

Pacific Country Report

Sea Level & Climate: *Their Present State*

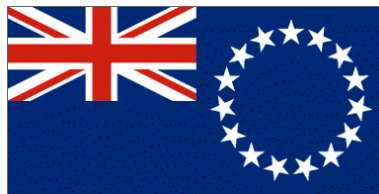
Cook Islands

December 2007

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



COOK ISLANDS

December 2007

Executive Summary

- A SEAFRAME gauge was installed in Rarotonga, Cook Islands, in February 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 +4.8 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 +4.9 mm/year. Nearby gauges, with longer records but less precision and datum control, show trends of +4.34 and +1.69 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 include more pronounced seasonal cycles and were likewise affected by the 1997/1998 El Niño.
- In October-November 1997 Tropical Cyclone Martin devastated the northern Cook Islands. In December 1997 Tropical Cyclone Pam passed Rarotonga as a category 2 cyclone and caused high sea levels and flooding.
- The SEAFRAME at Rarotonga, Cook Islands has recorded 12 separate tsunami events since its installation. The largest tsunami signal was recorded after an earthquake of magnitude Mw8.3 that occurred near the Kuril Islands on 15 November 2006. The trough-to-peak tsunami height was 40cm for the 1-minute sea level data, or 17cm for 6-minute sea level data.

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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** (**S**ea **L**evel **F**ine **R**esolution **A**coustic **M**easuring **E**quipment) gauge was installed at Avatiu Harbour, Rarotonga, Cook Islands, in February, 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 shifts in the vertical of the sea level sensors due to local land movement. A Continuous Global Positioning System (CGPS) station was installed in Cook Islands in September 2001 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.

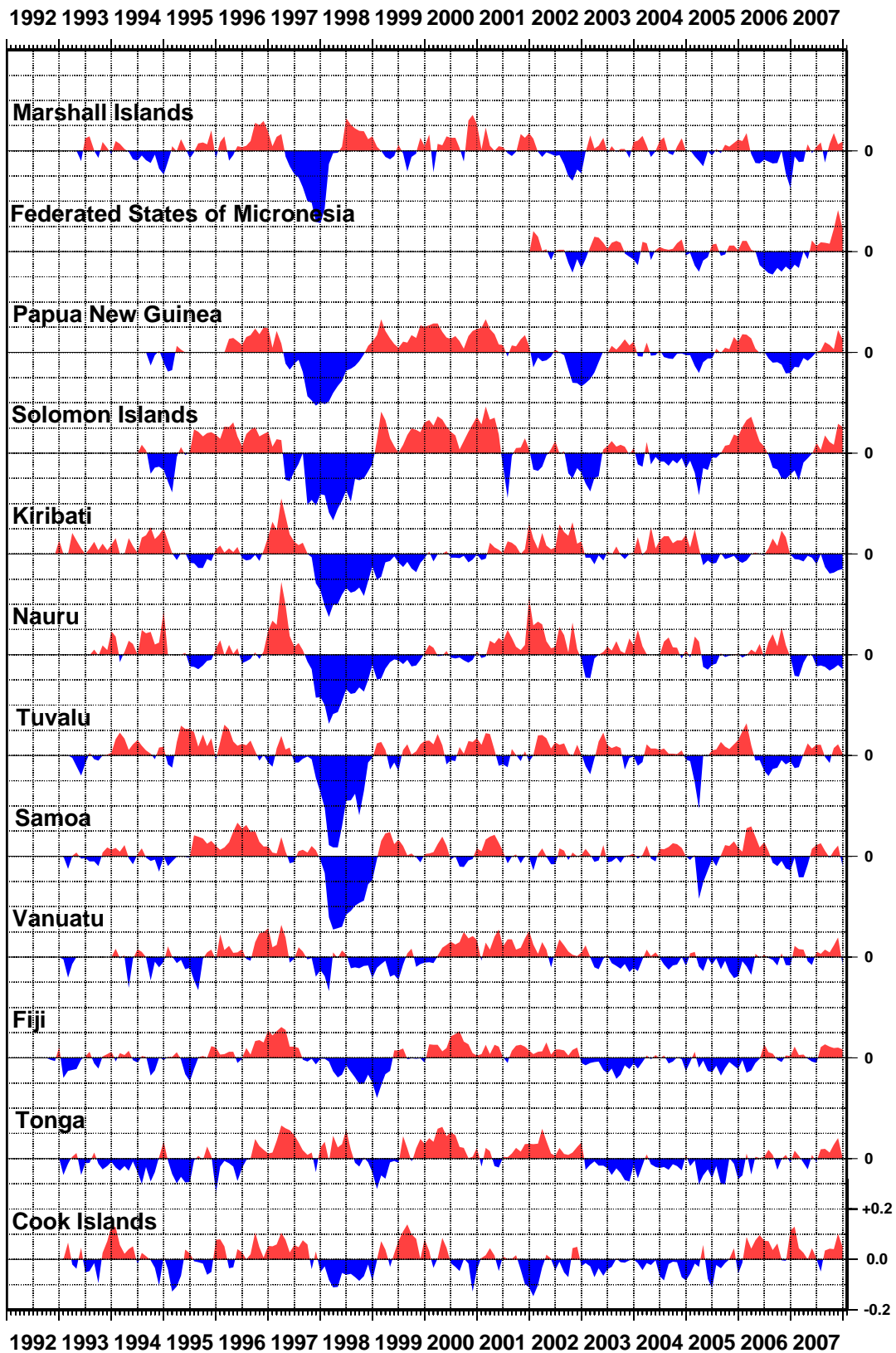
Compared to higher latitudes, air temperatures in the tropics vary little throughout the year. Of the SEAFRAME sites, those furthest from the equator naturally experience the most extreme changes – the Cook Islands (at 21°S) recorded the lowest temperature, 13.1°C, in August 1998. The Cook Islands regularly 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)	Maximum recorded air temperature (°C)
Cook Islands	13.1	32.0
Tonga	16.0	31.4
Fiji (Lautoka)	16.6	33.8
Vanuatu	15.2	33.3
Samoa	18.7	32.3
Tuvalu	22.8	33.7
Kiribati	22.4	32.9
Nauru	22.4	33.0
Solomon Islands	20.1	34.5
Papua New Guinea	21.5	31.8
Marshall Islands	22.0	31.9
FSM	22.6	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 recorded sea levels appear during the 1997/1998 El Niño. The most dramatic effects were observed at the Marshall Islands, PNG, Nauru, Tuvalu and Kiribati, and along a band extending southeastward from PNG to Samoa. The latter band corresponds to a zone meteorologists call the “South Pacific Convergence Zone” or SPCZ (sometimes called the “Sub-Tropical Convergence Zone”, or STCZ).

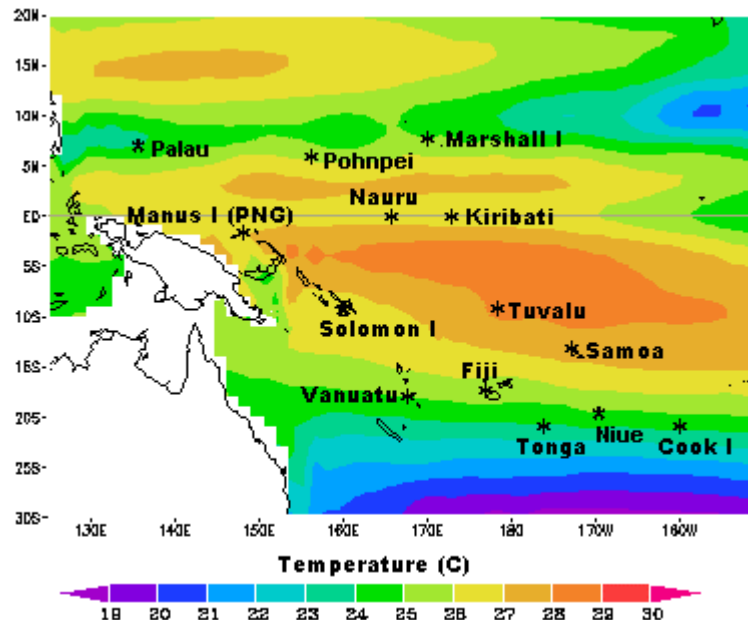
Figure 1. Sea level anomalies* at SEAFRAME sites



* 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 fueled 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.

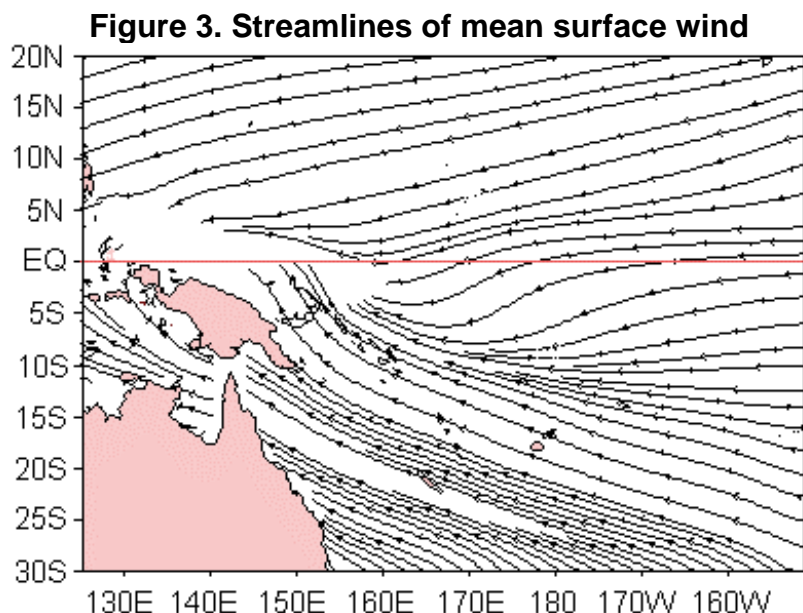
Figure 2. Mean surface water temperature



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) shows 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.



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).

