Variability of Storm-Forced Extreme Sea Levels Along the U.S. West Coast

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Abstract. Hourly tide gauge records along the U.S. West Coast from Southern California to southern Alaska yield meteorologically-forced non-tide residuals (NTR), providing a record of the incidence of storm-forced extreme sea levels. NTR were obtained from tide-removed hourly data bandpass-filtered between periods of 10 days and 2.5 hr, thus focusing on synoptic variablility and removing long period steric changes due to El Nino and changes in mean sea level. Comparisons were made for winter months (Nov. to Mar.) for stations having record lengths in excess of 50 yr, with the longest record at San Francisco from 1858 onward.

The cumulative extreme positive winter NTR levels (above the 98th percentile level, i.e. the top 2%) generally increase from south to north. At individual stations, cumulative extreme winter NTR commonly fall within a relatively consistent range, with no dominant trend observed at any of the stations over the full duration of the record. Winter extremes observed during the great El Ninos of 1982-83 and 1997-98 are generally not exceptional compared to prior strong El Ninos. Extreme winter NTR also show relatively pronounced quasi-periodic decadal-scale variability that is similar to that exhibited in the Pacific Decadal Oscillation (PDO), with the pattern of variability apparently reflecting the dominance of El Nino/Southern Oscillation (ENSO) related storminess at more southern locations, while La Nina conditions tend to have increasing influence moving north.

1. Introduction

Severe coastal erosion and flooding from intense storm activity along the California coast occurred during the great El Niño's of 1982-83 and 1997-98. How do these storm-forced sea levels compare with those during other strong El Niño's over the past century? Has storm intensity increased along the U.S. West Coast? Are the incidence, magnitude, and persistence of extreme sea levels increasing? Has their distribution along the West Coast changed over time? Knowing whether extreme sea levels along coasts are increasing is important for coastal planning and establishing design criteria for future coastal development, as well as being an indicator of potential anthropogenically-forced or naturally occurring climate change.

2. Non-Tide Water Levels

Tide gauge water levels are dominated by astronomically forced ocean tides (high amplitude blue spectral lines in Fig. 1), but also include internal wave energy and overtides that are generated over relatively local topography [*Munk and Cartwright*, 1966] as well as meteorologically forced components [*Flick*, 1986]. Other factors affecting water levels include steric, wind-forced, and atmospheric pressure changes associated with local storms and with seasonal variation, as well as with anomalous climatic variations such as El Niño [*Reid and Mantyla*, 1976]. Although a key indicator of storm intensity is the temporal distribution (magnitude, duration, and incidence) of long period wave energy, tide gauges respond primarily to local sea level pressure (SLP) forcing (i.e. local storms) and thus do not give an accurate record of long period wave activity.

The astronomical tidal constituents vary slightly over time [*Cartwright*, 1972], and the amount of internal

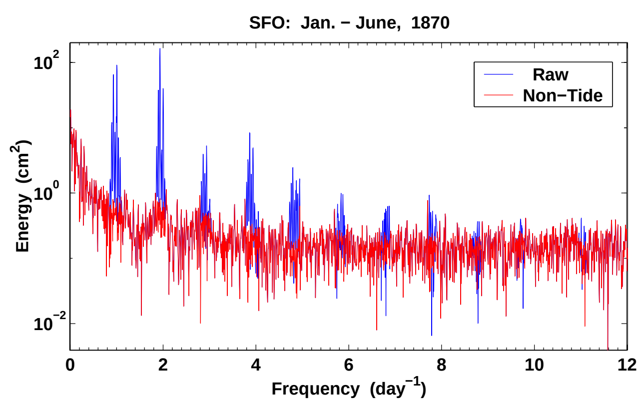

Figure 1. Representative tide gauge spectrum (blue) with the associated non-tide spectrum (red) obtained from a 4096 hr data segment of San Francisco (SFO) tide gauge data at the beginning of 1870.

wave energy found within the tidal species is difficult to estimate. The need for estimating these factors was eliminated by implementing a spectral method of tide constituent removal that preserves estimates of the meteorologically-forced components across the tidal species [*Bromirski et al.*, 2003]. Assuming that the continuum non-tidal forcing varies smoothly across the tidal species (Fig. 1, high amplitude blue bands), non-tide water levels are obtained with frequency domain operations that estimate continuum spectral levels (Fig. 1, red line) within the tide bands. The resulting non-tide amplitude spectrum across the tidal species is essentially indistinguishable from unmodified spectral estimates on either side of the tide bands.

