J Coast Conserv
DOI 10.1007/s11852-010-0086-3

# Sea level extremes in the U.S.-Affiliated Pacific Islands—a coastal hazard scenario to aid in decision analyses

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Received: 18 May 2009 / Revised: 3 November 2009 / Accepted: 5 January 2010

**Abstract** The objective of this study is to provide a perspective on the extremes of sea-level variability and predictability for the U.S.-Affiliated Pacific Islands (USAPI) on seasonal time-scales. Based on the Generalized Extreme Value (GEV) model, the *L*-moments method has been used to estimate the model parameters. The bootstrap method has been used to define the exceedance probability level of upper and lower bounds of the return periods at the 90% confidence interval. On the basis of these return calculations and expected extremes of high sea level, the seasonal maxima of sea level and the varying likelihood of extreme events have been estimated. For analyzing the predictability of the extremes of sea-level, a canonical correlation analysis (CCA) statistical model has been developed. Findings reveal that there is seasonal climatology of extreme events in the vicinity of USAPI that are variable on temporal and spatial scales. Some of the islands (Yap and Saipan) display considerably higher seasonal extremes than the others for 20 to 100 year return periods because of typhoon-related storm surges. These surges are likely to cause huge tidal large sea-level inundations and increased erosion to low-lying atolls/islands and result in considerable damage to roads, harbors, unstable sandy beaches, and other major infrastructures. Finally, the need for evaluating the extreme events and associated typhoons from a regional perspective has been stressed for coastal hazard management decision analyses in the USAPI.

**Keywords** Sea level · Generalized Extreme Value (GEV) · Intergovernmental Panel for Climate Change (IPCC) · Canonical Correlation Analyses (CCA) · U.S.—Affiliated Pacific Islands (USAPI)

## Introduction

The U.S.-Affiliated Pacific Islands (USAPI) include the Territory of Guam, Republic of Palau (R-Palau), Commonwealth of the Northern Mariana Islands (CNMI), Republic of the Marshall Islands (RMI), Federated States of Micronesia (FSM), and American Samoa (Fig. 1). Other than American Samoa, these islands are small, low lying, highly vulnerable to coastal surges and are subject to sea-level changes on seasonal to longer time scales. The most vulnerable communities are those of impoverished peoples occupying marginal environments (see http://www.soest.

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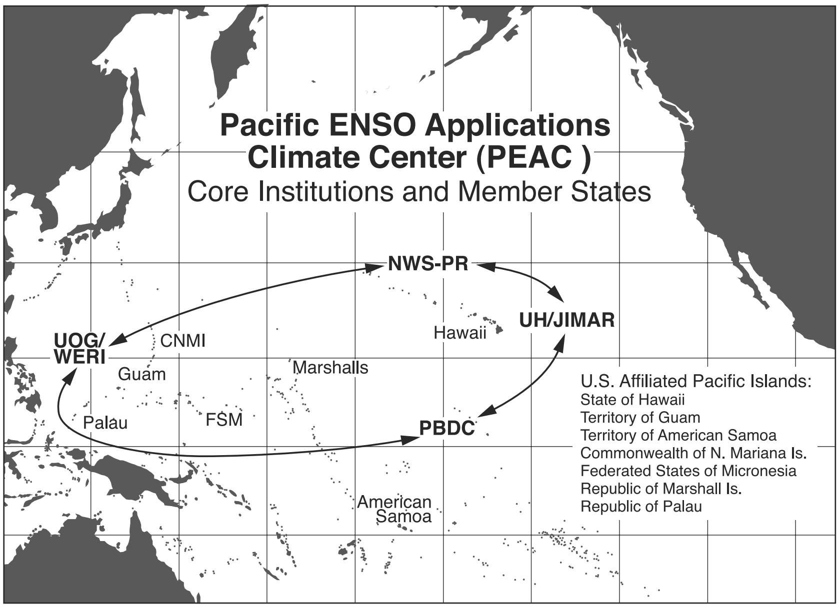


**Fig. 1** Geographical locations (see Table I for latitude/longitude) of the U.S.-Affiliated Pacific Islands (USAPI). Note that the core institutions of PEAC are the University of Hawaii-Joint Institute for Marine and Atmospheric Research (UH/JIMAR), the National Weather Service-Pacific Region (NWS-PR), the University of Guam-Water and Energy Research Institute (UOG/WERI), and the Pacific Basin Development Council (PBDC)

hawaii.edu/MET/Enso/map/map.html for details on environmental settings of these islands). Therefore, all of the coastal structures and activities in these islands need to adapt to this temporal fluctuation in sea level. As a result, there is a demand for sea-level information that can define thresholds on seasonal timescales.

The monthly sea-level variability of most of these northern Pacific Islands by and large displays a strong annual cycle with a gradual increase of sea-level from January to July and recession from July to December (Chowdhury et al,. 2007a). On the other hand, the lone south Pacific island (American Samoa), tended to show several peaks in the annual cycle. The El Niño-Southern Oscillation (ENSO) climate cycle has been found to have a strong impact on the sea-level variability at these islands. In general, El Niño (either strong/or moderate) corresponded to low sea-level, and La Nina (strong/or moderate) corresponded to high sea-level in these islands.

