THE AUSTRALIAN BASELINE SEA LEVEL MONITORING PROJECT

ANNUAL SEA LEVEL DATA SUMMARY REPORT

JULY 2010 - JUNE 2011

This report was prepared under the Australian Climate Change Science Program for the Department of Climate Change and Energy Efficiency, supported by the National Tidal Centre, Bureau of Meteorology.

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Quality Certification:

I authorise the issue of this Australian Baseline Sea Level Monitoring Project Annual Sea Level Data Summary Report for July 2010 - June 2011 in accordance with the quality assurance procedures of the National Tidal Centre, Australian Bureau of Meteorology.

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Manager,
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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 sea level data reports for the Australian Baseline Sea Level Monitoring Project (ABSLMP) to June 2011, with a particular focus on the recent twelve month period from July 2010 – June 2011 (2010/11). This report, the monthly sea level data reports and the quality-controlled data are available in electronic form from the Bureau of Meteorology website at:
http://www.bom.gov.au/oceanography/projects/abslmp/abslmp.shtml.

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

The main findings during the July 2010 – June 2011 period include:

- The sea level monitoring network has performed well following its refurbishment in 2009-10 with modernised data loggers and improvements to occupational health and safety.
- The station at Port Stanvac was removed in December 2010 to allow ExxonMobil to decommission the Port Stanvac oil refinery.
- Three tsunami events were observed by the Australian Baseline sea level monitoring network during the July 2010 to June 2011 period, including the tsunami that devastated Japan following a magnitude Mw9.0 earthquake.
- One of the strongest La Niña events on record occurred in 2010/11, driven by cooler than normal ocean temperatures across the central equatorial Pacific and stronger than normal Trade Winds. Higher than normal sea levels were observed around much of the Australian coastline and rainfall across eastern Australia was particularly high causing extreme flooding.
- Although the length of record from Baseline stations is relatively short in climate terms there are a number of clear results emerging. The sea level records for all stations, when corrected for local land movement and changes in atmospheric pressure, demonstrate a regional pattern of sea level trends that is consistent with sea level changes detected by satellite-based altimeters.
- The largest sea level trends over the duration of the project have been observed in the northern and western Australian region.
- The quality-controlled observations collected by the Australian Baseline stations continue to be used for research into sea level, climate variations and climate change, while real-time data streams allow for the monitoring of tsunamis, storm surges and under-keel clearances at ports.
- It remains the aim of the project that the high-quality sea level observations will provide an accurate means of long-term sea level monitoring, especially as the length of record increases.

Sea level monitoring station at Portland.

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1. BACKGROUND

The management and operational support of the Australian Baseline Sea Level Monitoring Project (ABSLMP) was, up until the end of June 2011, partly funded by a grant under the Australian Climate Change Science Program for the Department of Climate Change and Energy Efficiency. The Baseline sea level network is designed to monitor sea level and climate around the coastline of Australia. The primary goal is to identify long period sea level changes, with particular emphasis on the enhanced greenhouse effect sea level signal. In addition, the Baseline array underpins the advanced technologies gathering global observations for climate change research. The in-situ sea level observations from tide gauges are essential for calibrating satellite altimeters and for understanding coastal impacts that are not adequately sampled from space.

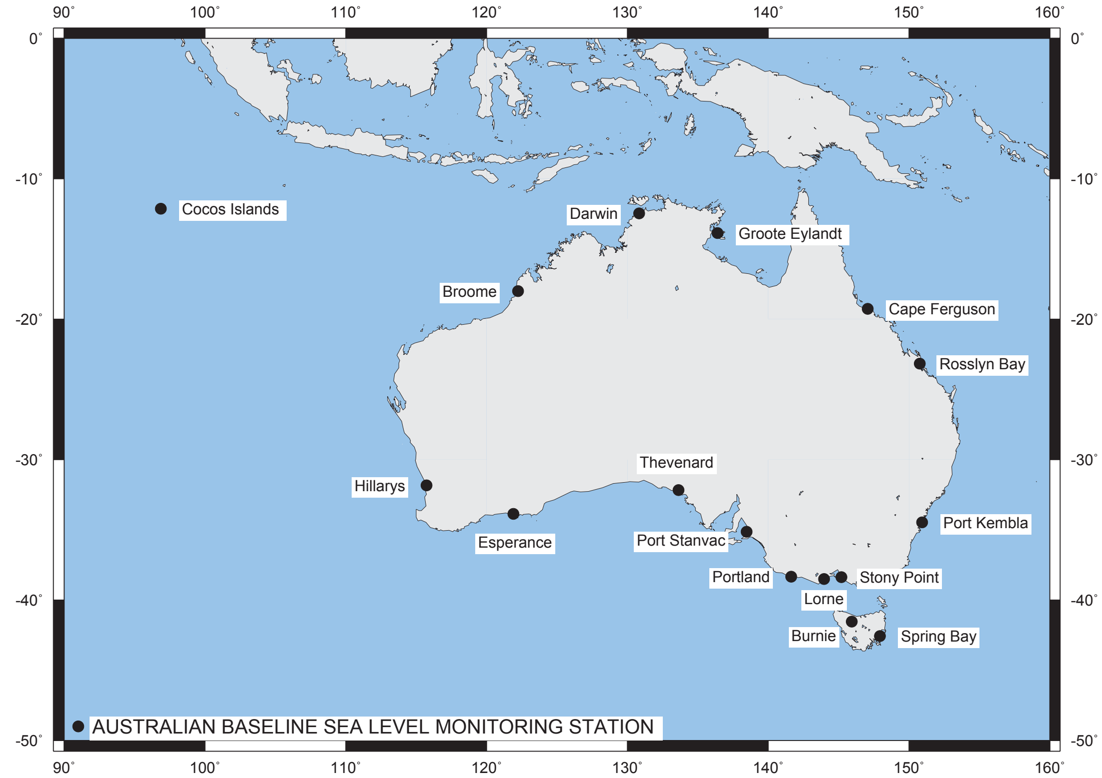
Long term sea level trends and their projected acceleration are a focus of the Intergovernmental Panel on Climate Change (IPCC) as a primary indicator of climate variation and change. Accelerated sea level rise would be deemed to be a consequence of an enhanced Greenhouse Effect, due to the increased emission of Greenhouse gases as a result of industrialisation and other anthropogenic effects. The IPCC Scientific Assessment predicts that the rate of sea level rise will increase over the next century. More information on the IPCC can be found at http://www.ipcc.ch/.

The project involves maintenance of an array of SEAFRAME (SEA-level Fine Resolution Acoustic Measuring Equipment) stations, which measure sea level very accurately, and also record meteorological parameters. The array consists of fourteen standard stations supported by the National Tidal Centre (NTC) as well as two customised stations supported by the private sector; Lorne by the Port of Melbourne Corporation and Stony Point by Port of Hastings Corporation. The installation of three of the standard stations (Darwin, Spring Bay and Cocos Islands) was supported by the National Oceanographic and Atmospheric Administration /National Ocean Service of the United States. The Division of Marine Research, CSIRO and the TOPEX/POSEIDON satellite altimetry experiment supported the installation of the gauge at Burnie.

The NTC is responsible for maintaining the Australian Baseline sea level monitoring network and data analysis activities as part of its operations. More information on the NTC and its functions can be found at http://www.bom.gov.au/oceanography/.

2. SEA LEVEL MONITORING NETWORK

The sea level monitoring network consists of 14 standard SEAFRAME stations at representative sites around the Australian coastline, as well as 2 customised stations at Lorne and Stony Point (Figure 1 and Table 1). The SEAFRAME at Port Stanvac was removed in December 2010 to allow Mobil Refining Australia to decommission the oil refinery. Re-establishment of the SEAFRAME station at Port Stanvac is a priority but is dependent on decisions relating to the future of the wharf.



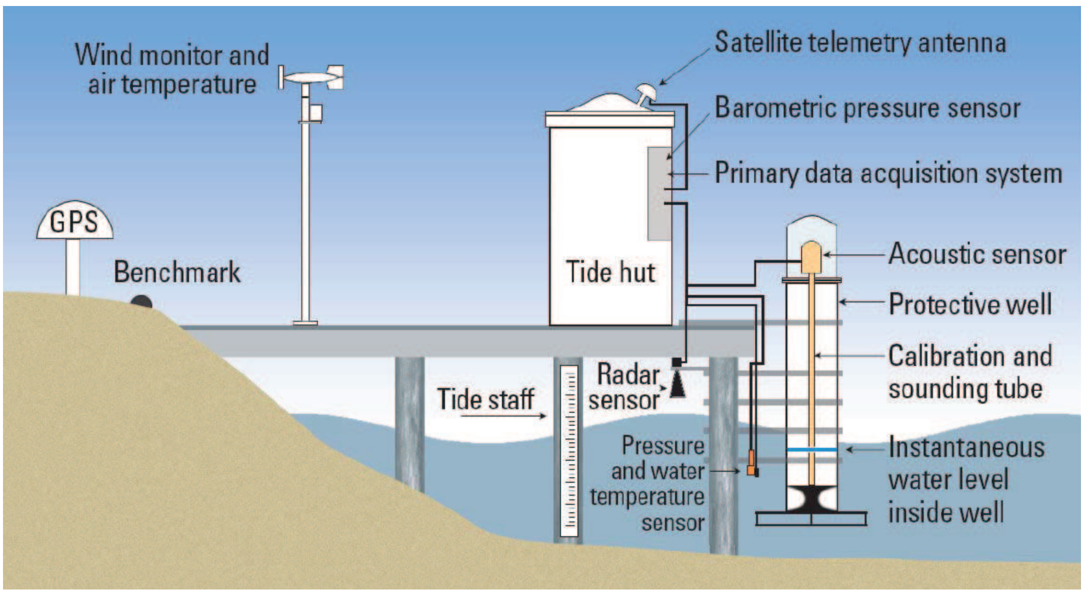


Figure 1. Australian Baseline Sea Level Monitoring Project sites (top) where SEAFRAME stations (bottom) are installed.

SEAFRAME gauges 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 contribute to the research and analysis efforts of the Centre for Australian Weather and Climate Research (CAWCR) and the Bureau's National Climate Centre to investigate and monitor regional climatic and oceanographic conditions. Sea level research is also performed through cooperation between CSIRO's Wealth from Oceans National Research Flagship and the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC) and presented at http://www.cmar.csiro.au/sealevel/index.html. Real time and operational users of the data include local port operators, the BLUElink - Ocean Forecasting Australia project through partnership between the Bureau, CSIRO and the Australian Navy, as well as the Joint Australian Tsunami Warning Centre and other international tsunami warning agencies. Sea level data is submitted to international sea level data centres such as the University of Hawaii Sea Level Centre and the Permanent Service for Mean Sea Level. The SEAFRAME stations also contribute to the Global Sea Level Observing System (GLOSS) under the auspices of the World Meteorological Organisation (WMO) and Intergovernmental Oceanographic Commission (IOC).

Through its membership of the Intergovernmental Committee on Surveying and Mapping (ICSM) Permanent Committee on Tides & Mean Sea Level (PCTMSL), NTC and Geosciences Australia strive to sustain a geodetic levelling program supported by the state surveying organisations. Periodic surveys at each SEAFRAME site are necessary to relate the gauge to a nearby array of deep benchmarks and monitor any vertical movements of the instrumentation.

Station	Latitude	Longitude	Installation Date
Cocos Islands	12° 07' 0.1" S	96° 53' 30.9" E	Sep 1992
Groote Eylandt	13° 51' 36.2" S	136° 24' 56.1" E	Sep 1993
Darwin	12° 28' 18.4" S	130° 50' 45.1" E	May 1990
Broome	18° 00' 03.0" S	122° 13' 07.1" E	Nov 1991
Hillarys	31° 49' 32.0" S	115° 44' 18.9" E	Nov 1991
Esperance	33° 52' 15.2" S	121° 53' 43.3" E	Mar 1992
Thevenard	32° 08' 56.2" S	133° 38' 28.8" E	Mar 1992
Port Stanvac	35° 06' 31.0" S	138° 28' 1.3" E	Jun 1992
Portland	38° 20' 36.4" S	141° 36' 47.4" E	Jul 1991
Lorne	38° 32' 49.4" S	143° 59' 19.8" E	Jan 1993
Stony Point	38° 22' 19.7" S	145° 13' 28.9" E	Jan 1993
Burnie	41° 03' 0.3" S	145° 54' 54.0" E	Sep 1992
Spring Bay	42° 32' 45.1" S	147° 55' 57.8" E	May 1991
Port Kembla	34° 28' 25.5" S	150° 54' 42.7" E	Jul 1991
Rosslyn Bay	23° 09' 39.7" S	150° 47' 24.6" E	Jun 1992
Cape Ferguson	19° 16' 38.4" S	147° 03' 30.4" E	Sep 1991

Table 1. Locations and installation dates for the Australian Baseline sea level array.

