AN EMPIRICAL METHOD FOR ESTIMATING SURF HEIGHTS FROM DEEP WATER SIGNIFICANT WAVE HEIGHTS AND PEAK PERIODS IN COASTAL ZONES WITH NARROW SHELVES, STEEP BOTTOM SLOPES, AND HIGH REFRACTION

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1. INTRODUCTION

Accurate and timely surf forecasts communicated in a clear, concise manner are essential in planning nearshore activities. In Hawaii, a large population of recreational enthusiasts comprised of both residents and visitors use surf forecasts on a daily basis. Forecasts are vital to commercial ventures, coastal engineers, ecosystem and geophysical researchers, and governmental coastal planners in making safe, strategic, and cost effective decisions.

The National Oceanic and Atmospheric Administration (NOAA) Weather Service Forecast Office (WFO) in Honolulu, Hawaii issues surf height predictions explicitly for the north, east, south, and west-facing shores in pursuit of protection of life and property. For each shore, the forecast is given as a range of expected breaker heights (feet) defined as the trough to crest vertical distance on the shoreward side of the wave. Forecasts are validated by interpretation of offshore buoy measurements and visual surf observations. The complex transformation of wave characteristics from offshore to the surf zone leads to uncertainty in validating breaker heights with deep-water buoy data. Visual breaker observations are the best means of verifying a surf forecast.

Surf observations in Hawaii are routinely made by various entities and made publicly available via the media. Digitized records of daily surf observations from select locations around Oahu extend back into the 1960s. Heights have traditionally been made in Hawaii scale feet (HSF), which is roughly half of the trough to crest heights. The WFO historically issued forecasts in HSF until April 2001, when trough to crest (full face) heights were employed. Since April 2001, surf observations have been made in both the HSF and trough to crest fashion. Confusion in the translation from HSF to trough to crest values has added uncertainty to daily surf reports and to the surf forecast validation.

Estimates of offshore wave characteristics have improved in recent years. The Wave Watch III (WWIII) model (Tolman, 2002) produces operational global wave field estimates for the oceans and major seas. The high quality of the model output has been verified through comparisons with buoy measurements (Wingeart et. al., 2001). At several fixed, nominal locations surrounding the Hawaiian Islands, the WWIII produces a time series of predicted deep water significant height, peak period, and direction. This represents a valuable resource for surf forecasts.

A network of permanent NOAA buoys is located roughly 100 to 300 km offshore of the Hawaiian Islands and has been in place for two decades. Closer to shore near Oahu, the University of Hawaii has maintained directional waverider buoys for several years off Kailua on the windward side and Waimea Bay on the north shore. Data from these instruments are critical for fine tuning the short term surf forecasts.

Although the offshore wave characteristics are well predicted and observed around Hawaii by the WWIII model and buoys, respectively, the transformation of waves from deep water to the surf zone has not been understood well enough to adopt an operational method, which can utilize the offshore information in making explicit surf height estimates.

A thorough literature review concerning the transformation of waves both theoretically and empirically is provided by Walker (1974). For oceanic island locations, various studies have been made. An investigation was undertaken by Lugo-Fernandez et. al. (1994) at Margarita Reef in southwestern Puerto Rico to relate wave energy distribution to observed reef damage following a hurricane-generated swell. Shoaling effects were calculated from linear wave theory (Kinsman, 1965; USACE, 1984) and refraction coefficients were derived from refraction diagrams (Arthur et. al., 1952). Bottom friction was shown to be negligible. Comparisons of the predictor to observations showed a one to one agreement with an 85% level of confidence. Wave refraction at Jaws, Maui, Hawaii has been quantified by Fearing, (2000) using a combined refraction/diffraction model (Kirby and Dalrymple, 1983, 1994). It estimates the wave height amplification and depth of breaking point as a function of varying offshore heights and periods. The refractive amplification on the reef is greater than a factor of 2 relative to an offshore height of 10 feet and period of 15 seconds. Walker (1974) estimated shoaling and refraction on an idealized three-dimensional Hawaiian Island reef using both Airy theory and a finite height method. A refraction coefficient greater than 2 was found to occur over the center of the reef. His results show that conventional refraction analysis is a function of finite height and wave breaking.

This paper presents an empirical method for estimating surf heights. It is based on a comparison of visual surf observations and breaker heights estimated from significant wave heights and peak periods measured at a nearshore, deep water buoy.

2. STUDY AREA AND DATA

The north shore of Oahu, Hawaii (Figure 1a) is recognized as one of the world's premier epicenters of surfing due to various physical and geophysical factors. The relatively close proximity of the north shore to the north Pacific storm track means less wave energy loss, which occurs during swell propagation primarily due to dispersion and angular spreading. The coastline faces the predominant northwesterly swells (Caldwell, 2005) while the common

