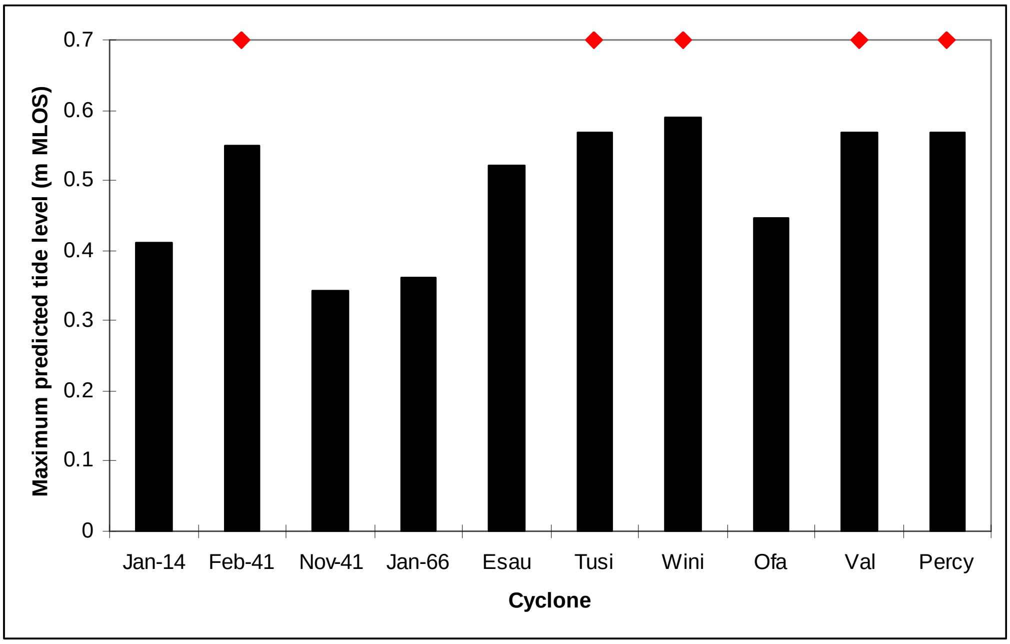

Figure 16: Maximum astronomical tide levels during the passage of cyclones affecting Tokelau over the last 100 years. The red diamond marks the cyclones that occurred within two days either side of a Spring tide.

3.1.2 Long period sea level fluctuations

In addition to the daily sea-level fluctuations due to the tide, there are both long-term fluctuations (months to years) and short-term fluctuations (hours to days), more commonly known as storm surge (see next section). The main long–term fluctuations are:

- annual (seasonal heating and cooling cycle driven by the sun acting on the ocean surface);

- interannual (2 to 5 year El Niño-Southern Oscillation cycles); and
- interdecadal (20 to 30 year Interdecadal Pacific Oscillation or IPO cycles).

The effects of climatic features such as El Niño tend to have a greater influence on sea level closer to the equator. The South Pacific Sea level and climate monitoring project has been recording sea levels at twelve sites through the Pacific region over the last 12 years. The closest gauges to Tokelau are those at Apia and Funafuti. Over the last twelve years these have recorded variations in mean monthly sea level of between approximately +0.15 m to –0.3 m at Apia, and +0.15 m to –0.35 m at Funafuti (Bureau of Meteorology, 2005). This is similar in magnitude to a longer-term record (1957 to 2001) recorded at Pago Pago in American Samoa (Figure 17). The effect of the strong El Niño events in 1982-83 and 1998-99 on lowering mean sea levels can be clearly seen.

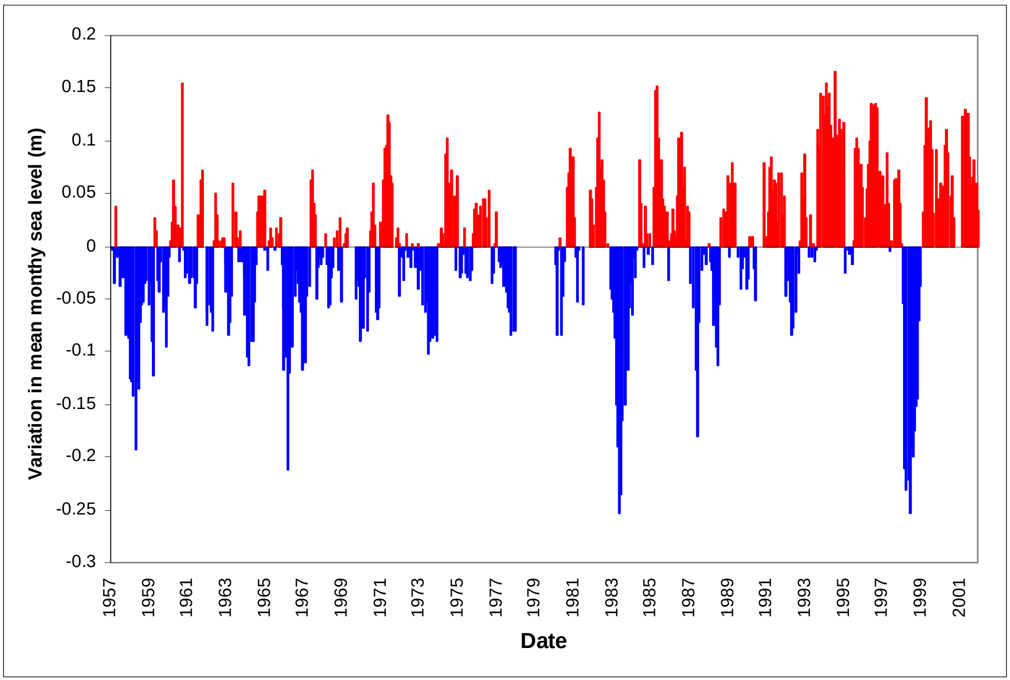

Figure 17: Variation in mean monthly sea level at Pago Pago (American Samoa) between 1957 and 2001.

Using this as a guide, this suggests that Tokelau is likely to experience fluctuations in mean sea level of up to about 0.5 m due to long-term climate variability such as ENSO and IPO.

3.1.3 Storm surge

The increase in sea level due to the reduction in atmospheric pressure close to a cyclone (inverse barometer effect) combined with the influence of wind stress on the ocean's surface is known as the storm surge. The water elevation created by the combination of the tide and storm surge is commonly known as the storm tide. During a cyclone, the magnitude of the storm surge depends on:

- The cyclone's central pressure (known as the intensity of the cyclone).

- The track of the cyclone (its direction and speed of movement) relative to the location of interest.

- The size of the cyclone (the distance from the centre of the cyclone to the region of maximum winds).