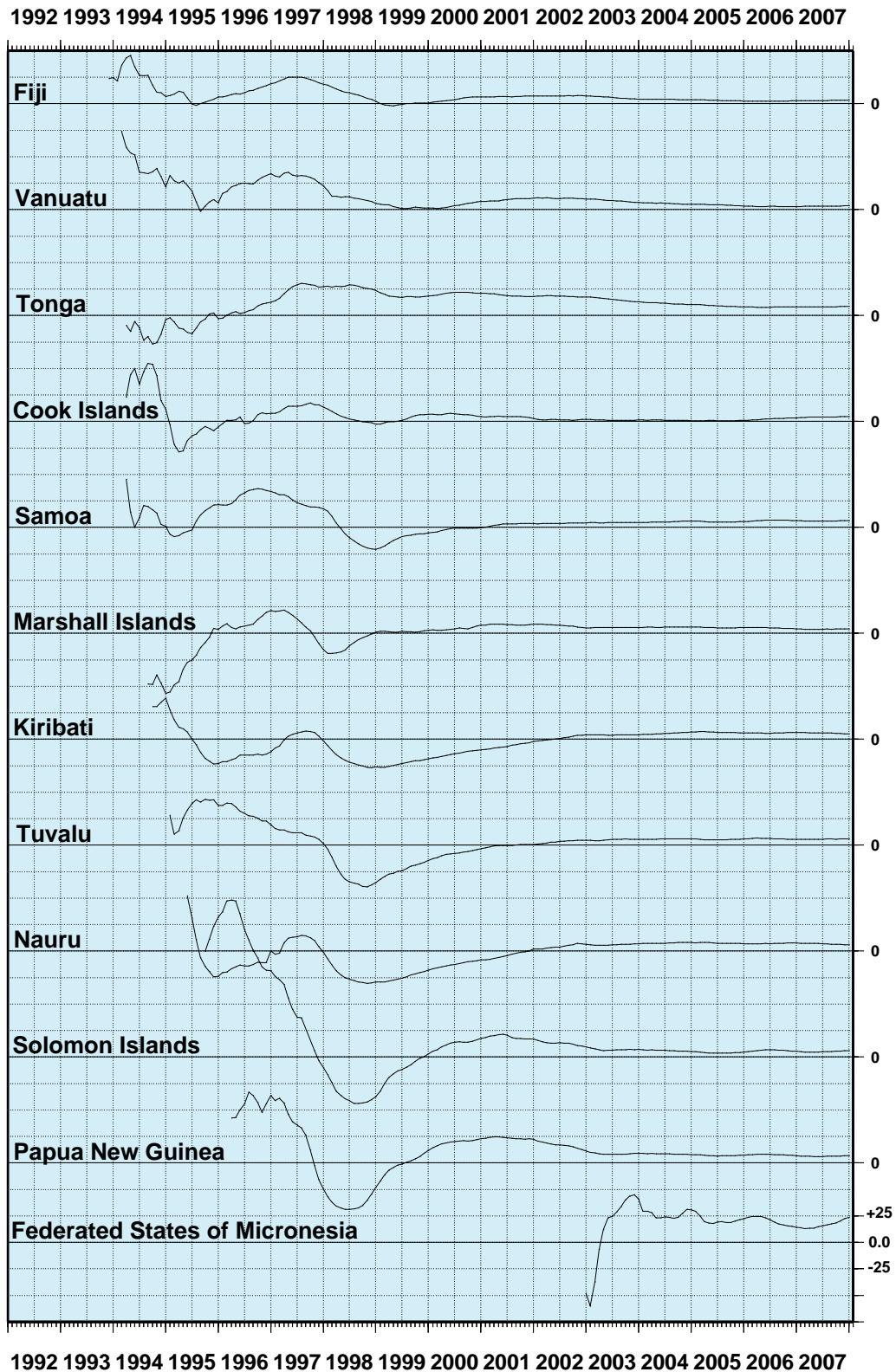
2.2. Sea Level Datasets from SEAFRAME stations

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 SEAFRAMES 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 hourly via satellite and are processed using specific quality control procedures.

The project's data collection program has been operating for a relatively short term 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 trend estimates will begin to reflect longer-term change rather than short-term fluctuations. Figure 4 shows how the sea level trends from SEAFRAME stations have evolved from one year after installation to the present. These trends will continue to stabilise for many more years, 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 lengths of records increase.

SEA LEVEL TRENDS THROUGH DECEMBER 2007 (mm/year)



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 periodically, preferably every eighteen months. 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 a storm. The rates of vertical movement of the gauges relative to the TGBM (determined by fitting a straight line to the survey results) that are contributing to the observed sea level trends are listed in Table 2. Substantial subsidence of the tide gauge at Samoa is occurring at a rate of -1.0 mm/year. Subsidence is also occurring at Marshall Islands. The tide gauges at Cook Islands and Fiji are rising with respect to the tide gauge benchmark. The rates of vertical tide gauge movement are used to correct observed rates of relative sea level change.

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	8	+0.3
FSM	0.115	0.7	2	-0.4
Fiji	0.522	1.4	8	+0.5
Kiribati	0.835	1.8	9	+0.1
Marshall Is	0.327	1.1	8	-0.6
Nauru	0.120	0.7	9	+0.2
PNG	0.474	1.4	7	-0.1
Samoa	0.519	1.4	8	-1.0
Solomon Is	0.394	1.3	4	-0.4
Tonga	0.456	1.4	8	-0.7
Tuvalu	0.592	1.5	8	-0.1
Vanuatu	1.557	2.5	7	+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 meaningful 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 relative sea level rise. Known as the inverted barometer effect, if a 1 hPa fall in barometric pressure is sustained over a day or more, a 1 cm rise is produced in the local sea level (within the area beneath the low pressure system). 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 will cause a 10 mm/year increase (decrease) in relative sea level.

Estimates of the contribution to relative sea level trends by the inverted barometric pressure effect at all SEAFRAME sites over the period of the project are listed in Table 3. The estimates are mostly positive, which means relative sea level trends are being overestimated without taking the barometric pressure effect into consideration.

Table 3. Recent short-term barometric pressure trends expressed as equivalent sea level rise in mm/year based upon SEAFRAME data to December 2007.

Location	Installed	Barometric Pressure Contribution to Sea Level Trend (mm/yr)
Cook Is	19/02/1993	0.2
FSM	17/12/2001	-0.5
Fiji	23/10/1992	1.1
Kiribati	02/12/1992	0.5
Marshall Is	07/05/1993	0.2
Nauru	07/07/1993	0.6
PNG	28/09/1994	1.6
Samoa	26/02/1993	0.4
Solomon Is	28/07/1994	-0.2
Tonga	21/01/1993	0.8
Tuvalu	02/03/1993	0.6
Vanuatu	15/01/1993	1.2

*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 has not been geographically uniform, but rather there exists a spatial pattern that is in agreement with observations taken by satellite altimeters over a similar timeframe. The changes between neighbouring stations are reasonably smooth and are due to regional oceanographic and geodynamic factors rather than poor data quality. The sea level trend at FSM is comparatively large because it is derived from a comparatively short record. The net sea level trend at Tonga is large in comparison to its neighbouring sites (Cook Islands and Fiji), which could possibly be due to vertical motion of the island, but the CGPS record there is still too short (since February 2002) for this motion to be reliably quantified.

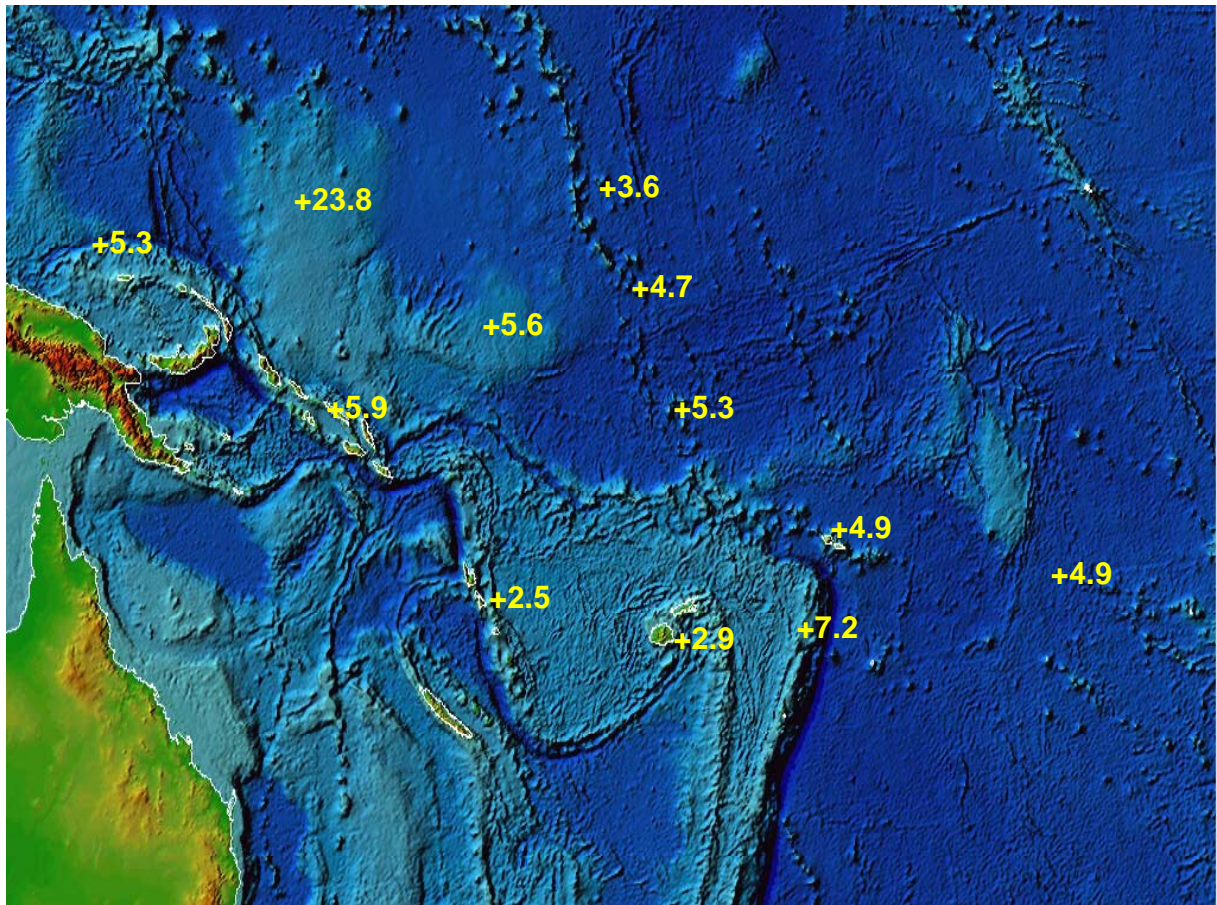
Table 4. The net relative sea level trend estimates as at December 2007 after the inverted barometric pressure effect and vertical movements in the observing platform are taken into account.

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	-0.3	4.9
FSM**	17/12/2001	23.7	-0.5	0.4	23.8
Fiji	23/10/1992	3.5	1.1	-0.5	2.9
Kiribati	02/12/1992	5.1	0.5	-0.1	4.7
Marshall Is	07/05/1993	4.4	0.2	+0.6	3.6
Nauru	07/07/1993	6.0	0.6	-0.2	5.6
PNG	28/09/1994	7.0	1.6	+0.1	5.3
Samoa	26/02/1993	6.3	0.4	+1.0	4.9
Solomon Is	28/07/1994	6.1	-0.2	+0.4	5.9
Tonga	21/01/1993	8.7	0.8	+0.7	7.2
Tuvalu	02/03/1993	6.0	0.6	+0.1	5.3
Vanuatu	15/01/1993	3.6	1.2	-0.1	2.5

*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 2007.

