Seasonal Sea Level Outlook and Reducing Vulnerability to Coastal Hazards—the experience of the 'Pacific ENSO Applications Center'

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Abstract: The occurrence of extreme sea levels and the associated erosion/inundation problems are important issues for the small and most vulnerable communities in the vicinity of U.S-Affiliated Pacific Islands (USAPI). Therefore, the objective of this study is to provide an improved outlook on the extremes of seasonal sea-level variability for the USAPI. The target is to aid in decision analyses for coastal hazards management.

Right now, the 'Pacific ENSO Applications Center' (PEAC), produces a 'sea-surface temperatures' (SST)-based operational forecasting schemes for sea-level variability; these forecasts are also successfully disseminated to the USAPI communities. The present study further examines the variability of seasonal extremes of sea-levels; the results are expressed by relative to the tidal datums for each station. This information is then collated with PEAC's forecasts on sea-level variability for low and high tide predictions. All these information are then synthesized to generate an advance seasonal sea level outlook for the island communities.

The PEAC has already started disseminating this 'advance seasonal sea level outlook' *via* teleconference and newsletter '*Pacific ENSO Update*' (also available at: *http://www.soest.hawaii.edu/MET/Enso/peu/update.html*), and all these PEAC's focused programs have been found to be instrumental in decision analyses for coastal hazards management.

Keyword: Sea level, generalized extreme value, coastal hazards, U.S.–Affiliated Pacific Islands (USAPI), and. Pacific ENSO Applications Center (PEAC).

1.0 Introduction

The U.S-Affiliated Pacific Islands (USAPI) communities 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 (a)]. These islands are small, low lying, and highly vulnerable to coastal surges [Fig. 1 (b)]. 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). Chowdhury et al. (2007a) provided a diagnostic discussion on seasonal sea-level variability in these islands. The coastlines of these islands are subject to tidal variations on daily to yearly time-scales. All coastal structures and activities, including agriculture, in these islands must adapt to this temporal fluctuation in sea level. Therefore, there is demand for sea-level data that can define thresholds of various temporal ranges on seasonal-to-annual scales.

