Effect of barometric pressure on sea level variations in the Pacific region

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ABSTRACT

Barometric pressure and sea level data sets from the South Pacific Sea Level and Climate Monitoring Project funded by AusAID were analysed for twelve Tropical Pacific island countries. During mid-1997 and 1998 pressure anomalies over the Pacific region were strongly positive and sea level dropped significantly. As a consequence, sea level trends in the Pacific region suddenly changed from positive to negative. It was believed that the delayed effect of the 1997 strong El Niño episode was directly linked to these positive pressure anomalies. The same observations were made in 2002 and 2003 during another El Niño episode which was however not as strong as the previous one. The La Niña episode which followed the 1997-98 El Niño in 1999 had opposite effects. The pressure anomalies were negative and the sea level anomalies were positive. While the thermal effect due to global warming is still the cause of sea level rise in the Pacific region, it is clearly evident that the barometric pressure effect on sea level is more abrupt and it can overshadow the other effects at least temporarily.

1 INTRODUCTION

Sea level is a measurable quantity and it can be generally defined as the results of all influences, including tides, atmospheric pressure, winds, thermal effect, seismic activity (tsunami), vertical land movement, oceanographic effects such as El Niño, etc., which affect the height of sea surface (Aung *et al.* 1998). Among all these influences, one significant single component that affects the sea level more abruptly than the others is atmospheric pressure.

In this paper, the correlation between atmospheric pressure and sea level in the Pacific region will be discussed using the data sets from 1991 to July 2005 derived from an AusAID funded project, namely the *South Pacific Sea Level and Climate Monitoring Project*. However, it is important to note that the effect of barometric pressure on sea level variation is not long-term.

A notable aspect of climate variability is an oceanic feature known as El Niño. El Niño is an unusual warming in the sea surface temperature off the coast of Peru in South America with an onset near to the Christmas season. El Niño is characterised by a large scale weakening of the trade winds and warming of the surface layers in the eastern and central equatorial Pacific Ocean (Lefale *et al.* 2003). This causes the rain area, which would normally be found in the western equatorial Pacific, to migrate eastward. The El Niño generally means drought in Australia, Indonesia, the Philippines and Papua New Guinea with tropical storms in the ascendancy in Tahiti and Polynesia in general (Kaluwin *et al.* 1998). As the El Niño conditions subside, a significant cooling of the sea surface occurs in the eastern Pacific. This cooling is referred to as a La Niña and its effect on the atmosphere is opposite to that of an El Niño (Aung *et al.* 1998).

A study done by the US Geological Survey (USGS) revealed that during the winter of 1997-98 wind driven waves and abnormally high sea levels significantly contributed to hundreds of millions of dollars in flood and storm damage in the San Francisco region. Analyses of nearly 100 years of sea level records collected near the Golden Gate Bridge revealed that the abnormally high sea levels were the direct result of that year's El Niño atmospheric phenomenon.

Studies have been done on the effects of barometric pressure on sea level variations (Pugh 2004) but none have been done in the South Pacific region.

2 AIR PRESSURE AND ITS UNITS

In meteorology, atmospheric pressure is measured in hectoPascals (hPa) or millibars (mb) instead of the standard Nm^{-2} or Pa (Pascal). There is high atmospheric pressure near the Earth's surface due to the great number of air molecules compressed by the weight of the air above the surface. The standard atmospheric pressure at sea level is taken as 1013.25 hPa or 1013.25 mb, but the air pressure at sea level normally varies between about 1040 hPa and 970 hPa.

2.1 ATMOSPHERIC PRESSURE IN THE PACIFIC REGION

The atmospheric pressure at a given locality varies continually. These variations may be regular or irregular. Irregular variations are sometimes due to the passage of pressure systems. The development or decay of a pressure system may also produce changes of this type. The regular variations have various periods. The most important regular oscillation has a period of about twelve hours. It is therefore called the semi-diurnal variation of pressure (Crowder 1995).

