Sea-level variability and change in the US-affiliated Pacific Islands: understanding the high sea levels during 2006–2008

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Introduction

The US-affiliated Pacific Islands (USAPI) include the Territory of Guam, the Republic of Palau (ROP), the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of the Marshall Islands (RMI), the Federated States of Micronesia (FSM), and American Samoa (AS) (Figure 1). Tide stations used in this study include the following locations: Apra Harbour in Guam; Malakai Harbour in the ROP; Saipan in the CNMI; Kwajalein and Majuro in the RMI; Yap, Pohnpei and Kapingamarangi in the FSM, and Pago Pago in AS. These and neighbouring islands are among the world's most vulnerable communities to climate variability and change, especially sea-level rise, as many parts of them are regularly affected by erosion and inundation. The small size, lower elevations and extensive coastal areas of the islands, their remoteness and limited financial resources and, in some cases, poor economic and social decisions contribute to great ecosystem and human vulnerability to disasters (Shea *et al.*, 2001).

Climate literature provides abundant evidence that tropical climate variability is heavily influenced by the El Niño Southern Oscillation (ENSO) climate cycle (Bjerknes, 1966, 1969; Lau, 1985; Ropelewski and Halpert, 1987; Chu, 1995). Anomaly patterns in tropical Pacific sea-surface temperatures (SSTs) can thus be used to forecast regional climate fluctuations (Barnston and He, 1996; Yu *et al*., 1997). Based on the pervasive tropical Pacific zonal wind anomalies accompanying ENSO fluctuations, recent studies at the Pacific ENSO Applications Climate Center (PEAC) have described the degree of sensitivity of sea-level anomalies in the tropical Pacific Island communities to the phase of the ENSO cycle, with below-normal sea level observed during El Niño events and above-normal sea level observed during La Niña events (Chowdhury *et al*., 2007a, 2007b). Because of the change in wind-stress anomaly from westerly to easterly, the northwestern Pacific Islands experience a significant drop in sea level during El Niño events due to the redistribution of heat by Kelvin waves. Information of a more general nature about ENSO and tropical Pacific sea-level variability is provided in Xue *et al*. (2000) and Xue and Leetmaa (2000).

During the 2006–2008 El Niño and La Niña events, many Pacific Islands continuously experienced high sea levels for a period of 18 months. From July to December 2006, weak-to-moderate El Niño conditions influenced the ocean and atmosphere; then, after a brief transition through ENSO-neutral conditions, weak-to-moderate La Niña conditions developed and persisted from February 2007 until May 2008. In order to determine the relative intensity of each of the El Niño and La Niña events, we employ the Southern Oscillation Index (SOI) and the Oceanic Niño Index (ONI). According to these two indices, the 2006/2007 El Niño is considered to have been a weak-to-moderate event and the 2007/2008 La Niña event is considered to have been moderately strong. Likewise, the 1997/1998 and 1986/1987 El Niño events are classified as strong and moderate, respectively, and the 1998/1999 and 1988/1989 La Niña events are classified as moderately strong. When the rise in sea level during these two moderately strong La Niña events is compared with that in the 2007/2008 event, the latter was found to be considerably higher. Most of the USAPI tide stations recorded elevated sea levels from July 2006 to June 2008. This is, historically, quite significant, since no other El Niño event on record has resulted in an observed sea-level rise in the USAPI. Therefore, the elevated sea level during the El Niño period July-August-September (JAS) and October-November-December (OND) of 2006 was an anomaly. The authors hypothesize that other factors in addition to ENSO contributed to this unusual sea-level rise.

The goal of this study is to explore the factors potentially influencing the positive sea-level anomaly in the USAPI from mid-2006 to mid-2008, in addition to the La Niña of 2007/2008. In investigating this, the sea-level variability of two other major ENSO reversals consisting of an El Niño immediately followed by a La Niña is also examined: 1987–1989 and 1997–1999. At this exploratory stage, comprehensive analyses to isolate the role of atmospheric and

