THE SOUTH PACIFIC SEA LEVEL & CLIMATE MONITORING PROJECT

SEA LEVEL DATA SUMMARY REPORT

JULY 2008 - JUNE 2009

This project is sponsored by the Australian Agency for International Development (AusAID)
and managed by the Australian Bureau of Meteorology

This report was prepared by:

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Quality Certification:

I authorise the issue of this "South Pacific Sea Level and Climate Monitoring Project: Sea Level Data Summary Report, July 2008 to June 2009" in accordance with the quality assurance procedures of the National Tidal Centre, Australian Bureau of Meteorology.

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Please note the following:

EXECUTIVE SUMMARY

This report provides a consolidated overview of the data collected, analysed and presented in the monthly data reports for the South Pacific Sea Level and Climate Monitoring Project (SPSLCMP) to June 2009, with a particular focus on developments since July 2008. The monthly data reports are available via the project website: http://www.bom.gov.au/pacificsealevel/index.shtml

A summary of the key observations is given with some additional commentary on how the results relate to broader scientific findings of the international community concerning sea level rise as the result of climate change.

The main findings during the July 2008 - June 2009 period include:

- SEAFRAME instrumentation continued to return high-quality observations applicable for regional sea level analysis and in determining sea level response to climate variations and climate change.
- Sea level trends from SEAFRAME stations installed in the southwest Pacific region in the early 1990's are larger than the global average, which is in agreement with satellite altimeter observations.
- The observational record is relatively short in climate terms and so the derived sea level trend values are still being influenced by inter-annual and inter-decadal sea level variability. Nevertheless similar trend values are beginning to emerge across the region especially after corrections for local land movement and atmospheric pressure changes are applied.
- Neutral climate conditions with respect to the El Niño – Southern Oscillation cycle prevailed across the equatorial Pacific for the duration of the July 2008 – June 2009 period. Some climate indicators similar to La Niña developed in response to cooling ocean temperatures between November 2009 and February 2009, but ocean warming prevented the development of a basin-wide La Niña and by June 2009 the equatorial Pacific appeared to be in the early stages of a developing El Niño.
- Highest monthly mean sea levels on record were observed at Vanuatu in November 2008, Tonga in January 2009 and Fiji in February 2009.
- The SEAFRAME network assisted in monitoring extreme events, including a tsunami generated by a magnitude Mw7.6 earthquake near Tonga on 19th March 2009. Tsunami heights of up to 15cm were detected on a number of the SEAFRAME stations.
- Six tropical cyclones developed in the southwest Pacific region, although none of them developed into severe tropical cyclones. A tropical storm caused heavy rainfall and severe flooding in Fiji in January 2009.
- It remains the aim of the SPSLCMP that the high-quality sea level observations will be able to provide the required confirmation of sea level trends in the region, especially as the length of record increases.

This report and the monthly sea level data reports are available in electronic form on the Bureau of Meteorology web site: http://www.bom.gov.au/oceanography

Sea level monitoring station at Kiribati

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1. BACKGROUND

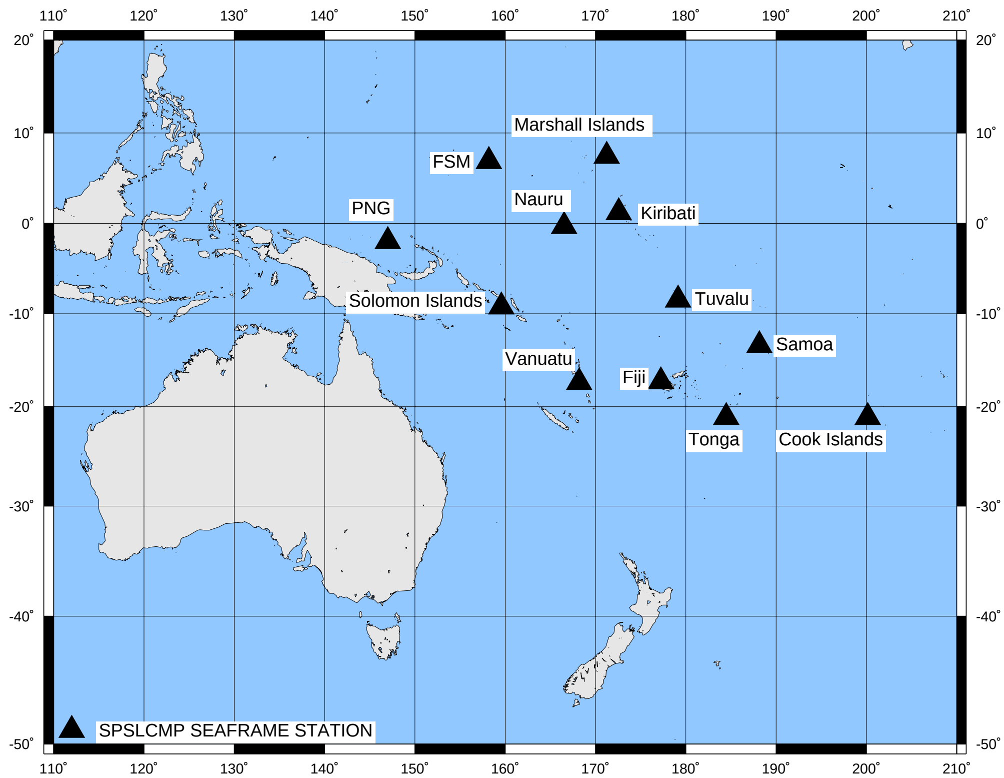
The South Pacific Sea Level and Climate Monitoring Project (SPSLCMP) developed as an Australian response to concerns voiced by Pacific Island countries about the potential impacts of human-induced global warming (the "greenhouse effect") on climate and sea levels in the South Pacific. The project is sponsored by the Australian Agency for International Development (AusAID) and has been implemented over a number of multi-year phases.

The first two phases of the project (from July 1991 to December 2000) established sea level/meteorological monitoring stations at eleven sites, one each in Cook Islands, Fiji, Kiribati, Marshall Islands, Nauru, Papua New Guinea, Solomon Islands, Tonga, Tuvalu, Vanuatu, and Samoa. Another station was established in December 2001 in the Federated States of Micronesia during the project's third phase (January 2001 to December 2006). The third phase also involved installation of continuous global positioning systems (CGPS) at many of these locations in order to monitor vertical movements of the islands upon which the sea level monitoring stations are based.

> The SPSLCMP has, as its principal objective:
>
> *"The provision of an accurate long term record of sea level in the South Pacific for partner countries and the international scientific community, that enables them to respond to and manage related impacts"*

The project has moved into its fourth phase and is now managed by the Australian Bureau of Meteorology. The Bureau's National Tidal Centre (NTC) is responsible for maintaining the SPSLCMP sea level monitoring network and data analysis activities as part of its operations. The monthly sea level reports and this consolidated data report are accordingly prepared by the NTC. More information on the NTC and its functions can be found at http://www.bom.gov.au/oceanography

More information on the overall project can be found at http://www.bom.gov.au/pacificsealevel/index.shtml



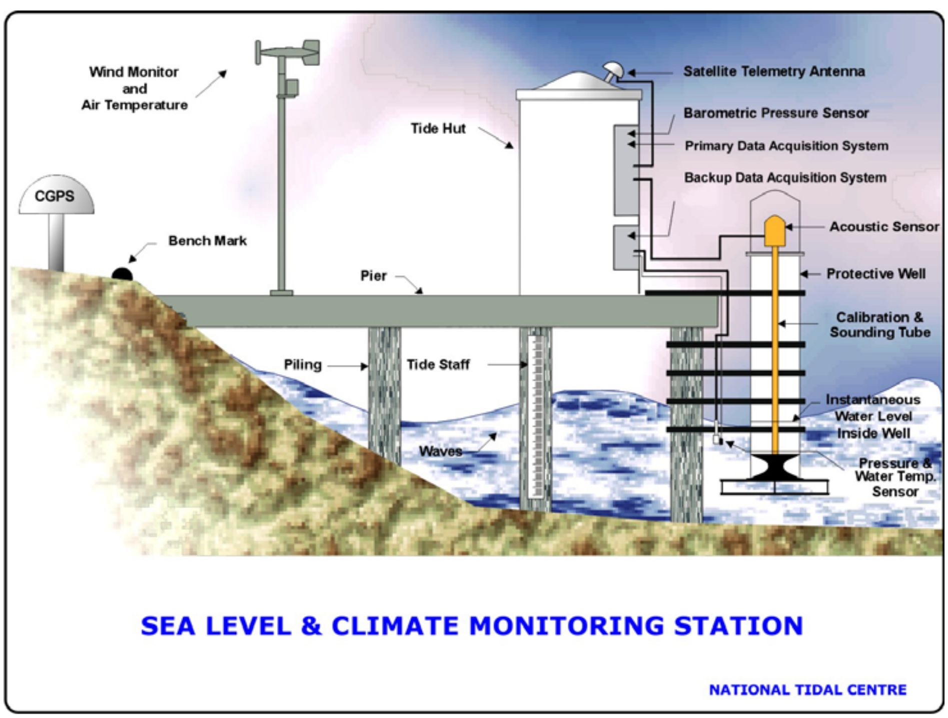


Figure 1. South Pacific Sea Level and Climate Monitoring Project sites (top) where sea level and climate monitoring stations (bottom) are installed.

2. SEA LEVEL MONITORING NETWORK

The project's sea level and climate monitoring network consists of 12 stations providing a wide coverage across the Southwest Pacific basin (Figure 1 and Table 1). The so-called SEAFRAME (an acronym of **SEA** Level **F**ine **R**esolution **A**coustic **M**easuring **E**quipment) stations not only measure sea level by two independent means, but also observe a number of "ancillary" variables - atmospheric pressure, air and water temperatures, wind speed and direction.

The SEAFRAME observations are used in conjunction with analyses performed by the National Climate Centre (NCC) of the Australian Bureau of Meteorology to examine the climatic and oceanographic conditions for the region. The SEAFRAME observations are also used in research and operations associated with Australia's BLUE-link Ocean Forecasting and Tsunami Warning systems and international monitoring efforts such as the Global Sea Level Observing System (GLOSS), Global Ocean Observing System (GOOS) and Pacific Tsunami Warning System (PTWS).

Country	Location	Date of Installation
Fiji	Lautoka	23/10/92
Kiribati	Tarawa	02/12/92
Vanuatu	Port Vila	15/01/93
Tonga	Nuku'Alofa	21/01/93
Cook Is.	Rarotonga	19/02/93
Samoa	Apia	26/02/93
Tuvalu	Funafuti	02/03/93
Marshall Is.	Majuro	07/05/93
Nauru	Nauru	07/07/93
Solomon Is.	Honiara	28/07/94
PNG	Lombrum, Manus Island	28/09/94
FSM	Pohnpei	17/12/01
Niue	No gauge at present	
Palau	No gauge at present	

Table 1. Locations and installation dates for the project sea level monitoring array.

An associated programme of precise leveling of the sea level sensors to land-based benchmarks is being undertaken to monitor any vertical shifts of the equipment relative to the local land. Continuous Global Positioning System (CGPS) measurements are also being undertaken to monitor vertical land movements with respect to the International Terrestrial Reference Frame. Further information about the CGPS programme can be found on the Geoscience Australia website:
http://www.ga.gov.au/geodesy/slm/spslcmp/

3. CLIMATIC AND OCEANOGRAPHIC CONDITIONS

The combination of a number of climatic and oceanographic conditions can affect sea levels across the region. These are described below, including a summary of the present conditions. Supporting information is sourced from the National Climate Centre of the Australian Bureau of Meteorology, the Intergovernmental Panel on Climate Change (IPCC), the UK Met Office, the University of Washington and the University of Colorado.

