Response of Extreme Storm Tide Levels to Long-term Sea Level Change

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Abstract **- The occurrence of dangerously high or low water levels at coastal locations is an important public concern and is a significant factor in coastal hazard assessment, navigational safety, and ecosystem management. The monthly highest and lowest water levels at 117 NOAA/National Ocean Service water level stations show a clear response to local mean sea level trends. The extreme levels reached by hurricanes and extra-tropical storms of the past can be adjusted for sea level trend, so that unbiased comparisons can be made. A data set of the annual highest and lowest water levels is derived from the monthly data and used to determine the expected frequency of future storm tides rising above or falling below any given level. The same analysis is also applied to the data for each individual month in order to estimate the varying likelihood of extreme high or low levels by season. The results are a set of annual and monthly exceedance probability levels relative to the tidal datums for each station. This information should prove useful for identifying, in real time, when a rare event threshold has been crossed. The exceedance probability levels can be adjusted in the future to reflect newly-updated tidal datums.**

I. INTRODUCTION

Most of the U.S. coastline is subject to a regular daily tidal variation. All coastal processes, structures, and lifeforms must adapt to this daily fluctuation in water level. However, rare meteorological events can raise or lower the coastal water level far beyond the diurnal tide range, causing hazardous conditions and disruption in systems that aren't prepared for extreme events. This paper uses historical U.S. water level data to define thresholds beyond the daily tidal range that have low but finite probabilities of being exceeded.

The Center for Operational Oceanographic Products and Services (CO-OPS), a component of NOAA's National Ocean Service (NOS), operates the National Water Level Observation Network (NWLON). Many of these stations have been in operation for several decades with some having over a century of data. As historical data are accumulated for each station, more and more rare events are recorded and the tails of the station's probability distribution are filled in.

This paper only utilizes historical data recorded by a water level gauge to define extreme probability levels. The results may or may not be comparable with the Federal Emergency Management Agency (FEMA) 100-year base flood elevations (BFEs) or stillwater levels. FEMA makes use of a range of techniques at different locations, if it judges the historical record inadequate, and also incorporates other physical phenomena including wave effects, coastal erosion, and tsunamis [1]. Furthermore, NWLON stations are generally located in sheltered harbors or at the end of long piers beyond the surf zone. Consequently, during extreme events, much higher or lower levels may be likely even short distances from a station, depending on the configuration of the shoreline.

II. EXTREME VALUE THEORY

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 [2], [3], [4]. The GEV probability distribution functions (pdfs) are defined by a location parameter (mean), a scale parameter (variance), and a shape parameter (Fig. 1). If the shape parameter is zero, the pdf is known as a Gumbel distribution. If the shape parameter is positive, the pdf is called a Frechet distribution; if the shape parameter is negative, the pdf is called the Weibull distribution. The Frechet distribution has a thicker positive tail indicating a higher probability of extreme positive outliers. In contrast, the Weibull distribution actually goes to zero above some limiting positive value.

Software for the application of extreme value theory has been developed at the National Center for Atmospheric Research [4]. The location, scale, and shape paremeters can be solved for by an iterative maximum likelihood estimation process. The ExtremesToolkit software package (http://www.isse.ucar.edu/extremevalues/extreme.html) will be used to fit GEV pdfs to block maxima or block minima data, which are data series consisting of the extreme values in sequential equal-length segments (e.g., monthly extremes or annual extremes).