Over the ocean, in deep water, only the tide and inverse barometer effect have an influence on sea level. The general rule of thumb is that a 1 hPa drop in atmospheric pressure results in approximately a 1 cm increase in sea level (known as the *inverted barometer* effect), although the exact increase depends on the track and speed of movement of the cyclone. Being within 10º of the equator, mean atmospheric pressure in Tokelau will tend to be between approximately 1005 and 1010 hPa. Figure 18 shows the estimated pressure at mean sea level at the centre of Cyclone Percy during the period 24 February to 05 March along with the pressure measured every 3 hours on Nukunonu and Swains Island. Also shown is the corresponding approximate inverted barometer effect on sea level in close proximity of the centre of the cyclone (assuming a mean atmospheric pressure of 1008 hPa).

For the inverted barometer effect to increase sea levels significantly, the centre of the cyclone needs to pass close to the location of interest, as the pressure within the cyclone increases rapidly with distance away from the centre. In the case of Cyclone Percy, which tracked about 100 km west of Nukunonu, the reduction in atmospheric pressure would only have been around 15-25% of that at the centre of the cyclone (with an associated storm surge of about 0.1m to 0.15 m).

The ability of strong winds to increase water levels decreases with increasing water depth, with it being most important when the wind blows over a region of shallow water. Since Tokelau, like most atolls, is characterised by a rapid increase in water depth off the seaward edge of the reef, the wind stress component of the storm surge is relatively small (less than 0.1 m).

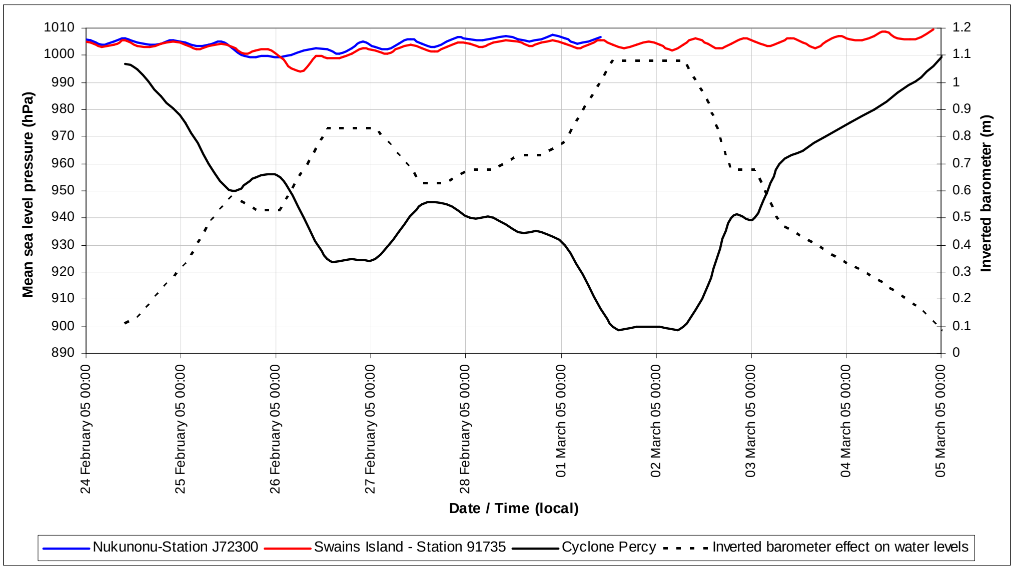

Figure 18: Pressure at mean sea level estimated at the centre of cyclone Percy, and measured 3 hourly mean sea level pressure at Nukunonu and Swains Island. Also shown is the approximate corresponding inverted barometer effect on sea level at the centre of the cyclone.

Within the lagoon, wind set-up may be slightly greater depending on whether the wind direction is aligned closely with the maximum fetch length[6] over the lagoon. Maximum fetch lengths over the lagoon are around 6 km, 9 km and 7 km for Atafu, Nukunonu and Fakaofo respectively, with maximum wind set-up of about 0.5 m likely under the most severe cyclone conditions. However, typically it is unlikely to be more than about 0.2–0.3 m.

Hence, any significant increase in water level due to storm surge will be generally limited to a region within a few 10's of kilometres from the centre of the cyclone. In many cases it is the action of large waves, created by the cyclone, breaking on the edge, and propagating over the reef, that has the greatest impact on water levels over the reef flat and within the lagoon. Whilst the tide and storm surge may not create an extremely high water level, the degree of wave impact, run-up and overtopping on the shoreline, can be extremely sensitive to even very small increases in water level. Wave conditions are discussed next.

[6] The distance over the lagoon over which the wind can act to produce waves or to increase water levels at the downwind lagoon shoreline.

3.1.4 Influence of waves on water levels

Waves, typically acting during a high tide or storm tide, are the dominant cause of both coastal erosion and coastal inundation. After tide fluctuations, it is wave set-up caused by waves breaking on the edge of the reef that will typically cause the largest increase in water levels over the reef flat and within the lagoon. The size of waves propagating over the reef flat and reaching the shoreline of the motu is also very sensitive to water levels over the reef flat. The most damaging waves typically occur due to:

- Extreme wind conditions during tropical cyclone events.
- Large swells pushed ahead of eastward trending cyclones that pass across the large open fetch to the west of Samoa (e.g., as occurred in 1996, Cyclone Esau in 1981 and Cyclone Wini in 1987).
- Distantly generated long period swell that travels from lower latitudes in both southern and northern hemispheres.

The wave climate in Tokelau is dominated by the easterly and southeasterly tradewinds and occasionally influenced by tropical cyclones. There are no known wave measurements anywhere close to Tokelau. However, the general wave climate and distribution of oceanic wave heights (i.e., before the influence of land and shallow water effects) can be obtained from global wave models, such as the NOAA Wavewatch III hindcast[7]. Figure 19 shows the general wave climate and wave height distribution for the three atolls over the 2004 calendar year, suggesting a mean significant wave height[8] of around 1.8 m, with the wave rose demonstrating the dominance of waves generated by the easterly trade winds.

There is little data on extreme wave conditions experienced during tropical cyclones. Waves, at a particular location, can vary from cyclone to cyclone, being dependent on the track and intensity of the cyclone and, when reaching land, the state of the tide. The global hindcast models tend to underestimate wave conditions that occur during cyclones as the spatial resolution of the model is not sufficient to properly account for the rapidly changing wave conditions within such an event.

[7] http://polar.ncep.noaa.gov/waves/Welcome.html.
[8] Significant wave height (H_s) is the average of the highest one third (33%) of waves over a particular period. Maximum wave heights are typically around $1.7H_s$.

