Frequency and Duration of Coinciding High Surf and Tides along the North Shore of Oahu, Hawaii 1981-2007

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ABSTRACT

Wave run-up along the north shore of Oahu has an annual cycle with a maximum centered on boreal winter. An understanding of the variability of exceptionally high wave wash is important for coastal planning, safety, transportation, property protection, and various research themes such as the hydraulic flow properties of aquifers. Wave run-up increases with increasing surf size and tidal height. This study analyses hourly historic wave data and predicted tides from 1981-2007 to determine how often and for what duration in hours do high surf and tides coincide categorized by thresholds of surf and tidal height.

The Waimea buoy was the primary source for deep-water wave height and period. However this series only began in 2001. NDBC buoy 51001 extends back to 1981. The location is sufficiently remote from Oahu to warrant a correction in significant wave height. The correction was based on a linear fit of overlapping, daily mean, Waimea buoy and 51001 pairs. Surf heights were calculated using an empirical transformation scheme.

Nominally, marginal run-up events are represented by surf $\approx$ 9 m and tides $> 1\ \sigma$ above the mean, have occurred on average ten times per year since 1981, range in duration from 1-8 hours and last on average 3.1 hours . Significant episodes are associated with surf $\approx$ 12 m and tides $> 1.5\ \sigma$, have happened once annually on average, range in duration from 1-5 hours and last on average 2.5 hours. Extreme high wash occurrences are related to surf $\approx$ 15 m and tides $> 2.0\ \sigma$ or surf $>$ 18 m and tides $> 1\ \sigma$, have taken place on average every seven years, range in duration from 1-4 hours and last on average 1.9 hours. The paper does not attempt to define the vertical reach relative to a datum.

INTRODUCTION

Understanding of the frequency, magnitude, and duration of wave run-up caused by high seasonal surf is of immense importance to coastal stakeholders. Not only are the high breakers a danger to people in the surf zone and on the shore, they also pose damage to shorelines and the adjacent man-made structures such as homes, harbors, and highways. High wave setup even influences ground water table elevations as much as 5 km inland (ROTZOLL, 2007).

Tsunamis and hurricanes pose the greatest potential for coastal damage in the Hawaiian Islands. Tsunamis have brought the most extreme coastal inundation on Oahu, Hawaii. CURTIS (1998) estimates wave run-up to 9 m above sea level at select locations of Oahu under the strongest tsunami events of the last century. Hurricanes have also delivered severe coastal flooding to the Hawaiian Islands, although the magnitude of run-up on Oahu is low in recent decades compared to Kauai, where Hurricanes Dot, Iwa, and Iniki struck in 1959,1982 and 1992, respectively (SCHROEDER, 1998).

Tsunamis and hurricanes in Hawaii are rare. On the other hand, high breakers occur frequently on north shores of Hawaii during the high surf season, which begins in September and ends in May. North Pacific extra-tropical cyclones are a common source for near shore hazards and coastal flooding. FLETCHER et al. (2002) have ranked the coastal hazards from high waves for coastlines around Hawaii. Aucan (2006) derived a directional wave climatology for the north shore of Oahu based on four years of near-shore, deep-water, directional buoy measurements near Waimea Bay, Oahu and 45 years of wave model reanalysis output. These results agree well with the surf climatology based on 35 years of visual observations from the north shore of Oahu (Caldwell, 2005). The dominant wave direction is from the northwest (315^o) with the high season predominantly occurring November to March. Every high season has numerous days of large breakers. The average number of days per year based on 35-years of daily observations with surf at least 5 and 9 m is 76 and 21, respectively (Caldwell, 2005). The inter-annual variability of the number of days per year with large to extreme surf is high, up to a factor of two (Aucan, 2006).

Coastal erosion and wave run-up in areas with energetic wave climatology have been well studied. RUGGIERO et al. (1997) analyzed the effects of extreme surf on erosion along the coasts of Oregon and Washington. The aim was to understand the wave climatology based on four long-term records and to derive a 50-year design wave height. RUGGIERO et al. (2001) followed up on this work with a model to evaluate the susceptibility of coastal properties to erosion based on extreme water levels and storm waves. Their paper gives a review of similar studies to date from other regions of the globe. For application to the north and west shores of Hawaii, VITOUSEK and FLETCHER (2007) primarily used National Oceanic and Atmospheric Administration (NOAA) Data Buoy Center (NDBC) platform 51001 to test three approaches in determining the maximum annually recurring significant height at this deep water location, with a conclusion of 7.7 ± 0.2m. Various physical and geophysical aspects pertinent to the State of Hawaii shoreline certification process have been described by FLETCHER and HWANG (1994).

The strongest high seasonal wave inundation of the last 50 years occurred from back-to-back extreme episodes during December 1-4, 1969 (BOTTOMS, 1970). In the Sunset Beach area of Oahu on December 1, wave run-up topped a 7 m shoreline embankment, demolishing 14 homes and damaging many other properties. Costs in this area alone were $535,000, nearly half the $1.27 million (1970 dollars) loss island-wide.

This extreme event occurred with neap tides. The damage would have been more severe if it occurred under spring tides.

The 1969 episode was atypical. More commonly, high wave run-up is a result of high surf coinciding with high tides. As described by RUGGIERO et al. (2001), the erosion potential also depends on the duration of wave run-up exceeding a threshold. This study seeks to understand the frequency and duration of coinciding high surf and tides on the north shores of Oahu, Hawaii based on hourly historical wave data and predicted tides.

