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Validity of North Shore, Oahu, Hawaiian Islands Surf Observations

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ABSTRACT

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Surf information is imperative for safety, coastal planning, and engineering applications. Daily surf observations made primarily by lifeguards along the north shore of Oahu, Hawaii, have been digitized for the 35-year period from 1968 to 2002. The subjective nature of observations introduces uncertainty. This study analyzes the temporal consistency and estimates the accuracy of the observations. Comparisons are made to breaker heights derived from significant wave height and dominant wave period as measured by the nearest environmental buoys, one of which has a series length of 22 years. The comparison pairs are picked from the high-surf season of October through March for days dominated by long-period swell. The analysis shows the surf observations are consistent in time. The uncertainty is between 10% and 15% of the reported height, and the magnitude of the error increases with surf height. Given the large range in breaker heights on the north shore of Oahu, this error is small. Although the visual observations have low precision and only represent daylight hours, the time series are longer and more continuous than other breaker height data for this region. Thus, these observations represent the best available resource for understanding regional surf climatology, which is described in this study.

ADDITIONAL INDEX WORDS: *Visual observations, buoy data, breaker height, surf climatology.*

INTRODUCTION

The northern shores of the Hawaiian Islands receive abundant swell energy during fall through spring seasons. The breakers, defined as the moment in time when some portion of the front face of the wave becomes vertical and unstable, have a wide range from nil to the height of a five-story building (25 m). The pattern of arrival frequency, directions, maximum heights, and duration of swell episodes varies significantly from week to week as well as from year to year.

Knowledge of surf conditions is crucial for public safety. In Hawaii, surf is the number one weather-related killer. Between 1993 and 1997, 238 people drowned and 473 people were hospitalized for ocean-related spine injuries (NOAA, 1993–97). Surf information is therefore essential in planning for recreational, commercial, and scientific, coastal activities. Historical records of surf heights are regularly used by environmental scientists, coastal engineers, and lawyers.

Information regarding the nearshore wave variability in Hawaii has been essential for a wide range of scientific studies. Given the importance of tourism to Hawaii and the high cost of shoreline property, beach erosion is a critical regional issue and is better understood through knowledge of the wave climate (FLETCHER *et al.,* 1997). The surf climate is a primary factor in determining the spatial variability of coral reef ecosystems in the islands with extreme wave events being one of the key limiting factors on coral development (DOLLAR and TRIBBLE, 1993).

A few studies have looked specifically at wave patterns around Hawaii. MOBERLY and CHAMBERLAIN (1964) discussed the wave climate around the islands as it relates to beach dynamics. The amount of data used in their study was limited. Using satellite altimeter data, FLAMENT *et al.* (1996) produced averages of the offshore combined sea and swell heights around the Hawaiian Islands as a function of season. FLETCHER *et al.* (2002) detailed a history of high-surf events for the various shores of Oahu and ranked the hazard potential in the coastal zones of all the main Hawaiian islands.

Visual observations have made important contributions to environmental science. The Beaufort Wind Scale was developed in the early 1800s to allow a visual means of estimating wind force at sea. Such observations are an important contribution to global marine atlases. Visual estimates of rogue wave heights by mariners at sea have been utilized in assessing naval design considerations (KJELDSEN, 1997).

Several papers have estimated the accuracy of visual breaker height observations. PERLIN (1984) conducted a study at the Duck, North Carolina, research facility comparing observations to simultaneously collected wave gauge measurements over a 25-hour period with wave heights rang-

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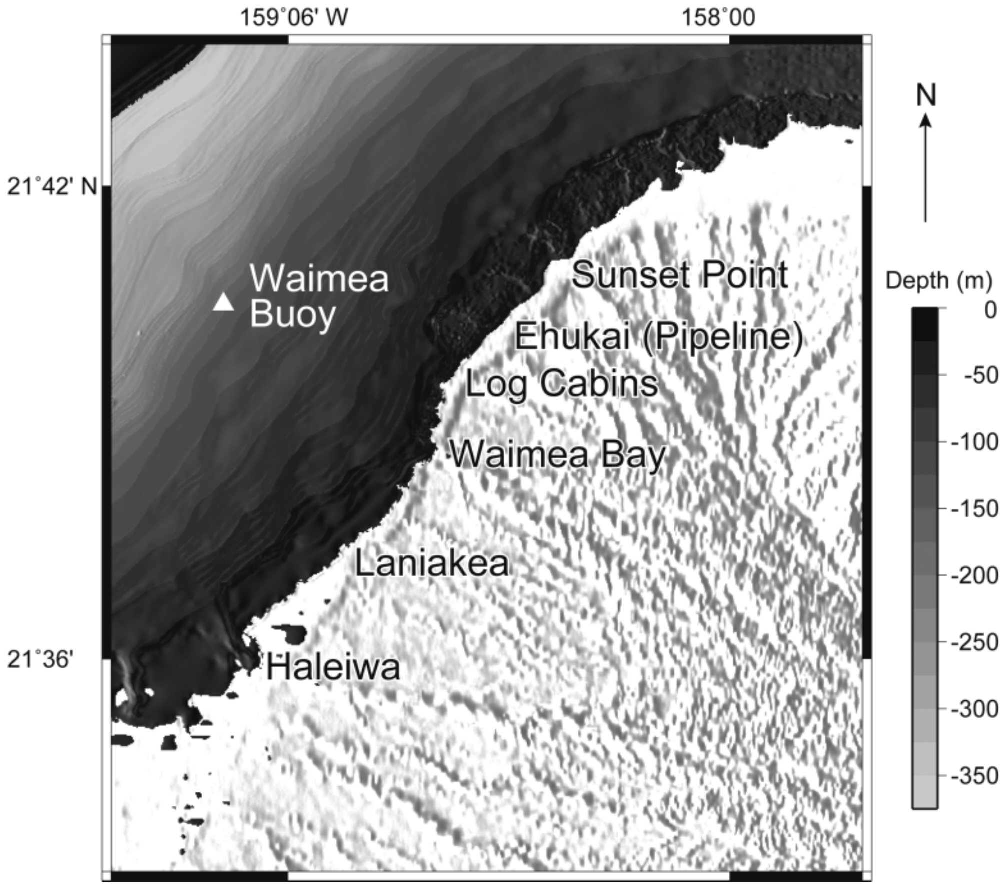