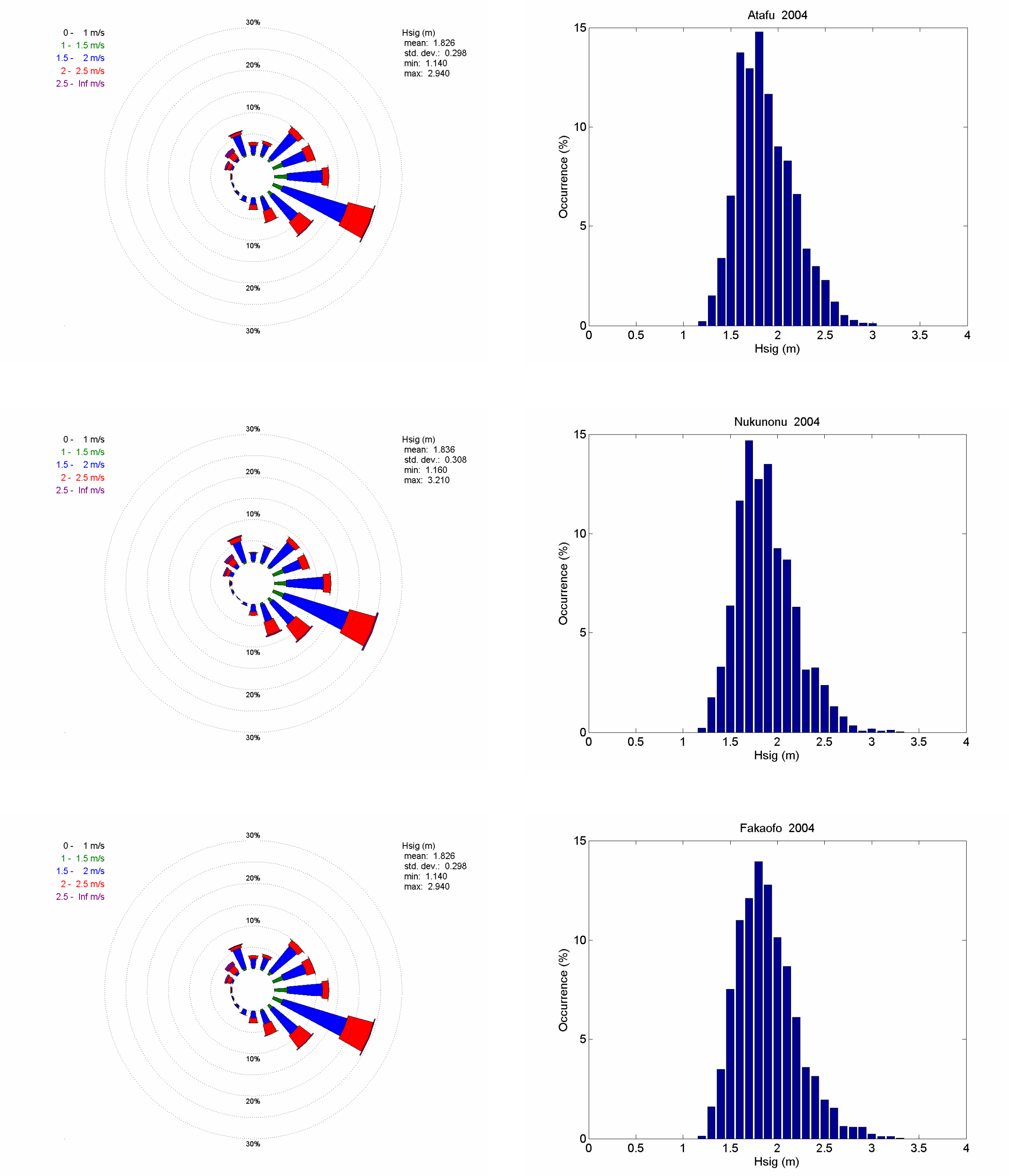

Figure 19: Wave rose (left) and significant wave height distribution (right) for Atafu (top), Nukunonu (middle) and Fakaofo (bottom) derived from the NOAA Wavewatch III simulation for the calendar year 2004. The wave rose shows the joint occurrence distribution of significant wave height and peak wave direction, with bars oriented in the direction FROM which waves propagate.

To provide an indication of wave conditions during Cyclone Percy, use was made of a simple parametric model. As the cyclone passed the three atolls, winds exceeding 64 knots occurred within about 20 nm of the centre, 50 knots within 40 nm and 34 knots within about 100 nm. The model suggested that significant wave heights may have been around 7.5 – 8 m near the centre of the storm, around 5.5-6 m at Nukunonu and Fakaofo, and between about 4-5 m at Atafu. Peak wave period would have been around 11-12 s. Such wave conditions will be fairly typically for a cyclone moving along a south-easterly track to the west of Tokelau and, depending on the speed of the cyclone, large wave conditions would be unlikely to continue for more than 6-12 hours. Given that wave heights are Raleigh distributed, the maximum wave height over a period of about 6 hours would be close to twice the significant wave height.

For more distant cyclones (such as Cyclones Esau, Wini and the 1966 cyclone) the major contribution to the large waves that affect Tokelau is from swell propagating away from the cyclone. Given the easterly track of these cyclones, swell wave conditions will affect Tokelau from several positions of the cyclone. Waves of higher period would arrive sooner but with lower amplitude, whereas shorter (lower period) waves would persist for longer. It is possible for these particular cyclone tracks that different period waves from different positions of the cyclone may have coincided at Tokelau resulting in a wider spread of wave energy and larger wave conditions than would normally have occurred (a similar occurrence has been noted due to damaging waves at Vaitupu in Tokelau due to Cyclone Nina, which followed a similar easterly track to the south west of Vaitupu, (Laing 1993)).

A reasonable estimate of swell wave conditions that have propagated away from more distant cyclones, as has occurred during Cyclones Wini in 1987, Esau in 1981 and in January 1996 can be obtained from the global wave models described above. Data from the NOAA Wavewatch III model is only available from 1997 and therefore does not cover any of these events. However, information can be had from a longer time series that is available from the NIWA WAM model hindcast for the South Pacific region (1979-1998)[9]. Wave information from this model needs to be used with caution as the northern boundary is at 9ºS, very close to Tokelau. Despite this, swell conditions propagating from the south-west should be reasonably well represented. Wave conditions experienced on the three atolls between January and April 1981 and between February to May 1987 are summarised in Figures 20 and 21.