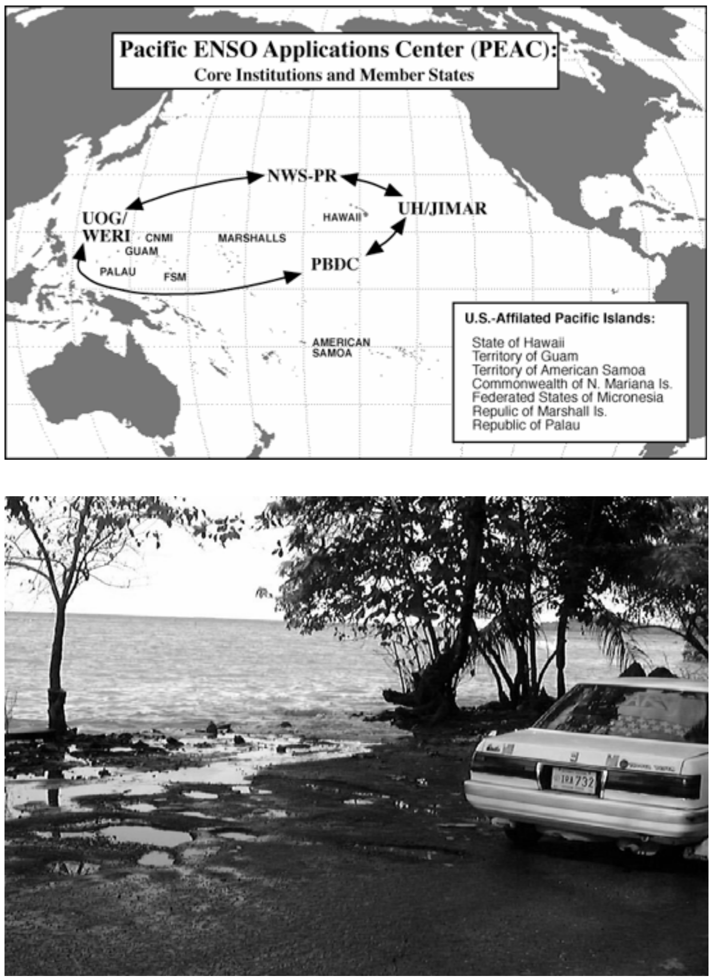

Figure 1: The core members of PEAC and the geographical locations of the USAPI (top panel) and a photograph of typical coastal community in Marshalls Island (bottom panel). [(Note that the PEAC was established in August 1994 as a multi-institutional partnership of the National Oceanic and Atmospheric Administration (NOAA) Office of Global Programs (OGP), the National Weather Service–Pacific Region (NWS-PR), the University of Guam–Water and Energy Research Institute (UOG/WERI), the University of Hawaii–School of Ocean and Earth Science and Technology (UH/SOEST), the Pacific Basin Development Council (PBDC), and a regional association of the USAPI governments)].

The primary objective of this study is to examine the varying likelihood of extremely high sea levels for the USAPI. Also, the climatology of the annual cycle pertinent to all the respective tide-gauge stations is discussed here. This study uses hourly sea-level data from the University of Hawaii sea level center (UHSLC) and defines thresholds on the seasonal and annual ranges that have low but finite probabilities of being exceeded. Based on the Generalized Extreme Value (GEV) model, the *L*-moments method has been used to estimate the model parameters. The exceedance probability graphs for high sea level are prepared for four successive seasons: January-February-March (JFM), April-May-June (AMJ), July-August-September (JAS), and October-November-December (OND). This information is then collated with other PEAC's products on sea level [(see Chowdhury et al. (2007b) for SST-based canonical correlation analysis (CCA) model forecasts for sea level); also see '*Pacific ENSO Update*' (available at: *http://www.soest.hawaii.edu/MET/Enso/peu/update.html*) for low and high tide predictions)] and an advance seasonal sea level outlook is generated for the island communities.

Finally, this outlook is disseminated *via* teleconference—a PEAC sponsored monthly workshop format discussion forum with participation from major regional and local institutions—and hardcopy newsletter '*Pacific ENSO Update*'. All these PEAC's focused programs on seasonal sea level outlook have been found to be instrumental in decision analyses for coastal hazards management in the USAPI.

2.0 Extreme Value and Exceedance Probability

The expected statistical distribution of the extreme values of any sequential process or set of observations is described by the generalized extreme value (GEV) theory. A very brief summary of the GEV analyses is illustrated in the following section.

In engineering and environmental applications, a quantile is often expressed in terms of its "return period". The quantile of return period T, Q_T, is an event magnitude so extreme that it has probability $1/T$ of being exceeded by any single event. That is

$$Q_T = x(1-1/T) \qquad (1)$$

The shape of a probability distribution of a random variable X with quantile function $x(u)$ has traditionally been described by the moments of the distribution, which can be expressed as

$$\mu_1 = E_X(X) = \int_0^1 x(u)du$$

$$\mu_r = E_X(X-\mu_1)^r = \int_0^1 (x(u)-\mu_1)^r du,\ r = 2,3,... \qquad (2)$$

The L-moments are an alternative system of describing the shapes of probability distribution, which historically arose as modifications of the "probability weighted moments" (Greenwood et al., 1979). In practice, L-moments must often be estimated from a finite sample. Let's assume the sample size is N and the sample is arranged in ascending order. That is, $\mathbf{X} = \{x_1, x_2, ..., x_N \mid x_1 \le x_2 \le .... \le x_N\}$. Then, the sample L-moments are defined by

$$l_{r+1} = \sum_{k=0}^{r} P_{r,k}^{*} b^{k}\ ,\ r = 0,1,..., N-1$$

$$\text{where } P_{r,k}^{*} = (-1)^{r-k} \binom{r}{k} \binom{r+k}{k} = \frac{(-1)^{r-k}(r+k)!}{(k!)^2 (r-k)!}\ ,\ k = 0,1,...,r$$

$$b_r = \frac{1}{N} \binom{N-1}{r}^{-1} \sum_{j=r+1}^{N} \binom{j-1}{r} x_N = \frac{1}{N} \sum_{j=r+1}^{N} \frac{(j-1)(j-2)...(j-r)}{(N-1)(N-2)...(N-r)} x_N \qquad (3)$$