Figure 1. Waimea waverider buoy and surf observation locations on the north shore of Oahu, Hawaii. The bathymetry is derived from the NOAA National Ocean Service Hydrographic Surveys Data, Version 3.3.

ing from 30 to 90 cm. A study over a greater time span and range of heights was conducted in Monterey Bay, California, by PLANT and GRIGGS (1992). In both studies, the observers underestimated the wave heights.

In support of recreation and safety on Oahu, visual surf observations are made public. Records have been digitized for the daily maximum observations along the north shore of Oahu between Haleiwa and Sunset Point (Figure 1) since 1968. This represents a valuable resource for scientific study and coastal planning. However, uncertainty in the accuracy arises because of the subjective nature of each observation and the long-term nonhomogeneity of the data set resulting from different observers through the years. This study examines the temporal consistency and accuracy of the observations by comparisons to the nearest available wave-measuring buoys (Figure 2).

OBSERVATIONS

For several decades, surf height estimates at select locations on Oahu have been visually observed by various entities and made publicly available via the media. The primary observers have been the City and County of Honolulu lifeguards and employees of the Surf News Network (SNN), Inc. The observational period usually lasts between 15 and 30 minutes with reports given typically at 0700, noon, and 1500 Hawaii Standard Time (HST). Reports are given as a range of the lower and upper most regular heights and sometimes with notes regarding occasional breakers above the common spread. These observations systematically underestimate breaker size by as much as one-half, and this bias is referred to as the Hawaii scale. Although exactly when and why this tendency originated is highly disputed, it became the primary means of communicating surf size by the late 1960s.

There is a consensus among the lifeguards and employees of the SNN on the breaker size that a given Hawaii scale value represents. For instance, if one mentions 6 Hawaii scale feet (Hsf), then the image in their minds would be similar. However, in converting the Hawaii scale values to the trough-to-crest heights for the shoreward side of the wave, there are two schools of thought. One approach is to assume the Hawaii scale height represents one-half of the height at the moment of highest cresting for the section along the wave front of greatest peakedness. Another approach is that the Hawaii scale height represents two-thirds of the average wave front, trough-to-crest height from the highest peak to the lower wave shoulder. When the surf is large (greater than

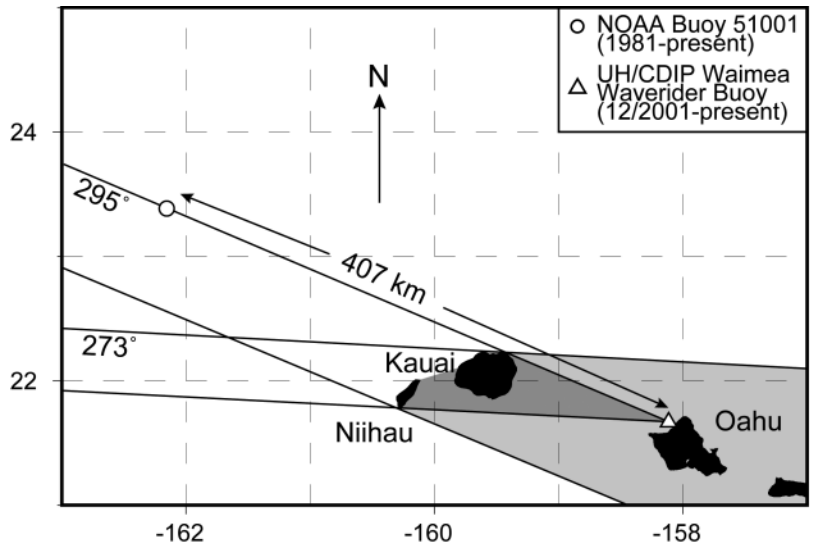

Figure 2. Buoy locations, separation distance, and swell shadow lines for Oahu.

15 Hsf), the former view approaches two-thirds, while the latter assumption nears unity.

Deep-water waves have highly variable instantaneous characteristics. Simultaneously arriving swell groups from different sources with differing characteristics are common in the open ocean region around Hawaii. To quantify the sea state, common descriptors such as significant height and dominant period and direction represent average wave conditions as measured by offshore, mooring-based sensors. The complexity of the wave characteristics increases as the swells arrive in the coastal zone, especially for regions such as the north shore of Oahu, where the sea floor has an irregular pattern of troughs and ridges at varying orientations relative to the shore. The resultant breakers vary in size and shape along any given reef as well as from reef to reef. Thus, any means of quantifying the surf energy is challenging, and visual observations are especially arduous. To augment the quality of observations, reporters incorporate benchmarks and indicators.

