

**Sea Level Extremes in the U.S.-Affiliated Pacific Islands—A coastal hazards scenario to aid in decision analyses**

Journal:	<i>Meteorological Applications</i>
Manuscript ID:	MET-08-0042.R3
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	27-Mar-2009
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Keywords:	Sea level, generalized extreme value (GEV), IPCC, canonical correlation analyses (CCA), U.S.-Affiliated Pacific Islands



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**Sea Level Extremes in the U.S.-Affiliated Pacific Islands—A coastal  
hazard scenario to aid in decision analyses**

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**March 2009**

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## Sea Level Extremes in the U.S.-Affiliated Pacific Islands—a coastal hazards scenario to aid in decision analyses

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**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 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 activities 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), and U.S.-Affiliated Pacific Islands (USAPI).

## 1. 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 (Figure 1). 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.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 of 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

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3 distribution as the length of the sample goes to infinity (Gnedenko 1943; Zwiers and  
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5 Kharin, 1998). The bootstrap resampling method is used here to simulate the sampling  
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7 distributions of the sea levels at return periods from 1 to 100 years. This method provides  
8  
9 upper and lower bounds of the probability estimates of the return periods. The central  
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11 assumption in applying the bootstrap technique is to represent the population by the  
12  
13 available sample. A complementary paper on sea level extremes and hazard management  
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15 for the Hawaiian and U.S.-Trust islands has been published (Chowdhury *et al.* 2008).  
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17 Based on these GEV analyses, the exceedance probability graphs for high sea levels are  
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19 prepared for four successive seasons: January-February-March (JFM), April-May-June  
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21 (AMJ), July-August-September (JAS), and October-November-December (OND).  
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27 As there is a demand for advance information on sea-level extremes, the potential  
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29 scope for predictability of sea-level has been investigated from the ENSO climate cycle.  
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31 Previous studies of Chowdhury *et al.* (2007a, b) have identified that the sea level  
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33 variations in the USAPI are very strongly correlated with ENSO cycle and the SSTs in  
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35 the tropical Pacific Ocean. From this correlation, an operational canonical correlation  
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37 analysis (CCA) statistical model for forecasting the seasonal mean sea-level variations  
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39 has been developed. The present CCA model, which uses monthly maximum data, is an  
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41 expansion of our previous study in which the CCA model was developed from monthly  
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43 mean data.  
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48 Finally, following an overview of the GEV model and climatology of sea-level  
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50 extremes, the results are compared and evaluated with respect to the global sea-level rise,  
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52 and the impact of extremes is studied for coastal hazard management in the USAPI.  
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## 2. Data

Research-quality, hourly sea-level data are used in this study (Source: <http://ilikai.soest.hawaii.edu/uhs/c/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 here. Exact locations (latitude, longitude) and length of data records of the tide gauge stations are listed in Table I (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).

## 3. GEV, Return Periods, and Climatology of Seasonal Extremes

This paper is intended to be a complementary paper of 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 S, 2001; Mendez *et al.*, 2007; Felici *et al.*, 2007; and Chu *et al.*, 2008 for a comprehensive treatment of GEV, *L*-moments, and bootstrap analysis).

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 II. 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

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3 lot of random resampling; the confidence level provides a bound for the estimation, and  
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5 the margin between the two bounds (given a fixed quantile or return period, either way)  
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7 can be a good measure of the sensitivity of the estimated value.  
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10 Note that the monthly sea-level fluctuations of north Pacific islands are  
11 significantly correlated to each other (Chowdhury *et al.*, 2007a); therefore, for simplicity,  
12 GEV plots for a few stations are presented in this paper. Seasonal extremes in Guam are  
13 presented in Figure 2 [(i) to (iv)]. Pago-Pago and Yap are shown in Figure 3 (*left* and  
14 *right* panels). Pago-Pago is shown because this is the lone south Pacific island in this  
15 study and it displays slightly different monthly sea-level fluctuations. Yap is shown here  
16 as this is the most vulnerable island, the habitability of which is seriously affected by a  
17 combination of extreme events, sea-level rise, and typhoon activities. Note that because  
18 of typhoon-affected data, very wide intervals were seen in the GEV plots of Yap in some  
19 seasons (i.e., JFM and AMJ). This typhoon-affected data are removed and the GEV plots  
20 are re-drawn; the results are presented with and without the typhoon-affected data. Also,  
21 note that *typhoon* refers to a strong tropical cyclone in the region of the western North  
22 Pacific (WNP) Ocean and seems to be modulated by inter-annual and inter-decadal  
23 oscillations in the atmosphere/ocean.  
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43 Figure 2 shows that, as the return period increases, the upper and lower bounds of  
44 the exceedance level widen. Compared to the other three seasons, the upper and lower  
45 bounds of JFM exceedance level are more narrowly separated, indicating less uncertainty  
46 in JFM [Figure 2 (i)]. The AMJ and OND displayed wider upper and lower confidence  
47 intervals [Figures 2 ((ii) and (iv))]. The JAS displays the widest gap between the upper  
48 and lower boundaries, implying that the uncertainty in predicting JAS sea level extremes  
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3 is greater than the other three seasons at higher recurrence intervals [Figure 2 (iii)]. Some  
4 narrow intervals were noticeable in Pago-Pago (Figure 3, *left panel*). Other stations—  
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8 Majuro and Kwajalein—also displayed narrow intervals (not shown in Figure 3).  
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11 With a few exceptions, most of the stations displayed similar features in their  
12 upper-and lower-bound exceedance levels. As mentioned, among the exceptions, very  
13 wide intervals were seen in Saipan (for season OND) and Yap (for seasons JFM and  
14 AMJ). The reason for these high values is that Saipan and Yap have undergone large and  
15 significant *storm tides*. GEV Plots for these sites with typhoon-affected data are shown in  
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22 Figure 4.  
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25 It is therefore evident from the discussion that the GEV shape parameter can  
26 significantly change, making a big difference in the 20 and 100 year levels when the  
27 record contains only a few tropical cyclone events (Figures 3 and 4). Upon removal of  
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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.