3. CLIMATIC AND OCEANOGRAPHIC CONDITIONS

Sea level is affected by a combination of tidal, weather, climate and oceanographic conditions as well as geodynamic processes. These effects are described in more detail below, including a summary of the present conditions.

3.1. Extreme Events

Extreme sea levels arise when reinforcing combinations of tides, short-term weather effects, tsunamis or climate conditions occur. Abnormally high sea levels can cause flooding, coastal erosion and property damage. Abnormally low sea levels can be hazardous for navigation and reduce under-keel clearances for shipping operations in ports.

Tsunamis are long waves caused by seismic disturbances that can result in extremely high (or low) sea levels if their arrival coincides with a high (or low) tide. Storm surges refer to periods of elevated sea levels lasting several hours to several days as a result of wind and wave activity and low barometric pressure. Conversely, high barometric pressure and strong offshore winds can produce depressed sea levels. Over longer periods, sea levels along the coast are influenced by sea surface gradients spun-up by wind driven surface currents or depth-integrated geostrophic flow. The frequency and intensity of extreme events are modulated by climate variability. Australia typically experiences more tropical cyclones during La Niña episodes for example. Rising sea levels will reduce the average return interval of dangerously high sea levels.

A useful datum to distinguish abnormally high sea levels is the *Highest Astronomical Tide* (HAT), the highest level that can be predicted to occur under any combination of astronomical conditions. Likewise the *Lowest Astronomical Tide* (LAT) is the lowest level that can be predicted under any combination of astronomical conditions. To properly determine HAT and LAT tidal predictions must span at least 18.6 years, which is the period of a full rotation of the moon's orbital plane about the ecliptic.

The monthly maximum sea levels recorded above HAT and the monthly minimum sea levels that fall below LAT at SEAFRAME stations (Figure 2 and Figure 3) illustrate occurrences of extreme high or low sea levels over the duration of the project. Extreme sea levels are observed more frequently along the southern Australian coastline from Hillarys to Port Kembla due to regular low-pressure systems tracking across the Southern Ocean. Elevated sea levels, which are more prominent during winter months, can often be tracked from one station to the next moving as a coastally trapped wave around the southern Australian coastline. Along the northern Australian coastline the occurrence of atmospheric and oceanographic conditions conducive to extremely high (or low) sea levels is less common. Nevertheless when such conditions arise the effects can be dramatic, such as was observed at Groote Eylandt in February 2001 when sea levels reached 1.3 m above HAT at the time of Tropical Cyclone Winsome.

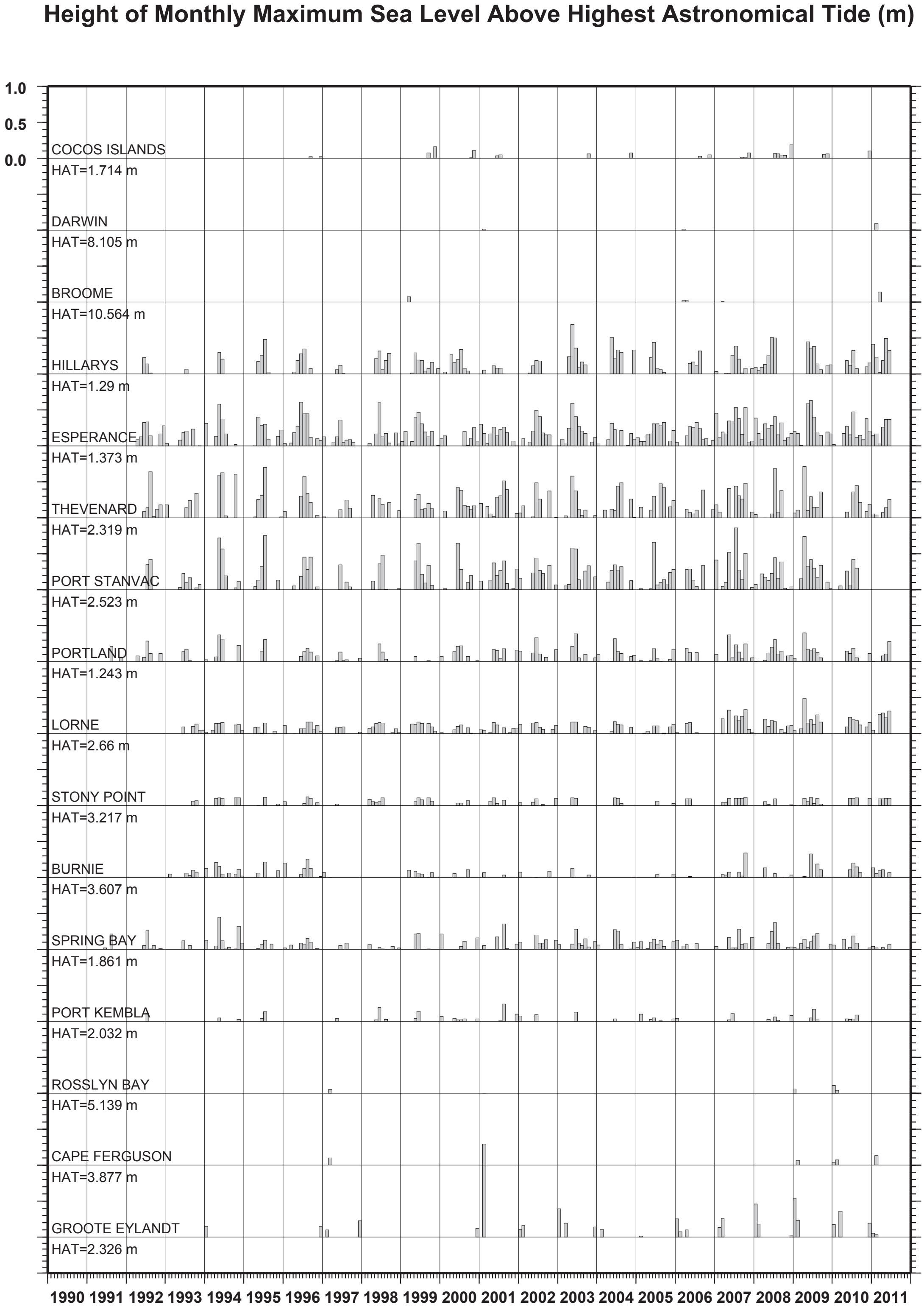


Figure 2. Monthly maximum sea levels at SEAFRAME stations that have exceeded the Highest Astronomical Tide (HAT).

Height of Monthly Minimum Sea Level Below Lowest Astronomical Tide (m)

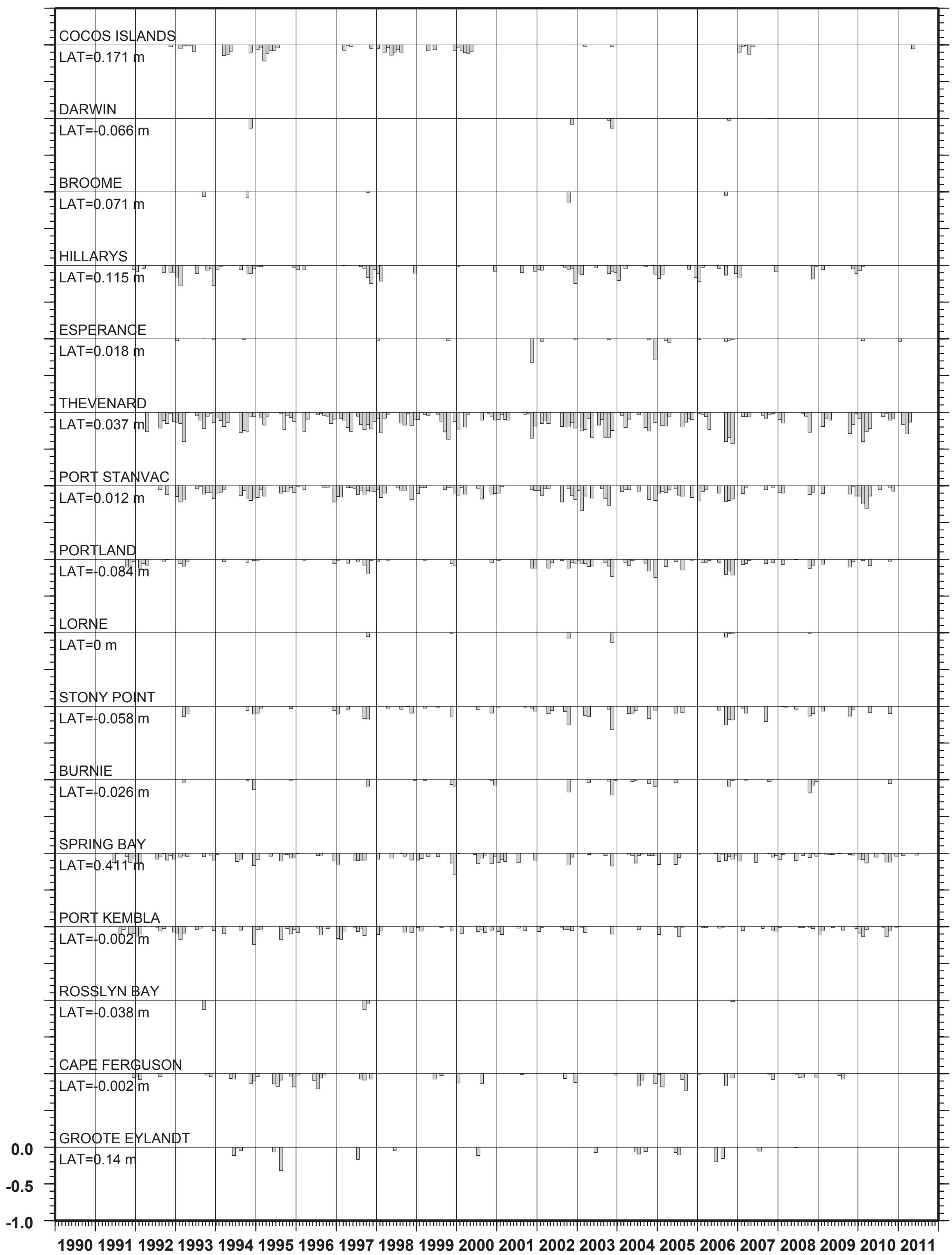
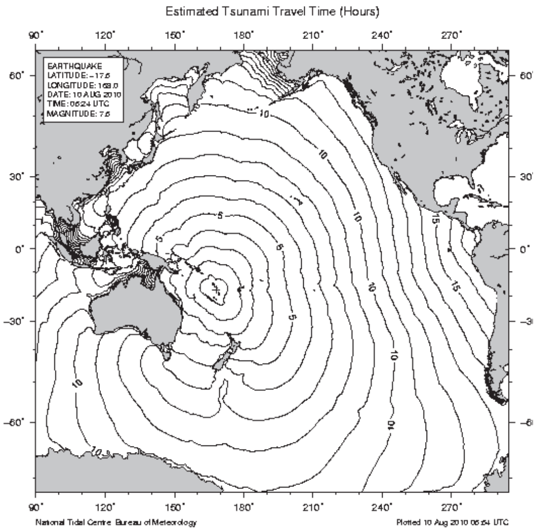


Figure 3. Monthly minimum sea levels at SEAFRAME stations that have fallen below the Lowest Astronomical Tide (LAT).

3.1.1. Tsunamis

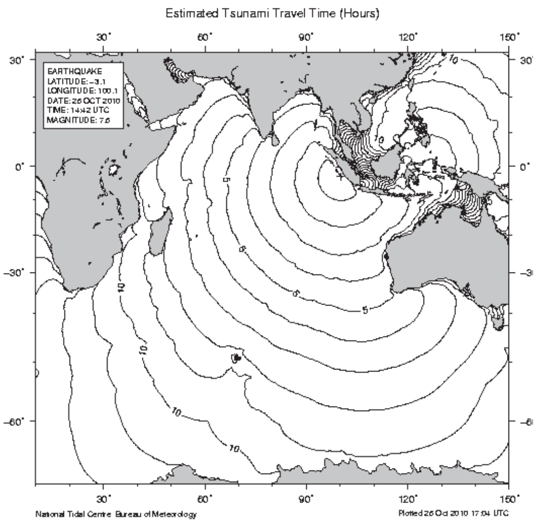
The SEAFRAME stations established under the project are also an integral part of sea level monitoring networks associated with Australian and international tsunami programs such as the Australian Tsunami Warning System (ATWS), the Pacific Tsunami Warning System and the proposed tsunami warning system for the Indian Ocean. Further information about these programs may be found at
http://www.bom.gov.au/tsunami/index.shtml
http://www.ioc-tsunami.org/

Tsunamis are observed on average every 1 to 2 years in Australia. The following three tsunami events were observed by the Australian Baseline SEAFRAME network during the July 2010 to June 2011 period.