For small breakers nearshore, a person riding a wave is a common benchmark for surf reports. However, on the north shores of Oahu during high-surf episodes, the wave cresting usually begins a long distance from the beach with the troughs typically not visible because of remnant waves closer to shore. For extremely plunging breakers, troughs are below the ambient water level because of draw down of water off the reef, making the trough minimum hard to assess. For spilling breakers, troughs can be well ahead of the crests, shoreward of which the gradually tapering slope makes definition of the lowest point difficult. To quantify the surf heights in a consistent fashion relative to the amount of swell energy during one observational period versus another, the wave reporter uses indicators. The most common is the distance seaward and/or parallel to the given reef where the waves are breaking as compared to other days. This varies greatly from reef to reef depending on the sea floor topography and the incident wave characteristics. Other benchmarks are the strength of rip currents, the power and extent of the beach run-up, waves breaking in deep channels between reefs, and waves breaking on outer reefs. After years of watching hundreds of swell episodes grow and wane, the observers have developed a vast knowledge base that is essential for numerating the varying levels of surf energy. As breakers get bigger, the comprehensive view of the coastal ocean state for estimating the surf size becomes more important.

Two individuals have taken interest in making computer-ready files of the available visual observations. Mr. Larry Goddard logged heights from 1968 through September 1987, and the author has done similarly from September 1987 to the present. The records have been combined to form the Goddard and Caldwell (GC) time series of visual surf observations.

In the GC data set, a single value is logged daily to represent the highest waves reported on the north shore of Oahu. Sunset Point is usually the observing location with the highest breakers during surf episodes up to roughly 15 Hsf, while Waimea Bay is the reporting spot for very large surf occurrences above 15 Hsf. The daily GC value represents the high end of the range as given in the reports. For instance, if the surf report was 4–6 Hsf in the morning and 2–4 Hsf in the afternoon, then 6 Hsf would be recorded. If a report mentioned occasional breakers at higher heights, such as 12–15 occasionally 18 Hsf, then 18 Hsf was logged. The concept was not to record the single highest wave but to log a value roughly equivalent to $H_{1/10}$, or the average of the one-tenth highest waves.

The GC data set also includes a rough estimate of dominant swell direction in a 16-point compass system beginning in 1990. The assumed incident swell direction is based on comparisons of visual observations from different sides of the islands and from personal knowledge of the author, who studies the daily weather products for preparation of surf forecasts. Since December 2001, a directional buoy near Waimea, Oahu, has been the primary source.

For recent years, digital video cameras have been maintained at Sunset Point and Waimea Bay and made available via the Internet. This allows an opportunity to cross-check the lifeguard and SNN reports and also to acquire late-day observations under rising swell conditions. Estimating the breaker heights as seen on the cameras requires experience. Presently, this information is utilized only when the author makes the estimate. A few other Internet sites provide daily digital pictures and comments from experienced wave observers.

BUOY DATA

As part of a permanent national network, the National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center has maintained an environmental buoy with a nondirectional wave sensor in the Northwest Hawaiian Islands since February 1981. The location of buoy 51001 (Figure 2) is approximately 274 km west-northwest of Kauai and about 407 km west-northwest (295°) of Waimea Bay, Oahu, which is shadowed by Kauai and Niihau for incident swell directions between 273° and 295°. The ocean depth is greater than 3 km. The type is a boat-shaped platform referred to as a NOMAD buoy. It has a hull of dimensions 6 m long and 3 m wide with an 8-metric-ton displacement. The location has changed twice after buoy replacements, although each change was less than 2 km from the original location.

The wave measuring instrumentation has been thoroughly described (STEELE and METTLACH, 1993). An accelerometer is utilized to measure the heave acceleration of the buoy hull during the wave acquisition time, defined as a 22-minute interval that begins roughly 30 minutes prior to the reporting hour. The sampling rate is 1 Hz. A fast Fourier transform is applied to derive a wave energy spectrum, from which significant wave height and average and dominant wave period are obtained (BRIGHAM, 1988).

Data are typically available hourly except during periods of low battery voltage in which case the reports are given every 3 hours. It is common for data gaps on the order of months to exist in the series every few years. The finalized, calibrated data are made available by the NOAA National Oceanographic Data Center.

Through various funding channels, the Department of Oceanography at 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 of ocean depth since 9 December 2001. The buoy is a 0.9-m metallic floating sphere with a combination of a bungee and chain anchoring system. The long-term availability of this mooring is uncertain.

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. The information is relayed to a shore data logging platform every 30 minutes. The Coastal Data Information Program (CDIP) are the primary stewards of the real-time data, while UH handles maintenance duties. The finalized, calibrated data enter the NOAA posterity archive.