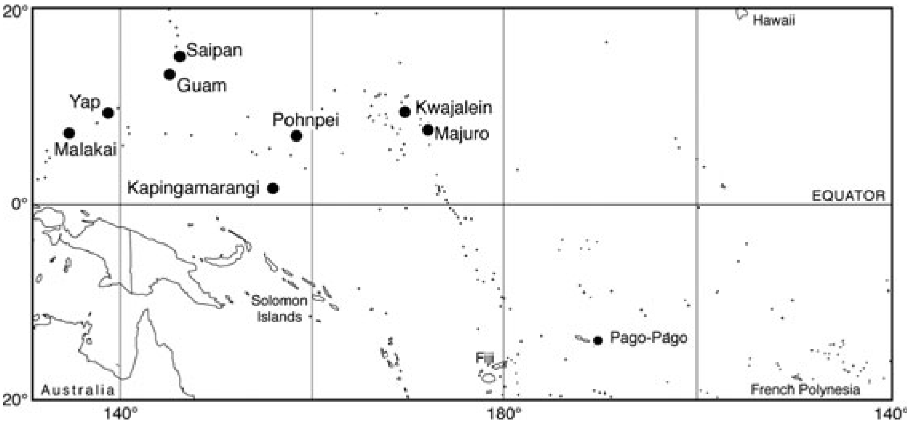

Figure 1. Locations of tropical Pacific tide gauges. Those in USAPI discussed here are labelled with large black circles.

oceanic dynamical factors are beyond the scope of this paper; our approach is mainly empirical. It will be shown that statistical analyses of our observations support the anecdotal assertions of sea-level rise in general in recent decades; we are led to believe that the globally pervasive rise in sea level very much applies to the general vicinity of the USAPI, and is accentuated in particular USAPI sub-regions.

Data and monthly time-series analysis

The monthly time series for sea-level deviations is taken from the University of Hawaii Sea Level Center (UHSLC) (ftp://ilikai.soest.hawaii.edu/islp/slpp.deviations). The climatological base period derived from this data set is 1975–1995[1]; accordingly, sea level anomalies are defined as the difference between the mean sea level for the given month and the 1975–1995 mean monthly sea level for the given station. The seasonal cycle is not removed in our formulation of sea-level deviations. Although a seasonal cycle of sea level is noticeable at some of the stations, it is not large, and no serious problems were found in our analyses and their interpretation. The observed monthly time series of sea-level anomalies (anomaly and deviation are used synonymously in this paper) for the three periods to be compared – July 2006 to June 2008, July 1997 to June 1999, and July 1987 to June 1989 – are presented in Figure 2 for the eight locations in the USAPI.

As compared to the 2006–2008 ENSO reversal event, the 1997–1999 ENSO reversal event had two distinct features: an El Niño enduring from JAS of 1997 to January-February-March (JFM) of 1998, followed by a La Niña from JAS of 1998 (Table 1). A considerable fall in sea level was observed from July 1997 to March 1998, after which a gradual rise was visible (Figure 2). Similarly, the 1987–1989 reversal event consisted of El Niño from JAS to OND of 1987, followed by La Niña beginning in AMJ of 1988. A fall in sea level was observed from JAS to OND 1987, followed by a gradual rise beginning in JFM 1988.

ENSO and sea-level variability

Although ENSO events differ substantially from one another in various respects, there are typical, commonly observed, characteristics of El Niño and La Niña. These have often been identified in terms of anomalies of sea-level pressure (SLP), SST, a combination of these, or additional variables. Such general defining patterns and their duration are often used as criteria for identifying specific ENSO events. Further, criteria for ENSO event strength classification (e.g. weak, moderate, strong) have also been considered (Kousky and Higgins, 2007). The earliest index used – SOI – is an atmospheric index based on the SLP anomaly in the southeastern tropical Pacific at Tahiti (17.6° S, 149.6° W) minus the SLP anomaly in the far southwestern Pacific at Darwin, Australia (12.4° S, 130.9° E). SOI reflects the status of the Walker circulation (Troup, 1965), which is weakened during El Niño and enhanced during La Niña. Another more recently used ENSO index is the ONI, based directly on the SST anomaly in the NIÑO 3.4 index region, defined by the rectangle 5°N–5°S 120°W–170°W. The rationale