The semi-diurnal variation of pressure is rather complex. The changes are not perfectly symmetrical and they vary considerably with locality. In the Pacific region, the semi-diurnal variation of pressure is more evident than in higher latitudes. Figure 1a shows the pressure variations for a typical day at Port Moresby in PNG and Figure 1b shows the pressure variations in the Cook Islands for a month.

Within a 24-hour period, there are 2 instances of high pressure and 2 instances of low pressure (see Figure 1).

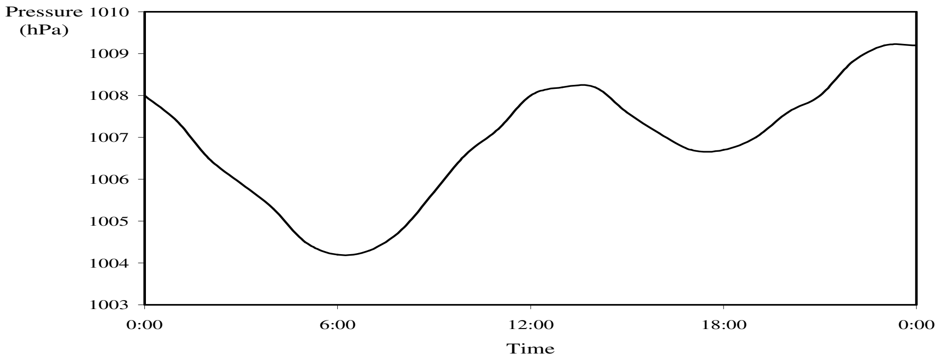

Figure 1a. Daily pressure changes at Port Moresby, PNG *(Data Source: National Tidal Centre, 2005).*

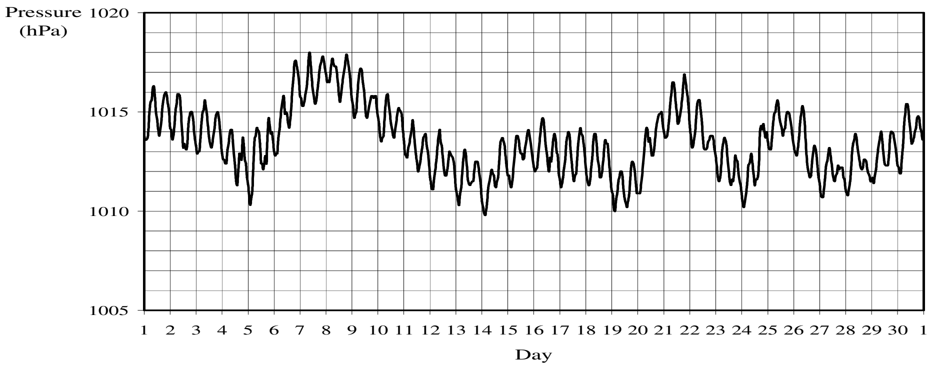

Figure 1b. Monthly pressure changes during November 1999 at Cook Islands *(Data Source: National Tidal Centre, 2005).*

3 SOURCE OF DATA

With the permission of *AusAID* the data set for this paper has been provided by the *South Pacific Sea Level and Climate Monitoring Project*. The long-term project was developed as an Australian response to concerns raised by members of the *South Pacific Forum* countries over the potential impacts of climate change and sea level rise in the region (http://www.pacificsealevel.org). The *National Tidal Facility (NTF)* of *The Flinders University of South Australia* undertook the management of the Project after it was awarded the contract in 1991. Recently, the name of the institution has been changed to *National Tidal Centre (NTC)* and now part of the *Bureau of Meteorology (BoM)* in Adelaide.

All of the twelve monitoring stations of the NTC are operational. Feasibility studies for Niue and Palau have been completed and monitoring stations are under consideration to be included as part of the network. The monitoring station here in Fiji is situated at Lautoka and has been in operation for the last 14 years. Length of data for the other member countries is slightly less than those for Fiji. The data is recorded by SEAlevel Fine Resolution Acoustic Measuring Equipment (SEAFRAME) stations that are situated at each of the member countries of the project except Niue and Palau. The data recorded are sea level, barometric pressure, wind speed, wind direction, wind gust, air temperature and water temperature.