#### 4 Synopsis of Sea Level Extremes

The deviations of sea-level extremes are presented in Figure 5. Note that these  
are deviations of the extremes from the average seasonal signal. While the median is



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3 sometimes considered to be a more robust statistic, we are using the mean here, partly  
4 because the 'University of Hawaii Sea Level Center' (UHSLC) calculates monthly mean  
5 sea levels. These analyses maintain uniformity and provide an added advantage to  
6 compare and coordinate with the UHSLC data base. We have not applied any sensitivity  
7 testing to the selection of this reference period. However, according to the UHSLC, the  
8 results would not change much if we were to select a longer period or the same period of  
9 time but with different start and end years (Personal communications). Note that these  
10 deviations are calculated by subtracting the average seasonal signal from the extremes.  
11 Also note that any deviations of 200 mm or more can cause serious adverse impact for all  
12 islands except for Micronesian islands (i.e., Yap, Pohnpei, and Kapingamarangi), where  
13 150 mm deviations can cause similar adverse impacts.  
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29 For the 20 year return period (henceforth, 20 RP), an extreme sea level rise of  
30 100-200 mm is prevalent for most stations. For the 100 year return period (henceforth,  
31 100 RP), a higher extreme is observed. As evident from Figure 5, all north Pacific  
32 stations experienced *the greatest* positive deviations either in OND or in JFM, while the  
33 lone south Pacific station (Pago Pago) tended to show the *greatest* positive deviations in  
34 AMJ, with 1-2 seasons time lag as compared to north Pacific stations. In general, the  
35 variations of the tropical Pacific sea-surface temperatures (SST) and the resultant  
36 atmospheric circulations in the equatorial Pacific are responsible for this lag relationship.  
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48 Observations have revealed that, among others, on 20 RP and 100 RP, Saipan  
49 and Yap recorded remarkably high extreme values in several seasons (OND for Saipan;  
50 JFM and AMJ for Yap) (Figure 5; Table II). As mentioned, the reason for these high  
51 values is that Saipan was hit by super typhoons (STY) *Kim* on December 03, 1986, and  
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3 *Wilda* on October 25, 1994. Similarly, the entire State of Yap was threatened by Typhoon  
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5 *Mitag* [closest point of approach (CPA) intensity winds 100-knot] on March 1-3, 2002.  
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8 Typhoon *Sudal* hit Yap during the Easter weekend (April 8-9) of 2004 packing 115-knot  
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10 winds and waves of more than 10.7 m.  
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13 Despite a slight positive deviation in Guam and Malakal, other neighboring  
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15 stations recorded no considerable variations caused by the same storm events. The  
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17 probable reason for this abrupt positive deviation at a specific station is that typhoons are  
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19 mesoscale systems and only affect a narrow swath under the storm path. Therefore, while  
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21 Saipan and Yap were severely affected by a typhoon, other stations remained less or  
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23 unaffected by the same storm.  
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27 A comprehensive analysis on historical typhoon statistics is beyond the scope of  
28  
29 this study. However, it is noted here that most tropical cyclones that develop in the WNP  
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31 form in the monsoon trough (Lander, 1994). On the inter-annual time scale, the most  
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33 prominent influence on tropical cyclone activity over the WNP is due to El Niño and La  
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35 Niña events and, on inter-decadal time scales, this has a periodicity of about 20 years or  
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37 longer. During El Niño, the genesis region for tropical Pacific shifts eastward and  
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39 equatorward, but during La Niña the genesis region shifts westward and poleward (Chu,  
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41 2004).  
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#### 45 46 **5.0 Sea-level Extremes and Hazard Scenario: USAPI**

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48 It is evident from Figure 5 that, except for Saipan and Yap, a projected extreme  
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50 event causing a positive deviation of 0.10~0.30 m is expected within the vicinity of  
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52 USAPI for a shorter return period (20 RP) (also see Table II). While a 0.10 m deviation  
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54 may cause slight local inundations, a deviation of 0.30 m can cause tidal inundations and  
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3 increased erosion. This in turn causes damage to roads, harbors, and unstable sandy  
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5 beaches, etc. It may also adversely affect marine ecosystems, wastewater, and  
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7 infrastructures. For a longer return period (100 RP), positive deviation of 0.10~0.50 m is  
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9 expected. As before, while a 0.10 m positive deviation may cause slight local inundation,  
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11 a positive deviation of 0.50 m can cause serious tidal inundations and major permanent  
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13 erosions. This can result in serious adverse effects on wetlands, private property, roads,  
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15 unstable sandy beaches, airports, harbors, and most utilities. For small low-lying islands  
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17 like Yap and Chuuk, which has a land area of only 119 km<sup>2</sup>, the situation is the most  
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19 severe. As evident from the 2007-08 La Niña events, several small islands (Majuro,  
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21 Kwajalein, Yap, and Chuuk) were affected by the high tides (0.15~0.2 m higher than the  
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23 normal). Among others, Chuuk and Yap sustained serious damage and declared states of  
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25 emergency. Roads and other infrastructures in several villages in Chuuk were invaded by  
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27 salt water during high tides and waves. Significant damage to crops (taro, breadfruit,  
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29 banana, and coconut) was reported and greatly impacted the economy, agriculture, and  
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31 general livelihood of these island communities.  
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## 38 **6. Global Sea-level Rise and Potential Implications: Small Island Countries**