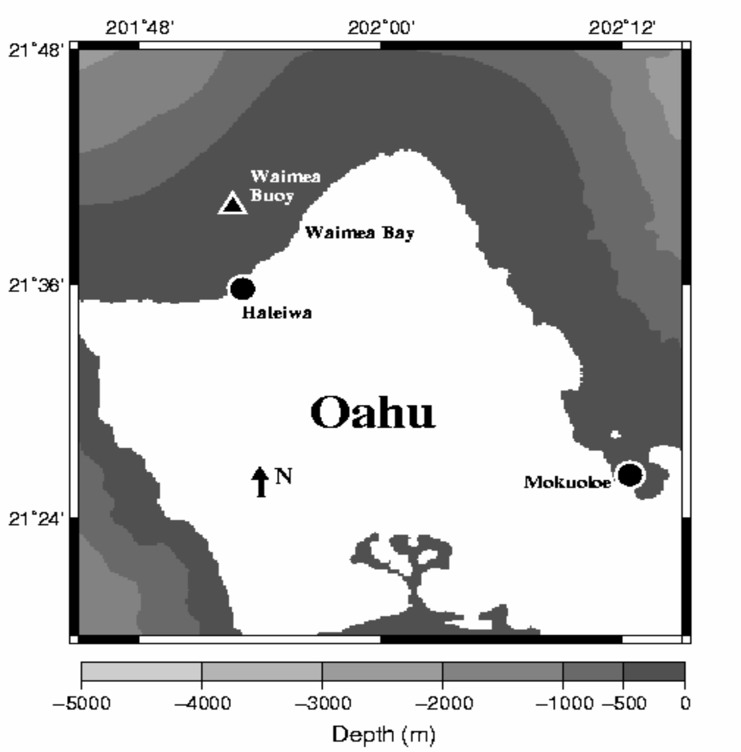


Figure 1. Study area and locations of tide gauges (circles) and buoy (triangle).

DATA AND METHODS

Since 1997, the NOAA Pacific Tsunami Warning Center has maintained a tide gauge in Haleiwa Harbor (Figure 1) in support of tsunami warning and research (LUTHER et al., 1998). The instrument is a shaft-encoder, float-and-stilling-well type gauge with samples digitized at two-minute intervals, from which spot hourly data are acquired. The data have not been linked to a fixed datum or calibrated to a single reference level, since the focus is on short-term variability. Due to the lack of a known datum, a nearby tide gauge augments this study.

The NOAA National Ocean Service has maintained an acoustic tide gauge (Gill et al., 1992) with six-minute digitized samples in Kaneohe Bay at Mokuoloe since 1957 as part of the national water level network. The data are calibrated and geodetically linked to fixed benchmarks.

The difference in daily averages (not shown) between Haleiwa and Mokuoloe gauges has a steady signature in the mean level from 1998 through 2004, which suggests a steady reference level for Haleiwa during this period. 2001-2002 Haleiwa hourly data were chosen for tidal analysis (FOREMAN, 1977), since the inter-annual variability of Mokuoloe was low and near the long term mean (Figure 2). PARRISH (1992) found very high coherence among sea level stations on Oahu for variations with 3 to 180 day periods. Thus, hourly tidal predictions made for 1981-2007 are assumed to be relative to an unknown long-term mean for the north shore of Oahu. In this study, variability of the tides is the focus. The exact height of the tide relative to a known datum is not approached. Heights of the tide in this study are relative to the standard deviations of the predicted tide. The inter-annual variability has low magnitude (Figure 2) and is not taken into consideration.

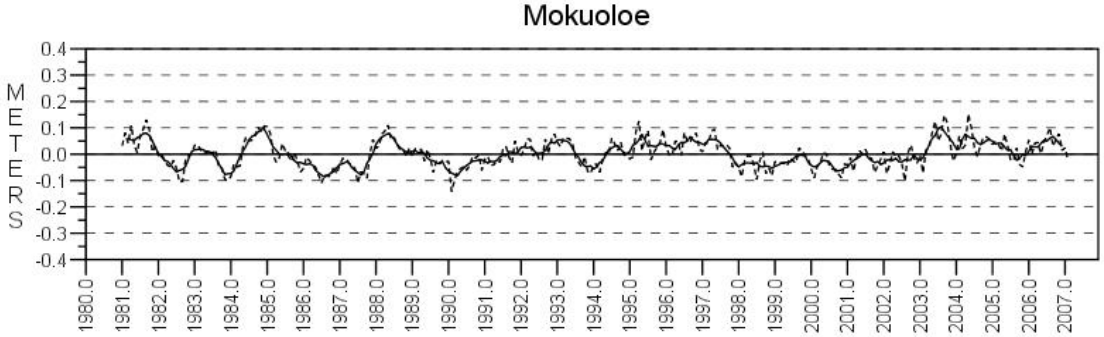


Figure 2. Monthly sea level (dashed) at Mokuoloe, Oahu. The solid curve shows the inter-annual variability with the average annual cycle and linear trend removed. The plot was downloaded from http://co-ops.nos.noaa.gov.

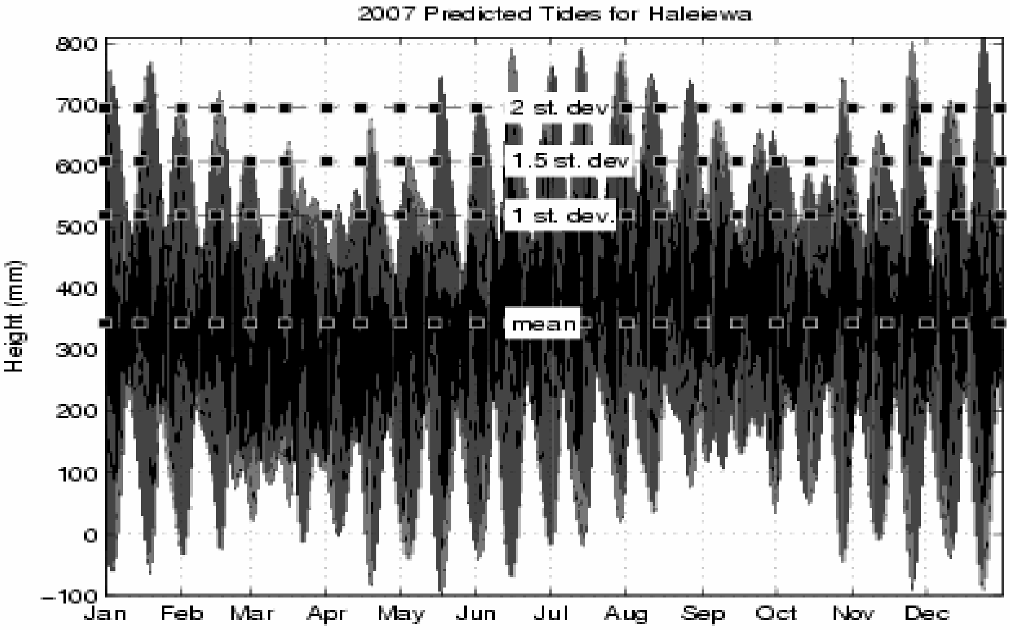


Figure 3. 2007 hourly predicted tides for Haleiwa Harbor, north shore, Oahu.