[9] http:www.niwa.co.nz/nco/forecast

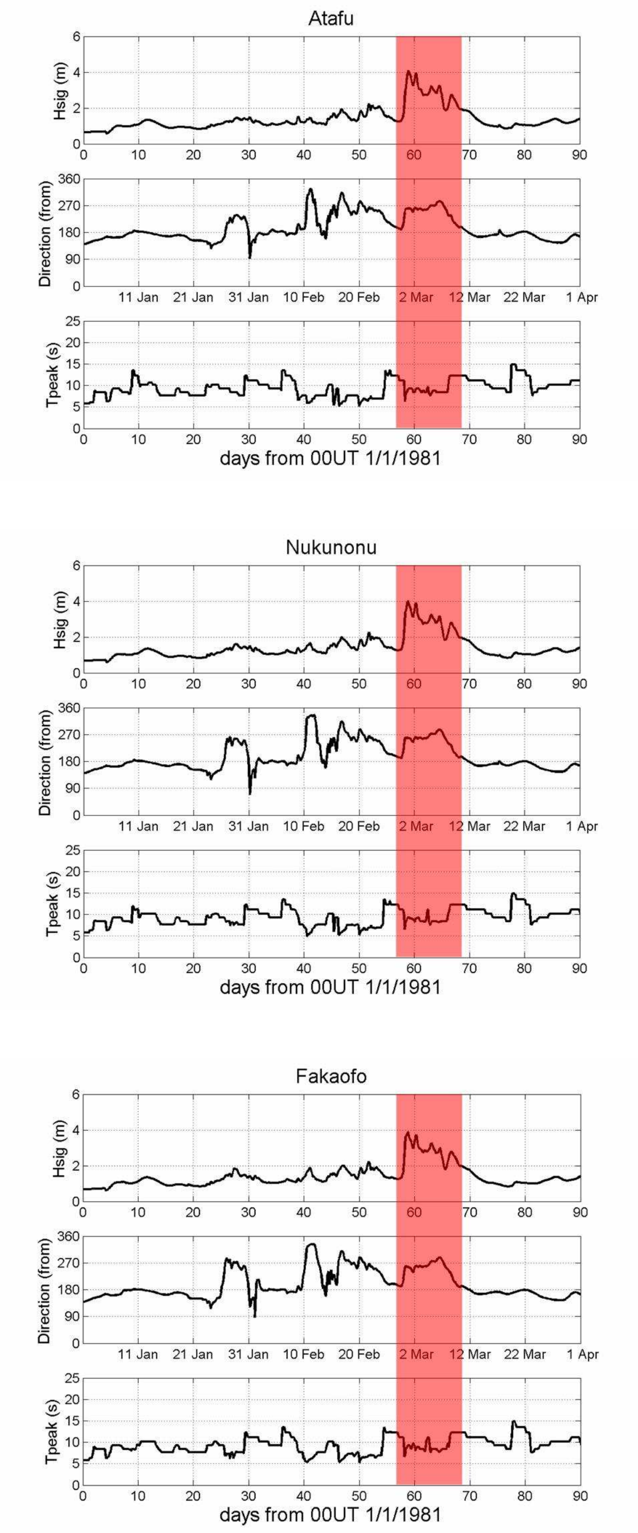

Figure 20: Wave time series between January and April 1981 for Atafu (top), Nukunonu (middle) and Fakaofo (bottom). The wave conditions generated by Cyclone Esau are highlighted in red.

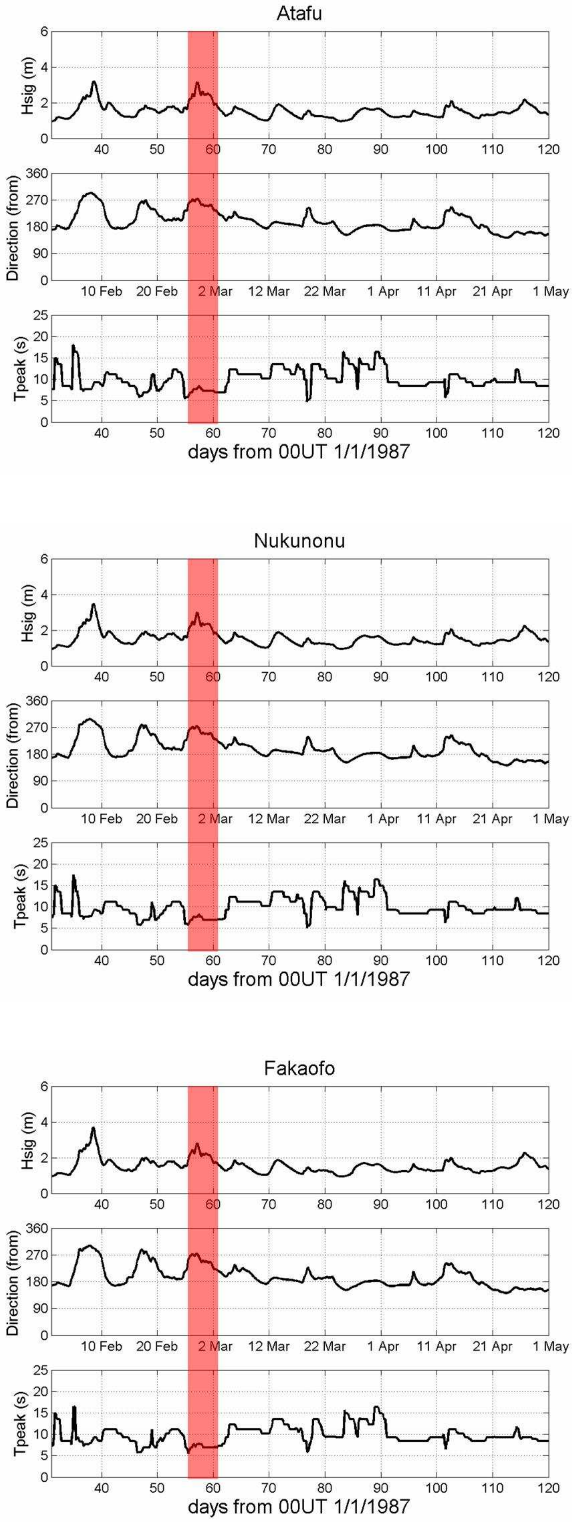

Figure 21: Wave time series between February and May 1987 for Atafu (top), Nukunonu (middle) and Fakaofo (bottom). The wave conditions generated by Cyclone Wini are highlighted in red.

The model suggests that swell waves with a significant wave height of around 4 m were experienced after Cyclone Esau, with swell of over 2 m continuing for around 10 days. Similarly, the swell created by Cyclone Wini, with a significant wave height of over 3 m, continued for around a week (which corresponds to observations recorded by Richards (1990)).

Swell from the northern hemisphere can also occasionally affect South Pacific Islands, particularly when it coincides with a high tide. Matthews (1971) described damage on northern shorelines of a number of Pacific Islands in early December 1969 due to two storms in the North Pacific (between 40ºN and 50ºN), with the resulting swell waves travelling over 7000 km to the south. Large swell between 4 m and 6 m high affected the northern coasts of Kiribati, Tuvalu, Samoa, Cook Islands and Tahiti, and although not recorded would also have affected the northern coastlines of Tokelau.

Extreme waves offshore of the three atolls can result in an increased water level (wave set-up) over the reef flat and within the lagoon, and larger than normal waves translating over the reef flat and reaching the shoreline causing overtopping and overwashing, (Figure 12). Waves breaking on the reef “pump” water over the reef and, where there are no motu, into the lagoon. Where outflow from the lagoon is restricted, which is the case for the three atolls on Tokelau, where there are no natural passages from ocean to lagoon, water levels in the lagoon at low water can be up to about 1 m higher than the surrounding ocean.