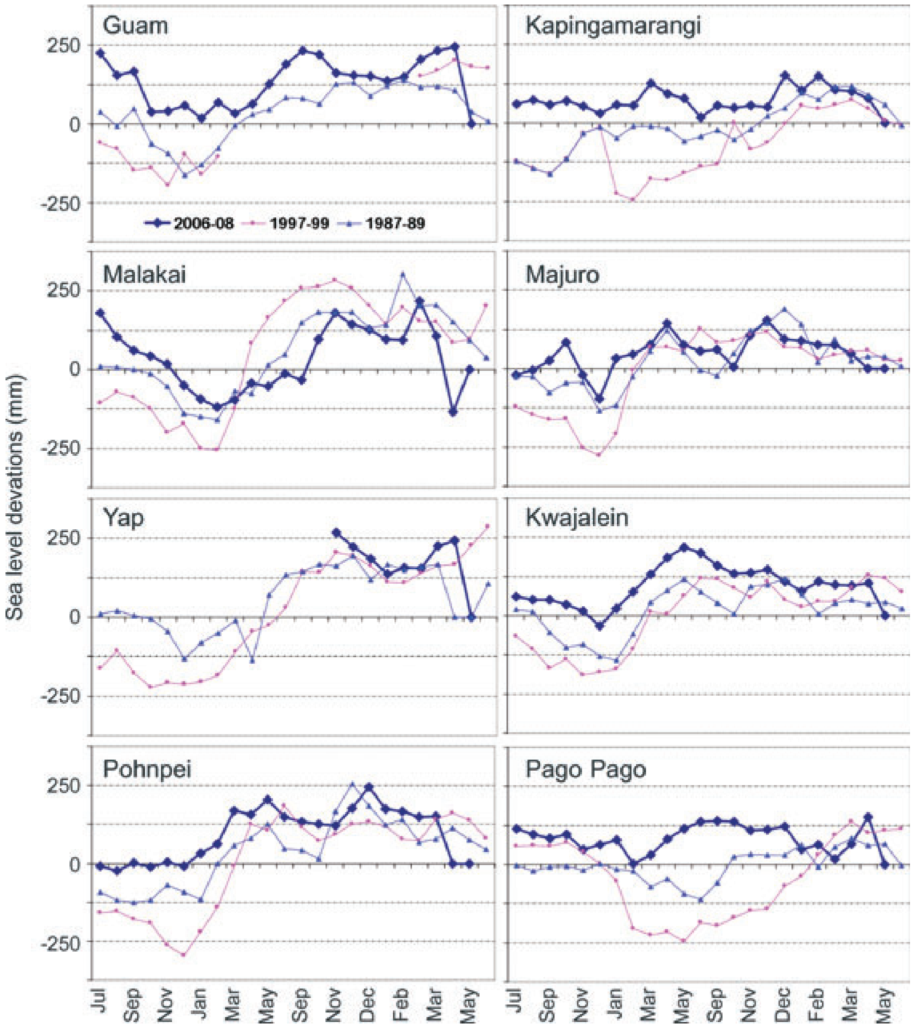

Figure 2. Time-series of monthly sea-level deviations for 24-month periods (July–June). X-axis: months; Y-axis: sea-level deviations in millimetres.

Table 1

Intensity of El Niño/La Niña events for three-month periods during three two-year episodes with El Niño during the first year, followed by La Niña during the second year.

Season	2006–2008	1997–1999	1987–1989
JAS	Weak El Niño	Strong El Niño	Strong El Niño
OND	Moderate El Niño	Strong El Niño	Moderate El Niño
JFM	Transition	Strong El Niño	Transition
AMJ	Neutral	Transition	Moderate La Niña
JAS	Weak La Niña	Weak La Niña	Moderate La Niña
OND	Moderate La Niña	Moderate La Niña	Strong La Niña
JFM	Moderate La Niña	Moderate La Niña	Strong La Niña
AMJ	Moderate La Niña	Moderate La Niña	Moderate La Niña

JAS (July-August-September), OND (October-November-December), JFM (January-February-March) and AMJ (April-May-June).

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[1] Quality control procedures and issues are discussed in Caldwell and Kilonsky (1992).

for use of the NIÑO 3.4 SST region to best represent ENSO is highlighted in Barnston *et al.* (1997). SOI and ONI are negatively correlated with one another (Figure 3).[2]

Another index of the ENSO state, developed in the 1980s, is the Multivariate ENSO Index, or MEI (Wolter and Timlin, 1998), which incorporates the spatial fields of SLP, SST, and other ENSO-related variables such as cloud cover (Outgoing Longwave Radiation, or OLR) and anomalous winds across the tropical equatorial Pacific. MEI is based on the leading empirical orthogonal function (EOF) from historical data of all of the constituent variables, and the patterns of the relative weighting of the variables is thus objectively determined so as to define the coherent variability. MEI thus captures the multifaceted nature of ENSO, resulting in a more balanced and complete index, and this is considered its main advantage. A disadvantage is that it is less simple to define and understand than a univariate index such as SOI or ONI. For example, the pattern of the weighting of the constituent fields would change when the index is updated with additional years of data.