Several studies have estimated breaker heights given deep water swell characteristics (KOMAR and GAUGHAN, 1973; MUNK, 1949). This study follows the methodology of the latter,

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

where

H_b = predicted wave height at breaking
H_o = deep water significant wave height
P = dominant wave period
g = gravity

It is assumed wave energy flux is conserved from deep water to the time of breaking, which 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 purpose of this exercise is to develop a simplified proxy for comparisons of the buoy data to surf observations, not to reproduce the exact breaker heights.

Several factors must be taken into account prior to direct comparison between the shoaling-corrected buoy heights and the surf observations. This led to the creation of subsets from the original data files.

Since buoy 51001 does not measure wave direction, only the months of October through March were selected to minimize the influence of southerly swell. The swells from the south have two sources. The first source is from storms driven by the austral circumpolar jet stream in the latitude band of roughly 35–65° S. These swells are most active from April through September. The second source is from tropical activity in the north-central Pacific with greatest frequency in late summer to early fall (SCHROEDER, 1998). The first source usually has longer dominant periods and is more common.

North shore, Oahu surf observations are made at locations (Figure 1) shadowed from the common, short-period swell generated by the trade winds. It is desirable to focus on days dominated by long-period swell created by storms in the north Pacific. Thus, only days at buoy 51001 with dominant wave periods greater than 11 seconds and wind speeds less than 22 knots were chosen. No preference was given to wind direction.

Since the buoy data are hourly while the surf observations are daily, the hour of a given day with the maximum shoaling-corrected buoy height was chosen for a time window representing the daylight hours on Oahu. For the Waimea buoy, the time window is 0700 to 1700 HST. For buoy 51001, the time window is from 2100 (observation day minus one) to 1200 HST. This window was chosen to account for wave propagation assuming the most common swell direction is from 325° with a dominant wave period of 14 seconds (Table 1).

Reduction described previously for the GC and buoy 51001 data pairs resulted in a large sample of 1,202 days for 1981–

Table 1. *Pertinent wave characteristics and travel time from NOAA Buoy 51001 to Waimea Bay, Oahu.*

Deep-Water Swell Characteristics				Travel Time to Oahu (hours) for Swell Direction (degrees)			Depth Swell Becomes Shallow Water Wave	
Period	Length		Group Speed	295	325	355		
(s)	(m)	(ft)	(knots)	(cos 0)	(cos 30)	(cos 60)	(m)	(ft)
11	189	619	16.7	15.4	13.3	7.7	94	310
14	306	1,003	21.2	12.1	10.4	6	153	502
17	451	1,479	25.8	9.9	8.6	5	225	740
20	624	2,047	30.3	8.4	7.3	4.2	312	1,024
25	975	3,199	37.9	6.8	5.9	3.4	487	1,599

2002. A secondary subset was selected using the dominant wave direction in the GC data set for 1990–2002, and consequently 483 pairs were obtained. There are two conditions when incident swell direction adds uncertainty to the comparison. First, under dominant west to west-northwest swell (Figure 2), shadowing effects by Kauai and Niihau cause buoy 51001 to overestimate the Oahu breaker heights. Second, the more northerly the component, the less the time lag between the buoy and Oahu (Table 1) as well as the potential for a gradient in size perpendicular to the axis between the buoy and Oahu. The gradient could favor either side equally. Thus, pairs were selected only when the GC data set had northwest or north-northwest swell direction. This consideration was also applied in selecting days from the Waimea buoy, which is available from December 2001 through 2002. The GC and Waimea comparison set comprises 60 pairs.

RESULTS

One of the primary objectives of this study is to validate the consistency of the surf observations over time. A simple means is a time-series plot of the difference between the GC and buoy 51001 breaker height pairs (Figure 3a). This plot suggests the surf observations are temporally consistent. It is not important to this study that the surf observations are biased low relative to the shoaling-corrected buoy heights, which are used only as an index in checking long-term consistency.