Wave set-up on fringing reefs is often the most significant factor raising water levels over reef flats; in some cases, such set-up can be half the offshore wave height. Wave breaking, wave set-up, the transformation of waves and wave-induced flows over the reef to the shoreline or lagoon are heavily influenced by the shape of the reef profile and how it varies along the coast. The magnitude of wave set-up tends to increase with increased wave height. It is also heavily dependent on the tide level and magnitude of storm surge, with increasing influence exerted by the reef top topography as the depth of water over the reef flat decreases (with wave set-up generally decreasing with increasing water depth over the reef). However, due to the complexity of the physical processes occurring, present understanding of wave set-up is relatively limited. Furthermore, many of the reports of the large waves during cyclones describe one wave or a series of large waves which cause the most damage, as summarised below:

- The Great Cyclone in 1914 (quoted in Matagi Tokelau, 1991):

It was getting towards night, the swells increased in strength. The evening was dark when a huge wave came, the upper story of a coral lime house at Maluatea [the pastor's compound] fell, while the basic structure still stood. The church of the Catholics collapsed with that wave, when two girls were inside praying. (Fakaofo).

The very last large wave felled the church which had stood at the oceanside on the Pastor's land. (Atafu).

Then came the wave that broke down the church carried all away, with everyone swimming along in water which was 8 to 10 feet above ground level.…… when the wave came down it was like a caterpillar tractor loaded with soils and swept away house, coconut palms, trees and people, and broke the longboats from their lashings. (Nukunonu).

- The swell waves following Cyclone Wini in 1987 (quoted in Matagi Tokelau, 1991, and by Rhys, 1990):

Three breakers were particularly enormous. Standing by the side of a lagoon-side house, they appeared above the palms in the school courtyard. (Fenuafala).

At nine in the evening, there was the ultimate wave, reaching perhaps ten feet in height, which smashed through the main door of the Church……. (Nukunonu).

On the shore the main waves continued from the west but additional waves came alongshore from north and south and met and collided by the landing and then were driven ashore by the main wave front. (This phenomenon was reported to have also occurred in previous storms in 1914, 1966 and 1981). The largest of these combined waves struck around 9 pm when the whole village was awash and seawater was pushed up the incline of the concrete steps of the church and broke down the double doors. These waves had thus reached from five to six metres above still water level. (Nukunonu).

At Fale of Fakaofo, after several days of similar strong westerly winds and tides a metre or more higher than normal, the main storm waves struck at dusk on 28 February with the largest waves some four or five minutes apart between 9pm and 11pm. (Fakaofo).

The discussions held on each atoll, particularly those on Nukunonu and Fakaofo, also identified an extreme wave during Cyclone Percy.

These comments highlight a number of other complex factors that have a bearing when extreme waves break on the fringing reef. The first is the influence of wave grouping, which has a significant influence of wave set-up on the reef top. Large waves in a wave group discharge a greater than average volume of water on to the reef-top or into the lagoon (Gourlay, 1996), increasing the wave set-up and allowing larger waves to translate over the reef flat to the shoreline. After these large waves have passed, the smaller waves following cannot sustain this set-up, and water flows back seawards over the reef edge, particularly through the lower lying sections of the reef (e.g., reef channels). This seaward flow steepens the smaller waves, causing them to break more fully and resulting in much smaller waves translating over the reef flat to the shore. This process is repeated when the next group of large waves breaks on the reef edge. This dynamic fluctuation in reef top set-up (known as surf beat) varies with the timing of the wave groups (hence the largest waves being four to five minutes apart in the description above).

Such conditions can also result in edge waves. These are waves that are reflected back from the shoreline and then become trapped by refraction. They are typically formed when waves approach the shoreline at an angle, or when the coastline is irregular, and can travel along the coastline or occur as standing waves, which could explain the comments relating to alongshore waves from north and south at Nukunonu.

Taking these factors in to account, the methodology suggested by Gourlay (1996) has been used to estimate potential wave set-up during Cyclone Percy. For the significant wave height and period ranges for Cyclone Percy calculated above, Table 5 summarises the estimated mean wave set-up for three water depths over the reef flat (tide + storm surge). Seelig (1993) showed that wave set up due to wave grouping followed a normal distribution. Table 5 also shows the influence of wave grouping on wave set-up and the extreme wave-induced set-up level equalled or exceeded 1% of the time under the particular offshore significant wave height condition.

A further phenomenon observed to have caused substantial damage on coastal structures on reef coastlines in Japan during cyclone events is the amplification of surf beat by resonance at the natural frequency of the water body on the reef top (Nakasa and Nino, 1990; Nakasa et al. 1990). This is dependent on the width of the reef and total water level (i.e., tide + storm surge + wave setup).

Table 5: Estimates of wave set-up along motu shorelines for various water depths over the reef flat based on estimated significant wave heights offshore of each atoll during Cyclone Percy[10].

Atoll	Offshore Hs	Wave period (s)	Tide + storm surge depth (m)	Mean wave set-up (m)	Influence of wave groups on wave set-up (m)	1% exceedence wave set-up (m)
Atafu	4	11	0.5	0.98	0.57 – 1.40	1.97
	5	12	0.5	1.28	0.76 – 1.79	2.51
	4	11	1.0	0.75	0.36 – 1.15	1.67
	5	12	1.0	1.04	0.55 – 1.52	2.19
	4	11	1.5	0.58	0.20 – 0.96	1.45
	5	12	1.5	0.83	0.36 – 1.31	1.93
Nukunonu	5.5	11	0.5	1.34	0.84 – 1.85	2.56
& Fakaofo	6	12	0.5	1.52	0.94 – 2.10	2.91
	5.5	11	1.0	1.10	0.62 – 1.58	2.23
	6	12	1.0	1.27	0.72 – 1.72	2.57
	5.5	11	1.5	0.89	0.43 – 1.35	1.97
	6	12	1.5	1.05	0.53 – 1.58	2.29

The values in the table above are for wave set-up levels along sections of reef flat backed by a motu. Where waves can translate over the reef and into the lagoon, wave set-up (and hence lagoon water levels) will not be quite as high.

The total water level over the reef flat also determines the size of the waves that can translate over the reef flat. As waves break on the edge of the reef, they reform into smaller waves that are limited by the depth of water over the reef flat. The reformed waves behave as solitary waves, with the speed that they approach the shore being proportional to the water depth over the reef flat. Hence, when wave grouping results in increased water depth behind the crest of a wave, larger waves from behind travelling faster in the deeper water can overtake the wave in front. This situation can occasionally permit localised elevated water levels, which allows larger waves to reach the shore.

A reasonably well accepted relationship for maximum wave height on the top of reef flats is that it is generally around 0.55 times the water depth (Nelson, 1994). For example, a water depth of 3 m limit waves to a maximum height of about 1.65 m.

[10] A value for the reef breaker index, $\gamma_r = 0.4$, and the reef profile shape factor, $K_p = 0.44$, have been assumed in the waves set-up calculations.