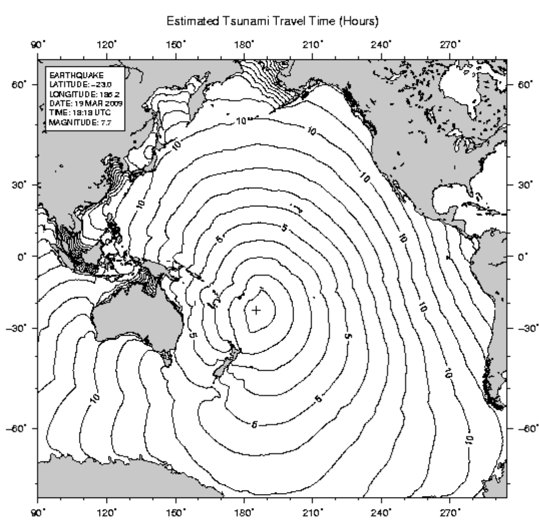
3.1. Extreme Events

Extreme events such as tsunamis (small to potentially large waves caused by seismic disturbances) and cyclones (through associated storm surges) can affect sea levels on short time-scales. The SEAFRAME stations allow tsunamis to be detected and storm surges monitored in real time, and have the capability to report sea levels at one-minute intervals.

3.1.1. Tsunamis

The SEAFRAME network detected one tsunami event during the July 2008 - June 2009 report period.

19 March 2009
An earthquake of magnitude Mw7.6 near Tonga generated a tsunami that was recorded on the SEAFRAME stations at Tonga (15cm trough to peak tsunami signal), Cook Islands (15cm), Lautoka, Fiji (less than 2cm) and Vanuatu (10cm). A tsunami signal of 7cm was also recorded on a SEAFRAME tide gauge at Suva, Fiji. There were no reports of damage, injuries or deaths.



3.1.2. Tropical Cyclones

Six tropical cyclones (TC) developed in the southwest Pacific region during the 2008-2009 season, namely TC Hettie, TC Innis, TC Joni, TC Ken, TC Jasper and TC Lin (Figure 2). None of these tropical cyclones developed into Severe Tropical Cyclones whereby winds exceed 64 knots. TC Lin was the strongest storm and reached its peak as it passed over Tonga, with barometric pressure dipping to 975hPa and winds reaching 60 knots (110 km/hr). The SEAFRAME at Tonga recorded sea levels 0.5m higher than the predicted tide.

Tropical storms caused heavy rainfall and severe flooding in Fiji from 8-10 January 2009. The floods and associated mudslides killed at least 11 people in Fiji, while 6,000 people were displaced from their homes and extensive damage was endured. The SEAFRAME at Lautoka in Fiji recorded stormy sea levels and strong winds.

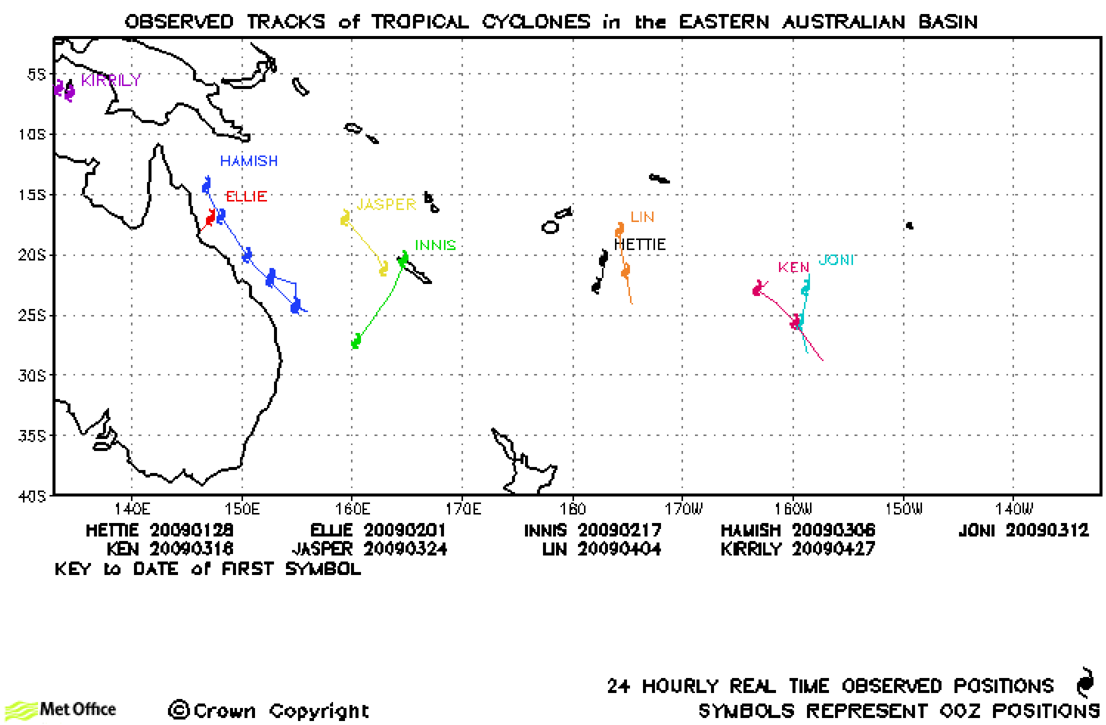


Figure 2. Tropical cyclone tracks in the southwest Pacific during the 2008-2009 tropical cyclone season. (Figure courtesy of the UK met office)

3.2. El Niño – Southern Oscillation (ENSO)

The El Niño – Southern Oscillation (ENSO) refers to the periodic change in atmospheric and oceanic patterns in the tropical Pacific Ocean. The warm phase of the ENSO cycle is often simply referred to as El Niño, whilst the cool phase is termed La Niña. ENSO events have a return period of between four to seven years and typically last for around 12 to 18 months. They are a natural part of the climate system and have been affecting the Pacific Basin for thousands of years.

During neutral (i.e., non-El Niño or La Nina phases) conditions (middle panel of Figure 3), the easterly trade winds blow across the tropical Pacific. These winds pile up warm surface water in the west Pacific, so that the sea surface is about 50 cm higher at Indonesia than at Ecuador. The sea surface temperature is about 8°C higher in the west, with cool temperatures off South America, due to an upwelling of cold water from deeper levels. This cold water is nutrient-rich, supporting high levels of primary productivity, diverse marine ecosystems, and major fisheries. Rainfall is found in rising air over the warmer western waters and the east Pacific is relatively dry.

During El Niño events (top panel of Figure 3), the trade winds relax in the central and western Pacific. This reduction in the winds causes a reduction in the upwelling along the equator, leading to a depression of the ocean thermocline. This can lead to a "pulse" (called a Kelvin Wave) which in turn depresses the thermocline right across to the eastern Pacific. If the warmer sub surface water migrates to the surface and triggers deep atmospheric convection in areas to the east of their normal location, this can further reduce the trade winds and the cycle is reinforced. The result is a rise in sea surface temperature and a drastic decline in primary productivity, the latter of which adversely affects higher trophic levels of the food chain, including commercial fisheries in this region. Impacts of this shift eastwards in the circulation over the tropical Pacific may include increased cyclone activity in the central Pacific, flooding in Peru or drought in Indonesia and Australia. Large-scale teleconnections may also force changes to the climate of regions far removed from the tropical Pacific.

The opposite phase of El Niño is called La Niña (bottom panel of Figure 3). La Niña is characterised by unusually cold ocean temperatures in the equatorial Pacific, as compared to El Niño, which is characterised by unusually warm ocean temperatures in the equatorial Pacific. Global climate anomalies associated with La Niña tend to be opposite those of El Niño.

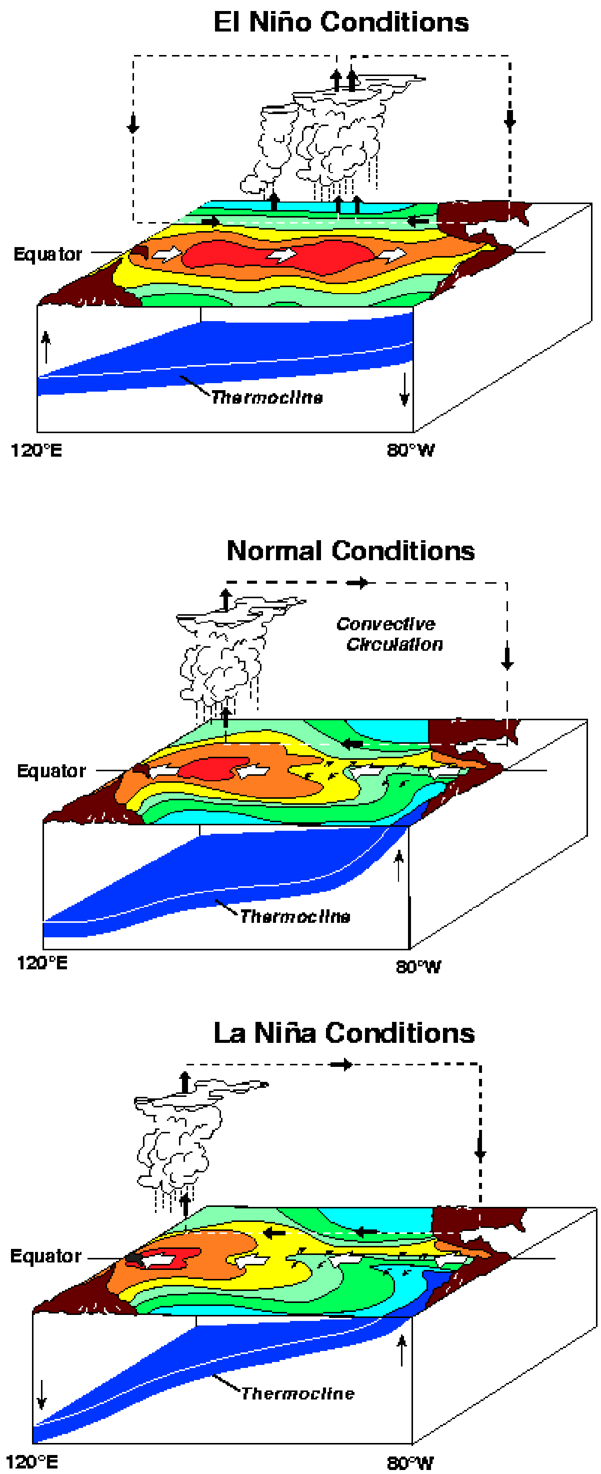


Figure 3. Schematic of atmospheric and ocean conditions associated with El Niño and La Nina.

3.2.1. ENSO conditions July 2008 – June 2009

Climate conditions during the July 2008 – June 2009 period were predominately neutral in terms of the El Niño – Southern Oscillation. Some La Niña characteristics were observed in the equatorial Pacific climate from November 2008 through to February 2009, including cooler than normal ocean heat content across the central to eastern Pacific (Figure 4, Figure 5), stronger than normal Trade Winds, below average cloudiness in the vicinity of the dateline and high values of the Southern Oscillation Index (Figure 6). However, equatorial Pacific temperatures did not cool to the levels required for the development of a basin-wide La Niña event.

Ocean temperatures began to warm slowly across the equatorial Pacific from March 2009 accompanied by a weakening of the Trade Winds. By May 2009 ocean heat content across the equatorial Pacific had become warmer than normal and other climate patterns were consistent with the early stages of a developing El Niño. By the end of June 2009 strong indicators of a developing El Niño continued to persist, including sea surface temperatures 1ºC above normal and sub-surface temperatures as much as 4ºC warmer than normal. Trade Winds were weaker than normal and cloudiness in the vicinity of the dateline was steadily increasing.