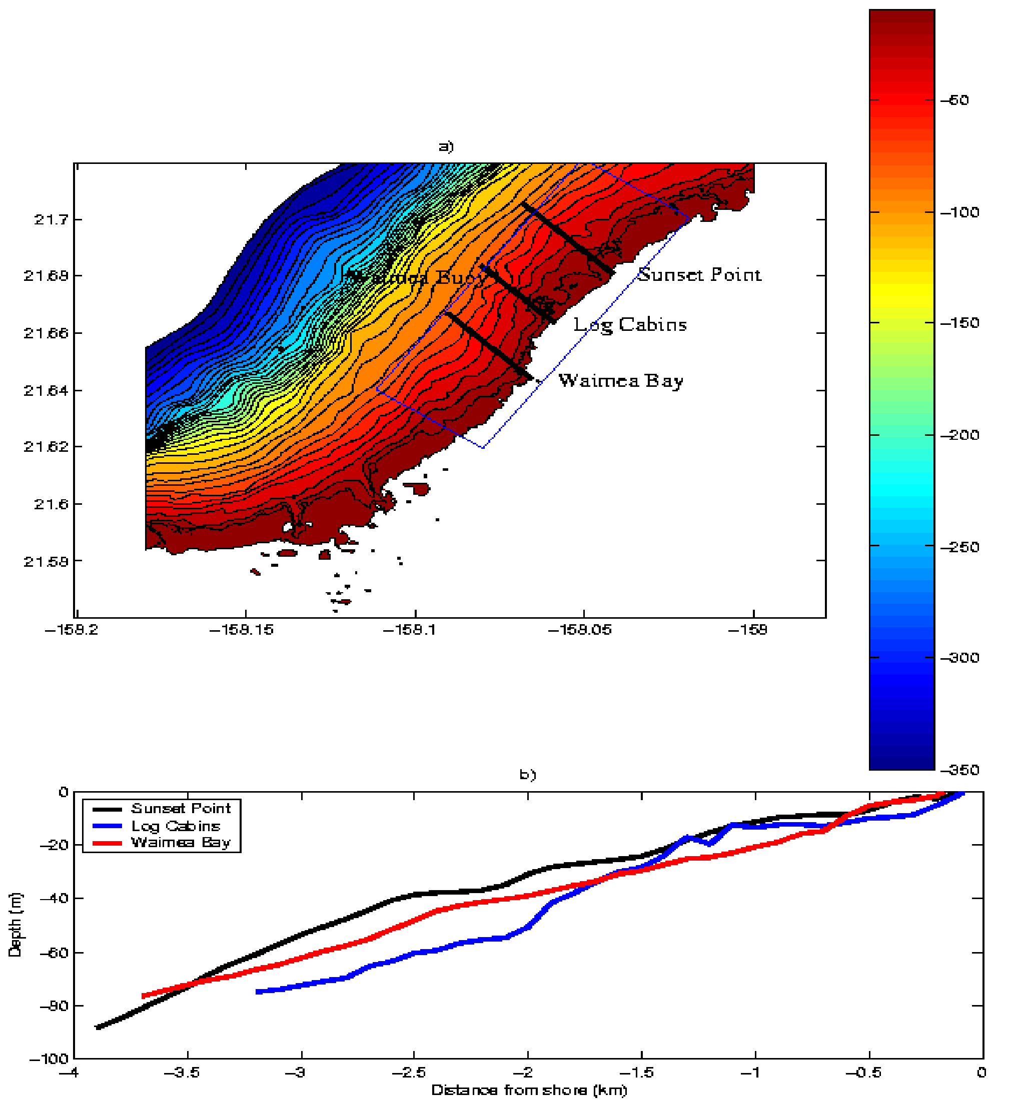

Figure 1. *(a) Study area, depths(m). The blue box denotes the SWAN model domain as shown in Figure 2. (b) Coastal seafloor slopes for cross sections shown as solid black lines in Figure 1a.*

trades blow against the waves creating desirable surfing form. The coastal bathymetry includes a narrow shelf, a steep slope (Figure 1b), and a pattern of underwater troughs and ridges near the surf zone associated with reef systems, submerged river and stream beds, and ancient lava flows. The narrow shelf means a minimal loss of energy due to bottom friction during wave transformation from deep to intermediate depths. The steep nearshore slope and sharp gradients in depth parallel to the shore result in significant height amplification from shoaling and refraction as waves enter the surf zone.

With the growth of surfing in the 1960s on the north shore came routine observations made by surfers, and later in the 1970s, by lifeguards and commercial surf report ventures. Observations were reported in HSF.