An objective procedure for classifying ENSO event intensity is proposed in Kousky and Higgins (2007), based on the maximum departure of ONI from its mean during the course of the event. Other criteria for defining event strength would also be possible and reasonable – for example, one that accounts for the aggregated departures over the event as a whole, or over its strongest three-month periods. The ranking of the intensity of events during the last few decades would differ depending on which criteria were used. Observations indicate a fair amount of variability in the life cycles of individual El Niño and La Niña events, including cases of irregular development and demise. Therefore, even when using SOI and ONI, some subjective component commonly enters into any ENSO event strength-ranking process.

The ranking method that we adopt here uses both SOI and ONI, and is as follows. If the values of SOI are (i) less than -1.0 then it is a moderate-to-strong El Niño, and (ii) if the values are more than +1.0 then it is a moderate-to-strong La Niña event. The values of -0.5 to -1.0, or 0.5 to 1.0, correspond to a weak-to-moderate El Niño or La Niña event, respectively. Similarly, values of ONI of (i) more than +1.0 define moderate-to-strong El Niño, and (ii) less than -1.0 define a moderate-to-strong La Niña event. The values of 0.5 to 1.0, or -0.5 to -1.0, correspond to a weak-to-moderate El Niño or La Niña event, respectively. Based on these thresholds of SOI and ONI, the intensity of those two-year periods (eight consecutive seasons) having a reversal of warm-to-cold ENSO episodes may be categorized, as shown in Table 1. As discussed above, two-year periods are considered here because some El Niño events are followed immediately by a La Niña event, with the pair of events spanning two full years. The examples of greatest interest to us here are the pairs observed in 2006–2008, 1997–1999, and 1987–1989. The seasonal sea-level deviations and the corresponding ONI values for these three two-year pairs are shown in Figure 4. Table 2 presents a comparative perspective of sea-level rise. In all three cases, during the second year of the two-year pairs (i.e. 2007, 1998, and 1988), the La Niña event is established by the JAS season (Figure 4, Table 1); therefore only the JAS season of this second year is examined in this analysis of the three cases. We primarily focus on tide-gauge locations that tend to show the greatest tidal range, while still presenting a representative view of the entire region.

Among these, the Micronesian Islands of Yap, Pohnpei, Kapingamarangi, and Chuuk displayed an alarming picture.[3] During the 2007/2008 La Niña event, Chuuk and Pohnpei sustained serious damage from high tides, and the governors of both states declared states of emergency. As a result, Presidential Disaster Declarations were issued by the US Government for all of the states in the FSM. Significant damage to crops (taro, breadfruit, banana, and coconut) and infrastructure greatly impacted the agriculture, economy and general livelihood of these island communities. Sea-level rise has also been observed in Guam, Palau and AS, but because of higher elevations and better developed infrastructure, it has not caused serious damage there. The RMI (Majuro and Kwajalein) also recorded sea-level rise, with some reports of minimal damage. Given the severity of damage caused in the FSM, those islands are the primary focus in the following analysis; however, we also include Guam and Pago Pago to help provide a comprehensive regional perspective.

As is evident from Table 2, the sea-level rise recorded in 2007/2008 was remarkably high at several locations. Despite somewhat smaller ONI values (indicating a weaker La Niña) as compared with the ONI values during the 1998/1999 and 1988/1989 events (relatively stronger La Niña events), most of the islands recorded higher sea levels during the 2007/2008 event. SOI and ONI are assumed to effectively determine the approximate strength of the El Niño and La Niña events, and less ENSO-related sea-level rise is expected in a weaker La Niña year than in a stronger La Niña year. Based on this loosely proportional relationship between ENSO strength and sea-level anomaly, scientific reasoning suggests that, in addition to the La Niña of 2007/2008, there must have been other factors responsible for this rise. This assumption is supported by the fact that the sea level in several locations was elevated above normal before the onset of La Niña in JAS of 2007/2008 (Figure 2). Since the sea level was already elevated even during the El Niño seasons (JAS and OND of 2006), the ensuing La Niña further elevated these levels. In such a case, the non-negligible recovery time for large volumetric changes underlying the sea level could limit the speed of the sea-level change. Nonetheless, the underlying question remains: why were sea levels higher than average during the weak-to-moderate El Niño year to begin with? In fact, the sea level for the two earlier cases clearly showed below-average sea level during the initial El Niño year. It has been shown in Table 1 that the El Niño part