The non-tide spectrum provides an estimate of meteorologically forced water levels. In this study, non-tide residual (NTR) water levels are obtained from the non-tide data by bandpass ($[1/10, 2.5]\ day^{-1}$) filtering. This passband excludes steric and other sea-level variation at time scales longer than 10 days and short-period variation resulting from overtides and minor data irregularities.

3. Meteorologically-Forced Sea Level Changes

Variation in sea level pressure (SLP) causes an "inverse barometer" effect on tide gauge water levels, with water levels tending to rise under low SLP and be depressed under high SLP [*Chelton and Davis*, 1982]. Because the water level response to meteorological events depends on the location of the center of the low relative to the tide gauge, the SLP gradient (and associated wind speed and direction), and the rate of storm movement, meteorologically-forced water level fluctuations at coastal locations can include a non-local component that reduces the correlation with SLP measured near the tide gauge. Also, longshore winds south of the tide gauge can generate coastally-trapped waves that propagate northwards and elevate water levels[(*Enfield and Allen*, 1980]. Thus, NTR variation provides a local-to-regional scale measure of sea level variability. The importance of the regional component on NTR is demonstrated in Fig. 2 where the variation in NTR (thick line) follows the variation in SLP (dot-dashed line), but the relative amplitudes of the peaks do not always correspond. (Note that the band used to produce Figures 2 & 3 includes energy excluded in this study.) However, in general, low SLP (i.e. intense storminess) corresponds to high non-tide residuals with correlations between high winter NTR levels and negative SLP anomalies of $\mathcal{R}^2 \approx 0.70$.

The longest hourly record along the West Coast is from San Francisco, CA (SFO, 1858-2000), and is used to demonstrate the analysis method employed. The variation of extreme NTR over winter months (Nov.-Mar.) provides a means to compare of North Pacific extreme sea level height (SLH) variability. NTR levels above

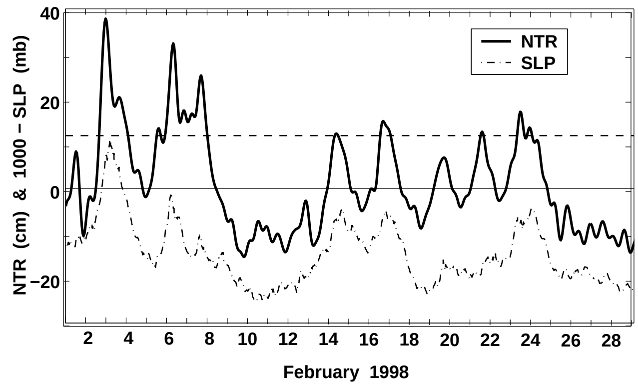

Figure 2. Non-tide residuals (NTR in the $[1/30, 2.5]day^{-1}$ band, thick line) and SLP (dot-dashed line) at San Francisco (SFO) during Feb. 1998, a month during El Niño with exceptionally high storm activity at SFO. Note that 1000 - SLP is plotted, so SLP>0 corresponds to sea level pressure less than 1000 mb, i.e. an intense storm. The 98^{th} percentile from the ranking of all hourly winter (Dec. - Mar.) NTR at SFO from 1858 to 2000 (horizontal dashed line) [from *Bromirski et al.*, 2003].

the hourly 98^{th} percentile level (see Fig. 2, dashed line) result from strong meteorological forcing, thus giving a measure of storms with high intensity. Cumulative sums of NTR levels and the number of hours above the 98^{th} percentile threshold for all positive hourly NTR (Fig. 3) give magnitude and duration measures, respectively, of extreme winter conditions. A single extreme event occurs for the time NTR persists above the hourly 98^{th} percentile level. These cumulative indices indicate that incidence of extreme sea levels, compared with stormy winters prior to 1930, has not increased along the central California coast near San Francisco during recent El Niños. Some winters have extreme NTR levels nearly 10% of the time.