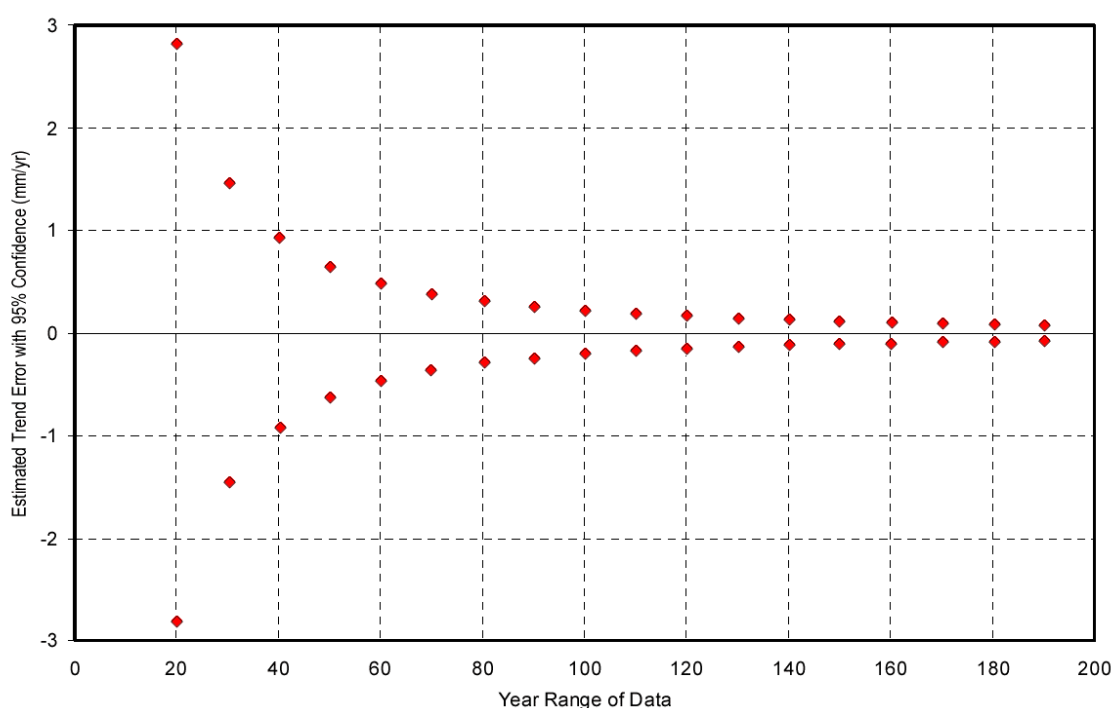


2.3. Sea Level Datasets from Additional Stations

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://uhscl.soest.hawaii.edu/uhscl/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. Such variability or 'noise' affects estimates of the underlying long-term trend. In general, more precise sea level trend estimates are obtained 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 in trend due to tectonic 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 record¹.



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

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 datum.

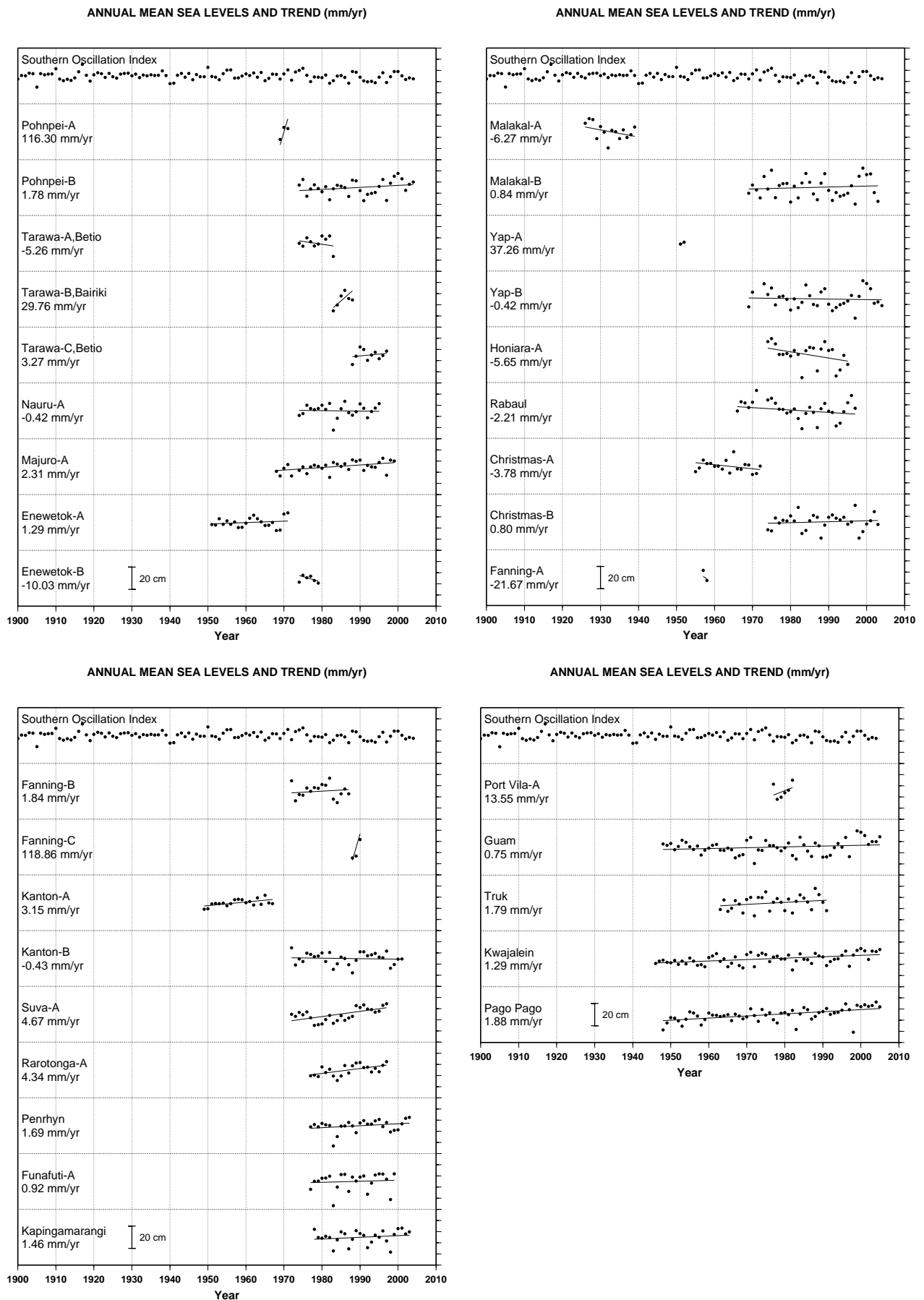
Diverse climatic and oceanographic environments are found within the Pacific Islands region. Different rates of vertical land movement are likely at different stations. Many of the historical tide gauges were designed to monitor tides and sea level variability caused by El Niño and shorter-term oceanic fluctuations rather than long-term sea level change and 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 1.16 mm/year.

Table 5. Sea level trends for Pacific Forum Stations on the Joint Archive for Sea Level Data Holdings as at December 2007.

JASL	STATION	COUNTRY	START DATE	END DATE	SPAN (years)	TREND (mm/yr)
001a	Pohnpei-A	Fd St Micronesia	1-Jan-1969	31-Dec-1971	3	116.3
001b	Pohnpei-B	Fd St Micronesia	1-Jan-1974	31-Dec-2004	31	1.8
002a	Tarawa-A, Betio	Rep. of Kiribati	1-Jan-1974	31-Dec-1983	10	-5.3
002b	Tarawa-B, Bairiki	Rep. of Kiribati	1-Jan-1983	31-Dec-1988	6	29.8
002c	Tarawa-C, Betio	Rep. of Kiribati	1-Jan-1988	31-Dec-1997	10	3.3
004a	Nauru-A	Rep. of Nauru	1-Jan-1974	31-Dec-1995	22	-0.4
005a	Majuro-A	Rep. Marshall I.	1-Jan-1968	31-Dec-1999	32	2.3
006a	Enewetok-A	Rep. Marshall I.	1-Jan-1951	31-Dec-1971	21	1.3
006b	Enewetok-B	Rep. Marshall I.	1-Jan-1974	31-Dec-1979	6	-10.0
007a	Malakal-A	Rep. of Belau	1-Jan-1926	31-Dec-1939	14	-6.3
007b	Malakal-B	Rep. of Belau	1-Jan-1969	31-Dec-2003	35	0.8
008a	Yap-A	Fd St Micronesia	1-Jan-1951	31-Dec-1952	2	37.3
008b	Yap-B	Fd St Micronesia	1-Jan-1969	31-Dec-2004	36	-0.4
009a	Honiara-A	Solomon Islands	1-Jan-1974	31-Dec-1995	22	-5.7
010a	Rabaul	Papua New Guinea	1-Jan-1966	31-Dec-1997	32	-2.2
011a	Christmas-A	Rep. of Kiribati	1-Jan-1955	31-Dec-1972	18	-3.8
011b	Christmas-B	Rep. of Kiribati	1-Jan-1974	31-Dec-2003	30	0.8
012a	Fanning-A	Rep. of Kiribati	1-Jan-1957	31-Dec-1958	2	-21.7
012b	Fanning-B	Rep. of Kiribati	1-Jan-1972	31-Dec-1987	16	1.8
012c	Fanning-C	Rep. of Kiribati	1-Jan-1988	31-Dec-1990	3	118.9
013a	Kanton-A	Rep. of Kiribati	1-Jan-1949	31-Dec-1967	19	3.2
013b	Kanton-B	Rep. of Kiribati	1-Jan-1972	31-Dec-2001	30	-0.4
018a	Suva-A	Fiji	1-Jan-1972	31-Dec-1997	26	4.7
023a	Rarotonga-A	Cook Islands	1-Jan-1977	31-Dec-1997	21	4.3
024a	Penrhyn	Cook Islands	1-Jan-1977	31-Dec-2003	27	1.7
025a	Funafuti-A	Tuvalu	1-Jan-1977	31-Dec-1999	23	0.9
029a	Kapingamarangi	Fd St Micronesia	1-Jan-1978	31-Dec-2003	26	1.5
046a	Port Vila-A	Vanuatu	1-Jan-1977	31-Dec-1982	6	13.5
053a	Guam	USA Trust	1-Jan-1948	31-Dec-2005	58	0.8
054a	Truk	Fd St Micronesia	1-Jan-1963	31-Dec-1991	29	1.8
055a	Kwajalein	Rep. Marshall I.	1-Jan-1946	31-Dec-2005	60	1.3
056a	Pago Pago	USA Trust	1-Jan-1948	31-Dec-2005	58	1.9

The mean trend for datasets that span more than 25 years (bold font) is 1.16 mm/yr.
Data from JASL as at December 2007

