Pacific Country Report

Sea Level & Climate:
Their Present State

Marshall Islands

December 2010

PACIFIC COUNTRY REPORT
ON
SEA LEVEL & CLIMATE: THEIR PRESENT STATE

MARSHALL ISLANDS

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Executive Summary

- A SEAFRAME gauge was installed in Majuro, Marshall Islands, in May 1993. It records sea level, air and water temperature, atmospheric pressure, wind speed and direction. It is one of an array designed to monitor changes in sea level and climate in the Pacific.

- This report summarises the findings to date, and places them in a regional and historical context.

- The sea level trend to date is +4.3 mm/year but the magnitude of the trend continues to vary widely from month to month as the data set grows. Accounting for the precise levelling results and inverted barometric pressure effect, the trend is +3.8 mm/year. Nearby gauges, with longer records but less precision and datum control, show trends of +2.3, +1.3, and +1.7 mm/year.

- Variations in monthly mean sea level include a moderate seasonal cycle and were affected by the 1997/1998 El Niño.

- Variations in monthly mean air and water temperature were likewise affected by the 1997/1998 El Niño.

- Typhoon Paka passed the Marshall Islands on 10th December 1997 and caused around US$80 million (1997) in damage.

- The SEAFRAME at Majuro, Marshall Islands has recorded 14 separate tsunami events since its installation. The largest tsunami signal with trough-to-peak height of 11 cm was recorded after an earthquake of magnitude Mw8.3 that occurred near Kuril Islands on 4th October 1994.

Contents

Appendix

1. Introduction

As part of the AusAID-sponsored South Pacific Sea Level and Climate Monitoring Project ("Pacific Project") for the FORUM region, in response to concerns raised by its member countries over the potential impacts of an enhanced Greenhouse Effect on climate and sea levels in the South Pacific region, a **SEAFRAME** (**Sea** Level **F**ine **R**esolution **A**coustic **M**easuring **E**quipment) gauge was installed at Majuro, Marshall **I**slands, in May, 1993. The gauge has been returning high resolution, good scientific quality data since installation.

SEAFRAME gauges not only measure sea level by two independent means, but also a number of "ancillary" variables - air and water temperatures, wind speed, wind direction and atmospheric pressure. There is an associated programme of levelling to "first order", to determine vertical movement of the sea level sensors due to local land movement. A Continuous Global Positioning System (CGPS) station will be installed in Marshall Islands to determine the vertical movement of the land with respect to the International Terrestrial Reference Frame.

When change in sea level is measured with a tide gauge over a number of years one cannot be sure whether the sea is rising or the land is sinking. Tide gauges measure relative sea level change, i.e., the change in sea level relative to the tide gauge, which is connected to the land. To local people, the relative sea level change is of paramount importance. Vertical movement of the land can have a number of causes, e.g. island uplift, compaction of sediment or withdrawal of ground water. From the standpoint of global change it is imperative to establish absolute sea level change, i.e. sea level referenced to the centre of the Earth, which is to say in the terrestrial reference frame. In order to accomplish this, the rate at which the land moves must be measured separately. This is the reason for the addition of CGPS near the tide gauges.

2. Regional Overview

2.1. Regional Climate and Oceanography

Variations in sea level and atmosphere are inextricably linked. For example, to understand why the sea level at Tuvalu undergoes a much larger annual fluctuation than at Samoa, we must study the seasonal shifts of the trade winds. On the other hand, the climate of the Pacific Island region is entirely ocean-dependent. When the warm waters of the western equatorial Pacific flow east during El Niño, the rainfall, in a sense, goes with them, leaving the islands in the west in drought.

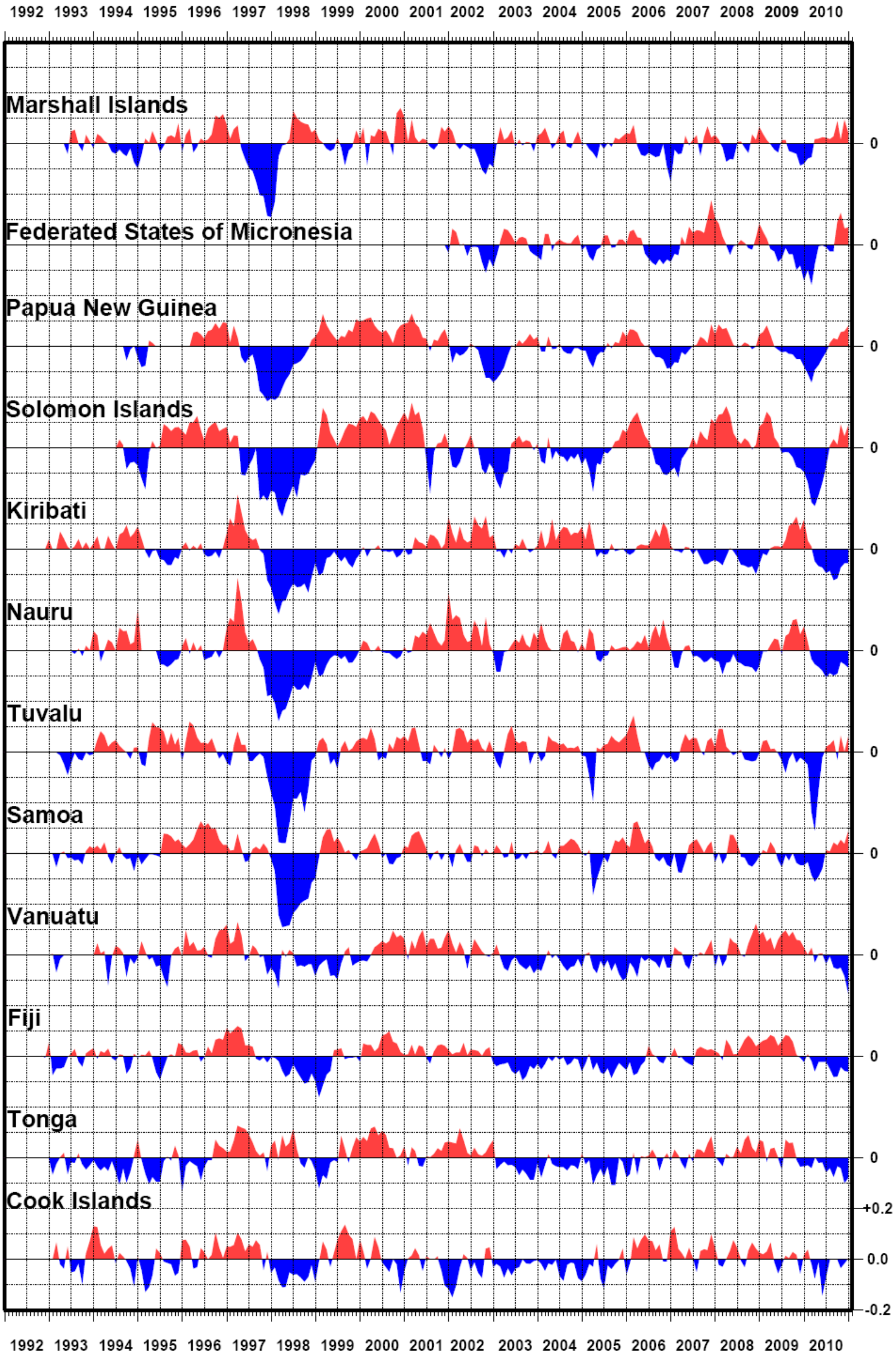
Compared to higher latitudes, air temperatures in the tropics vary little throughout the year. Of the SEAFRAME sites, those furthest from the equator naturally experience the most extreme changes – the Cook Islands (at 21°S) recorded the lowest temperature, 13.1°C, in August 1998. The Cook Islands regularly fall to 16°C while Tonga (also at 21°S) regularly falls to 18°C in winter (July/August).

Table 1. Range in air temperatures observed at SEAFRAME stations

SEAFRAME location	Minimum recorded air temperature (°C)	Mean recorded air temperature (°C)	Maximum recorded air temperature (°C)
Cook Islands	13.1	24.2	32.0
Tonga	15.3	24.2	31.4
Fiji (Lautoka)	16.6	26.0	33.9
Vanuatu	15.2	25.1	33.3
Samoa	18.7	26.6	34.3
Tuvalu	22.4	28.5	33.7
Kiribati	22.2	28.2	32.9
Nauru	19.6	28.0	33.0
Solomon Islands	20.1	26.8	34.5
Papua New Guinea	21.5	27.3	32.0
Marshall Islands	20.9	27.7	32.6
FSM	22.6	27.6	31.8

The most striking oceanic and climatic fluctuations in the equatorial region are not the seasonal, but interannual changes associated with El Niño. These affect virtually every aspect of the system, including sea level, winds, precipitation, and air and water temperature. Referring to Figure 1, we see that at most SEAFRAME sites, the lowest sea level anomalies appeared during the 1997/1998 El Niño. The most dramatic effects were observed at Marshall Islands, PNG, Solomon Islands, Nauru, Kiribati, Tuvalu and Samoa. PNG, Solomon Islands, Tuvalu and Samoa lie along a band that meteorologists refer to as the “South Pacific Convergence Zone (SPCZ)”. The SPCZ is a zone of Trade Wind convergence that extends southeastward from the equator and can sometimes be identified as a cloud band in satellite pictures.

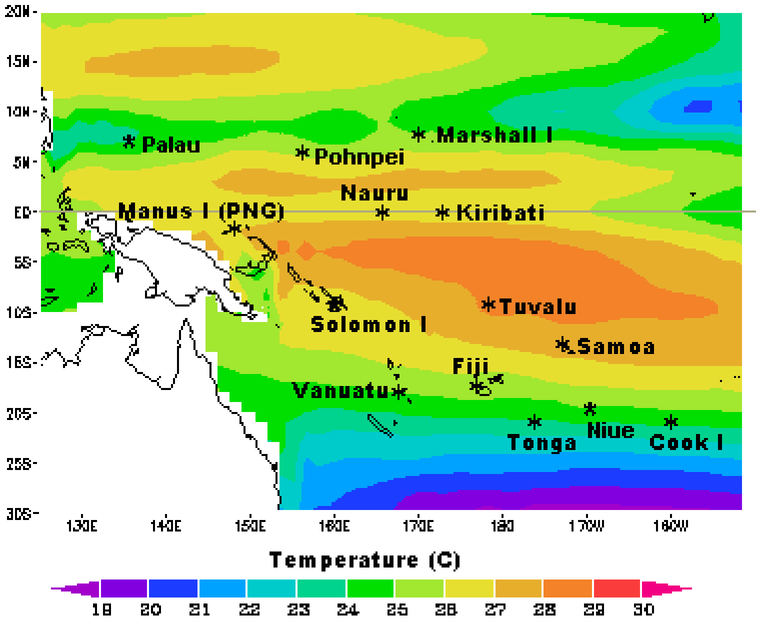
Figure 1. Sea level anomalies* at SEAFRAME sites



* Sea level "anomalies" have had tides, seasonal cycles and trend removed from the sea level observations.

Most Pacific Islanders are very aware that the sea level is controlled by many factors, some periodic (like the tides), some brief but violent (like cyclones), and some prolonged (like El Niño), because of the direct effect the changes have upon their lives. The effects vary widely across the region. Along the Melanesian archipelago, from Manus Island to Vanuatu, tides are predominantly diurnal, or once daily, while elsewhere the tide tends to have two highs and two lows each day. Cyclones, which are fuelled by heat stored in the upper ocean, tend to occur in the hottest months. They do not occur within 5° of the equator due to the weakness of the "Coriolis Force", a rather subtle effect of the earth's rotation. El Niño's impact on sea level is mostly felt along the SPCZ, because of changes in the strength and position of the Trade Winds, which have a direct bearing on sea level, and along the equator, due to related changes in ocean currents. Outside these regions, sea levels are influenced by El Niño, but to a far lesser degree.

Figure 2. Mean surface water temperature

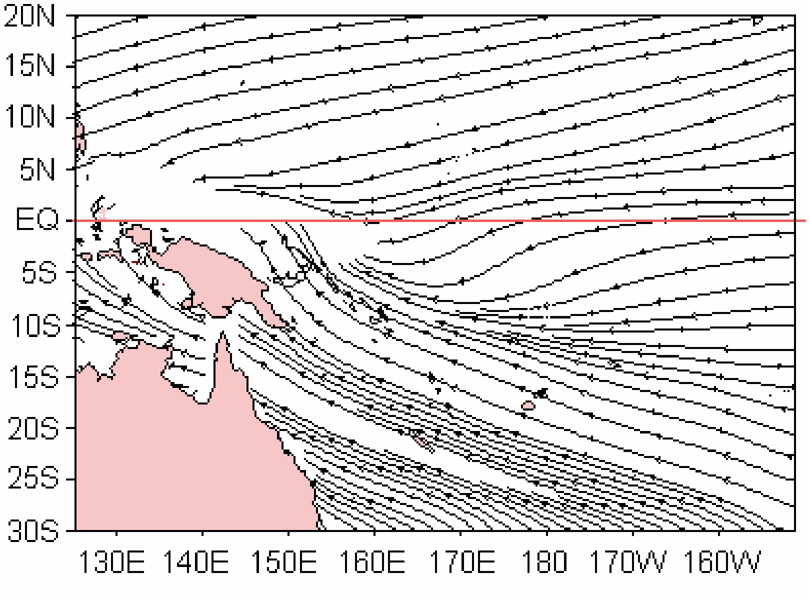


Note the warm temperatures in the SPCZ and just north of the equator.

The convergence of the Trade Winds along the SPCZ has the effect of deepening the warm upper layer of the ocean, which affects the seasonal sea level. Tuvalu, which is in the heart of the SPCZ, normally experiences higher-than-average sea levels early each year when this effect is at its peak. At Samoa, the convergence is weaker, and the seasonal variation of sea level is far less, despite the fact that the water temperature recorded by the gauge varies in a similar fashion. The interaction of wind, solar heating of the oceanic upper layer, and sea level, is quite complex and frequently leads to unexpected consequences.