The Generalized Extreme Value (GEV) method has been used for analyzing the extremes of sea level. This is justified by the fact that the distribution of the maximum of a sample of independent and identically distributed variables converges to the GEV distribution as the length of the sample goes to infinity (Gnedenko 1943; Zwiers and Kharin, 1998). The bootstrap resampling method is used here to simulate the sampling distributions of the sea levels at return periods from 1 to 100 years. This method provides upper and lower bounds of the probability estimates of the return periods. The central assumption in applying the bootstrap technique is to represent the population by the available sample. A complementary paper on sea level extremes and hazard management for the Hawaiian and U.S.-Trust islands has been published (Chowdhury et al. 2008). Based on these GEV analyses, the exceedance probability graphs for high sea levels are prepared for four successive seasons: January-February-March (JFM), April-May-June (AMJ), July-August-September (JAS), and October-November-December (OND).

As there is a demand for advance information on sea-level extremes, the potential scope for predictability of sea-level has been investigated from the ENSO climate cycle. Previous studies of Chowdhury et al. (2007a, b) have identified that the sea level variations in the USAPI are very strongly correlated with the ENSO cycle and SSTs in the tropical Pacific Ocean. From this correlation, an operational canonical correlation analysis (CCA) statistical model for forecasting the seasonal mean sea-level variations has been developed. The present CCA model, which uses monthly maximum data, is an expansion of our previous study in which the CCA model was developed from monthly mean data.

Finally, following an overview of the GEV model and climatology of sea-level extremes, the results are compared and evaluated with respect to the global sea-level rise, and the impact of extremes is studied for coastal hazard management in the USAPI.

## Data

Research-quality, hourly sea-level data are used in this study (Source: http://ilikai.soest.hawaii.edu/uhslc/rqds.html). All these sea-level heights have been referred to the station *tide staff zero* which is linked to fixed bench marks. The sea level change over 30 to 50 years was found to be small relative to the variability of the extremes, so no further correction factor was added. Exact locations

**Table 1** Geographical details (latitude, longitude) and length of data records for each of the tide sea-level gauge stations

| Islands | Tide gauge stations | Latitude | Longitude | Years of data records |
|---|---|---|---|---|
| Guam | Marianas | 13.44°N | 144.65°E | 1948–2003 |
| CNMI | Saipan | 15.23°N | 145.75°E | 1978–2003 |
| R-Palau | Malakai | 7.33°N | 134.47°E | 1969–2003 |
| FSM | Yap | 9.51°N | 138.14°E | 1973–2004 |
| FSM | Pohnpei | 6.98°N | 158.25°E | 1974–2004 |
| FSM | Kapingamarangi | 1.1°N | 154.78°E | 1978–2003 |
| Marshalls | Majuro | 7.1°N | 171.36°E | 1968–2004 |
| Marshalls | Kwajalein | 8.73°N | 167.73°E | 1946–2003 |
| A-Samoa | Pago Pago | 14.29°S | 170.69°W | 1948–2004 |

CNMI, R-Palau, FSM, and A-Samoa stands for Commonwealth of the Northern Mariana Islands, Republic of Palau, Federated States of Micronesia, and American Samoa respectively.

(latitude, longitude) and length of data records of the tide gauge stations are listed in Table 1 (note that because of lack of data; the station Chuuk at FSM could not be included for further analyses). This study utilizes only historical data recorded by a tide gauge. The technical aspects of quality-control procedures of these sea-level data have been well documented in Kilonsky and Caldwell (1991) and Caldwell and Kilonsky (1992).

## GEV, return periods, and climatology of seasonal extremes

This paper is intended to be a complementary paper to Chowdhury et al. (2008). Therefore, relevant explanations for probability and cumulative distribution functions (PDF and CDF) of GEV are not provided here; these are summarized in Chowdhury et al. (2008) (also see Gnedenko, 1943; Efron and Tibshirani, 1993; Chu and Wang, 1997; Zwiers and Kharin, 1998; Katz et al., 2002; Coles 2001; Mendez et al., 2007; Felici et al, 2007; and Chu et al., 2009 for a comprehensive treatment of GEV, *L*-moments, and bootstrap analysis). A common approach to model extreme events is to use two-parameter (location, scale) Gumbel distribution. In this study, a three-parameter (location, scale, and shape) GEV is used because the introduction of the shape parameter is found to improve the fit of the upper tail of the distribution.

Sea-level extremes for seasonal (JFM, AMJ, JAS and OND) scale on 1 to 100 year return periods have been plotted, with both upper and lower bounds being at the 90% confidence level. The upper and lower bounds of sea level extremes are presented in Table 2. Although we did not design a sensitivity test with the GEV model, the bootstrap procedure itself actually has implied it. If we look at the bootstrap method, it involves a large number of random resampling; the confidence level provides a bound for the estimation, and the margin between the two bounds (given a fixed quantile or return period, either way) can be a good measure of the sensitivity of the estimated value.

