Pacific Country Report

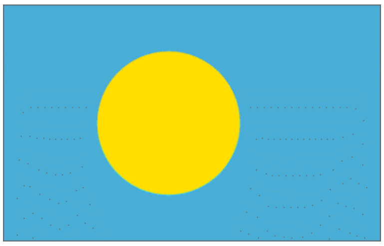
Sea Level & Climate:
Their Present State

Palau

June 2002

This project is sponsored by the Australian Agency for International Development (AusAID), managed by Australian Marine Science and Technology Ltd (AMSAT), and supported by NTF Australia at the Flinders University of South Australia.

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



THE REPUBLIC OF PALAU

June 2002

Executive Summary

● Since 1992, SEAFRAME gauges have been installed in many Pacific Island countries. They record sea level, air and water temperature, atmospheric pressure, wind speed and direction. The array is designed to monitor changes in sea level and climate in the Pacific.

● An instrument recently installed at Palau by the University of Hawaii shares many of the SEAFRAME features.

● This report summarises the available data, and places them in a regional and historical context.

● An older tide gauge at Malakal (near Koror, Palau), with a thirty year record but less precision and datum control than the SEAFRAME instruments, shows a trend of +0.64 mm/year.

● Variations in monthly mean sea level are affected by the 1997/1998 El Niño, with a moderate seasonal cycle.

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

● Tropical cyclones are rare in Palau, which lies on the edge of the cyclone belt.

● The tsunami caused by the Peru earthquake of June 2001, which registered strongly on many Pacific SEAFRAME gauges, had negligible effect in the Palau region.

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Feedback

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Dear Pacific Island Government Representative

Welcome to the first **Pacific Country Report**, containing a summary of the sea level, climate, oceanography and extreme events for each of the twelve SEAFRAME monitoring sites, plus Palau and Niue. We intend to produce them to coincide with the Forum Meetings.

Your feedback is essential to ensure that improvements are made, that what is important to **you** is addressed and explained. Your feedback will help guide the frequency of publishing and distribution. We invite you to give us both positive and negative feedback (your comments will remain confidential) because what might be obvious to you might be overlooked by scientists.

You can tear out this page, jot notes on it, and mail or fax it to us at the address above. Or you can email comments to us. A few words is all we need.

1-Did you find it informative?

2-What significant information have we omitted?

3-Would you like to see additional emphasis on any topic? If so, what?

4-Would you like more explanation on any topic? If so, what?

5-Any other suggestions or constructive criticism?

Name (optional)

Country

Thank you for your time!

Introduction

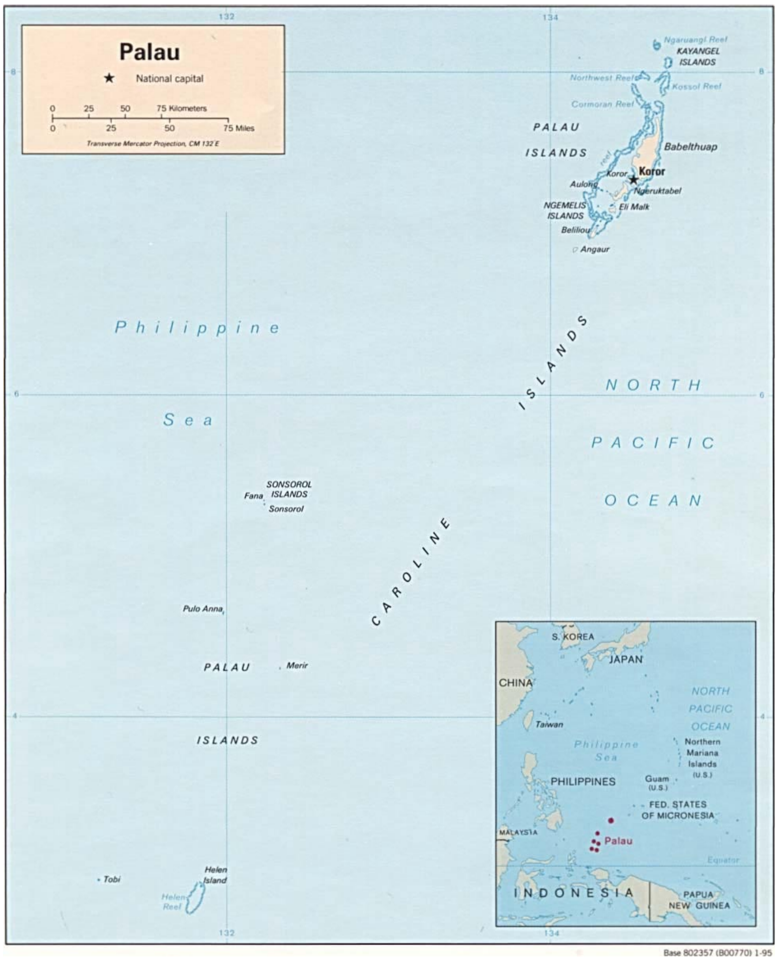
As part of the AusAID-sponsored South Pacific Sea Level and Climate Monitoring Project ("Pacific Project") for the FORUM region, in response to concerns raised by its member countries over the potential impacts of an enhanced Greenhouse Effect on climate and sea levels in the South Pacific region, **SEAFRAME** (**Sea** Level **F**ine **R**esolution **A**coustic **M**easuring **E**quipment) gauges have been installed in twelve forum countries. This report provides background information regarding sea level and climate in the region of Palau based on available data.