For further information see: http://www.bom.gov.au/climate

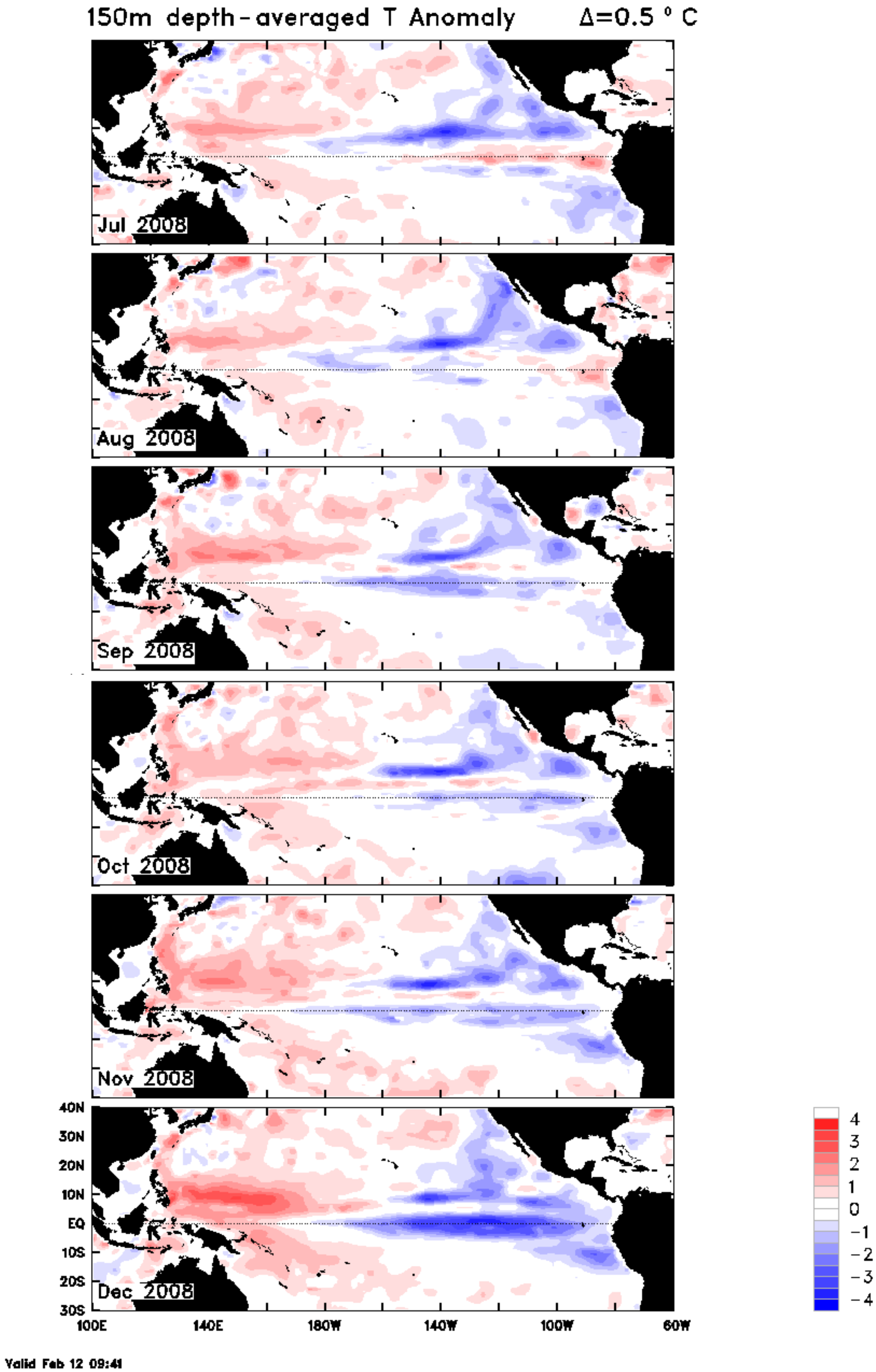


Figure 4. Ocean Temperature Anomalies Jul 2008 –Dec 2008

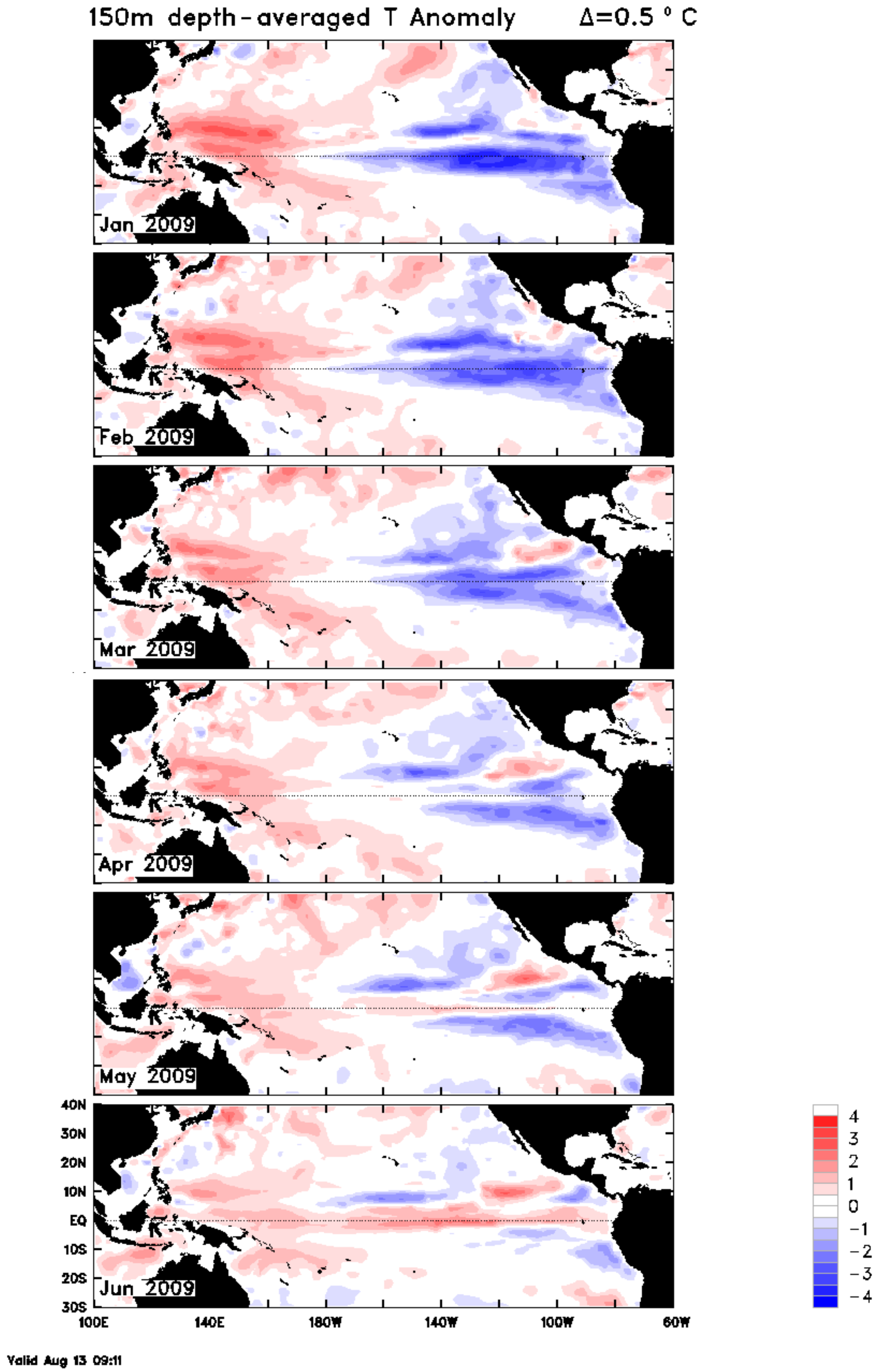


Figure 5. Ocean Temperature Anomalies Jan 2009 – Jun 2009

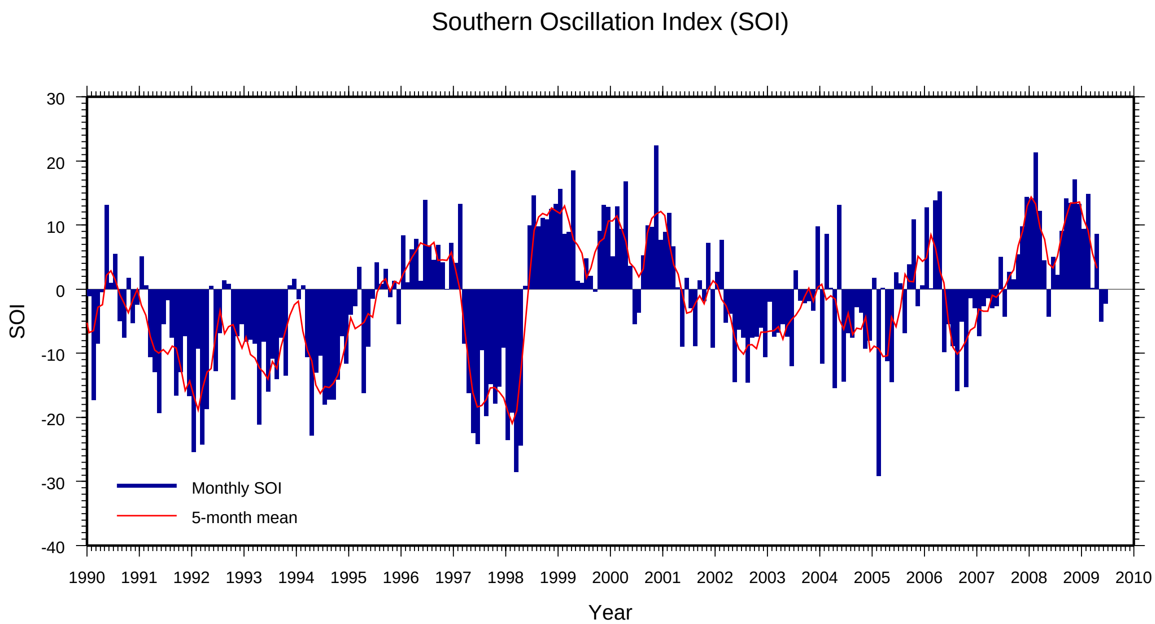


Figure 6. Southern Oscillation Index

3.3. Pacific Decadal Oscillation

Decadal fluctuations are found in a number of different records such as ocean temperature, rainfall, fish populations and sea level. One such fluctuation that has attracted recent attention from scientists is the so-called Pacific Decadal Oscillation (PDO). The PDO is proposed to be a fluctuation of the Pacific Ocean that has similarities to El Niño, but operates over a much longer time period of 20 – 30 years. The positive phase of the PDO is typified by warmer than normal ocean temperature and hence higher than normal sea surface in the eastern equatorial Pacific while a horseshoe pattern of cooler than normal ocean temperature and lower than normal sea surface connects the north, west and south Pacific. During the negative phase, the situation is reversed as outlined in Figure 7.

