Annual climatologies of extreme water levels

M.A. Merrifield, 1 Y.L. Firing, 2 and J. J. Marra 3

Abstract. Annual climatologies of coastal high water levels are examined using hourly averaged time series from a global network of tide gauges. For each station, 95% exceedance levels for each day of the year are estimated as the superposition of tidal, high frequency (e.g. storms, eddies), and seasonal components. The annual climatologies illustrate the general character of extremes at each site, ranging from locations where extreme occurrences are due primarily to storms, to those where spring tides are the main determining factor. For the latter category of stations, extreme levels tend to cluster around the semi-annual peaks in spring tides. These peaks fall at the equinoxes at stations having a dominant semidiurnal component, and at the solstices at stations with diurnal-dominant tides. The impact of storms is heightened in some locations when seasonal storms arrive during the semiannual maxima in spring tide elevations. A tide model is used to show the semiannual range in solstitial and equinoctial spring tides around the globe.

Introduction

Extreme coastal water level events often result from a superposition of processes, primarily associated with storms and tides. In areas with large tidal ranges, the coincidence of a storm with a high spring tide will have a significant impact at the coast. Conversely, a potentially damaging storm event may have relatively minor impact if the peak of the event coincides with unusually low tides. Non-tidal variations in sea level associated with seasonal heating and wind forcing, interannual fluctuations (e.g., El Niño and other climate variations), as well as long-term secular trends also may contribute to the present and future impacts of high water level events by adding additional height to a short-term extreme event. Because storms, tides, and sea level all tend to have seasonal variations, we seek a climatology that depicts the separate and combined impacts of these processes in determining high water level extremes in the coastal zone as a function of year-day. In addition, we wish to assess how extreme events are affected by low frequency fluctuations and trends in sea level that are not captured in an annual climatology.

For this purpose we use hourly sea level records available from coastal tide gauges. A number of studies have examined the statistics and nature of extreme events in tide gauge time series, as reviewed recently by Lowe et al. (2007). The present study complements previous studies, particularly that of Woodworth and Blackman (2004), in that we seek a deconstruction of extremes in terms of tides, water level fluctuations on storm time scales, and seasonal water level variations. We emphasize the seasonality of these contributors to high events by forming annual climatologies of water level exceedance levels. Our study differs from that of Woodworth and Blackman (2004) who considered tidal, annual, and short-term contributions to extremes in tide gauge records in the context of systematic changes over time, whereas our focus is on the seasonal climatology.

The climatologies illustrate that in many locations the tide plays a strong role in establishing extreme levels, and as a result the seasonality of spring tides is a contributing factor to the timing and amplitude of extremes. It is well known that maximum semidiurnal spring tides occur at the equinoxes (Pugh, 1987). Similarly, the diurnal tide-producing forces are at a maximum at the solstices. Here we seek to examine the spatial patterns associated with these semiannual modulations in the context of observed extreme occurrences. The semiannual modulation is first described in terms of standard tidal analysis techniques developed by Doodson (1921), and the spatial patterns are illustrated using tidal harmonics obtained from a global tide model.

Data and methods

Hourly and daily mean tide gauge data were obtained from the University of Hawaii Sea Level Center for stations with data from at least 1993 through 2005 (Figure 1). We deconstruct the water level time series from each location into components with different time scales. A linear trend is removed from the time series and low-frequency sea level variability is obtained by smoothing daily data with a running Gaussian-shaped low-pass filter (half power period at ∼5 months). The seasonal sea level cycle is defined

1 University of Hawaii, Honolulu, Hawaii, USA
2 Scripps Institution of Oceanography, La Jolla, California, USA
3 NOAA IDEA Center, Honolulu, Hawaii, USA
by computing the average daily mean water level over all years for each year-day. High-frequency sea level is then the residual of the daily means after removal of the trend, low frequency, and seasonal cycle time series. The tidal component is predicted using tidal fits (Foreman, 1978) to the hourly data. Water levels are referenced to mean sea level (MSL) computed from each time series using data spanning the 1990s, a period of high data return for the entire network of gauges. In describing tidal ranges, we also make reference to the station mean higher high water (MHHW) calculated from the predicted tide.