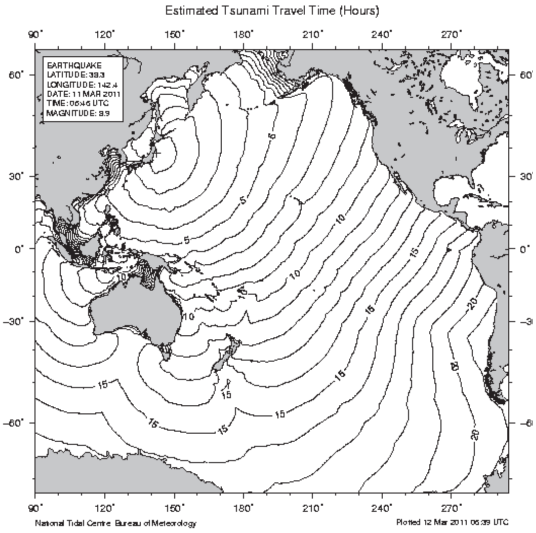
Vanuatu 10 August 2010 (Mw7.3)

A magnitude Mw7.3 earthquake struck at 05:24 UTC on 10 August 2010 near Vanuatu. It produced a tsunami which measured 0.25m from trough to crest at the Australian Baseline sea level station at Rosslyn Bay and less than 0.1m at Cape Ferguson. The SEAFRAME station at Port Vila, Vanuatu recorded a 0.5m tsunami.



Indonesia 25 October 2010 (Mw7.7)

On 25 October 2010 an earthquake of magnitude Mw7.7 occurred at 14:42 UTC in the vicinity of the Mentawai Islands off Sumatra, Indonesia generating a tsunami that was detected by the Australian Baseline sea level stations at Cocos Islands, where the trough-to-crest tsunami height was 0.3m, and Hillarys where the tsunami was 0.1m.

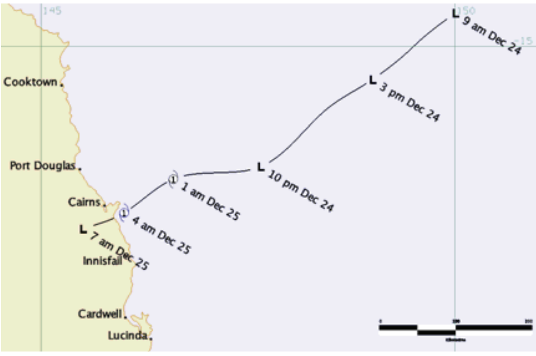


Japan 11 March 2011 (Mw9.0)

On 11 March 2011 at 05:46 UTC a very large earthquake of magnitude Mw9.0 struck off the east coast of Japan. The large tsunami which followed inundated the Japanese coastline and caused severe destruction and loss of life. The tsunami propagated across the entire Pacific Ocean and was recorded by the Australian Baseline sea level stations at Cape Ferguson (0.2m from trough to crest), Rosslyn Bay (0.4m), Port Kembla (0.6m), Spring Bay (0.6m), Burnie (0.2m) and Portland (0.2m). Evidence of the tsunami was also detected at Stony Point and Lorne.

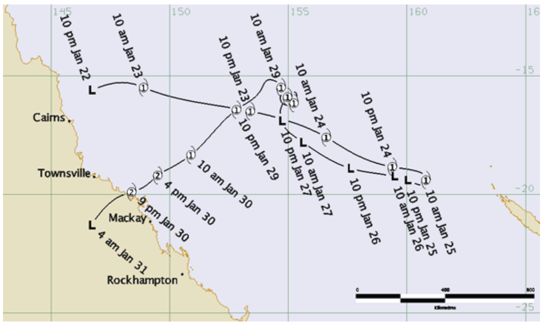
3.1.2. Tropical Cyclones

Five tropical cyclones made or came near to landfall on the Australian coastline during the 2010/2011 season. These were Tropical Cyclone *Tasha* (25 Dec 2010), Tropical Cyclone *Anthony* (22-31 Jan 2011), Tropical Cyclone *Bianca* (26-29 Jan 2011), Tropical Cyclone *Yasi* (30 Jan – 3 Feb 2011) and Tropical Cyclone *Carlos* (21-25 Feb 2011). Further information about these and other tropical cyclones is available from the Bureau's website at http://www.bom.gov.au/cyclone/. The tracks of the cyclones and their intensity are shown below, alongside a description of the observed effects at the Australian Baseline SEAFRAME stations.



Tropical Cyclone *Tasha*
25 Dec 2010 (Category 1)

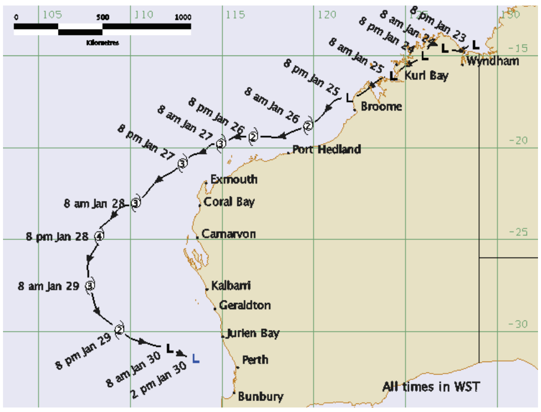
Cape Ferguson: Sea level surged to 0.4m above the predicted astronomical tide on 25 December.



Tropical Cyclone *Anthony*
22-31 Jan 2011 (Category 2)

Cape Ferguson: Wind gusts to 15 m/s (55 km/h) on 30 January.

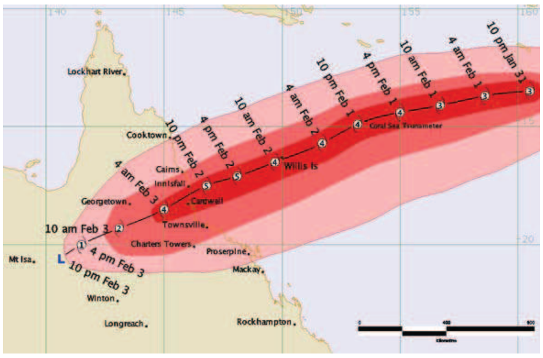
Rosslyn Bay: Wind gusts to 15 m/s (55 km/h) on 30 January.



Tropical Cyclone *Bianca*
26 - 29 Jan 2011 (Category 3)

Broome: No notable effects recorded by the SEAFRAME station.

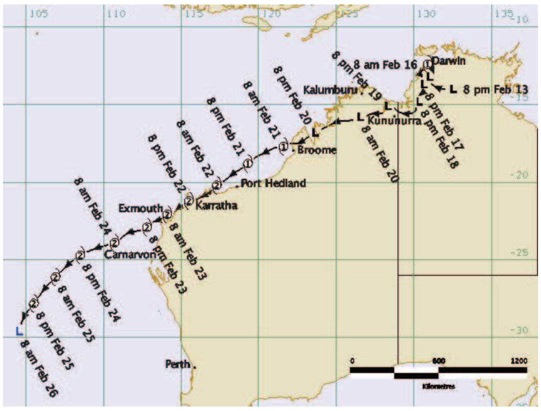
Hillarys: Sea level surged to 0.6m above the predicted astronomical tide on 30 January.



Tropical Cyclone *Yasi*
30 Jan – 3 Feb 2011 (Category 5)

Cape Ferguson: Sea levels surged to 2.0m above the predicted astronomical tide and wind gusts reached 38 m/s (140 km/h) on 2 February.

Rosslyn Bay: No notable effects recorded by the SEAFRAME station.



Tropical Cyclone *Carlos*
21-25 Feb 2011 (Category 2)

Darwin: Sea levels surged to 0.9m above the predicted astronomical tide and wind gusts reached 25m/s (90 km/h) on 15 February.

Broome: No notable storm surge. The wind monitor was not operational at the time.

3.2. Climate Variability

Variations in sea level and climate are inextricably linked, with both undergoing interrelated seasonal, interannual and interdecadal fluctuations. Fluctuations associated with natural phenomena such as the El Niño – Southern Oscillation can be large and cause significant social and economic impacts. The presence of these low frequency variations can mask the underlying long-term trend in sea level records that are less than three decades in length.

3.2.1. El Niño – Southern Oscillation (ENSO)

The El Niño – Southern Oscillation (ENSO) refers to the periodic change (between four to seven years) in atmospheric and oceanic patterns in the tropical Pacific Ocean.

During neutral conditions (middle panel of Figure 4) easterly trade winds blow across the tropical Pacific and the sea surface is about 50 cm higher and 8°C warmer in the far-western Pacific adjacent to Indonesia than in the eastern Pacific adjacent to South America. 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 4), the trade winds relax in the central and western Pacific resulting in an eastward shift of the circulation over the tropical Pacific. Lower than normal sea levels and cooler than normal sea surface temperatures are experienced in the far-western Pacific, while higher than normal sea levels and warmer than normal sea surface temperatures are experienced in the central and eastern equatorial Pacific. Impacts during El Niño 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 4). 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.

ENSO conditions July 2010 – June 2011

One of the strongest La Niña events on record occurred during the July 2010 – June 2011 period, as indicated by sustained positive values of the Southern Oscillation Index (Figure 5). Climate conditions across the central equatorial Pacific during the La Niña included cooler than average sea surface temperatures, stronger than normal Trade Winds and below average cloudiness in the vicinity of the dateline. By contrast La Niña conditions in the Australian region featured warmer than normal ocean temperatures, higher than average rainfall in the north and east and higher than normal sea levels.

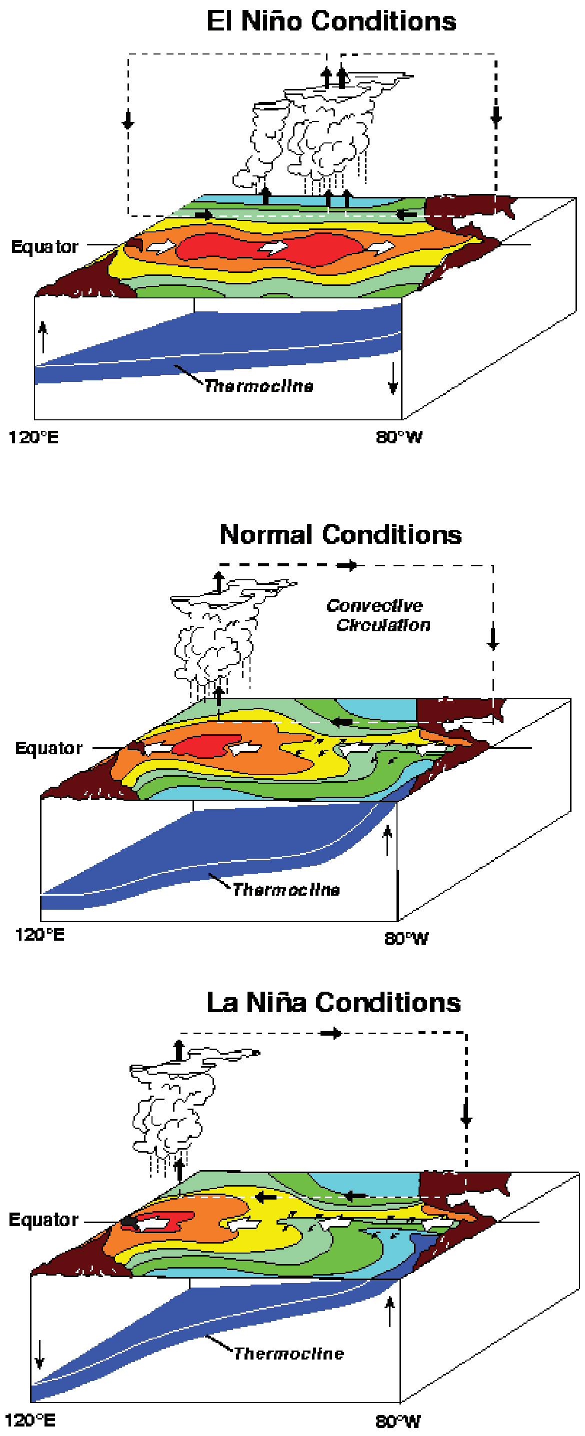


Figure 4. Schematic of atmospheric and ocean conditions associated with El Niño and La Nina.