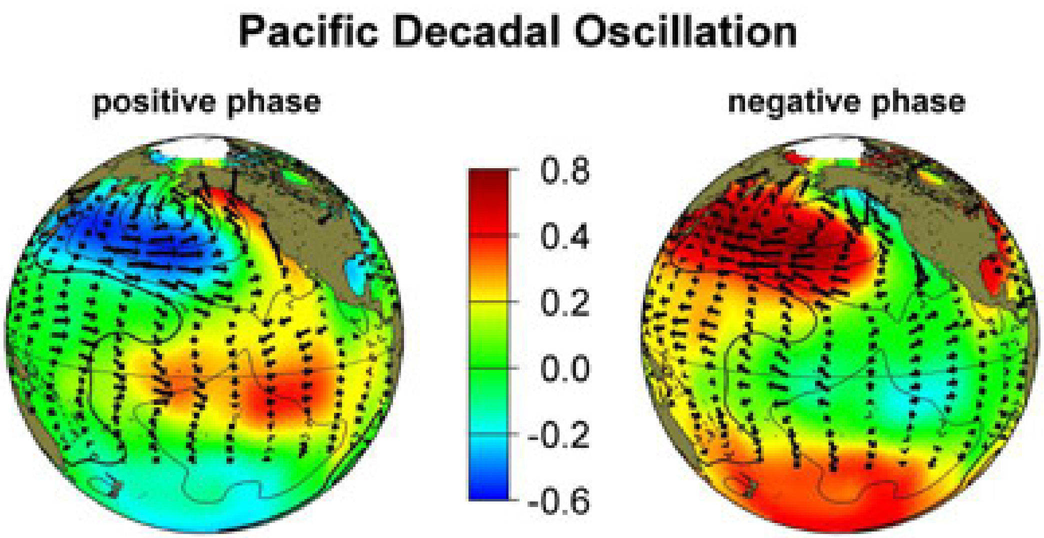


Figure 7. Schematic of sea surface temperature (°C) and wind stress anomalies during positive and negative phases of the Pacific Decadal Oscillation. Figure courtesy of University of Washington.

In order to track the PDO over time scientists have used temperature data to construct a PDO Index, which is shown plotted in Figure 8. The PDO Index shows SEAFRAME stations installed in the early 1990's have collected sea level data while the PDO has predominantly been in its positive phase. Satellite altimeter measurements show evidence of a decadal slosh of Pacific sea level, with sea level having risen in the southwest Pacific and fallen in the northeast Pacific since 1992 (Figure 18).

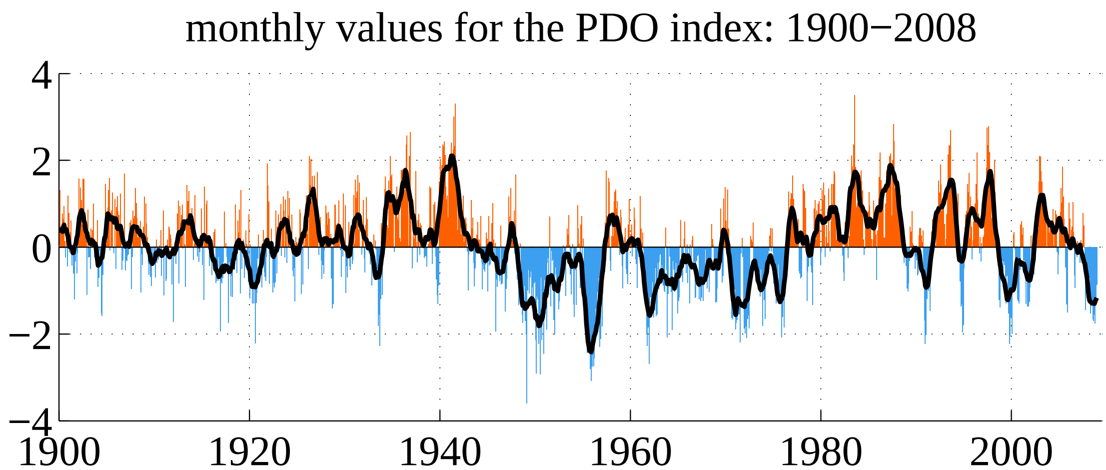


Figure 8. Monthly values for the Pacific Decadal Oscillation Index: 1900-2008. Figure courtesy of University of Washington.

3.4. Sea Level Rise due to Climate Change

As discussed in detail by the Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report (IPCC AR4, 2007), sea level change is an important consequence of climate change, both for communities and the environment.

“Mean sea level” at the coast is defined as the height of the sea with respect to a local land benchmark, averaged over a period of time, such as a month or a year, long enough that fluctuations caused by waves and tides are largely removed. Changes in mean sea level as measured by coastal tide gauges are called “relative sea level changes”, because they can come about either by movement of the land on which the tide gauge is situated or by changes in the height of the adjacent sea surface (both considered with respect to the centre of the Earth as a fixed reference). These two terms can have similar rates (several mm/yr) on time-scales greater than decades.

To detect sea level changes arising from changes in the ocean, the movement of the land needs to be subtracted from the records of tide gauges and geological indicators of past sea level. Widespread land movements are caused by the isostatic adjustment resulting from the slow viscous response of the mantle to the melting of large ice sheets and the addition of their mass to the oceans since the end of the most recent glacial period (“Ice Age”). Tectonic land movements, atoll decay, rapid displacements (earthquakes) and slow movements (associated with mantle convection and sediment transport) can also have an important effect on local relative sea level.

Eustatic sea level change results from changes to the density or to the total mass of water, both of which are related to climate change. Density is reduced by thermal expansion, which occurs as the ocean warms. The total mass of oceanic water can change through transfers from glaciers, ice caps and the Greenland and Antarctic Ice Sheets.

The IPCC AR4, 2007 estimates that global average eustatic sea level rise over the last century was 1.7 ± 0.5 mm/yr. From 1961 to 2003, the average rate of sea level rise is estimated as 1.8 ± 0.5 mm/yr. IPCC AR4, 2007 also recognises that sea level records contain a considerable amount of inter-annual and decadal variability. For instance, the average rate of sea level rise for the decadal period 1993 – 2003 based on satellite altimetry is 3.1 ± 0.7 mm/yr. Studies have shown that comparably large rates of average sea level rise have been observed in previous decades.

Projections of future sea level rise, according to an assessment of global coupled ocean-atmosphere climate computer models in IPCC AR4, 2007, ranges from 0.18 to 0.59 m at 2090-2099 relative to 1980-1999. These projections include contributions from thermal expansion and land ice contribution. In all scenarios the thermal expansion contribution accounts for around 75 % of the total sea level rise. Thermal expansion is expected to continue well after climate stabilises because of the large heat capacity of the ocean.

Although simulations of recent sea level rise (eg 1993 to 2003) are in reasonable agreement with observations, longer-term sea level rise has not been satisfactorily modelled. This implies a deficiency in the current understanding, which is partly related to the poor global coverage of high quality historical tide gauge records and the uncertainty in the corrections for land motions. The high-accuracy sea level stations, in conjunction with the CGPS stations to monitor land motion, installed for the SPSLCMP will help address these issues in future.

Sea level change is not expected to be geographically uniform, so information about its distribution is needed to inform assessments of the impacts on coastal regions. The regional pattern depends on ocean surface fluxes, interior conditions and ocean circulation. The most serious impacts are caused not only by changes in mean sea level but by changes to extreme sea levels, especially storm surges and exceptionally high waves, which are forced by meteorological conditions. Climate-related changes in these phenomena therefore also have to be considered.

For more information on sea level change under climate changes see:

http://www.ipcc.ch/

For a discussion of the sea level trends being observed in the SPSLCMP, see section 4.3.

4. SEAFRAME DATA ANALYSIS

4.1. Monthly mean sea levels

The monthly mean sea levels at the SEAFRAME stations (Figure 10) are influenced by climate fluctuations including regular seasonal and annual cycles, transient events such as El Niño and La Niña and longer-term climate change. A 20cm annual sea level cycle is observed at many of the sites. The 1997/98 El Niño clearly disrupted the regular annual sea level cycles at many stations and lowered sea levels across the region.

During the July 2008 to June 2009 period three stations recorded their highest monthly mean sea level on record. These were Vanuatu in November 2008, Tonga in January 2009 and Fiji in February 2009.

4.2. Anomalies

The following section describes the anomalous observations in the records from the SEAFRAME stations, that is, the departures from normal conditions.

4.2.1. Sea level anomalies

The sea level anomalies (Figure 11) are derived by removing the predicted tides (including seasonal and annual cycles) and a linear trend from the sea level data. The anomalies highlight irregular events, such as the effects of the 1997/98 El Niño during which sea levels became significantly lower than normal (20-30 cm) at many of the SEAFRAME stations.

The effects of El Niño (or La Niña) upon sea level is felt strongly along the equator as well as along the South Pacific Convergence Zone (SPCZ). The SPCZ is a region where convergent trade winds produce enhanced cloudiness and deepening of the warm upper layer of the ocean (Figure 9). A change in the strength or position of the SPCZ can produce large sea level effects at PNG, Solomon Islands, Tuvalu and Samoa.

Between July 2008 and June 2009 sea level anomalies did not exceed ±10cm at most stations, indicative of near-normal sea levels in accordance with the predominance of neutral climate conditions. At many stations a general fall in sea level anomaly was observed, from slightly higher than normal sea levels around January - March 2009 to slightly lower than normal sea levels around May- June 2009. This was due to a decrease in ocean heat content in the far western Pacific and weakening Trade Winds, in association with the developing El Niño conditions.

Sea level anomalies remained higher than normal at Vanuatu and Fiji for most of the July 2008 to June 2009 period. At the equatorial stations of Kiribati and Nauru, sea level anomalies rose during the July 2008 – June 2009 period due to a gradual deepening of the thermocline (warm upper ocean layer) in response to warming ocean temperatures in the western equatorial Pacific.

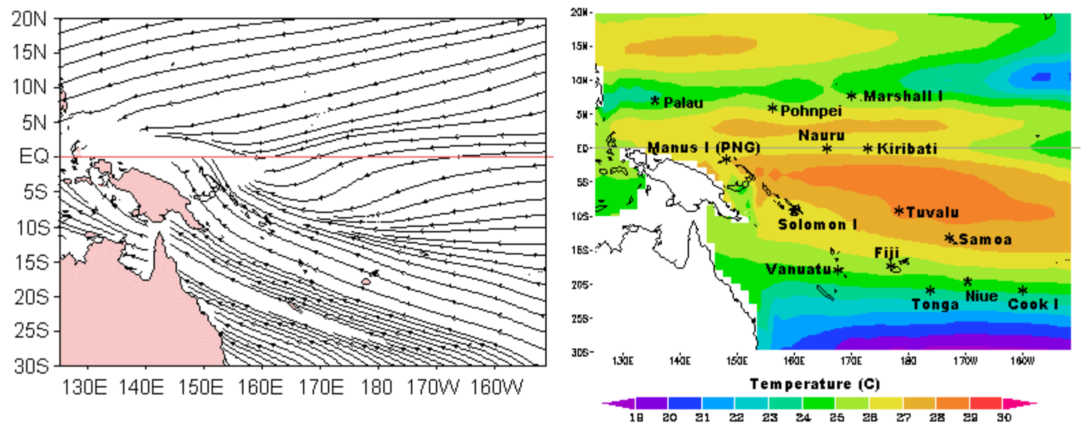


Figure 9. Streamlines of mean surface winds (left) and mean surface temperature (right). The region of convergent trade winds and warm surface temperatures extending from PNG through Tuvalu and beyond is known as the South Pacific Convergence Zone.

4.2.2. Barometric pressure anomalies

The barometric pressure anomalies (Figure 12) were strongly positive at all stations during the 1997/98 El Niño event. Between July 2008 and June 2009, barometric pressures were generally near normal across the region, with some stations showing a tendency for slightly higher than normal barometric pressure in the latter half of 2009 and slightly lower than normal barometric pressures in the first half of 2009.

4.2.3. Water temperature anomalies

The water temperature anomalies (Figure 13) show a sustained period of warmer than normal water temperatures was observed at the southern stations of Vanuatu, Fiji, Tonga and Cook Islands from July 2008, but cooling to near normal conditions had occurred by June 2009. Conversely the equatorial stations at Kiribati and Nauru experienced cooler than normal water temperatures in July 2008 slowly warming to near normal conditions by June 2009, in agreement with a warming trend across the equatorial Pacific.