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41 The primary mechanism for global sea-level rise is thermal expansion of the  
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43 oceans. Glaciers also make an important contribution. Thermal expansion is thought to  
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45 play a significant role in its contribution to the global mean sea-level (GMSL) budget.  
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47 Just as the mechanisms for GMSL are varied, the distribution of sea-level rise is not  
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49 uniform globally either. The geographic distribution of sea-level rise reveals that the most  
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51 significant changes are concentrated in the low-latitude central and eastern Pacific and  
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53 parts of the eastern Indian Ocean near Indonesia [IPCC, 2007a (chapter 5)]. Other areas  
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3 reflect signs of sea-level fall, such as in the Central Indian Ocean and along the central  
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5 equatorial Pacific.  
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8 The sea level in the USAPI displays a long-term rising trend (Church *et al.*,  
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10 2006). This trend shows a close correspondence with the Intergovernmental Panel for  
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12 Climate Change (IPCC) report, which indicates a 20<sup>th</sup> century global sea-level rise at an  
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14 average rate of 1.8 mm per year (IPCC, 2007a). The rate was higher over 1993 to 2003:  
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16 about 3.1 [2.4-3.8] mm per year. Whether the faster rate for 1993 to 2003 reflects decadal  
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18 variability or an increase in the longer-term trend is unclear. There is *high confidence* that  
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20 the rate of observed sea-level rise increased from the 19th to the 20th century.  
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25 The IPCC report has already projected that coasts are to be exposed to increasing  
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27 risks, including coastal erosion, due to climate change and sea-level rise (IPCC, 2007b).  
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29 The effect will be exacerbated by increasing human-induced pressures on coastal areas.  
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31 Low-lying reef islands on the rim of atolls are perceived as particularly vulnerable to the  
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33 impacts of sea-level rise (Woodroffe, 2008). While IPCC projections of sea-level rise  
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35 increase concern globally, it is especially alarming for the small island countries like the  
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37 USAPI. As observed from the 20 years (1988-08) of tide-gauge records, the rising trend  
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39 in the USAPI stations shows a close correlation with the faster rate of rise as observed by  
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41 IPCC (i.e., 3.1 mm/year). In fact, for some stations within the Federated States of  
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43 Micronesia, the rate of rise is even higher (*Pacific ENSO Update*, 2008). The implied  
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45 implication seems to be that these regions will continue to experience greater than  
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47 average sea level rise. These islands are therefore especially vulnerable to the effects of  
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49 climate change, sea level rise, and extreme events.  
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3 While sea-level rise alone can cause many adverse impacts, the combination of  
4 extreme events (e.g., typhoons) and long-term sea-level rise will have a devastating  
5 impact on these islands. Such effects may include increased coastal and beach erosion,  
6 higher and more frequent storm-surge flooding with more extensive coastal inundation,  
7 changes in surface water quality and groundwater availability, increased loss of coastal  
8 property and habitats, increased flood risk and potential loss of life, loss of cultural  
9 resources and values, impacts on agriculture and aquaculture through decline in soil and  
10 water quality, and loss of tourism, recreation, and transportation functions (see Hay and  
11 Mimura, 2005; Mimura, 1999; Woodroffe, 2008 and references therein for a  
12 comprehensive discussion of the impact of sea-level rise and island communities).  
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27 Deterioration in coastal conditions, such as erosion of beaches and coral bleaching,  
28 is expected to affect local resources, e.g., fisheries, and reduce the value of these  
29 destinations for tourism. On many small islands, critical infrastructure tends to be located  
30 in or near coastal areas; this infrastructure would be highly vulnerable to the effects of  
31 extreme events. Inundation, storm surge, erosion and other coastal hazards, will thus  
32 threaten vital infrastructure, settlements, and facilities that support the livelihood of  
33 island communities. The increased incidence of extreme high sea level (excludes  
34 tsunamis) is, according to the IPCC, a likely event with 66 to 90% probability. Major  
35 impacts are likely to occur in agriculture and forestry ecosystems as a result of increasing  
36 salinity in irrigation water, estuaries, and freshwater systems. The decreasing freshwater  
37 availability due to saltwater intrusion will then affect the health sector by increasing risk  
38 of deaths and injuries by drowning in floods; migration-related health effects, and food  
39 availability. Finally, the commerce, settlement, and society will be affected by the  
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3 increased costs of coastal protection, costs of land-use relocation; and potential for  
4 movement of populations and infrastructure (IPCC 2007b; Table SPM-1).  
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## 7. CCA Model Forecast and Hindcast Skill for Seasonal Maxima