In the analysis, sea level residuals are the differences between the observed sea levels and the predicted tides. The anomalies are the difference between the present value and the long-term average of the parameter being analysed.

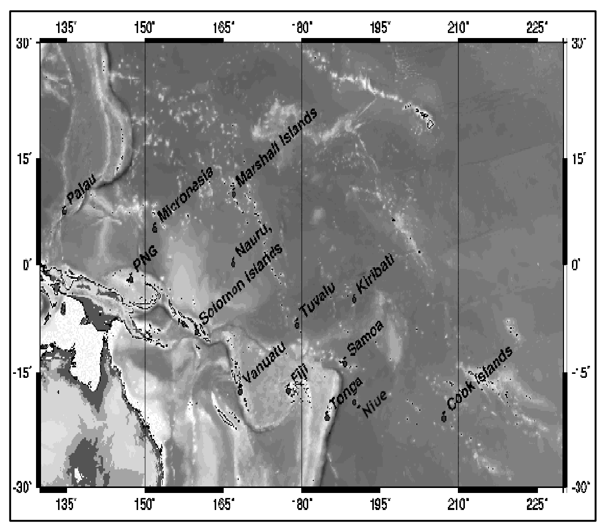

Figure 2. South Pacific Sea Level and Climate Monitoring Project Monitoring Sites
(Data Source: National Tidal Centre, 2005).

4 EFFECTS OF ATMOSPHERIC PRESSURE ON SEA LEVEL

A change of barometric pressure by 1 hPa may cause ~1 cm variation in sea level by using the formula

$$\Delta P = \Delta h \rho g$$

and substituting the typical values. Here ΔP represents atmospheric pressure difference, ρ is density of seawater, g is acceleration due to gravity and Δh is the change of sea level height due to pressure.

This depression of the water surface under high atmospheric pressure, and its elevation under low atmospheric pressure, is often described as the inverted barometer effect (Crowder 1995). The water level does not adjust itself immediately to a change of pressure and it responds to the average change in pressure over a considerable area. Changes in sea level due to barometric pressure seldom exceed 30 cm (Aung *et al.* 1998). It is also to be noted that a decrease of barometric pressure by 1 hPa may cause a ~1 cm rise in sea level and vice versa.

5 RESULTS

Using the data sets from the South Pacific Sea Level and Climate Monitoring Project, our analyses are based on the barometric pressure and sea level data using the sea level residuals and the anomalies of sea level and barometric pressure.

5.1 A BRIEF VIEW ON EXTREME EVENTS

In view of better understanding and appreciation of the barometric pressure effect it is useful to deal with the extreme events, for example, when the tropical cyclone, *Gavin*, hit Fiji on 7th March 1997. Since this was a very strong cyclone, the average barometric pressure drop was ~30 hPa and sea level rose by approximately 65 cm (including the effects due to winds), as can be seen in Figures 3a and b.