Note that the monthly sea-level fluctuations of North Pacific islands are significantly correlated to each other (Chowdhury et al., 2007a); therefore, for simplicity, GEV plots for only a few stations are presented in this paper. Seasonal extremes in Guam are presented in Fig. 2. Pago-Pago and Yap are shown in Fig. 3 (*left* and *right* panels). Pago-Pago, the lone south Pacific island in this study, is included because it displays slightly different monthly sea-level fluctuations. Yap is shown here as this is the most vulnerable island, the habitability of which is seriously affected by a combination of extreme events, sea-level rise, and typhoon activities. Note that because of typhoon-affected data, very wide intervals were seen in the GEV plots of Yap in some seasons (i.e., JFM and AMJ) (Fig. 4). These typhoon-affected data are removed and the GEV plots are re-drawn (Fig. 3, *right panel*); the results are presented with and without the typhoon-affected data. Also, note that *typhoon* refers to a strong tropical cyclone in the region of the western North Pacific (WNP) Ocean and seems to be modulated by inter-annual and inter-decadal oscillations in the atmosphere/ocean.

Figure 2 (JFM, AMJ, JAS, and OND) shows that, as the return period increases, the upper and lower bounds of the exceedance level widen. Compared to the other three seasons, the upper and lower bounds of the JFM exceedance level are narrowly separated, indicating less uncertainty in JFM. The AMJ and OND displayed wider upper and lower confidence intervals. The JAS displays the widest gap between the upper and lower boundaries, implying that the uncertainty in predicting JAS sea level extremes is greater than the other three seasons at higher recurrence intervals. Some narrow intervals were noticeable in Pago-Pago (Fig. 3, *left panel*). Other stations—Majuro and Kwajalein—also displayed narrow intervals (not shown).

With a few exceptions, most of the stations displayed similar features in their upper-and lower-bound exceedance levels. As mentioned, among the exceptions, very wide intervals were seen in Saipan (for season OND) and Yap (for seasons JFM and AMJ) (Fig. 4). The reason for these

**Table 2** Lower and upper bound limits of sea level extremes at 20 and 100 year return period (Note that these are deviations of the extremes from the average seasonal signal)

| Stations | Sea level extremes (mm) at 20year Return Period | | | | Sea level extremes (mm) at 100year Return Period | | | |
|---|---|---|---|---|---|---|---|---|
| | **JFM** | **AMJ** | **JAS** | **OND** | **JFM** | **AMJ** | **JAS** | **OND** |
| Marianas (Guam) | 119~159 | 110~168 | 96~228 | 120~203 | 138~202 | 138~243 | 151~441 | 155~299 |
| Saipan | 98~188 | 79~152 | 122~214 | 93~228<br>**(127~675)**[a] | 127~285 | 97~214 | 166~333 | 57~628<br>**(395~1846)**[a] |
| Malakal (Palau) | 170~301 | 127~194 | 163~230 | 108~220 | 243~479 | 162~278 | 204~311 | 111~306 |
| Yap | 129~329<br>**(210~624)**[a] | 45~170<br>**(138~624)**[a] | 163~244 | 132~285 | 45~170<br>**(299~1394)**[a] | 70~315<br>**(186~1687)**[a] | 213~341 | 163~425 |
| Pohnpei | 108~179 | 106~186 | 102~178 | 146~289 | 126~244 | 132~278 | 117~240 | 179~411 |
| Kapingamarangi | 112~243 | 70~184 | 54~127 | 84~193 | 135~350 | 79~265 | 60~177 | 90~250 |
| Majuro | 71~122 | 80~128 | 84~167 | 119~195 | 88~163 | 93~164 | 105~243 | 149~269 |
| Kwajalein | 96~129 | 79~128 | 81~119 | 101~149 | 122~176 | 98~175 | 101~157 | 117~192 |
| Pago-Pago | 69~131 | 121~166 | 72~131 | 57~93 | 88~194 | 143~211 | 92~190 | 71~120 |

[a] Results with typhoon-affected data are bold (in parenthesis), JFM, AMJ, JAS, and OND stand for January-February-March, April-May-June, July-August-September, and October-November-December

high values is that Saipan and Yap have undergone large and significant *storm tides*.

It is therefore evident from the discussion that the GEV shape parameter can change significantly, making a big difference in the 20 and 100 year levels when the record contains only a few tropical cyclone events (Figs. 3 and 4). Upon removal of typhoon-affected data, the range of variability is notably reduced. For example, with typhoon-affected data, Yap displayed 138~624 mm and 186~1687 mm rise on 20 and 100 year return periods; these values are found to be 45~170 mm and 70~315 mm when the typhoon-affected data is removed (Table 2). Broad discussions related to GEV and typhoon is beyond the scope of this study, so we simply present two types of plots (with and without typhoon) here for the affected sites. The intent here is to provide a perspective of the extreme events and associated typhoon activities for coastal hazard management decision analyses.