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10 Because one of the main goals of this study is to forecast sea-level extremes, a  
11 canonical correlation analysis (CCA) statistical model for seasonal sea-level forecasts  
12 with seasonal maxima has been developed here.  
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17 The ENSO climate cycle and the sea-surface temperatures (SSTs) in the tropical  
18 Pacific Ocean are taken as the primary factors in modulating sea-level variations on the  
19 seasonal time scales. The hindcast skill of the CCA model for 1975-2006 is estimated  
20 using a cross-validated scheme. The CCA method has been described extensively in the  
21 literature (see Barnston 1994; Chu and He 1994; Barnston and He 1996; Barnston and  
22 Smith 1996; and Yu *et al.* 1997). Also, a similar discussion on CCA analyses for sea-  
23 level forecasts for the USAPI communities is available in Chowdhury *et al.*, 2007b.  
24 Therefore, only a short summary of some of the most interesting findings is presented in  
25 the following section.  
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38 To provide a predictive skill at longer lead time, CCA cross-validation skills up to  
39 three seasons in advance are calculated; the average skills at 0 to 3 seasons lead time are  
40 presented in Figure 6. As indicated, different islands show different levels of predictive  
41 skill. In general the forecast skills for all stations are well predicted with average  
42 correlation skills of 0.639, 0.556, 0.506, and 0.474 at 0 to 3 seasons lead time,  
43 respectively. Among all islands, the average predictive skill for Pohnpei has been found  
44 to be strongest (0.761 and 0.631) at 0 and 1 season lead time, respectively. Other than  
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3 Kapingamarangi and Majuro, which tended to show a relatively lower skill, all other  
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5 stations displayed similar correlation skills.  
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8 It is worth noting here that, as compared to sea-level forecasts from seasonal  
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10 mean, the overall forecast skills from the seasonal maxima have been found to be slightly  
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12 low. A simple answer for this lowered skill is that the CCA analysis is primarily rooted  
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14 on the mean values, so it handles the mean data better than the maximum values. Based  
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16 on the tropical pacific SST alone, more skillful CCA forecasts from the same sea-level  
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18 data are unlikely. Perhaps a complete overhaul with a different SST region (i.e., other  
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20 than in the tropics) would slightly change the forecasting skill. Alternatively, with the  
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22 addition of other oceanic/atmospheric variables (indices), the predictive skill of sea-level  
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24 forecasts may be improved, but it will make the model more complicated for operational  
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26 use in the USAPI. A comprehensive research related to these issues is in progress.  
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### 31 **8. Summary and Conclusions**

32 One of the most important findings revealed that two islands (Saipan and Yap)  
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34 have recorded extreme sea levels caused by direct hits by typhoons. These two extreme  
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36 values have significantly affected the GEV shape parameters, making the return period  
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38 curve rise rapidly as return periods approach large values. This is a clear indication that  
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40 one or two extreme events can change the shape parameter from negative to positive,  
41  
42 making a big difference in the return calculations. If other stations had such a direct hit in  
43  
44 the past 100 years their GEV curves may resemble the Saipan and Yap curves. It was  
45  
46 very difficult for us to verify if there were any typhoon events that remained unrecorded;  
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48 moreover, some of the islands have no tide gauges (e.g., Chuuk). However, our current  
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50 experience yields no strong reason to believe that other stations would not experience the  
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3 same storm surges in the future as Saipan and Yap. Therefore, the extreme events of  
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5 Saipan and Yap should be seen as a problem for the whole region, and a unified regional  
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7 planning approach for coastal hazard management is essential to tackle this problem.  
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11 (i) In addition to considering the consequences of extreme events and long-term  
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13 sea level rise, the island communities will continue to face short-term or  
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15 medium-term sea-level variability. In some locations in the Pacific (i.e.,  
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17 Chuuk and Yap in FSM) temporary rises in sea level from storms, tides, and  
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19 ENSO events raise the sea level even higher than is projected for the next  
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21 century.  
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- 24 (ii) Most of the coastal hazards are climate related; so management of these  
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26 hazards will need the integration of weather and climate monitoring in the  
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28 process. Therefore, expanding our capability in areas of observing the ocean  
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30 and the atmosphere for accurate and timely forecasts of extreme sea level is  
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32 necessary.  
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- 35 (iii) The coastal management policies and plans for most of these islands are not  
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37 well developed, e.g., there are few sea walls or dykes to protect existing  
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39 property and infrastructure. To confirm the level of government interest in the  
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41 issue of sea level extremes and rise, new legislation and resolutions related to  
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43 these issues are essential.  
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48 Finally, considering the potential for increased rates of sea level rise, the return  
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50 analyses are best considered minimums. For example, we have a 20 year return interval,  
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52 that due to sea level rise, in 20 years will have a higher elevation than it does now or 20  
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54 years from now the elevation now expected to be achieved on average only once in every  
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3 20 years will be likely to be achieved more frequently than that. The current analysis is  
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5 stationary, and in reality or ideally it needs to be "bumped-up" to account for future sea  
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7 level rise.  
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## 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, and Ms. Sarah Jones. Finally, thanks are also due to Ms. Diane Henderson and Nancy Hulbirt for proof editing.

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Table I: Geographical details (latitude, longitude) and length of data records for each of the tide 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

Note: 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. Note that because of lack of data, the stations Chuuk at FSM could not be included for further analyses.