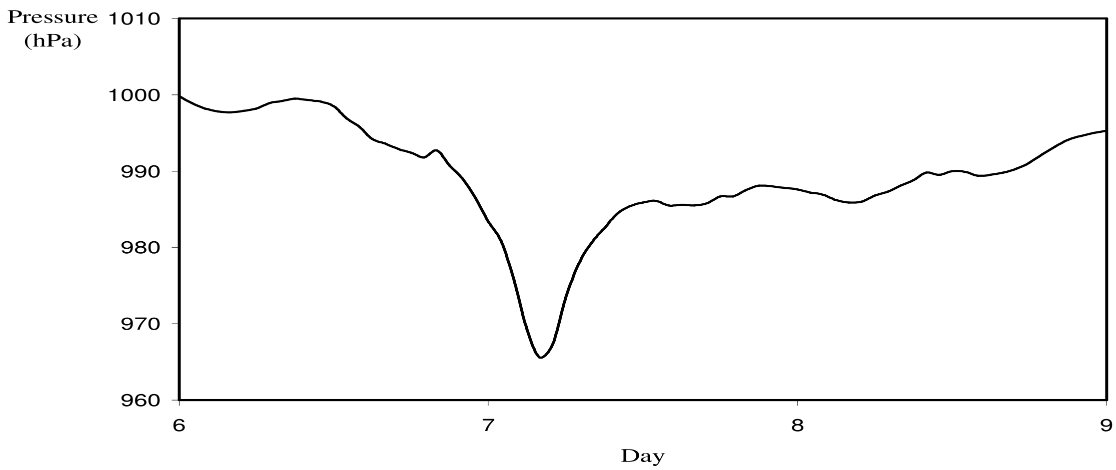

Figure 3a: Barometric pressure during the peak period *(Data Source: National Tidal Centre, 2005).*

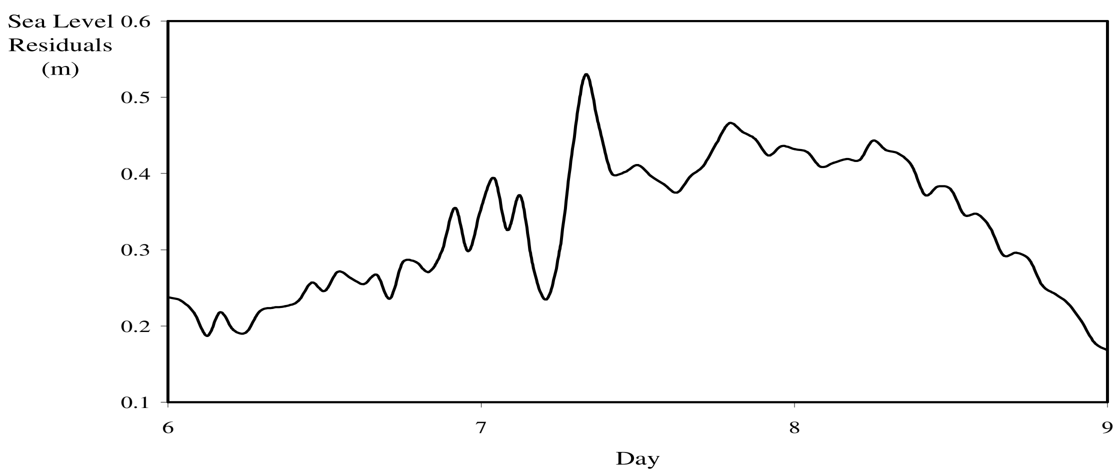

Figure 3b. Sea level residual during the peak period *(Data Source: National Tidal Centre, 2005).*

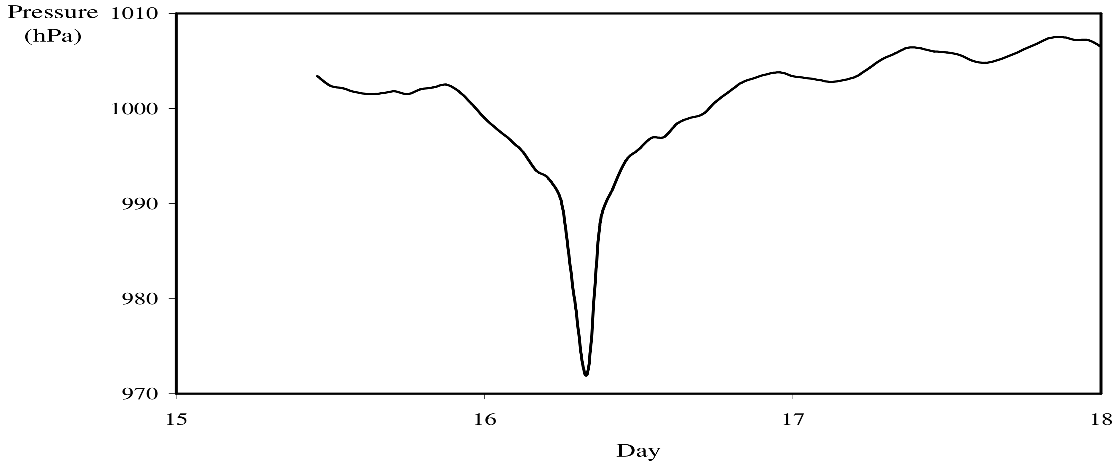

Figure 4a. Barometric pressure during the peak period *(Data Source: National Tidal Centre, 2005).*