The Palau region is relatively under-sampled and lies in an area critical to the formation of El Niño, making it invaluable for monitoring of both decadal and inter-annual variability. The University of Hawaii recently upgraded their Palau gauge, which was originally installed in 1969 at Malakal, near Koror on the main island of Bablethuap. The gauge is now comprised of SEAFRAME technology, and will be of the standard required to meet the goals of the Pacific Array, with the proposed addition of meteorological sensors and satellite communications.

University of Hawaii tide gauge at Palau showing twin Aquatrak acoustic gauges, CGPS receiver, and instrument hut.

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. Continuous Global Positioning System (CGPS) measurements are now also being made 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 vertical land movement and in particular the rate at which the land moves must be measured separately. This is the reason for the addition of CGPS near the tide gauges.



Regional Overview

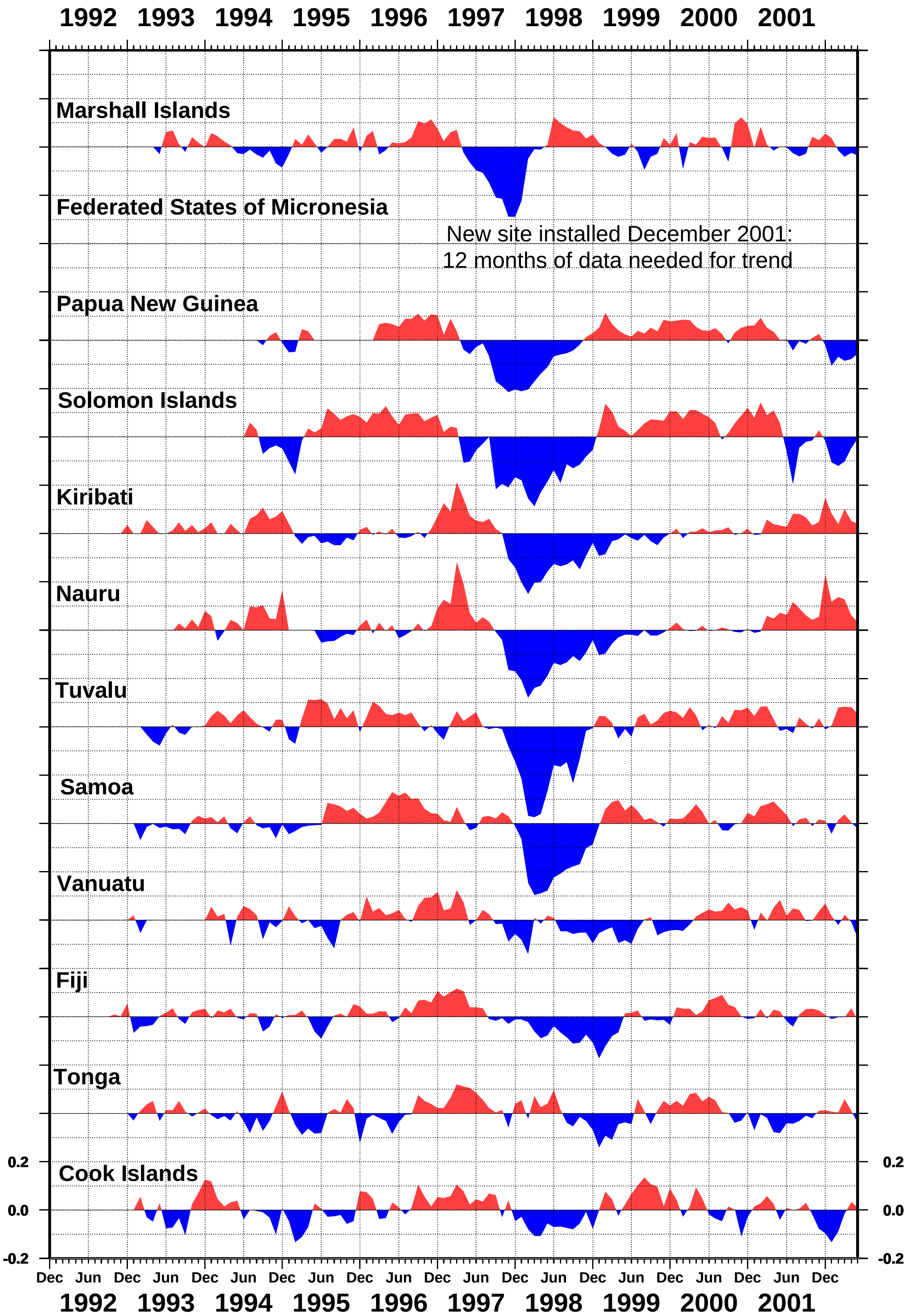
Variations in sea level and atmosphere are inextricably linked. For example, to understand why the sea level at Tuvalu undergoes a much larger annual fluctuation than at Samoa, we must study the seasonal shifts of the trade winds. On the other hand, the climate of the Pacific Island region is entirely 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, the most extreme changes are naturally experienced by those furthest from the equator – 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).