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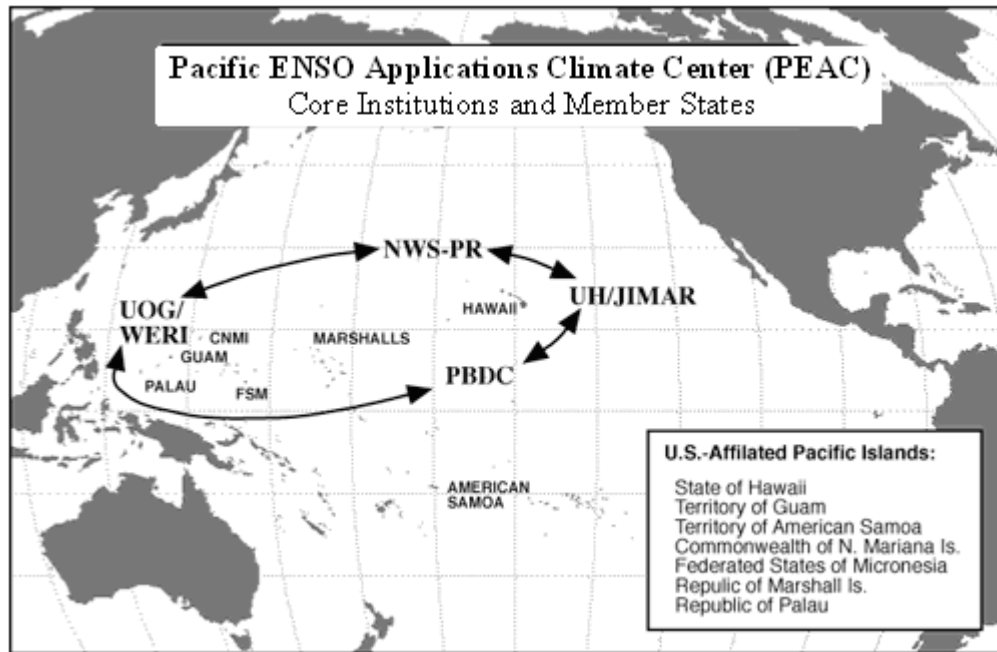
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Table II: Lower and upper bound limits of sea level extremes at 20 and 100 year return period (Note that these are deviations of the extremes from the average seasonal signal)

Stations	Sea level extremes (mm) at 20 year Return Period				Sea level extremes (mm) at 100 year 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 <b>(127~675)*</b>	127~285	97~214	166~333	57~628 <b>(395~1846)*</b>
Malakal (Palau)	170~301	127~194	163~230	108~220	243~479	162~278	204~311	111~306
Yap	129~329 <b>(210~624)*</b>	45~170 <b>(138~624)*</b>	163~244	132~285	45~170 <b>(299~1394)*</b>	70~315 <b>(186~1687)*</b>	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

Note: Left and right number denotes lower and upper bound limits, \* indicates results with typhoon-affected data, JFM, AMJ, JAS, and OND stand for January-February-March, April-May-June, July-August-September, and October-November-December.



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Figure 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).