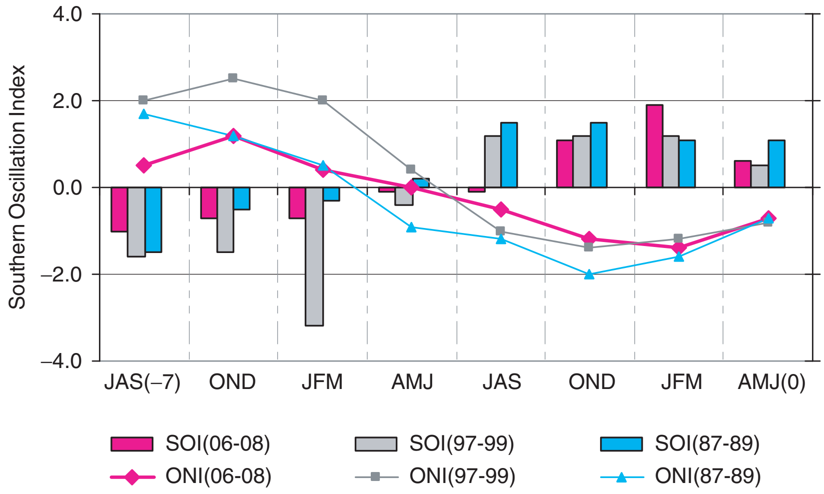

Figure 3. Seasonal time series of SOI and ONI for three two-year periods of the ENSO cycle.

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[2] The SOI and ONI data are taken from the Climate Prediction Center's (CPC) websites: (i) http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml, and (ii) http://www.cpc.ncep.noaa.gov/data/indices/soi

[3] Note that Chuuk does not currently have a tide-gauge station. However, although a comprehensive data analysis for Chuuk is not possible at this stage, available surrogate data reveals that sea-level variability in Chuuk is highly correlated to that of Yap.

(during JAS, OND, and JFM) of the other two cases was much stronger than that of 2006–2008, and this could be at least part of the reason for higher sea level in 2007/2008. But, again, the fact remains that the 2006/2007 sea levels were not much below average at all. Further study is needed here, and we are actively working to examine all possible causes. A possible cause other than global sea-level rise could involve the atmospheric circulation or zonal wind anomalies off the Equator, which might have significantly influenced the whole process. For example, easterly trade winds were stronger than normal in the western North Pacific during much of this El Niño, and this may have reduced the eastward transport of heat and the expected volumetric sea-level falls (Chowdhury *et al.,* 2007a).