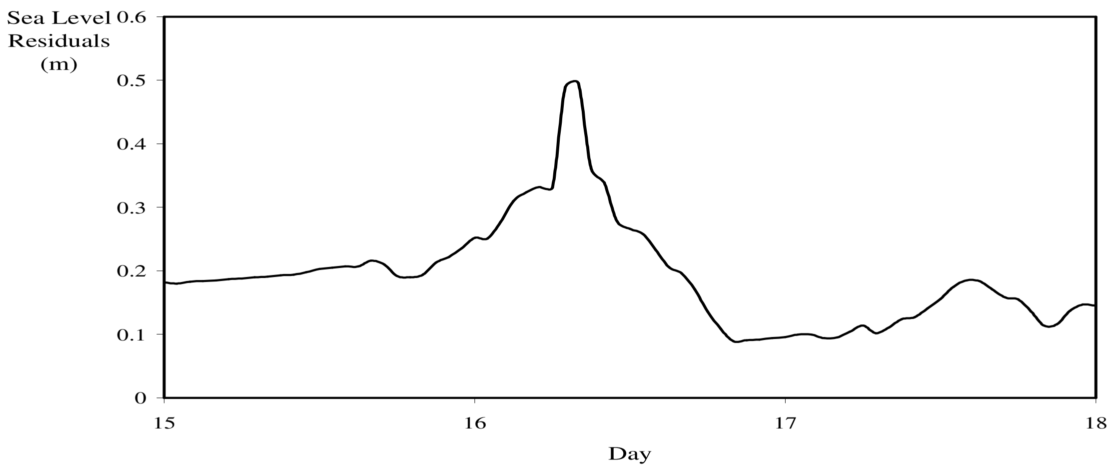

Figure 4b. Sea level residual during the peak period *(Data Source: National Tidal Centre, 2005).*

Later, on 16th March 1997, Tropical Cyclone *Hina* hit Tonga. This was also a severe cyclone. The sea level rose more than 60 cm (including sea level rise due to wind effects) and the average barometric pressure drop was about 35 hPa (Figures 4a and b).

So far we have looked at how sea level varies with changes in barometric pressure during the extreme events in the Pacific. However, it is to be noted that the sea level residuals that we were looking at are due to all the components that affect it, including for example, wind. The effects due to wind setup (sea surface elevation due to winds), for example, can be calculated separately using the values of wind speed, water depth, drag coefficient, densities of air and sea water, length of fetch (wind affected area) and acceleration due to gravity (Aung *et al.* 1998).

5.2 ANOMALIES OF BAROMETRIC PRESSURE AND SEA LEVEL

A plot of sea level anomalies from twelve Pacific Island countries (Figure 5) shows the anomalies from the average sea level from December 1992 (for some stations were deployed earlier than others) to July 2005.

During 1999, sea level anomalies for almost all stations were positive. However, if we look at the period between mid-1997 and almost the whole of 1998, most of the stations experienced significant negative sea level anomalies. These sea level changes may well be explained by the very positive pressure anomalies during the last very severe El Niño in 1997. It is to be noted that the delayed effect of 1997-98 El Niño may have been directly linked with the positive barometric anomalies for that period.

When we analyse the plot of barometric pressure anomalies shown in Figure 6, it is quite noticeable that the barometric pressure anomalies all over the Pacific are positive during late 1997 and 1998. The effect of barometric pressure on sea level, when compared to Figure 5, is clearly evident.