Tides in Hawaii are mixed semi-diurnal with the most extreme ranges occurring near and following the solstices (Figure 3). Heights above 1, 1.5, and 2 standard deviations (σ) occur 15.6, 7.2, and 2.5% of the time, respectively, and define the tidal thresholds for this study. The hour of the day of the daily maximum semi-diurnal peak has an annual cycle, with wintertime peaks overnight and summertime peaks under daylight (Figure 4). During the high surf season, the largest run-up events occur at night or the early morning hours.

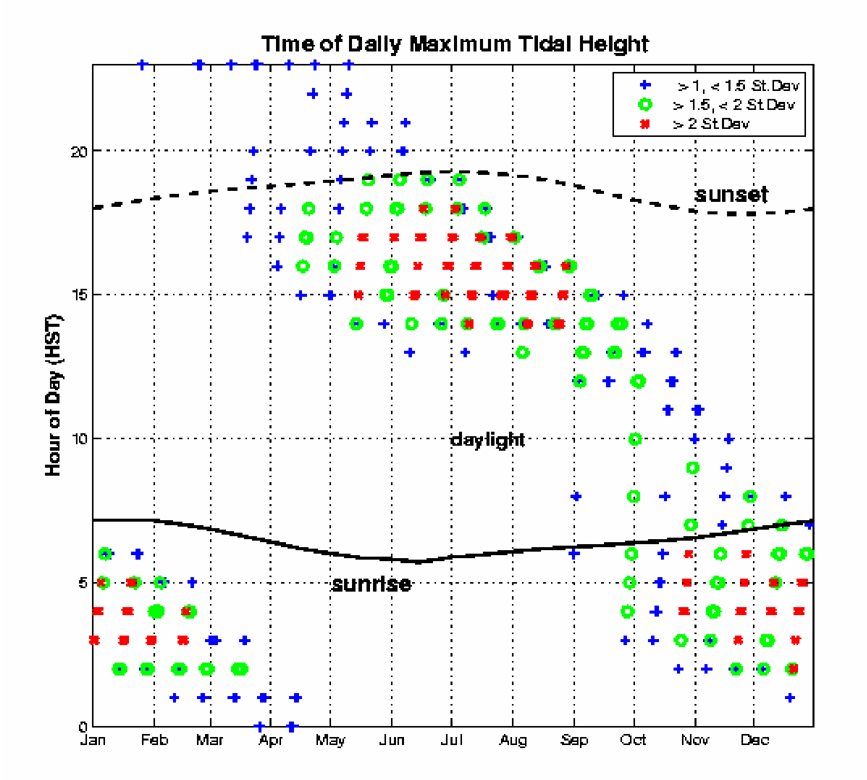


Figure 4. Time of day of peak of highest daily tide.

Since December 9, 2001, the Department of Oceanography at the University of Hawaii (UH) in collaboration with the Coastal Data Information Program (CDIP) of the Scripps Institute of Oceanography has maintained a Datawell directional waverider buoy roughly five km northwest of Waimea Bay, Oahu (Figure 1) in roughly 300 m ocean depth. The sampling rate is one Hz and the acquisition time is 20 minutes. Significant wave height (H_s), dominant wave period (P_d) and direction are digitized on 30-minute cycles. To create an hourly series in this study, the 30-minute sample closest to the hour was chosen. The series for this study ended on March 31, 2007.

The Waimea buoy is the primary source for wave data in this study. For gaps and time periods before the Waimea series, wave data from the NOAA NDBC buoy 51001 are utilized (Figures 5 and 6).

As part of a permanent national network, the NDBC has maintained an environmental buoy in the Northwest Hawaiian Islands since February 1981. The location of buoy 51001 is approximately 274 km west-northwest of Kauai and about 407 km west-northwest (295^{o}) of Waimea Bay, Oahu, which is shadowed by Kauai and Niihau for incident swell directions between 273-295^{o}. Starting in May 2005, directional wave data have been collected.

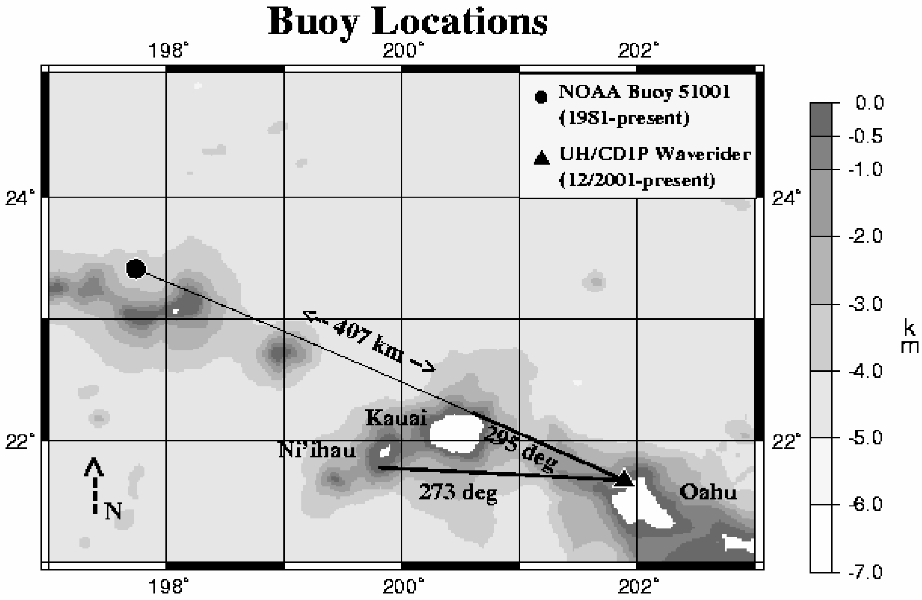


Figure 5. Location of buoys and shadow lines for north shore Oahu.