Signs of an emerging La Niña became evident in June 2010 as a result of ongoing cooling of ocean temperatures across the equatorial Pacific from earlier in the year. The early stages of a La Niña event was recognised in July 2010, and conditions continued to strengthen and reached a peak in early January 2011. The La Niña contributed to 2010 being Australia's third wettest year on record and Queensland having its wettest December on record. The high rainfall caused extreme flooding across eastern Australia. Sea levels around much of Australia were higher than normal, in association with warmer than normal ocean temperatures and lower than normal barometric pressure around Australia.

The La Niña began to decay in February 2011 as Pacific Ocean temperatures, especially below the surface, began to warm. Atmospheric indicators, such as high values of the Southern Oscillation Index and stronger than normal Trade Winds remained consistent with a well developed La Niña through March and April but eventually responded to the changes in the ocean. The La Niña reached its end in late May as climate conditions across the equatorial Pacific returned to neutral. Neutral climate conditions continued to be observed at the end of June 2011 and were expected to persist through into the southern hemisphere spring.

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

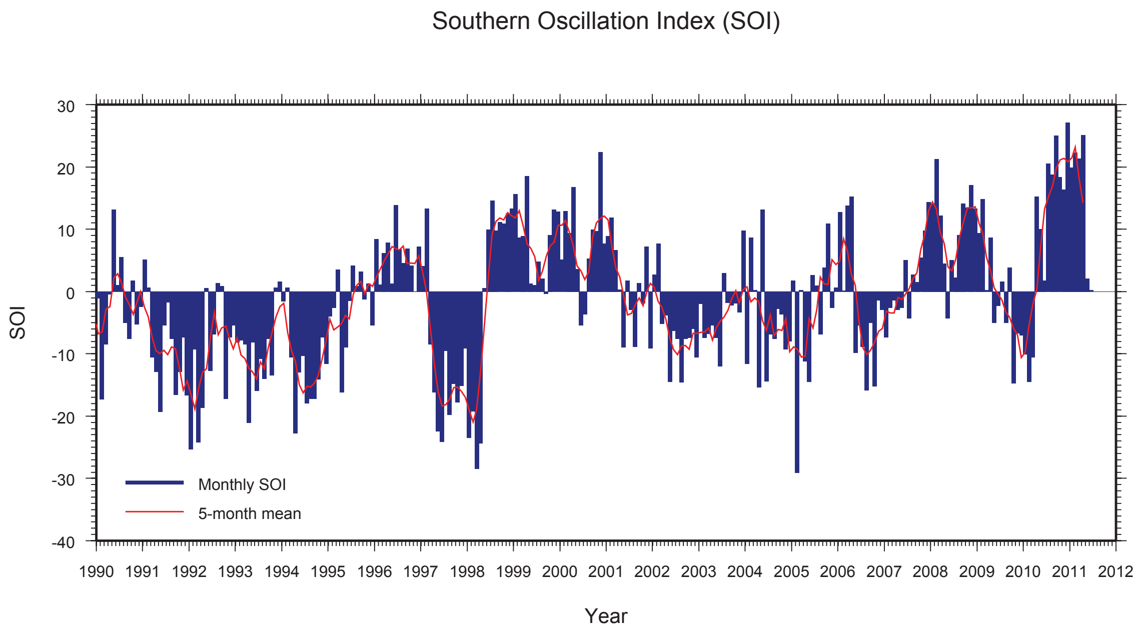


Figure 5. Southern Oscillation Index

3.2.2. Inter-decadal variability

Sea level and climate can fluctuate about a long-term climatological mean from one decade to the next. The project to date is only just beginning to span two complete decades, so it is important to recognise that the sea level change observed over this time is largely a measure of decadal *variability*. Continued monitoring is needed to quantify the longer-term trend that is associated with climate *change*.

An example of inter-decadal variability is evidence of a Pacific Decadal Oscillation (PDO), which some scientists believe is a fluctuation of the Pacific Ocean that has similarities to El Niño, but operates over a much longer time period of 20 – 30 years. During the negative phase of the PDO, the eastern equatorial Pacific experiences lower than normal ocean temperatures and lower than normal sea level while a pattern of higher than normal ocean temperatures and higher than normal sea level connects the north, west and south Pacific. During the positive phase, this situation is reversed (Figure 6). In order to track the PDO over time scientists have used temperature data to construct a PDO Index, shown plotted in Figure 7, which illustrates how climate, and hence sea level, can fluctuate across the Pacific on decadal timescales.

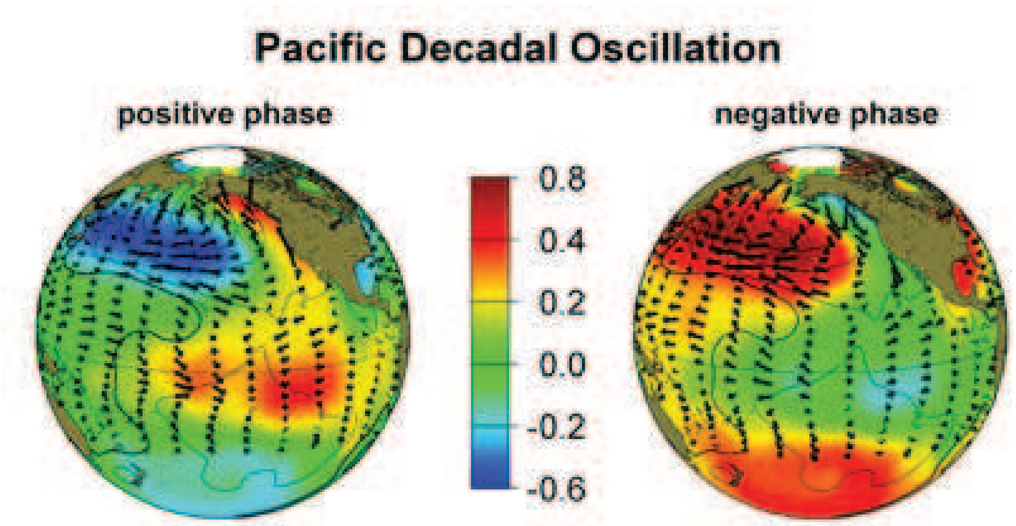


Figure 6. Schematic of sea surface temperature (°C) and wind stress anomalies during positive and negative phases of the Pacific Decadal Oscillation. Figure courtesy of University of Washington.

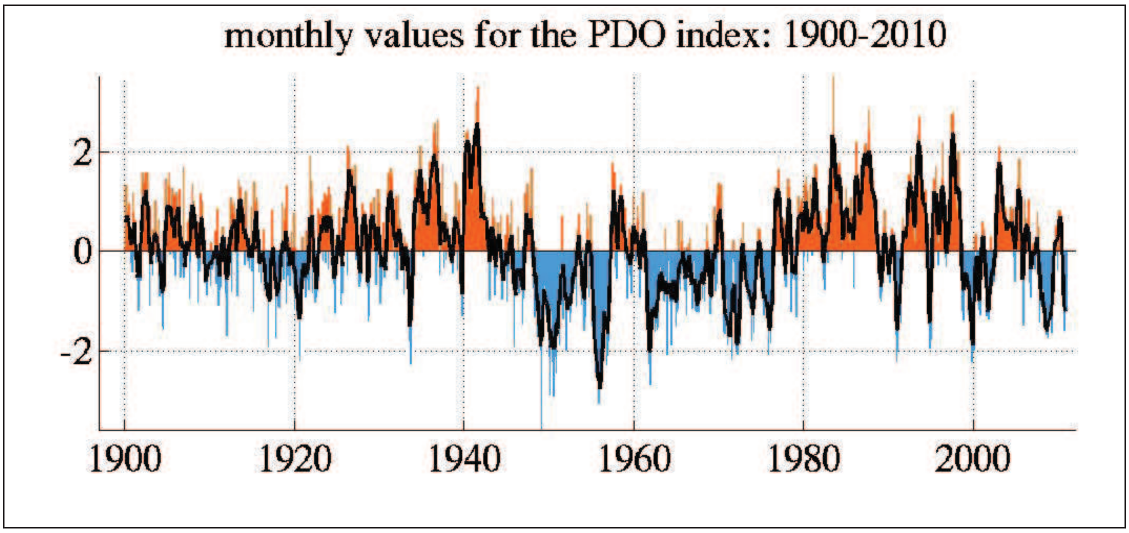


Figure 7. Monthly values for the Pacific Decadal Oscillation Index: 1900-2010. Figure courtesy of University of Washington.

3.3. 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 absolute sea level changes 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 effect 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.

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. 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 (as detected by satellite altimeters for example) 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 Australian Baseline sea level stations will help address these issues in the 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.

Further information regarding sea level rise is available from the following agencies
CSIRO: http://www.cmar.csiro.au/sealevel/index.html
IPCC: http://www.ipcc.ch/

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

4. SEAFRAME DATA ANALYSIS

4.1. Monthly mean sea levels

The monthly mean sea levels at the SEAFRAME stations (Figure 8) undergo climate-related changes such as seasonal and annual cycles, transient events such as the effects of El Niño and La Niña as well as decadal fluctuations. Underpinning these fluctuations is longer-term relative sea level rise. The annual sea level cycle is the most apparent feature and ranges from around 15 cm at Burnie up to 60 cm at Groote Eylandt. One effect of the 1997/98 El Niño was to disrupt the normal annual sea level cycle at many of the stations.

Over the past year record-high monthly mean sea levels were observed at Darwin in January 2011 and again in February 2011, Hillarys in February 2011, Rosslyn Bay in December 2010, January 2011 and again in February 2011 and Cape Ferguson in January 2011 and again in February 2011. These record-high monthly sea levels were, in part, a result of higher than normal sea levels that accompanied the recent 2010/11 La Niña.

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

Sea level anomalies are calculated by removing the predicted tides, seasonal cycles and linear trend. The sea level anomalies at the SEAFRAME stations (Figure 9) highlight irregular events such as lower than normal sea levels during the 1997/98 El Niño and higher than normal sea levels that followed during the subsequent La Niña.

The sea level anomalies around Australia generally follow the Southern Oscillation Index (SOI). High sea levels tend to coincide with high values of the SOI (La Niña) and low sea level coincides with low values of the SOI (El Niño). It follows that the El Niño - Southern Oscillation cycle is a major influence on sea levels around Australia.

In 2010/11 sea levels around Australia were predominantly higher than normal as a result of ocean and climate conditions associated with La Niña. The sea level anomalies, like other La Niña climate indicators, peaked during the summer months when they reached 10-20cm at most sites across the northern and western half of the Australian mainland and as much as 25cm at Hillarys near Perth. The positive sea level anomalies at Hillarys, Rosslyn Bay and Cape Ferguson during the 2010/11 La Niña were the highest since the stations were installed in the early 1990’s and were a major reason why record-high monthly mean sea levels were observed at these stations. The effect of La Niña on sea levels is less pronounced at Cocos Islands and across southeastern Australia although positive sea level anomalies in the 5-10cm range were still observed in these regions at the peak of the La Niña.

4.2.2. Barometric pressure anomalies

The barometric pressure anomalies around Australia (Figure 10) are also strongly influenced by the ENSO cycle, with higher than normal pressure over Australia being a feature of the 1997/98 El Niño. There is a relationship between barometric pressure and sea level, known as the inverse barometer effect, in which sea levels typically rise (fall) by 1 cm for every 1 hPa fall (rise) in barometric pressure.

Lower than normal barometric pressures were observed across Australia during the summer months of 2010/11, when the La Niña event was at its peak. Lower than normal barometric pressure lingered into autumn across the northern half of Australia but elsewhere barometric pressure rebounded quite quickly and proceeded to fluctuate around normal levels.

4.2.3. Water temperature anomalies

The water temperature anomalies (Figure 11) are not as indicative of ENSO cycles as either sea level or barometric pressure. Local effects, such as coastal upwelling, are as influential as broad-scale regional climatic conditions. Water temperatures during the July 2010 - June 2011 period were generally warmer than normal at Cocos Islands, Hillarys and Esperance and cooler than normal conditions developed at Groote Eylandt and Broome. Warm and cool anomalies exceeding 1˚C were also observed at other stations but they did not persist for any great length of time.

4.2.4. Air temperature anomalies

The air temperature anomalies (Figure 12) are similar to the water temperature anomalies in that they show elements of regionally coherent changes due to broad scale climate conditions as well as localised variability. During 2010/11 warmer than normal air temperatures initially prevailed at Groote Eylandt, Darwin, Broome and Cape Ferguson but cooler than normal conditions subsequently developed at these and other stations. Warmer than normal conditions were observed at Hillarys for most of 2010/11 while cooler than normal conditions prevailed at Thevenard.