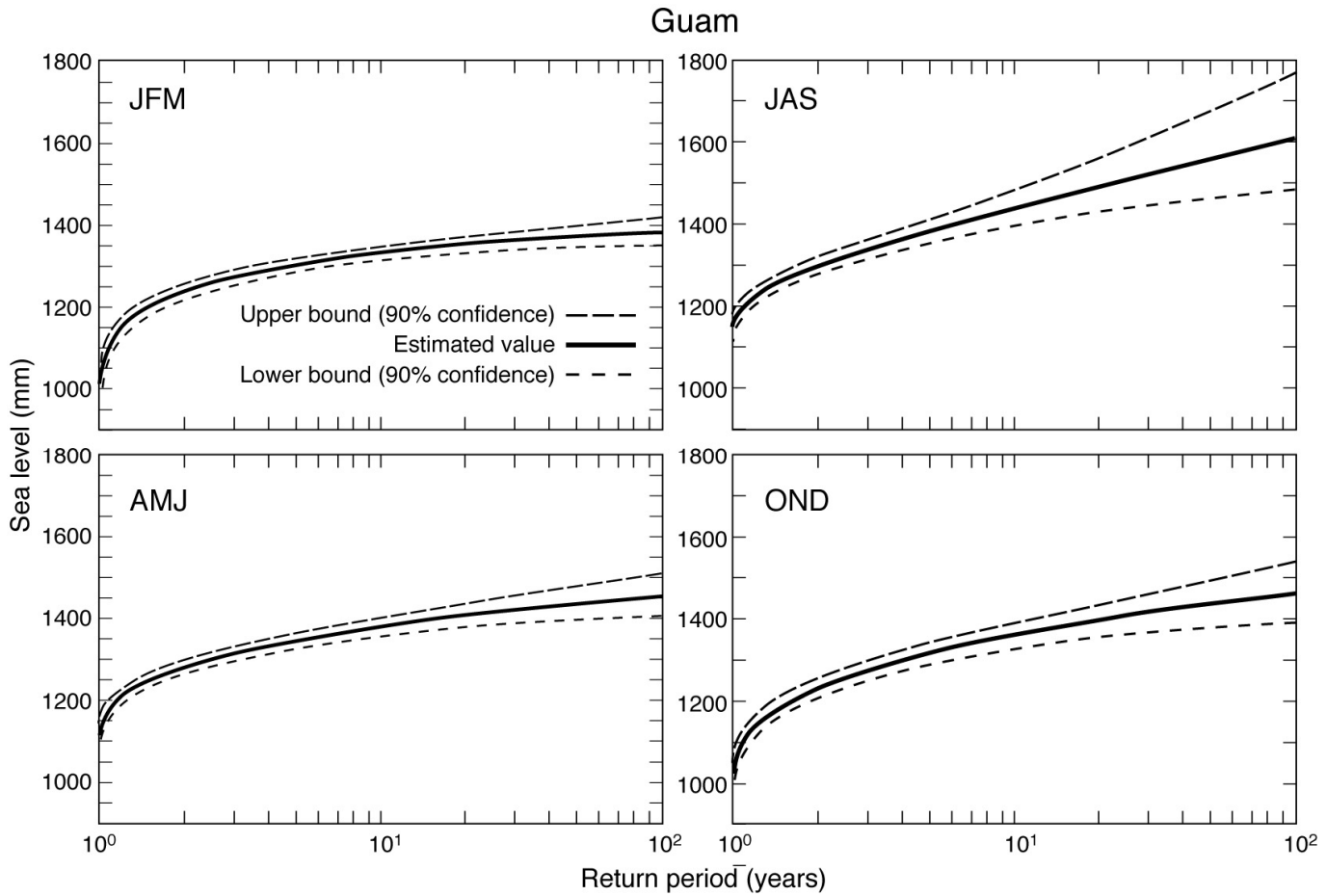


Figure 2: The seasonal extreme values for Guam at 1 to 100 years return periods. The solid line shows the estimated value by analyzing the true observations. The dashed and dotted lines demonstrate the upper and lower bounds at 90% confidence level. The X-axis denotes return periods (years), Y-axis denotes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

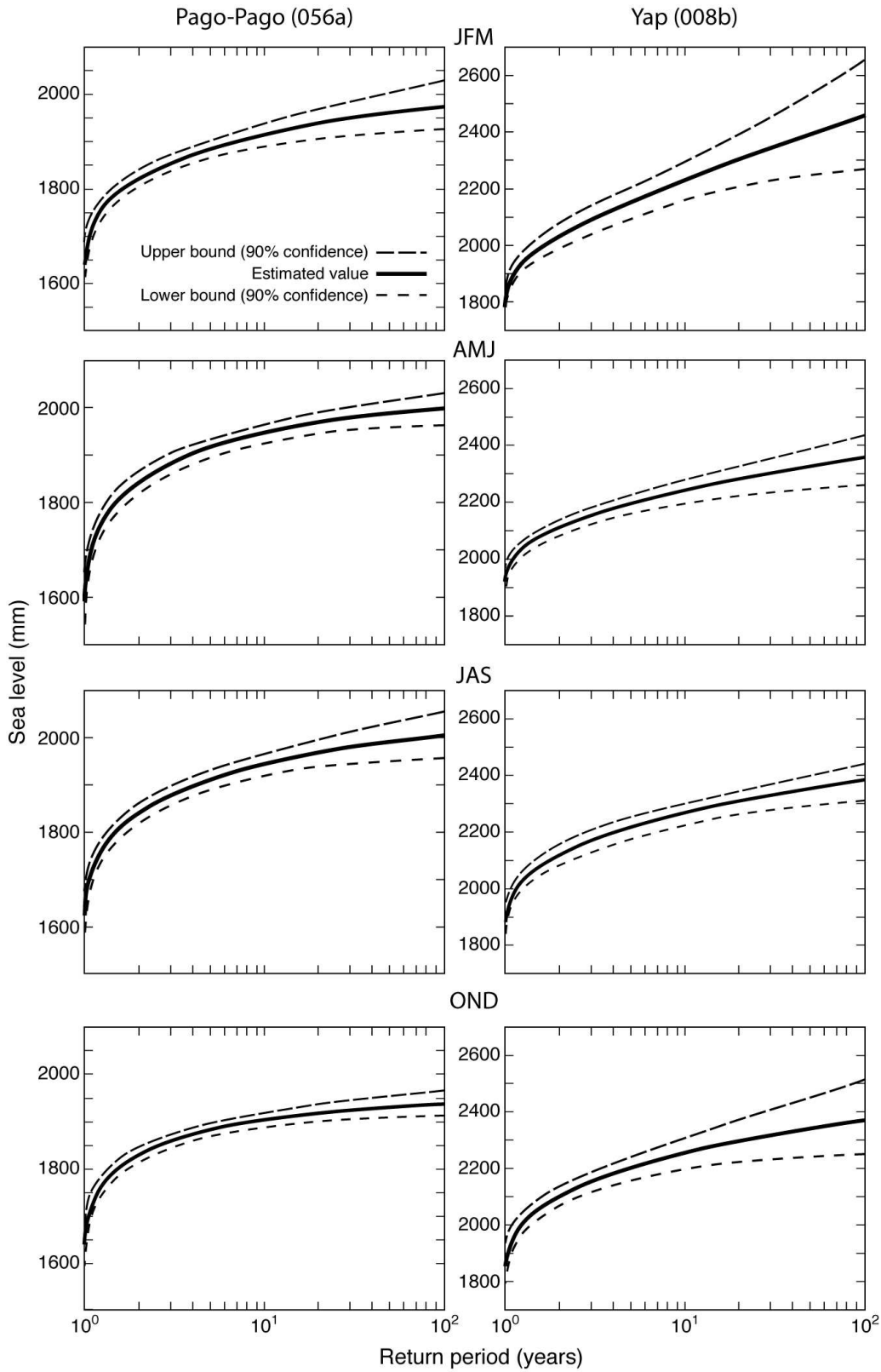


Figure 3. Same as Figure 2 except for Pago-Pago (left panel) and Yap (right panel). Note that typhoon-affected data for JFM and AMJ seasons were removed from Yap.