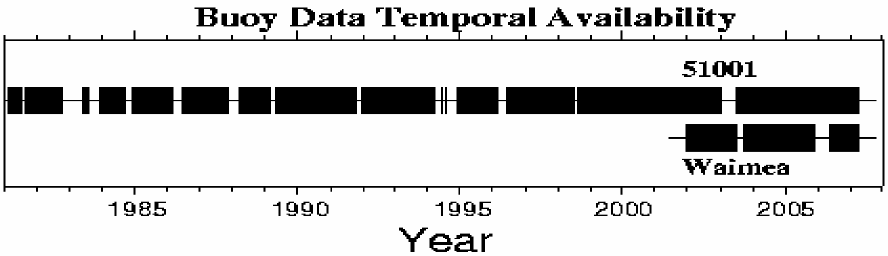


Figure 6. Data availability (vertical lines) for buoy data.

51001 data are typically available hourly except during periods of low battery voltage in which case the reports are given every three hours. There were seven time segments during high surf seasons of 1981-2007 lasting a few weeks to a few months with three-hourly recording. Rounded to the nearest month, three-hourly sampling occurred in October 1987, January-March 1989, January 1990, October 1996, December 1997-February 1998, December 1999-January 2000, and November 2000.

There are many extended gaps in the buoy 51001 wave time series (Figure 6). The entire high surf season centered on October 1982 – May 1983 is missing. This is significant, since occurrence of large to extreme surf episodes is higher during an El

Niño (ROONEY, 2004; CALDWELL, 2005; AUCAN, 2006), and 1982-83 was one of the strongest El Niño events on record (SMITH. and SARDESHMUKH, 2000). Other significant gaps rounded to nearest month are July – November 1983, November 1987 – February 1988, March-April 1989, October-November 1991, March 1992, March-November 1994, September-November 1997, and January-February 2003.

An hourly time series of deep water H_s and P_d offshore northern Oahu is essential for this study. The Waimea buoy is ideally situated. However, buoy 51001 is sufficiently distant to warrant a correction in H_s. The primary reason for the H_s difference (51001 minus Waimea) is the former is closer to the wave generation zone. PIERSON et al. (1955) showed dispersion of seas results in a rapid drop in significant wave heights over the first several hundred miles away from the generation area, beyond which the decay in heights is more gradual. Extreme surf episodes in Hawaii typically coincide with the generation source being closer. This would explain the increase in the difference with increasing H_s at 51001, since this would be in the area of rapid H_s attenuation due to dispersion. A secondary reason for the difference is the shadowing by Kauai for wave energy in 273-295 ° directional bands. The dominant wave period is assumed to be conserved during the travel from 51001 to Waimea.

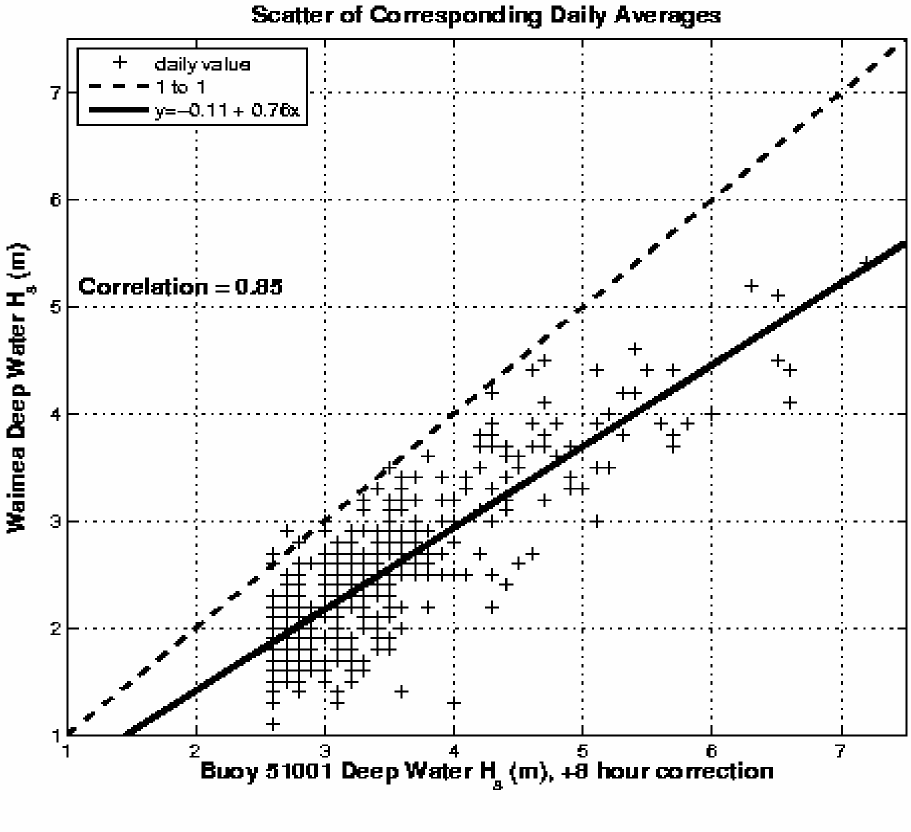


Figure 7. Comparison of daily-averaged Hs for the Waimea and buoy 51001.

A linear fit of daily means from these two buoys (Figure 7) for 51001 $H_s > 2.5$ m is used to define the H_s correction for the 51001. Daily pairs are only included if all available hours or half-hourly data were available from 51001 and Waimea buoys, respectively. Prior to the linear fit, the 51001 hourly data were shifted forward eight hours to compensate for the travel time, which varies between 5-12 hours for the 14-25 second wave periods within 295-345°--the most frequent high season directional band. Extreme surf episodes from the north to northeast are rare.

There was no filtering by direction prior to the linear fit, allowing directional biases to become a signature in the error. Caldwell (2005) discussed in detail the shadowing effect of Ni’ihau and Kauai on Oahu (Figure 4) and occurrences of east-west gradients of H_s between 51001 and Waimea under more northerly directions. The more northerly directions also have a shorter time lag between swell arrival at 51001 and Waimea.