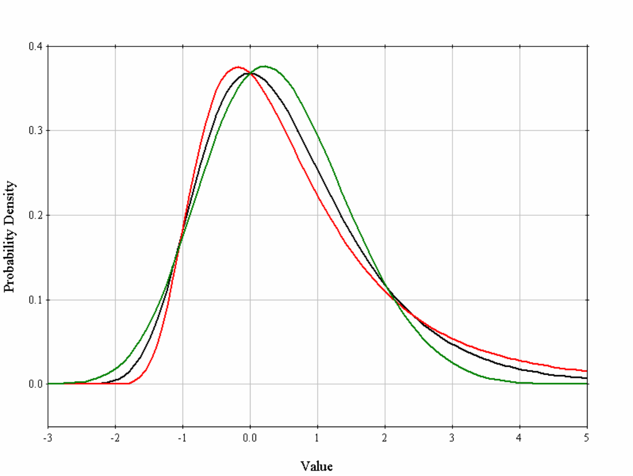

Fig. 1. Generalized extreme value probability density functions with a location parameter of 0 and scale parameter of 1. Black curve – Gumbel (shape parameter = 0), red curve – Frechet (shape parameter = 0.2), green curve – Weibull (shape parameter = -0.2).

III. DATA

The data utilized in this analysis are the monthly highest and lowest water levels at 117 NWLON stations. Exact locations of the stations can be found at http://tidesandcurrents.noaa.gov under Station Locator. The highest monthly water levels are referenced to mean higher high water (MHHW) and the lowest monthly water levels are referenced to mean lower low water (MLLW). Mean sea level (MSL) trends have previously been calculated for these stations [5] and these trends are subtracted from the monthly series. The resulting series consist of the levels of the extreme events beyond the normal diurnal tide range, as if they had all occurred in the same year. The annual highest and lowest water level series are derived from the monthly series using years with at least four months of data.

Four of the stations (Philadelphia, PA, Beaufort, NC, Wilmington, NC, and Anchorage, AK) are known to have undergone large and significant increases in their tidal ranges [6]. At these stations, calculated mean high water (MHW) and mean low water (MLW) trends, rather than MSL trends, were subtracted from the highest and lowest monthly water levels.

Extreme levels reached by tsunamis are not included in this analysis. Only five tsunami events (April 1946, November 1952, March 1957, May 1960, and March 1964) in CO-OPS' historical record were strong enough to result in the monthly highest or lowest water level at several stations. This is not a long enough extreme level record to treat tsunami event frequency in a statistical manner.

IV. SAMPLE ANALYSIS RESULTS

An example of the analysis results for one station with 85 years of data (The Battery, NY) is presented here. The annual exceedance probability curves and 95% confidence intervals are plotted in Fig. 2 versus the average return period in years (the inverse of event frequency). The GEV shape parameter for the high annual extremes is 0.08 indicating a Frechet (unbounded) distribution. The GEV shape parameter for the low annual extremes is -0.19 indicating a Weibull (bounded) distribution. The symbols are the N annual highest and lowest water levels, ranked as i=1,N, and plotted versus (N+1)/i. The vertical lines indicate the positions of the 99%, 50%, 10%, and 1% annual exceedance probabilities.

Fig. 3 shows the monthly highest and lowest water levels before the removal of the MSL trend at the Battery (2.77 mm/yr), along with the 99%, 50%, 10%, and 1% annual exceedance probability levels which rise in tandem with the MSL trend. The highest water levels are mostly due to northeasters, in addition to a few hurricanes. The lowest water levels are caused by southwesters.

A more concise way of presenting these results is shown in Fig. 4. The MHHW, MHW, MLW, and MLLW tidal datums are shown relative to MSL. Also indicated is the geodetic datum NAVD88 (North American Vertical Datum of 1988). The highest and lowest 99%, 50%, 10%, and 1% annual exceedance probability values are given relative to MSL.

The exceedance probability levels can also be obtained separately for each individual month. The results for The Battery are plotted in Fig. 5, showing the seasonal variation in the 99%, 50%, 10%, and 1% exceedance probability levels. Extreme values are more likely in the fall and winter and less likely in the spring and summer. The high peak in September is due to hurricanes.