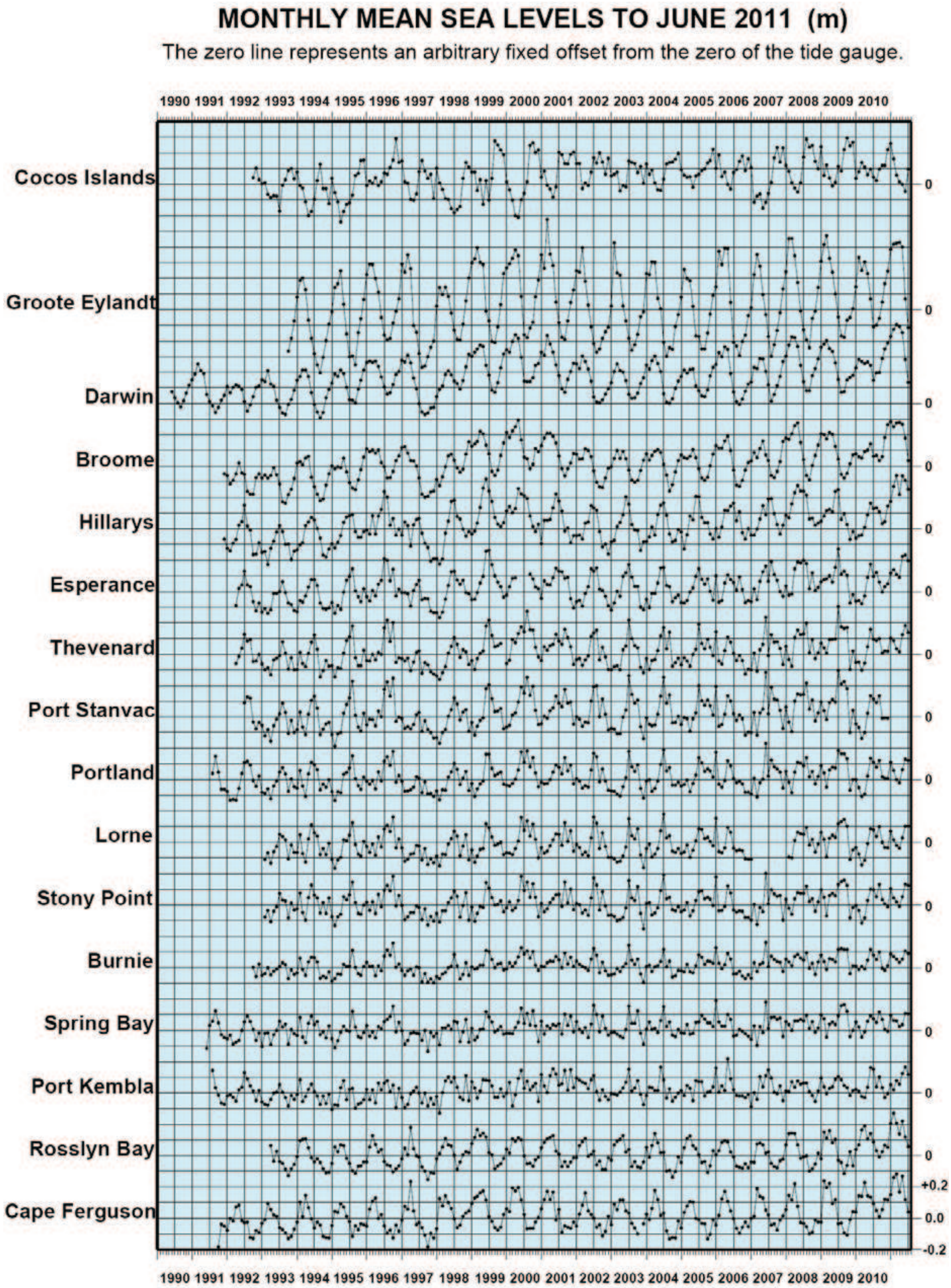


Figure 8. Monthly mean sea levels to June 2011.

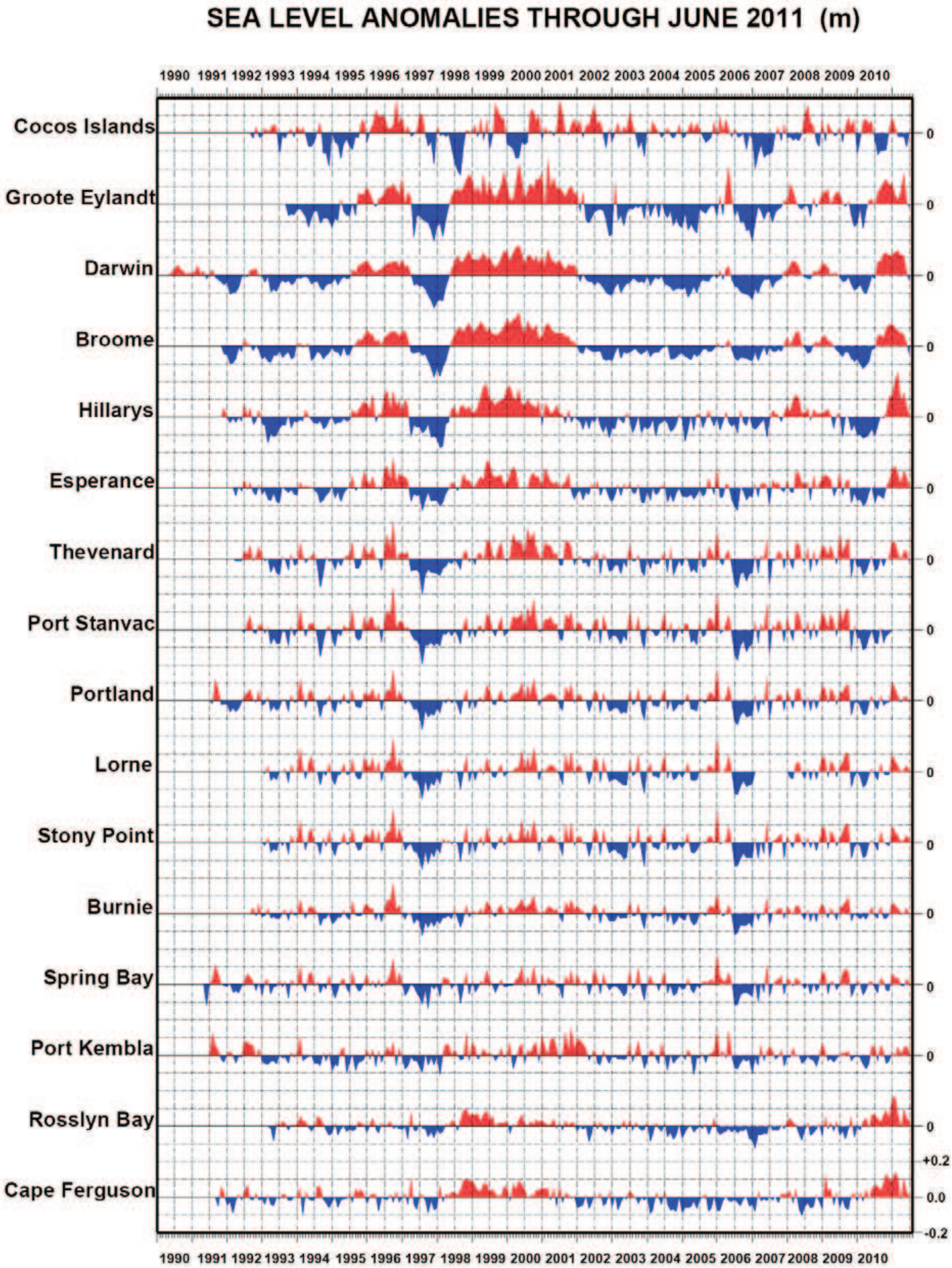


Figure 9. Sea level anomalies to June 2011.

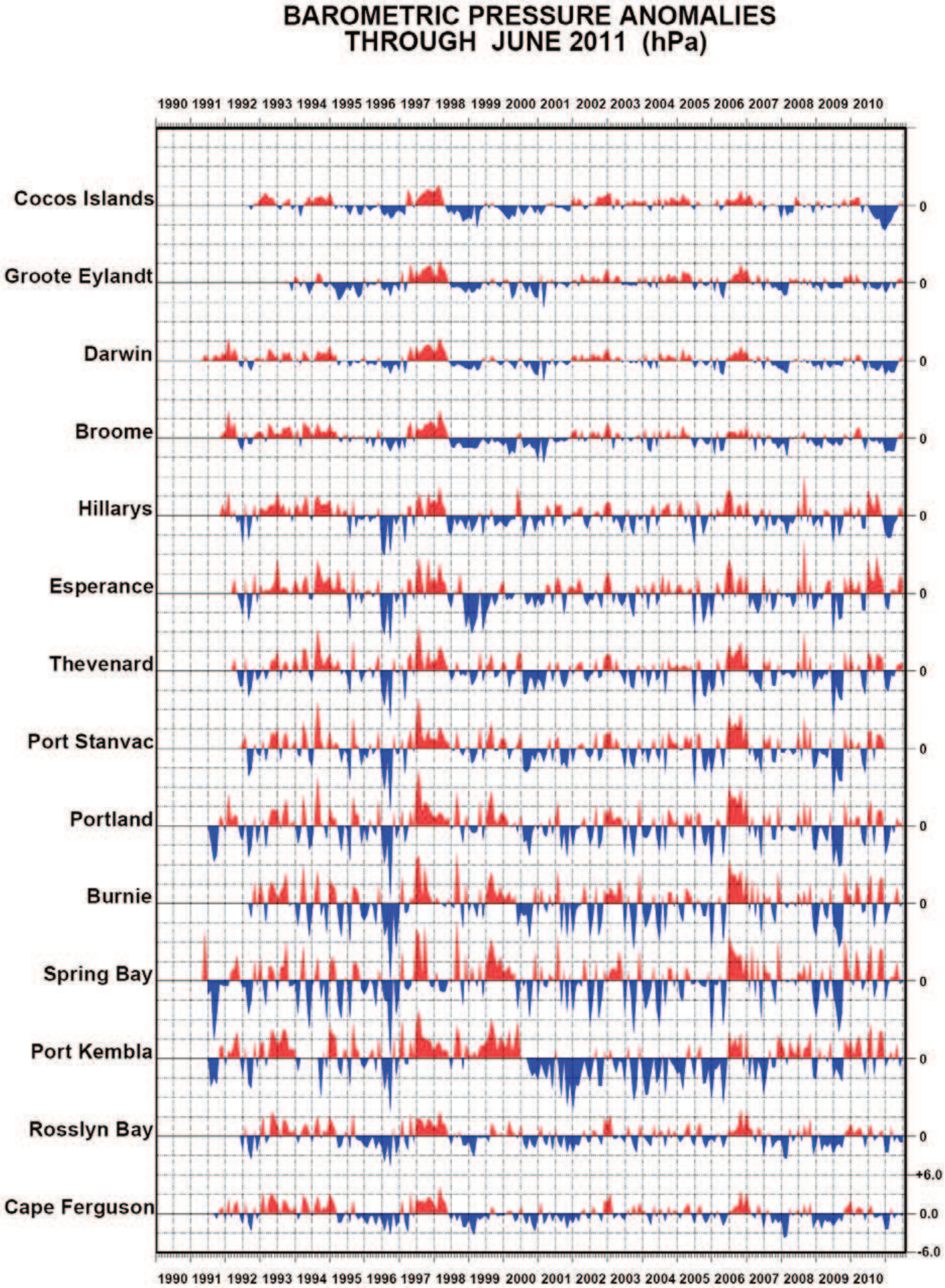


Figure 10. Barometric pressure anomalies to June 2011.