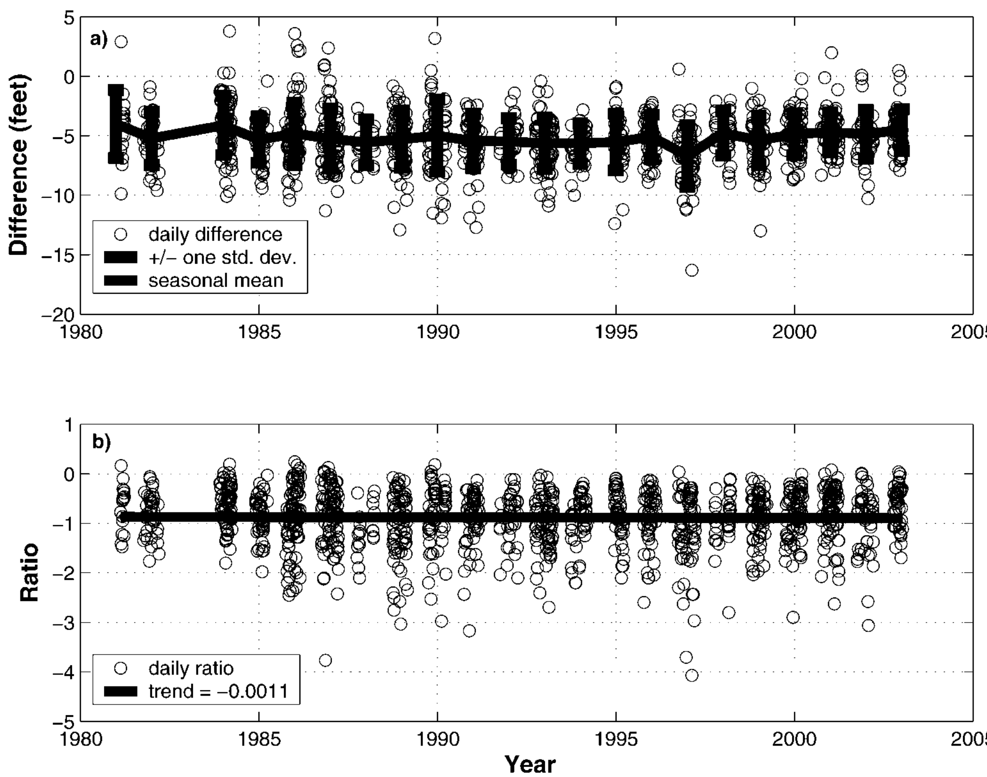

Figure 3. (a) Difference (surf observations minus shoaling-corrected buoy 51001 breaker heights) versus year. Seasonal (October through March) means and standard deviations are overlaid. (b) Ratio (difference as defined previously divided by the surf observation) versus year. Linear best fit is overlaid. Both panels suggest the surf observations are temporally consistent.

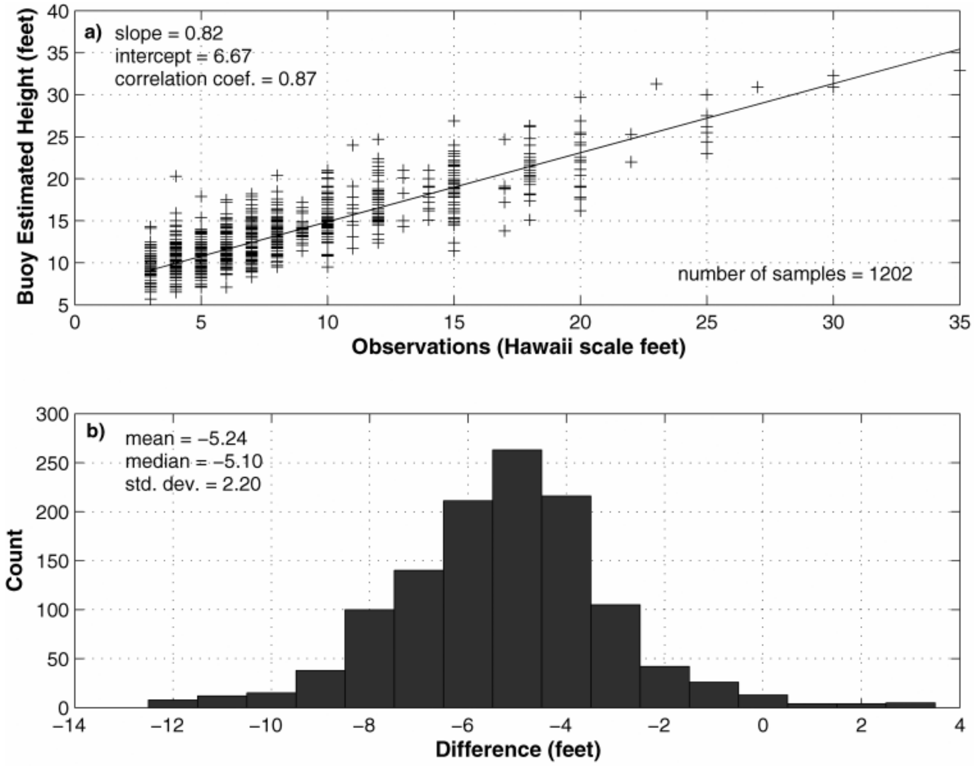

Figure 4. (a) Relationship of observations to shoaling-corrected buoy 51001 breaker heights. A best linear fit is overlaid. (b) Frequency distribution of the difference as defined in Figure 3a.

Another test for consistency in time is to plot the ratio of the difference to the surf observations (Figure 3b). For a given difference, the ratio becomes smaller as the surf observation increases. A linear fit was applied to the ratio versus time. No long-term trend in the ratio was detectable.

The relationship of observations to buoy 51001 breaker heights (Figure 4a) over 1981–2002 has a high correlation, which supports the credibility of the surf observations. The plot also shows the range of the surf observations and the scatter of corresponding buoy 51001 estimates. A histogram (Figure 4b) of the differences among the pairs shows a fairly normal distribution.

Products described previously for the directionally filtered subset (1990–2002) look similar to the 1981–2002 period. No temporal inconsistency could be identified in these products. The correlation coefficient is 0.91, which is higher than found in the 1981–2002 pairs.

Three-way comparisons between buoy 51001, the Waimea buoy, and the surf observations are made from the directionally filtered subset over the period of December 2001–2002. This analysis sheds light into the accuracy of the observations as well as the natural difference in wave energy between Oahu and buoy 51001.