The streamlines of mean surface wind (Figure 3) show how the region is dominated by easterly trade winds. In the Southern Hemisphere the Trades blow to the northwest and in the Northern Hemisphere they blow to the southwest. The streamlines converge, or crowd together, along the SPCZ.

Figure 3. Streamlines of mean surface wind



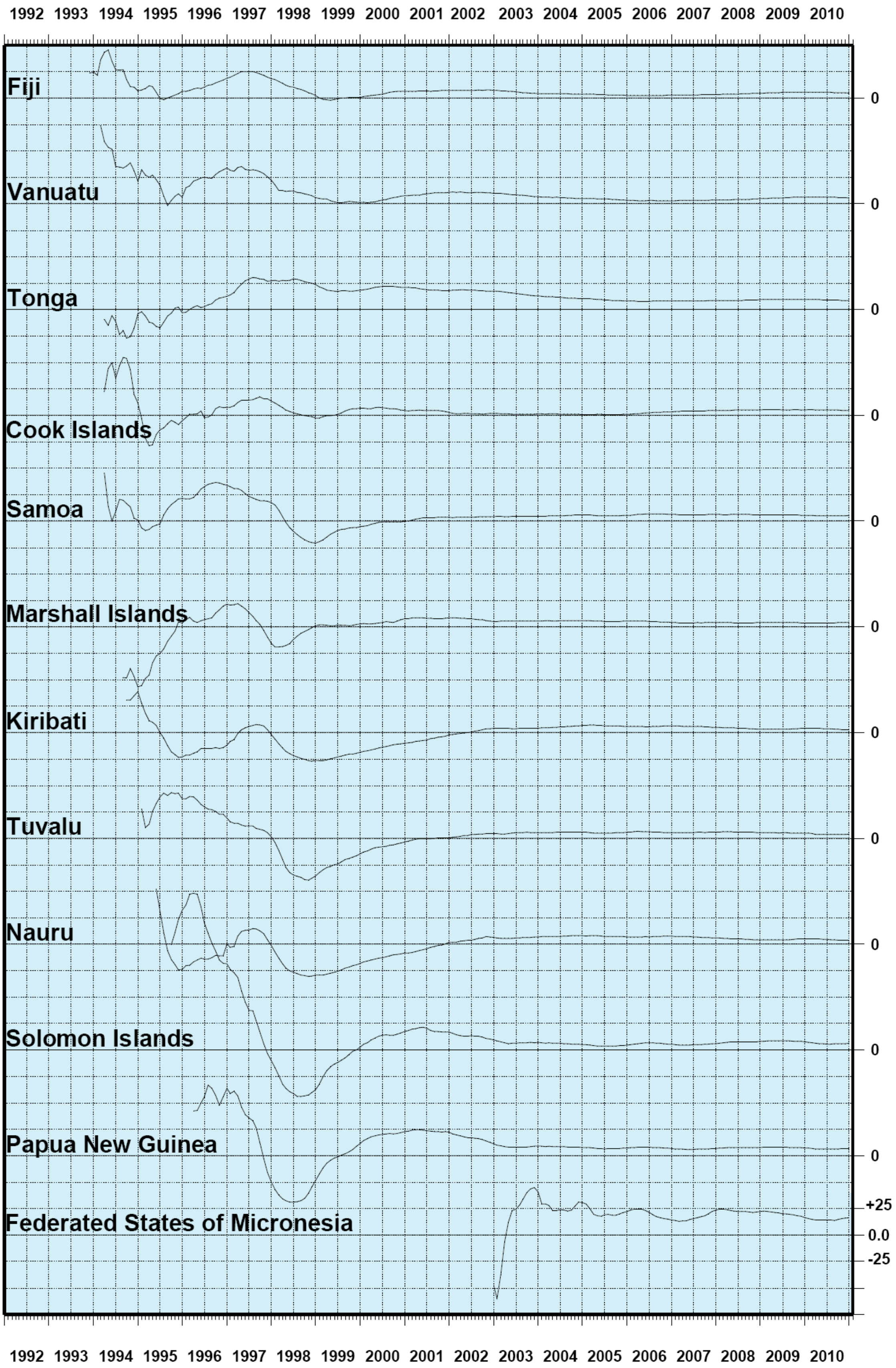
Much of the Melanesian subregion is also influenced by the Southeast Asian Monsoon. The strength and timing varies considerably, but at Manus Island (PNG), for example, the NW monsoon season (winds from the northwest) runs from November to March, while the SE monsoon brings wind (also known as the Southeast Trade Winds) from May to October. Unlike many monsoon-dominated areas, the rainfall at Manus Island is distributed evenly throughout the year (in normal years).

2.2. Sea Level Datasets from SEAFRAME stations

A key objective of the South Pacific Sea Level and Climate Monitoring Project (SPSLCMP) is to provide an accurate long-term sea level record. SEAFRAME stations were installed from 1992 onwards to provide precise relative sea level measurements. The SEAFRAME stations undergo regular calibration and maintenance and are levelled against a network of land-based benchmarks to maintain vertical datum control. The SEAFRAME observations are transmitted via satellite and are processed using specific quality control procedures.

The project's data collection program has been operating for a relatively short period with regards to long-term climate change and therefore the sea level trends are still prone to the effects of shorter-term ocean variability (such as El Niño and decadal oscillations). As the data sets increase in length the linear trend estimates will become increasingly indicative of the longer-term secular changes and less sensitive to large annual and decadal fluctuations. Figure 4 shows how the sea level trends from SEAFRAME stations have evolved from one year after installation to the present. These trends are expected to continue to stabilise, as is demonstrated by Figure 6.

Figure 4. Evolution of relative sea level trends (mm/year) at SEAFRAME stations. The trends continue to stabilise as the length of record increases.



2.2.1 Vertical datum control of SEAFRAME sensors

Precise levelling of the height of the SEAFRAME sea level sensor relative to an array of land-based benchmarks is undertaken by Geosciences Australia every eighteen months where possible. The precision to which the survey must be performed is dependent on the distance K_m (km) between the SEAFRAME sensor benchmark and the primary tide gauge benchmark (TGBM) and forms part of the project's design specifications.

The precise levelling program enables the vertical stability of the SEAFRAME stations to be monitored. Referencing the sea levels to land is especially important if the SEAFRAME needs to be replaced or relocated, or is displaced by a boat or large storm waves. The rates of vertical movement of the gauges relative to the TGBM (determined by fitting a straight line to the survey results after accounting for any adjustments to tide gauge zero) that are contributing to the observed sea level trends are listed in Table 2. Substantial subsidence of the tide gauges at Samoa and Cook Islands is occurring at rates of –0.9 mm/year and –0.7 mm/year. Subsidence is also occurring at Marshall Islands, FSM, Solomon Islands and Tonga. The tide gauges at Fiji and Nauru are rising with respect to the tide gauge benchmark at rates of +0.6 mm/yr and +0.2 mm/yr. The rates of vertical tide gauge movement are used to correct the observed rates of sea level change relative to the land-based primary tide gauge benchmark.

Table 2. Distance (km), required survey precision (mm), number of surveys and the rate of vertical movement of the SEAFRAME relative to the TGBM.

Location	**K_m (km)**	**$\pm 2\sqrt{K_m}$ (mm)**	**Number of Surveys**	**Vertical movement (mm/year)**
Cook Is	0.491	1.4	10	-0.7
FSM	0.115	0.7	4	-0.4
Fiji	0.522	1.4	11	+0.6
Kiribati	0.835	1.8	12	+0.0
Marshall Is	0.327	1.1	11	-0.5
Nauru	0.120	0.7	12	+0.2
PNG	0.474	1.4	10	-0.0
Samoa	0.519	1.4	10	-0.9
Solomon Is	0.394	1.3	6	-0.3
Tonga	0.456	1.4	11	-0.4
Tuvalu	0.592	1.5	11	-0.1
Vanuatu	1.557	2.5	10	+0.1

Continuous Geographical Positioning Systems (CGPS) stations have also been installed on all of the islands where SEAFRAME gauges are located. The purpose of the CGPS program is to close the final link in establishing vertical datum control – that is, to determine whether the island or coastal region as a whole is moving vertically with respect to the International Terrestrial Reference Frame. Early estimates of the rates of vertical movement are being calculated by Geosciences Australia but continued monitoring is necessary before long-term results emerge from the CGPS time series data. The latest CGPS information for the project is available from Geosciences Australia at http://www.ga.gov.au/geodesy/slm/spslcmp/

2.2.2. Inverted barometric pressure effect

Atmospheric pressure is another parameter that can potentially influence local measurements of relative sea level rise. Atmospheric pressure is also known as barometric pressure because it is measured by a barometer. The ‘inverse barometer effect’ refers to the sea level response to changes in barometric pressure, whereby a 1 hPa fall in barometric pressure that is sustained over a day or more typically causes local sea levels to rise about 1 cm (within the area beneath the low pressure system).

Scientific interest in accounting for the inverse barometer effect in sea level measurements arises because it is not directly related to global sea level rise due to global warming. Changes in barometric pressure does not cause changes in global ocean volume (because the oceans being a liquid are incompressible), but they can cause sea level to rise in some places and fall in other places due to shifting weather patterns. Global warming on the other hand does cause changes in ocean volume (and hence global sea level rise) due to the expansion of the oceans as they warm and the addition of land-based ice-melt.

Trends in barometric pressure over a period of time will cause changes in relative sea level. A 1 hPa/year decrease (increase) in barometric pressure for example would on average cause a 1cm/yr (or 10 mm/year) increase (decrease) in relative sea level. Estimates of the contribution to relative sea level trends by the inverse barometer effect at all SEAFRAME sites over the period of the project are listed in Table 3.

Table 3. Recent short-term barometric pressure trends expressed as equivalent sea level rise in mm/year based upon SEAFRAME data to December 2010.

Location	Installed	Barometric Pressure Contribution to Sea Level Trend (mm/yr)
Cook Is	19/02/1993	-0.2
FSM*	17/12/2001	-0.8
Fiji	23/10/1992	0.7
Kiribati	02/12/1992	0.3
Marshall Is	07/05/1993	0.0
Nauru	07/07/1993	0.4
PNG	28/09/1994	1.3
Samoa	26/02/1993	0.2
Solomon Is	28/07/1994	-0.3
Tonga	21/01/1993	0.4
Tuvalu	02/03/1993	0.2
Vanuatu	15/01/1993	0.9

*The trend at FSM is from a comparatively short series and therefore varies considerably.

2.2.3. Combined net rate of relative sea level trends

The effects of the vertical movement of the tide gauge platform and the inverse barometer effect are removed from the observed rates of relative sea level change and presented in Table 4 and Figure 5. The net sea level trends are positive at all sites, which indicates sea level in the region has risen over the duration of the project. The sea level rise is not geographically uniform but varies spatially in broad agreement with observations taken by satellite altimeters over a similar timeframe. The differences in the net sea level trends amongst the stations are largely due to regional oceanographic and geodynamic factors, excluding FSM where the trend is considerably large because it is derived from a shorter record than the other sites.

The net relative sea level trend at Tonga is larger than its neighbouring sites Fiji, Samoa and Cook Islands. Investigations that involve differencing of the sea level timeseries at Tonga from those of other stations suggest the sea level datum at Tonga is reasonably stable prior to 1996 and after 1998, but there is evidence of around 5cm of subsidence between 1996 and 1998. The impact of a tug boat occurred during this time but the precise levelling results show this collision caused less than 1cm of subsidence. Unfortunately, the CGPS station at Tonga was installed by Geosciences Australia at a later time (February 2002), and therefore it is difficult to determine whether additional subsidence is related to seismotectonic activity along the Tonga trench.

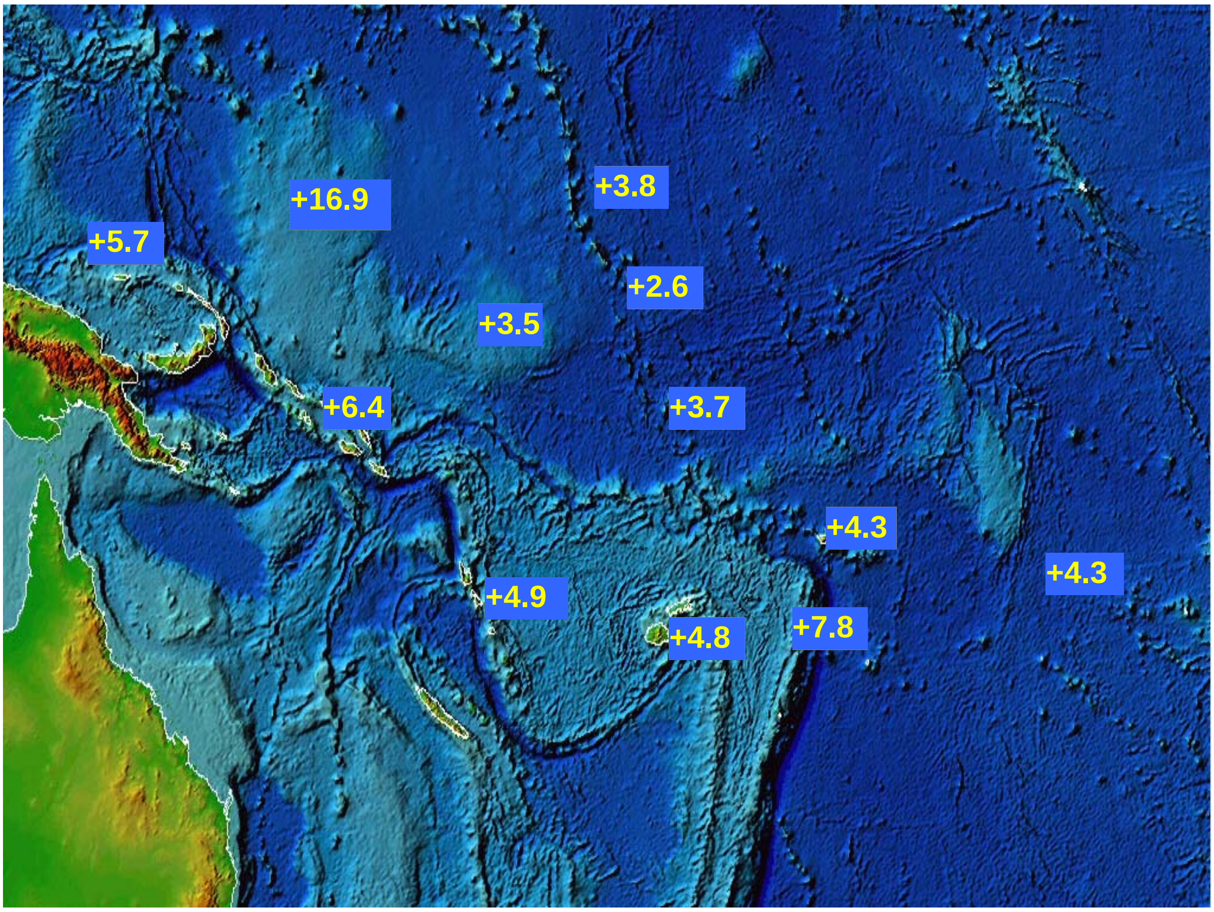
Table 4. The net relative sea level trend estimates as at December 2010 after the inverted barometric pressure effect and vertical movements in the observing platform relative to the primary tide gauge benchmark are taken into account.