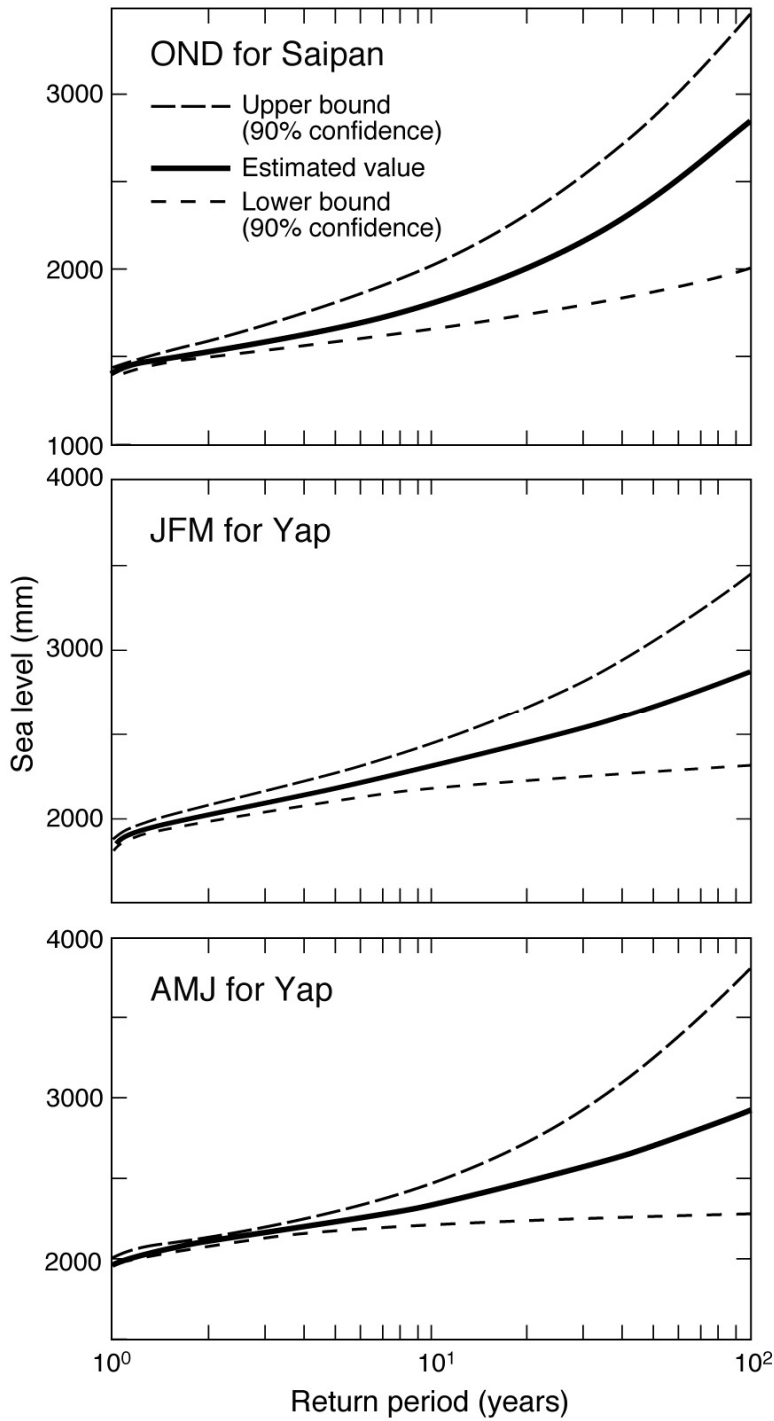
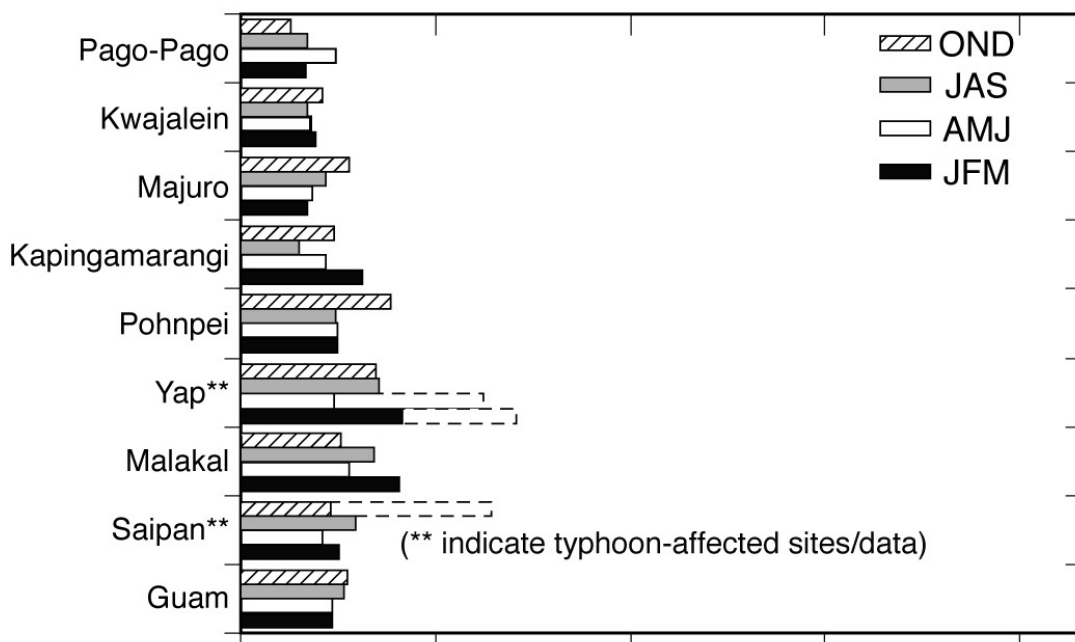


Figure 4. Same as Figure 2 and 3 except for typhoon-affected sites/data (Saipan for season OND; Yap for seasons JFM and AMJ).