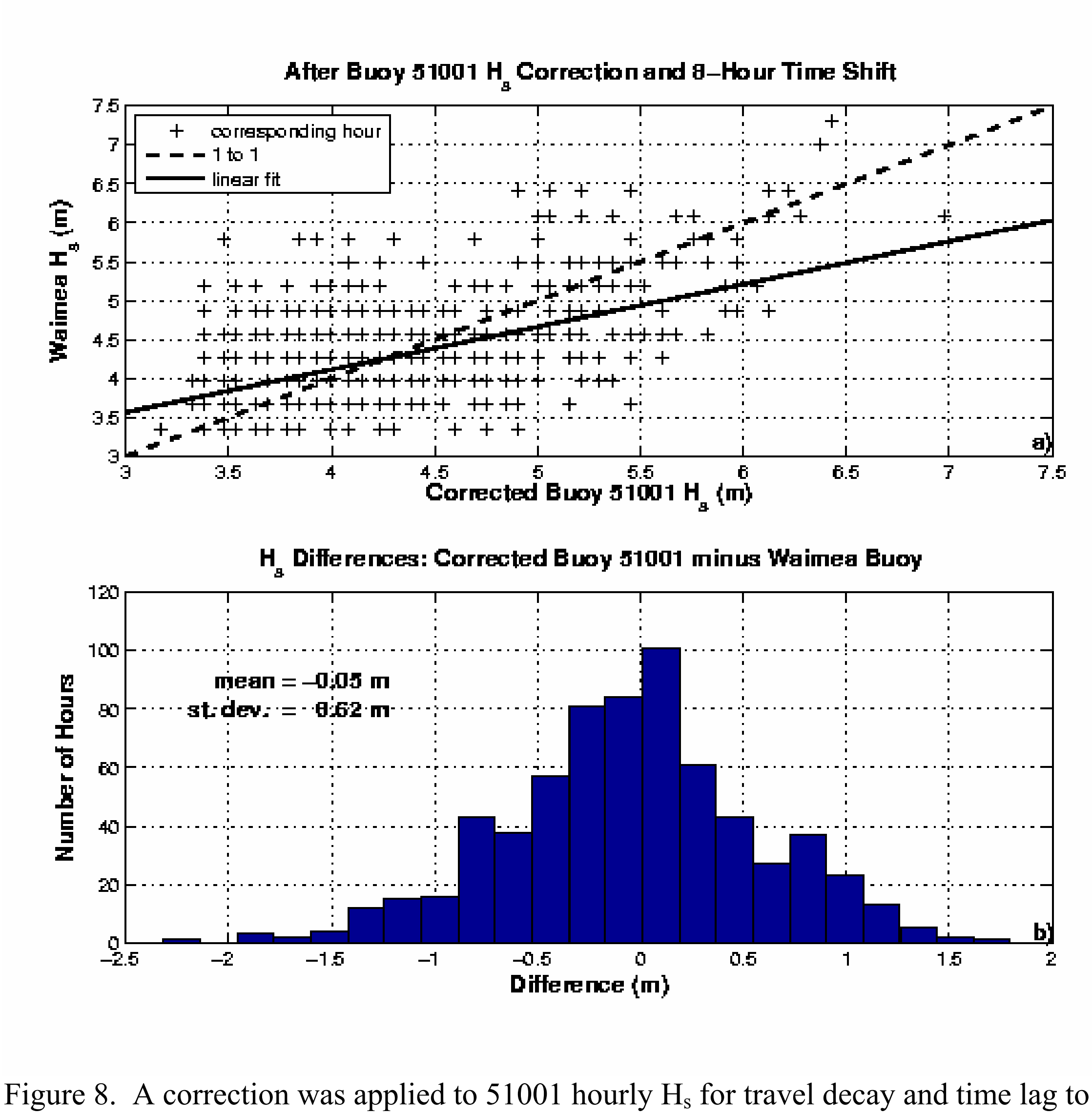


Figure 8. A correction was applied to 51001 hourly H_s for travel decay and time lag to Oahu. Comparison to the Waimea buoy is given as a) scatter plot and b) histogram.

A comparison of the corrected 51001 H_s and the Waimea H_s is shown in Figure 8. A linear fit of the hourly pairs shows a bias of the correction to underestimate the Waimea H_s for $H_s < 4$ m and to overestimate for $H_s > 4$ m. However, this linear fit is more greatly weighted by $H_s < 4$ m since there are more data points. For $H_s > 5$ m, the linear fit is nearly 1 to 1. Since the focus of this study is extreme events, this correction is sufficient for the present application.

a) Year	Month	Day	Est. Surf (m)	51001 H_s (m)	Est. Oahu H_s (m)	51001 Peak Period (s)	Est. Swell Direction (16-point)	Hour Peak Tide (GMT)	Height Peak Tide (st.dev.)
1986	2	23	14.4	7.3	5.4	16	WNW	13	1.9
1999	1	1	14.1	6.7	5	17.9	NW	13	2.2
1985	12	10	14.1	6.6	4.9	17.9	NW	13	2.1
1985	1	15	14	7.2	5.4	14.9	WNW	12	1.1
2003	1	5	13.8	7	5.2 (5.4)	15.6	NW	16	1.9
2002	11	26	13.4	6.3	4.7 (4.1)	17.7	NW	19	1.5
1986	2	16	13.3	6.5	4.8	16.5	NW	12	0.9
1989	1	29	13.2	6.3	4.7	15.9	NW	14	0.9
2005	1	17	13	6.4	4.7 (4.4)	16.4	NW	16	0.9
2002	1	7	12.9	6.2	4.6 (5.1)	16.8	NW	12	0.9

b) Year	Month	Day	Hour (GMT)	Est. Surf (m)	51001 H_s (m)	Est. Oahu H_s (m)	51001 Peak Period (s)	Est. Swell Direction (16-point)	Hour Peak Tide (GMT)	Height Peak Tide (st.dev.)
1986	2	23	16	19.6	9.5	7.1	20	WNW	13	1.9
1985	1	15	4	19.2	10.1	7.6	16.7	NW	12	1.1
1999	1	1	6	19.1	9.2	6.9	20	NW	13	2.2
2003	1	5	15 (11)	17.9	9.3	7 (7.2)	16.7	NW	16	1.9
1998	1	29	4	17.7	8.4	6.3	20	NW	14	2.1
1989	1	29	11	17.7	8.4	6.3	20	NW	14	0.9
1986	2	5	20	17.1	8	6	20	NW	12	2
2005	1	17	20 (17)	16.9	7.9	5.9 (5.6)	20	NW	16	0.9
1985	1	19	5	16.9	7.9	5.9	20	NW	13	2.1
1985	12	10	19	16.7	7.8	5.8	20	NW	13	2.1

Table 1a) 24-hour average and b) 24-hour maximum for top ten highest estimated (est.) surf episodes based on corrected 51001 H_s and P_d. Waimea H_s given in ( ) as available. Maximum daily tidal height in standard deviations (st. dev.) above the mean included.