4.2.4. Air temperature anomalies

The air temperature anomalies (Figure 14) show similar features to the water temperature anomalies, with sustained warmer than normal conditions at Vanuatu, Fiji, Tonga and Cook Islands from July 2008 cooling toward slightly cooler than normal air temperatures by June 2009. Kiribati showed a warming trend in air temperatures similar to that shown in water temperatures.

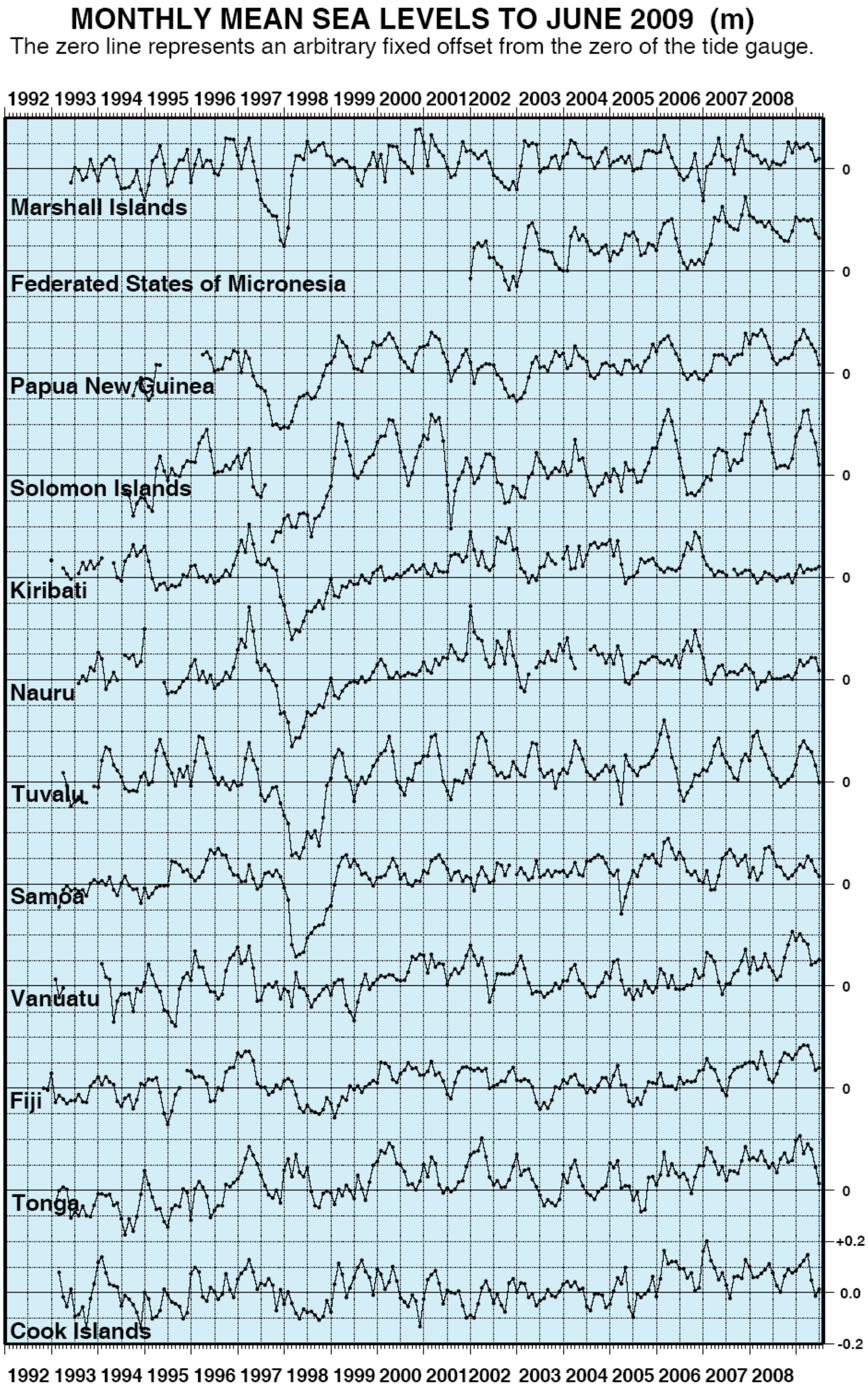


Figure 10. Monthly mean sea levels to June 2009.

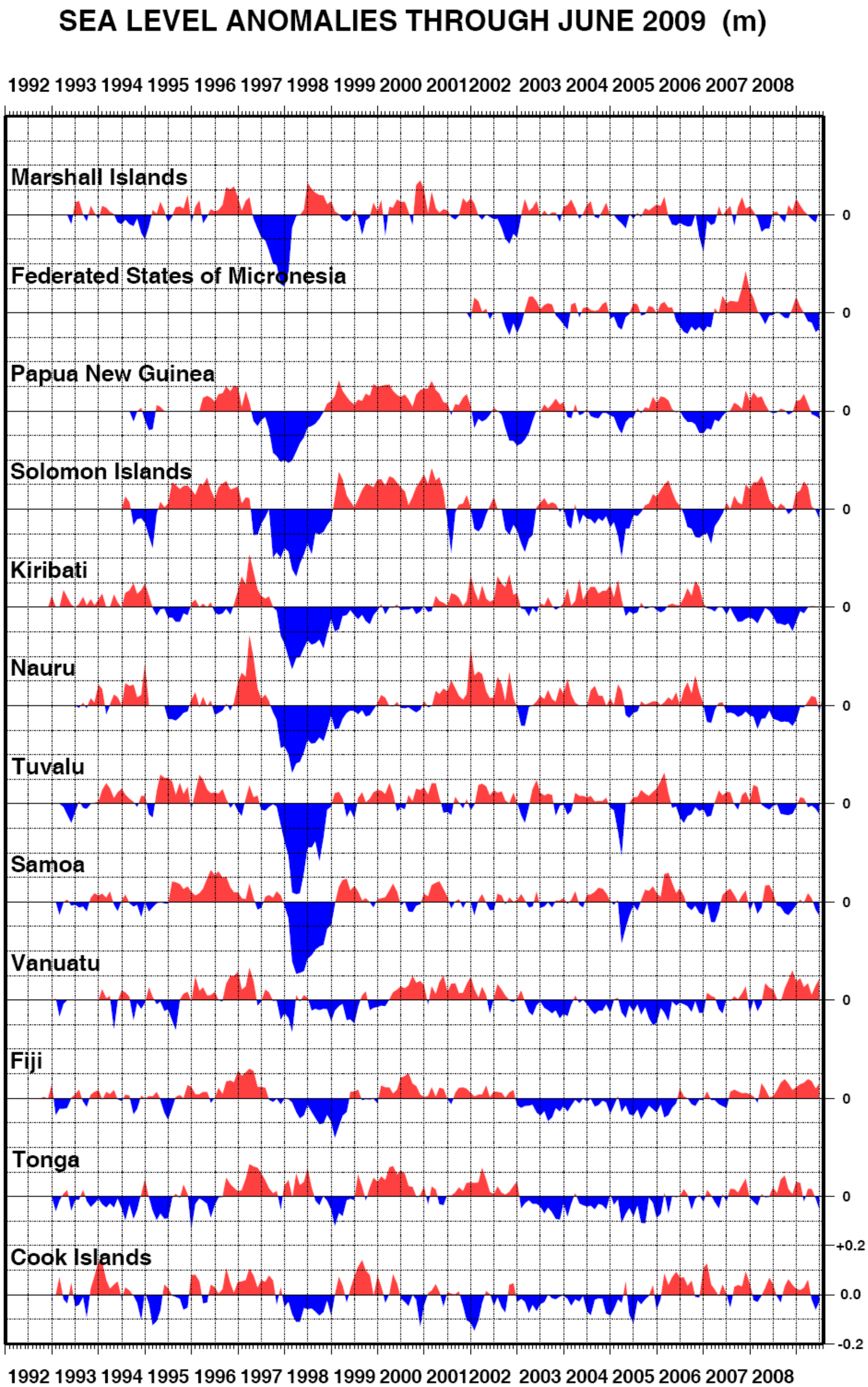


Figure 11. Sea level anomalies to June 2009.

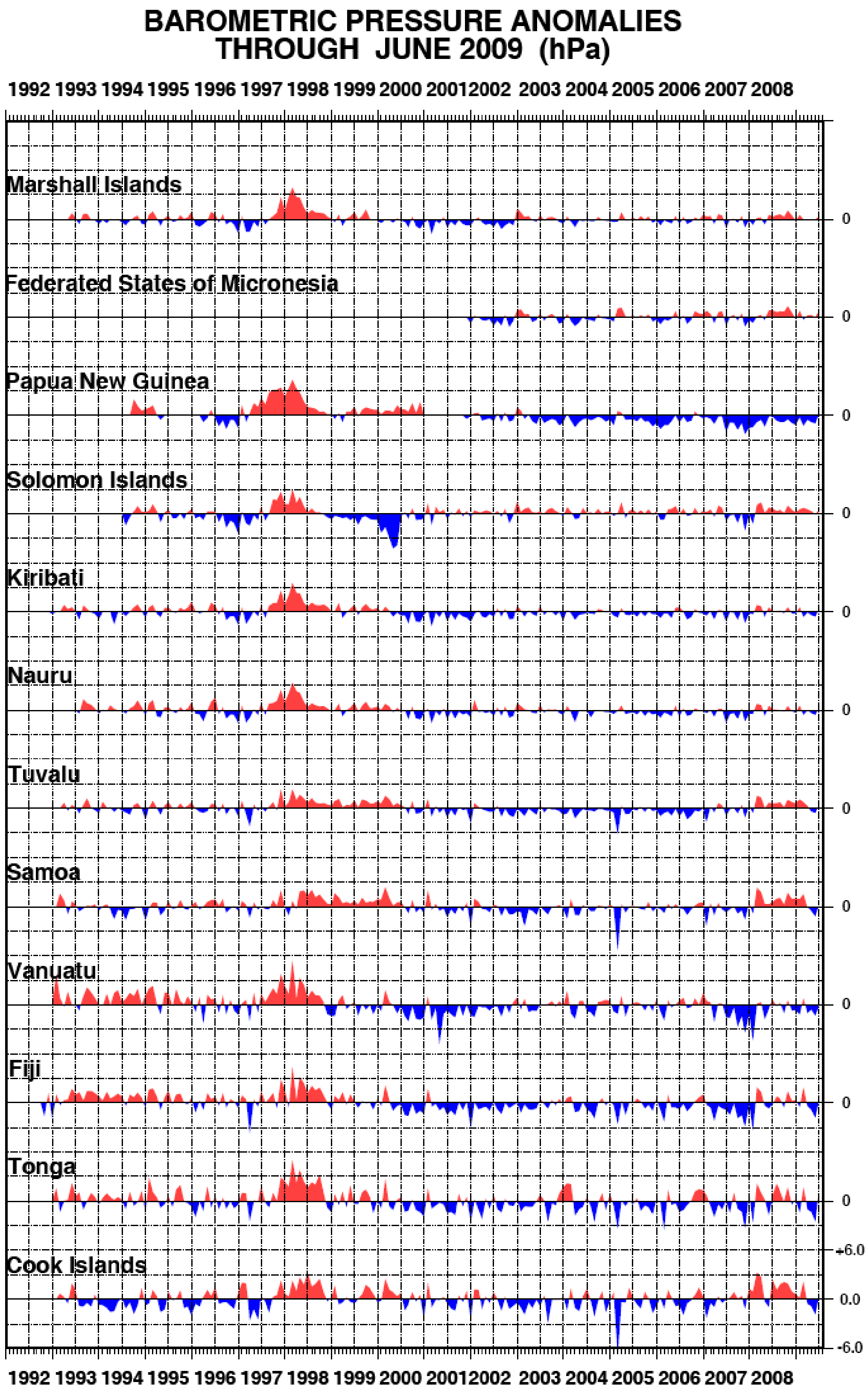


Figure 12. Barometric pressure anomalies to June 2009.