## Synopsis of sea level extremes

The deviations of sea-level extremes are presented in Fig. 5. Note that these are deviations of the extremes from the

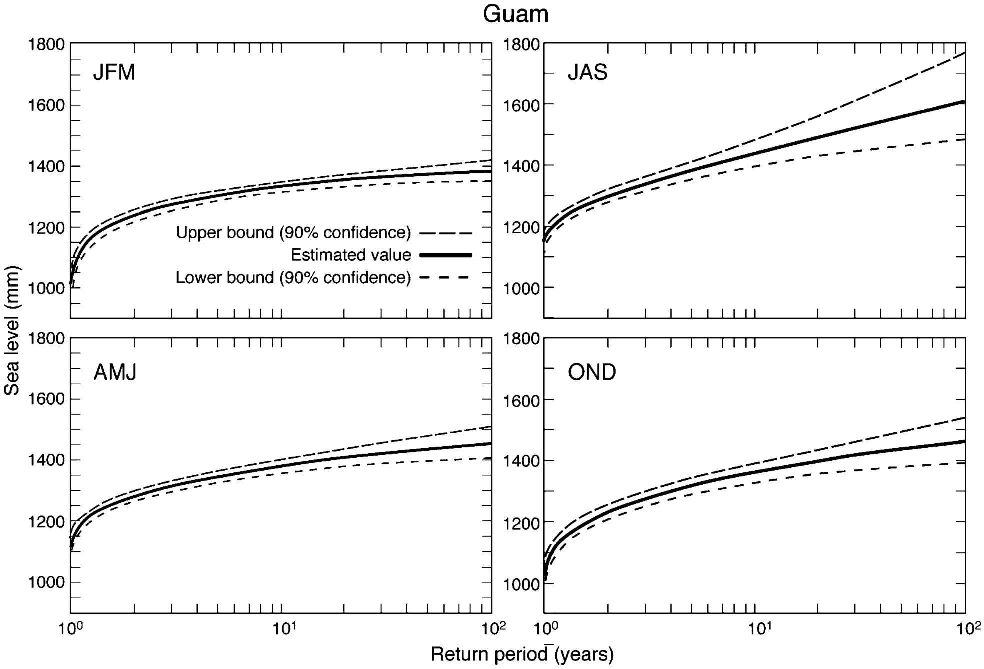
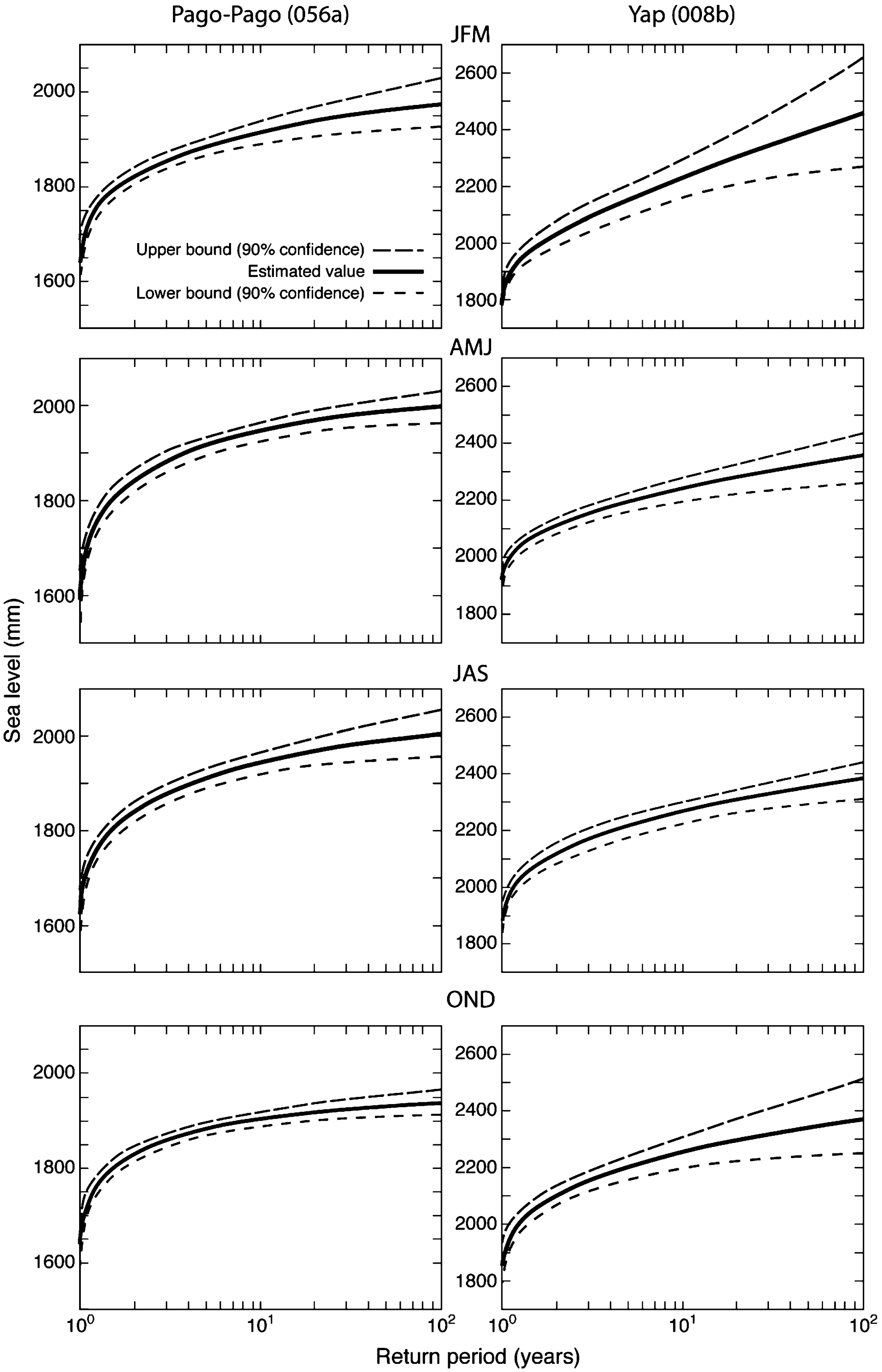