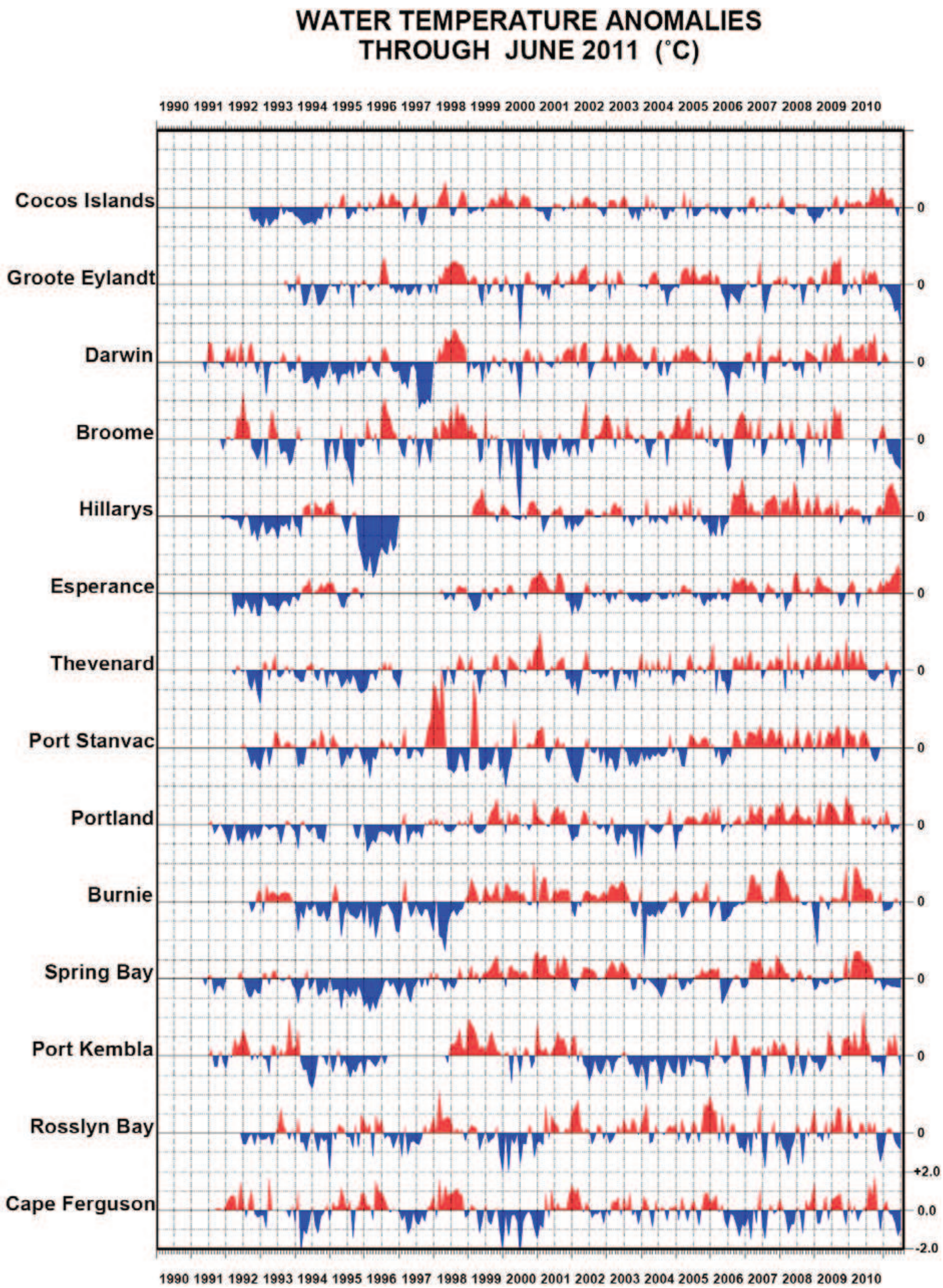


Figure 11. Water temperature anomalies to June 2011.

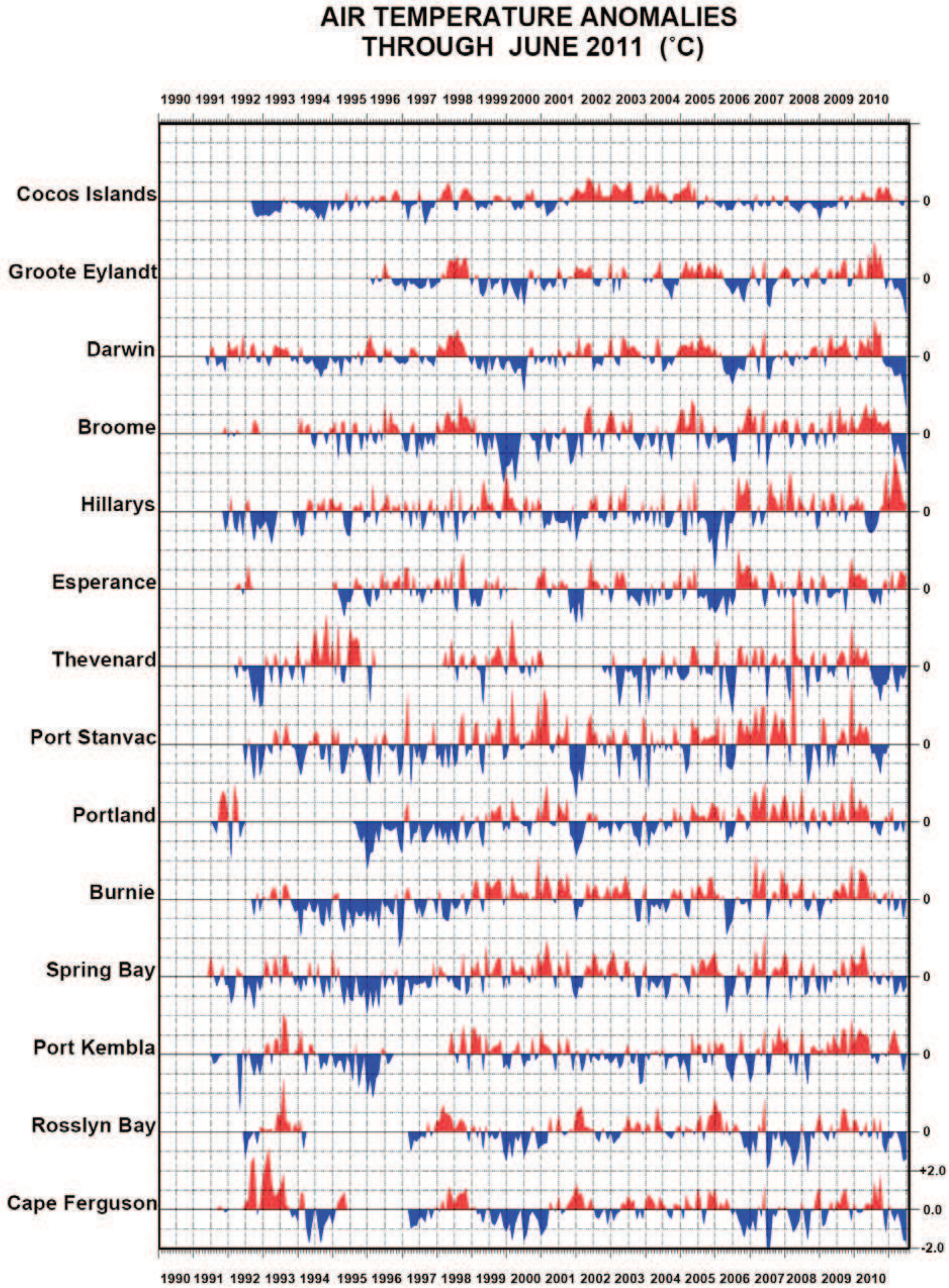


Figure 12. Air temperature anomalies to June 2011.

4.3. Sea Level Trends

4.3.1. Relative sea level trends

Sea level is influenced by natural climate *variations* such as El Niño and decadal oscillations in addition to longer-term climate *change* such as global warming. In fact over short periods of time the transient effects of climate variability are comparatively large and can conceal the slowly accumulating longer-term effects of climate change.

The vertical stability of the SEAFRAME stations also needs to be monitored. Precise levelling of the SEAFRAME to land-based benchmarks is essential for effective long-term relative sea level monitoring. Ideally, sea levels should also be referenced to an absolute frame of reference by tying the benchmark network to the International Terrestrial Reference Frame using methods such as a continuous GPS measurement program.

It is important to emphasise that as the ABSLMP sea level records increase in length, the sea level trend estimates will continue to stabilise and become more indicative of longer-term changes. Caution must be exercised in interpreting the 'short-term' relative sea level trends (Table 2) as they are based on short records in climate terms and are still undergoing large year-to-year changes.

Location	Installation Date	Sea Level Trend (mm/yr)	Change in trend from June 2010 (mm/yr)
Cocos Islands	Sep 1992	8.1	-0.6
Groote Eylandt	Sep 1993	9.0	1.9
Darwin	May 1990	8.6	1.4
Broome	Nov 1991	9.1	1.3
Hillarys	Nov 1991	9.1	1.5
Esperance	Mar 1992	6.0	0.7
Thevenard	Mar 1992	4.5	0.3
Port Stanvac*	Jun 1992	4.7	-0.3
Portland	Jul 1991	3.2	0.2
Lorne	Jan 1993	2.7	1.4
Stony Point	Jan 1993	2.6	1.3
Burnie	Sep 1992	3.1	0.2
Spring Bay	May 1991	3.5	0.1
Port Kembla	Jul 1991	3.2	0.2
Rosslyn Bay	Jun 1992	3.8	1.5
Cape Ferguson	Sep 1991	4.8	1.4

Table 2. Recent short-term relative sea level trends based upon SEAFRAME data to June 2011.

4.3.2. Precise levelling

Precise levelling support for the Australian Baseline Sea Level Monitoring Project is provided by relevant state agencies and Geosciences Australia. The purpose of levelling sea level monitoring gauges is to establish whether they are moving vertically with respect to the land. An array of coastal benchmarks must be surveyed periodically to allow stable benchmarks to be identified and used as a reference for the tide gauge. Further information about geodetic support for the Australian Baseline Sea Level Monitoring Project is available from Geosciences Australia.

The levelled heights of the SEAFRAME stations with respect to the local primary tide gauge benchmark that are available have been analysed and the rates of vertical movement are summarised in Table 3 and Figure 13 and Figure 14. Levelling results for the SEAFRAME at Cocos Island shows it is subsiding at a rate of 4.5 mm/yr. A correction for this movement will reduce the observed relative sea level trend. Stations around the Australian mainland appear more vertically stable, although there is evidence of both subsidence and emergence at some stations.

Location	Installation Date	Trend in the Datum of the Sea Level Sensor (mm/yr)
Cocos Islands	Sep 1992	-4.5
Groote Eylandt	Sep 1993	-0.2
Darwin	May 1990	0.2
Broome	Nov 1991	-0.1
Hillarys	Nov 1991	0.1
Esperance	Mar 1992	-0.4
Thevenard	Mar 1992	0.2
Port Stanvac	Jun 1992	-0.1
Portland	Jul 1991	0.1
Lorne	Jan 1993	0.1
Stony Point	Jan 1993	0.0
Burnie	Sep 1992	0.0
Spring Bay	May 1991	-0.1
Port Kembla	Jul 1991	0.0
Rosslyn Bay	Jun 1992	0.0
Cape Ferguson	Sep 1991	0.3

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.

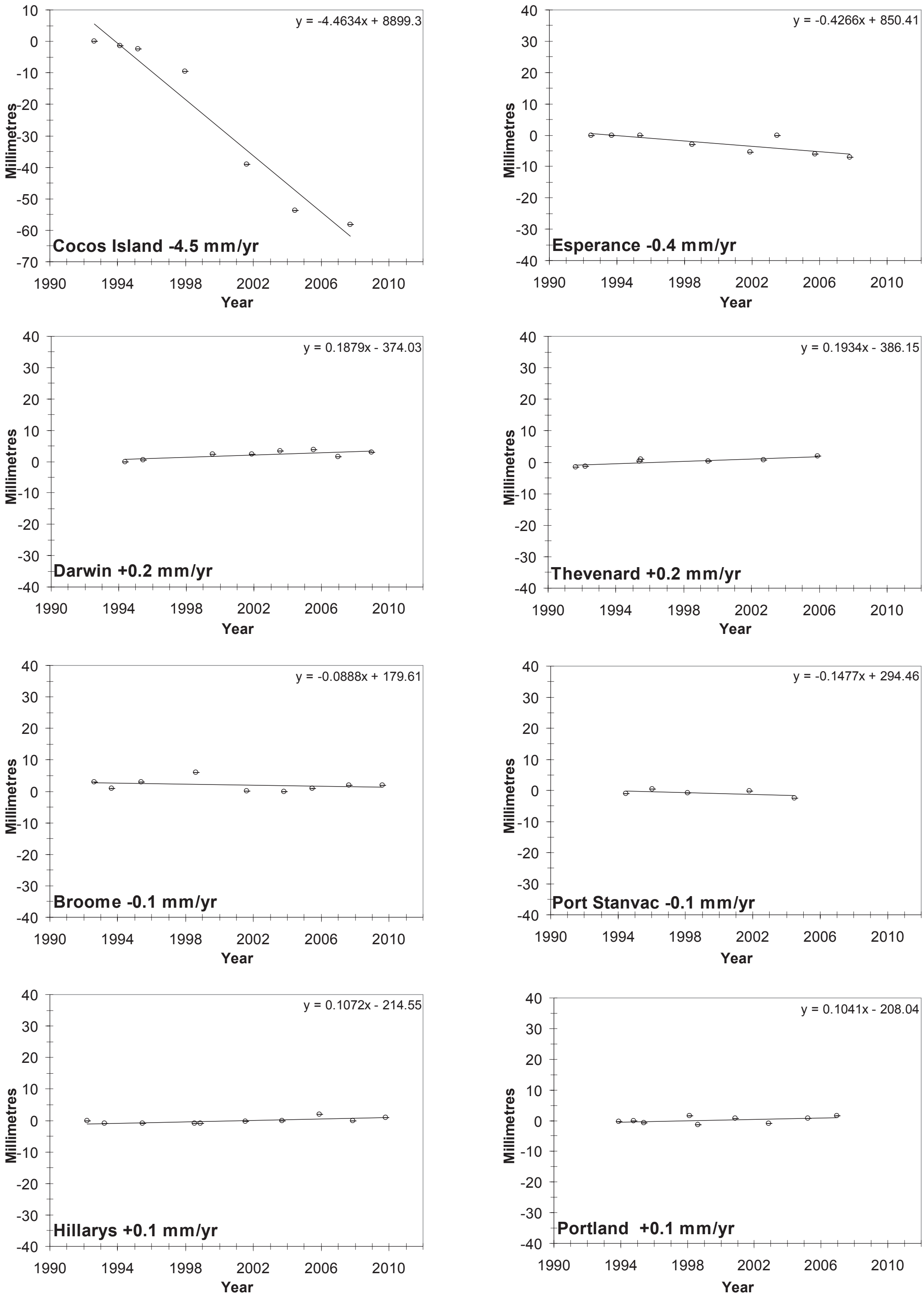


Figure 13. Surveyed heights of the SEAFRAME sea level sensor relative to the primary tide gauge benchmark and the overall trend in the datum as determined from precise levelling.