3.1.5 Accelerated mean sea-level rise

Over the coming century, and beyond, coastal hazards that affect Tokelau will also increasingly be influenced by global climate change.

Accelerated global sea-level rise is a well accepted feature of future climate change. Over the past century, global sea level has been rising at an average rate of about 1.8 mm per year (Douglas, 2001). There is no long-term sea level data for Tokelau, but sea level rise there is likely to be similar to other areas in the adjacent Pacific (e.g., American Samoa, where a rate of 1.6 mm/year was recorded at the Pago Pago tide gauge over the last fifty or so years, albeit without Continuous GPS recording to monitor any vertical land movements).

Figure 22 summarises the projections, from the latest IPCC (2001) report, for global mean sea level rise by 2050 and 2100, with a "most-likely" rise of:

- 0.14-0.18 m by 2050, and
- 0.31-0.49 m by 2100.

An important point to note from Figure 22 is that the acceleration of sea level rise is unlikely to be discernable from year-to-year variability for at least another 20 to 30 years.

There is no evidence yet to suggest that the rate of increase in high tides or extreme water levels will differ from that of mean sea levels. Hence, all things being equal, present-day extreme water levels will tend to be exceeded more frequently.

Other climate change factors that will potentially impact Tokelau are discussed by Mclean and d'Aubert (1993).

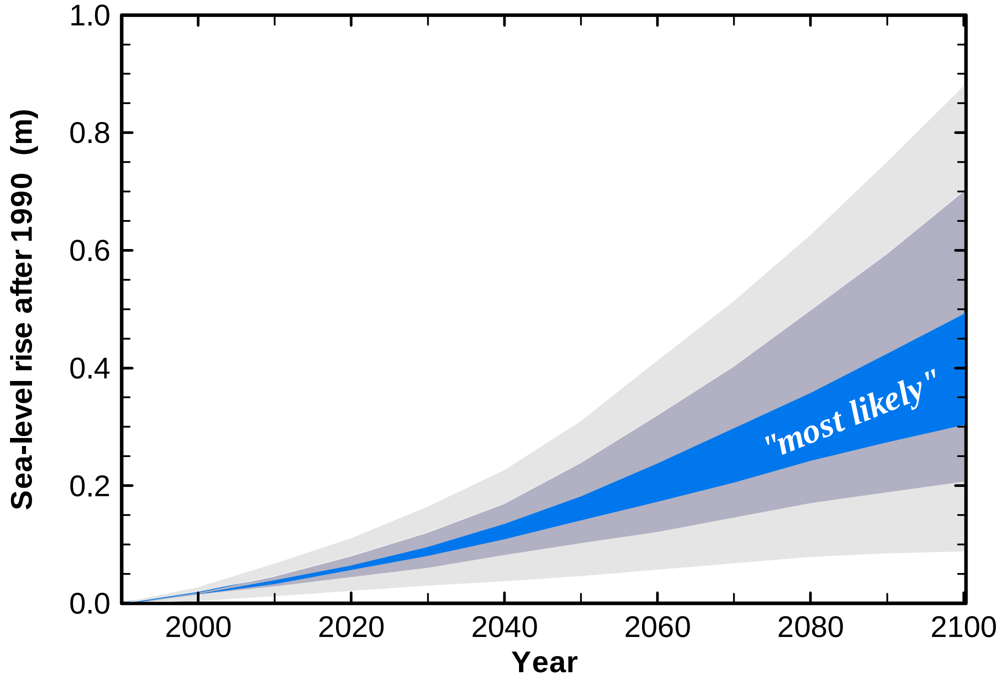

Figure 22: IPCC (2001) global mean sea level rise projections (tied back to 1990). Note that the blue band corresponds to the most likely range of sea-level rise, the dark grey to the intermediate zone, and light grey to the upper and lower extreme zones.

3.2 Development of design conditions

Methods for designing coastal structures are usually based on the concept of designing a structure to meet some design load criteria (e.g., a particular wave / water level combination). Typically, load criteria are expressed on a probabilistic basis, e.g., the 1 in 20 year return period wave height[11] (or expressed in a different way, a 5% chance of the wave height being exceeded in any one year). Full probabilistic methods are rarely used, a primary reason being the lack of understanding of the uncertainties associated with the interactions between the hydraulic loadings and failure modes of coastal structures.

A full probabilistic assessment of wave and water levels experienced in cyclone conditions is beyond the scope of this project (see Section 3.4 for further recommendations). Instead a pragmatic approach has been adopted to develop basic design conditions for future coastal engineering design on the three Tokelau atolls. However, if major capital infrastructure works, such as a wharf and boat harbour at

[11] The wave height likely to be exceeded on average once every 20 years.

Fakaofo are to proceed, a more rigorous and probabilistic assessment should be carried out.

Based on the analysis in Section 2.2, discussion on each atoll comparing the impacts of Cyclone Percy against previous cyclones, and the likelihood of more frequent La Niña conditions due to a dominance over the next 20 or so years, it is estimated that the wave and water level conditions experienced during Cyclone Percy (at Nukunonu and Fakaofo) constitute around a 15-year return period. Given the limitations of materials and construction methods on Tokelau, coastal defences designed to withstand damage that would impact on their serviceability under such conditions would appear to be a reasonable goal (and similar to design standards for village structures in Samoa). These conditions are summarised in Table 6 below.

Table 6: Summary of design wave and water levels on the ocean frontage.

Tide level equivalent to MHWS (0.5 m MLOS) which is approximately a water depth of 0.85 m above reef flat level:	0.85 m
Allowance for interdecadal fluctuations allowing for the fact that the tidal analysis was conducted during an El Niño period, that La Niña conditions are likely to dominate over the next 20 or so years, and sea level rise over the next 20 years is likely to be 0.04 m:	0.25 m
Storm surge:	0.3 m
Offshore significant wave height :	6 m
Offshore peak wave period:	12 s
Estimated mean wave set-up during a group of larger waves along sections of reef backed by a motu:	1.65 m
Tide + storm surge + wave set-up (design water level m above reef flat):	3.05 m
Corresponding depth limited wave height over the reef flat based on the relationship 0.55 x water depth. Due to the uncertainties and assumptions this has been assumed to be the significant wave height rather than the maximum wave height:	1.7 m

3.3 Influence of the reef channels on hydrodynamic processes

The influence of small boat channels on hydrodynamic processes over fringing reefs, particularly during cyclone conditions, is poorly understood. General environmental guidelines for the development of new reef channels (and for the further development of existing channels) were developed by Kaly & Jones (1990b) for NZAid as part of their research into the impacts of channel creation in the outer atolls of Tuvalu. Their adequacy was assessed in a subsequent review (Ramsay & Kaly, 2004). The initial guidelines consisted of a list of 10 general suggestions to be followed when constructing a new reef channel (listed in Table 7 below), with this list extended by Kaly (1998) to included a further 4 recommendations (listed in italics in the table below).