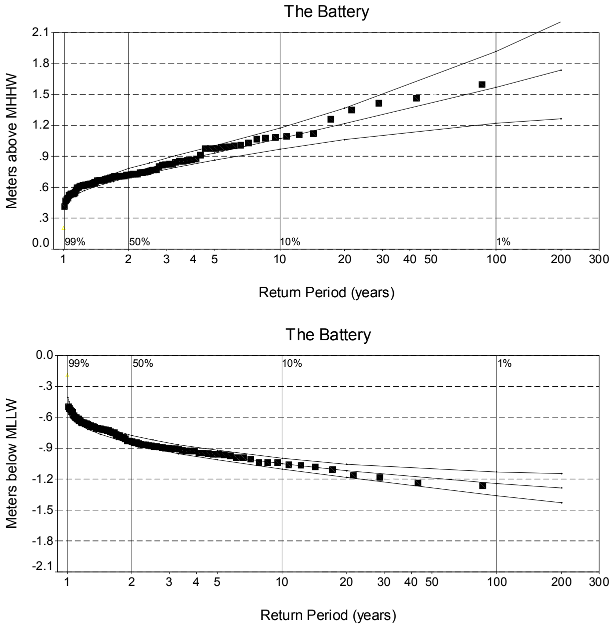

Fig. 2. Average return period in years for annual highest and lowest water levels in meters above MHHW or below MLLW at The Battery, NY. Curves are the GEV exceedance probabilities with 95% confidence intervals. Symbols are annual highest and lowest data. Vertical lines indicate annual exceedance probabilities for return periods of 1.01, 2, 10, and 100 years.

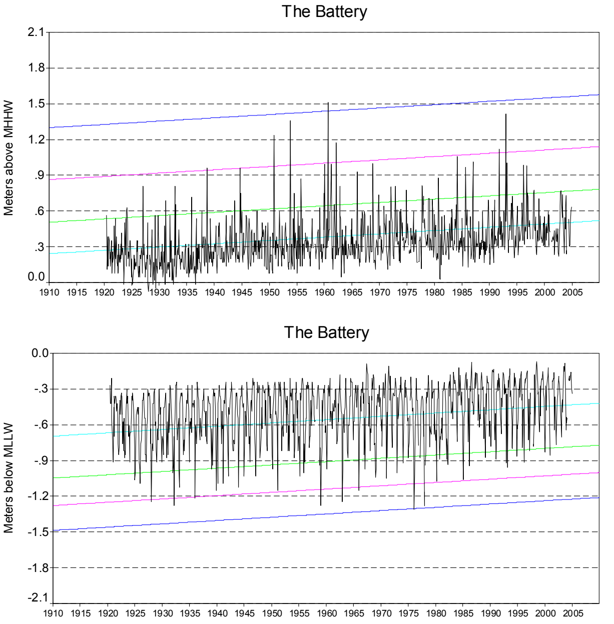

Fig. 3. Monthly highest water level above MHHW and lowest water level below MLLW at The Battery, NY. Also shown are the 99% (light blue), 50% (green), 10% (pink), and 1% (dark blue) annual exceedance probability levels. Hurricane Donna in September 1960 exceeded the highest 1% probability level and a winter storm in February 1976 exceeded the lowest 1% probability level.

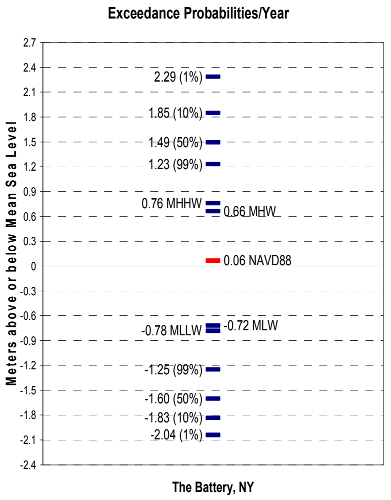

Fig. 4. Tidal datums, annual exceedance probability levels, and the geodetic datum NAVD88 (in red) relative to MSL at The Battery. 0.3 meters is about 1 foot.