Sea-level deviations at 20 RP



Sea-level deviations at 100 RP

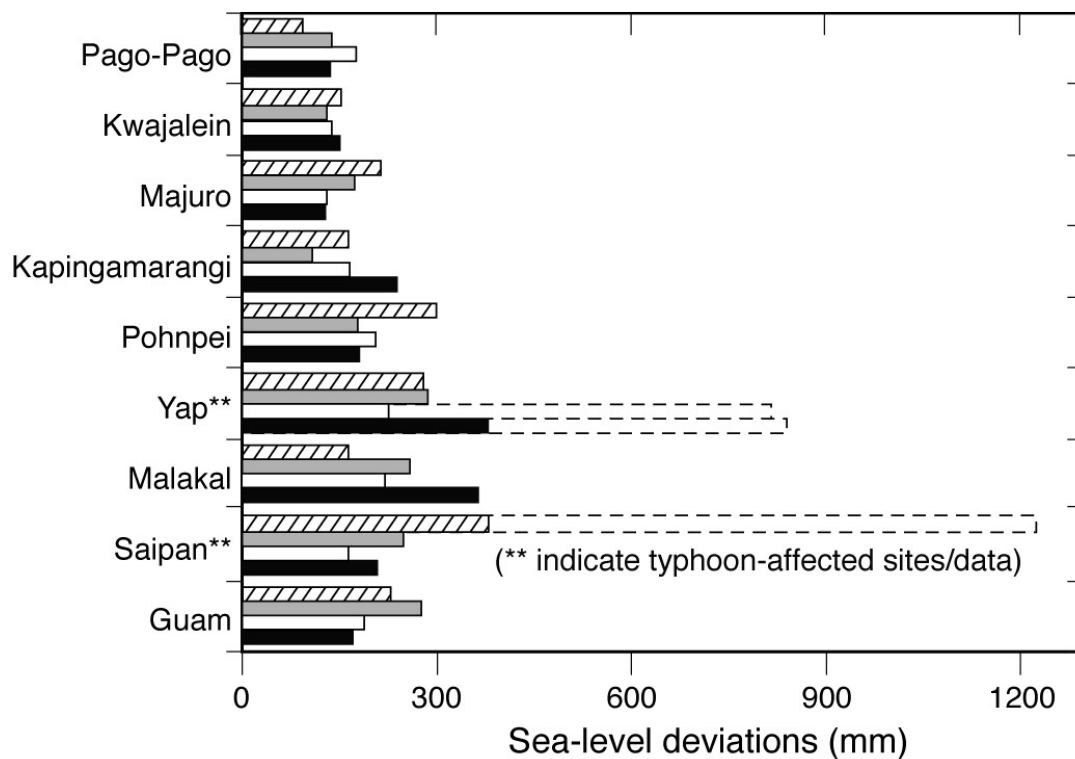


Figure 5. Seasonal sea-level deviations for all selected sites at (i) 20 RP (top panel) and (ii) 100 RP (bottom panel). Note that OND, JAS, AMJ, and JFM are the respective seasons.

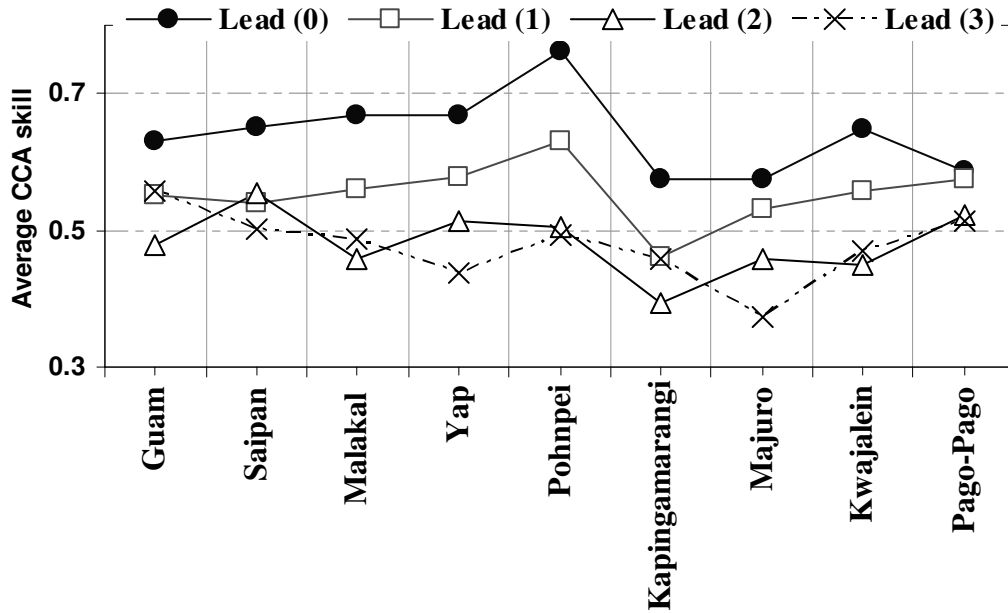


Figure 6. Average CCA cross-validation hindcast skills at 0 to 3 seasons lead time. Note that Leads 0, 1, 2, and 3 indicate ‘sea-level’ of target season (say for example, JFM) based on SSTs of previous seasons OND (lead 0), JAS (lead 1), AMJ (lead 2), and JFM (lead 3) respectively.