The guidelines were intended as general requirements, to be used alongside site-specific environmental assessment and recommendations to take account of local conditions and factors at each proposed or existing channel site. The guidelines can be split into two types: those necessary to avoid significant detrimental impacts either due to the construction activities or the effects of the channels on coastal processes; and those that help mitigate the overall impact that such construction activities have on small islands.

Table 7: General guidelines for the construction of reef channels (Kaly, 1998).

Guidelines aimed at avoiding detrimental impacts due to channel construction	Guidelines aimed at mitigating the overall impact of channel construction activities
• Limit the number of channels built on any one island • Minimize the size of channels and keep them away from the beach • Minimise the damage to fish (by only blasting between 11am and 6pm) • Avoid building or enlarging channels which connect with lagoons • Never build a channel connecting a ponding lagoon with the ocean • Build channels on protected side of islands, avoid points around the reef, use areas which have already been damaged in other ways • Do not spread spoil from blasting over a wide area of the tidal rock platform	• Build channels so that their walls and floors are complex • Channels may have boulder linings (although this is not required) • Stabilize the upper beach near channels • Reinforce the inside surface of soft rock channels with concrete ribs. • Relocate any corals likely to be damaged by construction or subsequent use of the channel. • Restore any newly-formed surfaces with coral seeding • Consider declaring a permanent marine reserve on each island which has channels

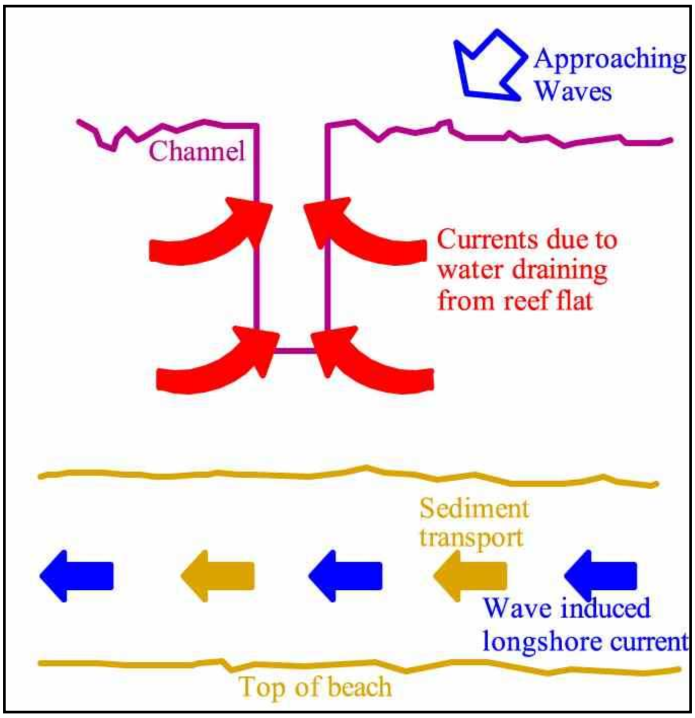

Figure 23: Rip currents over the reef flat created by the boat channel

Figure 24: The reef channel at Nukunonu provides an example of the influence of waves translating over the reef flat and the resulting effect on the shape of the coastline.

These guidelines take into account one of the main impacts of the channel, the creation of seaward-flowing rip currents by (1) ensuring the size of the channels are as small as is absolutely necessarily, and (2) ensuring the landward end of the channel is kept well away from the toe of the beach. The rip current forms when waves breaking on the edge of the reef raise the water level on top of the reef flat (wave set-up). As the breaking wave height is lower at the channel than over the reef either side of it, wave set-up is also higher either side of the channel. This results in a flow of water towards the channel which subsequently flows seawards out via the channel (i.e., the channel is the easiest way for the water on the reef flat to return to the ocean), (Figure 23).

If the landward edge of the channel has been built sufficiently far from the beach, under most conditions rip currents should not interact with the beach or longshore currents moving sand along the beach. However, if the channel is constructed close enough to the beach, such as at Nukunonu, (Figure 24), beach sediments can be eroded and transported seaward out through the channel. Similarly, as waves get bigger, for example during cyclones, the rip currents will tend to migrate closer to the beach, which can result in significant amounts of beach sediment being lost either into the channel, or transported down the channel and lost off the seaward edge of the reef.

Figure 24 also shows the impact of the channel on the pattern of waves translating over the reef flat and the effect this has on the shape of the coastline opposite the reef channel. The plan shape of the raised beach rock (*te papa*) along this section of coast suggests that there is likely to have been some form of natural channel on the outer part of the reef prior to the creation of the man-made one. However, the creation of the boat channel will have further influenced the way waves translate over the reef flat and the resulting impact on the shape of the coastline at this location.

On Atafu, detrimental effects of the reef channel are not as readily evident under normal wave conditions as it is located at the southern end of the motu in an area where accretion is occurring, with the landing platform and training walls also helping to reduce impacts at this location. Likewise at Fakaofo, it is difficult to determine whether the channel increases coastal hazard risk.

Discussions are currently taking place with the Earth Sciences Department at the University of Waikato for a Masters research project to investigate the effects of the Nukunonu small boat channel on coastal processes.

4. Extending our knowledge of coastal-related hazards in Tokelau for future management

This report summarises known information on cyclone-related coastal hazards affecting Tokelau. Our understanding of the physical coastal processes that occur during cyclones, and the resulting variability and extent of the impacts that occur within atoll communities, is still far from complete. A number of suggestions are outlined below that would aid ongoing activities relating to both this project and the UNDP-funded Strengthening Disaster Management and Preparedness project.

There was insufficient time on each atoll during the present project to discuss historical accounts of past cyclones in any great detail, with most of the comments related to the most significant events that have affected Tokelau (1914, 1966, Cyclone Tusi and the storm surge from Cyclone Wini). However, there is very little historical accounts or written information on cyclones prior to the 1914 event, largely due to the depopulation caused by the Peruvian slave trade in the 1860s and limited colonial presence (Prof. Judith Huntsman, pers. comm.). Furthermore, much of the information on cyclones during the past century, particularly the earlier events, has not been recorded in any detail. A comment was made at one of the community meetings that what happens during a cyclone is quickly forgotten as the community gets on with their day-to-day tasks. A programme of recording information and details of past cyclones as described by the senior community members would help retain such information and help relate future risk reduction activities to past impacts.

Furthermore, it is suggested that, as part of the Strengthening Disaster Management and Preparedness project, a methodology is developed, and on island training provided, to provide a system for the Tokelau communities to systematically record damage in the aftermath of future events.

Such work could be extended further to explore traditional knowledge of weather and climate variability and change. Similar projects have been initiated in other Pacific Islands and with Māori in New Zealand over the fears of a continued loss of such knowledge. These projects can help understand how island communities have adjusted to variability and change in the past, and how traditional knowledge can complement scientific approaches to provide clues on how to build resilience and develop adaptation strategies to help with future climate change.