Location	**Installed**	**Sea Level Trend (mm/yr)**	**Barometric Pressure Contribution (mm/yr)**	**Vertical Tide Gauge Movement Contribution* (mm/yr)**	**Net Sea Level Trend (mm/yr)**
Cook Is	19/02/1993	4.8	-0.2	+0.7	4.3
FSM**	17/12/2001	16.5	-0.8	+0.4	16.9
Fiji	23/10/1992	4.9	0.7	-0.6	4.8
Kiribati	02/12/1992	2.9	0.3	-0.0	2.6
Marshall Is	07/05/1993	4.3	0.0	+0.5	3.8
Nauru	07/07/1993	3.7	0.4	-0.2	3.5
PNG	28/09/1994	7.0	1.3	+0.0	5.7
Samoa	26/02/1993	5.4	0.2	+0.9	4.3
Solomon Is	28/07/1994	6.4	-0.3	+0.3	6.4
Tonga	21/01/1993	8.6	0.4	+0.4	7.8
Tuvalu	02/03/1993	4.0	0.2	+0.1	3.7
Vanuatu	15/01/1993	5.7	0.9	-0.1	4.9

*The contribution is the inverse rate of vertical tide gauge movement

** The sea level trend at FSM is derived from a comparatively short data record.

Figure 5. Map of region showing net relative sea level trends (in mm/year) after subtracting the effects of the vertical movement of the platform and the inverse barometric pressure effect, utilising all the data collected since the start of the project up to the end of December 2010.



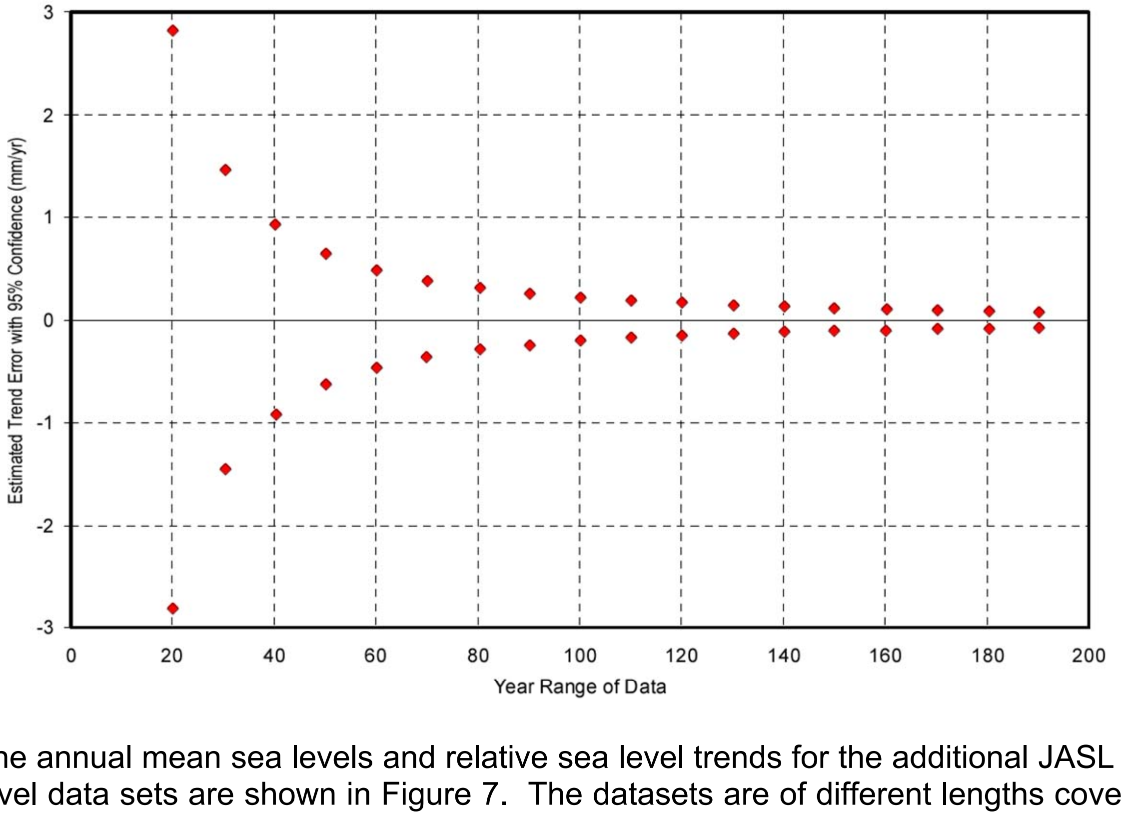
The net relative sea level measurements are important in terms of the local effects and adaptation strategies required on individual islands. Continued CGPS monitoring of the vertical motion of these islands will, in time, allow sea level trends to also be expressed in an absolute reference frame that will improve our understanding of the regional and global effects of climate change.

2.3. Sea Level Datasets from Additional Stations

Additional sea level data sets for the Pacific Forum Region are available from the Joint Archive for Sea Level (JASL). This archive was established in 1987 to supplement the University of Hawaii Sea Level Centre data holdings with contributions from other agencies. The research quality datasets available from the JASL may be accessed online at http://uhslc.soest.hawaii.edu/uhslc/jasl.html

Sea level in the Pacific Forum region undergoes large inter-annual and decadal variations due to dynamic oceanographic and climatic effects such as El Niño, and this ‘noise’ affects estimates of the underlying long-term trend. In general, sea level trend estimates are more precise and accurate from longer sea level records as is shown in Figure 6. Sea level records of less than 25 years are thought to be too short for obtaining reliable sea level trend estimates. A confidence interval or precision of 1 mm/year should be obtainable at most stations with 50-60 years of data on average, providing there is no acceleration in sea level change, vertical motion of the tide gauge, or abrupt shifts due to seismic events.

Figure 6. 95% Confidence Intervals for linear mean sea level trends (mm/year) plotted as a function of the year range of data. Based on NOAA tide gauges with at least 25 years of record[1].



The annual mean sea levels and relative sea level trends for the additional JASL sea level data sets are shown in Figure 7. The datasets are of different lengths covering different periods of time, and therefore different periods of climatic and sea level change. Many of the datasets are too short to provide reliable trend estimates. At some islands there are multiple sea level records, but joining them together can be problematic. They are archived separately on the Joint Archive for Sea Level

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1. Zervas, C. (2001) Sea Level Variations of the United States 1854-1999. NOAA, USA.

because they either originate from different tide gauge locations or they have unrelated tide gauge datums.

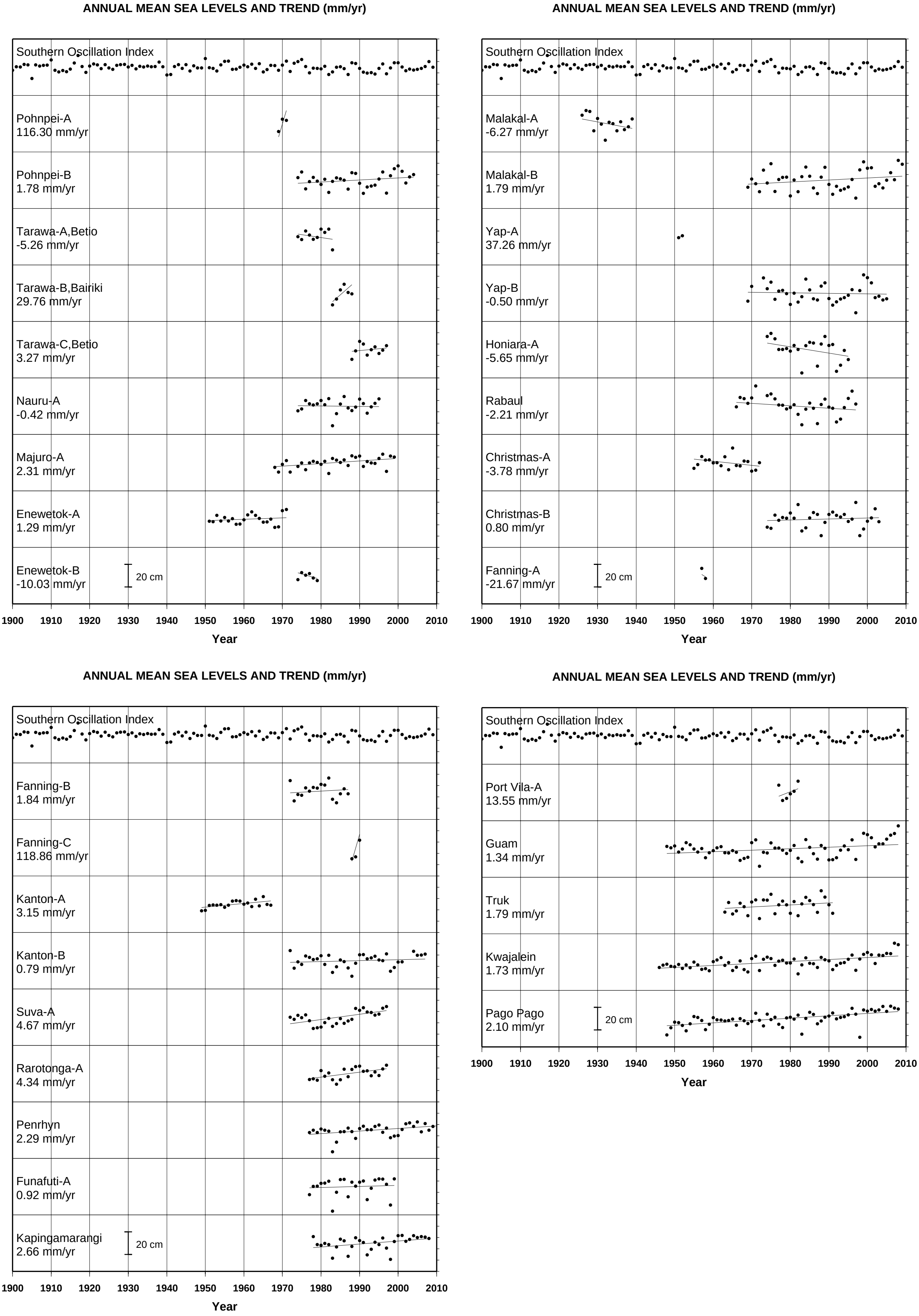
Diverse climatic and oceanographic environments are found within the Pacific Islands region. Different rates of vertical land movement are likely at different stations. Many of the historical tide gauges were designed to monitor tides and sea level variability caused by El Niño and shorter-term oceanic fluctuations rather than long-term sea level change, and therefore lack the required level of instrumental precision and vertical datum control. All of these factors potentially affect the rates of relative sea level change that are listed in Table 5. The overall mean trend from stations with more than 25 years of data is 1.3 mm/year, bearing in mind this is a very simple average that is based on datasets of different lengths that span different time periods.

Table 5. Sea level trends for additional Pacific Forum data holdings on the Joint Archive for Sea Level.