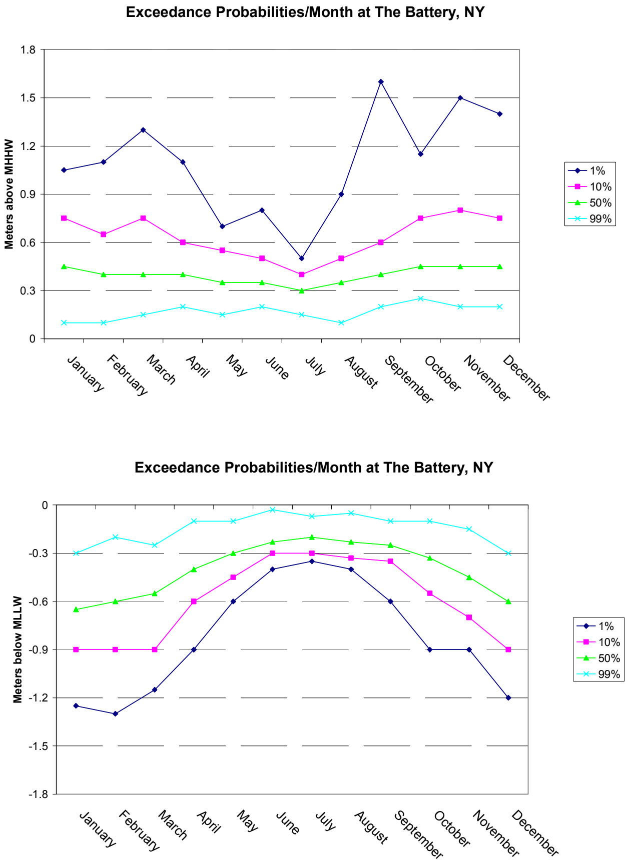

Fig. 5. Monthly variation of highest and lowest exceedance probability levels at The Battery relative to MHHW or MLLW.

V. GEV SHAPE PARAMETERS

The validity of the analysis results for one station can be better evaluated when they are compared to similar nearby stations, rather than when considered in isolation. Stations with short data lengths can be compared with stations with longer data lengths which have recorded extreme events missing from the shorter record. Sometimes, stations were destroyed during an extreme event while nearby stations were measuring their record highest or lowest water level.

When the GEV shape parameters are compared, it is possible to identify stations where the data may be inadequate for determining the more infrequent exceedance levels. When the shape parameters are negative (Weibull), there are relatively small differences in the levels of the four or five most extreme events. However, when the shape parameters are positive (Frechet), there can be large differences in the levels of the top four or five extreme events.

The GEV shape parameters for almost all of the low extreme levels are negative (Weibull) ranging from -0.5 to 0 (a Gumbel distribution). The GEV shape parameters are also negative for almost all of the high extreme levels at the Pacific coast, Alaskan, and Pacific island stations.

In contrast, most of the GEV shape parameters for high extreme levels are positive (Frechet) ranging from 0 to 0.5 at the Atlantic coast, Gulf of Mexico, and Atlantic island stations. This is usually due to the interaction of a few powerful hurricanes with a wide, shallow, continental shelf at these stations, resulting in a handful of extreme values significantly higher than the levels of the most powerful winter storms.

VI. 100-YEAR STORM TIDE LEVELS

The GEV exceedance probability curves (Fig. 2) are best constrained at the more frequent return periods and less well constrained near the 1% annual exceedance probability level (which can be considered as the 100-year storm tide level). In addition, if the GEV distribution has a positive shape factor (Frechet), the 95% confidence intervals widen considerably for the longer return periods, since they are dependent on the presence or absence of a few rare events in the data series.

A comparison of the 1% exceedance probabilty levels at adjacent stations can be a good method of judging the validity of each station's results. Fig. 6 shows the expected highest 100-year storm tide levels above MHHW; Fig. 7 shows the expected lowest 100-year storm tide levels below MLLW.