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	33.4
Vanuatu	16.5	33.3
Samoa	18.7	32.1
Tuvalu	22.8	31.6
Kiribati	22.4	32.9
Nauru	22.4	32.4
Solomon Islands	20.1	34.5
Papua New Guinea	21.5	31.1
Marshall Islands	20.5	31.9

The most striking oceanic and climate 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 the plot below, 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 “Sub-Tropical Convergence Zone” or STCZ. In the figure below, we see the effect of the 1997/1998 El Niño on all SEAFRAME stations.

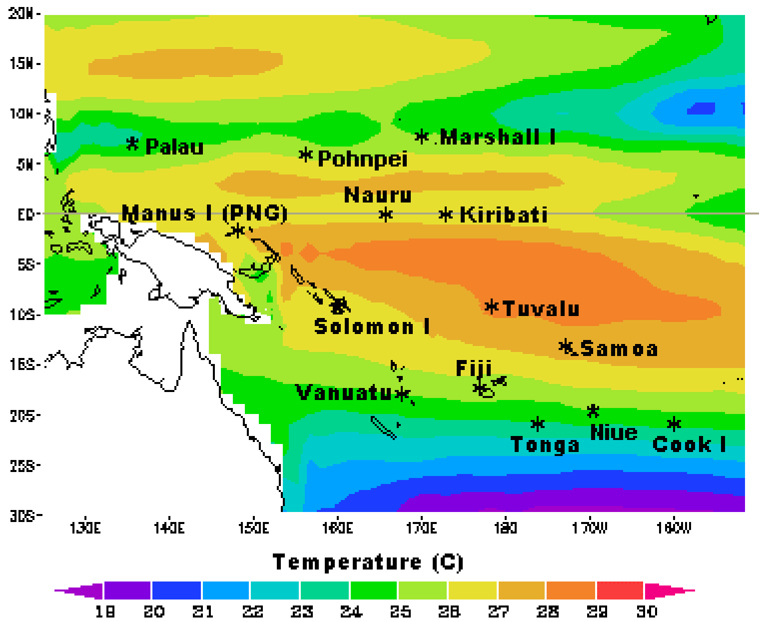
Sea levels* at SEAFRAME sites



* Plotted values are sea level "anomalies" (tides and trend removed from data).

Most Pacific Islanders are very aware that the sea level is controlled by many factors, some periodic (likes 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 month. 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 STCZ, 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.

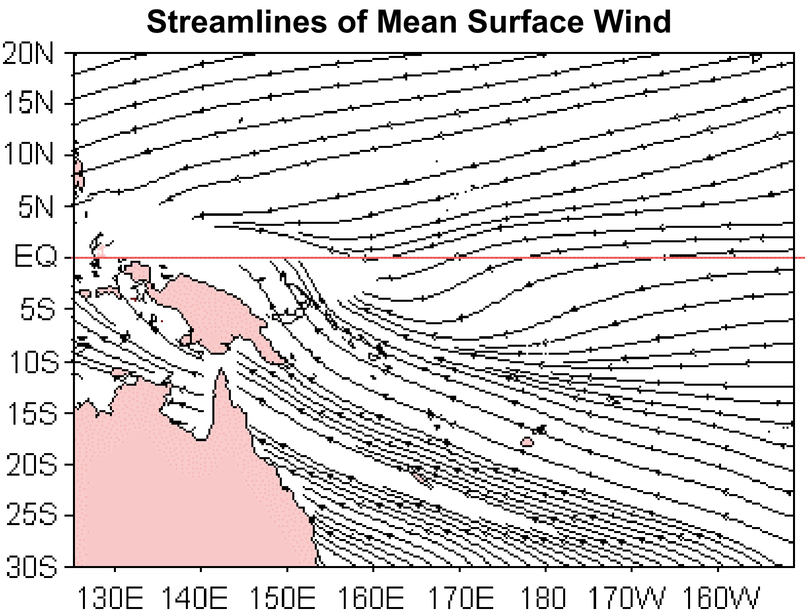
Mean Surface Water Temperature



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

The convergence of the Trade Winds along the STCZ 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 STCZ, 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 plot **Streamlines of Mean Surface Wind** 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 STCZ.



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).

