Kiribati Adaptation Programme. Phase II: Information for Climate Risk Management.

Sea levels, waves, run-up and overtopping

NIWA Client Report: HAM2008-022
September 2008
Updated April 2010

NIWA Project: GOK08201

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Doug Ramsay
Scott Stephens
Richard Gorman
John Oldman
Rob Bell

With assistance from:
Herve Damlamian (SOPAC)

NIWA contact/Corresponding author

Doug Ramsay

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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

Contents

Reviewed by:

Dr M. Pritchard

Approved for release by:

Dr M. Green

Formatting checked

Executive Summary

The Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report (AR4) released in 2007 identified that Pacific Island states are likely to be some of the most seriously impacted by climate change. However, AR4 highlighted that despite this, little specific work has been carried out to quantify the potential changes on hazard occurrence and magnitude due to climate-related hazard events and the implications this has on the specific risks facing different Pacific Island communities (i.e., risks at the island, community and village levels), different economic sectors, or to essential infrastructure.

A key objective of the *Climate information for risk management* component of the Kiribati Adaptation program was to derive such I-Kiribati-specific climate change projections. These are to be adopted as national standards for options analysis and technical design work ("climate proofing parameters"), particularly regarding coastal and water-related issues, and to be used to underpin and guide risk assessment and adaptation planning. This involved deriving information on:

- extreme rainfall and drought,
- mean and extreme sea-level and wave conditions, as well as site-specific shoreline wave conditions, wave run-up levels and overtopping volumes along the different shorelines of Tarawa,

and how these may change under different climate change scenarios. This is one of two technical reports and covers the coastal related aspects.

What influences sea levels in Kiribati?

The level of the sea in Kiribati is influenced by a number of components, the largest of which is the astronomical tide, the twice-daily rise and fall of water (although in the Line Islands the tide range is much smaller). High and low tide times and levels can be accurately predicted many years in advance. However, tide levels can be elevated (or lowered) by a number of factors including:

1. The 2 to 5 year El Niño Southern Oscillation (ENSO) cycle: During El Niño phases tide levels are pushed down (resulting in lower sea levels), and conversely during La Niña phases tide levels are pushed up, (resulting in higher sea levels). These effects can occur over a number of months to a year or more. Since monitoring of sea-levels began in 1974 the influence of ENSO has caused variations in monthly average sea-levels in Tarawa that range up to 0.43 m.

2. Over longer 20 to 30 year cycles a climate-ocean feature known as the Interdecadal Pacific Oscillation (IPO) influences the frequency and intensity of ENSO events. Between about 1978 to 2000, the IPO was in a phase where El Niño events were stronger and more frequent, hence

sea levels over this period tended to be lower on average. Since 2000 the IPO has been in a phase where La Niña events have been more common, resulting in higher sea levels relative to the twenty year period prior to 2000.

3. Storm surge: the temporary increase in sea level over 1 to 3 days due to a reduction in atmospheric pressure and influence of wind on the sea surface. Due to the lack of severe storms and cyclones affecting Kiribati, storm surge only has a very minor influence on sea levels, particularly on the ocean shoreline. Storm surge typically only adds a few centimetres to sea levels (and unlikely to contribute anything more than an additional 0.15 m in temporary sea level).

4. Wave setup: On ocean shorelines, the effect of large waves breaking on the seaward edge of the reef raises water levels over the reef flat. This has a much larger influence on sea levels along the ocean shorelines than storm surge and can raise reef flat water levels by up to about 1 m, particularly during large swell conditions.

5. Sea-level rise: the increase in sea levels due to increasing global temperatures resulting primarily in a warming of the oceans causing them to expand, and melting or discharge of ice sheets and glaciers on land.

How much have sea levels risen in Kiribati?

Sea-levels have been recorded at Betio on Tarawa since 1974. Between this time and the end of 2008, the trend in average sea level rise (mean level of the sea) was approximately 1.8 mm per year (or a rise of just over 6 cm over this time) which is very similar to global average rates over the last century.

Between 1993 (when the current SEAFRAME tide gauge was installed) and the end of 2008 the average rate of sea-level rise was 3.5 mm per year. However, while this larger rate is similar to the global rate of 3.2 mm per year measured by satellites between 1993 and 2008, is not necessarily an indication of an increasing rate of sea-level rise. It is in significant part, due to the fluctuating effect on average sea levels of the El Niño Southern Oscillation and the IPO. As there needs to be at least around 25 years of sea-level records before some judgement of long-term sea-level rise rates can be made, the SEAFRAME tide gauge data record will continue to result in monthly and annual variations in the rate of sea-level rise over the foreseeable future.

Is storm surge increasing?

Storm surge (the short term increase in sea level due to low atmospheric pressure and influence of wind) is a minor component of the sea levels experienced in Kiribati. There is nothing obvious in the sea-level record to suggest that storm surge has increased in magnitude or frequency over the last 35 years, and in any case is not a significant factor in high sea levels experienced on Tarawa.

What is the trend in the highest annual sea level?

Based on the sea-level record from 1974 to 2008, the upward trend in the highest sea level reached each year is 1.9 mm per year. This rate is very similar to that of the mean level of the sea. Over shorter time periods this can vary. For example since 1993 the trend in the highest sea level each year has been static, compared to a rising trend of 3.5 mm per year for the mean level of the sea. In Kiribati, in the long term, we would expect the trend in high sea levels to be similar to the trend in mean sea-level rise.

Are king tides becoming more frequent?

King tide is a popular name referring to any high tide or sea level that is well above an average height. Over much of the last ten years or so the perception is that king tides have become more frequent. This is indeed likely and is due to a combination of an increased frequency of La Niña events (compared to the period prior to 2000) which has pushed sea levels up and is further exacerbated by sea-level rise. For example the average number of hours that sea levels exceeded a level of 2.8 m above SEAFRAME datum in the 1970s was just over 5 hours per year. These exceedances have increased over the subsequent decades, occurring over 28 hours on average each year between 2000 and 2008.

Long-term sea-level rise will continue to push sea levels higher resulting in high tide levels increasingly exceeding what may be presently considered a king-tide level.

How much sea level rise will occur in the future?

Sea levels will continue to rise over the rest of the 21st century and beyond, primarily because of thermal expansion within the oceans and loss of ice sheets and glaciers on land. How much sea-level rise occurs depends on how humans continue to live and emit greenhouse gases. However, even if greenhouse gas emissions were stabilised today, sea levels would continue to rise. Indeed sea levels to about 2050 are relatively insensitive to changes in emissions over this timeframe because of the long time it takes the oceans to respond to changes in atmospheric temperatures, but future changes and trends in emissions become increasingly important in determining the magnitude of sea level rise beyond 2050.

As we don’t know exactly how much greenhouse gases will be emitted in the future and what the response of the large ice sheets in Greenland and Antarctica will be to rising temperatures, it is difficult to provide a best or upper estimate of sea-level rise over this century.

Based on discussions by the I-Kiribati Inter-governmental Working Group participants, three future timeframes that were representative for I-Kiribati decision-making and three future climate change scenarios, were selected to be used for routine climate change assessments. The decision was made to focus on the IPCC AR4 scenarios over the three timeframes, rather than accommodate some of the higher sea-level magnitudes now being suggested over this century on the basis that the global

community will eventually implement mitigation measures that limits these higher projections of sea-level rise.

The corresponding sea-level rise magnitude, relative to the average sea level between 1980 and 1999, are summarised in the table below for the three scenarios and timeframes.

Timeframe Name (English)	Timeframe Name (I-Kiribati)	Timeframe	Climate change scenario		
			Low	Intermediate	High
			SLR (m)	SLR (m)	SLR (m)
Grand children	Te tibu	2012 - 2036	0.09	0.13	0.20
Great-grand children	Tibu-toru	2036 - 2060	0.13	0.22	0.35
Great-great grand children	Tibu-mwamwanu	2060 - 2084	0.17	0.33	0.55

What effects will climate change have on other factors influencing coastal hazards?

Much less is known about how climate change will affect other factors that influence coastal hazards (such as swell and wave conditions, storm frequency and intensity and influence of El Niño). However, for Kiribati it is unlikely that there will be any noticeable change in astronomic tide characteristics and it is unlikely that there will be any significant noticeable change in the influence of storm surge on high sea levels.