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

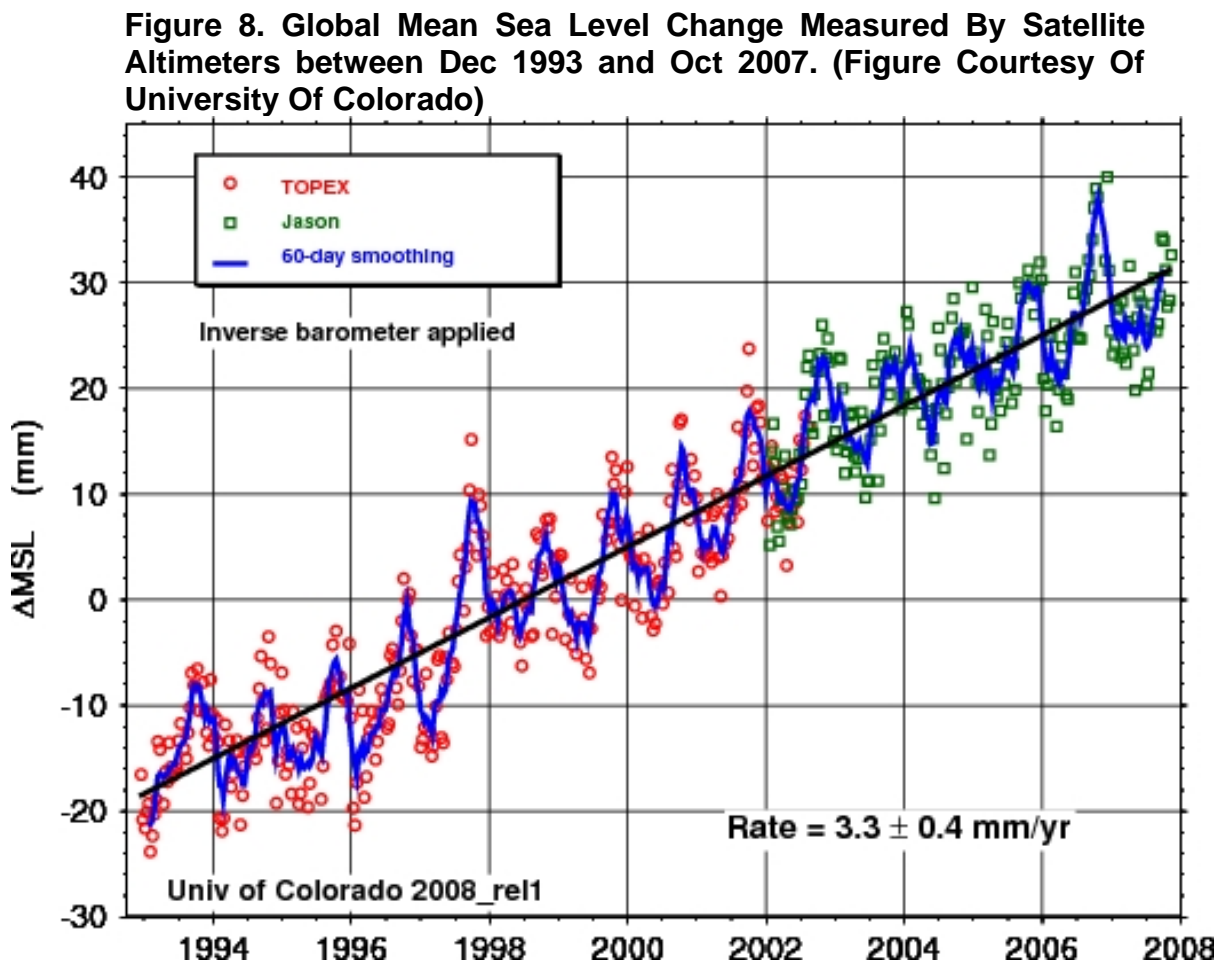


2.4. Satellite Altimetry

Satellite altimetry is technology that allows the height of the sea surface to be measured from satellites orbiting the earth. Satellites altimeters such as Topex/Poseidon and the follow-up mission Jason1 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.

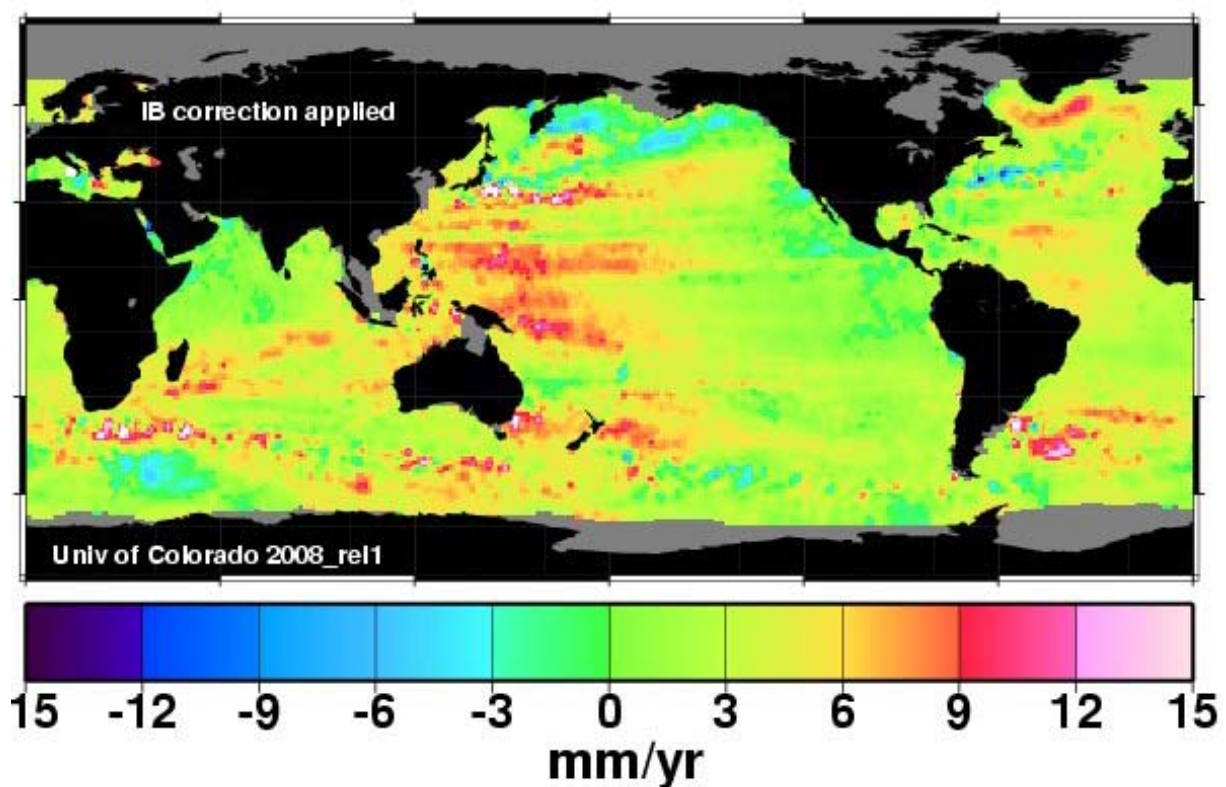
Satellite altimeters have an accuracy of several centimetres in the deep ocean, but are known to be inaccurate in shallow coastal regions. As such they cannot replace in-situ tide gauges. Tide gauges are needed to calibrate the satellite altimeters and provide accurate and more frequent sea level measurements 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 3.3 ± 0.4 mm/yr since late 1992 (Figure 8).



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 in the southwest Pacific region and has fallen in the northeast Pacific, 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 shown in Figure 8, but this is consistent with the map of regional sea level trends shown in Figure 9.

Figure 9. Regional Rates of Sea Level Change from December 1992 to October 2007 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 Cook Islands.

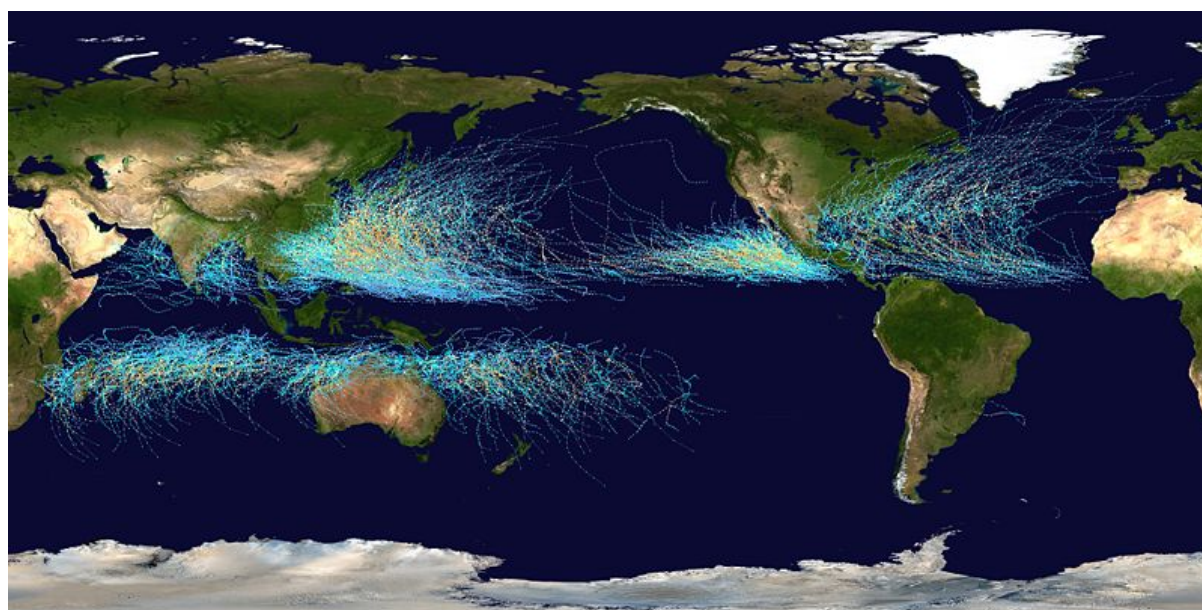
3. Project findings to date - Cook Islands

3.1. Extreme Events

3.1.1. Tropical Cyclones

Cook Islands is situated in the southwest Pacific in an area that experiences tropical cyclones as shown in Figure 10.

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



Since the SEAFRAME was installed in 1993, one of the worst cyclones of the century for the Pacific region struck the northern Cook Islands. In October/November 1997 Cyclone Martin brought high winds and mountainous seas to Pukapuka, Manihiki, and Ranahanga atolls, and sadly caused a number of deaths along with great destruction. The cyclone barely affected the island of Rarotonga, which is located 1200 km south. However, six weeks later, on 9 December 1997, Cyclone Pam did pass close to Rarotonga. Low pressures and high winds caused a storm surge, which flooded low-lying areas. Maximum winds recorded by the SEAFRAME were over 50 knots (92 km/hr).