Mean Sea Level Trends and their Confidence Intervals

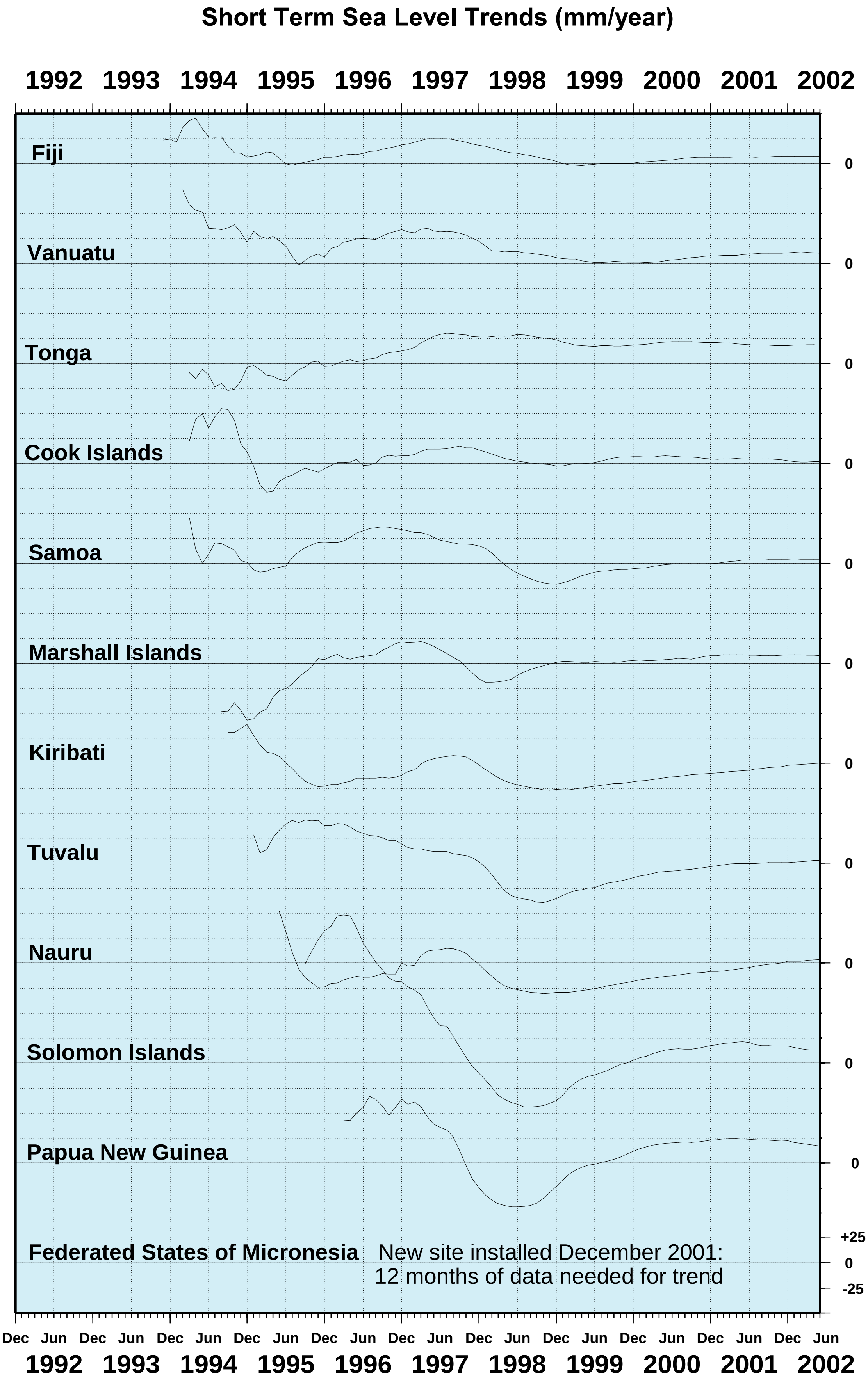
With the great diversity in climatic environments, vertical land movement and ocean variability, one might expect that that the sea level trends measured at different stations over the limited period for which tide gauge data has been collected may also vary. That this is indeed the case is demonstrated by the following table, which contains the relative sea level trends from all the regional stations for which at least 25 years of hourly data was available.

Location	Country	Years of data	Trend (mm/year)	Standard Deviation mm/year
Pago Pago	U S Trust	49.7	+1.43	1.5
Rarotonga	Cook Is	22.2	+3.80	3.7
Penrhyn	Cook Is	21.6	+0.89	3.4
Pohnpei	F S of Micronesia	26.9	+0.42	3.7
Kapingamarangi	F S of Micronesia	19.9	-1.04	4.7
Truk	F S of Micronesia	27.6	+1.79	3.3
Guam	U S Trust	50.1	+0.37	1.9
Yap	F S of Micronesia	30.9	-0.20	3.6
Suva	Fiji	24.8	+3.99	3.0
Christmas	Rep of Kiribati	40.3	-0.68	2.2
Kanton	Rep of Kiribati	45.0	+0.26	1.5
Fanning	Rep of Kiribati	16.8	+2.17	5.1
Tarawa	Rep of Kiribati	23.6	-2.24	3.6
Majuro	Rep of Marshall Is	30.8	+2.79	2.6
Enewetok	Rep of Marshall Is	24.5	+1.18	3.3
Kwajalein	Rep of Marshall Is	54.4	+1.13	1.3
Nauru	Rep of Nauru	24.2	-2.03	4.2
Malakal	Rep of Palau	30.1	+0.64	4.0
Honiara	Solomon Is	24.5	-2.21	4.8
Nuku'alofa	Tonga	9.4	+4.90	7.2
Funafuti	Tuvalu	21.6	+0.92	5.1
Port Vila	Vanuatu	11.3	+6.21	6.8