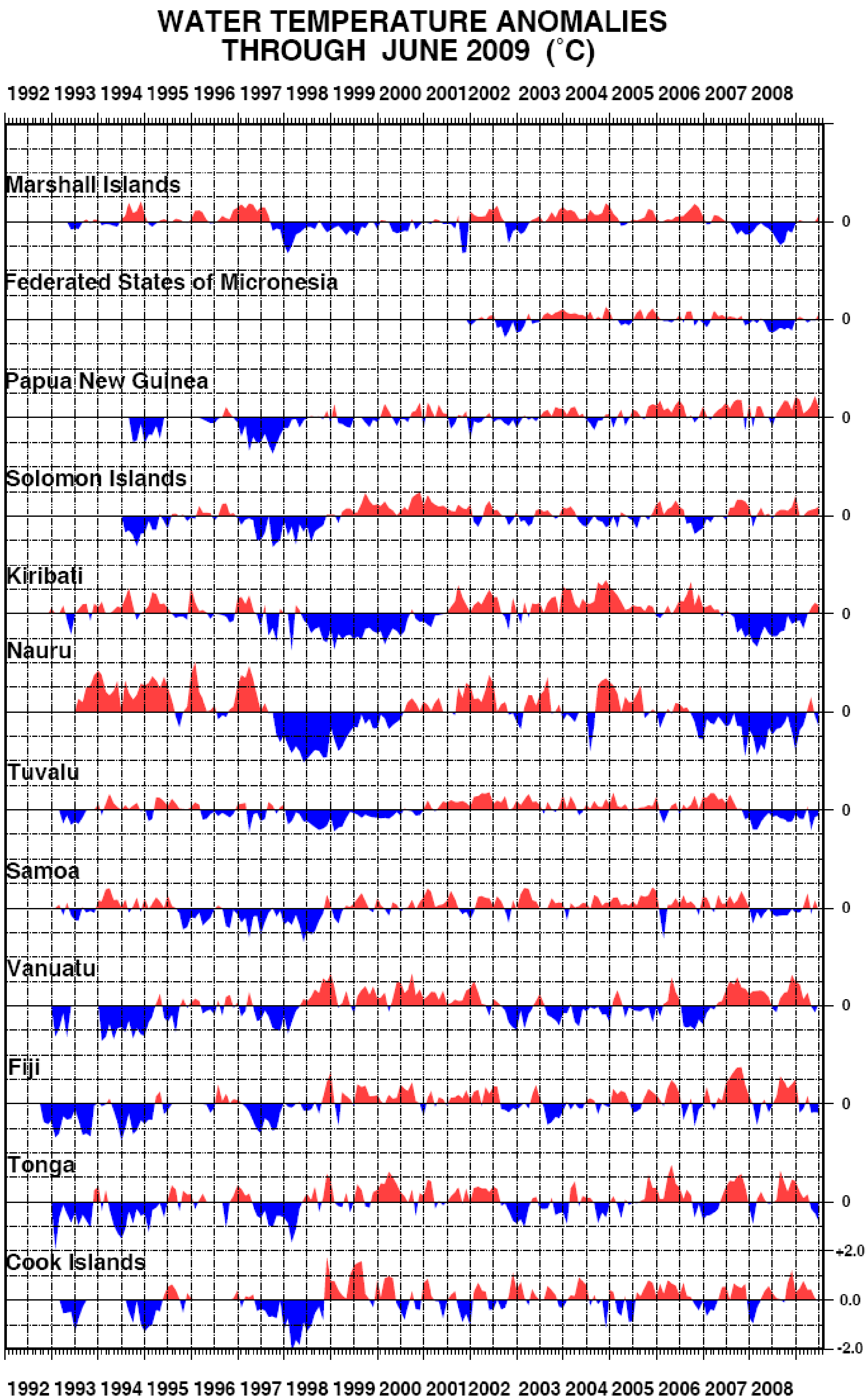


Figure 13. Water temperature anomalies to June 2009.

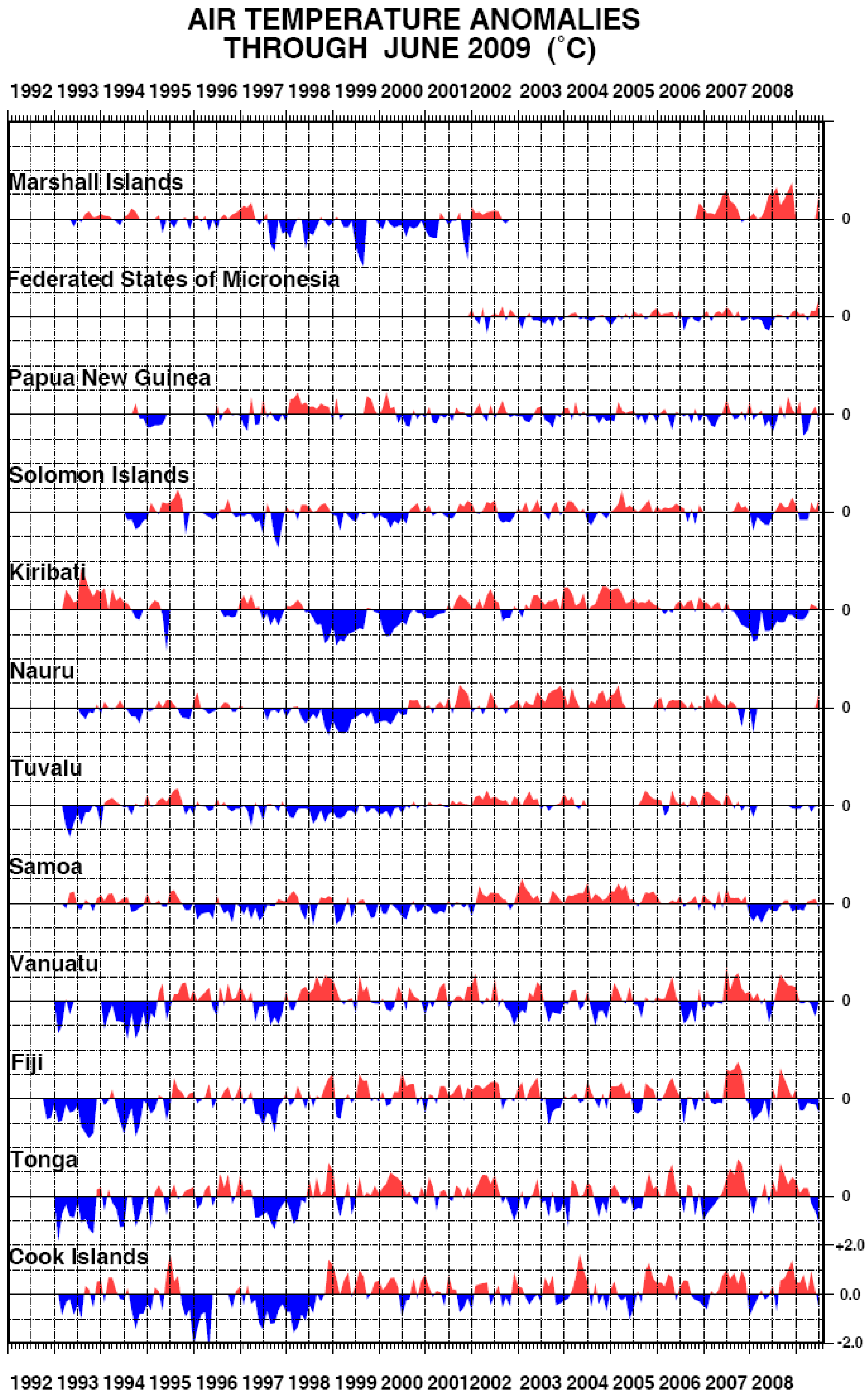


Figure 14. Air temperature anomalies to June 2009.

4.3. Sea Level Trends

4.3.1. Relative sea level trends

Sea level is influenced by natural climate variation (e.g. El Niño, decadal variations) in addition to long-term climate change (e.g. global warming, sea level rise). Over the short term, large climate fluctuations such as El Niño can conceal the longer-term climate change. Land movements may also contribute to trends in relative sea level, which is why differential leveling of the SEAFRAME to land-based benchmarks and continuous GPS measurements are being undertaken.

It is important to emphasise that as the sea level record becomes longer, the trend estimate becomes more stable and reliable, as shown in Figure 15. That is, the sea level trend becomes more indicative of longer-term changes. ***In the meantime caution must be exercised in interpreting the short-term trends –*** they will almost certainly change over the coming years as the data set increases in length.

Although the sea level trends are not yet indicative of long-term changes in mean sea level, they are showing coherent regional short-term changes. The latest relative sea level trend estimates are listed in Table 2. The agreement between neighbouring stations is confirmation that the regular calibration, maintenance and surveying of the SEAFRAMES and quality control of the collected data is meeting its objective of providing accurate long-term sea level records. Older sea level networks that were not designed for precise long-term sea level monitoring, but have since been adapted for such, typically do not display the same level of agreement between neighbouring stations.

The sea level trend at FSM is large compared to the other stations. This is because its sea level record is shorter and the trend is still stabilising. The trend at Tonga is also considerably larger than its neighbours Fiji and Cook Islands. Tonga lies in a tectonically active region. Continuous GPS monitoring at Tonga may help identify whether geodynamic factors are affecting the relative sea level trend there.

Recent short-term relative sea level trends in the project area based upon SEAFRAME data through June 2009				
	Location	**Installation Date**	**Trend (mm/yr)**	**Change from June 2008**
1	**Cook Is**	**19/02/1993**	**5.3**	**0.3**
2	**Tonga**	**21/01/1993**	**9.4**	**0.6**
3	**Fiji**	**23/10/1992**	**5.4**	**1.5**
4	**Vanuatu**	**15/01/1993**	**5.8**	**1.6**
5	**Samoa**	**26/02/1993**	**6.0**	**-0.5**
6	**Tuvalu**	**02/03/1993**	**5.6**	**-0.5**
7	**Kiribati**	**02/12/1992**	**3.3**	**-1.1**
8	**Nauru**	**07/07/1993**	**4.3**	**-0.8**
9	**Solomon Is.**	**28/07/1994**	**8.7**	**0.9**
10	**PNG**	**28/09/1994**	**8.1**	**0.3**
11	**FSM**	**17/12/2001**	**20.2**	**-2.2**
12	**Marshall Is.**	**07/05/1993**	**4.2**	**0.3**

Table 2. Recent short-term relative sea level trends in the project area based upon SEAFRAME data to June 2009. The record at FSM is considerably shorter, resulting in a comparatively large trend.