The sample L-moment l_r is an unbiased estimator of L-moment λ_r. Now via Eqs. (1 to 3), one can calculate the quantile Q_T given the return period T (also see Zwiers and Kharin, 1998) and L-moments.

Although the historical sea-level data are used, the sample size is relatively small (40 to 60 years of data). In order to build a good approximation to the sample distribution of sample statistics (i.e., return periods), we use the nonparametric resampling procedure called the bootstrap technique. The bootstrap is a data-based, computer-intensive simulation technique for statistical inference and it operates by generating artificial data batches from the existing sample *with replacement*. Details of GEV, bootstrap methods applied to climate problems can be found in Chu and Wang (1997), Efron and Tibshirani, (1993), Katz et al., (2002), and Mendez et al., (2007).

3.0 Data

Research quality, hourly sea-level data based on years with at least 4 months of data has been used in this study. These data have been downloaded from the UHSLC web site (*http://ilikai.soest.hawaii.edu/uhslc/rqds.html*). All these sea-level heights have been referred to the station *tide staff zeros* which is linked to fixed bench marks. For prediction of tides, NOAA-COOPS (National Oceanic and Atmospheric Administration-Center for Operational Oceanographic Products and Services) data sources are used.

Exact locations (latitudes and longitudes) of the stations are: (1) *Marianas* at Guam (13.44°N, 144.65°E), (2) *Saipan* at CNMI (15.23°N, 145.75°E), (3) *Malakal* at R-Palau (7.33°N, 134.47°E), (4) *Yap* at FSM (9.51°N, 138.14°E), (5) *Pohnpei* at FSM (6.98°N, 158.25°E), (6) *Kapingamarangi* at FSM (1.1°N, 154.78°E), (7) *Majuro* at Marshalls (7.1°N, 171.36°E) (8) *Kwajalein* at Marshall (8.73°N, 167.73°E), and (9) *Pago-Pago* at A-Samoa (14.29°S, 170.69°W). This study utilizes only historical data recorded by a tide gauge.

4.0 Climatology of Annual Cycle

To quantitatively evaluate the importance of the annual cycle from these data, harmonic analysis has been performed on the monthly mean sea-level time-series (Fig. 2 – solid lines with open circle). Harmonic analysis consists of representing the fluctuations or variations in a time series as having arisen from the adding together of a series of *sine* and *cosine* functions (Wilks, 1995). These trigonometric functions are 'harmonic' in the sense that they are chosen to have frequencies exhibiting integer multiples of the 'fundamental' frequency determined by the sample size of the data. The first harmonic, which represents the annual cycle, explains a considerable percentage of variance of the sea-level variability in the north Pacific islands (Figs. 2a to 2e).