Not all strong El Niños coincide with high winter extreme NTR levels at San Francisco. This observation appears to be in general agreement with studies suggesting that the North Pacific atmospheric response to warming in the tropical Pacific is modulated by the phase relationship between the warming and the North Pacific Oscillation [*Gershunov and Barnett*, 1998]. In any case, linear least squares analysis indicates no statistically significant long term trend in monthly positive NTR, suggesting that there has been no substantial change in the occurrence and magnitude of extreme sea levels along the central California coast either for the last 140 yr or over the last 50 yr. There is a relatively small increasing trend in winter extreme NTR (thin dashed line, Fig. 3b). However, in contrast to mean monthly positive NTR (Fig. 3a), there is a substantial increasing trend in winter extreme NTR levels since about 1950 (thick dashed line, Fig. 3b). We note that the trend observed is strongly influenced by the height-

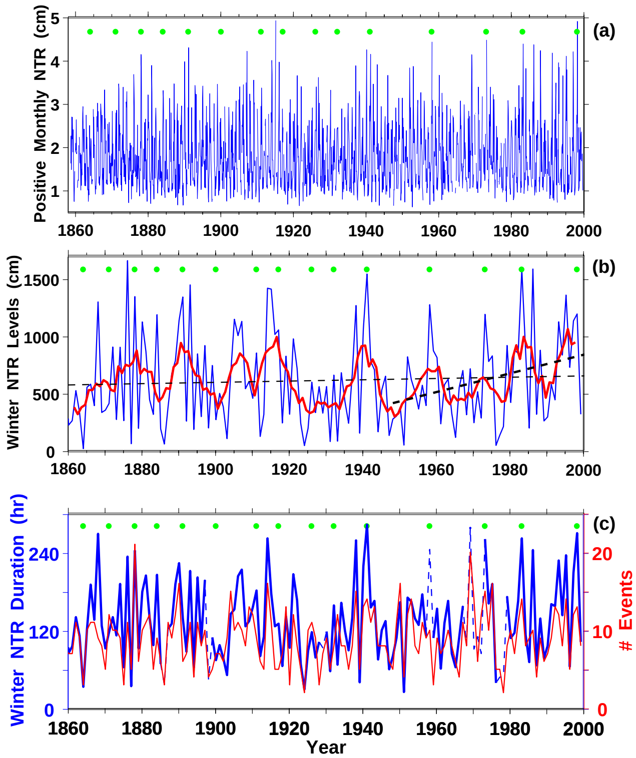

Figure 3. (a) Mean monthly positive non-tide residual (NTR, in the $[1/30, 2.5]day^{-1}$ band) water levels for the last 140 years at San Francisco (SFO). (b) Cumulative extreme NTR (exceeding the 98^{th} percentile level of 11.5 cm for the entire hourly NTR time series, see Fig. 2, dashed line) during winter months (Dec. - Mar.), with it's 5-yr running mean (thick red line). Least squares trend estimates for the entire winter record (thin dashed line) and since 1948 (thick dashed line). (c) Cumulative extreme winter hours (blue line) and events (red line). Dashed blue line indicates less than 90% of the hourly data were available, indicating that these periods may be underestimated. Times of strong, moderately strong, and very strong El Niño's [*Quinn and Neal*, 1987] are indicated by green dots (1998 was added) [from *Bromirski et al.*, 2003].

Figure 4. Locations of tide gauge stations used in this study. The La Jolla, CA (SIO) station is not labeled because of its proximity to San Diego.

ened activity in the last two decades. The extreme NTR data also indicate that this two-decade period was very active, but not extraordinarily so compared to pre-1948 epochs, e.g. 1865-1915 (Fig. 3b), suggesting that it is unlikely that these increasing trends will persist. Interestingly, no comparable trends in either winter duration or the number of winter events (Fig. 3c) are observed.

4. NTR Variability Along the West Coast

The distribution of extreme sea levels along the U.S. West Coast is determined using hourly data from nine tide gauge stations from San Diego, CA to Ketchikan, AK (Fig. 4). These stations were selected for their distribution and the length of their records, all of more than 60 years duration. The data from each of these

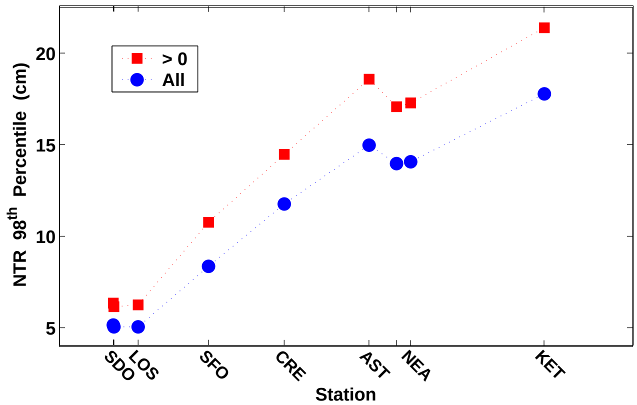

Figure 5. Winter 98^{th} percentile levels for all NTR during Nov. - Mar. (blue circles), and only for NTR > 0 (red squares). Stations are plotted at respective latitudes increasing from left to right (see Fig. 4). Locations and NTR levels of San Diego (SDO) and La Jolla (SIO) are indistinguishable, with only SDO labeled. The unlabeled tickmark next to Neah Bay (NEA) is for Seattle (SEA).

stations were carefully examined, with identified misentries corrected and bad data excluded from the analysis.