How will sea-level rise affect overtopping of the causeways and other seawalls?

Increases in sea level, and hence increased water depths over the reef flats, will result in larger wave conditions reaching the shoreline on Tarawa. As both wave run-up and overtopping of coastal defences can be extremely sensitive to small changes in water levels and wave conditions reaching the shoreline, even very small changes in sea-level rise may have a significant impact on the frequency and volume of inundation of the immediate coastal margins of Tarawa, or overtopping of the causeways between the various islets. As an example, for a storm condition that has a 10% chance of occurring in any one year and for the low, medium and high I-Kiribati sea-level rise scenarios, wave overtopping volume of the causeway between Bairiki and Betio could increase by 59%, 141% and 275% respectively by the period 2060 to 2084.

1. Introduction

1.1 Project overview

The Government of Kiribati (GoK) commissioned NIWA to carry out one of the components (KAP II Component 1.4.0 FS5) of Phase II of the Kiribati Adaptation Project. The overall objective of Phase II is to *implement pilot adaptation measures, and consolidate the mainstreaming of adaptation into national economic planning*.

The objective of this particular component is to develop climate risk information to be adopted as national standards for options analysis and technical design work ("climate proofing parameters"), particularly regarding coastal and water-related issues.

This report (technical report) focuses on the coastal-related aspects of the project. It is one of a series of reports produced as part of the *Climate Information for Risk Management* component (Component 1.4.0) of the Kiribati Adaptation Program Phase II (KAP II). Figure 1 summarises the linkages between the various reports produced as part of the *Climate information for risk management* component and the associated *Integrated climate change adaptation based risk diagnosis and response processes* component of KAP II. The rainfall and drought aspects of Component 1.4.0 are covered in a companion report (Thompson et al. 2008).

Following this report being finalised, a follow-on component was conducted between July 2009 and April 2010 with the aim of developing the depth of understanding and capacity within the GOK inter-ministerial working group to use and apply the coastal information derived during this component. During this follow-on component the opportunity was taken to bring some of the original analysis originally presented in this report up-to-date. Hence this report has been revised to incorporate the updated information.

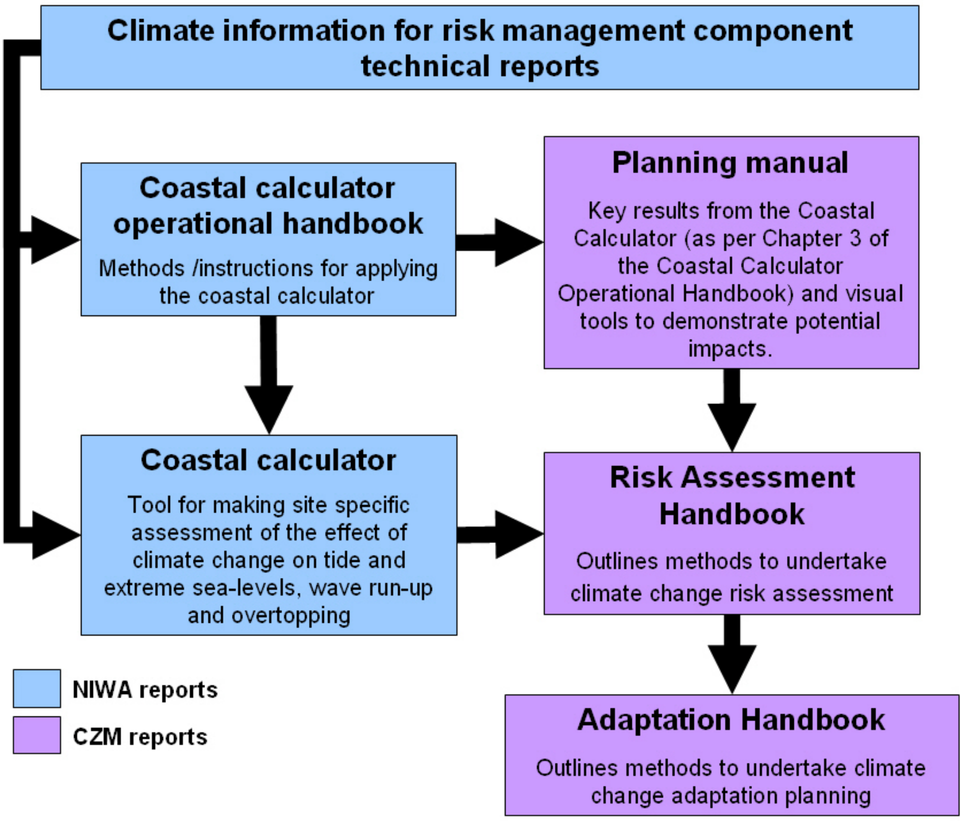


Figure 1: Linkages between the various reports produced as part of the *Climate information for risk management* component and the associated *Integrated climate change adaptation based risk diagnosis and response processes* component of KAP II.

1.2 Scope of the coastal component of the project

The terms of reference (contained in full in Appendix 1) for the project specified the following to be conducted for the coastal aspects of the project:

- Analysis and estimates of storm surge that accord with the 1%, 2% and 10% annual exceedance probability (AEP) giving explicit consideration of:
    - the inverse barometric effect;
    - wind stress;
    - wave set-up.

- Analysis and estimates of maximum at-shoreline wave heights that correspond with the 1%, 2% and 10% AEP.

- Analysis and estimates of maximum wave run-up levels for a range of differing foreshore slope angles.

- Generation of storm surge, wave height and run-up levels for a range of differing foreshore slope angles.

- Generation of storm-surge, wave height and run-up estimates for a range of differing island exposures that should at least include:

    - windward ocean shoreline;
    - leeward ocean shoreline;
    - windward lagoon shoreline;
    - leeward lagoon shoreline;
    - gross differences in reef platform width.

- In collaboration with the GoK CCST, identify combined scenarios of the risk of sea-level change and extreme water levels for three time horizons, 2025, 2050 and 2100.

In conjunction with the rainfall and drought aspects, in-country training on the use and application of the data derived as part of this project was conducted along with assistance in integrating climate risk information into awareness products.

1.3 Outline of this report

In the introduction to this report, the next section summarises some wave and sea level terminology that are used throughout the report.

Section 2: Presents and discusses the various climate, wave and sea-level datasets used in the study.

Section 3: Summarises the analysis of sea-level data at Tarawa, assesses the relative contributions of different sea-level components, such as astronomical tide, storm surge and fluctuation of the mean level of the sea, and assesses storm tide levels at 23 locations around the lagoon shoreline of Tarawa for the present-day and future sea-level rise scenarios.

Section 4: Provides an overview of climate change and the effect that may have on coastal processes (primarily sea-levels and wave conditions) of relevance to this study.

Section 5: Provides details of ocean shoreline deepwater wave conditions around each atoll in Kiribati along with details of the processes of wave set-up and wave height propagation over the fringing ocean-side reef flat.

Section 6: Provides information on wave conditions at 23 locations around the lagoon shoreline of Tarawa.

Section 7: Provides information on the correlation between extreme wave conditions and storm tide levels at 23 locations around the lagoon shoreline of Tarawa for the present-day and future sea-level rise scenarios, and for the north (east), south and west ocean coastlines of Tarawa.

Section 8: Discusses the wave run-up and overtopping processes on atoll beaches and various coastal defence structures.

Section 9: Provides a brief overview of the calculator developed to allow site-specific assessment to be made of wave run-up and overtopping on Tarawa.

Appendices contain more details on the various methodologies used within the study along with data tables not included in the main body of the text, including:

Appendix 1: Terms of reference.

Appendix 2: Glossary.

Appendix 3: Sea level, wave and joint probability analysis methodologies.

Appendix 4: Draft discussion on land level datum issues on Tarawa.

Appendix 5: High tide exceedance curves for each island.

Appendix 6: Extreme wave and storm tide level joint probability plots and tables for the 23 locations around Tarawa lagoon.

Reference should also be made to the training material (contained on the supporting CD to this report) that was presented during the workshops carried out in Tarawa during March 2008, July and November 2009.