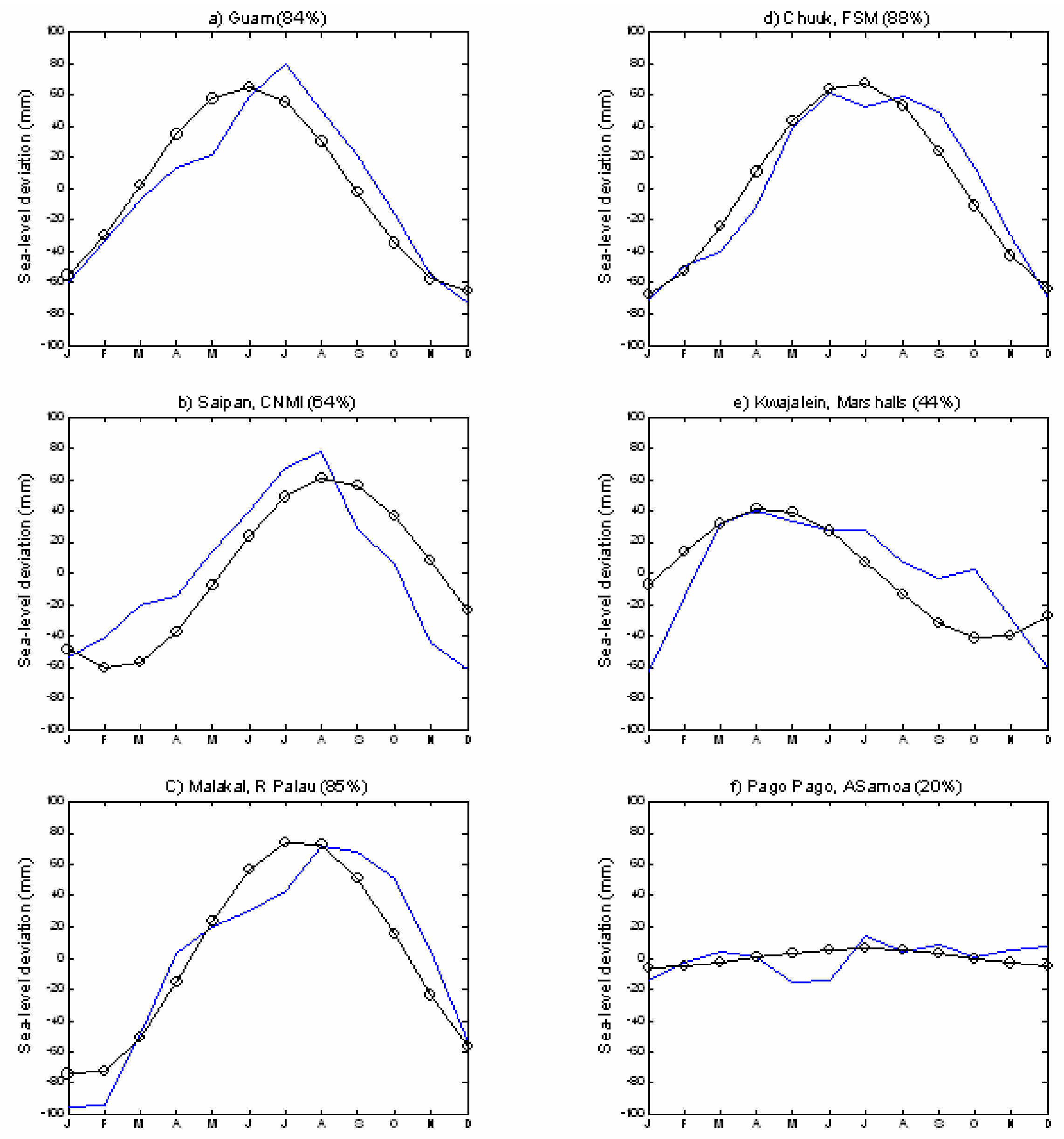

Figure 2: First harmonic of sea-level variability. Solid line denotes long term monthly average data records in individual tide gauge stations and solid line with <u>open circle</u> denotes first harmonic at corresponding locations. Values in parenthesis (top) are percentage of variances explained by the first harmonics *(X-axis: Months and Y-axis: Sea-level deviations in mm)*

The first harmonic for all Islands explains 44-88% of the variance. For the westernmost islands in the north Pacific (Guam, CNMI, RPalau, and in FSM), maximum rise of sea-levels occurs in summer months (June to August). For the Marshall Islands, the annual cycle appears to peak in April (Fig. 2e). The annual cycle is relatively weak in American Samoa (only 20% variance) (Fig. 2f). The second harmonic (Fig. 3), which represents the semiannual cycle, adds to the variance explained at Marshalls (17%) and American Samoa (11%) (Figs. 3e and 3f) (also see Chowdhury et al., 2007a).