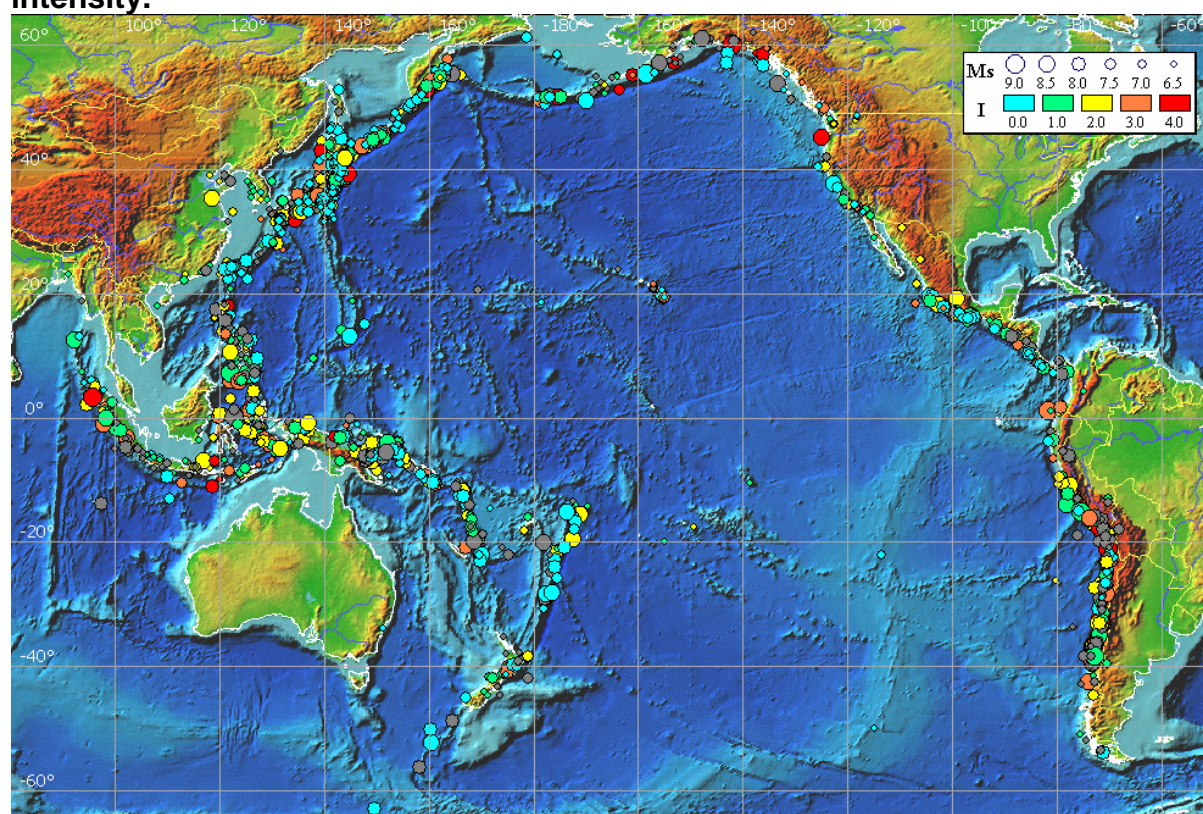
Enhanced tropical cyclone activity occurred during February and March 2005 in the southwest Pacific region that was sustained by higher than normal sea surface temperatures across the equatorial Pacific. Cook Islands encountered a sequence of four tropical cyclones, namely Cyclone Meena (6 February 2005), Cyclone Nancy (16 February 2005), Cyclone Olaf (18 February 2005) and Cyclone Percy (3 March 2005).

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. This shows that 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.

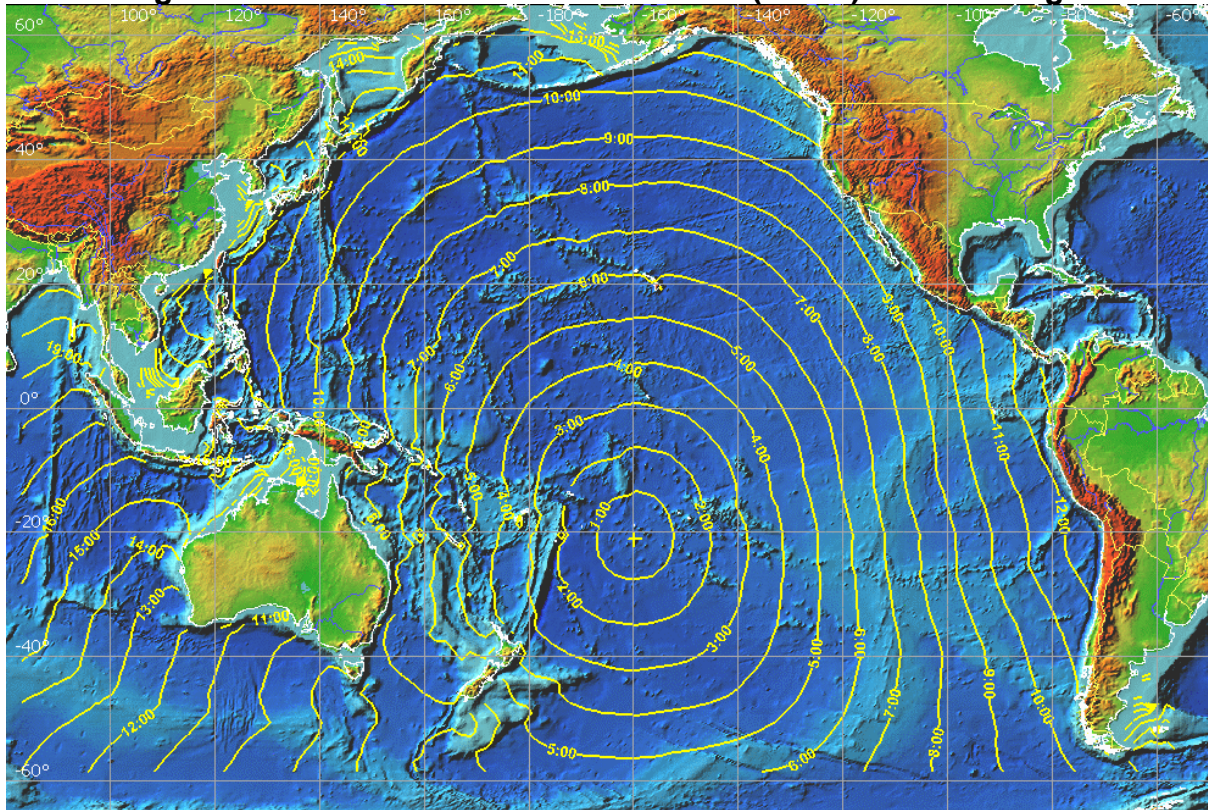
Figure 11. Historical Tsunami Events in the Pacific and Eastern Indian Ocean. Circle size indicates earthquake magnitude and colour indicates tsunami intensity.



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 Cook Islands from sources including Alaska, Loyalty Islands and Peru. Figure 12 shows the inverse tsunami travel time chart for Rarotonga, Cook Islands. This chart may be used to provide an estimate of the time taken for a tsunami to arrive at Rarotonga from any source location.

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



Since its installation in 1993, the SEAFRAME tide gauge at Cook Islands has detected 12 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-13b. 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 signals recorded by the SEAFRAME at Cook Islands since installation have trough-to-peak heights of around 15cm (in the 3-minute average sea level data stream recorded every 6 minutes), following a magnitude Mw8.0 earthquake near Tonga on 3rd May 2006 and magnitude Mw8.3 and Mw8.1 earthquakes near Kuril Islands in the northwest Pacific on 15th November 2006 and 13th January 2007 respectively. The 1-minute average sea level data show even larger tsunami signals, of up to 40cm. Tsunamis produced from earthquakes off Peru and Chile have also been detected by the SEAFRAME at Cook Islands.

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

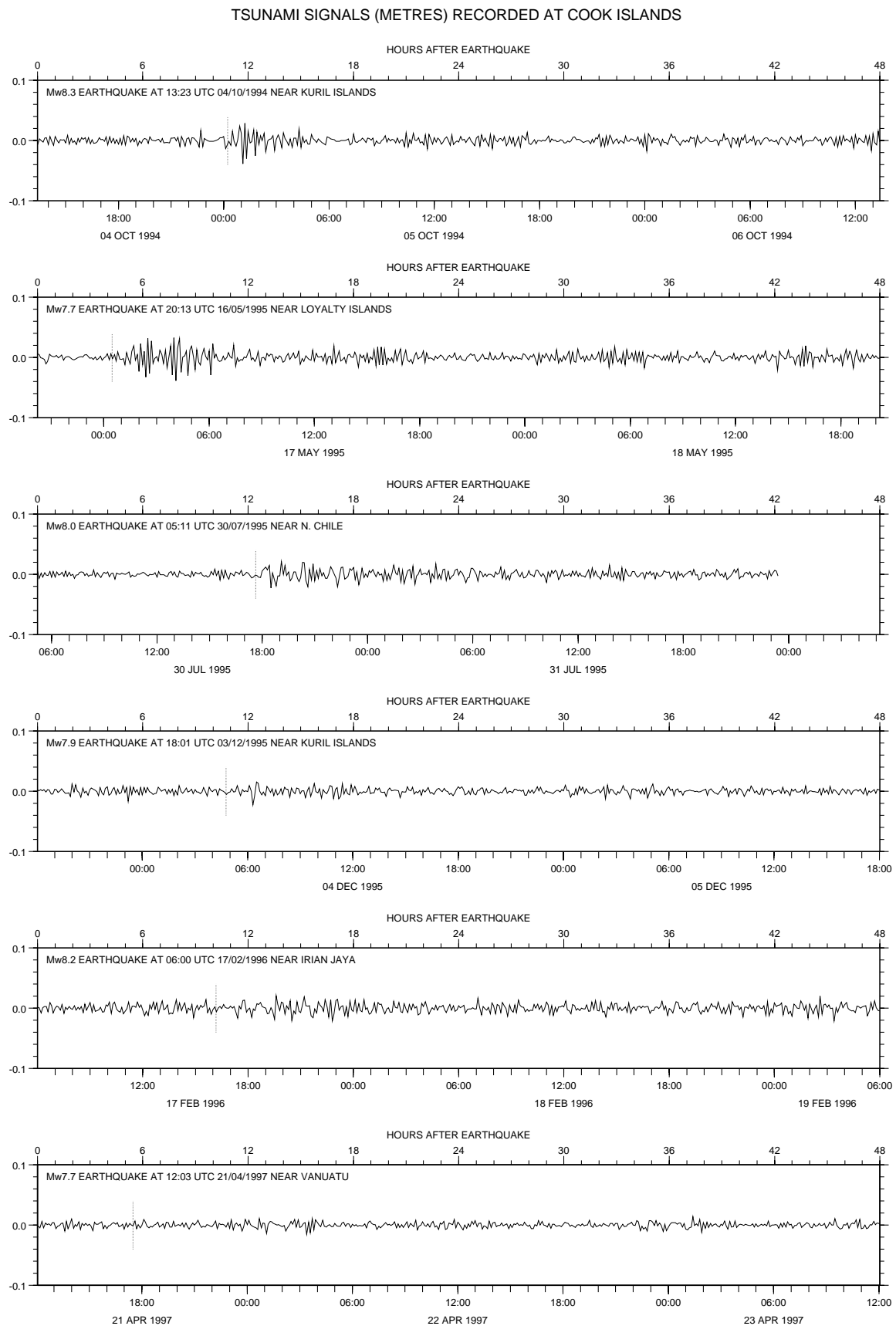
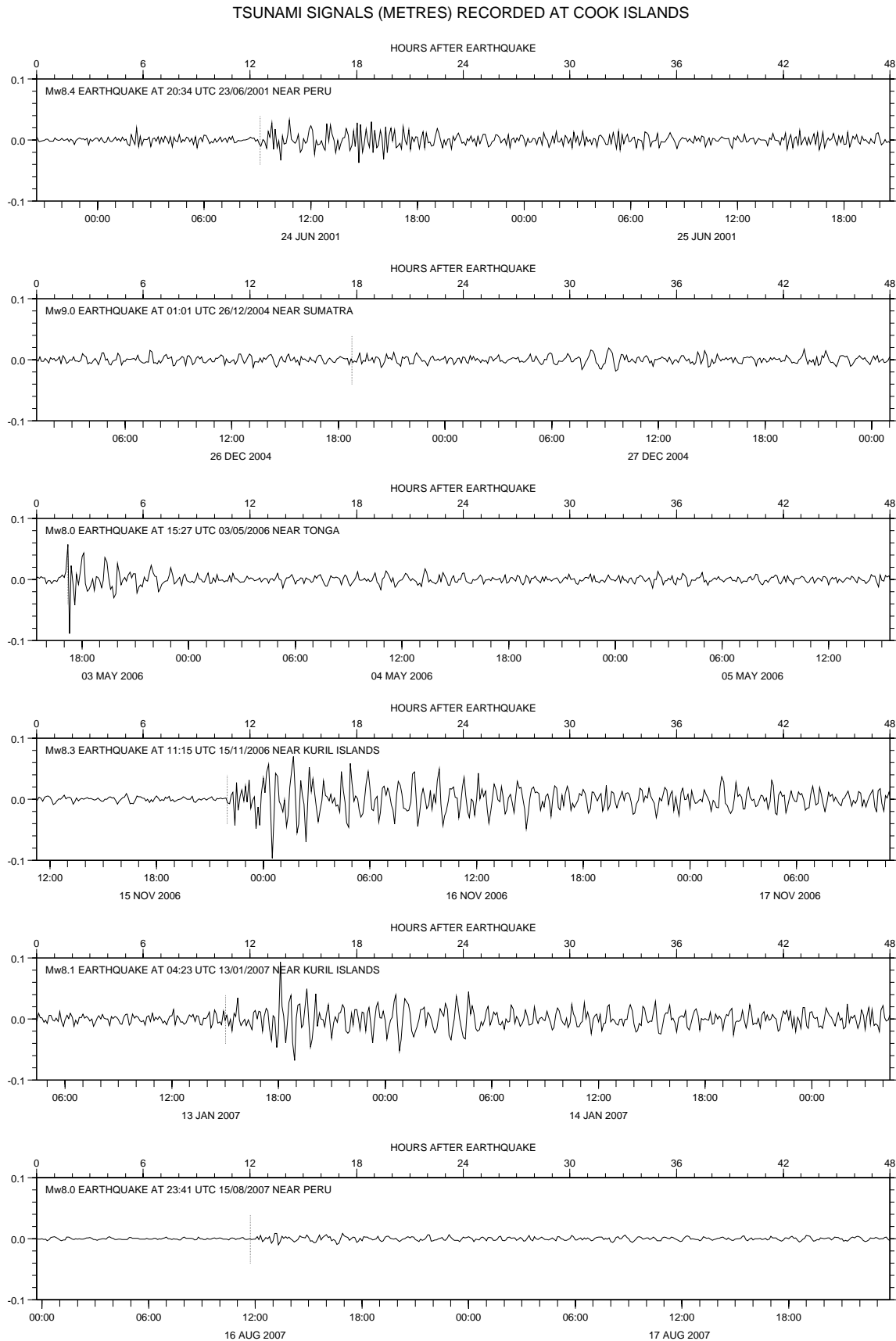