A scatter diagram (Figure 5a) depicts the high correlation between the shoaling-corrected breaker heights of the Waimea buoy and buoy 51001. The average difference (Waimea minus 51001) is −0.77 m (−2.54 ft), which reveals greater long-period wave energy near the latter. A majority of the winter swell episodes in Hawaii are from storms that track from the northwest to the north-central Pacific. Consequently, buoy 51001 is closer to the generation area than Oahu. However, this does not fully explain the difference. PIERSON *et al.* (1955) showed that 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 gradual. The longer the dominant wave period of a given swell group, the lesser the decay in height with distance. This is because waves of shorter periods have greater angular dispersion, thus a more rapid drop-off of energy with distance. Since wave sources are usually beyond 500 miles of buoy 51001, the amount of decay from the buoy to Oahu should be small during long-period swell episodes. It is likely that other factors are more important.

One possible explanation for the difference is that the breaker heights are derived from significant wave heights, which could have some component contributed from the common trade winds even on days dominated by long-period swell and with wind speeds less than 22 knots. Buoy 51001 is exposed, while the Waimea buoy is somewhat sheltered from easterly, short-period energy by the shadowing of northeast Oahu.

The shadowing effect of Kauai and Niihau for incident swell energy from 273° to 295° (Figure 2) is another reason why the buoy 51001 has greater long-period wave energy

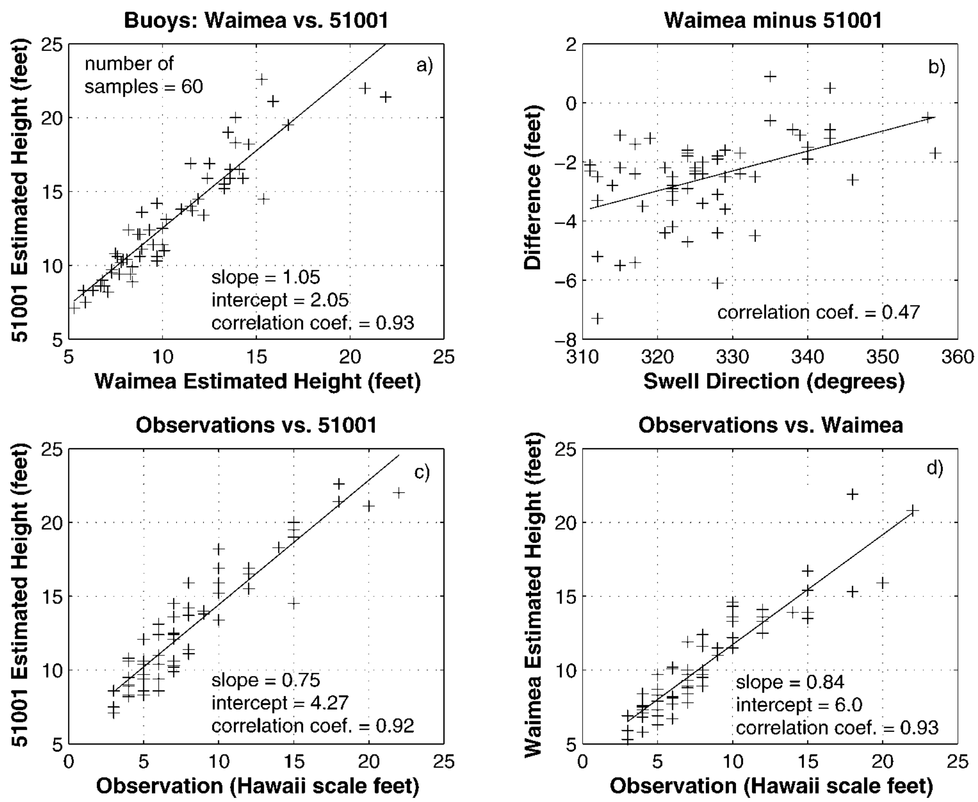

Figure 5. (a) Relationship of estimated breaker heights between buoy 51001 and the Waimea waverider buoy. The heights are shoaling corrected. (b) Variation of the difference in buoy height estimates versus dominant direction of the Waimea buoy. (c) Relationship of observations to shoaling-corrected buoy 51001 heights. (d) Relationship of observations to shoaling-corrected Waimea buoy heights. For all panels, a linear best fit is overlaid. The data are derived from the directionally filtered subset (NW and NNW swell only), December 2001 through 2002.

than the Waimea buoy. A plot (Figure 5b) of the difference (Waimea minus 51001) versus the Waimea buoy dominant wave direction shows a weak positive correlation. This is likely due to partial shadowing. Swell episodes can have a wide directional spread. Although the dominant direction may be more northerly than 295°, some energy with a directional component between 273° and 295° may be sensed at buoy 51001 yet be blocked by Kauai and Niihau from reaching the Waimea buoy. This explanation is likely the most important since this study is based on October through March, when a westerly component is common (Table 2). The Waimea buoy is at ocean depth of nearly 200 m; thus, long-period energy begins shoaling in the vicinity (Table 1). However, the shoaling contribution to wave height increase at the Waimea buoy is considered negligible.

Another comparison was made between the buoy 51001 and the surf observations (Figure 5c). The correlation coefficient is higher relative to the 1981–2002 (Figure 4a) and 1990–2002. The correlation coefficients of the three-way comparisons (Figures 5a, 5c, and 5d) are nearly identical, which reaffirms the consistency of the surf observations. It also suggests the surf observations could serve as a low-resolution proxy for the Waimea buoy, which is subject to gaps and discontinuation.