JASL	STATION	COUNTRY	START DATE	END DATE	SPAN (years)	TREND (mm/yr)
001a	Pohnpei-A	Fd St Micronesia	1-Jan-69	31-Dec-71	3	116.3
001b	**Pohnpei-B**	**Fd St Micronesia**	**1-Jan-74**	**31-Dec-04**	**31**	**1.8**
002a	Tarawa-A,Betio	Rep. of Kiribati	1-Jan-74	31-Dec-83	10	-5.3
002b	Tarawa-B,Bairiki	Rep. of Kiribati	1-Jan-83	31-Dec-88	6	29.8
002c	Tarawa-C,Betio	Rep. of Kiribati	1-Jan-88	31-Dec-97	10	3.3
004a	Nauru-A	Rep. of Nauru	1-Jan-74	31-Dec-95	22	-0.4
005a	**Majuro-A**	**Rep. Marshall I.**	**1-Jan-68**	**31-Dec-99**	**32**	**2.3**
006a	Enewetok-A	Rep. Marshall I.	1-Jan-51	31-Dec-71	21	1.3
006b	Enewetok-B	Rep. Marshall I.	1-Jan-74	31-Dec-79	6	-10.0
007a	Malakal-A	Rep. of Belau	1-Jan-26	31-Dec-39	14	-6.3
007b	**Malakal-B**	**Rep. of Belau**	**1-Jan-69**	**31-Dec-09**	**41**	**1.8**
008a	Yap-A	Fd St Micronesia	1-Jan-51	31-Dec-52	2	37.3
008b	**Yap-B**	**Fd St Micronesia**	**1-Jan-69**	**31-Dec-05**	**37**	**-0.5**
009a	Honiara-A	Solomon Islands	1-Jan-74	31-Dec-95	22	-5.7
010a	**Rabaul**	**Papua New Guinea**	**1-Jan-66**	**31-Dec-97**	**32**	**-2.2**
011a	Christmas-A	Rep. of Kiribati	1-Jan-55	31-Dec-72	18	-3.8
011b	**Christmas-B**	**Rep. of Kiribati**	**1-Jan-74**	**31-Dec-03**	**30**	**0.8**
012a	Fanning-A	Rep. of Kiribati	1-Jan-57	31-Dec-58	2	-21.7
012b	Fanning-B	Rep. of Kiribati	1-Jan-72	31-Dec-87	16	1.8
012c	Fanning-C	Rep. of Kiribati	1-Jan-88	31-Dec-90	3	118.9
013a	Kanton-A	Rep. of Kiribati	1-Jan-49	31-Dec-67	19	3.2
013b	**Kanton-B**	**Rep. of Kiribati**	**1-Jan-72**	**31-Dec-07**	**36**	**0.8**
018a	**Suva-A**	**Fiji**	**1-Jan-72**	**31-Dec-97**	**26**	**4.7**
023a	Rarotonga-A	Cook Islands	1-Jan-77	31-Dec-97	21	4.3
024a	**Penrhyn**	**Cook Islands**	**1-Jan-77**	**31-Dec-10**	**34**	**2.3**
025a	Funafuti-A	Tuvalu	1-Jan-77	31-Dec-99	23	0.9
029a	**Kapingamarangi**	**Fd St Micronesia**	**1-Jan-78**	**31-Dec-08**	**31**	**2.7**
046a	Port Vila-A	Vanuatu	1-Jan-77	31-Dec-82	6	13.6
053a	**Guam**	**USA Trust**	**1-Jan-48**	**31-Dec-08**	**61**	**1.3**
054a	**Truk**	**Fd St Micronesia**	**1-Jan-63**	**31-Dec-91**	**29**	**1.8**
055a	**Kwajalein**	**Rep. Marshall I.**	**1-Jan-46**	**31-Dec-08**	**63**	**1.7**
056a	**Pago Pago**	**USA Trust**	**1-Jan-48**	**31-Dec-08**	**61**	**2.1**

The mean trend for datasets that span more than 25 years (bold font) is 1.3 mm/yr.
Data from JASL as at March 2011.

Figure 7. Annual mean sea levels and linear sea level trends (mm/year) for additional stations on the Joint Archive for Sea Level.



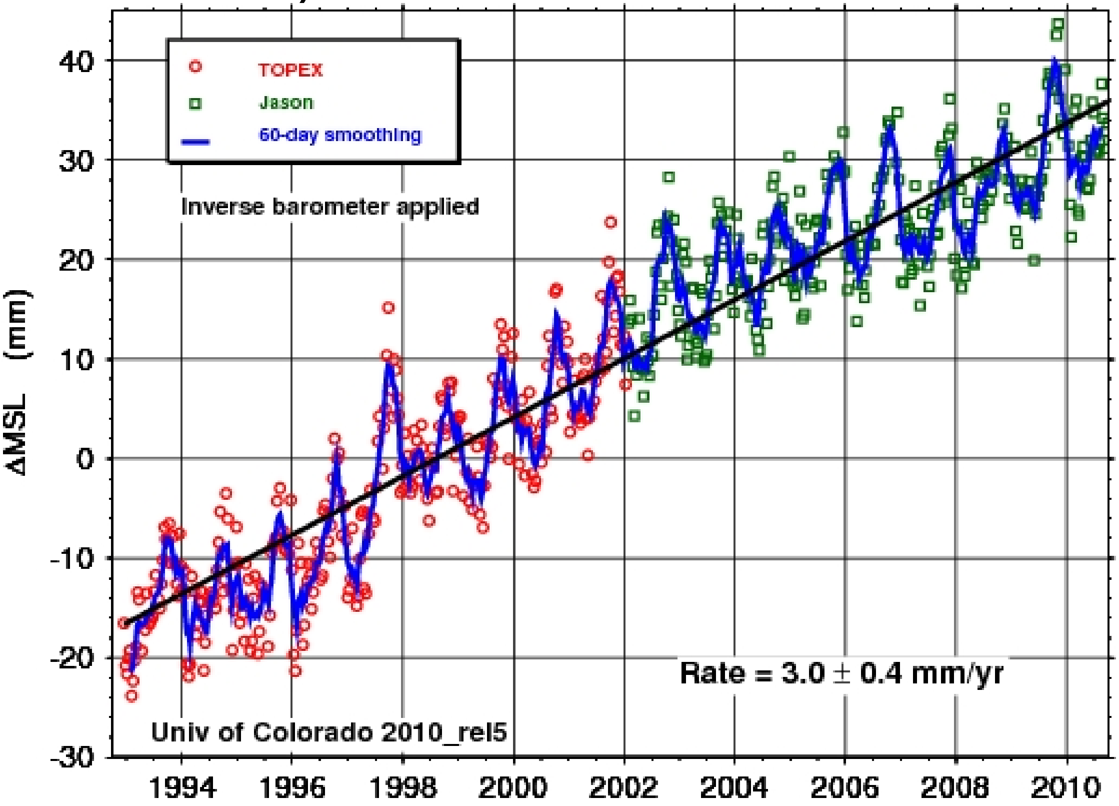
2.4. Satellite Altimetry

Satellite altimetry is technology that allows the height of the sea surface to be measured from satellites orbiting the earth. Satellite altimeters such as Topex/Poseidon and the follow-up missions Jason1 and Jason2 have provided a global record of sea level beginning in late 1992. Although the time interval between successive sea level measurements of the same position on earth is 10 days, the spatial coverage is particularly useful for mapping sea surface anomalies and monitoring development of basin scale events such as El Niño.

Satellite altimeters have an accuracy of several centimetres in the deep ocean, but they are known to be less accurate in shallow coastal regions and therefore are no replacement for in-situ tide gauges. Tide gauges are needed to calibrate the satellite altimeters and provide accurate and more frequent sea level measurements in specific locations where reliable tide predictions and real time monitoring of extreme sea levels is of prime importance.

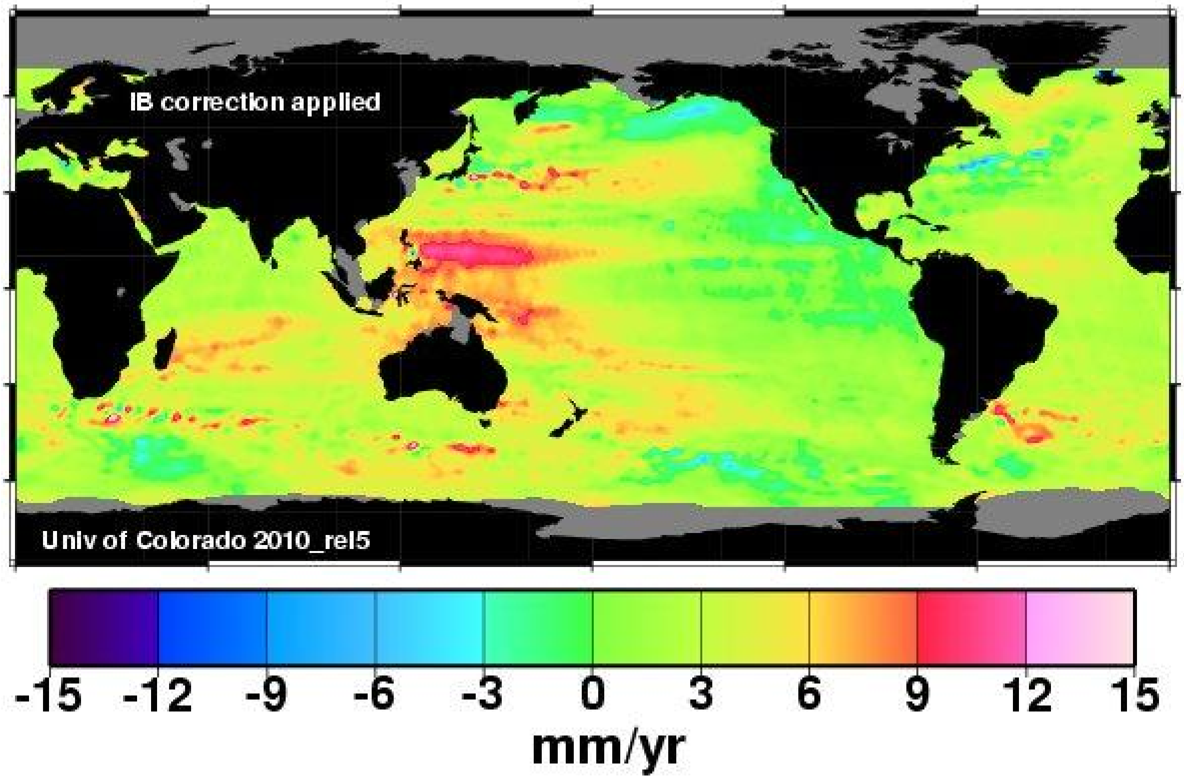
Information about global sea level change derived from satellite altimeters is available from the University of Colorado at http://sealevel.colorado.edu/. Sea level data collected by Topex/Poseidon and Jason show that global mean sea level has risen at a rate of 3.0 +/- 0.4 mm/yr since late 1992 (Figure 8).

Figure 8. Global Mean Sea Level Change Measured By Satellite Altimeters between 1992 and 2010. (Figure Courtesy Of University Of Colorado)



However, global mean sea level change during this time has not been geographically uniform (Figure 9) and continued monitoring is necessary. For example, sea level has risen at relatively high rates across the southwest Pacific but it has risen at relatively low rates across the northeast Pacific and has even fallen in some areas, illustrating basin-wide decadal variability in the Pacific Ocean. The satellite altimetry data has a similar length of record to the South Pacific Sea Level Monitoring Project SEAFRAME stations. The sea level trends from SEAFRAME stations (Table 4) are mostly higher than the global average rate, but this is consistent with higher rates in the southwest Pacific measured by satellite altimeters shown in Figure 9.

Figure 9. Regional Rates of Sea Level Change from 1992 to 2010 as measured by satellite altimeters. (Figure courtesy of University of Colorado)



This section has provided an overview of aspects of the climate and sea level of the South Pacific Sea Level and Climate Monitoring Project region as a whole. The following section provides further details of project findings to date that are relevant to Marshall Islands.

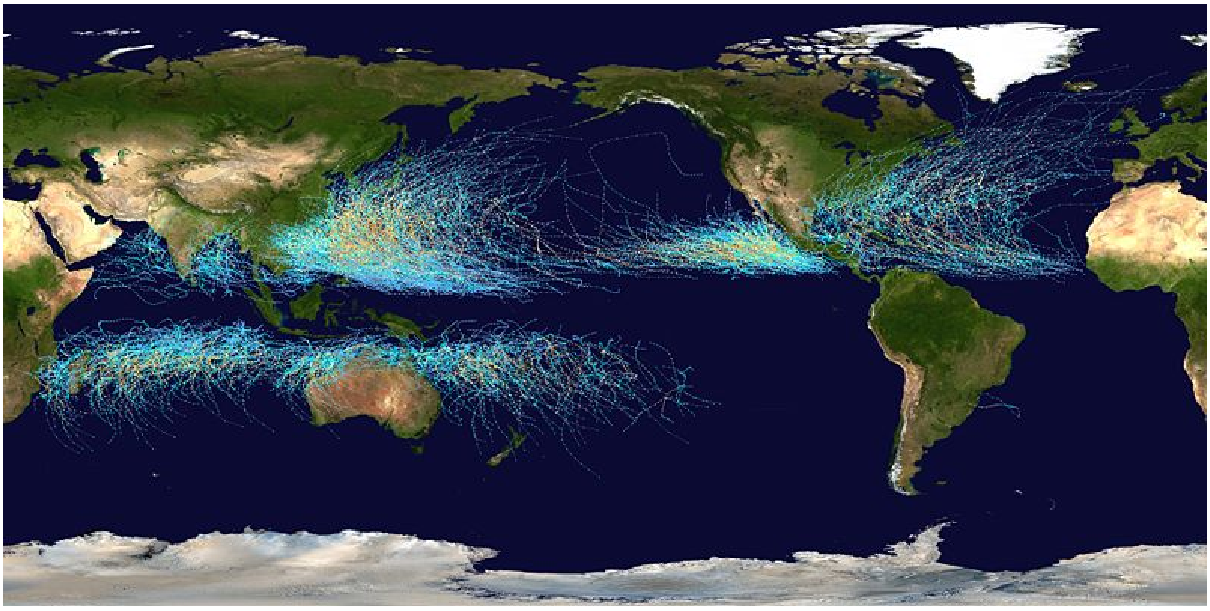
3. Project findings to date - Marshall Islands

3.1. Extreme Events

3.1.1 Tropical Cyclones

Marshall Islands is located in the western Pacific north of the equator in an area that historically experiences tropical cyclones as shown in Figure 10. The SEAFRAME at Majuro has recorded one tropical cyclone since installation in 1993. This cyclone, known as Typhoon Paka, passed the Marshall Islands on 10th December 1997, causing heavy rainfall and around US$80 million (1997) in damage. The barometric pressure at the time fell to 997.2 hPa, which is the lowest pressure recorded by the SEAFRAME at Majuro.