Because the astronomical tides and sea level trends are removed in the NTR analysis, the resulting variability in NTR can be used to directly compare sea level extremes along the West Coast. Winter (Nov. - Mar.) NTR 98^{th} percentile levels (obtained for all winters available at each station in the $[1/10, 2.5]\ day^{-1}$ band) generally increase with increasing latitude (Fig. 5). Stations in the same region have similar 98^{th} percentile levels, indicative of being subject to the same storm systems. SFO, CRE, and AST are at the mouths of major rivers, i.e. the Sacramento, Klamath, and Columbia Rivers, respectively, which may have elevated their levels somewhat. The tide gauges at SDO and SEA are somewhat sheltered from the open ocean compared to SIO and NEA, respectively. However, the close similarity between SDO and SIO and between NEA and SEA shows that the longer records at SDO and SEA are representative of the region, and indicates the dominance of SLP forcing on NTR extremes. The increasing difference between the 98^{th} percentile levels for "all" versus only "positive" NTR is indicative of increasing storm intensity from south to north.

The three longest hourly tide gauge records along the West Coast are from San Diego (SDO), San Francisco (SFO), and Seattle (SEA), with common recordings beginning about 1900. The cumulative winter (Nov. - Mar.) NTR extremes (above the 98^{th} percentile levels shown in Fig. 5, red squares) for these stations are shown in Fig. 6, with their 5-yr running means. These show that extreme levels at SEA have generally been

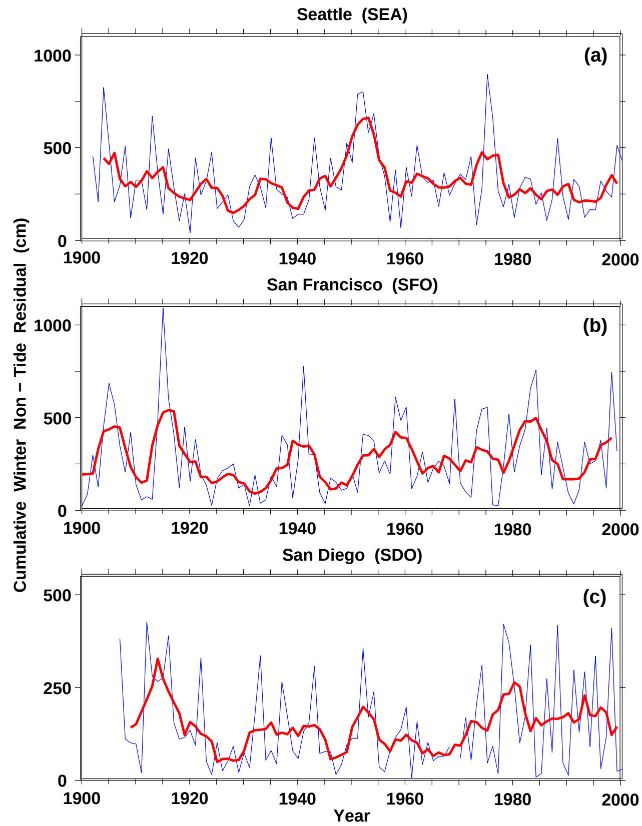

Figure 6. Cumulative winter non-tide residuals (NTR) above the 98^{th} percentile level (see Fig. 2) at (a) Seattle (SEA), (b) San Francisco (SF), and (c) San Diego (SDO) (thin blue lines), and their respective 5-yr running means (thick red lines).

decreasing since about 1950, while an increasing trend appears to have occurred at SDO (with intensification beginning in the mid- to late-1970's), consistent with a shift in storm tracks to the south identified by *Graham and Diaz* [2001]. In general, extreme sea levels at SFO and SDO occur during strong El Niño's, while at the same time relatively low levels are observed to the north at SEA. The 5-yr running means indicate that the period with the most extreme sea levels at SFO and SDO occurred between 1910 and 1920, while the longest period of extreme sea levels at SEA occurred during the early 1950's.

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