Mean trend: 1.11 mm/year (all data)   Mean trend of data > 25 years: 0.8 mm/year

Data from University of Hawaii as at June 2002

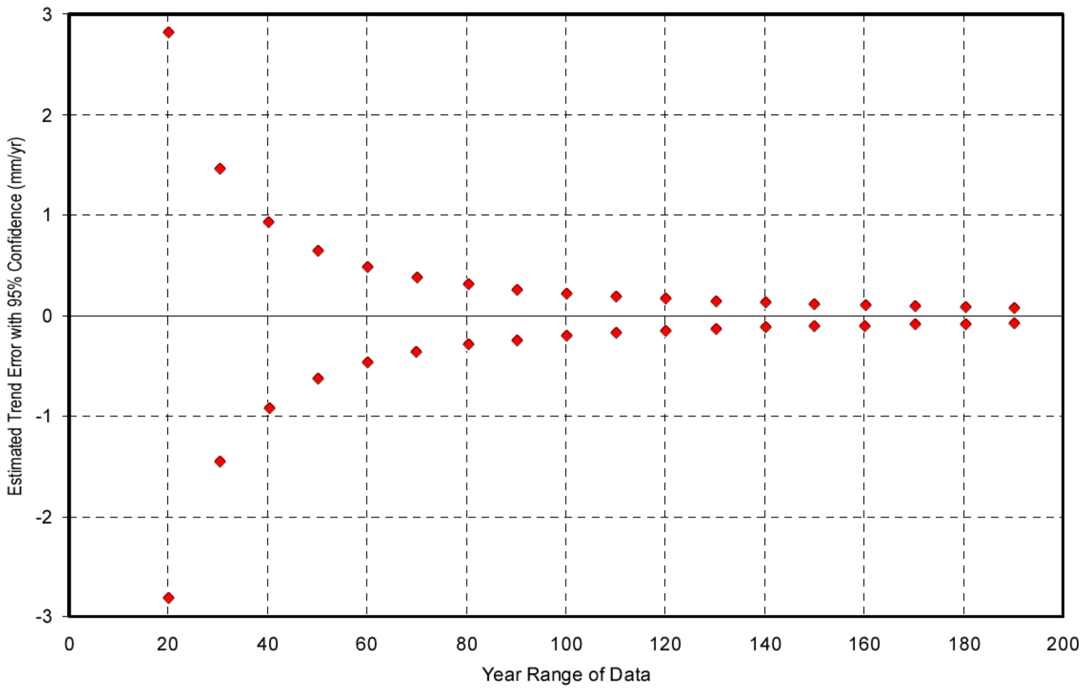
The following plot depicts the evolution of the short term sea level trends, at SEAFRAME stations, from one year after installation to the present. Please note that the trendlines have not yet stabilised.


Short Term Sea Level Trends (mm/year)
1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002
Fiji
Vanuatu
Tonga
Cook Islands
Samoa
Marshall Islands
Kiribati
Tuvalu
Nauru
Solomon Islands
Papua New Guinea
Federated States of Micronesia
New site installed December 2001:
12 months of data needed for trend
0
+25
-25
Dec Jun Dec Jun Dec Jun Dec Jun Dec Jun Dec Jun Dec Jun Dec Jun Dec Jun Dec Jun Dec Jun
1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002

June-2002

The expected width of the 95% confidence interval (±1.96 times the standard error) as a function of data length based on the relationship for all National Oceanographic and Atmospheric Administration (NOAA) gauges with a data record of at least 25 years are shown in the figure below. 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. In the figure, the 95% confidence intervals are plotted as a function of the year range of data, based on NOAA tide gauges with at least 25 years of record[1].

95% Confidence Intervals for Linear Mean Sea Level trends (mm/year)



This overview was intended to provide an introduction to the Pacific Islands regional climate, in particular those aspects that are related to sea level. This is an area of active research, and many elements, such as interdecadal oscillations, are only beginning to be appreciated. The individual country reports give greater detail on the variations experienced at the twelve SEAFRAME sites in the Pacific.

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

Project findings to date - Palau

The Climate and Oceanography of Palau

The main island of Palau, Babelthuap, is a relatively high, mountainous volcanic island located southeast of the Philippines at 7° 30' N, 134° 30' E. Its primary port is at the capital, Koror. There is little seasonal variability, although in normal (non El Niño) years June and July tend to be wetter than average. During the mature stage of El Niño, the rainfall is typically 20% below normal (during the most recent El Niño, there was severe drought at Palau).

The location of Palau is shown in the figure "Mean Surface Water temperature" on a background of sea surface temperature. The temperatures were obtained as averages over weekly values for a six year period. A broad "warm pool" can be seen northeast of Papua New Guinea. Tongues of warm water extend eastward and southeastward from the warm pool. These two tongues follow along special lines known to meteorologists as the Inter-Tropical Convergence Zone (ITCZ) and Sub-Tropical Convergence Zone (SPCZ), respectively. Palau is located on the northern edge of the warm pool and also within the ITCZ. The convergence zones are so-named because the near-surface winds tend to converge along these lines. Where convergence occurs, the air rises, carrying with it water vapour that condenses to form cloud bands. Thus, the ITCZ and SPCZ are visible as regions of relatively high cloudiness. Their positions shift somewhat with the seasons, but an even greater shift occurs during El Niño events.