In the previous section, a brief assessment was made of wave conditions during Cyclone Percy. However, to more accurately determine wave conditions during any particular cyclone typically would require detailed hydrodynamic and spectral wave modelling. Using such models to hindcast storm surge and wave conditions offshore of the three atolls from past cyclones is a relatively straightforward exercise, but is beyond the scope of this present study. However, such modelling, calibrated against past cyclone events, can be of considerable use in future disaster management planning. Some examples of typical applications include:

- Determining the track and combinations of cyclone parameters that create the most severe oceanic conditions (and how this compares to past cyclones).

- Developing sets of pre-simulated cyclone track and intensity scenarios that can be used to inform real-time emergency response.

- Probabilistic assessment of storm surge, extreme waves, overtopping and overwashing.

- Assessing the potential impacts of sea-level rise on inundation risks.

5. Conclusions

This report is one in a series prepared from on-atoll discussions and assessments of cyclone induced coastal hazards on each of the atolls of Tokelau. It provides a summary of known cyclone hazard and associated coastal hazard information to assist with future on-island decision making, education and awareness activities, and to provide potential design conditions for future coastal engineering works.

The review identified that:

12. Cyclone occurrence affecting the atolls of Tokelau is strongly influenced by interdecadal climate variability, with all cyclones that have significantly impacted on the three atolls occurring during El Niño periods.

13. There are few details of cyclones affecting Tokelau before the Great Cyclone (*Afa Lahi*) in 1914. Over the last century there have been approximately 10 cyclones that have caused significant damage to one or more of the Tokelau atolls, with the events of 1914 and 1966 most notable. A number of other cyclones have tracked within 300 km of the atolls but have caused less damage.

14. Of the cyclones that have affected Tokelau, three general patterns of tracks were identified:

    - The first set is characterised by Cyclones Tusi, Ofa, Val and Percy, which formed in southern Tuvalu and tracked eastwards before moving in a south easterly direction to the west of Tokelau. The inhabited motu are affected by high winds and high waves during this type of cyclone.

    - The second set is characterised by Cyclones Esau, Wini and the cyclone in 1966. This type tracks in an easterly direction well to the south of Tokelau close to Wallis and Futuna and Samoa. Winds tend not to reach hurricane force on Tokelau, but high swell waves emanating from the cyclone can affect the western coastlines of the atolls for prolonged periods.

    - The final set is characterised by Cyclones Bob, Collette, Keli and Ron. This type either passes close to Tokelau but tracks in a south west direction, or forms to the south of Tokelau and hence does not appear to cause significant damage to the inhabited sections of the atolls.

1. Over the period 1969 to 2005 there was about a 15% chance of one or more cyclones in any one year causing significant damage on one or more of the atolls of Tokelau. This likelihood was higher than the average over the period 1914 to 2005 which was about a 10% chance of one or more cyclones in any one year.

2. The potential effect of future climate change on the occurrence, strength and movements of tropical cyclones close to Tokelau is uncertain with present studies suggesting that peak wind intensities may increase by 10-20%. However, over the next 20 or so years the Interdecadal Pacific Oscillation is expected to be in a negative phase. This would tend to increase the occurrence of neutral or La Niña conditions, which may decrease the occurrence of cyclones affecting Tokelau compared to the last 20 to 30 years. In the longer term, increased sea-surface temperatures may increase the number of cyclones forming and tracking close to Tokelau.

3. Of the ten most significant cyclones, five coincided within two days of a spring tide. However, significant damage can still occur when a cyclone coincides with lower tidal ranges, as occurred during the 1966 event.

4. Extreme water levels experienced during cyclones are a combination of a number of factors:

    - The astronomical tide with a spring range of 0.98 m and neap range of 0.59 m. Mean High Water Springs (MHWS) is exceeded by around 33% of all high tides and is approximately 1.15 m above the level of the reef flat, with the highest tide around 1.35 m above the reef flat level.

    - Long-period sea-level fluctuations, including annual (seasonal heating and cooling), interdecadal (El Niño Southern Oscillation), and decadal (IPO related). These can cause long term fluctuations in sea level of around ±0.25 m, with higher mean sea-levels occurring during late summer, a strong La Niña and –ve phase of IPO.

    - Storm surge, caused by the combination of low atmospheric pressure and strong winds. These typically cause a relatively low increase in water levels in the ocean <u>unless</u> the cyclone tracks relatively close (< 50 km) to any of the atolls. For example, the storm surge caused by

Cyclone Percy would have been around 1 to 1.2 m close to the centre of the cyclone, but was only around 0.2 m to 0.3 m at Tokelau.

- The most significant influence on extreme water levels during cyclone events is typically due to wave set-up caused by waves breaking on the edge of the fringing reef. Wave set-up processes are extremely complex, varying both spatially along a section of coast, and temporally due to the particular wave spectrum and effects of wave grouping. Wave set-up during Cyclone Percy was estimated to have typically fluctuated between 1 to 2 m and up to 3 m during the largest wave grouping events.

- Mean sea levels in the Pacific region have risen about 0.16 m over the last century. This rate is expected to accelerate over the next century due to the effects of global climate change. Latest estimates give a "most likely" rise of 0.14-0.18 m by 2050 and 0.31-0.49 m by 2100. An important point to note is that this acceleration is unlikely to be discernible from the year-to-year variability in mean sea levels for at least another 20 to 30 years.

5. A design wave and water level condition has been derived based on estimates of conditions during Cyclone Percy, which is estimated to be around a 15-year return period event. This suggests:

   - An offshore significant wave height of 6 m and peak wave period of 12 s.

   - A design water level (astronomical tide + storm surge + wave set-up) of 3.05 m above reef flat level.

   - A depth limited significant wave height of 1.7 m on the reef flat.

   Such design conditions should be satisfactory for the design of future coastal protection structures. However, it is recommended that a more rigorous assessment be conducted for larger capital investment projects requiring such information, e.g., any proposed wharf.

6. The effects of the small boat channels exacerbating localised damage during cyclone events are not well understood. However, it would appear that the channel at Nukunonu does have a detrimental influence.

7. A number of suggestions are provided that would aid ongoing activities relating to both this project and the UNDP funded Strengthening Disaster Management and Preparedness project. These include:

   - Recording recollections of past cyclones, particularly those that occurred longer than 20 – 25 years ago.

   - Developing a methodology for each atoll community to systematically record the damage that occurs during a cyclone.

   - More detailed numerical modelling of cyclone storm surge and wave conditions to improve both design conditions and aid forecasting and warning systems for future events.

6. Acknowledgements

Colleagues at NIWA including Dr Rob Bell, Dr Richard Gorman, Dr Brett Mullan and Dr Jim Salinger who provided assistance with the preparation of data for this report are gratefully acknowledged.

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