The highest 100-year exceedance levels along the Atlantic coast (Fig. 6, top) are at Washington, DC which is primarily due to three precipitation-caused river floods in March 1936, April 1937, and October 1942. High 100-year exceedance levels are also found for the Long Island Sound and southern New England coastline, mainly due to hurricanes in September 1938 and August 1954. Stations that may have underestimated 100-year exceedance levels because of missing storms are Nantucket Island, Bridgeport, New Rochelle, Cape May, Solomons Island, and Mayport.

For the Pacific coast and Alaska (Fig. 6, middle), 100-year exceedance levels rise from south to north with the highest levels at Toke Point, WA and the Alaskan stations with the largest tide ranges. With narrow continental shelves and no hurricanes, Pacific coast 100-year exceedance levels can be reached only by some combination of a storm, a spring tide, and an El Niño event.

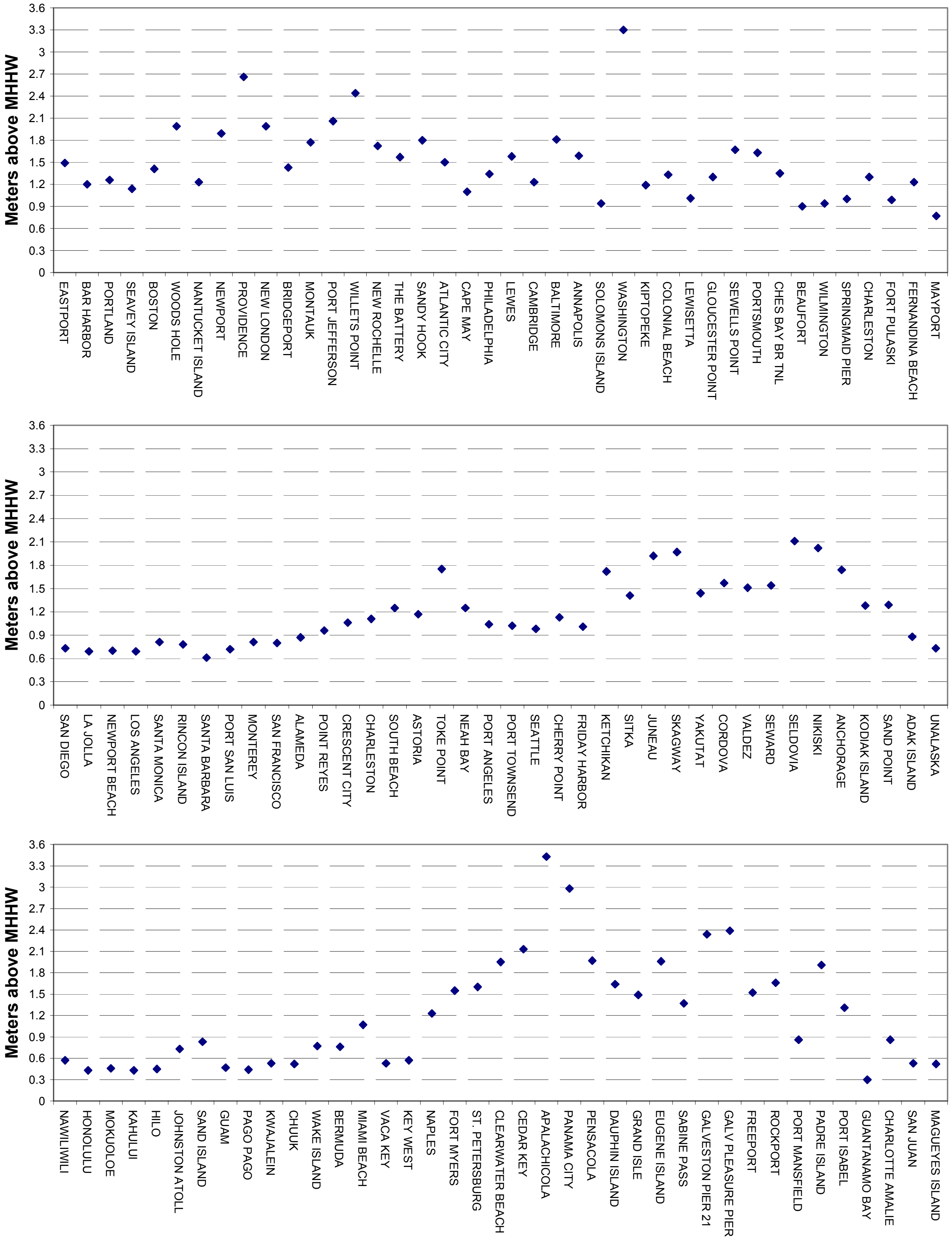

Fig. 6. 1% annual exceedance probability levels (100-year storm tides) above MHHW for Atlantic coast stations (top), Pacific coast stations (middle), and Pacific island, Gulf of Mexico, and Atlantic island stations (bottom).