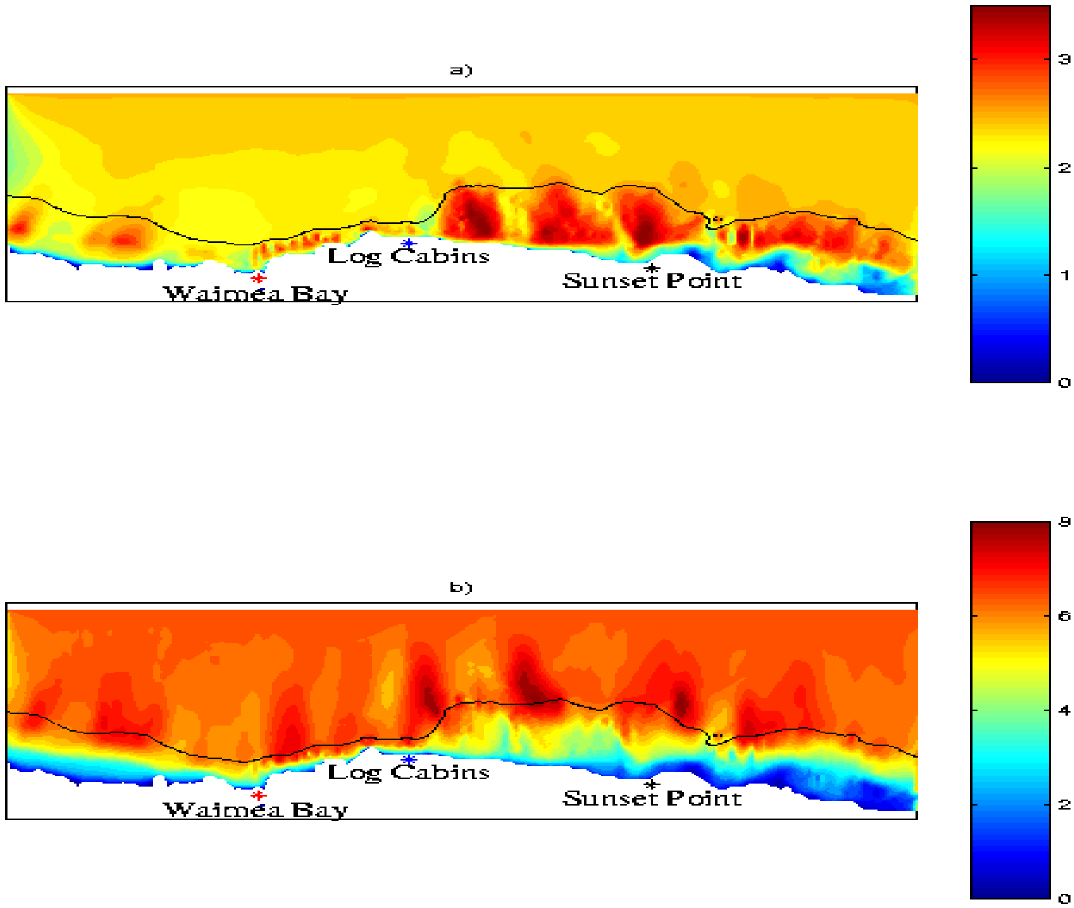

Figure 2. *(a) SWAN model significant wave height estimates (m) for a typical winter deep water swell of 2.5 m at 14 seconds from 315 degrees. (b) Similar output under extreme offshore swell of 6.5 m at 18.6 seconds from 317 degrees. The solid black line denotes the 20 m contour.*

Observations are reported as a height range. Observers ignore the smaller waves. As a simplified example, assume a given day has dominant wave energy in the 14-17 second wave period range with negligible energy outside this band. Assume five waves catch the eye of an observer every four minutes, or 100 waves every 80 minutes. This takes into account the time periods of varying length without waves arriving. The upper end of the reporting range is approximately equivalent to the $H_{1/10}$, the average of the highest 10 waves, which if evenly distributed in time, would occur every 8 minutes. The lower end of the observing range is near the $H_{1/3}$, or the average of the highest 1/3 waves, which if evenly distributed in time, would occur about every 3 minutes. The highest wave over this nominal 80-minute period with 100 waves, or $H_{1/100}$, would be equivalent to the observer's use of "occasional" heights in their reports.

A digital database of surf observations, referred to as the Goddard-Caldwell (GC) set, dates back to August 1968 for the north shore, and to March 1972 for the south shore of Oahu. It is described in more detail in Caldwell (2005). Data are recorded in HSF. The daily values in the GC database refer to the surfing location along the given coast with the highest reported breakers. For the north shore, most observations are taken at Sunset Point, which is usually one of the highest surf spots along the coast under the dominant northwest swell direction. For days of extreme surf with heights greater than roughly 15 HSF, visual observations are reported at Waimea Bay, where breakers are closer to shore. The surf reports are typically made several times per day. The daily value in the GC set represents the upper end of the reported height range for the observing time with the highest breakers. This number aims to be equivalent to $H_{1/10}$. Comparisons of the GC database to 1981-2002 data from NOAA buoy 51001, which is located roughly 400 km west-northwest of Oahu, show the surf observations are temporally consistent with the shoaling-only, buoy-estimated breaker heights and have an uncertainty of 10 to 15% of the surf height (Caldwell, 2005).

The University of Hawaii (UH) has maintained a Datawell Directional Waverider Buoy roughly 5 km northwest of Waimea Bay, Oahu (Figure 1) in roughly 200 m ocean depth since December 2001. For very long period swell of 17 seconds or greater, this location is at the starting zone of transformation. The buoy is a 0.9 m metallic floating sphere with a combination of a bungee and chain anchoring system.

The directional waverider measures the horizontal and vertical components of acceleration of the buoy, which rides up and down with the waves as it floats on the surface. The sampling rate is 1 Hz and the acquisition time is 20 minutes. From the accelerations of each acquisition time, spectra of energy by frequency and direction are derived. In addition, significant wave height and dominant wave period are calculated.

A Simulating Waves Nearshore (SWAN) model (Figure 2) is helpful in understanding the surf height variability along the north shore of Oahu. SWAN is a third generation wave model for use in coastal areas (Booij et. al., 1999). It includes wave generation by winds, propagation, shoaling, refraction, bottom friction and breaking. It uses a 50 m horizontal grid.

3. ANALYSIS

a. Translation of HSF to Trough to Crest Heights

A translation of the surf observations from HSF to trough to crest heights is essential for comparisons to surf estimates derived from offshore wave characteristics, for validating WFO surf forecasts, and for better understanding the historical GC database recorded in HSF. The GC dataset is the most requested regional data set from the NOAA Data Center Hawaii Liaison Office for a variety of engineering, research, commercial, and recreational objectives. A translation from HSF to trough to crest heights would also enhance the understanding of the north shore, Oahu surf climatology given in HSF as described by Caldwell (2005). A translation is presented in this paper based on photographic evidence (Caldwell and Aucan, 2004), using surfers as benchmarks.