Figure 13b. Tsunami signals (m) recorded by the SEAFRAME at Rarotonga, Cook Islands since installation.



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 2007, based on the short-term sea level rise analyses performed by the National Tidal Centre using the Rarotonga SEAFRAME data, a rate of **+4.8 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 **+4.9 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. In the early years, the trend appeared to indicate an enormous rate of sea level rise. During the 1997/1998 El Niño, when sea level fell 10 cm below average (once seasonal factors were subtracted), the trend actually went negative. Given the sea level record is relatively short, it is still too early to deduce a long-term trend.

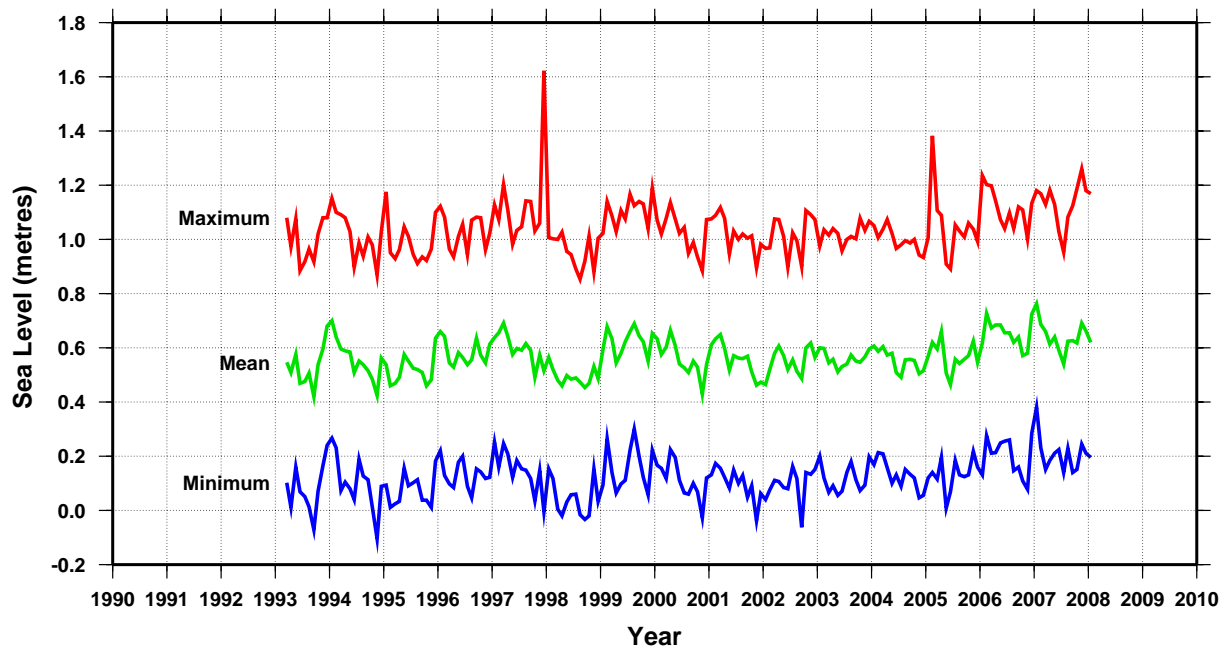
The sea level data recorded since installation is summarised in Figure 14. The middle curve (green) represents the monthly mean sea level. The upper and lower curves show the highest and lowest values recorded each month.

Unlike many of the SEAFRAME sites, sea level at Avatiu Harbour, Rarotonga did not experience a dramatic decrease in 1998 as a result of El Niño, although it did disrupt the normal seasonal cycle and produced a negative sea level anomaly of almost 20 cm between early 1997 and early 1998. Rarotonga is relatively far from the equator, which is where El Niño signals are most pronounced.

By inspection of the monthly maxima (red curve) it appears that the Cook Islands, like Tonga and Tuvalu, normally experiences highest sea levels around the summer months. At mid-year, the highest sea levels are typically about 20-30 cm less than when at the maximum. The mean sea level over the duration of the record is 0.57 metres, with a maximum of 1.62 metres in December 1997, and a minimum of -0.11 metres in November 1994. The highest monthly mean sea level was recorded in January 2007.

Figure 14

**Monthly sea level at Avatiu
SEAFRAME gauge**



3.3. Additional sea level records and trend

Additional sea level records for Cook Islands are available from the Joint Archive for Sea Level including Rarotonga (21 year record) and Penrhyn (27 year record). The monthly sea level data from these stations is shown in Figures 16 and 17, and contain relative sea level trends of +4.34 and +1.69 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