Figure 10. Global Tropical Cyclone Tracks between 1985 and 2005 (Figure courtesy of Wikipedia)

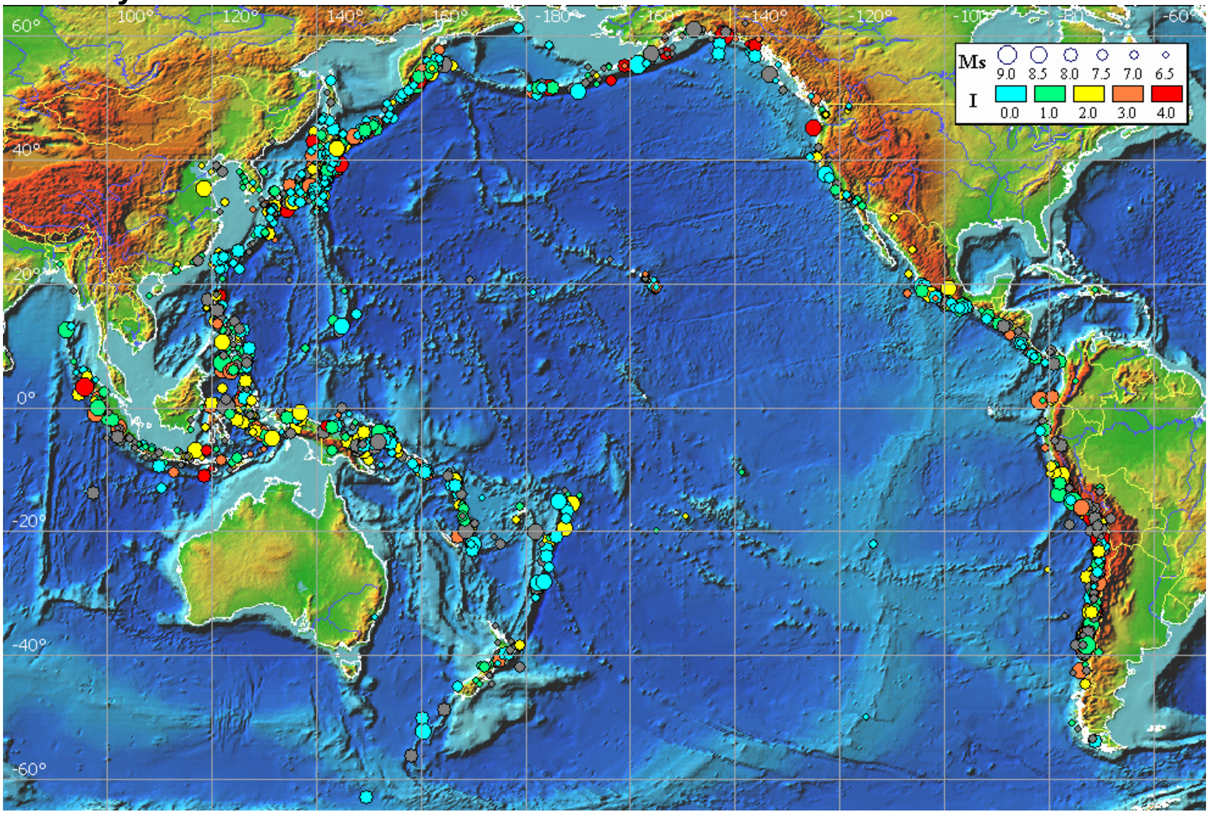


3.1.2. Tsunamis

A tsunami is a series of waves generated by an impulsive disturbance such as an undersea earthquake, coastal or submarine landslide, volcanic eruption, or asteroid impact. Tsunamis are most commonly generated along tectonic plate margins where earthquakes and volcanoes are found. Due to their association with seismic events tsunamis are also referred to as *seismic sea waves*. The term *tidal wave* is incorrect, as tsunamis have nothing to do with gravitational tide generating forces. Tsunami waves may be barely discernible in the open ocean but as they propagate into shallow coastal waters their size may increase significantly.

Figure 11 shows the sources of historical tsunami events listed in the *Integrated Tsunami Database for the Pacific and the Eastern Indian Ocean*[1]. A number of tsunamis have been generated in the South Pacific Sea Level and Climate Monitoring Project region. The SEAFRAME tide gauge network provides important real time tsunami monitoring capability in the region and contributes toward the tsunami warning system for the Pacific Ocean.

Figure 11. Historical Tsunami Events in the Pacific and Eastern Indian Ocean. Circle size indicates earthquake magnitude and colour indicates tsunami intensity.



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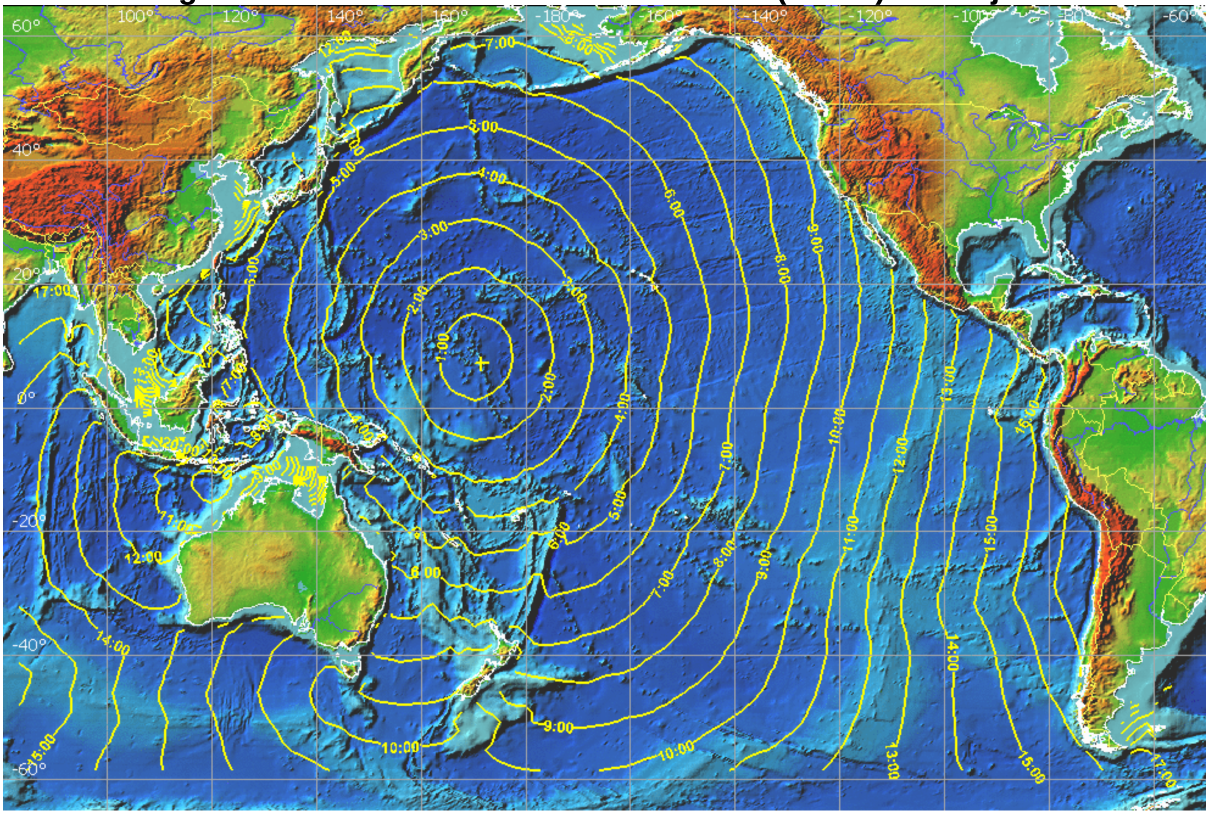
[1] ITDB/PAC (2004) Integrated Tsunami Database for the Pacific, Version 5.12 of December 31, 2004. CD-ROM, Tsunami Laboratory, ICMMG SD RAS, Novosibirsk, Russia.

The historical record reveals that tsunamis have been observed at Marshall Islands from sources including Papua New Guinea, Japan, Russia, Alaska, Chile and Peru. Figure 12 shows the inverse tsunami travel time chart for Majuro, Marshall Islands. This chart may be used to provide an estimate of the time taken for a tsunami to arrive at Majuro from any source location.

Figure 12. Inverse Tsunami Travel Times (hours) for Majuro.



Since its installation in 1993, the SEAFRAME tide gauge at Marshall Islands has detected 14 separate tsunami events. The non-tidal sea levels (3-minute averages recorded every 6 minutes) for each of these events are presented in Figures 13a-13c. Also shown (as vertical dotted lines) are tsunami arrival times, which have been computed independent of the observations by tsunami travel time software using the earthquake location as input.

The largest tsunami recorded by the SEAFRAME at Marshall Islands since installation had a trough-to-peak height of 11cm resulting from a magnitude Mw8.3 earthquake on 4th October 1994 near the Kuril Islands in the northwest Pacific. Another earthquake of magnitude Mw8.3 near the Kuril Islands on 15th November 2006 produced a 10cm tsunami. Appreciable tsunamis have also been detected by the SEAFRAME at Marshall Islands from earthquakes off Peru and Chile.

Figure 13a. Tsunami signals (m) recorded by the SEAFRAME at Majuro, Marshall Islands since installation.

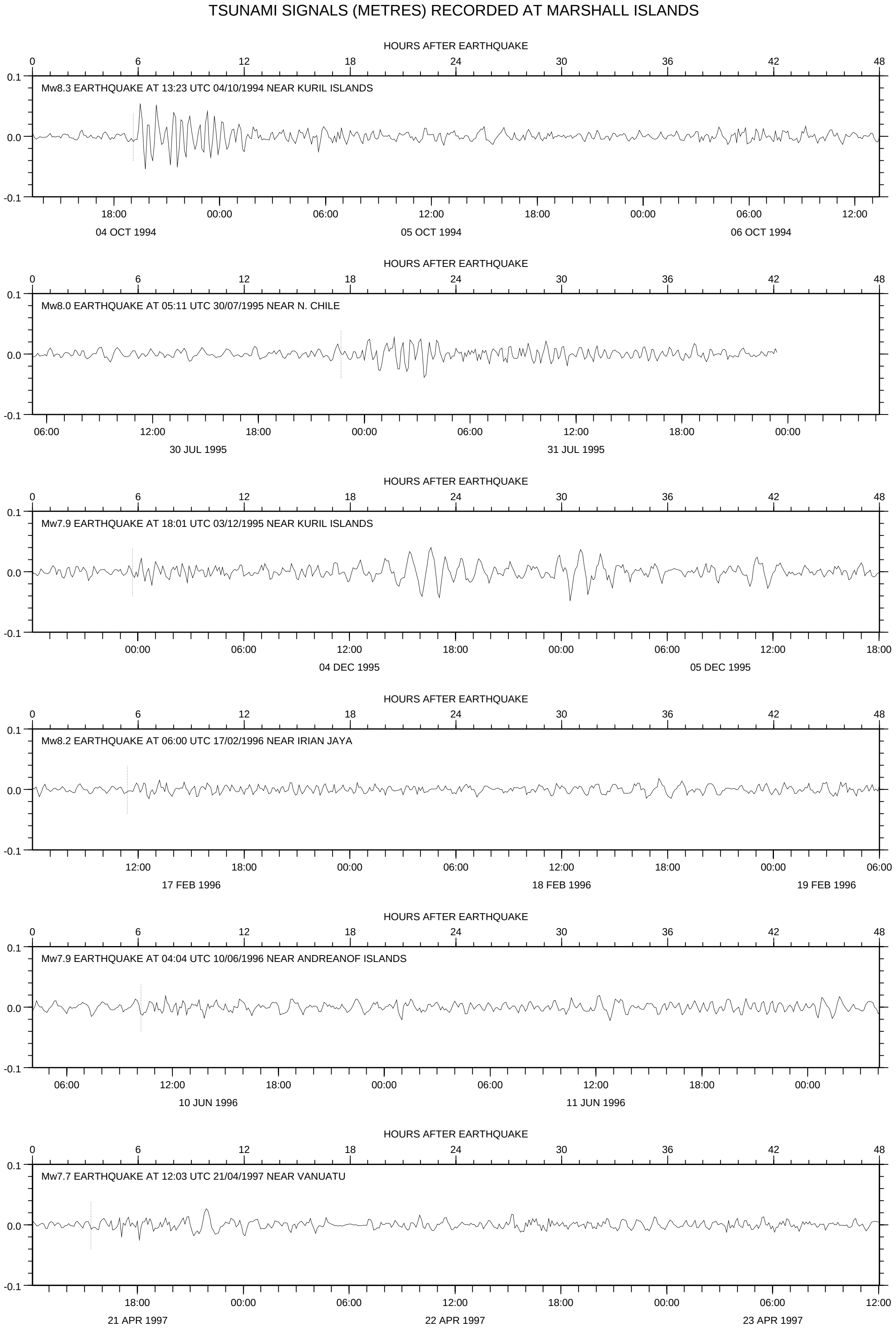


Figure 13b. Tsunami signals recorded by the SEAFRAME at Majuro, Marshall Islands since installation.