A breaker or surf is defined at the moment in time when some portion of the front face of a wave becomes vertical and unstable due to a decrease in water depth. The trough to crest surf height used in this paper is defined as the vertical distance between the crest and the preceding trough at the moment and location along the wave

	Hawaii Scale Feet	*Trough to Crest Height (feet)* Mean	St. Dev.	*Number of Photos*	*Translation Factor*
Non-Waimea Observing	2	5.07	0.5	15	2.54
	3	7.44	0.63	15	2.48
	4	9.5	0.79	15	2.38
	6	12.9	0.99	15	2.15

Locations	8	16.6	0.78	15	2.08
	10	20.28	1.64	15	2.03
	12	23.54	1.08	18	1.96
	15	28.4	4.16	8	1.89
Waimea Bay	15	25.73	1.27	8	1.72
	18	28.93	2.79	13	1.61
	20	31.69	2.59	16	1.58
	25	34.07	1.18	14	1.36
	27.5	38.5	1.14	11	1.4
	30	47.6	0.85	3	1.58
	35	51	0	1	1.46
Peahi (Jaws), Maui	18	35	2.78	5	1.94
	30	59.46	6.13	7	1.98
Oahu Outer Reefs	20	41.3	1.80	4	2.07
	27.5	50.1	1.24	4	1.82
	35	65.9	5	7	1.88

Table 1. Translation from Hawaii scale feet to trough-to-crest heights (feet). Non-Waimea refers to locations between Log Cabins and Sunset Point.

front of highest cresting, which has been shown in models and observations to be at the time and location of breaking (Walker, 1974). For locations with high refraction, such as Sunset Point, where most of the visual observations are made, the breaker often forms an A-shape. The trough to crest height refers to the center of the A, i.e., the point along the wave front with the highest height.

Photographs were obtained from Internet sites or directly from photographers. Location and date was a prerequisite. Photographs showing the highest waves of a given day were chosen from the available pool of pictures. Pictures were sorted by size in HSF matching the date to the GC database. Typically, 15 images for each size category were selected (Table 1).

Each photograph requires a surfer or some other identifiable object to use as a benchmark in estimating wave height. Dashed lines were superimposed on each photograph to indicate the approximate trough and crest. An arrow was overlaid next to each benchmark to denote a 5′ unit. The benchmark arrow was duplicated and subsequent arrows were stacked from trough to crest to gauge the wave size (Figure 3).

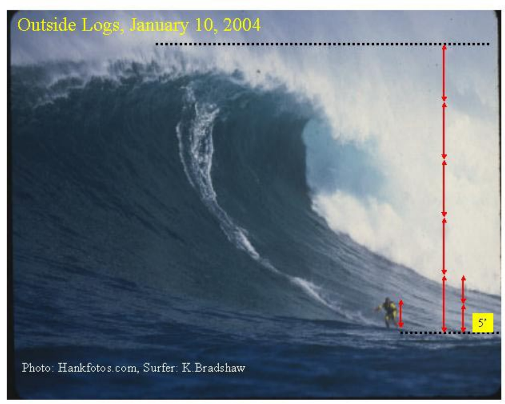

Figure 3. *Scaled surf photograph. The surfer in this picture is 6 feet tall. The red arrow next to the surfer is an estimation of a 5 feet unit, which is used to tally the size.*

Photographs capture a two-dimensional image of a three-dimensional world and distortions of shapes and sizes are inherent.

Shots taken from a high vantage point, such as a cliff or helicopter, make detection of the wave trough difficult. Wave size is distorted in pictures taken by a swimming photographer near the surfer. Priority in selecting shots was given to images taken by a photographer standing close to mean sea level either on shore or on a floating craft. Distortion of perception decreases as the distance between the camera and the surfer/wave increases.

There are various sources for errors in this exercise. The error associated with trough identification has been estimated at 10% of the wave height. The surfer's height is not known in most images. It is assumed that the average surfer height is 5'9″ and a typical surfer stance is roughly 5′ with a 6″ uncertainty, which leads to an error of 10% in the surf height estimate. For both cases, the errors average out as the number of photographs increases. Since the photographs were selected from still images, it is not certain that any given picture represents the highest height reached by that wave during breaking, or if these few select waves represent $H_{1/10}$, which is assumed in the GC database. With the small number of available pictures per day, the translation based on these pictures likely underestimates the heights in the GC database.

Each scaled photograph was examined to estimate the height to the nearest tenth of a foot. For each size category, a mean and standard deviation of the estimated trough to crest heights were computed (Table 1). For days with surf heights of 15 HSF or less, most photographs are taken at spots from Log Cabins to Sunset Beach, which typically has the highest surf on the north shore (Figure 2a). For days with surf heights greater than or equal to 15 HSF, photographs were further sorted by location: Waimea Bay, Oahu outer reefs, and Jaws (Peahi), Maui. Under northwest swell with 17-20 second wave periods, the travel time from Oahu to Maui is roughly three hours, which makes comparisons of daily data appropriate. Fewer photographs were available for the Oahu outer reefs than for Waimea Bay. The paired HSF and trough to crest heights are plotted in a scatter diagram (Figure 4).

For surf heights of two to six HSF the translation shows the trough to crest heights are more than double the HSF observations (Table 1, last column). From six to twelve HSF, the translation is close to double. An inadequate supply of photographs were available of Sunset Point for heights in the 13-15 HSF range, when the offshore-most breaking point is roughly one km from shore and strong currents impede water photography. The available images suggest the translation of 15 HSF