4.1 ENSO and Sea-level Variability

Figure 3 represents the monthly sea-level deviations during ENSO events. Because ENSO usually starts to develop in summer, reaches its peak phase in the following winter, and gradually weakens through the next spring, a composite of seasonal variations of sea level is made from July to the following June. In the cases of Guam and the Marshalls, the monthly average sea level shows large and negative deviations during strong El Niño events (Fig. 3). This is very distinct from the time of onset of events (i.e., summer) and continues up to March of the following year. Significantly lower than average sea-level was recorded in these months during the major or strong El Niño years. The moderate El Niño years also recorded lower than average sea-level—only the magnitude being smaller relative to strong El Niño. Thus, the strength of El Niño on sea-level variations (fall/rise) in Guam and the Marshalls is evident. Similar, but opposite, relationships exist in La Niña years; that is, both the strong La Niña and moderate La Niña years recorded higher than average sea level.

For American Samoa, there is no pronounced variation in sea-level from July to December during strong and moderate El Niño years (Fig. **3**). However, consistent with the previous findings for North Pacific Islands, El Niño years produced pronounced fall of sea-levels during January to June while La Niña years showed considerable sea-level rise during the same time period. Under the influence of ENSO, the trend of sea-level variations in American Samoa displays a couple of months delay with respect to sea-level variations in Guam and Marshalls.

5.0 Return Periods and the Deviations of Sea-level Extremes

Sea-level extreme for seasonal (JFM, AMJ, JAS and OND) scale on 1 to 100-year return period have been plotted, with both upper and lower bounds being at 90% confidence level. These two boundaries are calculated by using the bootstrap resampling method with 5000 iterations. Based on these extreme value analyses, the sea-level deviations are derived by subtracting the average values from the estimated sea-level extremes. The deviations of sea-level extremes are presented in Table 1. Positive deviations indicate rise from the climotological mean value while negative deviations indicate fall.