The various scatter diagrams between the surf observations and the buoys (Figures 4 and 5) show a range of shoaling-corrected breaker heights for each surf observation. This information is utilized to make an estimate of the accuracy of the observations.

As a first step in understanding the observational uncertainty, frequency distributions are plotted (Figure 6) for demeaned buoy 51001 shoaling-corrected breaker heights corresponding to various sizes of surf observations over the period 1981–2002. Given the quasi-normal distributions, the standard deviation is a proxy for error. The analysis detects a positive correlation between surf observation size and error, similar to results of PLANT and GRIGGS (1992).

A secondary test was performed using the relationships shown in Figures 4a, 5a, 5c, and 5d. Regression analysis between the observations and buoy breaker heights defines the linear best fit, which is used as an estimator. Subsequently, root mean square (RMS) error was calculated for select observation sizes based on the scatter of buoy heights about the estimator. The minimum sample size was set at five. The sample size decreases as surf observation size increases.

The results are shown in Figure 7. Another regression analysis was performed on the RMS error derived for select surf observation sizes of each subset. This linear best fit sug-

Table 2. *Monthly averaged number of days with incident waves within select directional brackets based on September 1990–June 2003. Bracket overlaps due to course resolution of each daily observation. Ave. denotes average; SD denotes standard deviation.*

	W or WNW		WNW or NW		NW or NNW		NNW or N		N or NNE		NNE or NE	
	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD
July	0	0	1	2	2	2	1	1	1	2	1	2
August	0	1	1	1	2	2	1	1	0	1	1	1
September	1	2	6	3	9	4	6	4	2	2	0	1
October	1	2	8	3	14	5	10	5	4	4	2	3
November	1	1	10	5	17	8	12	5	6	5	4	5
December	5	3	18	4	19	4	8	3	3	3	2	2
January	6	4	18	5	19	5	8	4	3	3	2	2
February	4	3	16	5	17	5	9	5	4	3	2	2
March	4	3	16	3	17	5	9	3	5	3	3	3
April	1	2	7	3	13	3	12	5	5	4	2	4
May	1	1	5	3	9	4	7	6	4	5	2	3
June	0	1	1	1	4	3	4	3	2	2	1	2

gests the observational uncertainty, which is positively correlated to the surf size. Assuming Hawaii scale heights are equal to one-half the maximum, wave front, trough-to-crest heights for surf up to 15 Hsf and equal to two-thirds of absolute heights for surf above 15 Hsf, the uncertainty varies from 10% to 15% of the reported height.

SURF CLIMATOLOGY

The GC data set is presently 35 years long. The various long-term, nondirectional buoys surrounding Hawaii give offshore conditions, but these data cannot easily be applied to surf estimates and are prone to large data gaps. Nearshore directional buoys have been available yet for limited duration. Thus, the visual observations offer the longest, most continuous records for understanding the regional surf climatology.

The annual variation of surf heights on northern and northwestern shores of Oahu has a quasi-normal distribution with a maximum in January and a minimum in July (Figure 8). On any given day during the fall through late spring sea-

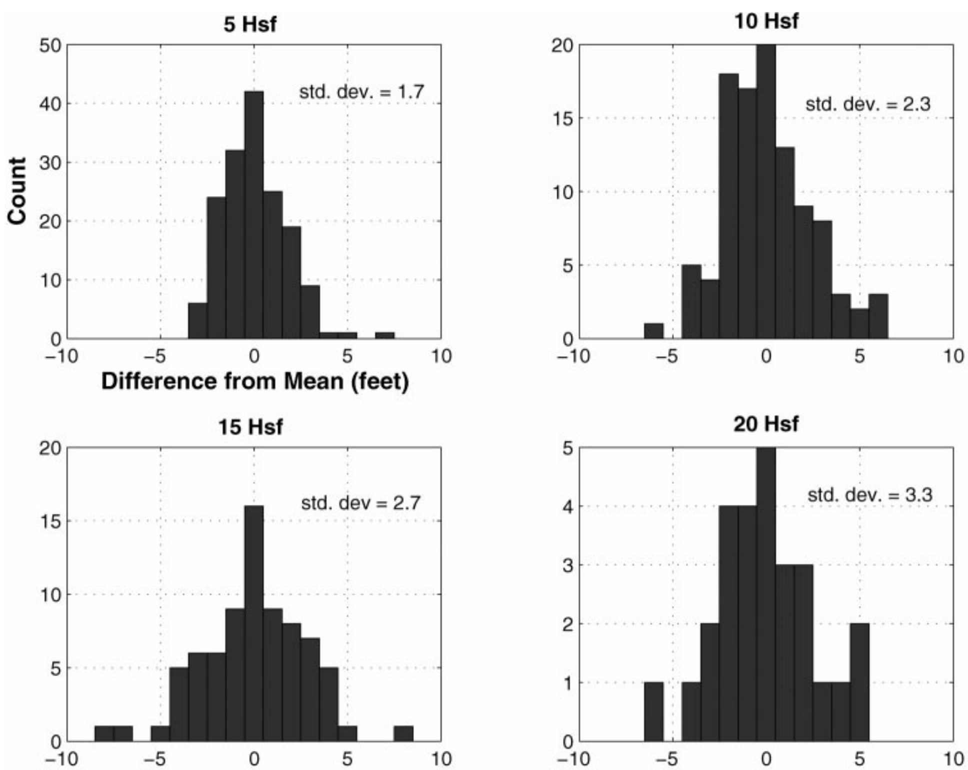

Figure 6. Frequency distributions of shoaling-corrected buoy 51001 heights corresponding to given observation sizes as noted in the title of each panel (Hsf = Hawaii scale feet) based on 1981–2002. The heights have been demeaned, and the difference refers to the separation from the mean. The standard deviations (std. dev.) are overlaid and suggest an increase in uncertainty with increasing surf heights.