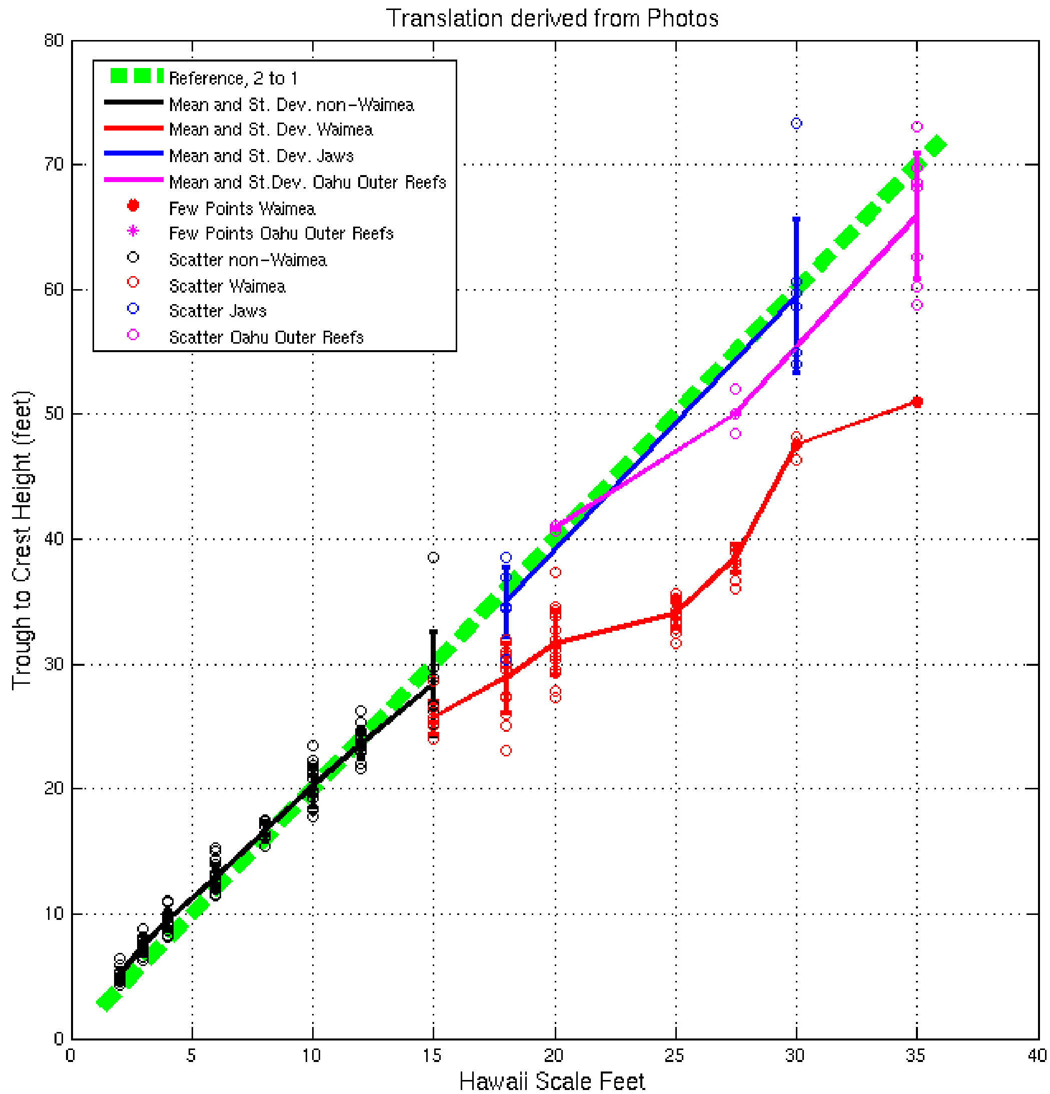

Figure 4. *HSF to trough-to-crest heights translation. Circles denote individual photographs. Non-Waimea refers to locations from Log Cabins to Sunset Point.*

to trough-to-crest heights is slightly less than double. For the entire range from two to fifteen HSF, the translation can simply be defined as double within the margin of error.

For surf above 15 HSF, the wave energy at Sunset Point becomes overwhelming and the resultant breakers occur unpredictably over a wide area both parallel and perpendicular to shore. This makes surfing dangerous due to difficulties in maintaining a safe wave-entry point. Under such extreme conditions, surfers historically challenged Waimea Bay, where the take-off zone is narrower and the proximity to shore allows landmark referencing for more precise wave-entry positioning.