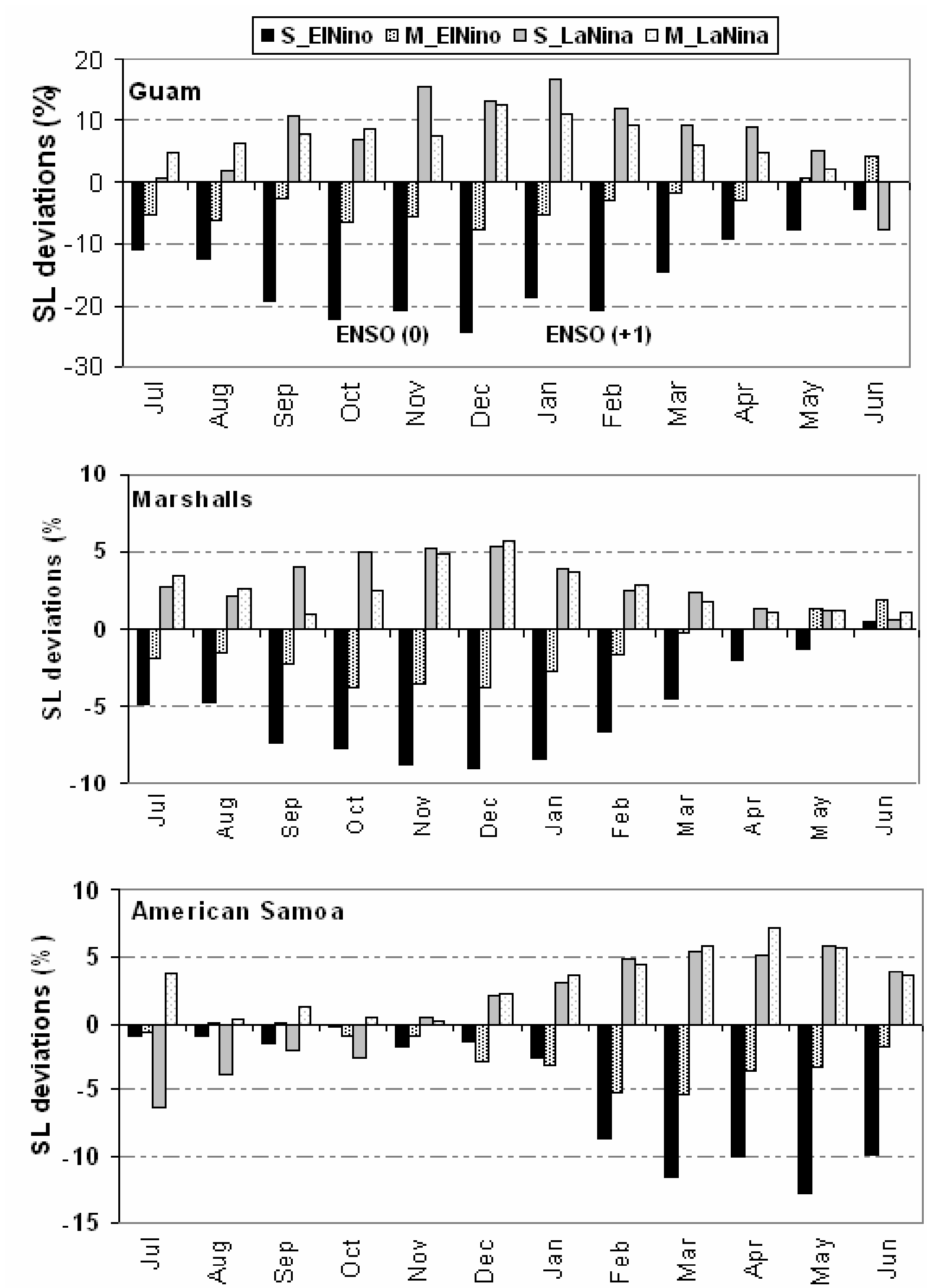

Figure 3: Composites of monthly sea-level deviations from the normal during the ENSO years starting from July and extending to June of the following year (*X-axis: Months, and Y-axis: Sea-level (SL) deviations in percentages).*Strong (S) El Niño years: 1951, 1957-58, 1972-73, 1982-83, and 1997-98/ Strong (S) La Nina years: 1964, 1973-74, 1975-76, 1988-89, and 1998-99/ Moderate (M) El Niño years: 1963, 1965, 1969, 1974, and 1987/ Moderate (M) La Niña years: 1956, 1970, 1971, 1984, and 1999.

Table 1: Deviations of sea-level extremes (in mm) at 20- and 100-year return periods

Stations	*Sea level deviations (mm)** (100 mm = 3.94 inch)							
	Sea level rise (mm)				**Sea level rise (mm)**			
	20 year Return Period				20 year Return Period			
	JFM	JFM	JFM	JFM	JFM	JFM	JFM	JFM
Guam	142	141	160	165	170	187	276	229
Saipan	151	127	176	775	209	162	248	1222
Malakal	244	166	205	155	364	221	259	163
Yap	425	372	214	208	839	813	286	279
Pohnpei	148	149	146	230	181	206	178	298
Kapingamarangi	187	130	90	145	239	165	107	162
Majuro	103	110	132	168	128	130	174	213
Kwajalein	115	107	103	126	150	138	130	153
Pago-Pago	101	147	103	76	136	175	137	94

*Note that positive deviations indicate rise from the climotological mean value; JFM, AMJ, JAS, and OND stands for January-February-March, April-May-June, July-August-September, and October-November-December.