Figure 5 clearly depicts that sea level anomalies were positive between the period 1999 and 2001. For the same period, although not that evident, there was negative barometric pressure anomalies observed as in Figure 6. This can be explained by the weak La Niña that followed the 1997-1998 El Niño.

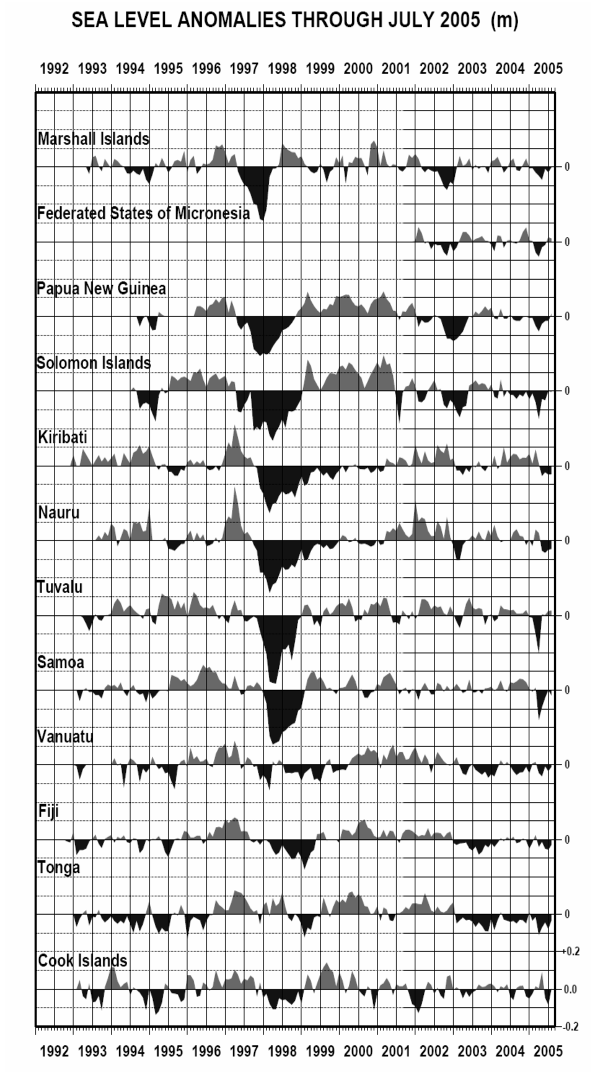

Figure 5. Sea level anomalies through July 2005 (*Data Source: National Tidal Centre,2005).*

During the 2002-2003 El Niño, which was not as strong as the 1997-1998 El-Niño, sea level anomalies were negative and the barometric pressure anomalies, as observed in Federated States of Micronesia, Solomon Islands, Tonga and Cook Islands, were positive.

In comparing the sea level anomalies in some countries (Figure 5) and the barometric pressure anomalies (Figure 6), it is interesting to note hat the timing of most of the negative sea level anomalies coincided with the positive barometric pressure anomalies during that period and vice versa. This clearly shows the effect of positive barometric pressure is a significant factor to depress the sea level and to produce negative sea level anomalies.

Due to the prolonged pressure increase in the region during 1997 and 1998, the sea level drop was significant and it changed the rate of sea level trends and most became negative for many more months even after the El Niño period. Although most of the sea level trends in the region are back to a normal pattern, which is positive (see Figure 7), the strong effect of barometric pressure is an important influential factor in changes to sea level in the region.

The recent sea level trends (mm per year) at individual stations starting from November 1992 (for stations deployed early) to July 2005 are plotted in Figure 7.