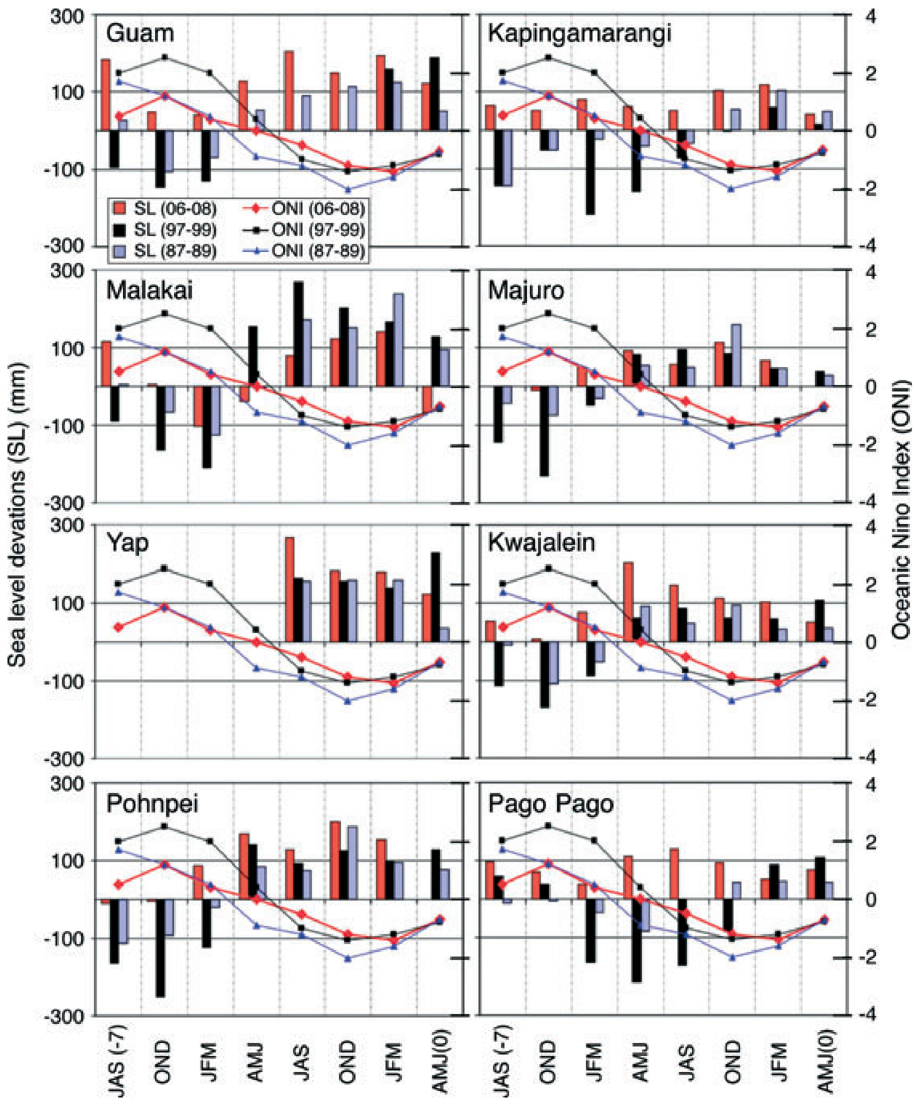

Figure 4. Seasonal sea-level deviations for three two-year periods of the ENSO cycle. Primary Y-axis: sea-level deviations; secondary Y-axis: ONI.

Sea-level variability and change: USAPI and global perspective

One immediate answer to this question appears to be in the tide-gauge records, which show a rising trend in sea levels at all stations, to varying degrees, over the past 15 to 20 years. This evidence supports the many anecdotal assertions that global extreme high-water levels have increased within recent decades (see Church *et al.* (2006) for more information on sea-level rise at tropical Pacific Islands). According to the Intergovernmental Panel for Climate Change (IPCC), global average sea level rose at a rate of 1.8 (1.3 to 2.3) millimetres per year over the period from 1961 to 2003. The rate was even faster from 1993 to 2003, with an average of about 3.1 (2.4 to 3.8) millimetres per year (IPCC, 2007a–2007c: Working Groups I, II, and III). This 3.1 millimetres per year rising trend is in approximate agreement with the rise observed in some of the USAPI locations, particularly within the FSM. In fact, the rate of rise at FSM is higher than that projected by the IPCC over the globe in general. The tide-gauge measurements elsewhere around the globe do indeed show qualitatively similar trends over the last two to three decades (Church *et al.,* 2006). Other scientific publications also projected sea-level rise in this century by a considerable amount (Hansen *et al.,* 2005; Otto-Bliesner *et al.,* 2006; Overpeck *et al.,* 2006; Rahmstorf, 2007). Sea-level represented by the upper layer volume (for 50–300 metres) across the

Table 2

Sea-level deviations in 2007/2008 minus deviations of 1998/1999, and sea-level deviations in 2007/2008 minus deviations of 1988/1989.