1.4 Water level and wave terminology

This report is focussed on water levels and waves, how these two parameters influence wave run-up, overtopping, overwashing and inundation of land areas on Kiribati, and how this may change in the future. Throughout this report the following has been assumed.

The elevated water level experienced at the shoreline during storm or large wave conditions is a combination of a number of processes (Figure 2) including:

- At any given time, there is a ***predicted astronomical tide*** level above a datum (for example SEAFRAME Gauge 0). The tide oscillates about the mean level of the sea (MLOS).

- The mean level of the sea (MLOS) is influenced by longer term climate fluctuations relating to ***seasonal effects*** (annual cycle), ***El Niño Southern Oscillation*** (ENSO) (2-4 year cycles) and the ***Interdecadal Pacific Oscillation*** (IPO) (20-30 year cycles). Seasonal sea-level fluctuations in Kiribati are relatively small. Fluctuations due to ENSO are more significant with sea levels tending to be depressed during El Niño phases, and higher during La Niña phases. IPO phase can also have a slight influence. Finally, MLOS is increasing due to global warming.

- ***Storm surge*** is the increase in regional sea level (excluding the effects of waves) due to low barometric pressure and set-up due to winds blowing onshore.

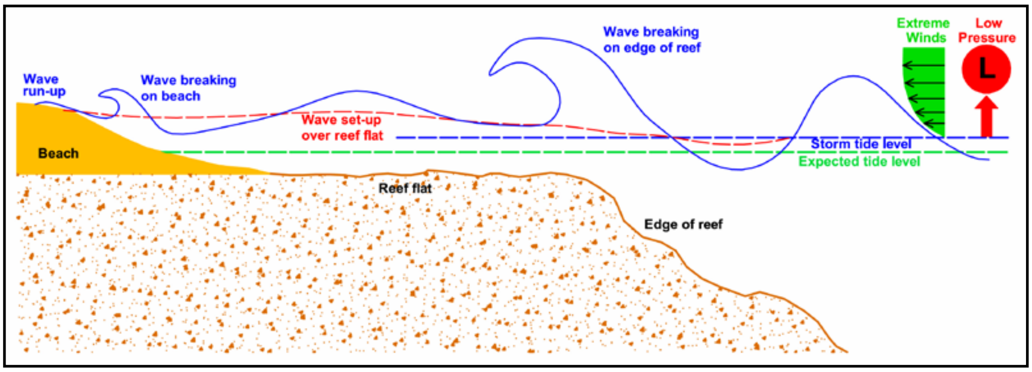


Figure 2: Components of water level over a fringing reef.

- In this report, ***storm tide*** is the term used to describe the temporary rise in level of the sea offshore of the wave breaker zone. Storm tide is the combination of the MLOS, the predicted astronomical tide at the time of the event, and the storm surge height.

- Over the reef flat along the ocean shoreline, ***wave set-up***, the increase in sea level over the reef flat due to waves breaking on the seaward edge of the reef, has a much larger influence on sea levels than storm surge. It is dependent on the height and period of the offshore wave conditions as well as the shape of the reef edge and rim. Some further wave set-up may occur at the shoreline due to waves translating over the reef flat and breaking close to the beach but this will be much more modest due to the reduced size of the waves over the reef flat.

- Wave set-up can vary considerably over short timescales (4-5 minutes) due to the influence of ***wave grouping***. Large waves in a wave group discharge a greater than average volume of water on to the reef-top 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 any lower lying sections of the reef (e.g., reef channels). This seaward flow steepens the smaller waves, causing them to break more fully, resulting in much smaller waves translating over the reef flat to the shore.

- At the shoreline, the maximum vertical elevation reached by the sea also depends on ***wave run-up*** (or swash). This acts on top of the storm-tide and wave set-up levels. Wave run-up is highly variable even over a short length of coast, varying according to the type of beach, beach slope, backshore features and presence of any coastal defence structure.

- Where wave run-up exceeds the level of the beach or coastal defence crest, wave ***overtopping*** occurs. The level of damage to buildings or infrastructure or danger to people depends on the volume of seawater that overtops which can vary significantly on a wave-by-wave basis.

In terms of extreme wave conditions, ocean shorelines in Kiribati are a mixture of more distantly generated ***swell*** waves and locally generated ***wind-sea***. However, it is swell conditions that will cause the most significant occurrences of wave set-up, run-up and overtopping on the ocean coasts. Waves tend to be defined in terms of their ***significant wave height***, which is the average height of the highest 33% of the waves over a certain period of time, their ***wave period***, which is the average time between successive waves, and the ***wave direction***.

2. Methodology overview and data sources

2.1 Methodology

Figure 3 summarises the methodology adopted for assessing extreme wave conditions, water levels and their joint occurrence along both the ocean and lagoon shorelines of Tarawa. The outputs from the wave and sea level assessment are contained within a spreadsheet database/tool (Coastal Calculator) where, on Tarawa, site specific wave set-up, run-up and overtopping calculations can be made and the potential effect of climate scenarios on these parameters investigated.

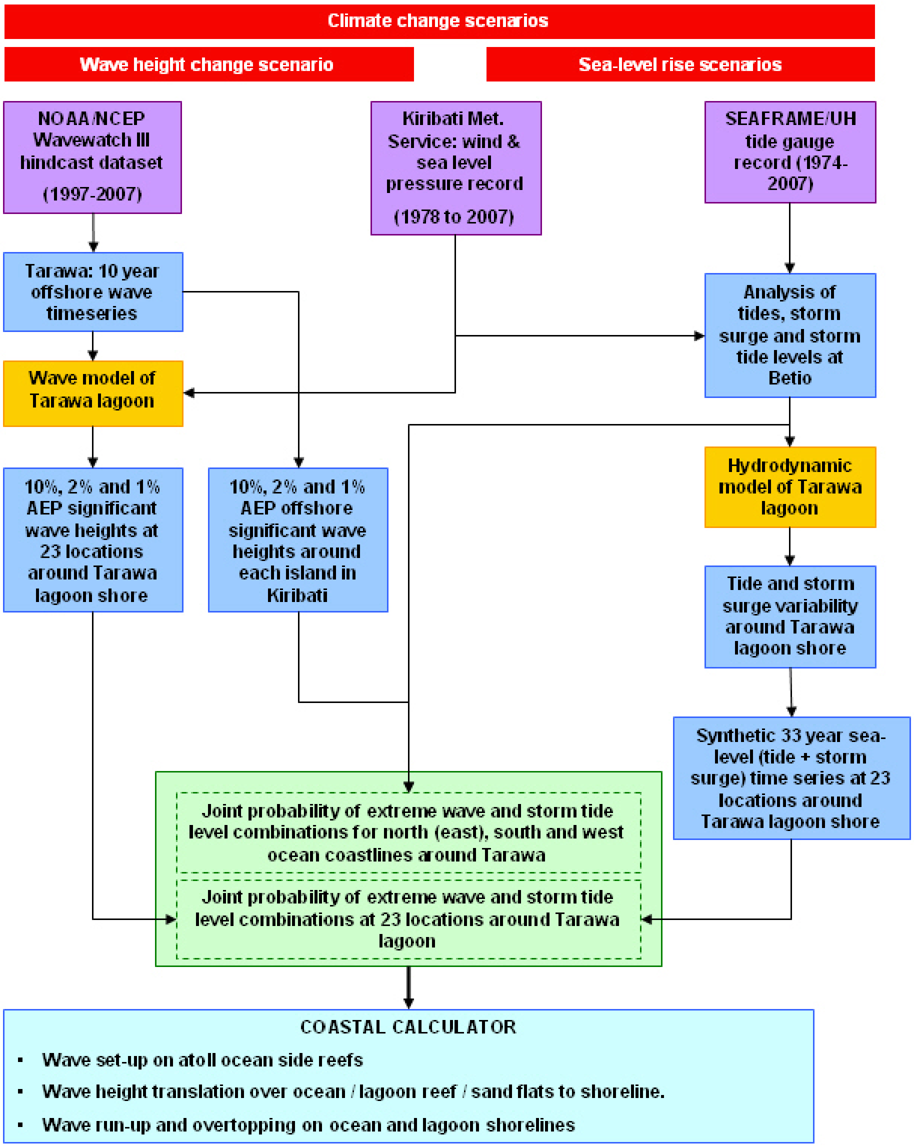


Figure 3: Methodology overview for deriving extreme wave height and water level probabilities.