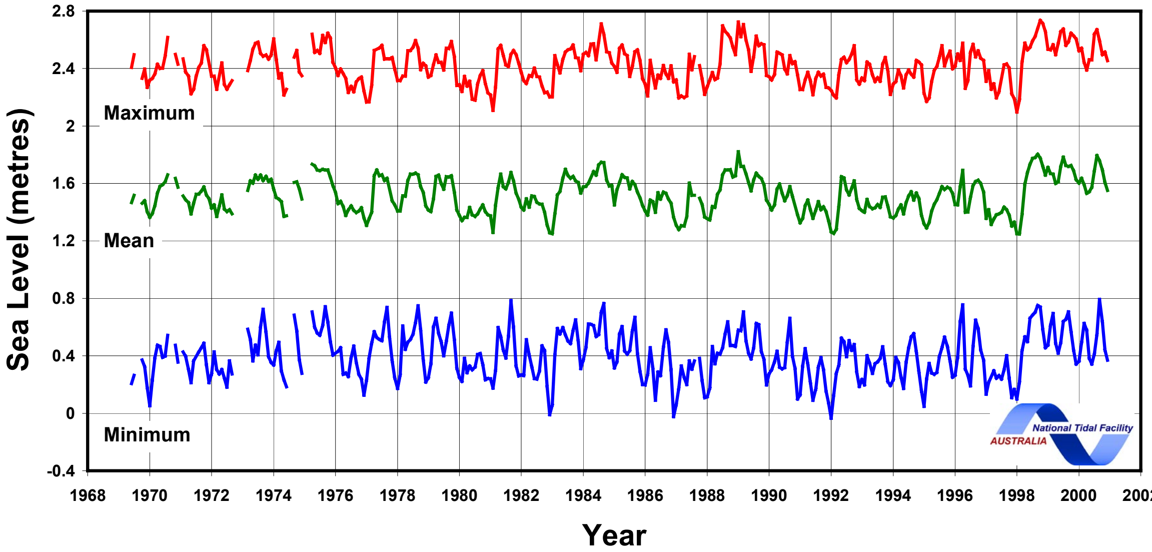
The location of Palau has added oceanographic significance due to its proximity to both the equator, and the western boundary of the ocean. During the early stages of El Niño, a complex series of inter-related atmospheric and oceanic processes simultaneously occur in the area previously referred to as the "warm pool". It is an invaluable site for monitoring these processes, which have a distinctive sea level signal.

Palau is a region of particular significance to the genesis of El Niño. Tide gauges at Palau, Yap, and elsewhere in the vicinity have given useful evidence in a number of studies of the dynamics of the tropical Pacific Ocean, and will doubtlessly continue to do so. This is because Palau is located near the confluence of several important oceanographic currents. The region can be thought of as the source of the North Equatorial Counter Current; which flows from west to east between the latitudes of 5° and 10° north of the equator. It is just east of the Halmahera Eddy, and also receives water from the extension of the South Equatorial Current, part of which flows north across the equator offshore of Papua New Guinea. Some of the southern water re-circulates into the eastward-flowing North Equatorial Current, some enters the Halmahera Eddy, and a substantial proportion enters the Indonesian Archipelago, through which it flows to the Indian Ocean, as part of the global overturning circulation.