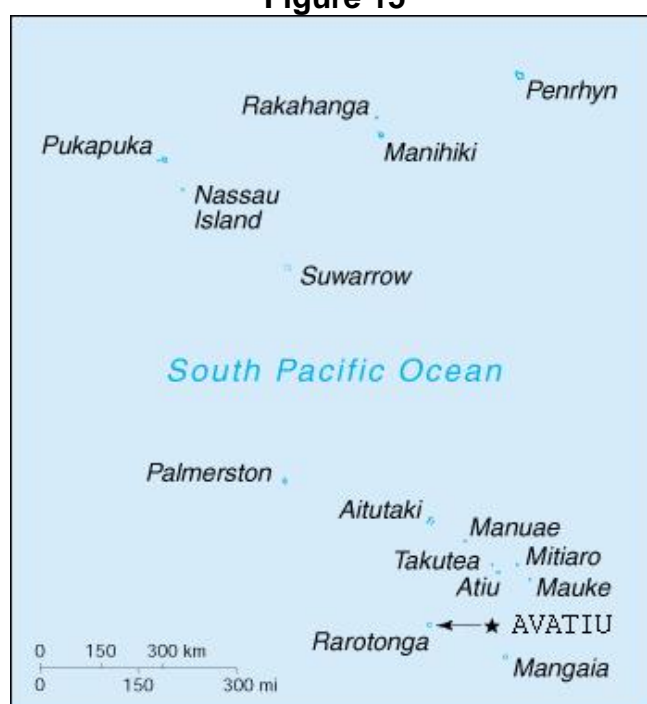


Figure 16

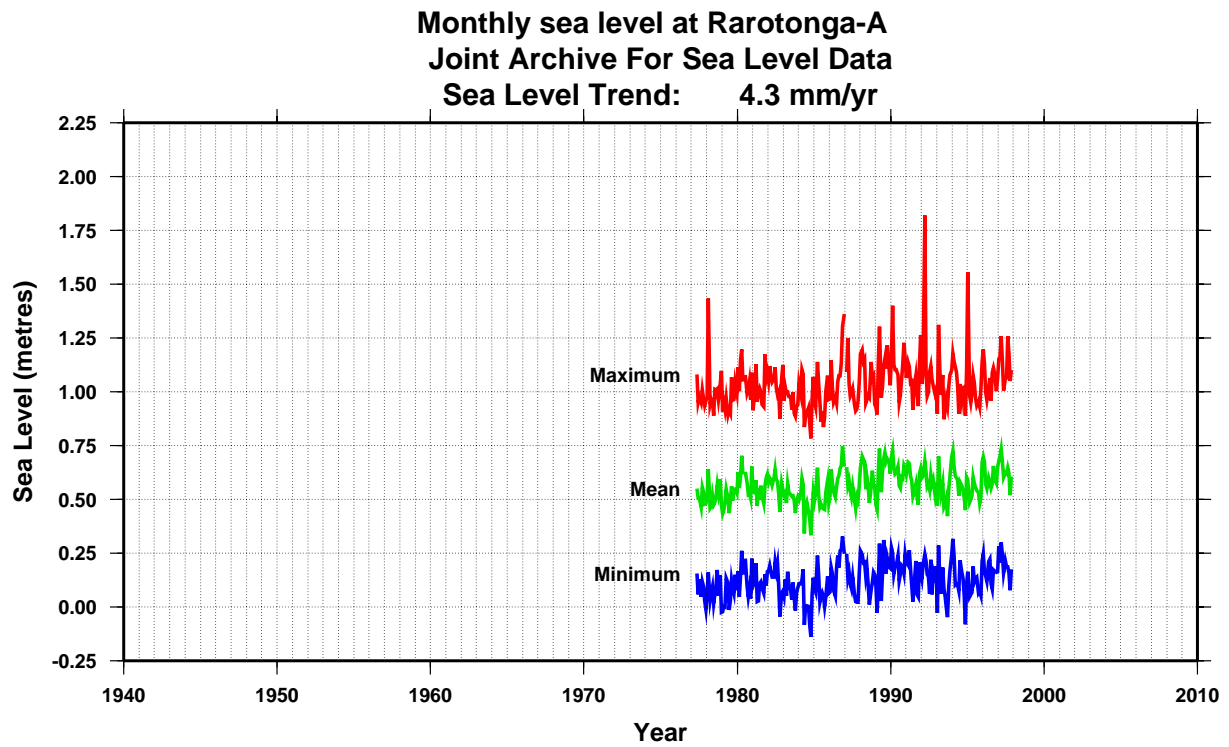
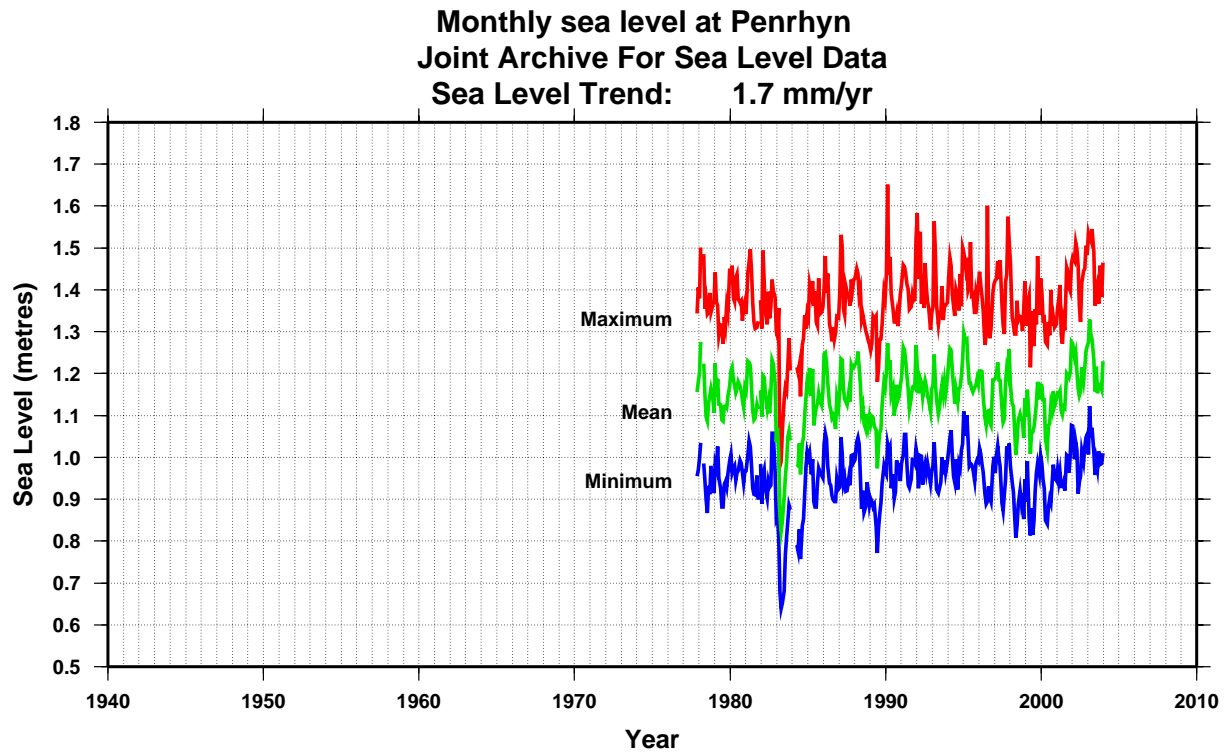


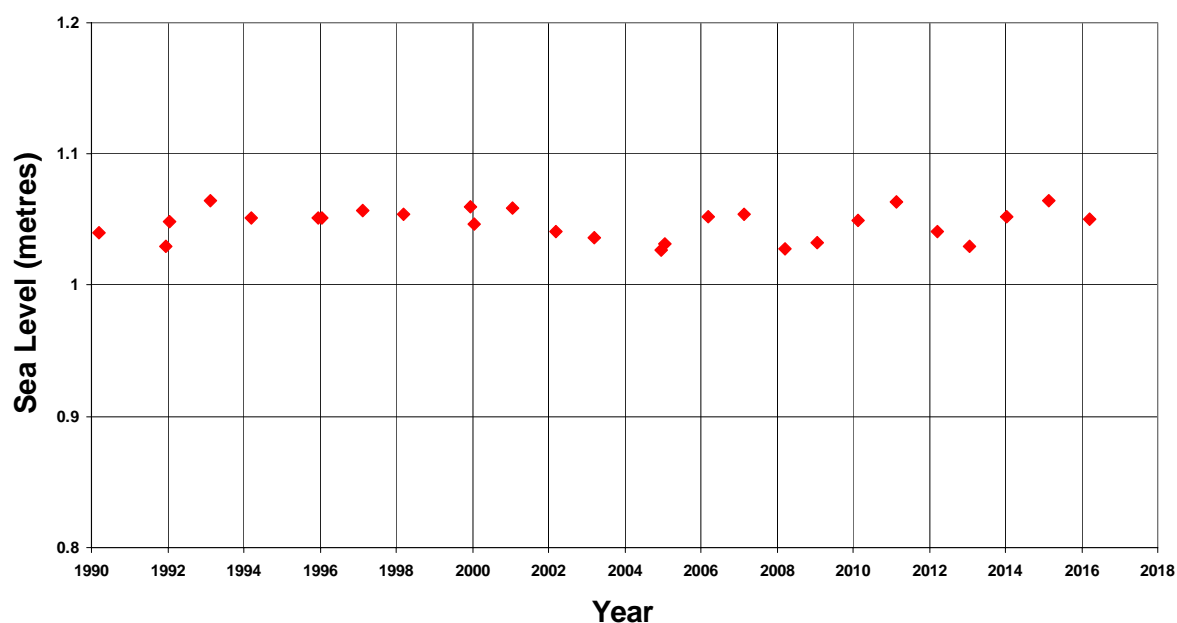
Figure 17



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 18 shows that the highest predicted level (1.06 m) over the period 1990 to 2016 was on 10 February 1993.

Figure 18
Predicted highest tide each year for Avatiu



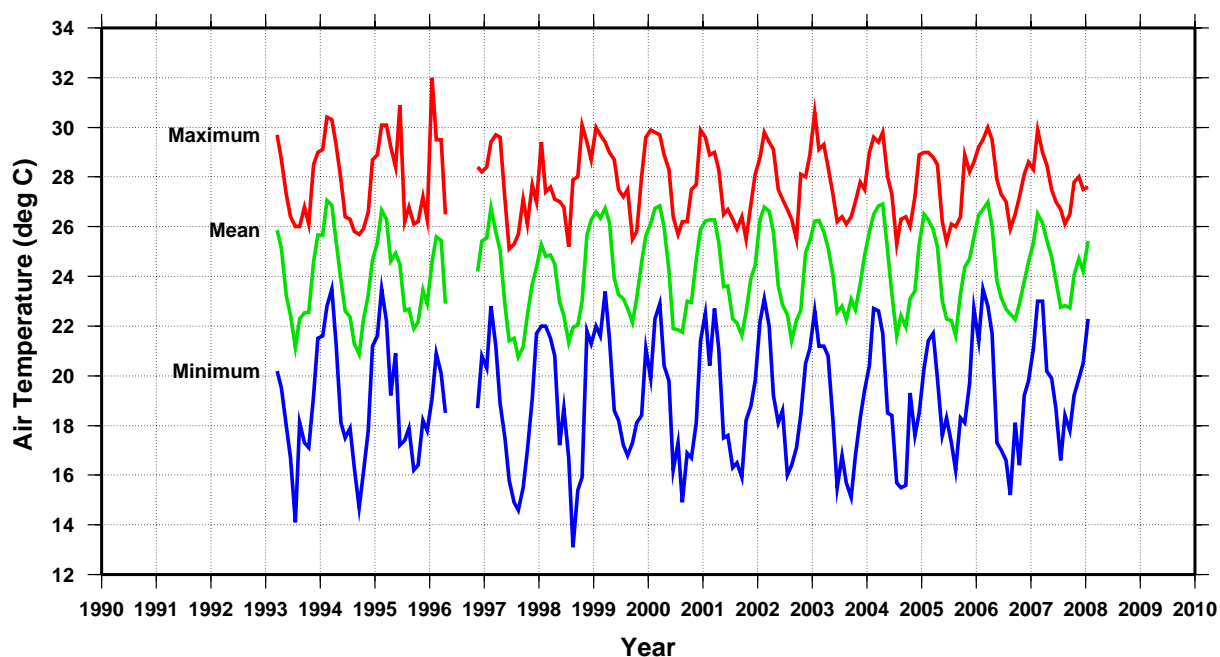
3.5. Monthly mean air temperature, water temperature, and atmospheric pressure

The data summarised in Figures 19-21 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.

Compared to equatorial sites, Rarotonga undergoes much greater seasonal temperature variations. The summertime highs are normally recorded in January or February. The mean air temperature over the duration of the record is 24.1°C. The minimum air temperature of 13.1°C was reached in August 1998, and a maximum of 32°C was reached in January 1996.

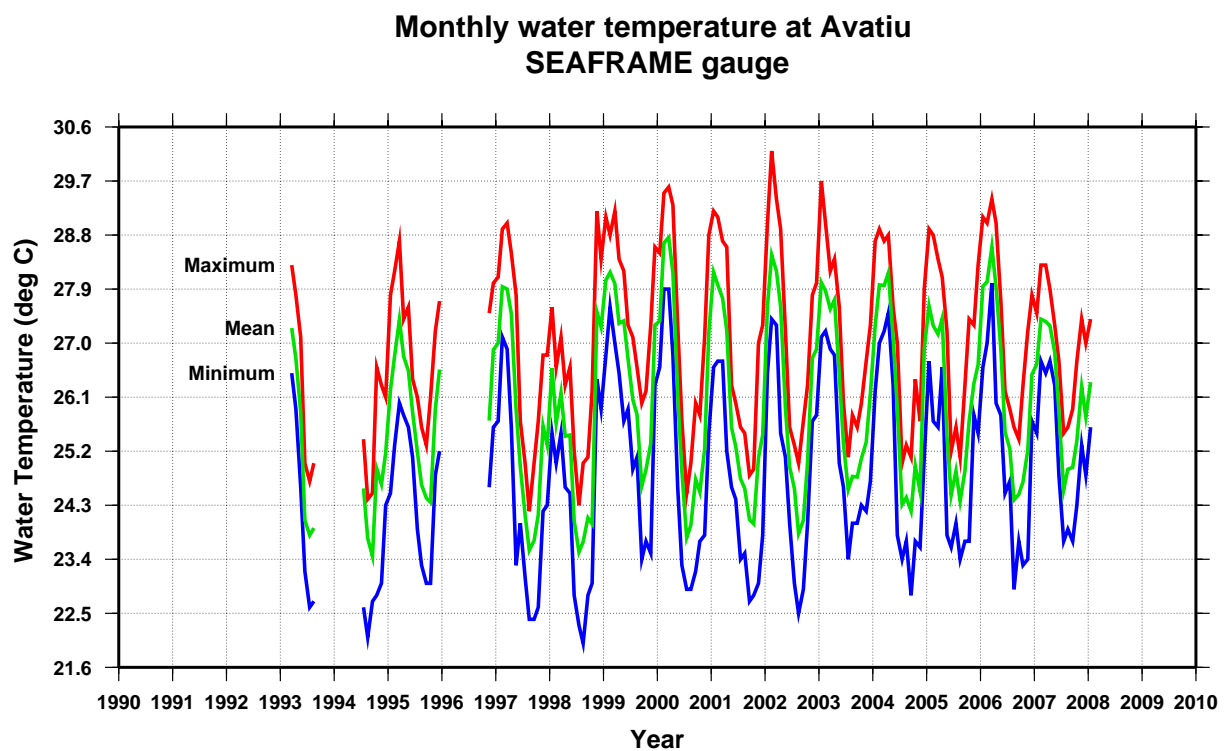
Figure 19

Monthly air temperature at Avatiu SEAFRAME gauge



Water temperature also undergoes seasonal oscillations, which are virtually in phase with those of air temperature. Interestingly, in several years the maxima in air and water temperature come a month or two after the sea level maxima. The mean water temperature over the duration of the record is 25.9°C. The maximum water temperature was 30.2°C in February 2002, and the minimum was 22.0°C in August 1998.