**Fig. 2** The seasonal extreme values for Guam at 1 to 100 years return periods. The solid line shows the estimated value by analyzing the true observations. The dashed and dotted lines demonstrate the upper and lower bounds at 90% confidence level. The X-axis denotes return periods (years), Y-axis denotes elevation of high sea level (mm) relative to the station tide staff zero, which is linked to fixed bench marks

**Fig. 3** Same as Fig. 2 except for Pago-Pago (left panel) and Yap (right panel). Note that typhoon-affected data for JFM and AMJ seasons were removed from Yap



average seasonal signal. While the median is sometimes considered to be a more robust statistic, we are using the mean here, partly because the 'University of Hawaii Sea Level Center' (UHSLC) calculates monthly mean sea levels. These analyses maintain uniformity and provide an added advantage to compare and coordinate with the UHSLC data base. We have not applied any sensitivity testing to the selection of this reference period. However, according to the UHSLC, the results would not change much if we were to select a longer period or the same period of time but with different start and end years. Note that these deviations are calculated by subtracting the

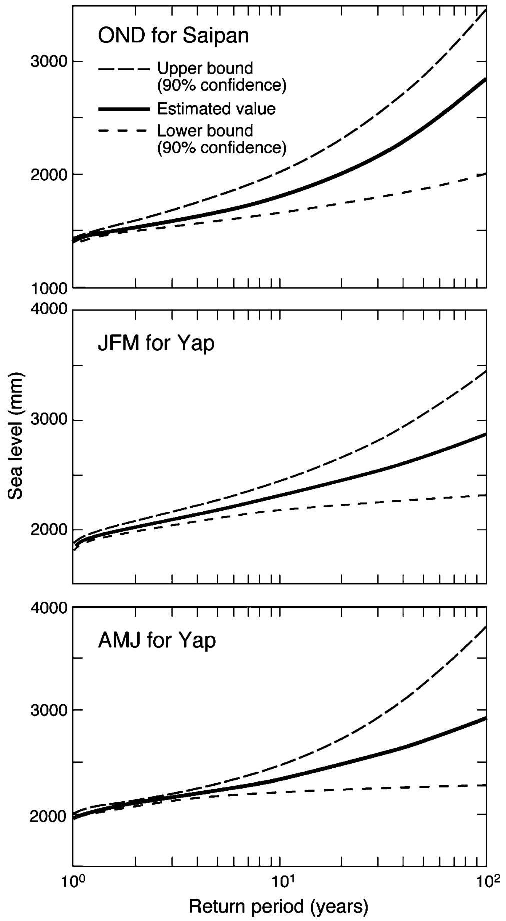


**Fig. 4** Same as Figs. 2 and 3 except for typhoon-affected sites/data (Saipan for season OND; Yap for seasons JFM and AMJ)

average seasonal signal from the extremes. Also note that any deviations of 200 mm or more can cause serious adverse impact for all islands except for Micronesian islands (i.e., Yap, Pohnpei, and Kapingamarangi), where 150 mm deviations can cause similar adverse impacts.

For the 20 year return period (henceforth, 20 RP), an extreme sea level rise of 100–200 mm is prevalent for most stations. For the 100 year return period (henceforth, 100 RP), a higher extreme is observed. As evident from Fig. 5, all North Pacific stations experienced *the greatest* positive deviations either in OND or in JFM, while the lone south Pacific station (Pago Pago) tended to show the *greatest* positive deviations in AMJ, with 1–2 seasons time lag as compared to North Pacific stations. In general, the variations of the tropical Pacific sea-surface temperatures (SST) and the resultant atmospheric circulations in the equatorial Pacific are responsible for this lag relationship.