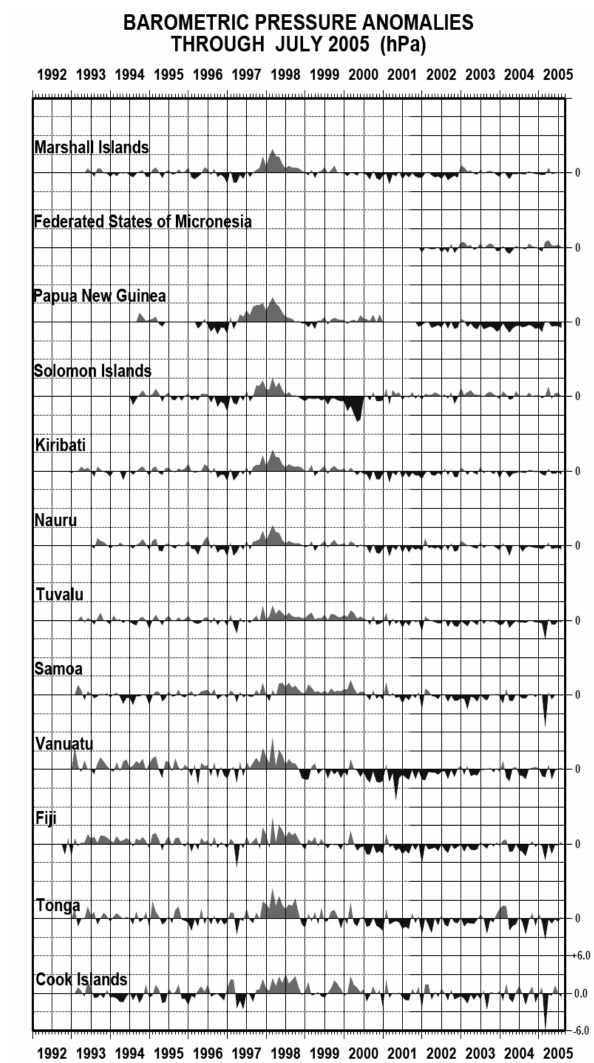

Figure 6. Barometric pressure anomalies through July 2005 (*Data Source: National Tidal Centre, 2005).*

The values are calculated based upon statistical methods and details are available from the National Tidal Centre under the Australian Bureau of Meteorology. These sea level trends are produced by fitting a straight line to a full year of data. As subsequent months of data are added, the entire data series is re-analysed and a new trend value is estimated and plotted each month. In this way, the trend line grows gradually. Due to relatively shorter length of data sets for some countries, for example, Solomon Islands and PNG, and because they are sitting in the famous west Pacific warm pool region and have diurnal tides, the patterns are distinctly different from other countries. However, when the data length gets longer, the fluctuation will be reduced like other stations.

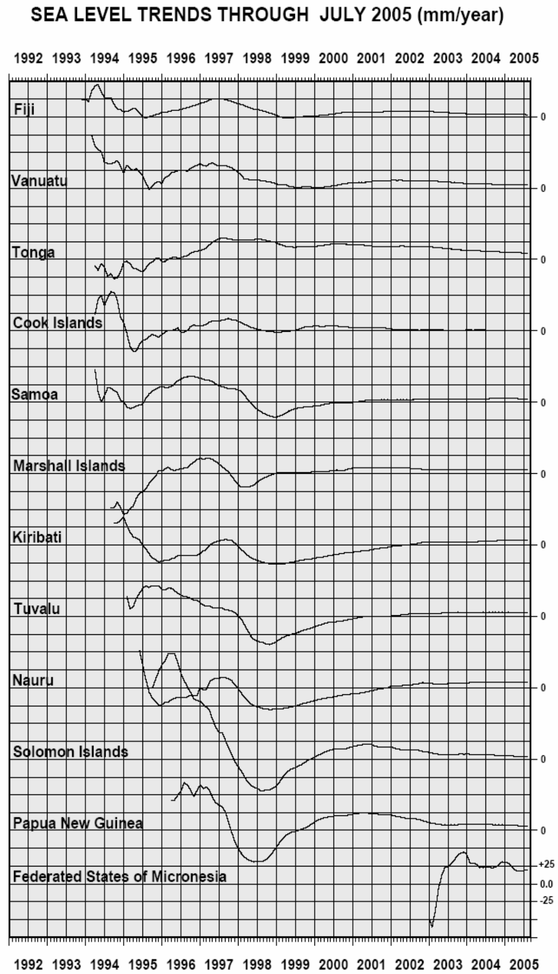

Figure 7. Sea level trends through July 2005
(Data Source: National Tidal Centre, 2005).