2.2 Data sources

2.2.1 Sea level measurements

A SEAFRAME sea-level recording gauge was installed in Betio, Tarawa, Kiribati, in December 1992. It records sea level, air and water temperature, atmospheric pressure, wind speed and direction (AMSAT et al. 2004). As the original benchmark for marine surveys in Tarawa is unrecoverable (AMSAT et al. 2004), the SEAFRAME Gauge 0 has become the reference level of choice for modern tidal forecasts and reporting (e.g., NTC 2007, Paul Davill, Bureau of Meteorology, pers. comm.). Older historical records were also obtained for use in this study (Table 1, Figure 4).

Table 1: Sea level records used in this study. The tabulated datum shift is that used to adjust the historical records (Figure 4) to create a seamless 33.25-year record relative to SEAFRAME Gauge 0 (Figure 5).

Name	Location	Start date	Finish date	Datum shift (mm)
Tarawa A	Betio	31 May 1974	31 Dec 1983	+419
Tarawa B	Bairiki	17 May 1983	10 May 1988	+23
Tarawa C	Betio	20 Jan 1988	31 Dec 1997	+23
SEAFRAME (D)	Betio	27 Mar 1993	31 Aug 2007*	0

*The analysis of mean sea-level rise was extended to 31 December 2008 during the follow-on component.

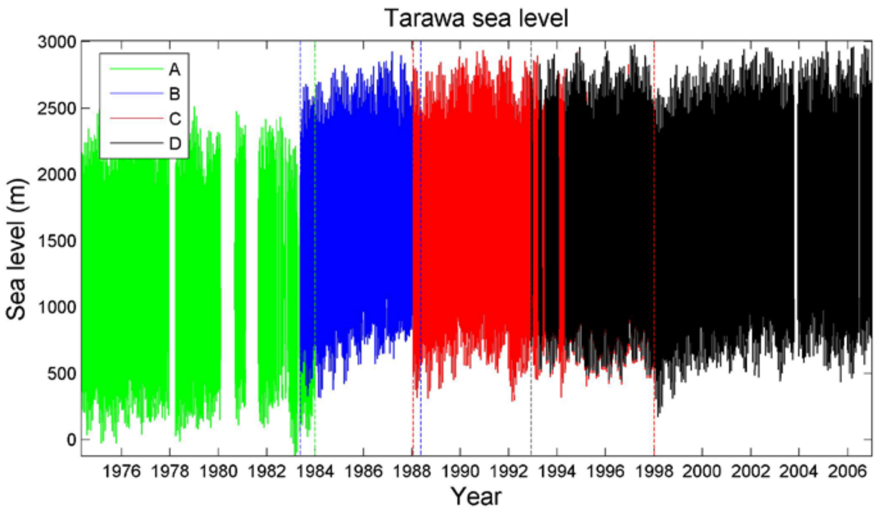


Figure 4: Plot of raw sea levels used for this study (Table 1).

The overlapping portions of the records were examined and the historical records were adjusted to SEAFRAME Gauge 0 (Figure 5). In merging the records it has been assumed that the sea level characteristics from the Bairiki deployment are not significantly different to those at the Betio site. However, geographical differences are likely to modify some characteristics of tidal propagation, amplification and wind set-up and set-down, in particular. The implications of this are discussed in Appendix 3, (Section 13.1).

A discussion of datum issues on Tarawa is contained in Appendix 4. It must be stressed that there is some considerable uncertainty over the relationship between the University of Hawaii Gauge 0 datum (to which all vertical land levels are measured to) and the SEAFRAME Gauge 0 datum. To avoid potential datum problems, all sea-level analysis in this report has been conducted relative to SEAFRAME Gauge 0 datum.

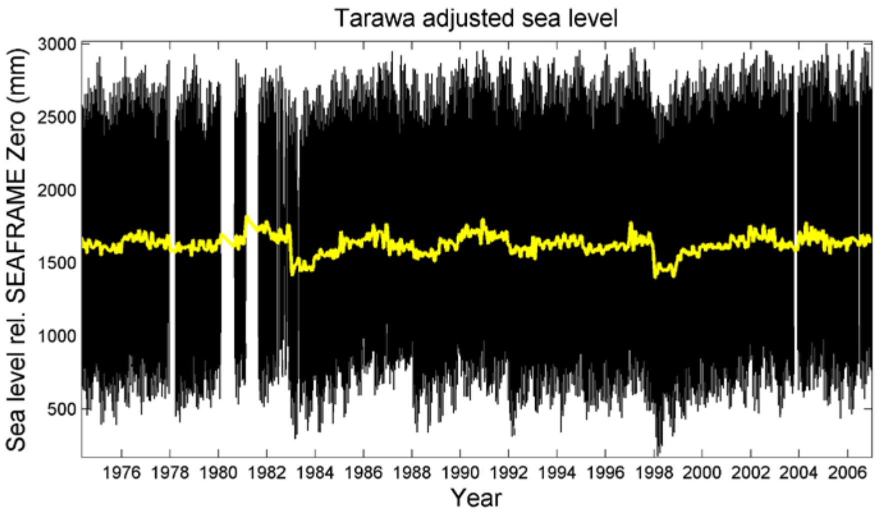


Figure 5: Plot of adjusted raw sea levels (black) used for this study. The yellow line marks mean monthly level of the sea. The datum is SEAFRAME Gauge 0.

2.2.2 Wave data

No known measurements of wave conditions have been carried out in the Kiribati region to permit extreme wave statistics to be derived.

Instead the NOAA/NCEP Wavewatch III hindcast dataset (Tolman, 1999; Tolman et al. 2002) has been used to derive offshore (deep-water) wave climates around each atoll. This provides hindcasts and forecasts of wave conditions on a global domain at a resolution of 1.25° in longitude and 1.0° in latitude. Input winds are taken from

NCEP's operational Numerical Weather Prediction models. Predictions of wave height, period, direction and associated wave spectrum parameters are available every hour. The dataset covers the period between 1 February 1997 to 1 November 2007 (~10 years of data).

2.2.3 Tarawa meteorological and oceanographic datasets

Air temperature, atmospheric pressure, wind speed and direction were obtained from the SEAFRAME station from 27 March 1993 to 31 August 2007. Atmospheric pressure data was also obtained for the period 4 July 1978 to 15 December 1993 from Kiribati MetService Tarawa station, (agent number 5976, network number J61000). Wind speed and direction were obtained from the same station, for the period 4 July 1978 to 31 March 1996.

3. Present day sea-levels: Extremes, variability and recent change

3.1 Introduction

The ~33 years of sea-level data from the University of Hawaii and SEAFRAME gauges at Tarawa (Figures 4 & 5) were analysed to assess:

- The relative contribution of the various sea-level components (tides, storm surge, longer term sea-level fluctuations).
- 10%, 2% and 1% AEP values of storm-tide levels at Betio.
- The trend in mean sea-level rise since 1974.

The methodologies used in the assessment are summarised fully in Appendix 3, with key results outlined in the next sections.

3.2 Sea-level components

Analysis of the sea-level data record at Betio allows an assessment of the relative magnitude of the various components that make up the sea level at any particular time, specifically:

- The astronomical tide component.
- The variability in mean level of the sea (MLOS) due to interdecadal and decadal fluctuations in sea level (for example due to ENSO influence).
- Storm surge, i.e., the influence of atmospheric pressure and winds on sea level, and the relative contributions of atmospheric pressure (inverted barometer) and wind effects to storm surge.

Figure 6 shows the breakdown of the various sea-level components for the entire ~33 years of data available, with Figure 7 providing a summary of the range for each component.

The astronomic tide has by far the largest influence on sea level, followed by long-term fluctuations in the mean level of the sea (MLOS), which over the last 33 years have caused MLOS to vary by up to 0.43 m.