Observations have revealed that, among others, on 20 RP and 100 RP, Saipan and Yap recorded remarkably high extreme values in several seasons (OND for Saipan; JFM and AMJ for Yap) (Fig. 5; Table 2). As previously mentioned, the reason for these high values is that Saipan was hit by super typhoons (STY) *Kim* on December 03, 1986, and *Wilda* on October 25, 1994. Similarly, the entire State of Yap was threatened by Typhoon *Mitag* [closest point of approach (CPA) intensity winds 100-knot] on March 1–3, 2002. Typhoon *Sudal* hit Yap during the Easter weekend (April 8–9) of 2004 packing 115-knot winds and waves of more than 10.7 m.

Despite a slight positive deviation in Guam and Malakal, other neighboring stations recorded no considerable variations caused by the same storm events. The most likely cause of this abrupt positive deviation at a specific station is that typhoons are mesoscale systems and only affect a narrow swath under the storm path. Therefore, while Saipan and Yap were severely affected by a typhoon, other stations remained less or unaffected by the same storm.

A comprehensive analysis on historical typhoon statistics is beyond the scope of this study. However, it is noted here that most tropical cyclones that develop in the WNP form in the monsoon trough (Lander, 1994). On the interannual time scale, the most prominent influence on tropical cyclone activity over the WNP is due to El Niño and La

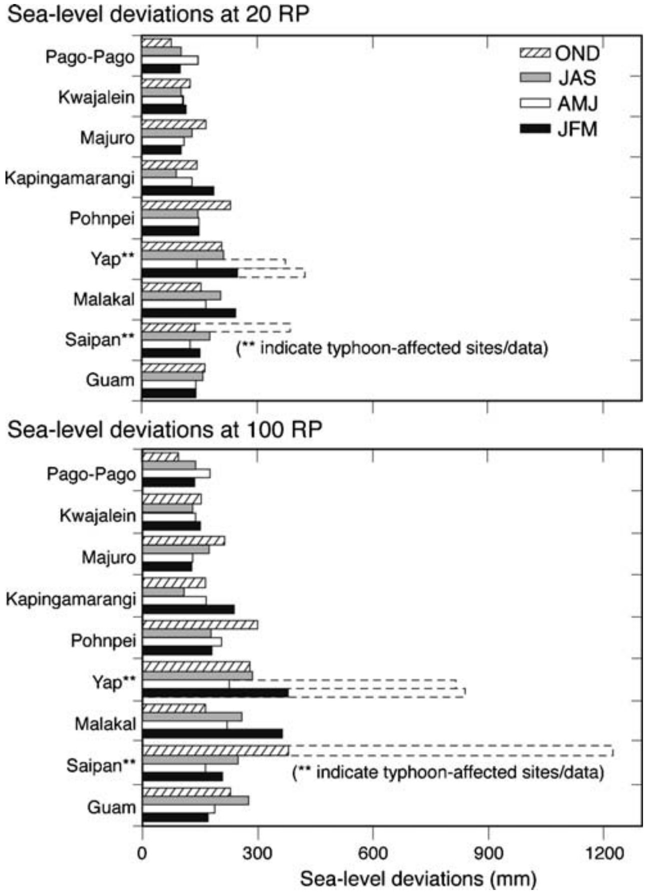


**Fig. 5** Seasonal sea-level deviations for all selected sites at (i) 20 RP (top panel) and (ii) 100 RP (bottom panel). Note that OND, JAS, AMJ, and JFM are the respective seasons

Niña events and, on inter-decadal time scales, this has a periodicity of about 20 years or longer. During El Niño, the genesis region for tropical Pacific shifts eastward and equatorward, but during La Niña the genesis region shifts westward and poleward (Chu, 2004).

## Sea-level extremes and hazard scenario: USAPI

It is evident from Fig. 5 that, except for Saipan and Yap, a projected extreme event causing a positive deviation of 0.10 ~ 0.30 m is expected within the vicinity of USAPI for a shorter return period (20 RP) (also see Table 2). While a 0.10 m deviation may cause sea-level inundations, a deviation of 0.30 m can cause tidal inundations and increased erosion. This in turn causes damage to roads, harbors, and unstable sandy beaches, etc. It may also adversely affect marine ecosystems, wastewater, and infrastructures. For a longer return period (100 RP), positive deviation of 0.10 ~ 0.50 m is expected. As before, while a 0.10 m positive deviation may cause sea-level inundations, a positive deviation of 0.50 m can cause serious tidal inundations and major permanent erosion. This can result in serious adverse effects on wetlands, private property, roads, unstable sandy beaches, airports, harbors, and most utilities. For small low-lying islands like Yap and Chuuk, which has a land area of only 119 $km^2$, the situation is the most severe. As evident from the 2007–08 La Niña events, several small islands (Majuro, Kwajalein, Yap, and Chuuk) were affected by the high tides (0.15 ~ 0.2 m higher than the normal). Among others, Chuuk and Yap sustained serious damage and declared states of emergency. Roads and other infrastructures in several villages in Chuuk were invaded by salt water during high tides and waves. Significant damage to crops (taro, breadfruit, banana, and coconut) was reported and greatly impacted the economy, agriculture, and general livelihood of these island communities.