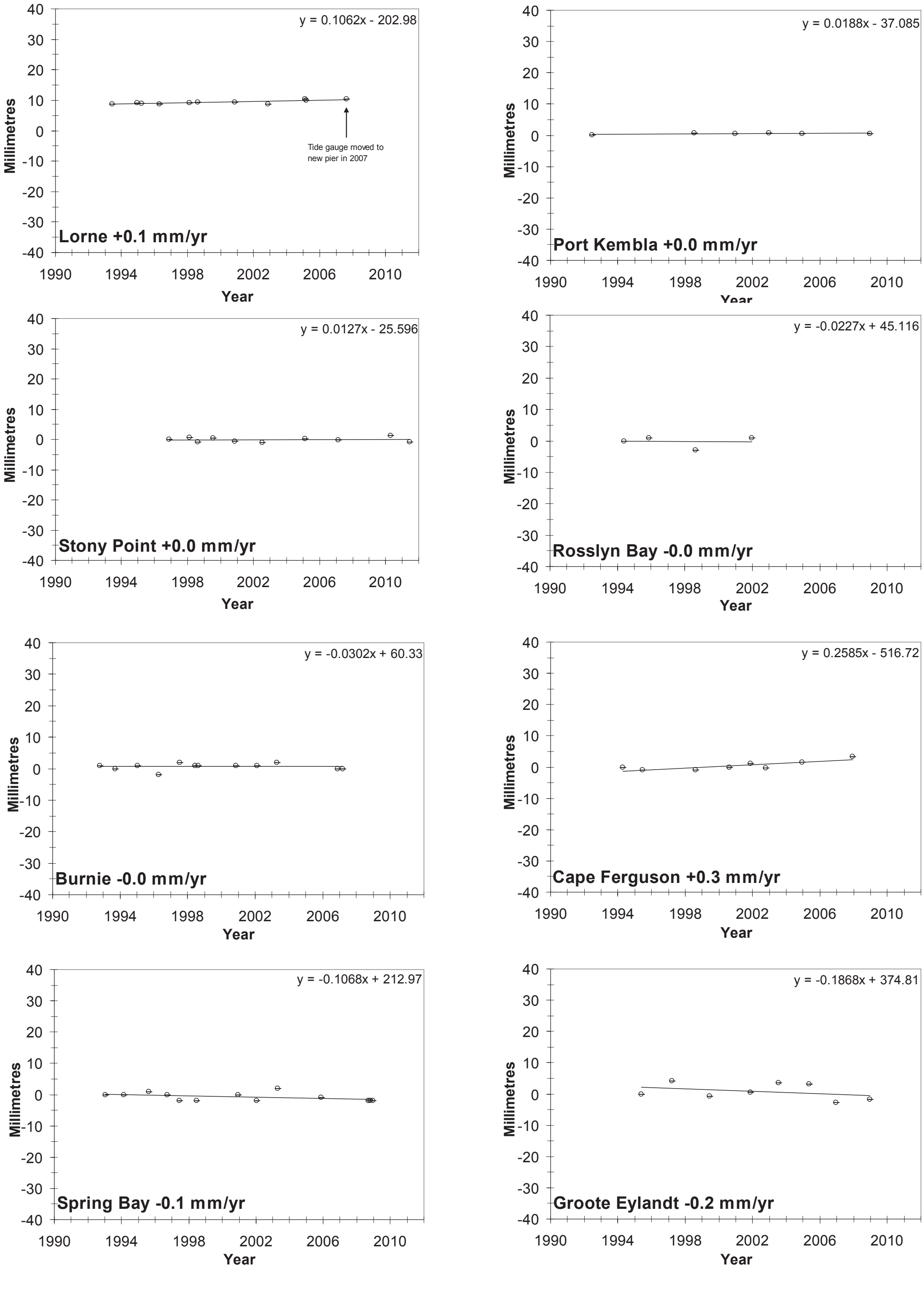


Figure 14. Surveyed heights of the SEAFRAME sea level sensor relative to the primary tide gauge benchmark and the overall trend in the datum as determined from precise levelling.

4.3.3. Inverted barometric pressure effect

Another parameter that influences the rates of relative sea level rise is barometric pressure. Known as the inverse 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 recorded at the tide gauge sites will therefore have contributed to the observed relative sea level trends.

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. The contributions have been mostly positive, so a correction for the inverse barometer effect will reduce the observed relative sea level trends at most stations.

Location	Installation Date	Barometric Pressure Contribution to Sea Level Trend (mm/yr)	Change in B.P. trend contribution from June 2010 (mm/yr)
Cocos Islands	Sep 1992	0.2	0.3
Groote Eylandt	Sep 1993	-0.1	0.1
Darwin	May 1990	0.5	0.1
Broome	Nov 1991	0.6	0.0
Hillarys	Nov 1991	0.2	-0.1
Esperance	Mar 1992	0.1	-0.2
Thevenard	Mar 1992	0.4	-0.1
Port Stanvac	Jun 1992	0.3	-0.1
Portland	Jul 1991	0.2	-0.1
Lorne	Jan 1993	0.0	0.0
Stony Point	Jan 1993	0.0	0.0
Burnie	Sep 1992	0.2	-0.1
Spring Bay	May 1991	-0.3	-0.2
Port Kembla	Jul 1991	0.6	-0.3
Rosslyn Bay	Jun 1992	0.3	0.0
Cape Ferguson	Sep 1991	0.4	0.0

Table 4. Recent short-term barometric pressure trends expressed as equivalent sea level rise in mm/year based upon SEAFRAME data to June 2011.

4.3.4. Combined net rate of relative sea level trends

The effects of the vertical movement of the platform (relative to a local land-based benchmark) and the inverse barometer effect are removed from the observed rates of sea level change and presented in Table 5. The relative sea level rise over the duration of the project has not been geographically uniform, with the largest trends observed around the north and west Australian coastline adjacent to the Indian Ocean (Figure 15). This pattern, which is based on less than two decades of observation, is in agreement with maps of sea level change derived from satellite altimetry data over an equivalent period of time. With ongoing sea level monitoring the expectation is that better estimates of the longer-term sea level change signal will increasingly emerge from the 'noise' of decadal fluctuations.

The changes to the net sea level trends upon addition of another year of data to June 2011 are shown in Table 5 and Figure 16. The net sea level trends are mostly larger than they were 12 months ago due to the influence of higher than normal sea levels observed around Australia during the 2010/11 La Niña. The exception to this is Cocos Islands, which exhibits less sea level sensitivity to ENSO events, and Port Stanvac, which was removed in December 2010 before the peak of the La Niña.

Location	Installation Date	Net Relative Sea Level Trend (mm/yr)	Change from June 2010 (mm/yr)
Cocos Islands	Sep 1992	3.4	-0.9
Groote Eylandt	Sep 1993	8.9	1.8
Darwin	May 1990	8.3	1.3
Broome	Nov 1991	8.4	1.3
Hillarys	Nov 1991	9.0	1.6
Esperance	Mar 1992	5.5	0.9
Thevenard	Mar 1992	4.3	0.4
Port Stanvac	Jun 1992	4.3	-0.2
Portland	Jul 1991	3.1	0.3
Lorne	Jan 1993	2.8	1.4
Stony Point	Jan 1993	2.6	1.3
Burnie	Sep 1992	2.9	0.3
Spring Bay	May 1991	3.7	0.3
Port Kembla	Jul 1991	2.6	0.5
Rosslyn Bay	Jun 1992	3.5	1.5
Cape Ferguson	Sep 1991	4.7	1.4

Table 5. The net relative sea level trend estimates to June 2011 after vertical movements in the observing platform relative to a local land benchmark and the inverted barometric pressure effect are taken into account.

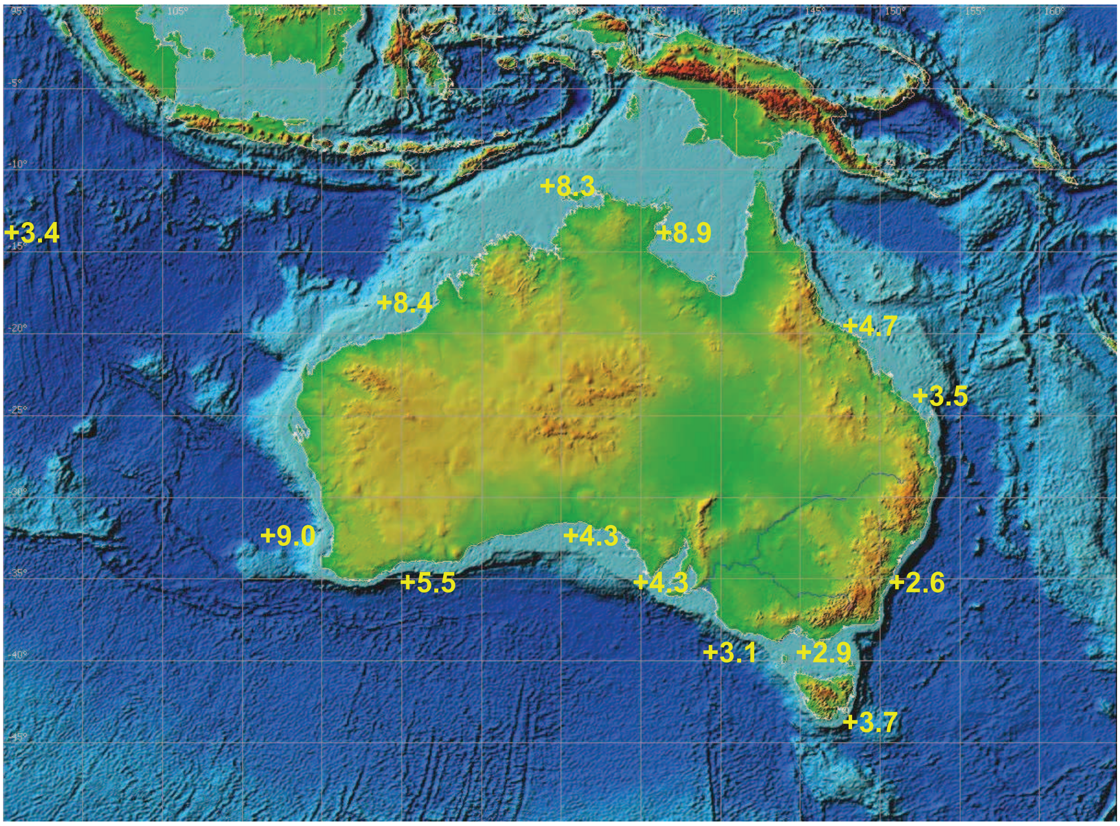


Figure 15. The net relative sea level trend in mm/year after subtracting the effects of the vertical movement of the platform and the inverse barometric pressure effect utilising all the data collected since the start of the project up to the end of June 2011.