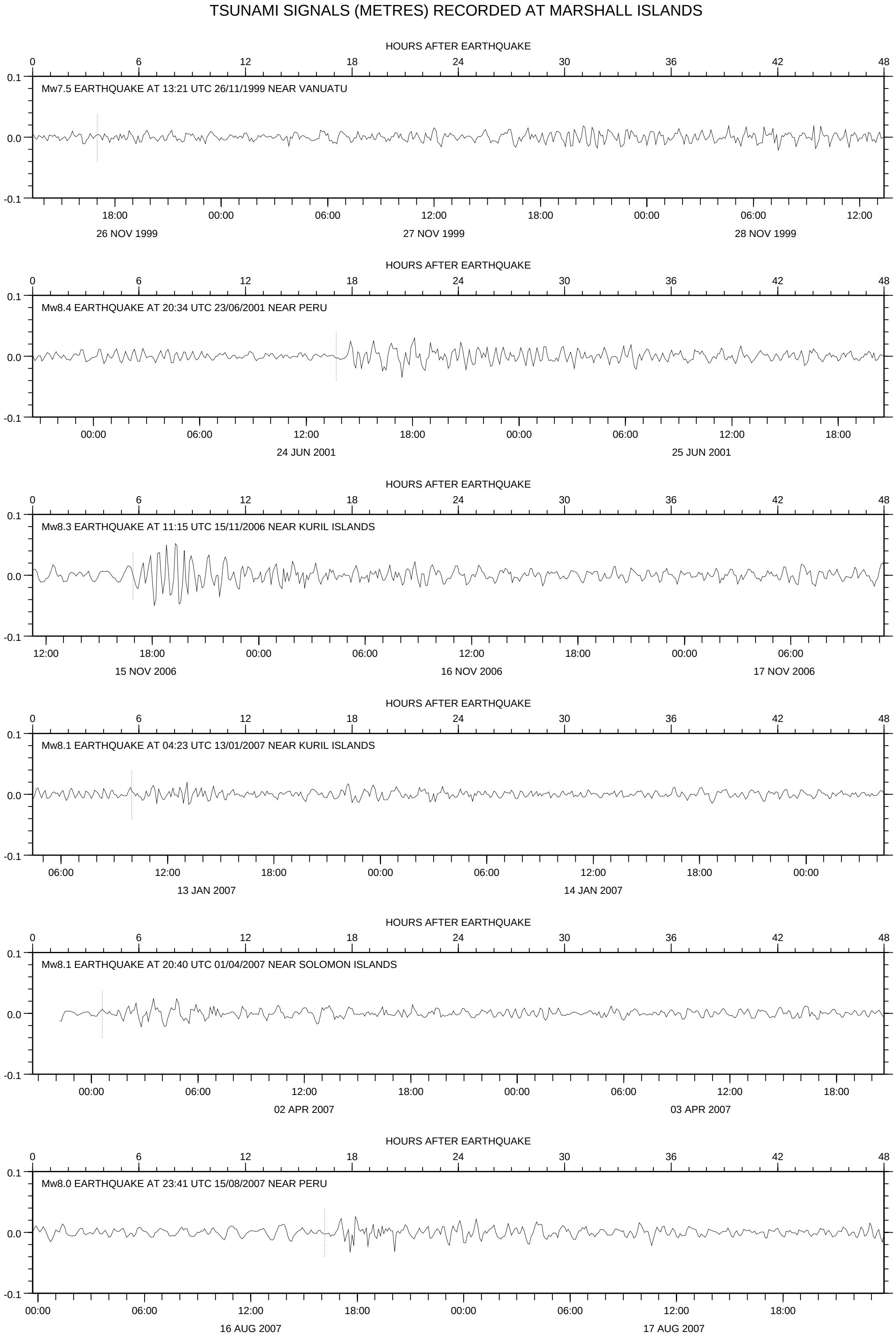
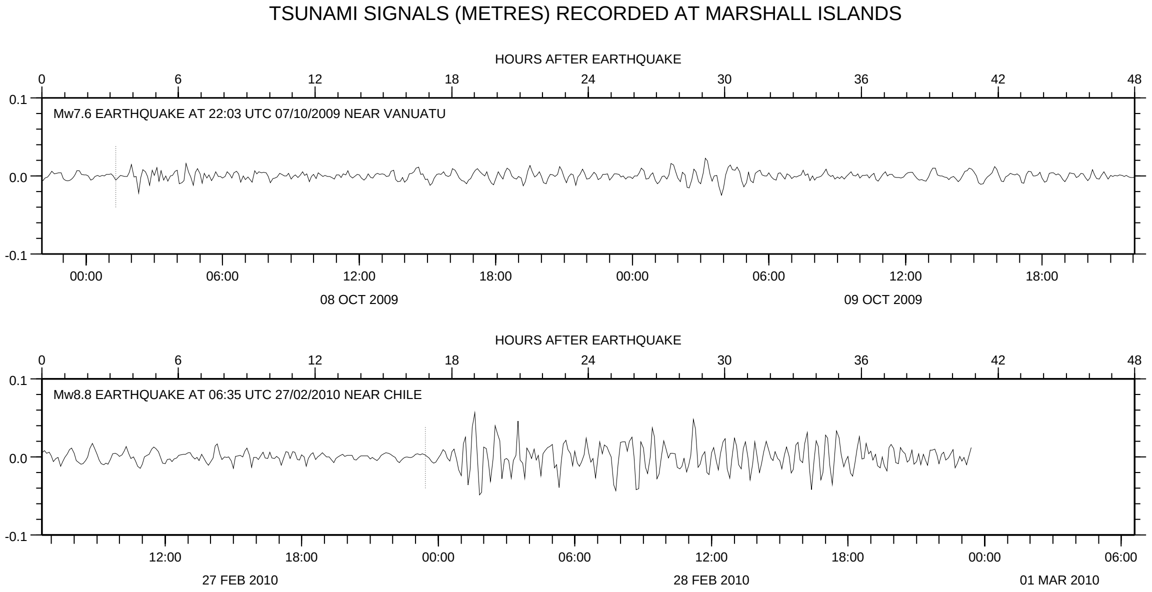


Figure 13c. Tsunami signals recorded by the SEAFRAME at Majuro, Marshall Islands since installation.



3.2. SEAFRAME sea level record and trend

A fundamental goal of the Project is to establish the rate of sea level change. It has been recognised since the beginning that this would require several decades of continuous, high quality data. The preliminary findings are being provided, but caution should be exercised in interpreting this information. Figure 6 shows that confidence in trend estimates improve as more data becomes available.

As at December 2010, based on the short-term sea level trend analyses performed by the National Tidal Centre using the Majuro SEAFRAME data, a rate of **+4.3 mm per year** has been observed. Accounting for the inverted barometric pressure effect and vertical movements in the observing platform, the sea level trend is **+3.8 mm per year**. By comparison, the Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report (IPCC AR4, 2007) estimates that global average long-term sea level rise over the last hundred years was of the order of 1 to 2 mm/yr.

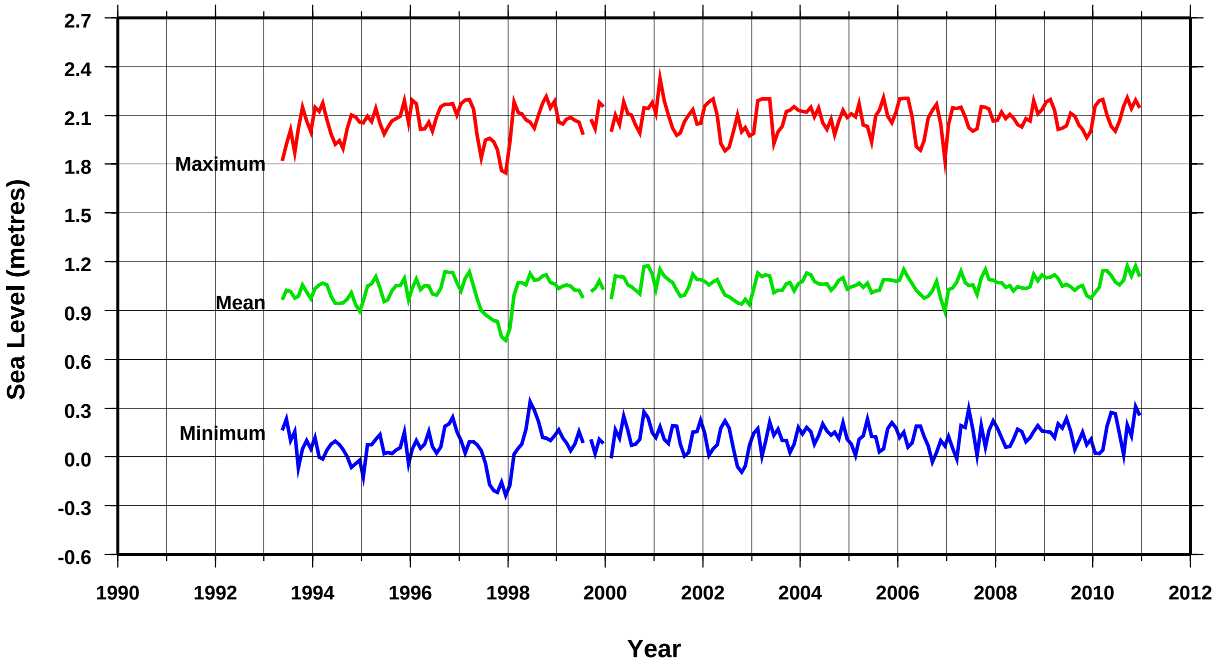
Figure 4 shows how the trend estimate has varied over time. At first the trend appeared to indicate an enormous rate of sea level decline, followed by a period of apparent rise. Due to the 1997/1998 El Niño when sea level fell 29 cm below average, the trend went negative again, and remained so for about one year. Given the sea level record is still relatively short, it is still too early to deduce a long-term trend.

The sea level data recorded since installation is summarised in Figure 14. The middle curve (green) represents the monthly mean sea level. The upper and lower curves show the highest and lowest values recorded each month. We see that largely, the monthly mean values are quite stable throughout the year, with the exception of 1997 and 1998, where the level fluctuates during the El Niño.

Seasonal cycles are weak. There is normally about a two metre difference between the highest and lowest recorded levels in a given month, a relatively limited range in comparison to many sites, but similar to that of Tuvalu, which is located approximately as far south of the equator as Majuro is to the north of it. However, the annual sea level cycle at Majuro is far less pronounced than at Tuvalu (which is located in the South Pacific Convergence Zone). The mean sea level over the duration of the record is 1.045 metres, with a maximum of 2.327 metres on 9th of February 2001, and a minimum of -0.238 metres on 14th of December 1997.

Figure 14

Monthly sea level at Majuro, Marshall Islands
SEAFRAME gauge



3.3.Additional sea level records and trend

Additional sea level records for Marshall Islands are available from the Joint Archive for Sea Level including Majuro (32 year record), Enewetok (two separate records of 21 and 6 years) and Kwajalein (63 year record). The separate sea level records at Enewetok have not been joined to make longer records as they are based on different tide gauge datum. The monthly sea level data are shown in Figures 15-18. The longer records have relative sea level trends of +2.3, +1.3 and +1.7 mm/year.

Older tide gauge installations were primarily designed for monitoring tides and shorter-term oceanic fluctuations such as El Niño rather than long-term sea level monitoring which requires a high level of precision and datum control.

Figure 15

Monthly sea level at Majuro-A
Joint Archive For Sea Level Data
Sea Level Trend: 2.3 mm/yr

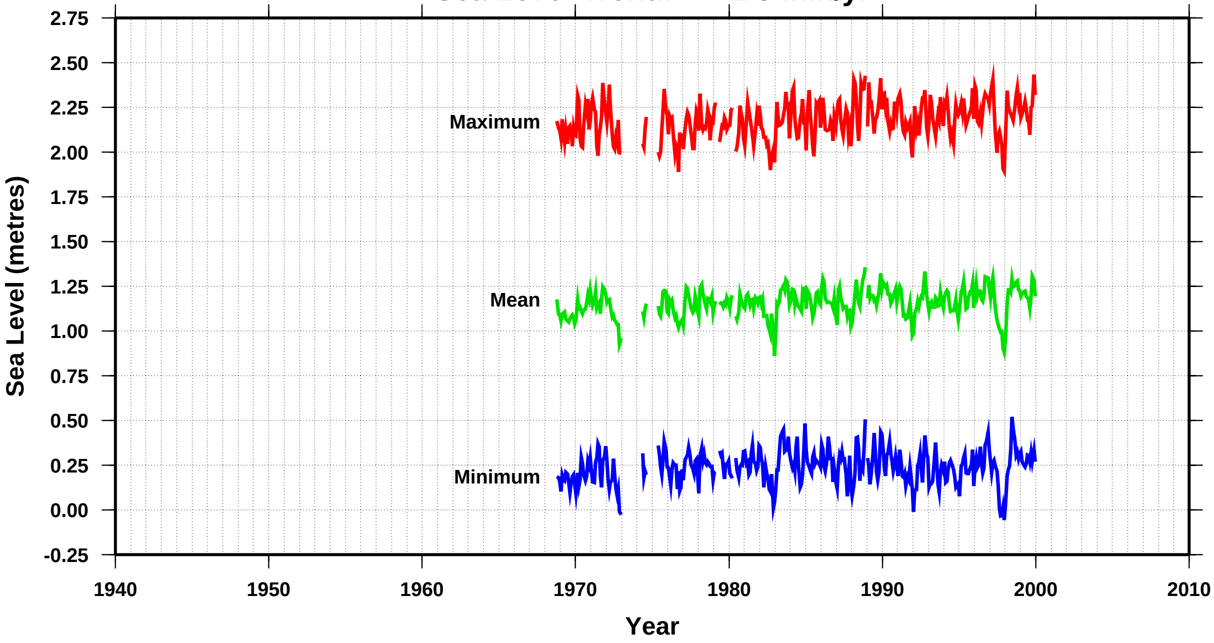


Figure 16

Monthly sea level at Enewetok-A
Joint Archive For Sea Level Data
Sea Level Trend: 1.3 mm/yr