The onset of an El Niño or a La Niña is determined by the Southern Oscillation Index (SOI). The SOI is calculated from the difference in pressure between Darwin and Tahiti. When the SOI is significantly negative, an El Niño is likely to occur. And when the SOI is significantly positive, La Niña is likely to occur. The values of the SOI are shown in Figure 8.

An interesting point to note is that below 17°S, that is, in Vanuatu, Fiji, Cook Islands and Tonga, the effect of the barometric pressure on sea level is not as significant as that on the islands that are above 17°S. There are reasons to believe that this situation is closely related with the orientation of the Inter Tropical Convergence Zone (ITCZ) in the Pacific Region. The location of the ITCZ varies with the ocean-atmosphere interaction.

6 CONCLUSIONS

After analysing the barometric pressure anomalies (see Figure 6), especially the positive anomalies all over the Pacific during mid-1997 and 1998, and 2002 and 2003, it was clear that the pressure effect on sea level was more abrupt and influential than other factors, at least for these months. However, it was coincident with the last very severe El Niño and the significant barometric pressure increase was distinctly linked with this extreme ocean-atmosphere interaction event. The changes in sea levels are not only due to changes in barometric pressure but also to numerous other factors, yet the barometric pressure effect alone can reverse the sea level trends of the Pacific region quite significantly. In fact, the effect is more pronounced than the thermal effect due to global warming at least over a short period of time.

The sea level rise issue is an important adaptation measure for the low laying islands in the Pacific region. However, if we carefully look at Figure 7, the sea level trend lines for all countries are basically horizontal and saturated for the short term (> 10 years timeframe). It may imply that the sea level trend values are not accelerating (increasing with time) and useful for Pacific governments to use these results to address short term coastal and ocean policies.

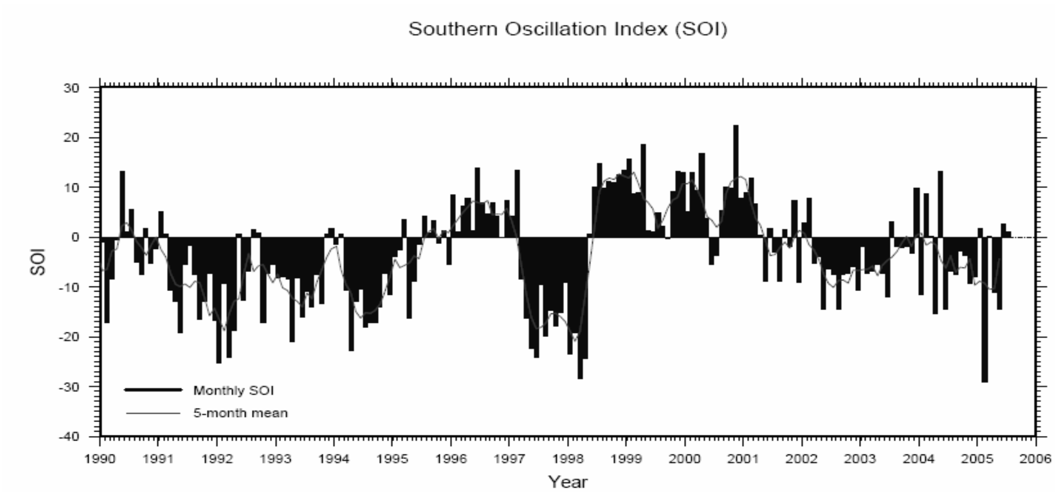

Figure 8. The five-month weighted mean and individual monthly means of the SOI
(Data Source: National Tidal Centre, 2005).

ACKNOWLEDGEMENTS

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