We define an extreme event climatology as the superposition of seasonal sea level, tidal, and high frequency water level components. The tidal contribution is the 95% exceedance threshold of daily highest water above the MHHW on each year-day. The high frequency variability is the 95% exceedance threshold of the high-pass filtered data (described above) on each year-day. These three components are stacked yielding a total water level, referred to as $H_{95}$, that is plotted versus year-day (Figure 1). The 95% exceedance threshold was chosen to characterize observed extreme levels while limiting bias errors associated with isolated erroneous data as discussed by Woodworth and Blackman (2004). The five highest hourly values measured (without subtraction of the linear trend) are denoted for comparison with the climatology (Figure 2).

Variations from the annual climatologies are considered in terms of the low-frequency time series, including the linear trend (Figure 3). To examine whether variations in extreme events are associated with low frequency sea level fluctuations, the annual 95% exceedance value for daily means with the secular MSL trend removed is included. Trends in these exceedance values would indicate long-term changes in event amplitudes not simply due to the rise or fall of mean sea level.

We investigate global patterns of tidal climatology using

Figure 1. Locations of tide gauges that have been examined as part of this study. The stations described in section 3 are indicated. Results for the other tide gauge stations will be presented in a later study.

Figure 2. Superposition of the components of annual high water level climatologies at six representative stations (locations indicated in Figure 1). The mean component is the seasonal cycle, while the 95% exceedance threshold of the tide and short-term variability are shown as explained in Section 2. Levels are relative to the mean higher high water (equal to 0.81 m at San Francisco, 0.67 m at Funafuti, 0.42 m at Pago Pago, 0.32 m at Honolulu, 0.18 m at Pensacola, and 1.85 m at Newlyn).
data from the TPXO6 tidal model and the Oregon State University (OSU) Tidal Prediction Software (OTPS) provided by G. Egbert and L. Erofeeva, OSU.

Case studies

To illustrate the information contained in the annual climatologies, we examine tide gauge stations for which different processes dictate the occurrence of extreme water levels. The extreme climatology at San Francisco (Figure 2) shows that high levels are most likely to occur in the winter (December through February), with a secondary maximum in the summer. The five largest observed events (hourly levels) all occurred during the winter \(H_{95}\) maxima. These events exceed the \(H_{95}\) climatology by 0.1-0.4 m, resulting in levels twice as high as the MHHW (0.81 m). The events are associated with winter storms, which are described for San Francisco in detail by Bromirski et al. (2003). The \(H_{95}\) climatology indicates that spring tides are 0.4 m higher than average during this time of year, thus enhancing the impacts of winter storms. The spring tide level has a second 0.4 m peak in July, but in the absence of the short-term (storm-related) component extremes are not expected. The seasonal variation of sea level, due in part to downwelling-favorable local winds, makes a relatively small contribution (< 0.1 m) to winter extremes. The importance of interannual variability at San Francisco is evident in that four of the five highest observed hourly levels were measured in El Niño years (Figure 3), when both low frequency sea level and storm occurrences are higher than normal (e.g. Bromirski, 2003). The five top events all have occurred since 1970. This is attributed to the long-term upward trend of 1.9±0.2 mm/yr in sea level, rather than an increase in the amplitude of extreme events, which has an insignificant trend of 0.2±0.4 mm/yr.

At Funafuti, a South-Pacific atoll that experiences severe flooding due to unusually high water levels, \(H_{95}\) levels are highest in March, mostly as a result of high tides but augmented by small, nearly coincident peaks in the seasonal sea level and short-term components (Figure 2). Consistent with the \(H_{95}\) climatology, the five highest observed water levels have occurred at this time of year. The observed events are \(∼ 0.1\) m above \(H_{95}\). At San Francisco (and Pago Pago and Honolulu, described below), the observed extreme levels are equivalent to a doubling of the MHHW, resulting in levels 1.4 m above mean sea level. The relatively large sea level trend of 2.9±2.8 mm/yr explains the five highest extremes all occurring since 1988 (Figure 3). The daily extreme levels are correlated \((r^2 = 0.62)\) with the low-frequency sea level variability, indicating that extreme high events tend to occur during La Niña years when regional sea levels are high. There is no significant trend in daily extremes above the mean sea level trend over the observation period (1977-2005).

Pago Pago is an example of a location with consistently low (0.2 m) \(H_{95}\) levels throughout the year (Figure 2). This implies no seasonality to high water level events, which is confirmed by the random occurrence of the five highest observed hourly levels. Noticeably absent are the semiannual tidal modulations that are seen at the neighboring Funafuti station. The 1.7±0.6 mm/yr trend in MSL (Figure 3) has a noticeable impact on extremes, with four of the five highs occurring since 1996. There is again no significant trend in extreme levels beyond the trend in background MSL. At Pago Pago extreme event occurrence is set not by the seasonal cycle but by interannual fluctuations: the time history of daily extremes is highly correlated \((r^2 = 0.80)\) with low frequency sea level.