Numerous photographs are available for Waimea Bay during

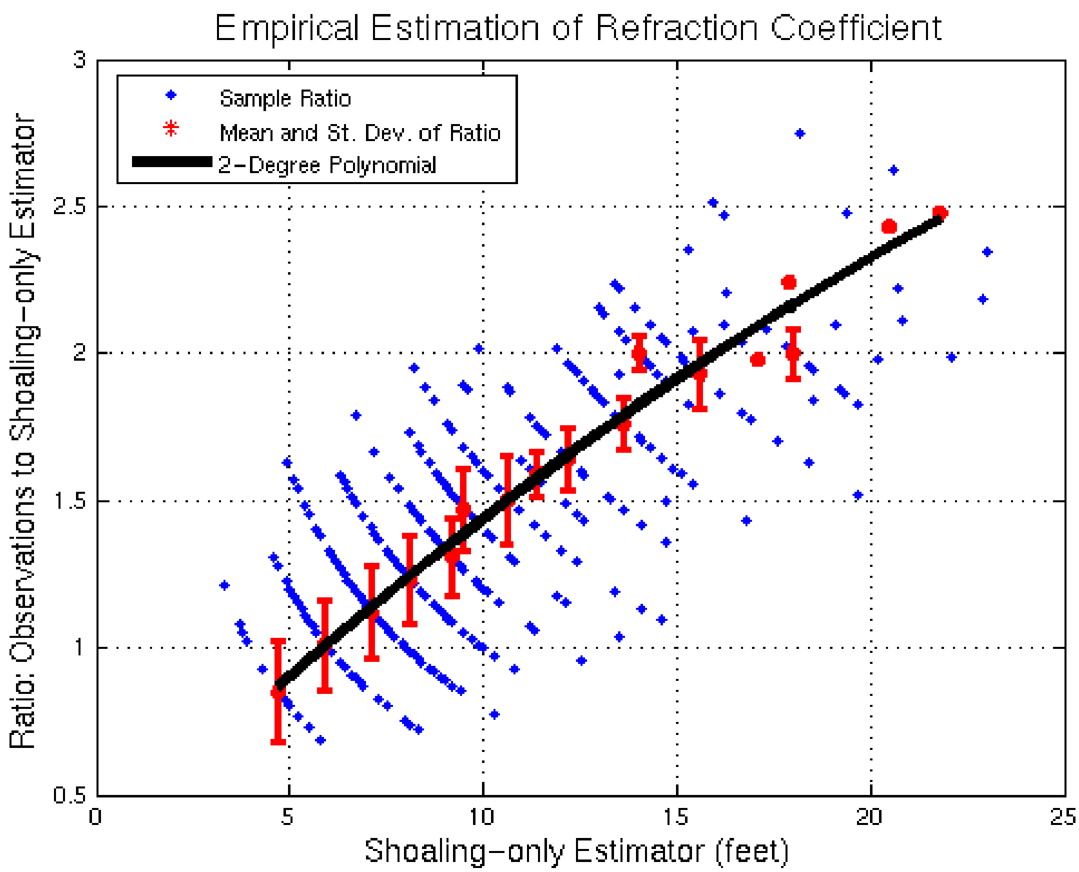

Figure 5. *The black line represents the refraction coefficient as a function of the shoaling-only estimator.*

surf in the 12-30 HSF range. The surfers enter the wave about 50-100 m outside the point on the northeast side of the bay and surf at an angle toward the safety of the deep waters in the center of the bay. The wave-entry point shifts northwest of the northeast point of the bay with increasing wave size. At approximately 30 HSF, the entire wave front cascades nearly simultaneously across the breadth of the bay, ending a surfer's chance for a safe ride.

The photographs at Waimea Bay suggest the trough to crest heights are roughly 1.5 times HSF during days with observations in the 15-30 HSF range. Within the collection of photographs, there are several occasions when images were available for the same day from both Waimea Bay and outer reefs of Oahu and Maui, where tow-in surfing (motor-powered-watercraft-assisted breaker entry) has gained popularity over the past decade. Over the submerged ridges of the offshore reefs to either side of Waimea Bay, the SWAN output (Figure 2b) shows increased heights due to convergence of wave rays, i.e. refraction. Photographs of tow-in surfers on outer reefs validate the larger heights relative to Waimea Bay.

In summary, the translation of HSF to trough-to-crest heights is a factor of two within the 10-15% margin of error for the full range of breaker sizes encountered in Hawaii. This assumes the height is defined as the highest height reached in the vertical from the trough to crest at any point along the wave front during breaking and zones of high refraction (outer reefs) are included for extreme days when Waimea Bay was the reporting location. The HSF, or simply dividing trough to crest height by two, has been adopted by other big wave enthusiasts around the globe as seen in pictures and dialogue from extreme surf contests in California, Peru, and South Africa. It is important for scientists and the general public to understand this relationship for utilizing surf observations reported in HSF.

b. Empirical Method for Estimating Surf Heights

The GC database in HSF was converted to trough-to-crest heights using the factor-of-two translation. These data were compared with corresponding data from the Waimea buoy to derive an empirical relationship.

Since the surf observations are made during daylight hours, buoy data from only 7 AM to 5 PM Hawaii Standard Time were considered. For each 30-minute buoy reading, a shoaling-only breaker height was calculated following the method of Komar and and Gaughan (1973),

$$H_b = H_o^{4/5}[(1/\sqrt{g})(gP/4\pi)]^{2/5} \quad (1)$$

where:

H_b = shoaling-only estimated wave height at breaking

H_o = deep water significant wave height

P = dominant wave period

g = gravity

Equation (1) assumes wave energy flux is conserved from deep water to the time of breaking, and wave breaking occurs in water depth approximately equal to wave height. Refractive focusing and diffraction are not considered. It also ignores other relevant physics such as bottom friction, currents, wave-wave interactions, and wind. The 30-minute buoy reading during the daylight hours with the maximum shoaling-only breaker height estimate was chosen for comparison with the daily surf observation.

Days of strong trade winds or moderate to strong onshore winds relative to Sunset Point were removed from the paired data sets. Under strong trades from 35^o to 120^o, the Waimea buoy registers wave energy while most reefs from Waimea to Sunset Point are sheltered. During onshore winds, wave observations are less accurate since surfers are usually not in the water and the breaking pattern is irregular. Additional filtering was performed for buoy wave directions greater than 10^o and less than 270^o, since the observing locations face roughly 315^o. The study focus is for remote northwest and north-central Pacific swell sources typical of the high surf season. The result was a sample size of 404 pairs.

A scatter diagram (Figure 5) shows the ratio, surf observations to H_b, as a function of H_b. The mean and standard deviation of the ratio for each HSF observation size was calculated and overlaid. A 2-degree polynomial was fit to the mean ratio. This model represents an empirical estimation of the refraction coefficient, K_r, as a function of the shoaling-only, buoy-estimated breaker height, H_b, or

$$K_r(H_b) = -0.0013*H_b^2 + 0.1262*H_b + 0.3025 \quad (2)$$

Thus, the estimated surf height, H_{surf}, based on offshore significant wave height and dominant period, including shoaling and refraction, is given by