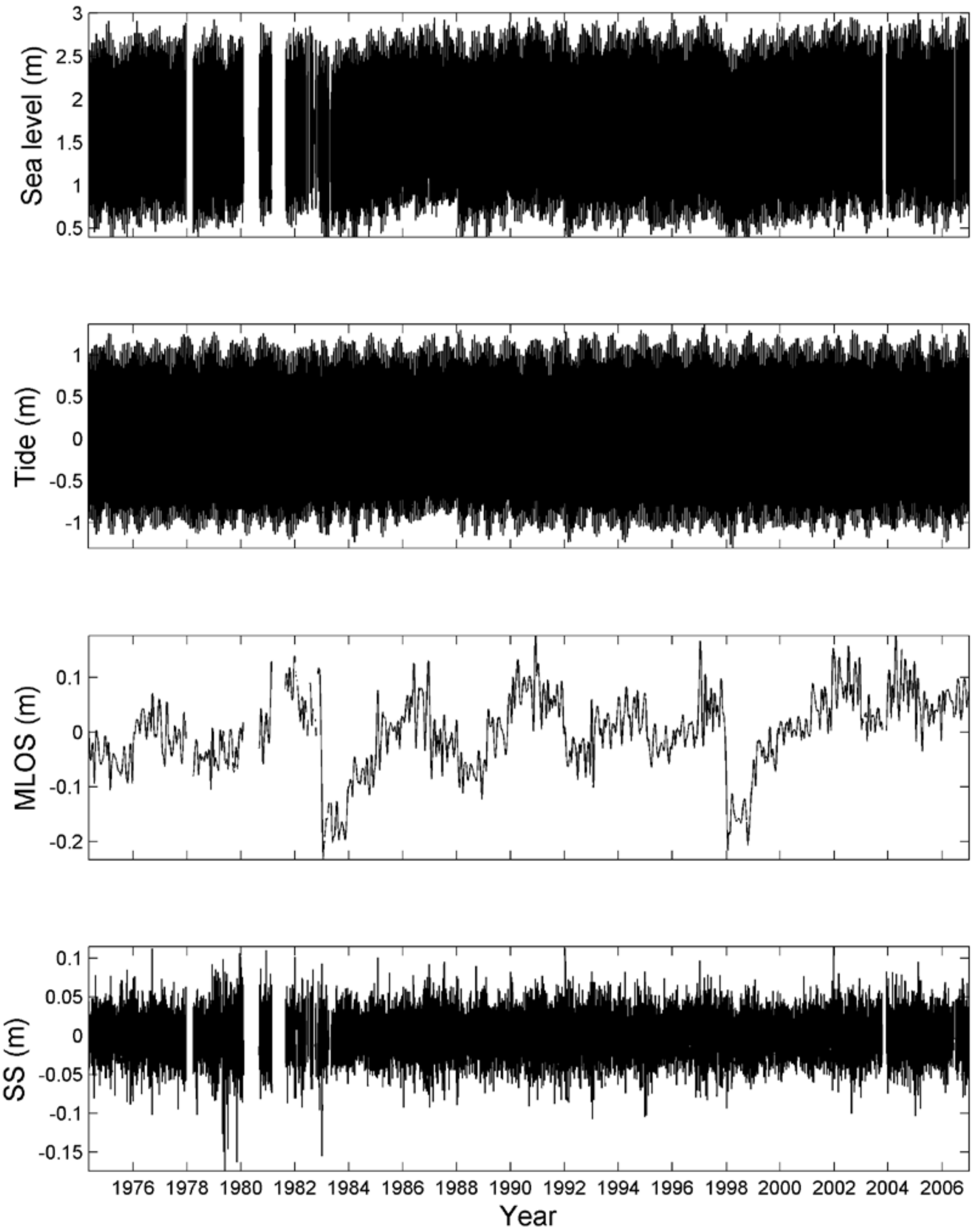


Figure 6: Sea-level components based on analysis of the ~33 years of sea-level data at Betio. The top plot shows the raw sea-level time series relative to SEAFRAME Gauge 0. The astronomical tidal component is shown in the second plot, the mean level of the sea (MLOS) component is shown in the third plot, and the storm surge (SS) component is shown in the bottom plot.

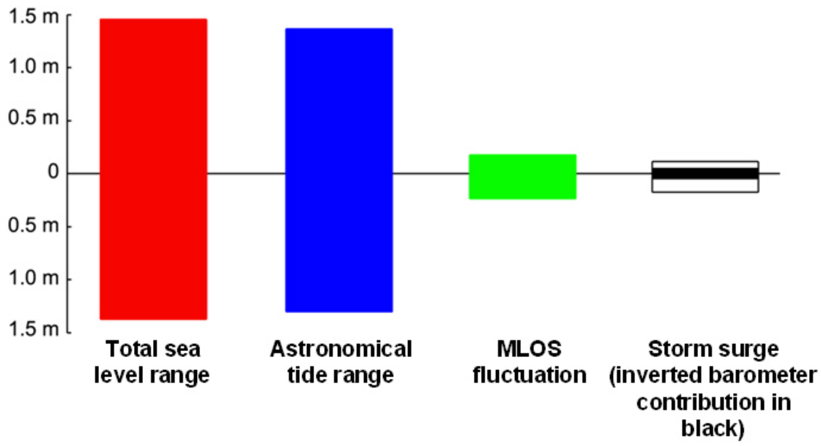


Figure 7: Magnitude of the fluctuations in sea level caused by the various components, estimated from the 33 years of sea-level data.

3.2.1 Astronomical tide characteristics

Details of the tidal harmonic analysis conducted on the ~33 years of sea-level data are given in Appendix 3 (Section 13.1.2). Based on this analysis we have derived a high-tide exceedance curve, Figure 8, from a prediction of all tides over the remainder of this century (01 January 2008 to 31 December 2099) for Tarawa relative to MLOS. This exceedance curve provides the frequency at which a given astronomical high tide is exceeded over this time period (i.e., excluding sea-level rise and climate / meteorology variability). Also shown are various tide markers such as Mean High Water Perigean Spring (MHWPS) the level of which is exceeded by around 15% of all high tides, Mean High Water Spring (MHWS) and Mean High Water Neap (MHWN). To translate the values on this curve to an elevation relative to the SEAFRAME Gauge 0 datum, MLOS (see below) needs to be added to the curve. For example the average MLOS over 2007 at Tarawa was 1.637 m above SEAFRAME Gauge 0.

Table 2 provides a summary of tide elevations relative to MLOS for Tarawa (based on the sea-level record analysis) and for most other islands in Kiribati. For the other islands, since there are no, or limited, recent tide measurements available, the levels are based on harmonic constants provided for each island location from the global tide model of Andersen (2006).

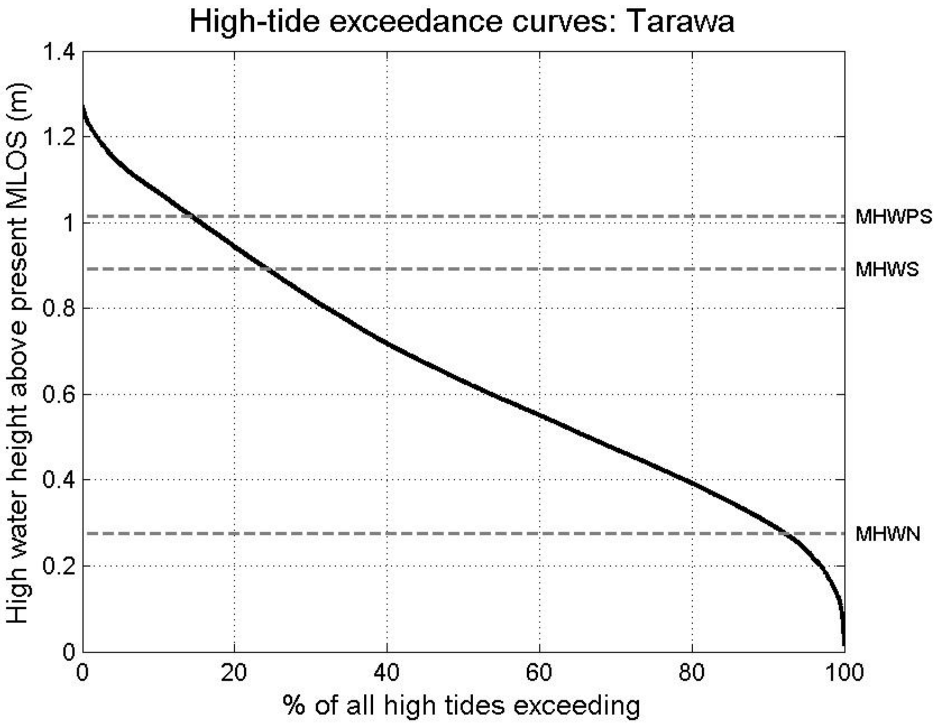


Figure 8: High-tide exceedance curve for Tarawa based on a simulation of tides between 01 January 2008 and 31 December 2099. Also shown are the Mean High Water Neap level (MHWN), Mean High Water Spring level (MHWS) and Mean High Water Perigean Spring (MHWPS) level (grey dashed lines).