Historical Sea Level Trend Assessment

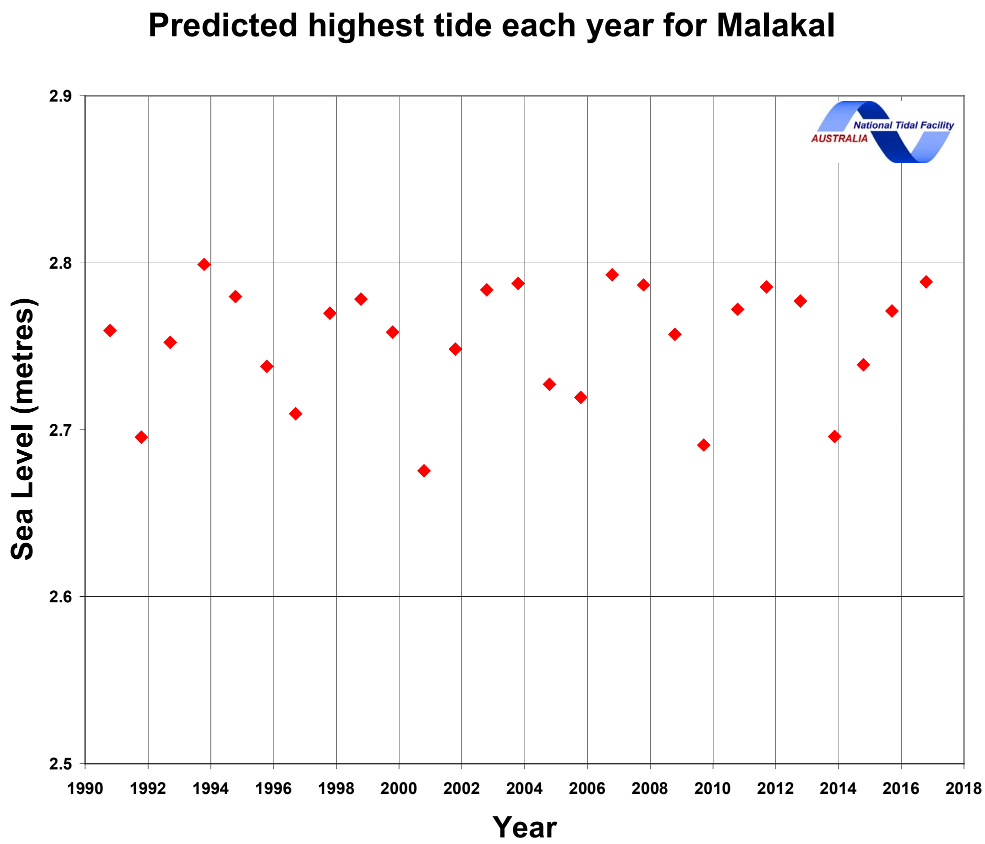
Sea level records since 1974 are available at Palau, from the Malakal (near Koror) tide gauge that operated from 1969 until 2000 - about **30 years of data**. The University of Hawaii (UH) data exhibits a sea level rise of **+0.64 mm/year** over the period. The gauge was designed to monitor the variability caused by El Niño and shorter- term oceanic fluctuations, for which the high level of precision and datum control demanded by the determination of sea level trend were not required. Hence, even with 31 years of data, the trend can not be established without sizeable uncertainties.

Monthly sea level at Malakal
University of Hawaii data



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. It is primarily due to the ellipticity of the orbit of the Earth around the Sun, and that of the the Moon around the Earth resulting in a point at which the Earth is closest to the Sun, combined with a spring tide in the usual 28 day orbit of the Moon around the Earth. The figure shows that the highest predicted level (2.53 m) over the period 1990 to 2016 was reached 16 October 1993.



Extreme Events

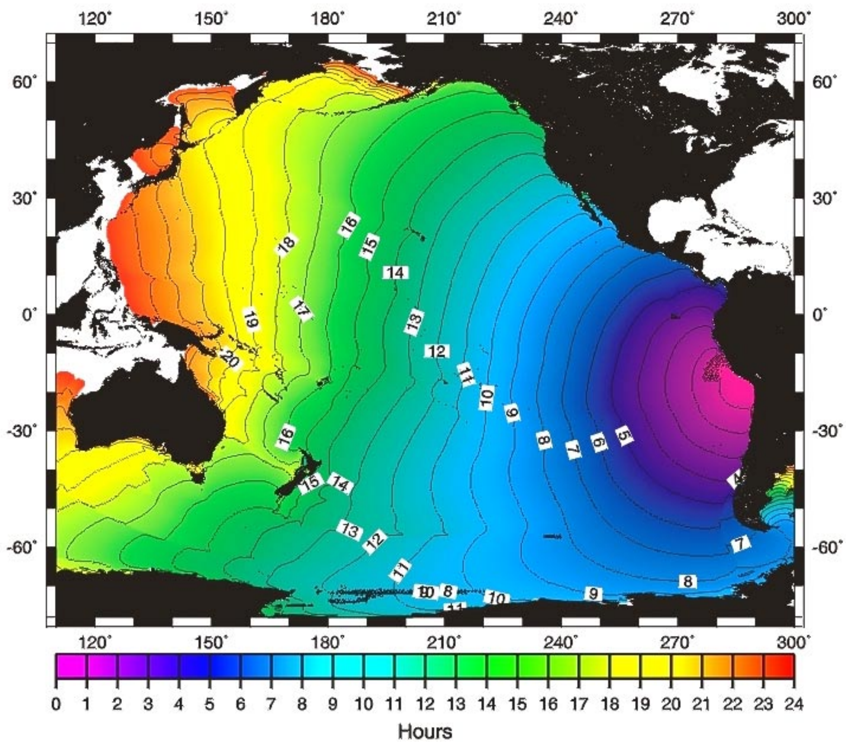
Tropical cyclones are rare in Palau, particularly in the southern portion which are too close to the equator for highly cyclonic winds to be sustained.