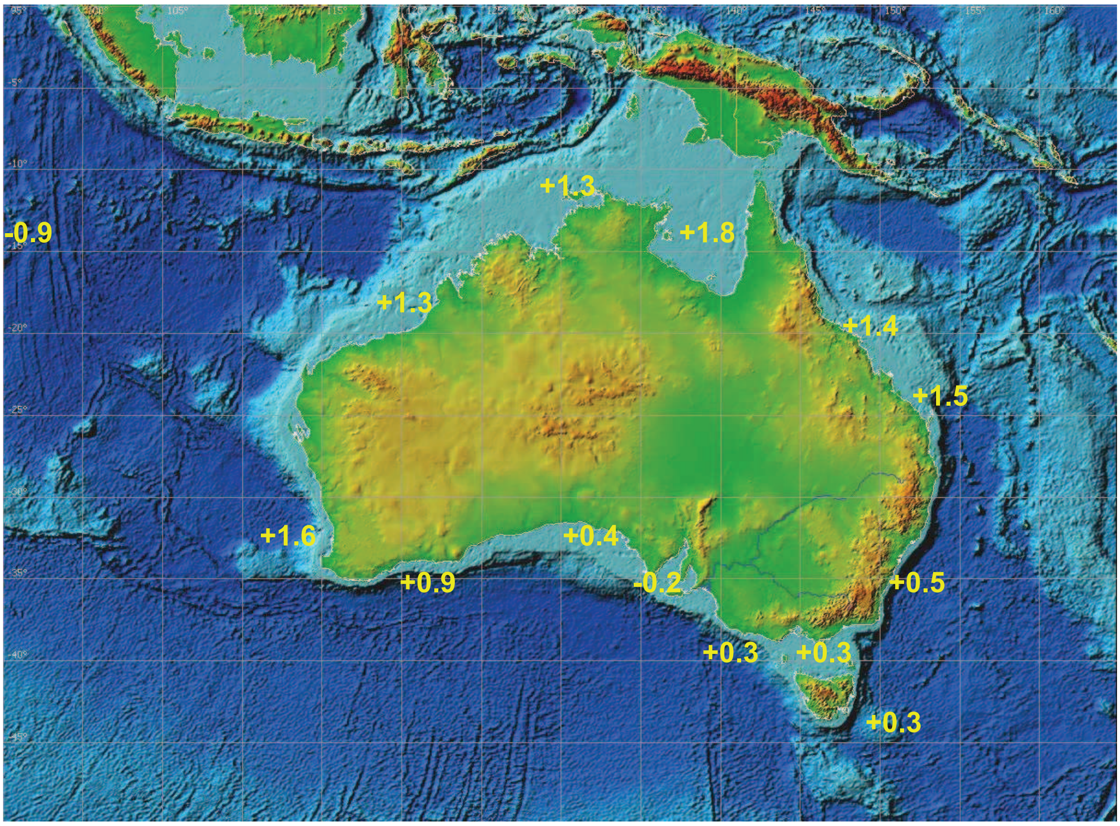


Figure 16. The change in the net relative sea level trend in mm/year between June 2010 and June 2011. The net trend is defined to be the relative sea level trend after subtracting the effects of the vertical movement of the platform and the inverse barometric pressure effect. Data from Port Stanvac has not been collected since November 2010.

The TOPEX/Poseidon (T/P) and subsequent Jason-1 and Jason-2 satellite altimeter missions have enabled sea levels to be measured on a global basis every 10 days since late 1992, around the time the ABSLMP began. The SEAFRAME stations have provided important 'ground-truth' sea level data for calibration and validation of the satellite altimeters.

The global distribution of satellite-altimeter derived sea level trends is presented in Figure 17. It shows that since 1992 sea levels have risen more substantially across the western Pacific than across the eastern Pacific. This geographical non-uniformity is related to inter-decadal sea level variability as described in section 3.2.2.

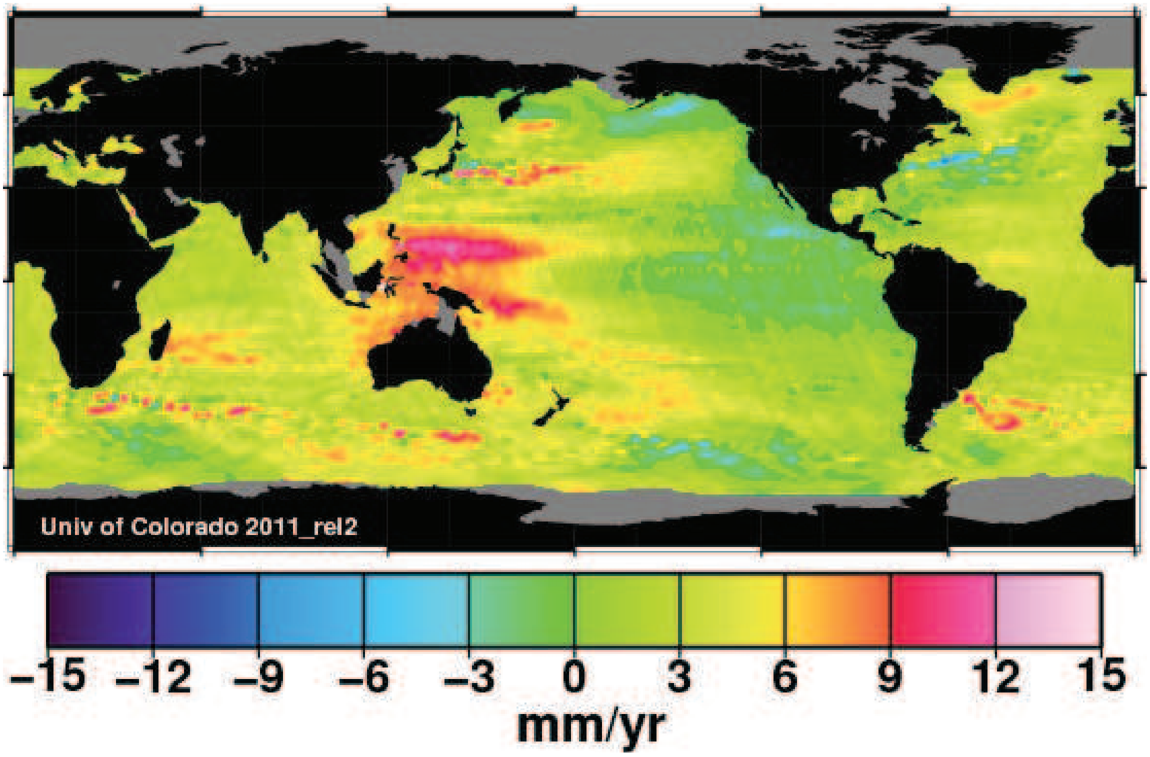


Figure 17. Global distribution of sea level trend (mm/yr) derived from Topex/Poseidon and Jason-1 satellite altimeter measurements from Dec 1992 to March 2011. Figure courtesy of University of Colorado.

5. SEAFRAME INSTRUMENT PERFORMANCE

For the period July 2010 to June 2011, the Australian Baseline sea level monitoring stations continued to return high rates of quality-controlled data, as shown in Table 6.

Scheduled calibration and maintenance visits performed during 2010/11 included Broome (September 2010), Darwin (September 2010), Thevenard (February 2011), Spring Bay (June 2011) and Burnie (June 2011).

The major instrumentation problems encountered in 2010/11 included:

Port Stanvac – The SEAFRAME station was removed in December 2010 (as discussed in section 2) resulting in a low data return of 41.9% for 2010/11.

Broome – Routine shutdown of the SEAFRAME while fuel-tanker ships are in dock continues to be required for occupational health and safety reasons, which lowered sea level data return to 96.0% for 2010/11. Lingering problems with the secondary water level sensor (since September 2009), water temperature sensor (since November 2009) and wind monitor (since November 2009) were all rectified during the calibration and maintenance visit in September 2010.

Burnie – The wind monitor propeller seized on 14 April 2011 and a new nose cone assembly was dispatched and fitted by local technicians on 26 April 2011, quickly returning the wind monitor to service.

Groote Eylandt – The wind monitor failed on 24 April 2010 and will be attended to at the next calibration and maintenance visit, although access to the equipment may be restricted as a consequence of revised occupational health and safety regulations at the port.

Esperance – Problems with the water temperature sensor module were encountered from 16 May – 21 July 2010 and data was removed from the archived record. The secondary sea level sensor failed from 15 October 2010 but was restored on 16 December 2010.

Portland - Problems with the water temperature sensor module were encountered from 1 October 2010 until 22 November 2010 and data was removed from the archived record.

Cape Ferguson – The wind monitor failed on 4 May 2011 and will be investigated at the next scheduled calibration and maintenance visit.

Darwin - Problems with the water temperature sensor module were encountered from 12 September 2010 until 14 October 2010. The water temperature sensor itself failed on 5 January 2011 and is scheduled to be replaced at the next calibration and maintenance visit.

Stony Point – The wind monitor reported erroneously high wind gusts during 2010/11 and data has been removed from the archived record pending further examination of the source of the problem. The wind monitor was also damaged in June 2011 and a replacement was due to be sent in July 2011. A calibration and maintenance visit is scheduled for September 2011 to diagnose any remaining wind monitor problems.

Spring Bay – Wind monitor problems occurred from 1-13 January 2011 and from 27 January 2011 until 26 June 2011 when the nose cone assembly was replaced.

Location	**Installation Date**	**Sea Level Data Return Since Installation (%)**	**Sea Level Data Return Jul10-Jun11 (%)**
Cocos Islands	Sep 1992	99.9	100.0
Groote Eylandt	Sep 1993	99.5	100.0
Darwin	May 1990	99.9	100.0
Broome	Nov 1991	98.4	96.0
Hillarys	Nov 1991	99.9	100.0
Esperance	Mar 1992	97.7	100.0
Thevenard	Mar 1992	99.5	100.0
Port Stanvac	Jun 1992	96.4	41.9
Portland	Jul 1991	99.2	100.0
Lorne	Jan 1993	98.2	99.8
Stony Point	Jan 1993	98.8	99.5
Burnie	Sep 1992	98.3	100.0
Spring Bay	May 1991	99.6	100.0
Port Kembla	Jul 1991	99.4	100.0
Rosslyn Bay	Jun 1992	95.9	100.0
Cape Ferguson	Sep 1991	98.0	99.4

Table 6. Quality-controlled sea level data return from Australian Baseline SEAFRAME stations.

6. COMMUNICATION OF RESULTS

Figure 18 shows the number of times the ABSLMP web pages have been visited, by month since January 2008. The web pages are available at http://www.bom.gov.au/oceanography/projects/abslmp/abslmp.shtml

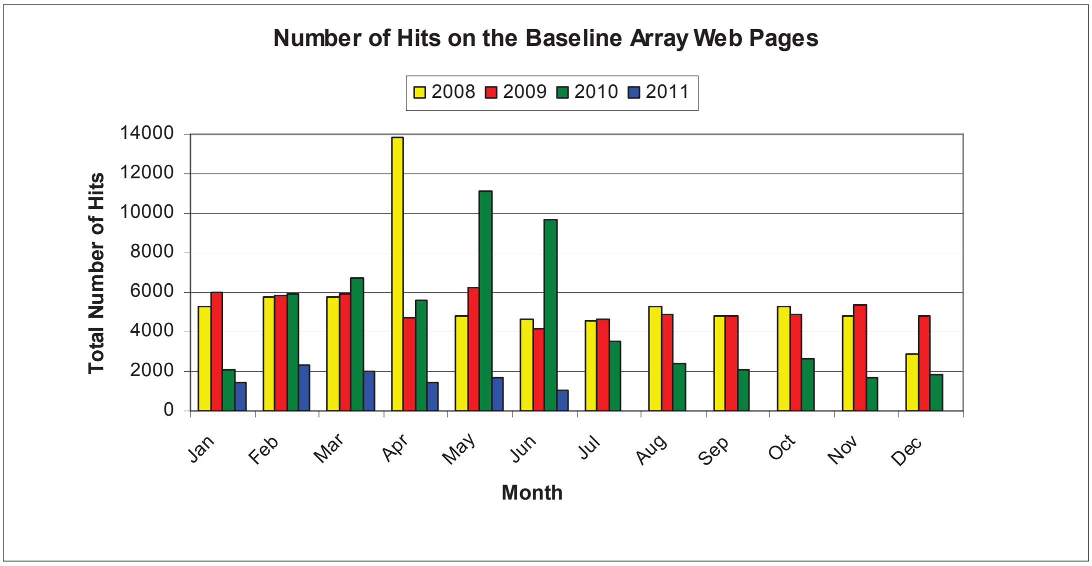


Figure 18. Number of Hits on the NTC Australian Baseline Array Web Page

7. FURTHER INFORMATION

Further information about the *Sea Level Data Reports* for the *Australian Baseline Sea Level Monitoring Project* 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/