$$H_{surf} = H_b * K_r(H_b) \quad (3)$$

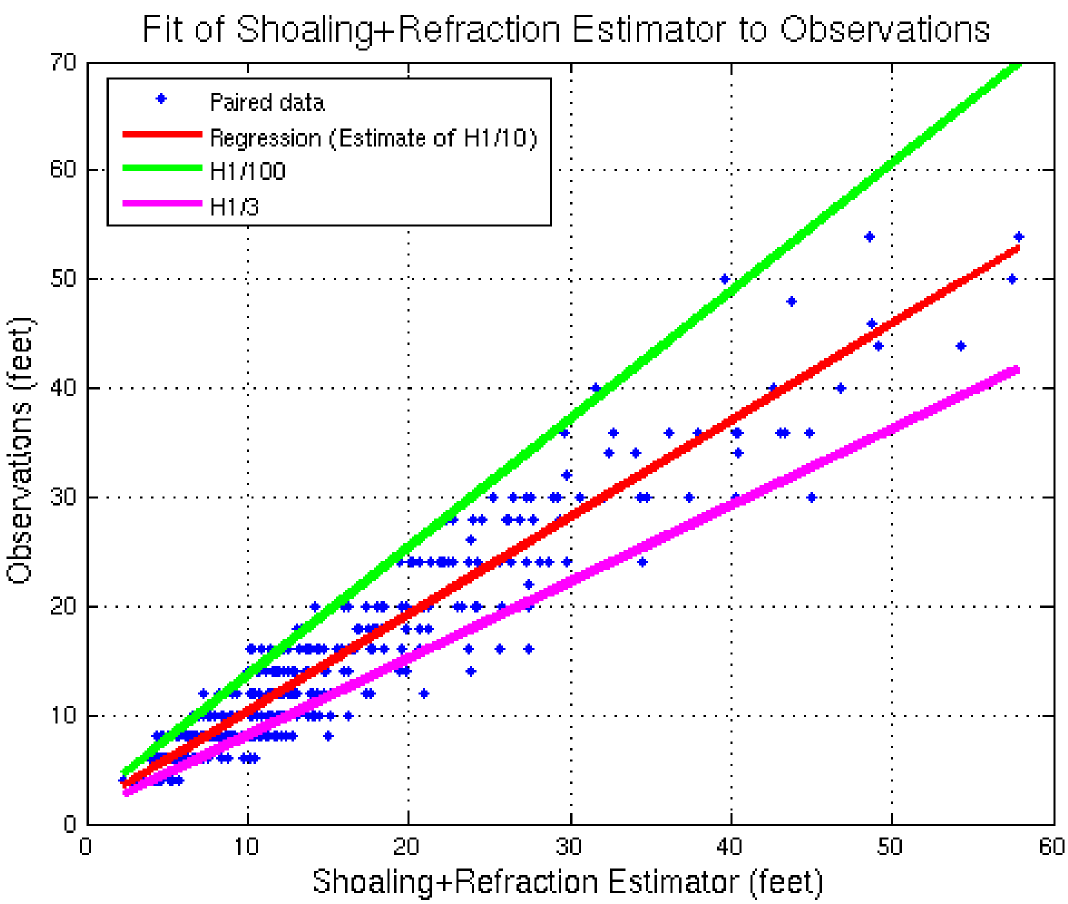

Figure 6. *Waimea buoy data are input into equation (3) to acquire H_{surf}, which is plotted against the surf observations.*

To test the validity of H_{surf}, Equation (3) was applied to the Waimea buoy data, with filtering based on wind conditions and swell directions as defined previously. A scatter diagram of H_{surf} versus the trough to crest surf observations is shown in Figure 6. The correlation coefficient among the pairs is 0.9486. A two-sample sign test and Wilcoxon rank sum test with 0.05 significance level and a Kolmogorov-Smirnov test at 0.01 significance level all supported the goodness of fit hypothesis that the samples were derived from the same population.

A linear least squares fit of these pairs shows a nearly one to one relationship. For H_{surf} greater than 30 feet, the predictor, H_{surf}, overestimates the observed heights by 6-8%, which errs toward safety. Since the observations are based on the $H_{1/10}$, it is assumed the regression line in Figure 6 represents the $H_{1/10}$. Estimated surf heights over a range of incident offshore heights and periods are depicted in Figure 7. Assuming a Raleigh distribution, additional statistical parameters can be defined,

$$H_{1/3} = 0.79 * H_{1/10} \quad (4)$$

$$H_{1/100} = 1.32 * H_{1/10} \quad (5)$$

The $H_{1/3}$ and $H_{1/100}$ are overlaid in Figure 6. The $H_{1/100}$ brackets most of the occasions when the $H_{1/10}$ underestimated the surf heights.