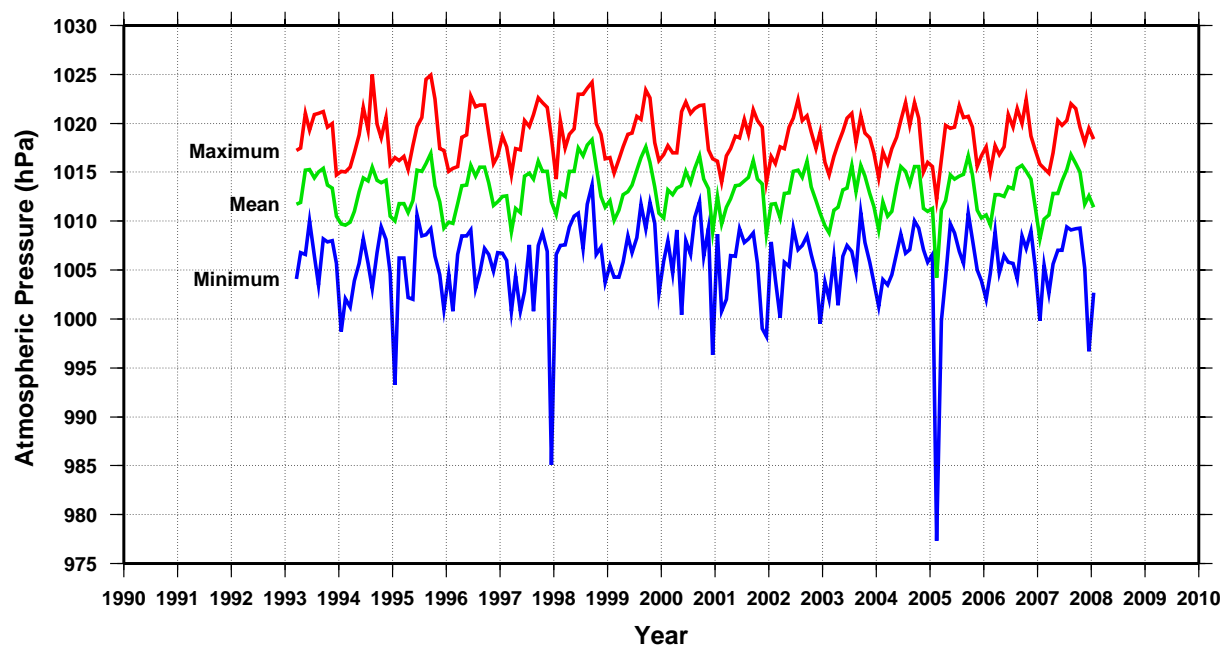
Figure 20



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 seasonal (summertime) high sea levels at Rarotonga are highly correlated with low barometric pressure systems. This is particularly the case for the very low pressure events (cyclones), most of which coincide with the highest sea levels for the year (since summer is also cyclone season). The mean barometric pressure over the duration of the record is 1013.1 hPa. The highest pressure recorded was 1025 hPa in August 1994, while the lowest was 977.3 hPa in February 2005 (Cyclone Meena).

Figure 21

**Monthly atmospheric pressure at Avatiu
SEAFRAME gauge**



3.6. Precise Levelling Results for Cook Islands

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 22 summarises the most important survey information being the movement of the SEAFRAME Sensor benchmark relative to the TGBM. 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 the Cook Islands found that the SEAFRAME Sensor benchmark had *fallen* relative to the TGBM by 1.5 mm. Following an incident several years after installation which left the instrument damaged and required a new survey, a new “zero” was established and since that time the SEAFRAME has been *rising* at a rate of +0.3 mm/year.

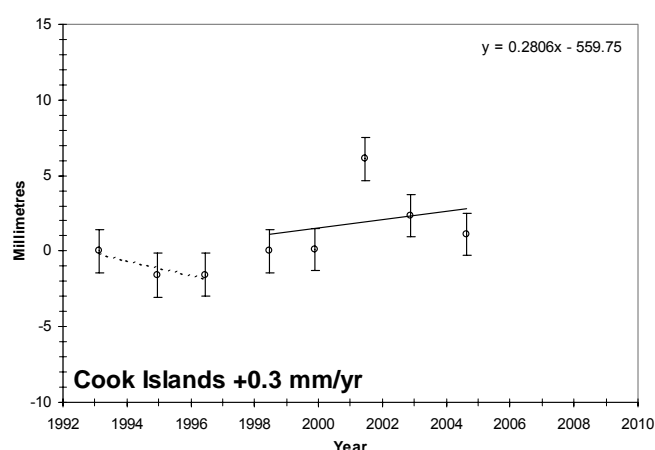


Figure 22. Movement of the SEAFRAME Sensor relative to the Tide Gauge Bench Mark.



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

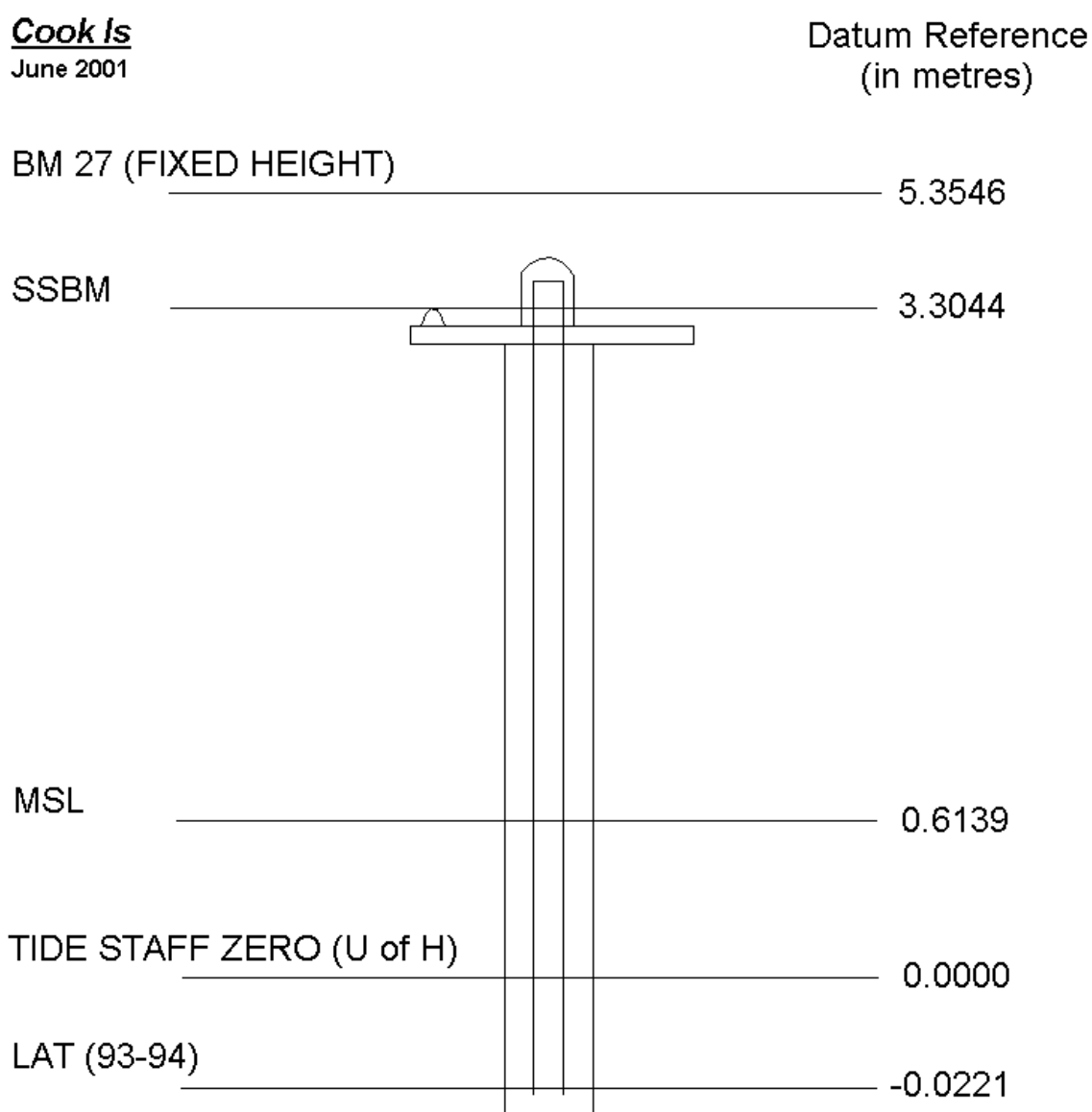
Appendix

A.1. Definition of Datum and other Geodetic Levels at Rarotonga, Cook Islands

Newcomers to the study of sea level are confronted by bewildering references to “Chart Datum”, “Tide Staff Zero”, and other specialised terms. Frequent 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 23



The word “datum” in reference 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 (such as shown in Figure 23) 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 sounding. Unfortunately, at Rarotonga the original benchmark used for the marine surveys is unrecoverable, so it is not possible to place CD on this chart. In the absence of a known CD, NTC has chosen to refer sea level to the older UH datum, or “Tide Staff Zero” (TSZ). With this choice, the Mean Sea Level of either data set is close (though not necessarily identical).

Mean Sea Level (MSL) in Figure 23 is the average recorded level over a period of time. The MSL at Rarotonga is 0.6139 metres above TSZ.

Lowest Astronomical Tide, or “LAT”, is based purely on tidal predictions over a 19 year period. In this case, LAT is -0.0221 metres below TSZ. 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.