## Global sea-level rise and potential implications: small island countries

The sea level in the USAPI displays a long-term rising trend (Church et al., 2006). This trend shows a close correspondence with the Intergovernmental Panel for Climate Change (IPCC) report, which indicates a *20<sup>th</sup> century* global sea-level rise at an average rate of 1.8 mm per year (IPCC, 2007a). The rate was higher over 1993 to 2003: about 3.1 [2.4–3.8] mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer-term trend is unclear. There is *high confidence* that the rate of observed sea-level rise increased from the 19th to the 20th century.

The IPCC report has already projected that coasts are to be exposed to increasing risks, including coastal erosion, due to climate change and sea-level rise (IPCC, 2007b). The effect will be exacerbated by increasing human-induced pressures on coastal areas. Low-lying reef islands on the rim of atolls are perceived as particularly vulnerable to the impacts of sea-level rise (Woodroffe, 2008). While IPCC projections of sea-level rise increase concern globally, it is especially alarming for the small island countries like the USAPI. As observed from the 20 years (1988–08) of tide-gauge records, the rising trend in the USAPI stations shows a close correlation with the faster rate of rise as observed by IPCC (i.e., 3.1 mm/year). In fact, a recent study by Chowdhury et al. (2010) shows some stations within the FSM exhibit a rate of rise even higher. Therefore, the implication seems to be that a number of these regions will continue to experience greater than average sea level rise. These islands are therefore especially vulnerable to the effects of climate change, sea level rise, and extreme events.

While sea-level rise alone can cause many adverse impacts, the combination of extreme events (e.g., typhoons) and long-term sea-level rise will have a devastating impact on these islands. Such effects may include increased coastal and beach erosion, higher and more frequent storm-surge flooding with more extensive coastal inundation, changes in surface water quality and groundwater availability, increased loss of coastal property and habitats, increased flood risk and potential loss of life, loss of cultural resources and values, impacts on agriculture and aquaculture through decline in soil and water quality, and loss of tourism, recreation, and transportation functions (see Hay and Mimura, 2005; Mimura, 1999; Woodroffe, 2008 and references therein for a comprehensive discussion of the impact of sea-level rise and island communities).

Deterioration in coastal conditions, such as erosion of beaches and coral bleaching, is expected to affect local resources, e.g., fisheries, and reduce the value of these destinations for tourism. On many small islands, critical infrastructure tends to be located in or near coastal areas; this infrastructure would be highly vulnerable to the effects of extreme events. Inundation, storm surge, erosion and other coastal hazards, will thus threaten vital infrastructure, settlements, and facilities that support the livelihood of island communities. Major impacts are likely to occur in agriculture and forestry ecosystems as a result of increasing salinity in irrigation water, estuaries, and freshwater systems. The decreasing freshwater availability due to saltwater intrusion will then affect the health sector by increasing risk of deaths and injuries by drowning in floods; migration-related health effects, and food availability. Finally, the commerce, settlement, and society will be affected by the increased costs of coastal protection, costs of land-use relocation; and potential for movement of populations and infrastructure (IPCC 2007b; Table SPM-1).

## CCA model forecast and hindcast skill for seasonal maxima

Because one of the main goals of this study is to forecast sea-level extremes, a canonical correlation analysis (CCA) statistical model for seasonal sea-level forecasts with seasonal maxima has been developed here.

The ENSO climate cycle and the sea-surface temperatures (SSTs) in the tropical Pacific Ocean are taken as the primary factors in modulating sea-level variations on the seasonal time scales. The robustness of the ENSO and sea-level relationship has been examined by analyzing the composites of seasonal variations and by correlating the SST time-series at each geographical grid-point with sea levels at various gages. For this study, the Extended Reconstructed SST (ERSST: version 2) data (Smith and Reynolds, 2002) from the National Oceanic and Atmospheric Administration (NOAA)—National Climate Data Center (NCDC) have been used. This SST data for the tropical region covered by latitude (30 S ~30 N) and longitude ($100^0$E ~$60^0$W) have been downloaded from the web link of International Research Institute for Climate and Society (IRI) (http://iridl.ldeo.columbia.edu/expert/SOURCES/.NOAA/.NCDC/.ERSST/.SST/). The time record is from January 1950 to December 2006. Data-related discussions are not extended further here, as more comprehensive discussions on this issue are available in Chowdhury et al, 2007b.

The hindcast skill of the CCA model for 1975–2006 is estimated using a cross-validated scheme. The CCA method has been described extensively in the literature (see Barnston 1994; Chu and He 1994; Barnston and He 1996; Barnston and Smith 1996; and Yu et al. 1997). Also, a similar discussion on CCA analyses for sea-level forecasts for the USAPI communities is available in Chowdhury et al, 2007b. Therefore, only a short summary of some of the most interesting findings is presented in the following section.

To provide a predictive skill at longer lead time, CCA cross-validation skills up to three seasons in advance are calculated; the average skills at 0 to 3 seasons lead time are presented in Fig. 6. As indicated, different islands show different levels of predictive skill. In general the forecast skills for all stations are well predicted with average correlation skills of 0.639, 0.556, 0.506, and 0.474 at 0 to 3 seasons lead time, respectively. Among all islands, the average predictive skill for Pohnpei has been found to be strongest (0.761 and 0.631) at 0 and 1 season lead time, respectively. Other than Kapingamarangi and Majuro, which tended to show a relatively lower skill, all other stations displayed similar correlation skills.