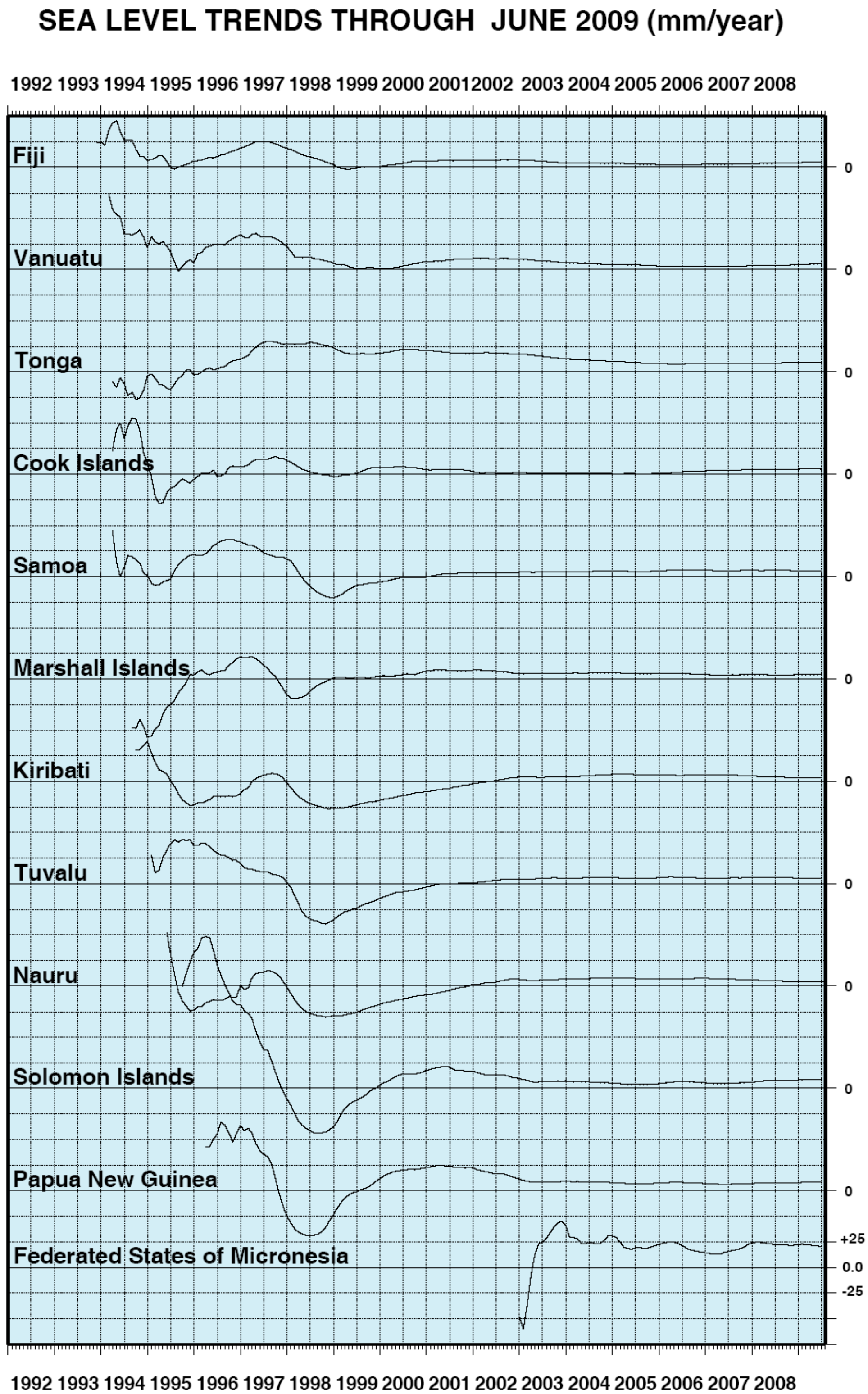


Figure 15. Sea level trends computed on a monthly basis from 12 months after installation to present. The monthly trend estimates are shown to become more stable and reliable as the length of record increases.

4.3.2. Precise levelling corrections

Near first-order precise levelling of the datum of the sea level observations is an important aspect of the project. The purpose is to monitor the vertical movement of the sea level sensor with respect to the land. Upon installation of the SEAFRAME stations an array of deep-driven benchmarks were established in the immediate vicinity of the instrument and out to a distance of several kilometres. The vertical height of the gauge is monitored by repeatedly surveying the height of the gauge and its benchmarks every 1-2 years. A stable benchmark is identified as the primary tide gauge benchmark against which the tide gauge and other benchmarks are referred.

The trend in the surveyed heights of the tide gauges with respect to their primary tide gauge benchmarks can be found in Table 3. The table also shows the number of surveys that have been conducted since each gauge was established.

Trends in the vertical movement of the tide gauge and/or supporting structure with respect to the tide gauge benchmark based upon precise levelling through June 2009			
No.	**Location**	**Number of surveys**	**Trend (mm/yr)**
1	**Cook Is**	**9**	**0.3**
2	**Tonga**	**9**	**-0.7**
3	**Fiji**	**9**	**0.5**
4	**Vanuatu**	**8**	**0.3**
5	**Samoa**	**9**	**-1.0**
6	**Tuvalu**	**9**	**-0.1**
7	**Kiribati**	**10**	**0.1**
8	**Nauru**	**10**	**0.2**
9	**Solomon Is.**	**4**	**-0.4**
10	**PNG**	**8**	**-0.1**
11	**FSM**	**5**	**-0.4**
12	**Marshall Is.**	**9**	**-0.6**

Table 3. Trends in the datum of the SEAFRAME sea level sensor as determined from precise levelling between the sensor and the tide gauge benchmark.

The precise levelling results indicate a substantial contribution to the relative sea level rise at Samoa is due to subsidence of the tide gauge at a rate of 1.0 mm/yr. Subsidence of a tide gauge produces a positive contribution to the rate of relative sea level rise. Subsidence is also occurring at Marshall Islands, FSM and Solomon Islands. A vertical displacement of the tide gauge at Tonga has been detected, but at this stage the cause is unknown. The tide gauges at Cook Islands, Fiji and Vanuatu are all rising with respect to the tide gauge benchmark.

4.3.3. Inverted barometric pressure effect

Another parameter that influences relative sea level rise is atmospheric pressure. 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 the barometric pressure recorded at the SEAFRAME stations have been examined to quantify what contribution they may be providing to the observed relative sea level trends. For example, a 1 hPa/year decrease (increase) in barometric pressure contributes to around 10 mm/year increase (decrease) in relative sea levels.

Table 4 contains the estimates of the contribution to relative sea level trends by the inverted barometric pressure effect in mm/year at all SEAFRAME sites over the period of the project. They are mostly positive, which shows barometric pressure changes are contributing to slightly higher rates of sea level rise.

Barometric pressure contribution to the relative sea level rise in the project area based upon SEAFRAME data through June 2009				
No.	**Location**	**Installation Date**	**Trend due to Inverse Barometer (mm/yr)**	**Change from June 2008**
1	**Cook Is**	**19/02/1993**	**-0.1**	**-0.1**
2	**Tonga**	**21/01/1993**	**0.6**	**-0.1**
3	**Fiji**	**23/10/1992**	**0.8**	**-0.2**
4	**Vanuatu**	**15/01/1993**	**1.1**	**-0.1**
5	**Samoa**	**26/02/1993**	**0.1**	**-0.2**
6	**Tuvalu**	**02/03/1993**	**0.2**	**-0.2**
7	**Kiribati**	**02/12/1992**	**0.4**	**0.0**
8	**Nauru**	**07/07/1993**	**0.4**	**-0.1**
9	**Solomon Is.**	**28/07/1994**	**-0.3**	**-0.1**
10	**PNG**	**28/09/1994**	**1.5**	**-0.1**
11	**FSM**	**17/12/2001**	**-0.8**	**-0.3**
12	**Marshall Is.**	**07/05/1993**	**0.1**	**-0.1**

Table 4. Recent short-term barometric pressure trends expressed as equivalent sea level rise in mm/year based upon SEAFRAME data to June 2009. The trend at FSM is from a comparatively short series and therefore varies considerably.

4.3.4. Combined net rate of relative sea level trends

The effects of the vertical movement of the platform and the inverse barometer effect are subtracted from the observed rates of relative sea level change and presented in Table 5 and Figure 16. Despite the short-term nature of the sea level records Figure 16 shows similar rates are being observed between neighbouring stations. FSM was installed at a much later stage and therefore has a notably different net trend. The net trend at Tonga appears large in relation to its surrounding sites. Tonga is situated in the vicinity of a tectonic subduction zone and so a significant contribution to the relative sea level trend estimate may be due to the vertical motion of the whole island. A CGPS station has only recently been installed at Tonga (in February 2002) and estimates of this motion are still too noisy to be reliable.

Between July 2008 and June 2009 large changes to the net rates of relative sea level rise at SEAFRAME stations were experienced at some stations. For instance, south of the equator the overall net sea level trends at Vanuatu, Fiji and Solomon Islands increased by more than 1mm/yr, whereas along the equator the net sea level trends at Nauru and Kiribati decreased by -0.7 mm/yr and -1.1 mm/yr. Year-to-year changes to the sea level trends of this magnitude illustrate the sea level record is still relatively short in climate terms.

Net relative sea level rise in mm/year through June 2009				
No.	**Location**	**Installation Date**	**Net Trend (mm/yr)**	**Change from June 2008**
1	**Cook Is**	**19/02/1993**	**5.7**	**0.4**
2	**Tonga**	**21/01/1993**	**8.1**	**0.7**
3	**Fiji**	**23/10/1992**	**5.1**	**1.7**
4	**Vanuatu**	**15/01/1993**	**4.8**	**1.7**
5	**Samoa**	**26/02/1993**	**4.9**	**-0.3**
6	**Tuvalu**	**02/03/1993**	**5.3**	**-0.3**
7	**Kiribati**	**02/12/1992**	**3.0**	**-1.1**
8	**Nauru**	**07/07/1993**	**4.1**	**-0.7**
9	**Solomon Is.**	**28/07/1994**	**8.6**	**1.0**
10	**PNG**	**28/09/1994**	**6.5**	**0.4**
11	**FSM**	**17/12/2001**	**20.6**	**-1.9**
12	**Marshall Is.**	**07/05/1993**	**3.5**	**0.4**

Table 5. The net relative sea level trend estimates after vertical movements in the observing platform and the inverted barometric pressure effect are taken into account.

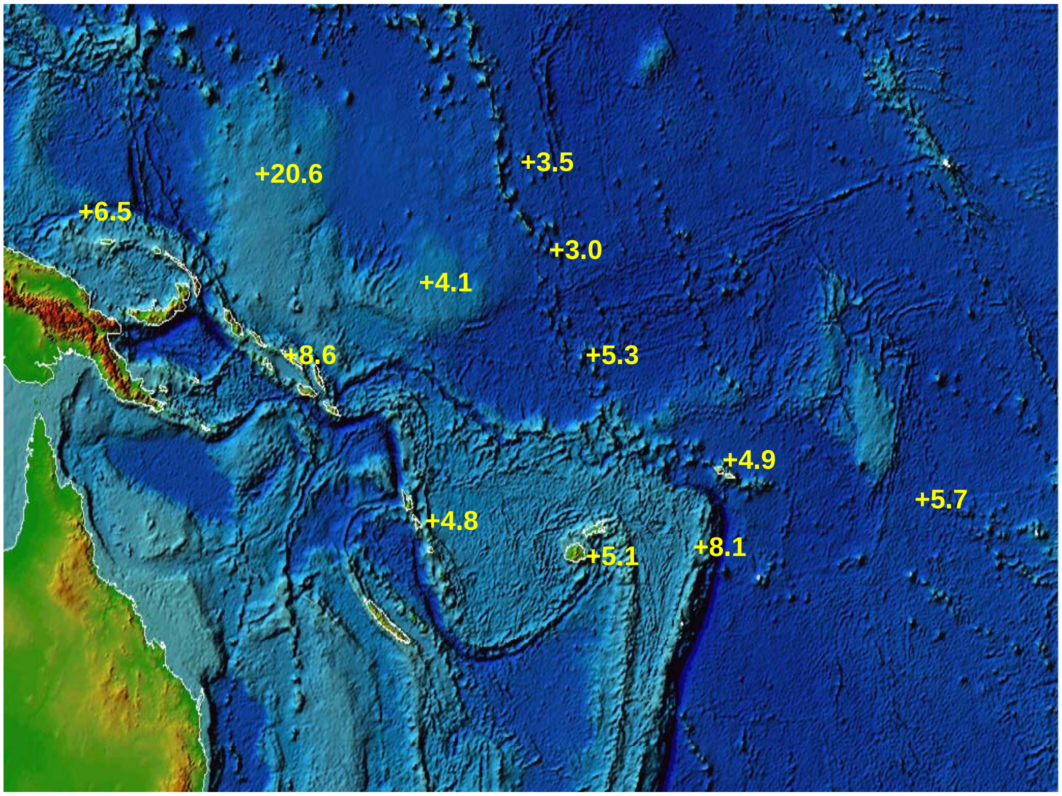


Figure 16. The net relative sea level trend in mm/year after subtracting the effects of the vertical movement of the platform and the inverse barometric pressure effect utilising all the data collected since the start of the project up to the end of June 2009.