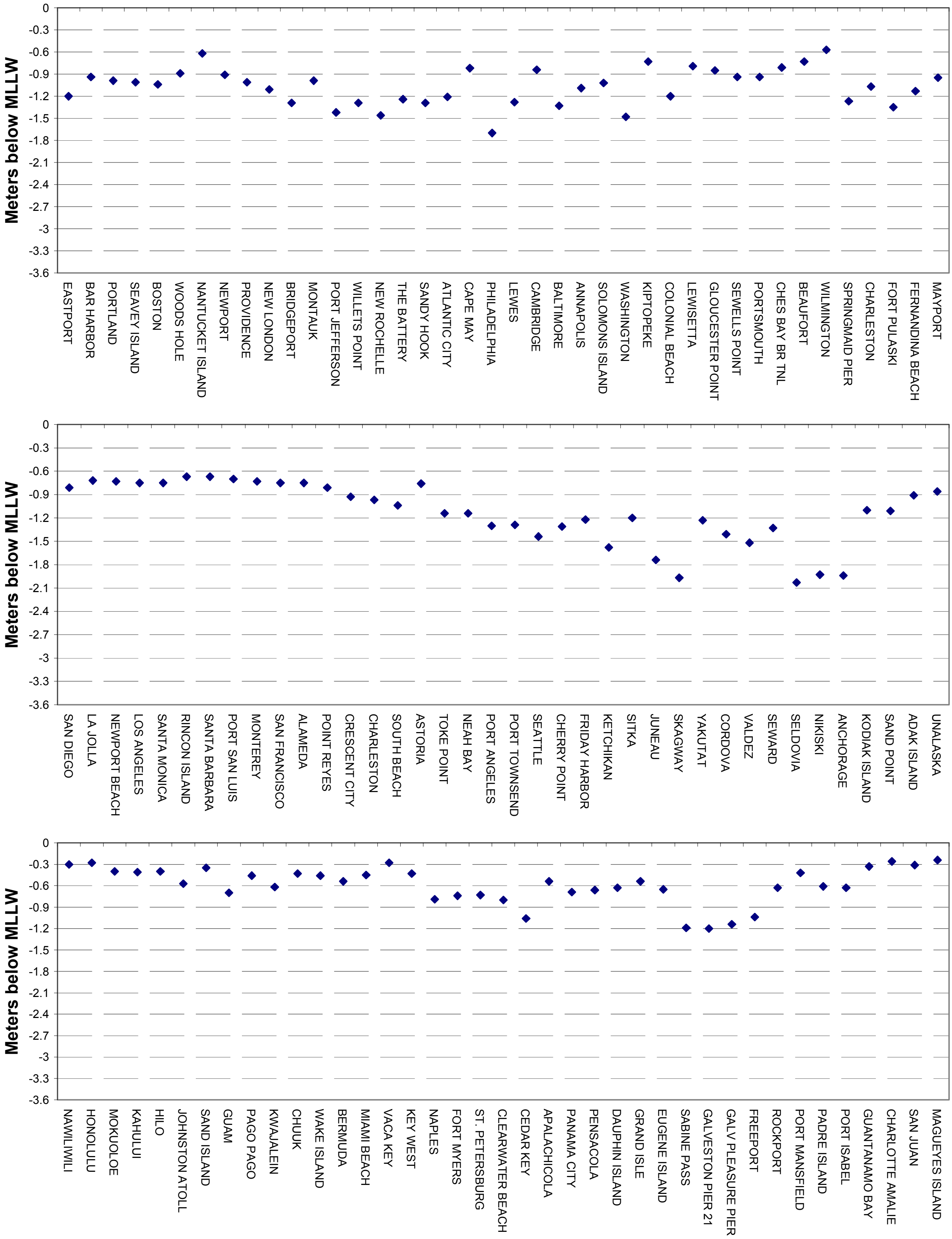

Fig. 7. 1% annual exceedance probability levels (100-year storm tides) below MLLW for Atlantic coast stations (top), Pacific coast stations (middle), and Pacific island, Gulf of Mexico, and Atlantic island stations (bottom).

For the Pacific island, Gulf of Mexico, and Atlantic island stations (Fig 6., bottom), 100-year exceedance levels are highest along the Gulf of Mexico where continental shelves are wide and hurricanes are frequent. Stations that may have underestimated 100-year exceedance levels are Grand Isle, Sabine Pass, Freeport, Port Mansfield, and Guantanamo Bay. The values at Apalachicola and Panama City are probably overestimated, since they had the only GEV shape parameters above 0.5 (Frechet distributions). Judging by the longer records at Cedar Key and Pensacola, they may have experienced an above-normal frequency of hurricane strikes in the past 30 years.

The lowest 100-year storm tide levels below MLLW (Fig. 7) are mostly determined by exceedance probablity curves with negative shape parameters (Weibull distributions), and are therefore less dependent on the presence or absence of two or three extreme events. For the Atlantic coast (Fig. 7, top), the lowest 100-year exceedance level is at Philadelphia, which had the lowest measured level in the whole data set (over 2 meters below MLLW) during a storm on New Years Eve 1962. The level at Cape May, NJ is probably not low enough. For the Pacific coast (Fig. 7, middle) the 100-year exceedance levels drop from south to north, with the lowest levels at Alaskan stations with the greatest tide ranges. For the Pacific island, Gulf of Mexico, and Atlantic stations (Fig. 7, bottom), the lowest 100-year exceedance levels are along the Texas coast near Galveston, where unexpected low levels can impact navigational safety and result in ship groundings.

By establishing 100-year exceedance probability levels, it becomes evident which stations have recorded events exceeding these levels. Some stations with over 100 years of data have not yet had such an event, whereas some stations with less than 100 years of data have had two such events. For example, Baltimore and Annapolis surpassed their highest 100-year exceedance probability levels during a hurricane in 1933 and again during Hurricane Isabel in 2003.

VII. CONCLUSIONS

In this study, exceedance thresholds are established for extreme storm tide events at 117 U.S. coastal water level stations. Historical monthly highest and lowest water level data have been adjusted for sea level trends, so that the resulting monthly and annual extreme value series can be analyzed without bias. Theoretical GEV exceedance probability curves were fit to the data to determine exceedance levels for various average return periods of interest.

As more and more data continues to accumulate at more NWLON stations, it is expected that these exceedance levels will become better defined. This information should prove useful in the fields of coastal hazard assessment, navigational safety, and ecosystem management, as well as the real-time monitoring of coastal water level data.

CO-OPS is the agency responsible for the establishment of the tidal datums for the United States [7]. The tidal datums were recently updated for the new National Tidal Datum Epoch of 1983-2001. The exceedance probability levels are tied to the position of the present-day tidal datums and can be adjusted in the future to reflect changing tidal datums.

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