ANALYSIS AND DISCUSSION

The hourly composite Waimea/corrected 51001 time series of deep water H_s and P_d spans from February 1981 through March 2007 with gaps as described above. Hourly breaker height estimates are made using the empirical transformation described in CALDWELL and AUCAN (2007). The surf heights refer to the average of the highest 1/10th heights (H_{10}) in zones of high refraction at the moment and location along the wave front of maximum cresting. For surf heights > 9 m, such zones are on outer reefs well away from shore. This hourly time series of estimated north shore surf heights serves as an important resource for other applications beyond this study.

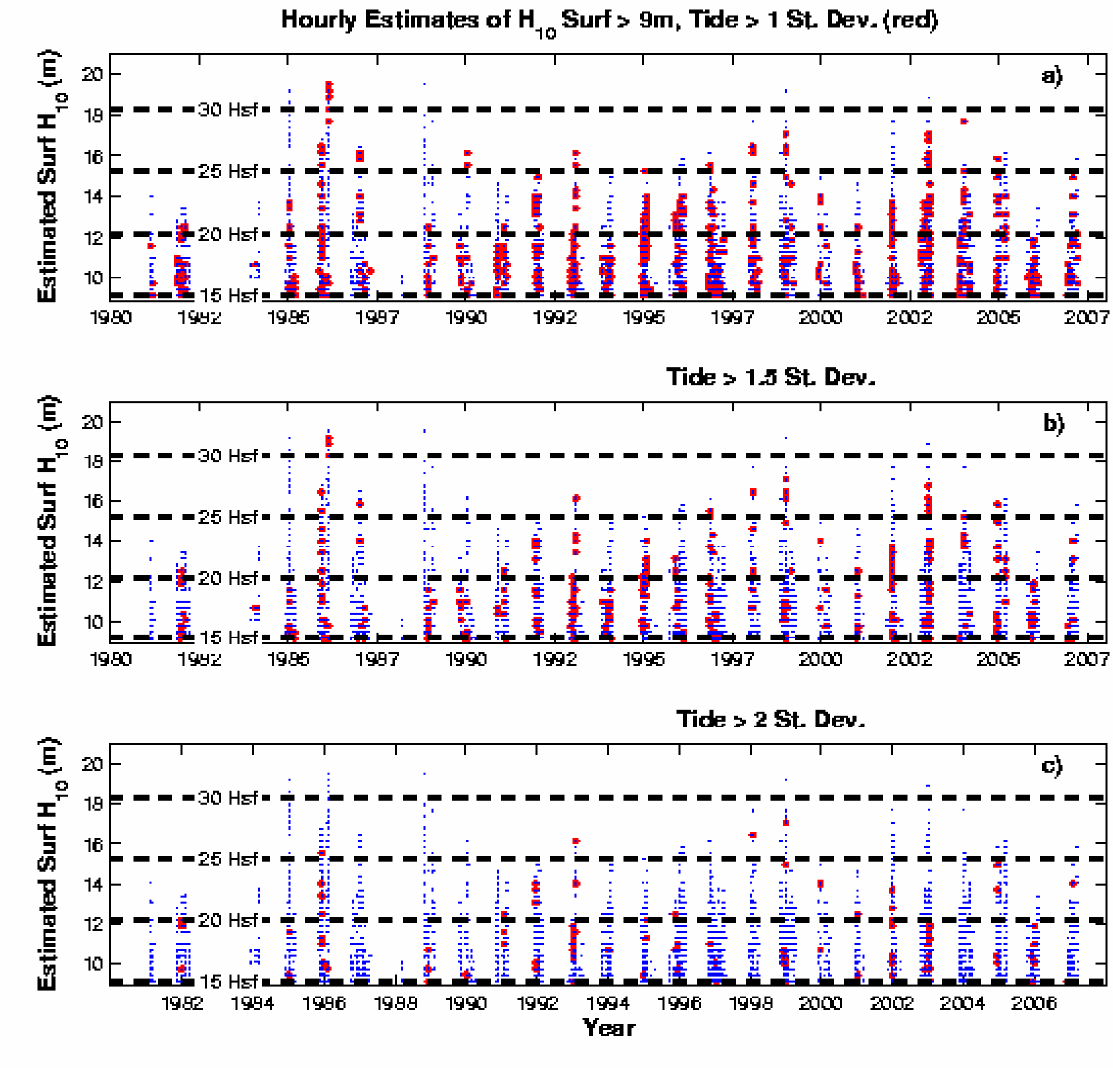


Figure 9. All hourly surf estimates > 9m (blue) coinciding with categories of the tide (red) for a) tide > 1 standard deviation (St. Dev.) b) > 1.5 St. Dev. and c) > 2 St. Dev. Estimated surf height in Hawaii scale feet (Hsf) is overlaid. Hsf is based on visual observations and relies highly on bench marks of near shore wave energy (CALDWELL, 2005), allowing a consistent method of validation and inter-comparison among events.

Daily averages and maximums of the highest ten estimated surf episodes based on the corrected buoy 51001 H_s and P_d are given in Table 1. Swell direction is derived from Waimea buoy when available; otherwise, it was hindcasted using NOAA Center for Environmental Prediction's historic six-hourly surface pressure charts. These top ten events highlight the dominance of long-period northwest swell, supporting the eight-hour time correction applied to the 51001 data. An episode on November 5, 1988, the day of the highest hourly reading at buoy 51001 of 12.4 m with a 14 s dominant period, was eliminated from the list because the swell direction was hindcasted to north-northeast, mostly missing Oahu to the west. For the few episodes when Waimea buoy data were also available, the 51001 estimated deep water Oahu H_s agrees well.