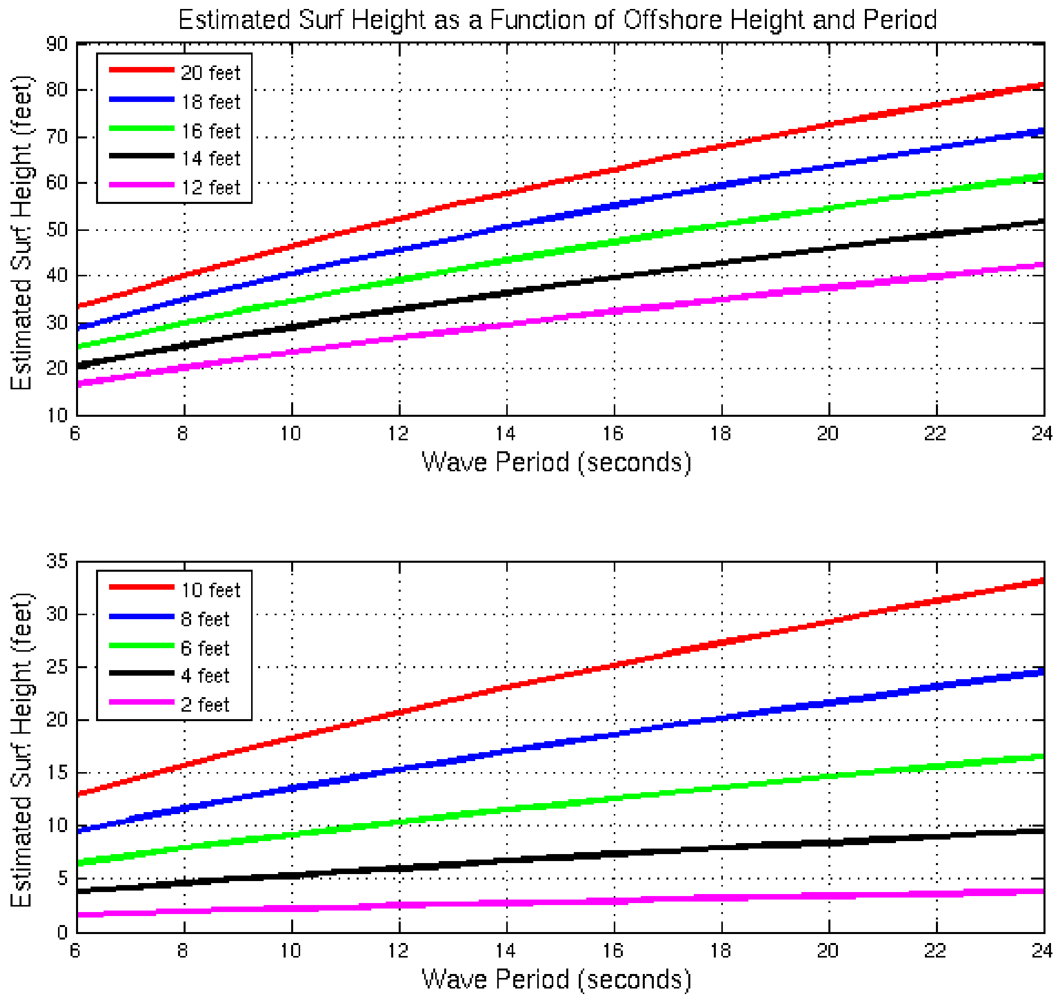

Figure 7. *The empirical* $H_{1/10}$ (H_{surf}) *for varying offshore conditions.*

Figure 6 shows occasions when the empirical method overestimates the waves. Given the tendency for observers to underestimate waves, these cases may be due to a low bias in the observations.

3. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

An empirical technique is described for estimating surf heights in coastal zones with narrow shelves, steep bottom slopes, and high refraction. The method is based on comparisons between visual surf observations from the north shore, Oahu, Hawaii and nearby, deep water, buoy-measured significant wave heights and peak periods. The technique provides estimates of the $H_{1/3}$, $H_{1/10}$ and $H_{1/100}$, which represent the lower and upper range of commonly arriving heights, and the occasional extreme height, respectively. Such information is vital for safety, engineering, environmental research, and coastal planning.

Using this approach, one can also derive an estimate of the maximum expected daily wave height. Since waves break in roughly a depth equal to the breaker height, the resulting surf estimates can be used along with high-resolution bathymetry to give warning to boaters of the offshore boundary of the expected surf zone.

The database of surf observations was recorded in HSF. A translation from HSF to trough-to-crest heights was performed based on photographic evidence. The translation is a simple factor of two within a 10-15% margin of error for the full range of breaker sizes encountered in Hawaii. This translation makes two important assumptions: 1) the trough to crest surf height is defined as the vertical distance between the crest and the preceding trough for the moment and location along the wave front of highest cresting and 2) zones of high refraction (outer reefs) are included for extreme days when Waimea Bay was the reporting location.

Offshore models of the deep-water wave field have improved in recent years and offshore buoys give short-term warnings with a lead-time that depends on the buoy's distance from shore.
The simple empirical formula for estimating surf heights opens the door for more accurate surf forecasts utilizing the offshore swell characteristics. The method should also be applicable in other coastal zones in the world with similar sea floor topography, which includes most of Hawaii. For future work, testing the use of this method in other areas will be undertaken.

There are opportunities to improve the empirical relationship presented in this paper. The number of samples of extreme surf without strong trade winds or onshore winds since the inception of the Waimea buoy in December 2001 is limited. Additional data will lead to a better-defined relationship. An improved fit is needed during low (<5 feet), long-period (>17 seconds) offshore conditions, during which surf heights are underestimated by the empirical formula. On the north shore, such conditions are usually short-lived and are associated with a rising swell episode generated by remote storm winds (>45 knots). One could improve the empirical formula employing more frequent visual observations during the short-lived occurrence of low-height, long-period offshore conditions. Future work also needs to target the short-period (<10 seconds) domain, during which surf heights are overestimated by the empirical formula. This study focused on a sample set representing remote source swell with wave periods primarily in the 10-20 second range. A similar empirical technique could be applied to surf observations from the windward side of Oahu and the nearby, deep-water buoy off Kailua for days dominated by short-period swell generated by the prevailing trade winds.

Utilizing high-resolution bathymetry, one can derive refraction coefficients under a range of offshore wave conditions (height, period, and direction) for the study locations used this paper– Sunset Point, Waimea Bay, and Outside Log Cabins. Both the traditional refraction diagram technique and the contemporary REF/DIF model can be employed. The results could help qualify the empirical method presented in this paper.

The empirical relationship presented in this paper could be used to calibrate the height scale of the SWAN model output. All coasts of Hawaii have regions with non-uniform topography. This results in high refraction at select locations of almost every stretch of coast. One could associate the zones of highest heights in the SWAN output to the surf heights derived from the empirical formula. This relationship could be used to adjust the scale of heights in the SWAN output, thus allowing more precise estimates for all surf zones in the SWAN domain. This would help define the upper limit of expected breakers and increase the accuracy of surf forecasts for all shorelines of Hawaii.

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