	Sea-level deviations in millimetres							
Season	Guam	Malakai	Yap	Pohnpei	Kapingamarangi	Majuro	Kwajalein	Pago Pago
JAS07–JAS88	+116.8	–93.9	+111.8	+53.3	+86.3	+7.6	+90.1	+129.5
JAS07–JAS98	*	–193.0	+104.1	+35.6	+127.0	–38.1	+58.4	+304.8
OND07–OND88	+33.0	–30.5	+22.9	+12.7	+48.3	–48.3	+17.8	+53.3
OND07–OND98	*	–81.3	+25.4	+76.2	+106.7	+27.9	+50.8	+180.3
JFM08–JFM89	+71.1	–99.1	+20.3	+60.9	+15.2	+22.9	+71.1	+5.1
JFM08–JFM99	+35.6	–27.9	+43.2	+58.4	+58.4	+22.9	+43.2	–38.1
AMJ08–AMJ89	+73.7	–165.1	+88.9	–78.7	–7.6	–27.9	+17.8	+33.0
AMJ08–AMJ99	–66.0	–198.1	–106.7	–129.5	+25.4	–38.1	–55.9	–33.0

* Missing data.

JAS (July-August-September), OND (October-November-December), JFM (January-February-March) and AMJ (April-May-June).

Pacific Ocean (15S–15N and 120E–80W) also show a similar rising trend (Figure 5; see Wyrtki (1985) for additional details).

Towards a more quantitative analysis, the trend of annual sea-level rise from 22 years (1987–2008) of sea-level deviation time series has been estimated and evaluated for statistical significance (Table 3). Based on both a simple linear regression (Hirschi *et al.,* 2007) and two-predictor multiple regression with NIÑO 3.4 SST and year number as predictors, the upward trends have been found to be positive in all cases; they are statistically significant in most cases of simple regression using the year number, and in nearly all cases when the ENSO state is accounted for with NIÑO 3.4 SST as a second predictor. More than half of the cases (19 out of a total of 32) exhibited statistical significance (at the 10% level or less) when the year number is the sole predictor. With the exception of the OND season, all seasons (JAS, JFM, and AMJ) experienced comparatively high annual rates of rise, and most of these trends are statistically significant. It is also notable that, despite a positive trend in Malakai and Yap, none of the relations for these two stations were found to be statistically significant (at the 10% level or less).

When ENSO is used as a second predictor, statistical significance of the trend is greatly increased (Table 3) because much of the non-trend variability is explained by ENSO. Here, 25 cases (out of 32) exhibited significance at the 1–10% level. Malakal and Yap also displayed significance in seasons JAS and OND. Because the seasons JAS and especially OND have the strongest ENSO signal, the statistical significance of the positive sea-level trend during those seasons is most greatly enhanced with inclusion of ENSO in the regression model.

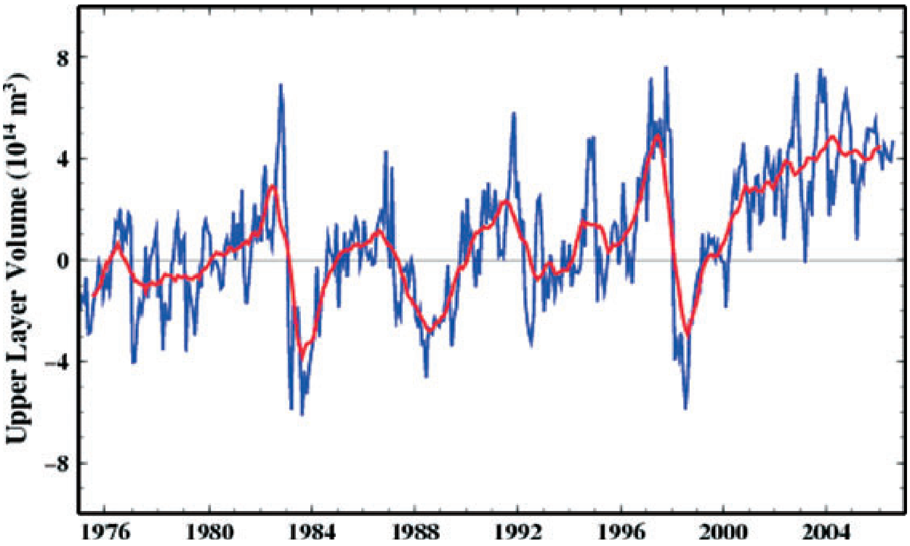

Figure 5. Upper layer volume in the Pacific Ocean (15S–15N and 120E–80W). Values are departures from a mean value of about 70x10^{14} m^3; the annual cycle is not removed here. (Source: http://ilikai.soest.hawaii.edu/uhslc/volume.html)

Table 3

Trend analysis and regression results (trends which are found to be significant at the 10% level are presented).