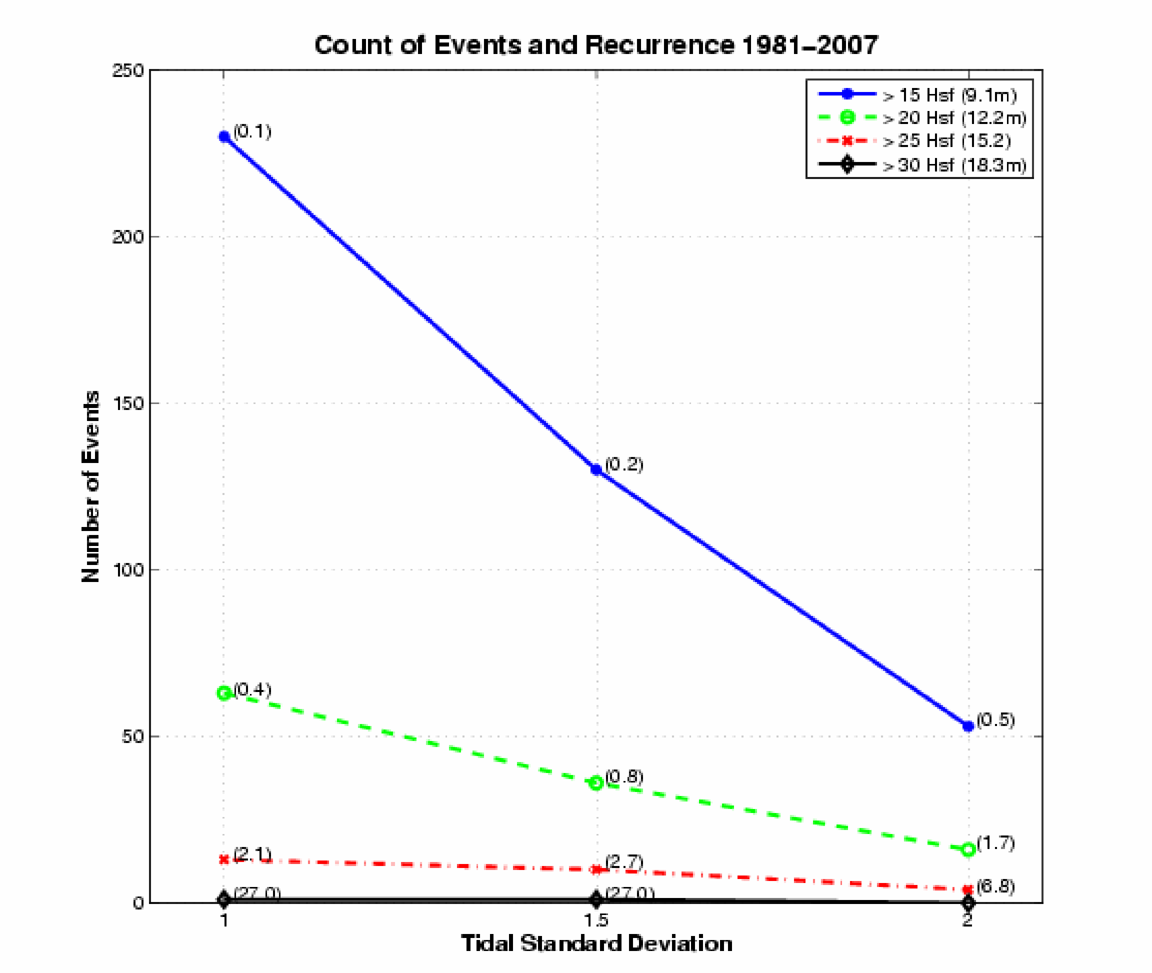
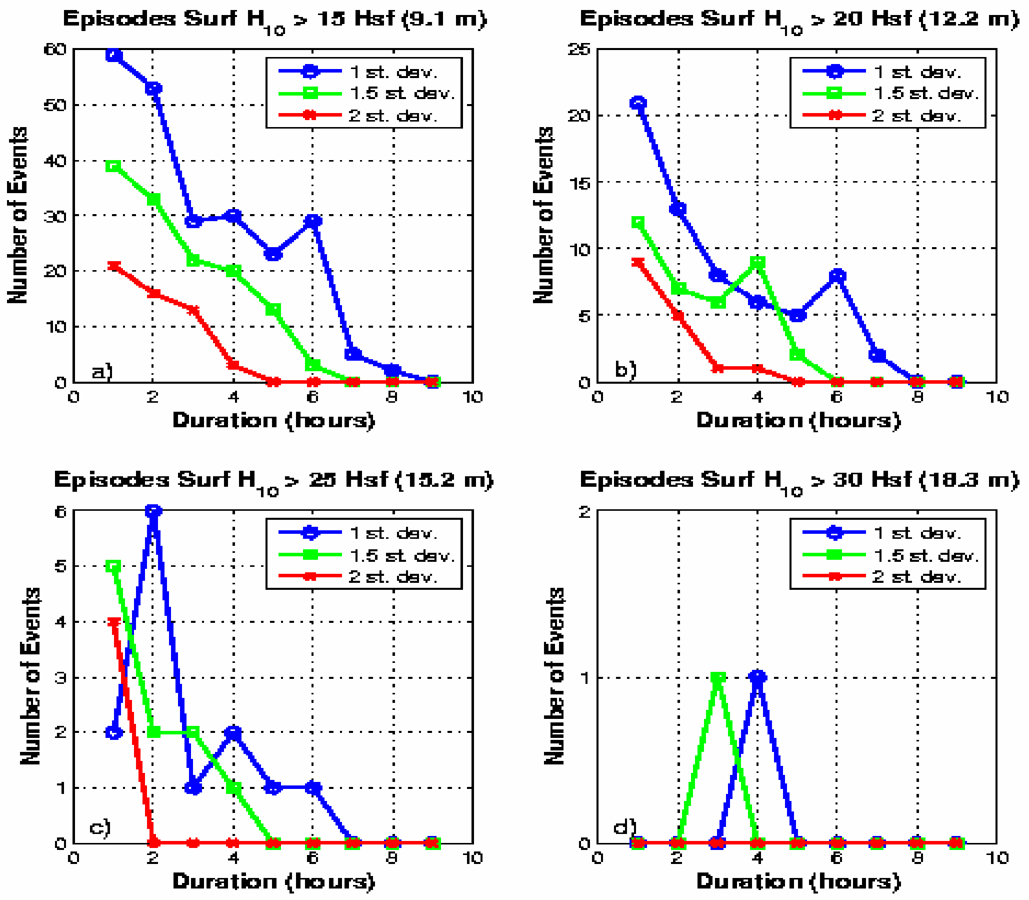


Figure 10. Counts of events over the 27-year period within each surf size and tidal height category or higher and annual recurrence ( ).