On a 20-year return period (henceforth, 20 RP), Saipan is likely to experience a sea-level extreme of 775 mm during OND. On a 100-year return period (henceforth, 100 RP), an extreme of 1222 mm is visible. Similarly, on 20 RP, Yap recoded remarkably high extreme values: 425 mm (in JFM) and 372 mm (in AMJ). On a longer time scale (100 RP); these values are 839 mm (in JFM) and 813 mm (in AMJ) respectively. The reason for these high values is that Saipan and Yap have undergone large and significant increases in their tidal range due to storms. Saipan was hit by super typhoons (STY) *Kim* on December 03, 1986 and *Wilda* on October 25, 1994. The closest point of approach (CPA) intensity for STY *Kim* was 135 nautical miles per hour (KT) and for *Wilda* was 115 KT. Similarly, the entire State of Yap was threatened by Typhoon *Mitag* (CPA intensity 100 KT) March 1-3, 2002. Typhoon *Sudal* hit Yap during the Easter weekend (April 15-16) of 2004 packing 115 KT winds and waves of more than 10.7 m. It is notable that, despite a slight sea-level rise in Guam and Malakal, other neighboring stations didn’t record any considerable variations due to the same storm events. The probable reason for this abrupt rise at a specific station is that typhoons 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.

6.0 Reducing Vulnerability to Coastal Hazards—PEAC Experience

The year-to-year El Nino-Southern Oscillation (ENSO) climate cycle has significant influence on the overall development of these islands. Therefore, based on ENSO and the sea-surface temperatures (SSTs) in the tropical Pacific, the Pacific ENSO Applications Center (PEAC) has developed an operational canonical correlation analysis (CCA) statistical model for sea-level forecasts with lead times of several months or longer. Results indicated that the SST-based CCA model is potentially useful in predicting seasonal sea-level variations for the USAPI. In addition to these SST-based CCA model forecasts, the PEAC has already started dissemination tidal predictions with the real-time highest and lowest sea level likelihood of extremes to the island communities, which greatly expanded the planning and decision options regarding hazard management in the USAPI.

PEAC also produces other types of forecasts: rainfall, tropical cyclones, and ENSO. In addition, statistical studies on regional climatology are regularly done at PEAC. These background information sources support development of ENSO-related impact criteria for the islands, through examination of historical floods and droughts and their causes/impacts on agriculture, and other information concerning water resources in each regional area. Also, information related to the pattern of severe weather phenomena such as hurricanes and typhoons in each regional area is also generated here.

PEAC explores all the available ENSO forecast models and develops an impact scenario for the USAPI. The models primarily consulted here are both dynamic and statistical. The techniques employed are based on exploration and interpretation of original research works by the International Research Institute for Climate and Society (IRI, http://iri.columbia.edu/climate/ENSO/currentinfo/QuickLook.htmlm), and the Climate Prediction Center (available at (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/index.html), where the onset of past ENSO cycles have been successfully predicted at lead times several months ahead of their actual appearance. Within a workshop format this product is discussed with representatives from the local, national, and international climate communities. Once a consensus is achieved, PEAC then places it before the PEAC-sponsored teleconference for discussion again within the framework of local/island climate dynamics. This effort helps to achieve a further validity of this consensus ENSO forecasts from the perspectives of island climate.

7.0 Summary and Conclusions

In addition to considering only the consequences of extremes of seal level due to storm events, as observed in this study, island communities will continue to face gradual long–term and medium-term seasonal sea level rise due to ENSO events. Therefore, in addition to considering only the consequences of a gradual, long-term rise in sea level, island communities will continue to face short-term or medium-term sea level changes. In some locations in the Pacific, temporary rises in sea level from storms, lunar tides, and El Nino-Southern Oscillation (ENSO) events raise the sea level even higher than is projected for the next century.

While the unprecedented impact of long-term sea level change may be primarily manageable by structural responses, medium- to short-term sea level variability can be managed efficiently by a combination of both structural and non-structural responses; the latter may consist of month-to-seasonal sea level forecasts and warning response system.

Finally, the Pacific Island communities are sensitive to climate variability and change. Advance information on sea-level and other climate variability can contribute significantly to hazard mitigations. The present sea-level forecasting schemes is greatly expanding the capabilities and decision options for hazard management in the USAPI.

Acknowledgements

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