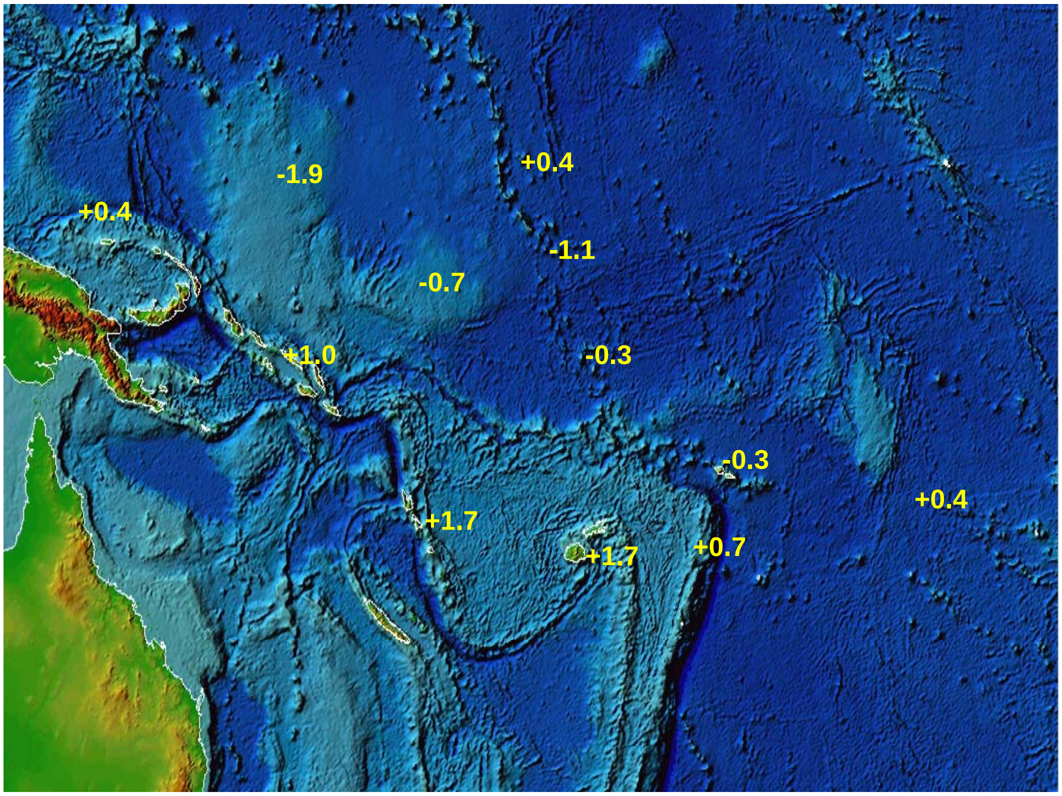


Figure 17. The change in the net relative sea level trend in mm/year between June 2008 and June 2009. The net trend is defined to be the relative sea level trend after subtracting the effects of the vertical movement of the platform and the inverse barometric pressure effect.

4.3.5. Comparison with satellite altimetry derived sea level trends

Satellite altimetry provides measurements of absolute sea level against which tide gauge measurements of relative sea level can be compared. It is important to recognise that satellite altimeters and tide gauges are complimentary datasets. The SEAFRAME sea level data is vital for calibrating and validating satellite altimeter measurements of sea level, as well as monitoring sea levels in coastal regions with accuracy and timeliness not provided by satellite altimeters.

The TOPEX/Poseidon (T/P) and subsequent Jason-1 satellite altimeter missions have enabled sea levels to be measured on a global basis every 10 days since late 1992. The installation of SEAFRAME stations occurred around the same time, and hence both of these measurement programs have covered approximately the same period of sea level change.

The global distribution of sea level trends derived from T/P and Jason-1 measurements from December 1992 to July 2009 is illustrated in Figure 18. Increasing sea levels in the western Pacific and falling sea levels in the eastern Pacific during this period are related to decadal fluctuations (see section 3.3). Sea level trends in the SPSLCMP region are generally higher than the global average, which currently stands at ~3.2 mm/yr. Satellite altimetry shows high rates of sea level rise have been observed along the South Pacific Convergence Zone, which is in agreement with the SPSLCMP results.

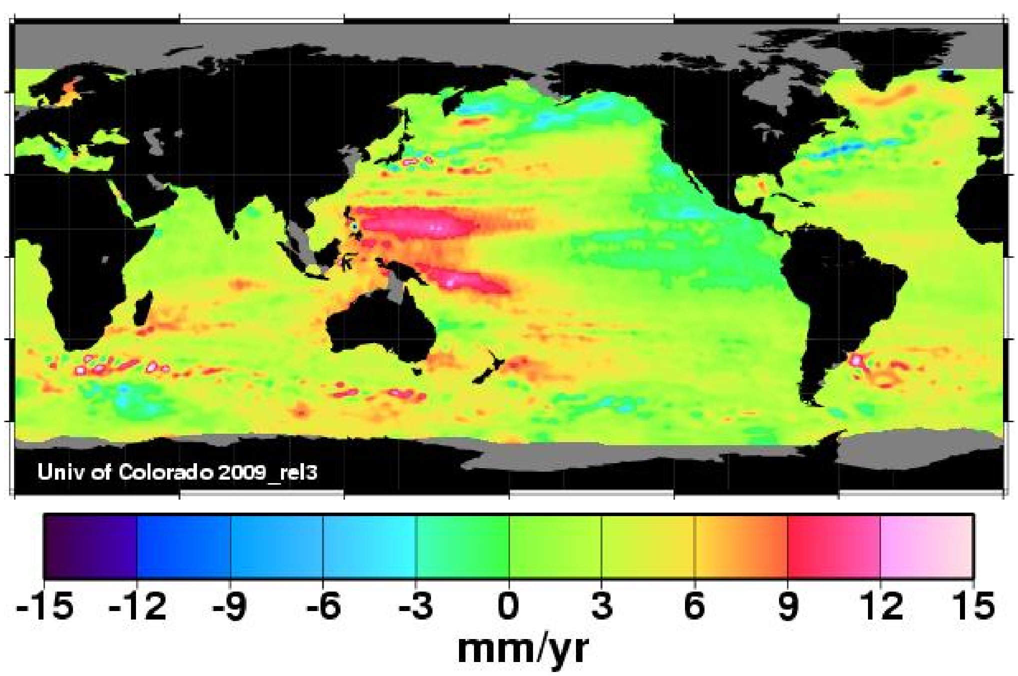


Figure 18. Global distribution of sea level trend (mm/yr) derived from Topex/Poseidon and Jason-1 satellite altimeter measurements from Dec 1992 to July 2009 and corrected for the inverse barometric pressure effect. (Figure courtesy of University of Colorado)

5. SEAFRAME INSTRUMENT PERFORMANCE

During the period July 2008 to June 2009, the following instrumentation problems were encountered and corrective actions undertaken:

- Calibration and maintenance visits were undertaken at Fiji (October 2008), Tuvalu (October 2008), Vanuatu (February 2009), PNG (March 2009), Solomon Islands (March 2009) and Nauru (June 2009).

- At Vanuatu the primary acoustic sea level sensor suffered damage from a forklift operating on the wharf on 28th January 2009, but was fixed during the calibration and maintenance visit in February 2009.

- At PNG a power supply problem caused a loss of data from 15th-30th March 2009. The problem was resolved during the calibration and maintenance visit.

- The air temperature sensors at Tuvalu and Nauru continued to experience problems but were replaced during the calibration and maintenance visits in October 2008 and June 2009 respectively.

- At Marshall Islands problems with the electronic circuit connecting the air temperature, water temperature and barometric pressure sensors developed and the resulting intermittent erroneous readings were removed from the record.

- Intermittent problems with dial-up communications were experienced at Nauru, Kiribati, Solomon Islands, Marshall Islands, Tuvalu, and PNG that resulted in some small data gaps where data was unable to be recovered.

6. COMMUNICATION OF RESULTS

Figure 19 shows the number of times the SPSLCMP pages on the Bureau of Meteorology website have been visited, by month since January 2006.

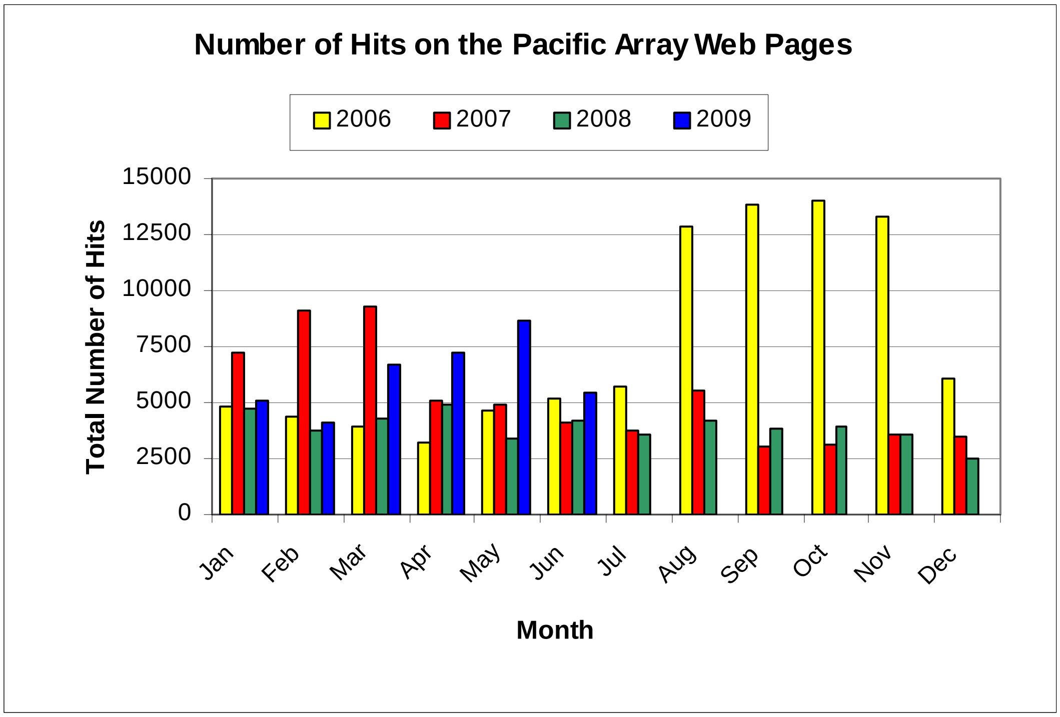


Figure 19. Number of Hits on the NTC South Pacific Array Web Page.

7. FURTHER INFORMATION

Further information on the South Pacific Sea Level and Climate Monitoring Project is available at the project website:

http://www.bom.gov.au/pacificsealevel/

Information relating specifically to the sea level monitoring program can be obtained from:

National Tidal Centre
Australian Bureau of Meteorology
PO Box 421
Kent Town SA 5067
Tel: (+618) 8366 2730
Fax: (+618) 8366 2651
Email: ntc@bom.gov.au
Website: http://www.bom.gov.au/oceanography/