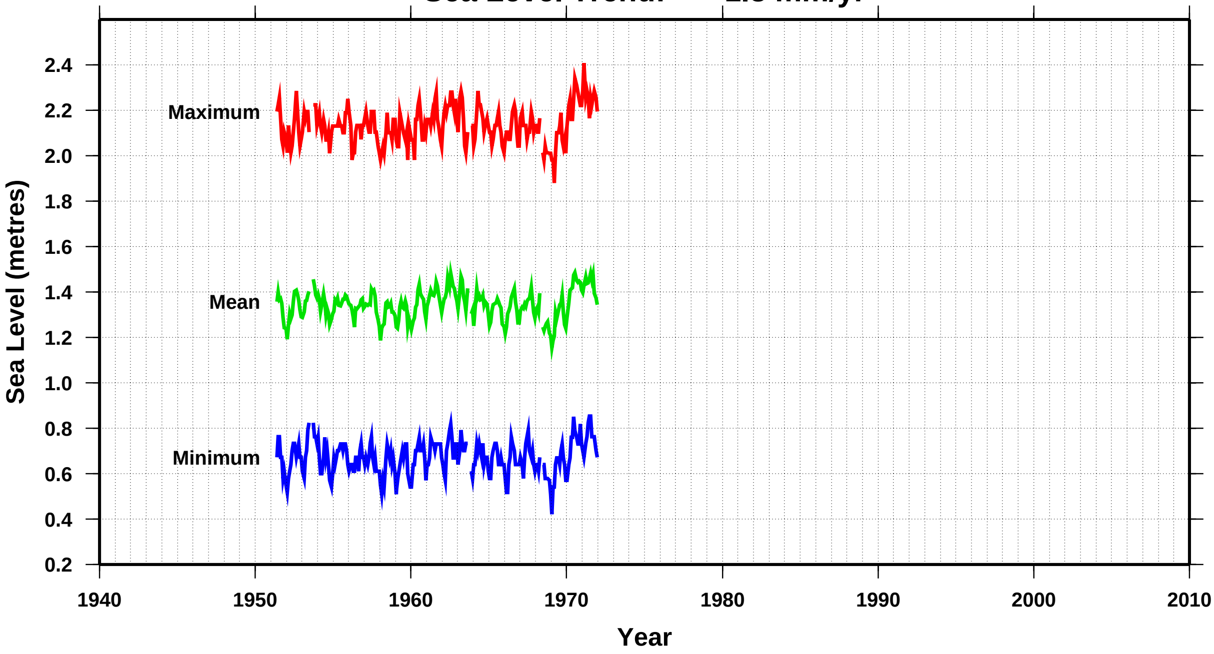
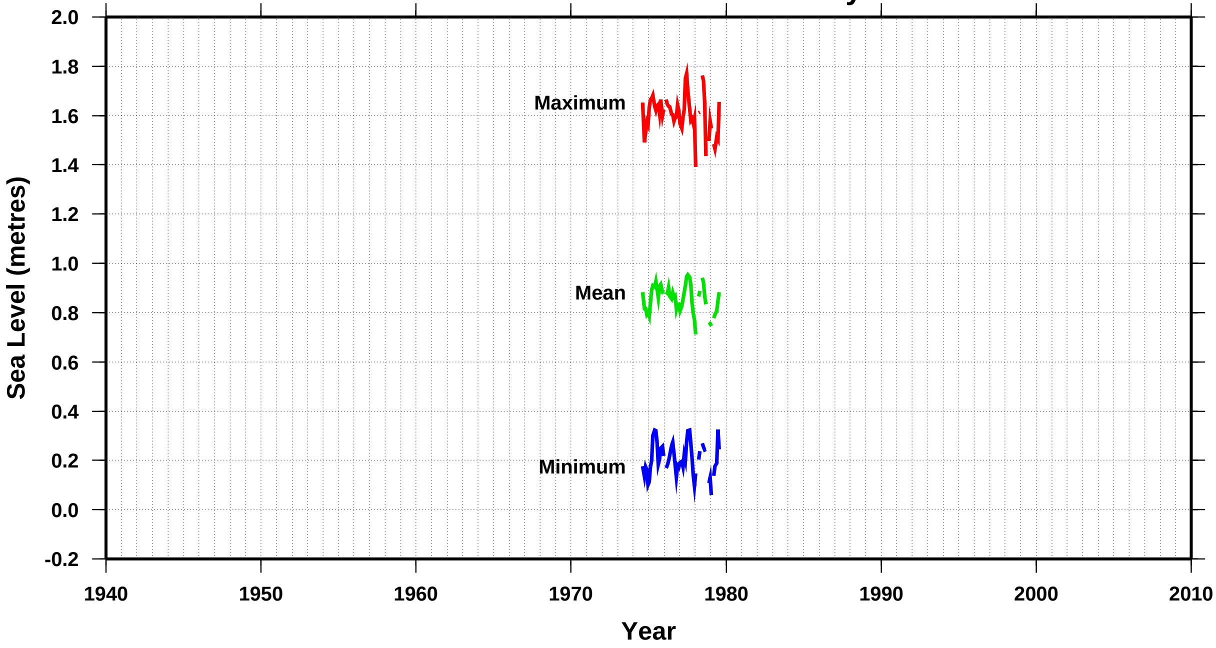
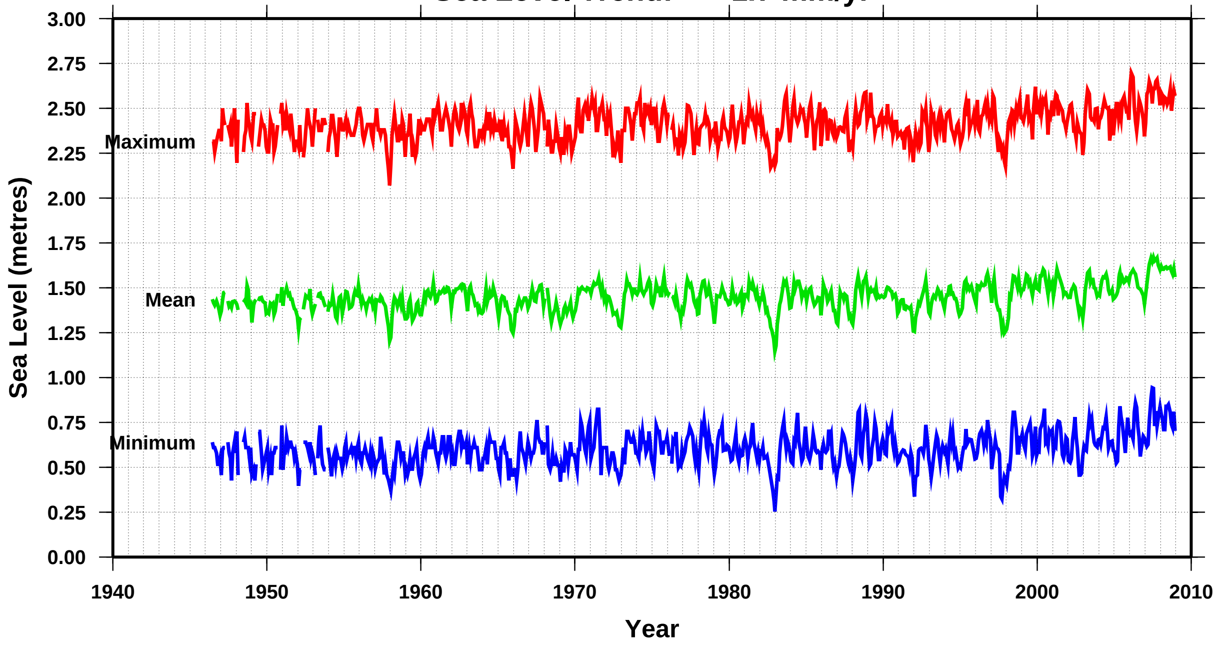


Figure 17



Monthly sea level at Enewetok-B
Joint Archive For Sea Level Data
Sea Level Trend: -10.0 mm/yr

Figure 18



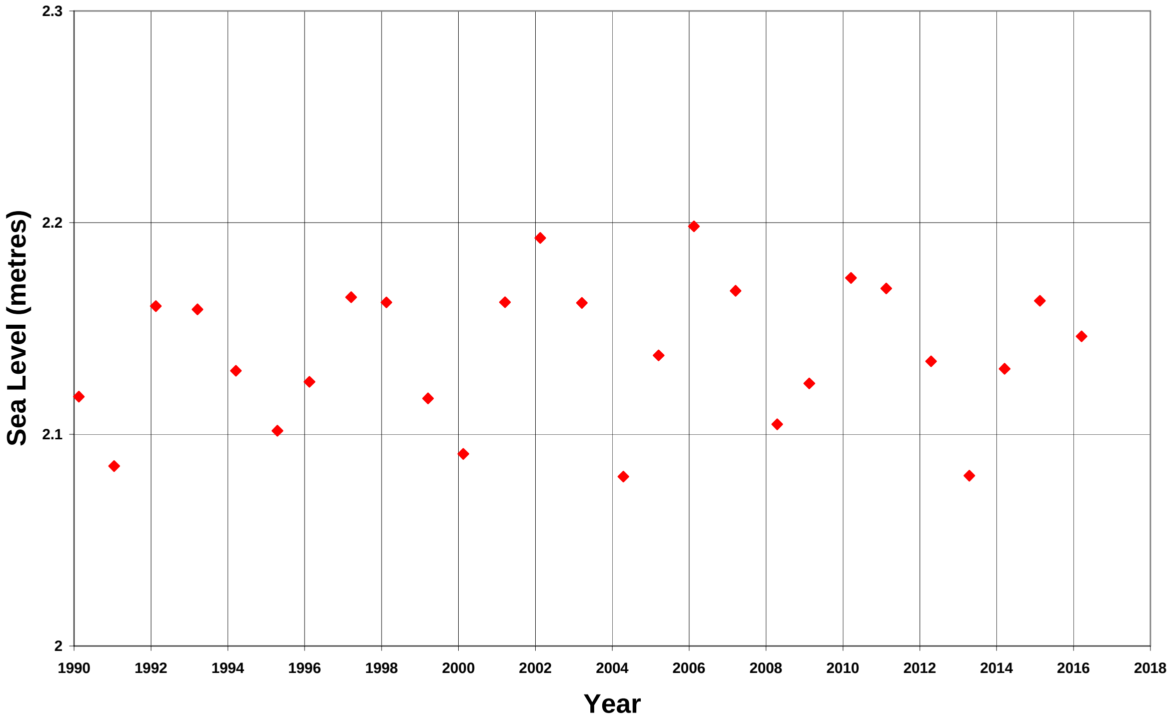
Monthly sea level at Kwajalein
Joint Archive For Sea Level Data
Sea Level Trend: 1.7 mm/yr

3.4. Predicted highest astronomical tide

The component of sea level that is predictable due to the influence of the Sun and the Moon and some seasonal effects allow us to calculate the highest predictable level each year. The highest astronomical tide is the highest sea level that can be predicted under any combination of astronomical conditions, including the proximity of the earth to the sun and the moon. Figure 19 shows that the highest predicted level (2.2 m) over the period 1990 to 2016 occurred at 16:55 Local Time on 28 February 2006.

Figure 19

Predicted highest tide each year for Majuro

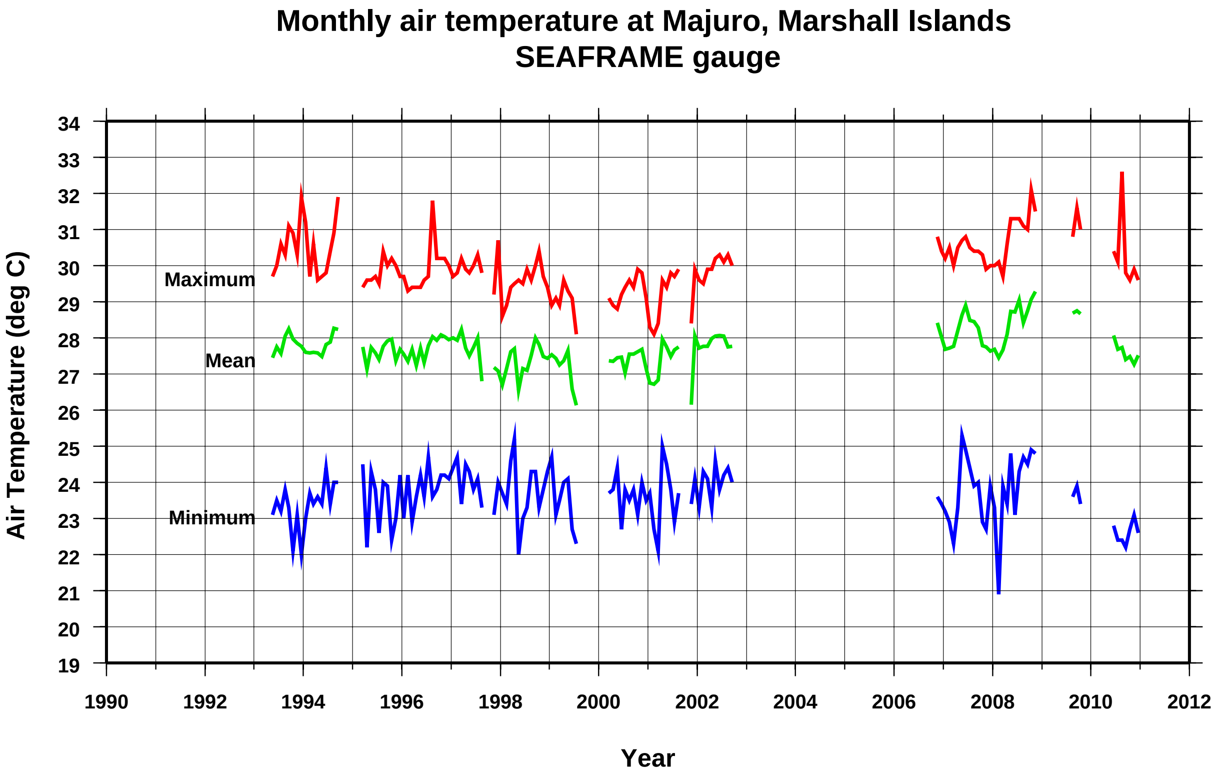


3.5. Monthly means of air temperature, water temperature and atmospheric pressure

The data summarised in Figures 20-22 follow the same format as the monthly sea level plot: the middle curve (green) represents the monthly mean, and the upper and lower curves show the highest and lowest values recorded each month.