Table 2: Summary of tide elevations (relative to MLOS) for various Kiribati islands. MHWPS is Mean High Water Perigean Spring level, MHWS is Mean High Water Spring tide level, and MHWN is Mean High Water Neap level. The corresponding equivalent tide range for each is simply double the value shown in the table: for example, the mean spring tide range for Butaritari is 2 x 0.872 = 1.744 m.

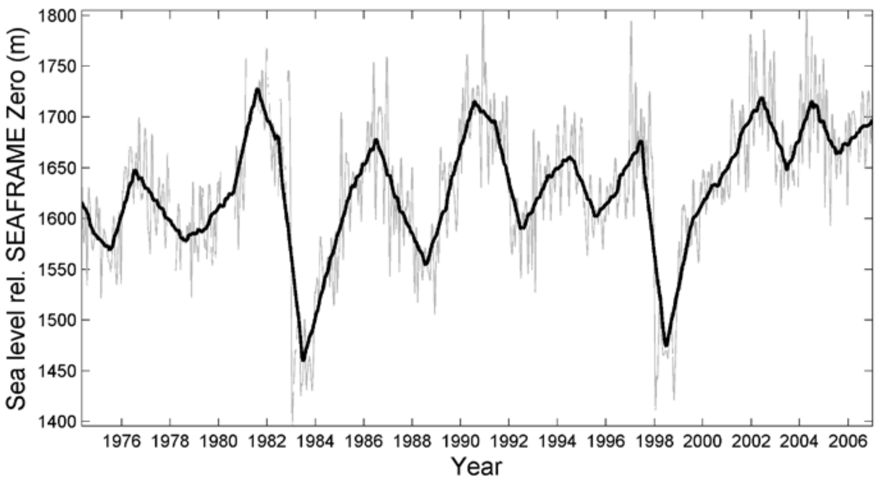
Location	MHWPS (m relative to MLOS)	MHWS (m relative to MLOS)	MHWN (m relative to MLOS)
Butaritari	0.982	0.872	0.286
Makin	0.973	0.865	0.283
Marakei	0.999	0.885	0.293
Abaiang	0.997	0.885	0.291
Tarawa	1.004	0.891	0.293
Maiana	1.011	0.896	0.298
Abemama	1.023	0.903	0.303
Kuria	1.02	0.901	0.311
Aranuku	1.02	0.901	0.311
Nonouti	1.029	0.906	0.304
Tabiteuea	1.024	0.901	0.307
Beru	1.012	0.886	0.31
Nikunau	1.007	0.881	0.311
Onotoa	1.011	0.886	0.312
Tamana	1.005	0.879	0.315
Arorae	0.997	0.87	0.314
Banaba	1.022	0.903	0.305
Kanton	0.718	0.62	0.26
Kiritimati	0.319	0.292	0.128

3.2.2 Variability in Mean Level of the Sea (MLOS)

The astronomical tide oscillates around the Mean Level of the Sea (MLOS). The value of MLOS itself is continuously varying due to the influences of long-period (seasonal and >1 year) climatic influences that cause fluctuations in sea level. Figure 9 shows how MLOS has varied at Tarawa since March 1974 based on the sea-level dataset.

It is MLOS that is analysed to assess trends in sea-level rise (see Section 4.2). Aside from any long-term trend in sea level due to climate change effects, the dominant influence on MLOS is due to the El-Nino Southern Oscillation (ENSO) cycle. Figure 9 (bottom plot) also shows the Southern Oscillation Index (SOI) which is a measure of the strength of an ENSO phase. Monthly MLOS and SOI are correlated, with MLOS lagging SOI by an average of 10 months. For example, the strong set-downs in MLOS that occurred in 1983 and 1998 are related to correspondingly strong El Nino (negative

SOI) events. Likewise, the high MLOS of 1990 was preceded by a strong La Nina event (positive SOI). Based on the analysis of MLOS, Table 3 provides annual exceedance probabilities for increased MLOS magnitude (see Appendix 3 for details).



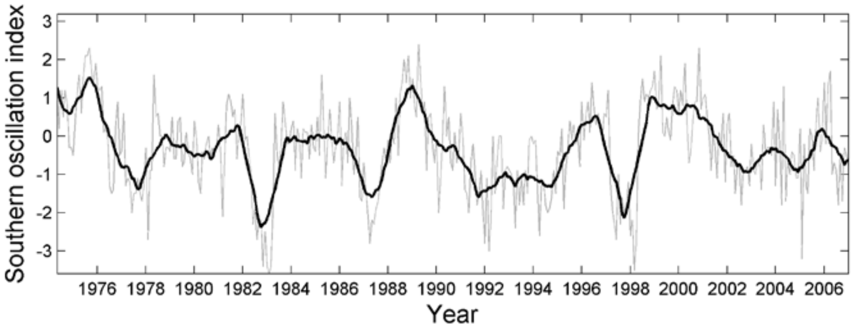


Figure 9: Upper plot: Mean level of the sea relative to the Tarawa SEAFRAME Gauge 0, since March 1974. The light line is the monthly MLOS and the bold line is the annual average MLOS. Lower plot: Variation of the Southern Oscillation Index with time. The light line indicates monthly values, while the bold line is the annual running average.

Table 3: Best estimate Predictions of MLOS annual exceedance probabilities (AEP). The range represents the uncertainty associated with each AEP estimate (5% to 95% tolerance intervals).

AEP	10%	2%	1%
MLOS fluctuation (+ve)	0.148 m (0.130 m – 0.164 m)	0.170 m (0.150 m – 0.185 m)	0.175 m (0.155 m - 0.192 m)

3.2.3 Trends in Mean Level of the Sea

Increasing global sea levels are a well established consequence of global climate change. Measurements of sea-level changes over the last two centuries have primarily come from long-term data from tide gauges mounted on land, supplemented since around 1993 by measurements made by satellites. The longest records suggest that the rate of rise of global sea levels began to increase from around the early to mid-1800s compared with a relatively stable sea level in the preceding century.

Over the 20th century global sea levels have increased by on average 0.17 m ±0.05 m (1.7 mm/yr ±0.05 mm/yr). Between 1963 to 2003, global sea-level rise rate was 1.8 mm/yr (1.3 to 2.3 mm/yr) and between 1993 to 2003, 3.1 mm/yr (2.4 to 3.8 mm/yr). Whether this more recent faster rate reflects decadal variability or an increase in the longer term trend (or both) is at present unclear.

In Kiribati, detailed analysis of the SEAFRAME sea level record provides a linear rate of sea-level rise between 1993 and 2003 of 4.5 mm/yr (compared to 3.1 mm/yr global average), Figure 10 and Table 4.