The Honolulu \(H_{95}\) climatology is similar to that of Pago Pago, with the exception of an annual spring tide minimum (around March) when extremes are less likely to occur (Figure 2). Extremes and interannual MSL are correlated \((0.75)\) here as at Pago Pago and San Francisco. Firing and Merrifield (2004) have shown that high water levels at Honolulu are often related to mesoscale eddies incident from the east, and the eddy events appear to be evenly distributed through the year. The MSL trend of 1.5±0.3 mm/yr places the five highest observed events in the latter half of the time series (Figure 3).

The \(H_{95}\) climatology at Pensacola (Figure 2) consists of approximately equal contributions from the mean, tide, and short-term components (0.15 m each). The \(H_{95}\) peak (0.4 m) in September is due to the superposition of the mean and tidal components. The short-term events are
nearly evenly distributed, with a small peak in February, likely due to winter storms. Extreme events at Pensacola are dominated by tropical storms and hurricanes; four of the five highest events were associated with hurricanes passing over or near the site, causing levels 1 to 1.8 m above the $H_{95}$ climatology (Figure 3). The storm events are in some ways anomalous; they are not reflected in the seasonal variation of short-term variability other than to cause spikes when they do occur. Because the tropical storm season peaks in the late summer, the impact of storms on extreme water level is heightened by large tides and high seasonal sea level coinciding with the storm occurrences. The trend in mean sea level (2.2±0.4 mm/yr, Figure 3) appears to have some effect on extreme levels, although the highest hourly level occurred during a storm in 1926 when mean levels were nearly 0.18 m lower than at present. The interannual variations in MSL and daily extreme amplitudes are uncorrelated (0.28), indicating that storm events are not related to slow changes in water levels. In addition, there is no significant trend in daily extremes above the MSL trend, suggesting that water-level-raising storm activity has been relatively constant over time.

Newlyn, like San Francisco, is subject to winter storms, although storm arrivals at Newlyn are less concentrated than at San Francisco, with the five highest levels occurring from late October to early April (Figure 2). The short-term climatology reflects this distribution with a broad peak of 0.3 m from November to March. The strong variation in spring tides over the year at this strongly semi-diurnal location puts the overall $H_{95}$ peak (0.9 m) in October, with a secondary maximum in March. Thus the impact of late season storms is ameliorated to some extent by diminished spring tides relative to the equinoctial peaks in March and October. Interannual MSL variability appears relatively unimportant (0.1 m) in determining extreme events; MSL and annual daily extremes are weakly correlated (0.55). The long-term MSL trend of 1.7±0.2 mm/yr also has little influence on extremes: the five highest observed levels are distributed from 1948 to the present (Figure 3).

The semiannual tidal cycle

Semiannual modulations of tidal range result from the declinations of the sun and moon. At the equinoxes the sun and moon are both nearly in the earth’s equatorial plane, leading to peak semidiurnal tidal forces; at the solstices the sun is at its maximum declination relative to the equator, leading to peak diurnal tidal forces. In terms of tidal constituents, this modulation is specified by $S_2$ and $K_2$ for the semidiurnal constituents, and $K_1$ and $P_1$ for the diurnal. These pairs of constituents have frequencies that differ by twice the annual frequency, giving rise to the semi-annual beat.

The relative phasing of the components is such that the semidiurnal envelope has maxima at the spring and fall equinoxes, while the diurnal envelope has maxima at the winter and summer solstices. In the common harmonic method of computing the tidal potential developed by Doodson (1921), the frequency of each constituent is a combination of integral multiples of six fundamental frequencies. Those of interest are $\omega_1$, $\omega_2$, and $\omega_3$, which have periods corresponding to the mean lunar day (1.0351 solar days), the sidereal month (27.3217), and the tropical year (365.2422), respectively. The contribution to the semidiurnal tide from the $S_2$ and $K_2$ components is

$$A_{S_2} \cos(2(\omega_1+\omega_2)t-2\omega_3t-G)+A_{K_2} \cos(2(\omega_1+\omega_2)t-G),$$

(1)

where $A_*$ is the constituent amplitude, $t = 0$ (by definition) at the spring equinox and $G$ is the phase relative to Greenwich, which we assume is approximately equal for these two constituents. We neglect other semidiurnal constituents with a $2\omega_3$ phase difference because their modulation amplitudes are much weaker than the $S_2$, $K_2$ pair. From equation (2), the semiannual modulation is largest when $\cos(2\omega_3t)$ is maximum, or when $\omega_3t = 0, \pi$, at spring and fall equinoxes. The maximum envelope size is $A_{S_2} + A_{K_2}$, and the minimum is $A_{S_2} - A_{K_2}$. Based on the tidal potentials of Doodson (1921), this corresponds to a ±20.5% variation in range.