The hourly estimated surf height time series was matched to the hourly-predicted tides with emphasis on water levels above 1, 1.5, and 2 σ relative to the mean (Figure 9). To better understand the frequency of occurrence above the various thresholds of surf and tidal height, counts per season were made (Figure 10). Annual recurrence is calculated by dividing the series length (27 years) by the number of events over the length of the series of each category.



Episodes Surf H_{10} > 15 Hsf (9.1 m)

Episodes Surf H_{10} > 20 Hsf (12.2 m)

Episodes Surf H_{10} > 25 Hsf (15.2 m)

Episodes Surf H_{10} > 30 Hsf (18.3 m)

Figure 11. Counts over the 27-year period of duration of events in hours at least as high as a given surf size/tidal category or higher.

Magnitude of coastal erosion is strongly dependent upon the duration of extreme run-up (RUGGIERO et al., 2001). For each episode of each surf/tide category, the duration in hours (Figure 11) and the average duration were calculated.

Nominally, marginal run-up events are represented by surf ≈ 9 m and tides > 1 σ above the mean, have occurred on average ten times per year since 1981, range in duration from 1-8 hours and last on average 3.1 hours . Significant episodes are associated with surf ≈ 12 m and tides > 1.5 σ, have happened once annually on average, range in duration from 1-5 hours and last on average 2.5 hours. Extreme high wash occurrences are related to surf ≈ 15 m and tides > 2.0 σ or surf > 18 m and tides > 1 σ, have taken place on average every seven years, range in duration from 1-4 hours and last on average 1.9 hours. The paper does not attempt to define the vertical reach relative to a datum.

As an independent check on the effects of run-up, descriptions of damage and physical effects on coastal highways were examined in two sources: the NOAA National Weather Service Storm Data reports (1996-2007) and the Hawaii Department of Transportation (HDOT) daily road clearance logs (1992-2006). The former had fewer events logged. For one of the largest surf episode, January 28, 1998, during the overlapping periods, the Storm Data series describes property damage and sand/debris on the Kamehameha Highway on the north shore of Oahu. However, the HDOT did not file a report for that day. The HDOT had several days listed when the surf was commonly high, around 4 m, on days with neap tides. The haphazard nature of these reports creates more questions than answers.

SUMMARY AND FUTURE WORK

Understanding the nature of extreme wave run-up is vitally important for safety, property protection, coastal planning, and research. Tsunamis and hurricanes pose the largest potential for coastal damage, although these events are rare. More commonly, coastal inundation results from coinciding high surf and tides. For the north shore of Oahu, an estimate of the frequency and duration of events categorized by surf and tidal height has been made using historical hourly buoy measurements and predicted tides.

The Waimea buoy was the primary source for deep water H_s and P_d. However this series only began in 2001. NDBC buoy 51001 extends back to 1981. The location is sufficiently remote from Oahu to warrant a correction in H_s. The correction was based on a linear fit of overlapping, daily mean, Waimea buoy and 51001 pairs.

From the 1981-2007 hourly series of measured and estimated deep water H_s and P_d off northern Oahu, surf heights were calculated using an empirical transformation scheme. This resultant time series of breaker heights has potential for applications beyond the scope of this paper, such as correlating water levels in aquifers to surf size. The hourly surf heights were matched with hourly predicted Haleiwa tides to count the number of occurrences above given thresholds of surf and tidal heights. Nominally, marginal run-up events are represented by surf $\approx$ 9 m and tides $> 1\ \sigma$ above the mean, have occurred on average ten times per year since 1981, range in duration from 1-8 hours and last on average 3.1 hours . Significant episodes are associated with surf $\approx$ 12 m and tides $> 1.5\ \sigma$, have happened once annually on average, range in duration from 1-5 hours and last on average 2.5 hours. Extreme high wash occurrences are related to surf $\approx$ 15 m and tides $> 2.0\ \sigma$ or surf $>$ 18 m and tides $> 1\ \sigma$, have taken place on average every seven years, range in duration from 1-4 hours and last on average 1.9 hours.

The focus of this paper has concerned the historical coincidence of high tide and high surf events. Future work includes the probabilistic occurrence of high tide and high surf events based on the joint probability of extreme events. Exceedance probability models can be constructed individually from long time series of wave and water-level data [RUGGIERO et al. (2001), VITOUSEK and FLETCHER (2007)] and combined into a joint exceedance probability model. Such a statistical model gives the time of expected coincidence of extreme events in a given period and may provide information on future erosion and coastal flooding hazards.

Future work is needed to acquire the optimal estimated deep water H_s and P_d off northern Oahu for time periods when Waimea buoy data are not available. The correction of buoy 51001 hourly H_s to Waimea could be improved by using an estimated wave direction from wave model output and the measured P_d. CDIP maintained a deep water (1100 m) wave rider gauge off Barking Sands, Kauai during 1982-1983, a period when 51001 was out of service. The U. S. Army Corp. of Engineers, Wave Information Studies provides hindcasts with output points around Hawaii as described in AUCAN (2006). This hourly model output begins in 1956 and could extend the series backwards by 25 years as well as provide estimates to fill gaps in the 51001 series.

The paper does not attempt to define the vertical wave run-up relative to a datum. This task should be undertaken. Geodetic surveys of run-up episodes at select locations, which can give explicit measurements for matching with the surf and tidal data. Since the daily maximum tides occur overnight during peak high surf season, the measured elevations are typically after the fact and depend on run-up signatures such as debris lines and water damage. The State of Hawaii Division of Lands and Natural Resources makes spot inspections after high episodes, although the data are not systematically stored or available. Oregon State University and the University of Hawaii have maintained a camera aimed at the beach in Waimea Bay since the late 1990s for studies of beach dynamics. These data will augment future studies.

The deep water estimated and measured H_s and P_d are ripe for a study similar to RUGGIERO et al.(2001), which defines return periods based on the data series length and models the combined effect of surf, tides, and inter-annual sea level variability. For this study, inter-annual variation of sea level was not taken into consideration because the signal is small. However, for explicit elevation reach, this information would add value. Other components to total run-up, such as wave set-up and Eckman pumping caused by regional winds, need further investigation.

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