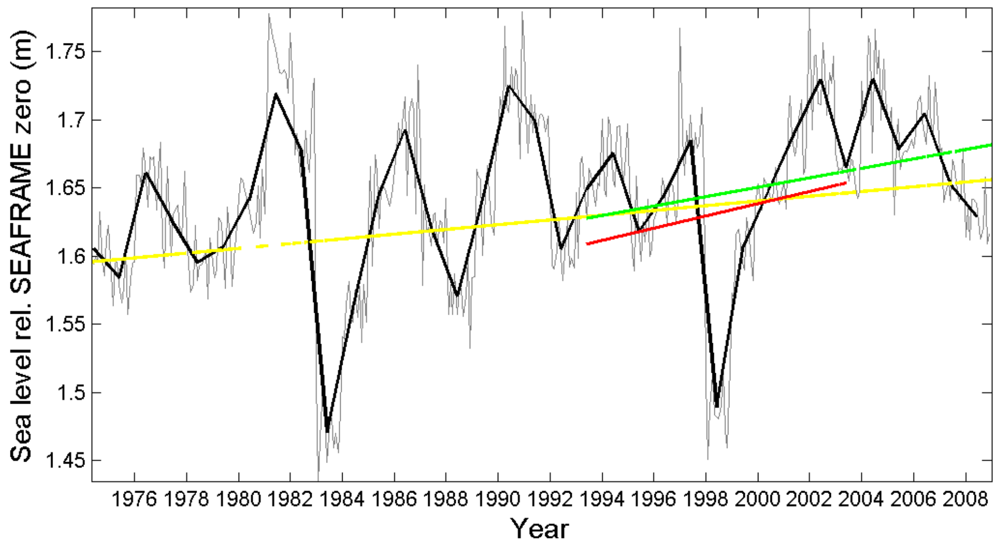


Figure 10: Linear rates of sea-level rise since 1974 to 2008 (yellow line), 1993 to 2003 (red line) and 1993 to 2008 (green line). The grey line is the Mean Level of the Sea (MLOS) as measured at the SEAFRAME and earlier sea level gauges, and the black line the annual average MLOS.

Table 4: Rates of sea level rise for different timeframes based on an analysis of available recorded sea-level data at Betio, Tarawa.

Start date	Finish date	Duration (years)	Sea level rise (mm/year)
May 1974	Dec 2008	32.7	+1.8
Jan 1993	Jan 2003	10	+4.5
Jan 2003	Dec 2008	14	+3.5

Including the sea-level record to December 2008 (i.e., March 1993 to December 2089) provides a linear rate in sea level rise of +3.5 mm/yr (excluding any allowance for trends in atmospheric pressure and any vertical movement of the tide gauge platform). confirming the rate provided in the most recent Bureau of Meteorology analysis report on the Tarawa SEAFRAME gauge (BoM, 2008). However, this rate will continue to vary from month to month due to the large inter-annual (e.g., due to ENSO effects) and inter-decadal fluctuations that influence Mean Level of the Sea. At least 25 years of sea-level data is required to begin to make some judgement of long-term sea-level rise rates.

Using the entire sea-level dataset (from June 1974, ~35-years) suggests a linear rate of mean sea-level of 1.8 mm/yr, which is similar to global average rates.

3.2.4 Storm surge characteristics

Storm surge is the increase in regional ocean or lagoon water levels (excluding the effects of waves) due to low barometric pressure and set-up due to winds. In the ocean around Kiribati, due to the depth of the ocean, wind set-up due to local weather events will be negligible and storm surge will be dominated by atmospheric pressure effects. However, in the relatively shallower lagoon areas, the influence of wind acting over the lagoon will have a greater influence on storm surge.

The inverse-barometer sea level (IB) is shown in Figure 11. This is the predicted response of sea level to atmospheric pressure changes. In the deep ocean a 1 hPa fall in pressure results in a 1 cm rise in sea level, and *vice versa*. At Tarawa although storm surge and IB are correlated, the correlation is small and IB contributes only about 18% of the total storm surge. Hence in Tarawa lagoon most of the storm surge component is dependent on local wind set-up within the lagoon. For Tarawa lagoon, annual exceedance probabilities for storm surge magnitude are provided in Table 5.

Figure 11 suggests that along ocean shorelines any storm surge is likely to be less than 0.15 m.

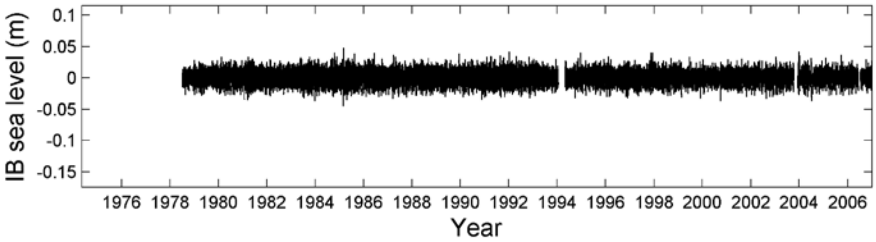


Figure 11: Calculated inverse-barometer (IB) sea level based on atmospheric pressure data from Tarawa assuming that a 1 hPa fall in pressure results in a 1 cm rise in sea level, and *vice versa*.

Table 5: Best estimate predictions of storm surge annual exceedance probabilities (AEP) for Tarawa lagoon. The range represents the uncertainty associated with each AEP estimate (5% to 95% tolerance intervals).

AEP	**10%**	**2%**	**1%**
Storm surge	0.103 m	0.120 m	0.127 m
	(0.096 m – 0.112 m)	(0.105 m – 0.139 m)	(0.107 m - 0.155 m)

3.2.5 Storm tide levels

For most practical purposes the interest is not in the magnitude of the various components of sea level but in how these components combine to create extreme sea levels. The term *storm tide* is used here to define extreme sea levels (i.e., the combination of MLOS, astronomical tide and storm surge causing an extreme sea level). Full details of the analysis of the ~33 year sea-level record to determine annual exceedance storm tide probabilities are provided in Appendix 3 (Section 13.1.5). A summary of storm tide AEP's levels is presented in Table 6.

Table 6: Best estimate predictions of storm tide levels (relative to SEAFRAME Gauge 0) based on the analysis of the sea-level dataset at Betio. The range represents the uncertainty associated with each AEP estimate (5% to 95% tolerance intervals).

AEP:	**10%**	**2%**	**1%**
Storm tide level:	2.970 m	2.991 m	2.996 m
	(2.954–2.985)	(2.972–3.005)	(2.975–3.012)

The highest storm-tide levels for each year from the sea-level record since 1974 are shown in Figure 12. Again the influence of the strong El Niño events in 1983 and 1998 in lowering sea levels can also be seen in the storm tide levels. The trend in the highest annual sea level for the same timeframes as assessed for mean level of the sea

(Table 4) is shown in Table 7. Over the entire period of sea-level monitoring the trend in the highest annual storm tide levels is close to the trend in mean level of the sea but over shorter timeframes but this can vary significantly, e.g., the period since 1993.

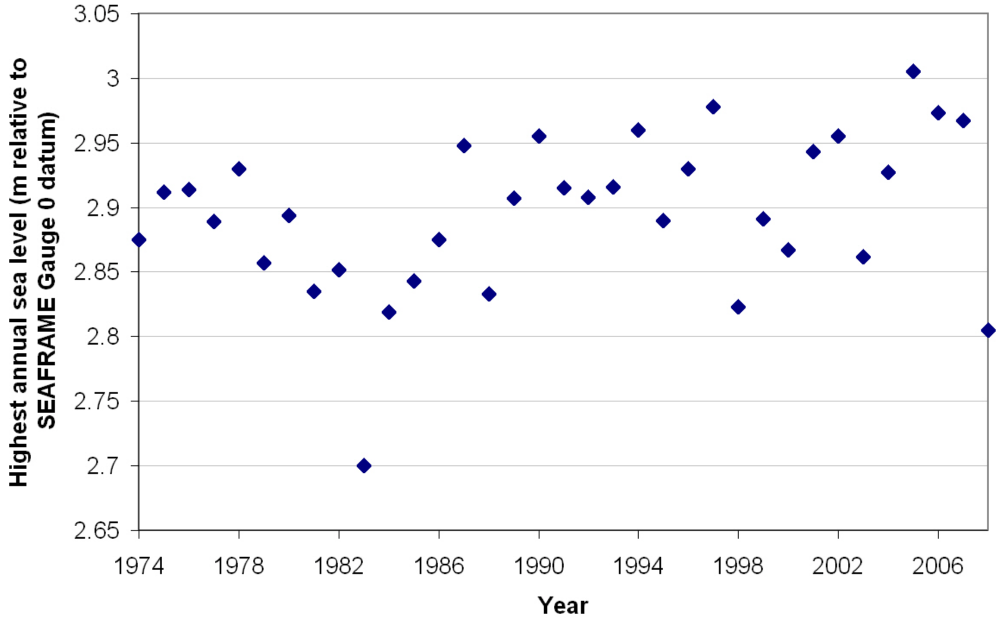


Figure 12: Highest annual sea levels between 1974 and 2008.