The $K_1$, $P_1$ modulation of the diurnal tide is given by

$$A_{K_1} \cos((\omega_1+\omega_2)t-G+\pi)+A_{P_1} \cos((\omega_1+\omega_2)t-2\omega_3t-G),$$

(2)

where we again neglect other diurnal constituent pairs with a $2\omega_3$ phase difference but weak modulation amplitude, and assume the same Greenwich phase for $K_1$ and $P_1$. The $\pi$ phase has been included to account for the phase difference of $K_1$ relative to $P_1$ (cf the Doodson tables, where the amplitude of $K_1$ is negative). The diurnal semiannual modulation is largest when $2\omega_3t = \pm \pi$, at winter and summer solstices. The envelope amplitude ranges from $A_{K_1} + A_{P_1}$ (maximum) to $A_{K_1} - A_{P_1}$ (minimum). From the Doodson tables, this corresponds to a ±44% variation in range.

Considering only these dominant contributors to the semiannual modulation, the range in semiannual tide amplitude is $R = 2A_{K_2} - 2A_{P_1}$, where a positive range indicates peak tides at the equinoxes, and a negative range peak tides at the solstices. In reference to the climatologies presented in Figure 2, $R$ provides an estimate of the range of the tidal component depicted for each station. In any given year, maximum spring tides may deviate considerably from this baseline level, for example at lunar perigee.

We compute $R$ using tidal constituents from the TPXO6 model (Figure 4). In general, the equinoctial tides are strongest at the coast, particularly at locations known for large semidiurnal tides such as the Bay of Fundy, the Aus-
Australian Northwest shelf, the Madagascar Strait, the European Atlantic coast, the western coast of Korean peninsula, and the Patagonia shelf. A substantial fraction of the open ocean shows weak semiannual modulation, particularly near major amphidromic points. The strongest solstitial tides tend to occur at high latitudes, particularly in the North Pacific. The map of $R$ from altimetry is consistent with the phase and amplitude of the semiannual modulation observed at all of the tide gauges considered in this analysis.

**Summary**

An annual climatology of high water level components provides a useful tool for diagnosing the nature of extreme events. A feature that stands out in many of the water level climatologies is the importance of peak spring tides in determining event occurrences. The semiannual modulation of peak tides at the solstices and equinoxes can enhance or weaken the impact of storms (e.g., San Francisco, Newlyn). In some cases, even small amplitude sea level anomalies are enough to cause coastal flooding when combined with the largest spring tides of the year (e.g., Funafuti, Honolulu). In areas where the semiannual modulation is weak and storms are rare, extreme events may have no specific seasonality (e.g., Pago Pago). The polarity of the semiannual modulation of the tide can change quickly in space, for example in the Southeast Asia region (Figure 4). Given the same storm variability, we would expect marked spatial variation in the climatological impacts of storms in coastal areas where the semiannual phase changes abruptly from solstitial to equinoctial dominant tides.

**Acknowledgments.** We thank Richard Ray of the NASA/Goddard Space Flight Center for bringing the semiannual modulations in the Doodson schedules to our attention. Shikiko Nakahara of the University of Hawaii assisted with the data analysis and figure preparations. The work was supported through the Joint Institute of Marine and Atmospheric Research (JIMAR) under NOAA Grant NA17RJ1230, which includes funding for Pacific Region Integrated Data Enterprise (PRIDE) activities, and support provided by the NOAA Office of Climate Observations.
References


M. A. Merrifield, Y. L. Firing and J. J. Marra, Department of Oceanography, University of Hawaii, Honolulu, Hawaii 96822, USA. (e-mail: markm@soest.hawaii.edu; yfiring@ucsd.edu; John.Marra@noaa.gov)

This preprint was prepared with AGU’s *L* *T* *E* *X* macros v4, with the extension package ‘AGU++’ by P. W. Daly, version 1.6b from 1999/08/19.