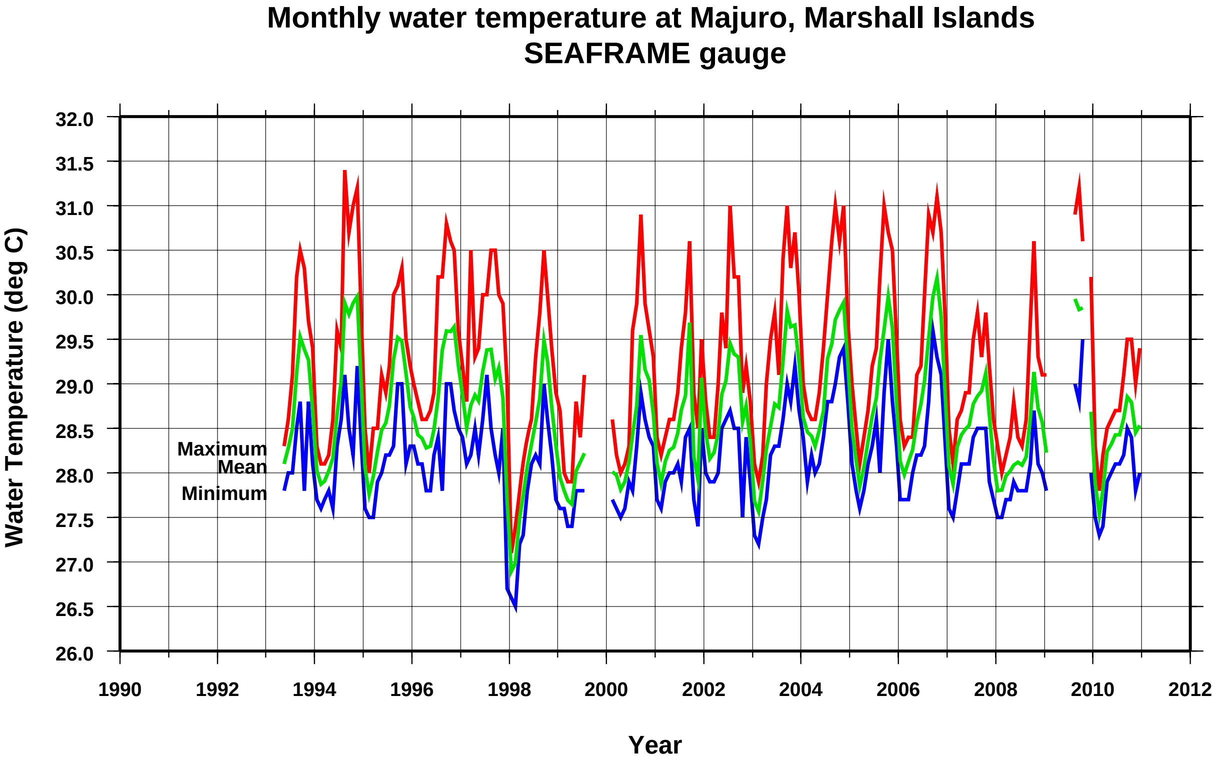
The mean air temperatures at Majuro show no clear seasonal cycle. The overall mean is 27.7°C, and the monthly means are normally within ± 2°C of this value throughout the year. There was a slight decrease in monthly mean air temperature during the 1997/1998 El Niño. The mean air temperature over the duration of the record is 27.7°C. The highest recorded air temperature was 32.6°C on 25th of August 2010, and the minimum was 20.9°C on 12th of February 2008. The air temperature sensor suffered a spate of technical problems between 2002 and 2006.

Figure 20



Unlike air temperature, the variability in water temperature at Majuro is dominated by the annual cycle, which peaks around August or September (late Summer). This may be due to the fact that the SEAFRAME gauge is located in an atoll lagoon, which traps solar heat, whereas the Trade Winds keep the surface air temperature more constant. The mean water temperature over the duration of the record is 28.7°C. The highest recorded water temperature was 31.4°C on 13th of August 1994, and the minimum was 26.5°C on 5th of February 1998 during the 1997-1998 El Niño.

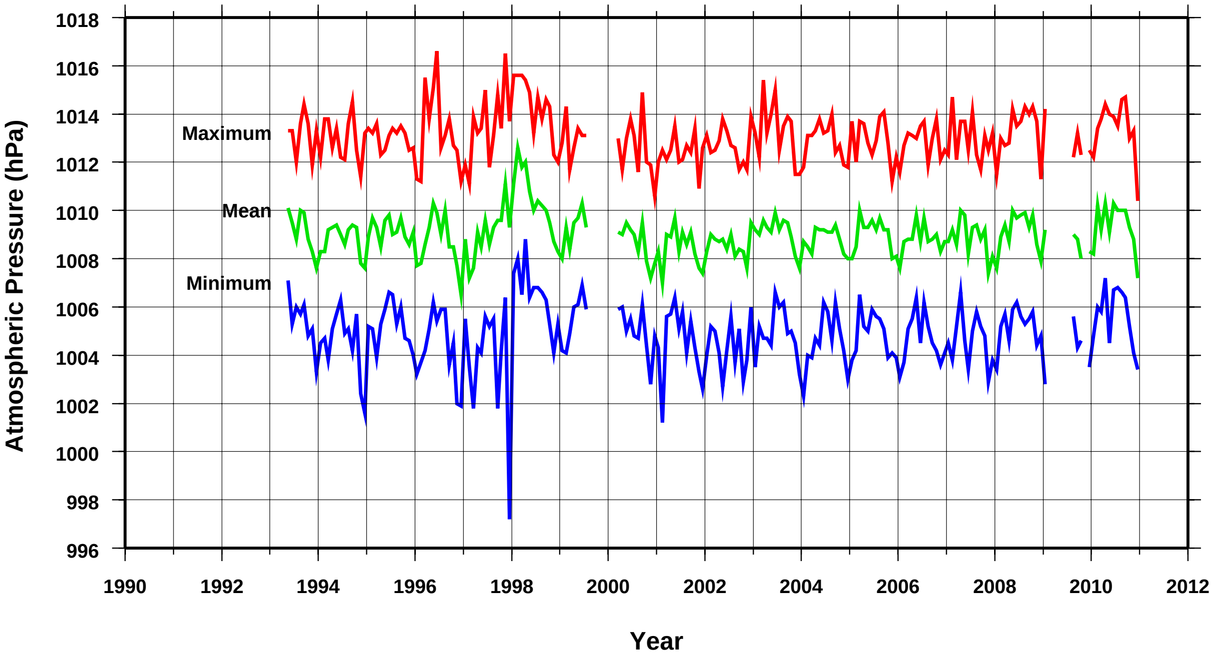
Figure 21



The sea level also responds to changes in barometric pressure. As a rule of thumb, a 1 hPa fall in the barometer, if sustained over a day or more, produces a 1 cm rise in the local sea level (within the area beneath the low pressure system). The monthly mean atmospheric pressure at Majuro reached a peak in early 1998 at the height of El Niño. The highest pressure recorded was 1016.6 hPa on 28th of June 1996, while the lowest was 997.2 hPa on 10th of December 1997 during the passing of a tropical cyclone known as Typhoon Paka. The mean barometric pressure over the duration of the record is 1009.0 hPa.

Figure 22

Monthly atmospheric pressure at Majuro, Marshall Islands SEAFRAME gauge



3.6. Precise Levelling Results for Majuro

While the SEAFRAME gauge exhibits a high degree of datum stability, it is essential that the datum stability be checked periodically by precise levelling to an array of deep-seated benchmarks located close to the tide gauge. For example, a wharf normally supports the SEAFRAME, and wharf pilings are often subject to gradual vertical adjustment, which in turn can raise or lower the SEAFRAME.

Precise levelling is carried out on a regular 18-monthly cycle between the SEAFRAME Sensor Benchmark and an array of at least six deep benchmarks. The nearest stable benchmark is designated the “Tide Gauge Benchmark (TGBM)”, and the others are considered the “coastal array”.

Figure 23 summarises the most important survey information being the movement of the SEAFRAME Sensor benchmark relative to the TGBM, as well as recent movement relative to the CGPS station. The graph does not include the results for the other benchmarks on the coastal array. In this graph, each survey is plotted relative to the first. Thus, the second survey at Majuro found that the SEAFRAME Sensor benchmark had *risen* relative to the TGBM by 1 mm, but overall, the Sensor benchmark has *fallen* at an average rate of -0.5 mm/year.

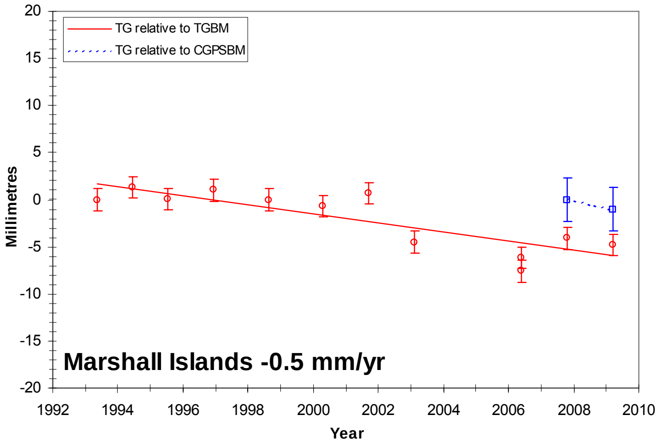


Figure 23. Movement of SEAFRAME Sensor relative to the Tide Gauge Bench Mark and CGPS station.

Levelling of SEAFRAME Sensor benchmark. Photo credit: Steve Turner, NTC.

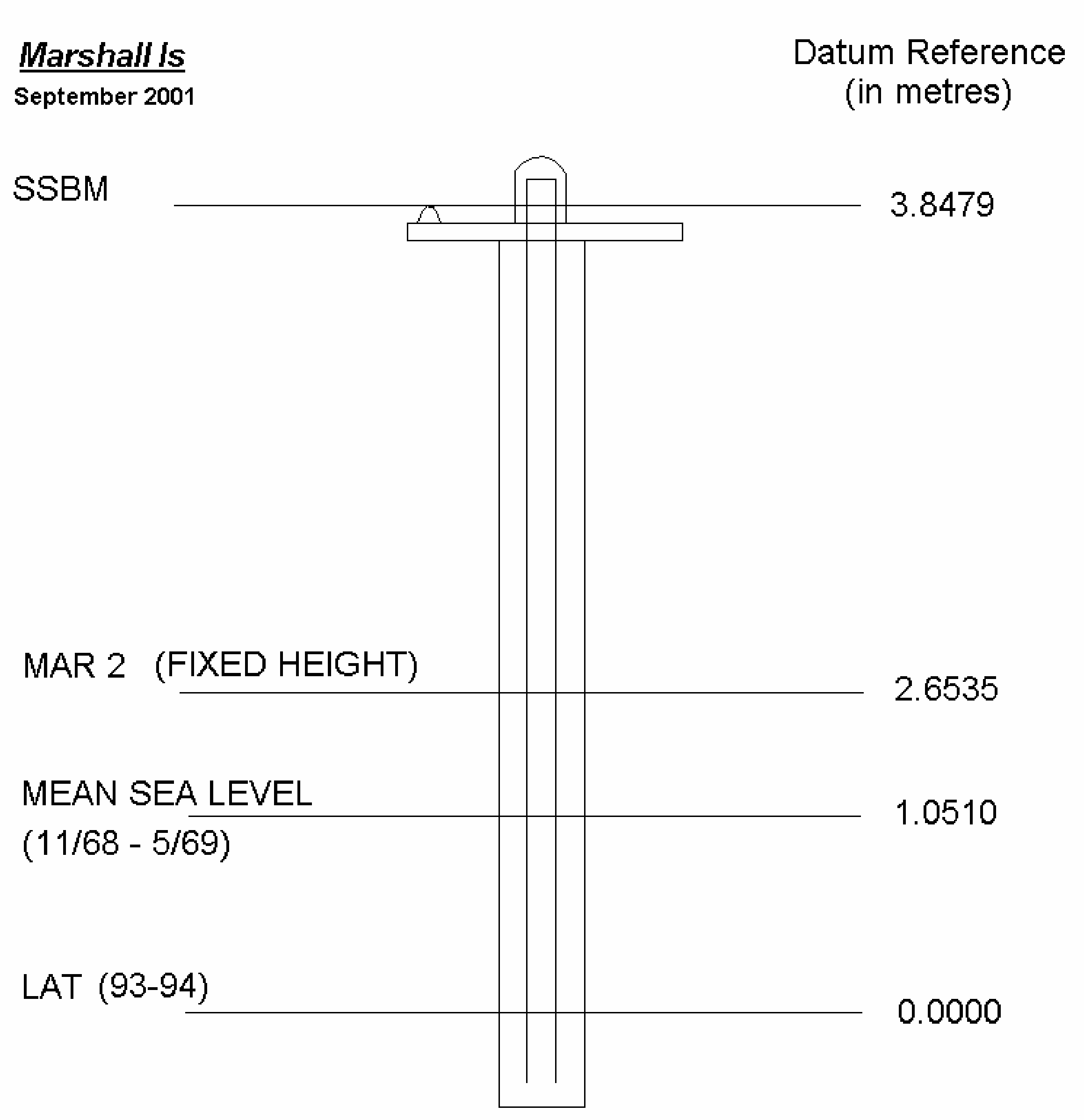
Appendix

A.1. Definition of Datum and other Geodetic Levels at Majuro

Newcomers to the study of sea level are confronted by bewildering references to “Chart Datum”, “Tide Staff Zero”, and other specialised terms. Frequently asked questions are, “how do NTC sea levels relate to the depths on the marine chart?” and “how do the UH sea levels relate to NTC’s?”.

Regular surveys to a set of coastal benchmarks are essential. If a SEAFRAME gauge or the wharf to which it is fixed were to be damaged and needed replacement, the survey history would enable the data record to be “spliced across” the gap, thereby preserving the entire invaluable record from start to finish.

Figure 24



The word “datum” in relation to tide gauges and nautical charts means a reference level. Similarly, when you measure the height of a child, your datum is the floor on which the child stands.

“Sea levels” in the NTC data are normally reported relative to “Chart Datum” (CD), thus enabling users to relate the NTC data directly to depth soundings shown on marine charts – if the NTC sea level is +1.5 metres, an additional 1.5 metres of water may be added to the chart depths. At Majuro, “LAT” (see below) provides an “equivalent” datum.

Mean Sea Level (MSL) in Figure 24 is the average recorded level at the gauge over an extended period of time.

Lowest Astronomical Tide, or “LAT”, is based purely on tidal predictions over a 19 year period. In this case, LAT is 0.000 metres, meaning that if the sea level were controlled by tides alone, the sea level reported by NTC would drop to this level just once in 19 years.