	Guam	Malakai	Yap	Pohnpei	Kapingamarangi	Majuro	Kwajalein	Pago Pago
Season JAS								
Trend alone								
Adjusted R^2	0.49	ns	ns	0.19	0.35	ns	0.19	0.26
Coefficient	9.8(4.5)****			6.0 (2.4)**	5.6 (3.5)***		4.2 (2.5)**	5.9 (2.9)***
Trend with ENSO included								
Adjusted R^2	0.64	0.61	0.74	0.84	0.34	0.50	0.64	0.27
Coefficient	9.5(5.4)****	3.8(1.8)*	6.2(3.2)***	5.7(5.2)****	5.5(3.4)***	2.3(1.8)*	4.0(3.5)***	5.9(2.9)***
Season OND								
Trend alone								
Adjusted R^2	0.18	ns	ns	ns	ns	ns	0.12	0.20
Coefficient	8.0 (2.3)**						4.9 (1.9)*	3.6 (2.5)***
Trend with ENSO included								
Adjusted R^2	0.69	0.85	0.84	0.89	ns	ns	0.89	0.17
Coefficient	7.5(3.6)****	4.8(3.4)***	4.4(2.8)***	4.5(3.2)***			4.4(5.2)****	3.6(2.5)**
Season JFM								
Trend alone								
Adjusted R^2	0.33	ns	ns	0.19	ns	0.18	0.22	0.11
Coefficient	10.8(3.3)***			6.6 (2.4)**		3.9 (2.3)*	5.0 (2.6)**	4.2 (1.9)*
Trend with ENSO included								
Adjusted R^2	0.71	ns	ns	0.88	ns	0.39	0.72	0.43
Coefficient	8.9(4.1)****			4.8(4.5)****		3.0(1.8)*	3.9(3.3)***	3.2(1.8)*
Season AMJ								
Trend alone								
Adjusted R^2	0.56	ns	ns	0.29	0.21	0.12	0.42	0.23
Coefficient	12.9(5.2)****			5.9 (3.1)***	5.2 (2.5)**	3.0 (1.9)*	6.7(3.4)****	7.3 (2.6)*
Trend with ENSO included								
Adjusted R^2	0.64	ns	ns	0.65	0.29	0.36	0.67	0.32
Coefficient	12.3(5.3)****			5.0(3.6)****	4.8(2.4)**	2.6(2.5)**	6.0(4.6)****	6.6(2.5)**

Numbers in parenthesis are t-values. Note that 1 asterisk (*) =0.10 significance, two(**)=0.05, three(***)=0.01, and four (****)=0.001. ns: not significant.

JAS (July-August-September), OND (October-November-December), JFM (January-February-March) and AMJ (April-May-June).

Concluding remarks

The sea-level rise in the USAPI for 1997 to 2008 maintains a close correspondence with the faster rate of predicted average global sea-level rise. However, it is unclear to what degree the rise is a reflection of recent decadal variability versus an actual increase in the rate of the longer-term trend; furthermore, we do not wish to explicitly attribute the sea-level rise to anthropogenic global warming at this time. However, the implication of global warming is certainly present, and subject to readers' interpretation for now. While more research is necessary to test the hypotheses of the longer-term trend, our immediate observations confirm that the sea levels have recorded a rise at most of the USAPI stations over approximately the last 20 years. Despite some uncertainties in sea-level behaviour, these findings from the USAPI are significant as they demonstrate that the rate of sea-level rise in parts of the tropical Pacific basin is higher than the general global projections made by the IPCC.

This regional example demonstrates the importance and societal ramifications of sea-level rise. Moreover, it supports the observations of sea-level rise worldwide, generating greater confidence that the rate of observed sea-level rise has increased from the nineteenth century to the start of the twenty-first century.

The material presented here is largely exploratory and empirical. However, the nature of the findings points to a path for future research to confirm more objectively their physical causes, and possible future scenarios. A more formal modelling effort is warranted – whether statistical, dynamical, or a combination of both. For example, the results of the IPCC-AR4 model output can be downscaled to target the USAPI region both statistically and with the use of regional dynamical models. The downscaled results may indicate features of SSTs, sea level and climate in greater spatial detail; a comparison of these results with the recent observations presented here may facilitate a better understanding of and greater confidence in why the pattern of recent increases in sea level has been taking place.

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