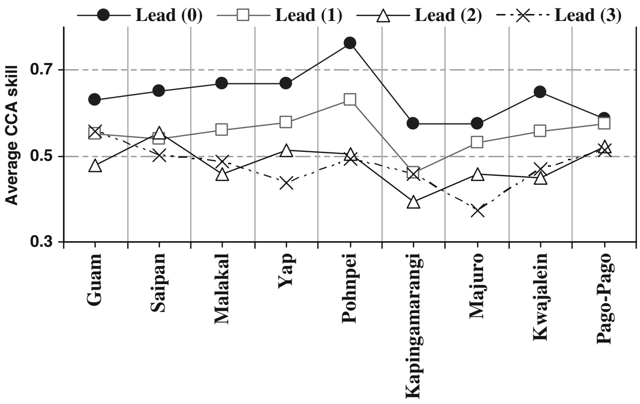


**Fig. 6** Average CCA cross-validation hindcast skills at 0 to 3 seasons lead time. Note that Leads 0, 1, 2, and 3 indicate 'sea-level' of target season (say for example, JFM) based on SSTs of previous seasons OND (lead 0), JAS (lead 1), AMJ (lead 2), and JFM (lead 3) respectively

It is worth noting here that, as compared to sea-level forecasts from seasonal mean, the overall forecast skills from the seasonal maxima have been found to be slightly low. A simple answer for this lowered skill is that the CCA analysis is primarily rooted on the mean values, so it handles the mean data better than the maximum values. Based on the tropical Pacific SST alone, more skillful CCA forecasts from the same sea-level data are unlikely. Perhaps a complete overhaul with a different SST region (i.e., other than in the tropics) would slightly change the forecasting skill. Alternatively, with the addition of other oceanic/atmospheric variables (indices), the predictive skill of sea-level forecasts may be improved, but it will make the model more complicated for operational use in the USAPI. A comprehensive research related to these issues is in progress.

## Summary and conclusions

One of the findings is that two islands (Saipan and Yap) have recorded extreme sea levels caused by direct hits by typhoons. These two extreme values have significantly affected the GEV shape parameters, making the return period curve rise rapidly as return periods approach large values. This is a clear indication that one or two extreme events can change the shape parameter from negative to positive, making a big difference in the return calculations. If other stations had such a direct hit in the past 100 years their GEV curves may resemble the Saipan and Yap curves. It was very difficult for us to verify if there were any typhoon events that remained unrecorded; moreover, some of the islands have no tide gauges (e.g., Chuuk). However, our current experience yields no strong reason to believe that other stations would not encounter the similar storm surges in the future to those experienced by Saipan. Therefore, the extreme events of Saipan and Yap should be seen as a problem for the whole region, and a unified regional planning approach for coastal hazard management is essential to tackle this problem.

(i) In addition to considering the consequences of extreme events and long-term sea level rise, the island communities will continue to face short-term or medium-term sea-level variability. In some locations in the Pacific (i.e., Chuuk and Yap in FSM) temporary rises in sea level from storms, tides, and ENSO events raise the sea level even higher than is projected for the next century.

(ii) Most of the coastal hazards are climate related; so management of these hazards will need the integration of weather and climate monitoring in the process. Therefore, expanding our capability in areas of observing the ocean and the atmosphere for accurate and timely forecasts of extreme sea level is necessary.

(iii) The coastal management policies and plans for most of these islands are not well developed, e.g., there are few sea walls or dykes to protect existing property and infrastructure. To confirm the level of government interest in the issue of sea level extremes and rise, new legislation and resolutions related to these issues are essential.

Finally, the return period analyses presented here are conservative when considering the potential for an increased rate of sea level rise. For example, a return interval could bring a higher elevation than initially expected. Or, that same interval could shrink, and bring back present levels sooner than anticipated. Current analysis is stationary, and needs adjustment to account for future sea level rise.

**Acknowledgments** This project was funded by cooperative agreement NA17RJ1230 between the Joint Institute for Marine and Atmospheric Research (JIMAR) and the National Oceanic and Atmospheric Administration (NOAA). The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subdivisions. This is SOEST contribution 6573.

Grateful acknowledgements are expressed to three anonymous reviewers for their valuable comments. We express our gratitude to Dr. Mark Merrifield and Ms. Shikiko Nakahara of the University of Hawaii Sea Level center for providing valuable comments on sea level data. Also, grateful acknowledgements are due to other PEAC colleagues Mr. James Weyman, Ms. Eileen Shea, Dr. Mike Hamnett, Mr. Charles Chip Guard, Dr. Mark Lander, Dr. Cheryl Anderson, Julie Earp, and Sarah Duncan. Finally, thanks are also due to Ms. Diane Henderson and Nancy Hulbirt for proof editing.

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