Table 7: Trend in highest annual sea levels.

Start date	Finish date	Duration (years)	Mean Sea level rise trend (mm/year)	Trend in highest annual sea level (mm/yr)
May 1974	Dec 2008	34.7	+1.8	+1.9
Jan 1993	Jan 2003	10	+4.5	-0.9
Jan 2003	Dec 2008	14	+3.5	0.2

Over the period since 1974 the number of hours each year that sea levels were above a certain level (above 2.8 m and 2.9 m relative to SEAFRAME Gauge 0) are shown in Figure 13. Sea-levels above such levels would be considered “King tides”. Again the influence of El Niño is observed in the variability from year to year but there is also a clear indication that over the last 20 or so years high tides have exceeded these levels for a longer cumulative period of time each year than over the previous 20 or so years.

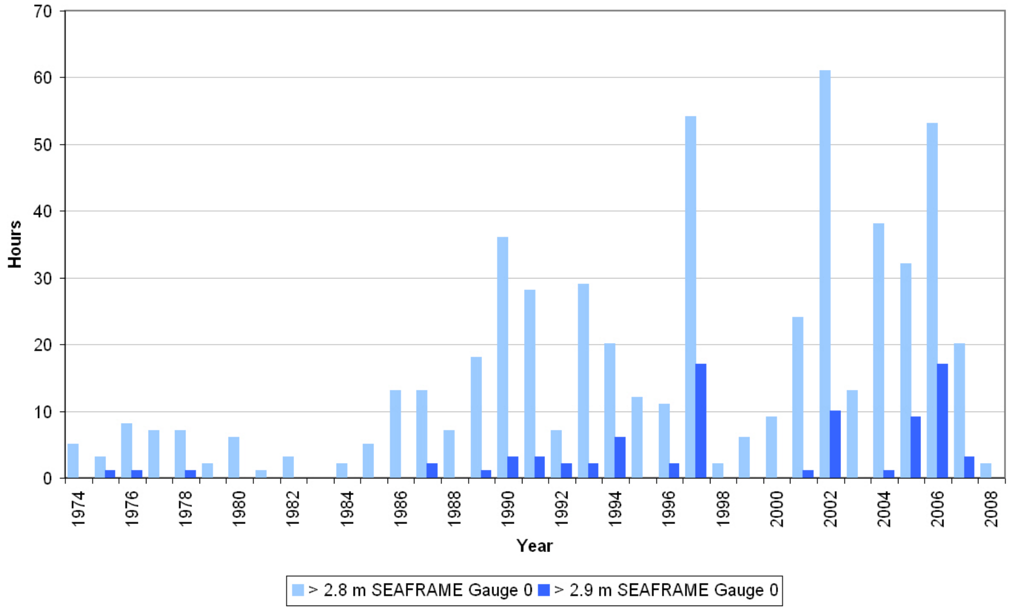


Figure 13: Number of hours each year that sea levels were above 2.8 m relative to SEAFRAME Gauge 0 (light blue), and above 2.9 m relative to SEAFRAME Gauge 0 (dark blue) in the sea-level data record.

3.2.6 Variability of storm tide levels around Tarawa lagoon

A hydrodynamic model[1] of Tarawa lagoon was used to investigate whether there was any significant variability in storm-tide levels around the lagoon shoreline (either due to variability in tide range or due to wind effects – the effects of atmospheric pressure likely to be consistent over the lagoon). The Tarawa lagoon model was developed, calibrated and verified by SOPAC as part of their EDF 8 *Reducing Vulnerabilities Project in Pacific ACP States* project and was used to simulate present day sea-level variability around the lagoon, and for rises in sea level of 0.48 m and 0.79 m (Section 4.2).

Storm tide levels were derived for 23 locations around the Tarawa lagoon shoreline (Figure 14). Figure 15 shows how the 10%, 2% and 1% AEP storm-tide levels vary around the lagoon for the present day, and with sea-level rises of 0.48 m and 0.79 m. This suggests that the variability in storm tide around the lagoon (at the lagoon edge of the sand flats) is only about 0.03 m, being slightly higher towards the southeastern (Bonriki) end of the lagoon compared to the southwestern and northern ends. The higher levels in the more enclosed part of the lagoon are caused by amplification of the tide and by wind set-up during westerly winds. Note: the analysis methodology used (i.e., the comparison of extreme values calculated from simulated data compared

[1] DHI MIKE 21 hydrodynamic model (www.dhisoftware.com)

to those from measured data) results in storm tide levels around 0.03 m higher (near Betio) than assessed from the sea level dataset (Table 6 above). This reason for this is discussed in Appendix 3 (Section 13.1.6).

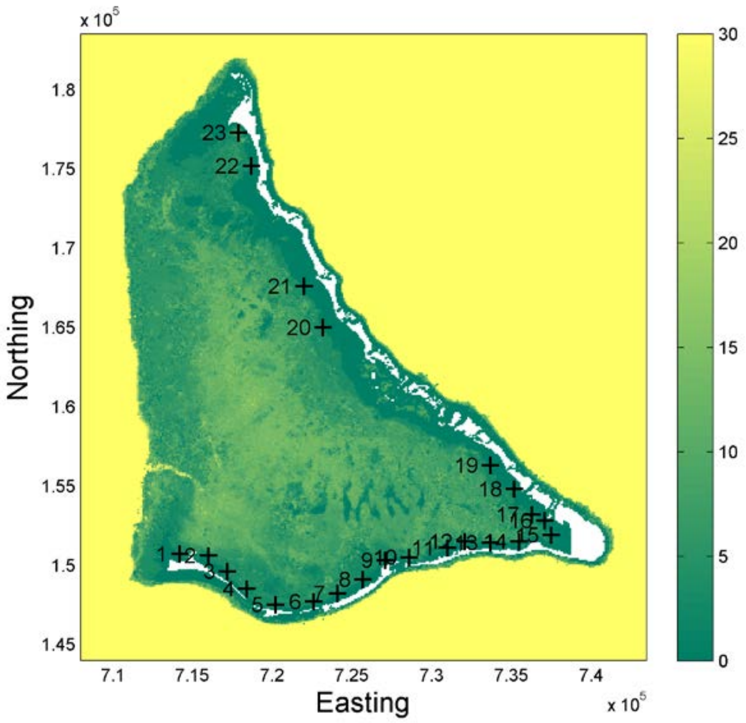


Figure 14: Locations where storm tide levels, extreme wave heights (see Section 6) and their joint occurrence (Section 7) were derived around the Tarawa lagoon shoreline. The colour shading represents the Tarawa lagoon water depths used in the hydrodynamic and wave modelling.

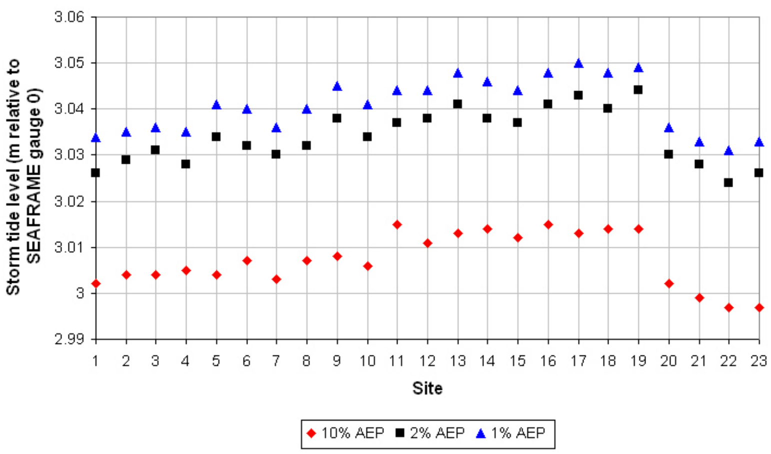


Figure 15: 10%, 2% and 1% Annual Exceedance Probability (AEP) storm tide levels (relative to SEAFRAME Gauge 0) at the 23 representative locations around Tarawa lagoon for the present day.