Tsunami records

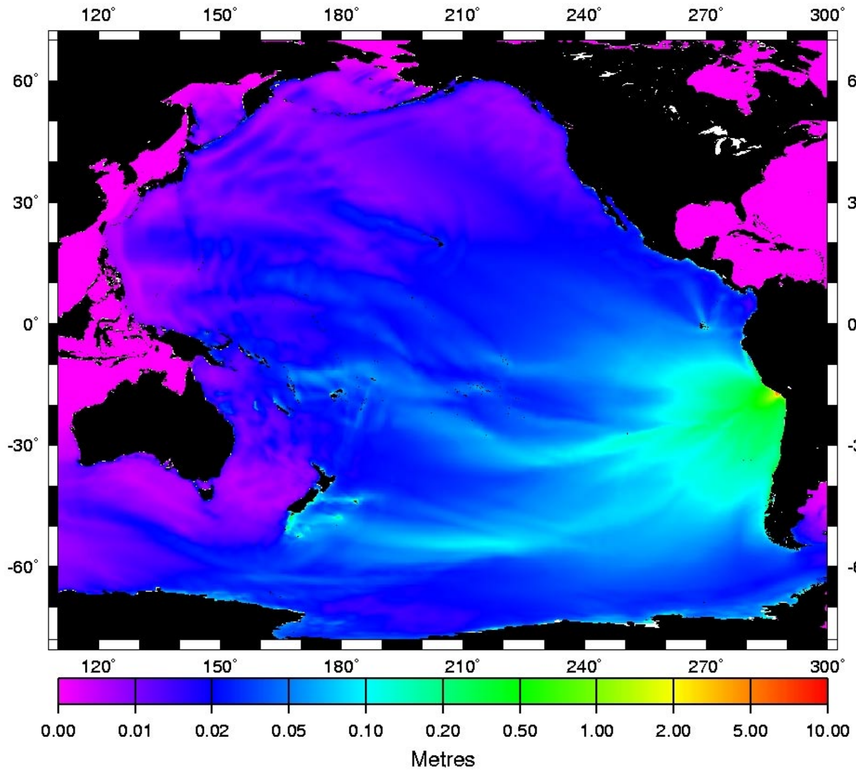
A tsunami can be defined as "A wave usually generated by seismic activity. Also called seismic sea wave, or, incorrectly, a *tidal wave*. Barely discernible in the open ocean, their amplitude may increase to over ten metres in the shallow coastal regions. Tsunamis are most common in the Pacific Ocean."

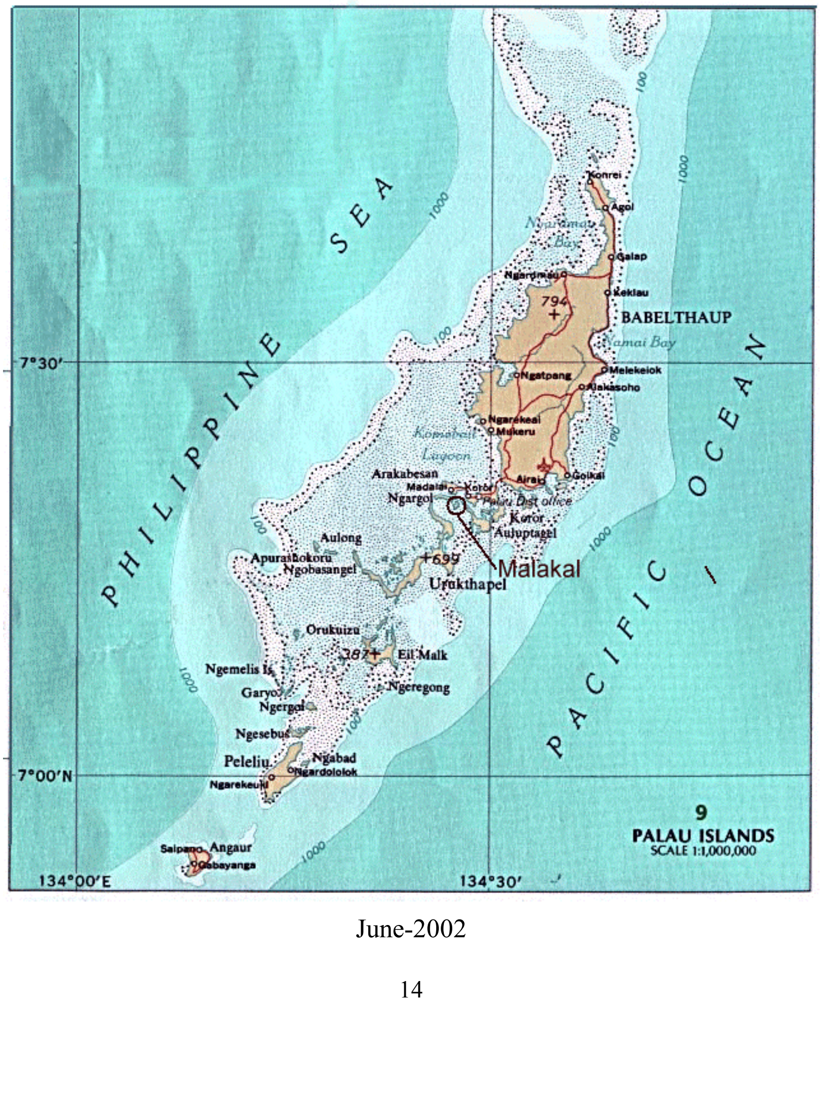
Despite recent history, Palau is not immune from potential problems should there be a large tsunami-generating undersea earthquake in the vicinity. The following plots show how, many hours after the initial earthquake, tsunamis can generate large disturbances in coastal locations.

Travel Times for Tsunami Wave from Peru Earthquake



Tsunami Wave due to Peru Earthquake (simulated magnitude)





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