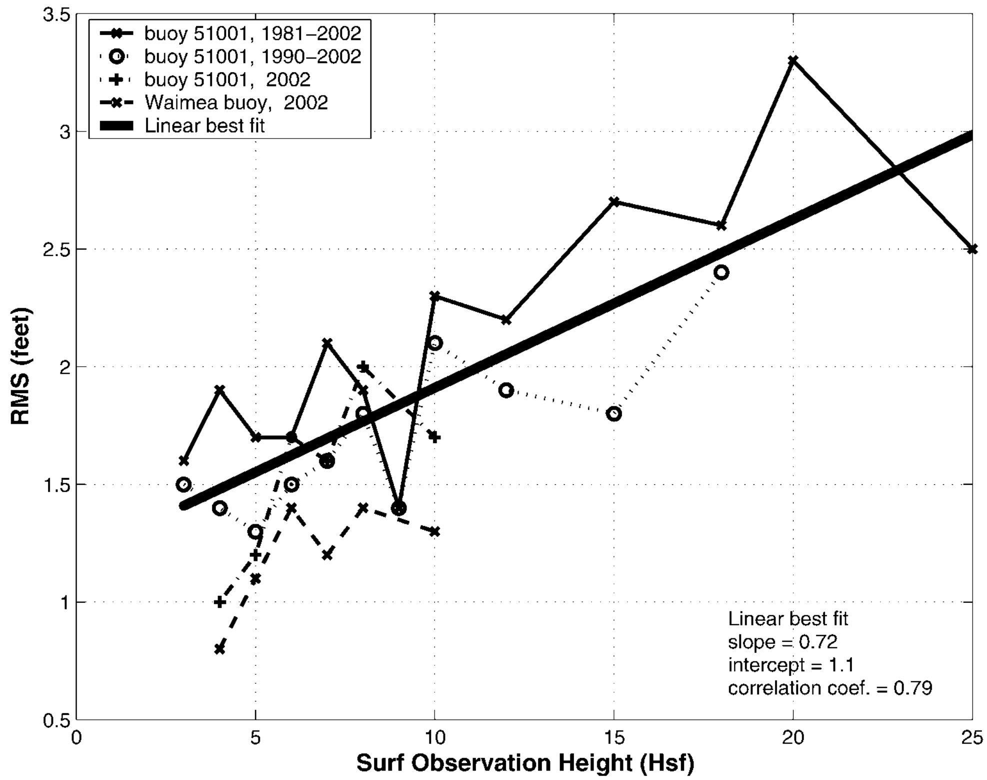

Figure 7. Root-mean-square (RMS) error estimates for various subsets versus the observation height (Hsf = Hawaii scale feet). A linear best fit for all subsets is overlaid.

son over this 35-year record, there has been an occurrence of high surf, defined as heights greater than 7 Hsf (maximum in Figure 8). Yet any calendar day has also had low surf (minimum in Figure 8). This reveals the great daily variability. Sample statistics help quantify the month-to-month variations (Table 3). This product shows that the average day during December through February has high surf. Greater detail in the annual cycle is displayed in Table 4, which can be used for anticipating the number of days per month within course-size brackets. The day counts within the size categories are very symmetrical around the January maximum. Annual variation in swell direction is depicted in Table 2. This product reveals the shift toward more west-northwesterly swell direction during the winter months, related to the southerly migration of the north Pacific storm track.

The surf pattern shows distinct year-to-year variations in the number of high-surf days for a given season, defined as September 1–May 31 (Figure 9). One conclusion from this plot is the minimal long-term tendency, reinforcing the preceding analysis that showed the surf observations to be temporally consistent. Another noteworthy observation is that the El Niño years (SMITH and SARDESHMUKH, 2000) are usually above average while La Niña years tend to be below average in occurrence of high surf. This agrees with the study by ROONEY *et al.* (2004) that found a similar pattern looking at large wave episodes of buoy 51001.

CONCLUSIONS

A 35-year time series of daily visual surf observations for the north shore of Oahu were temporally consistent and correlated well with buoy observations having an uncertainty of 10–15% of reported heights. The magnitude of the error increases with the size of the surf. Given the large range in breaker heights along this coast, the uncertainty is small. Three-way comparisons among the buoys and the observations for the directionally filtered 2002 subset resulted in very similar correlation coefficients of about 0.92, giving further credence to the validity of the surf observations. One important result is that surf observations could serve as low-resolution substitutes for missing data in the Waimea buoy series.

Although the visual observations have low precision and represent only daylight hours, the time series are longer and more continuous than other breaker height data for this region. Thus, these observations represent the best available resource for understanding the north shore, Oahu surf climatology. Results show the wide range of heights that could occur on any day during the fall through spring season and display the symmetrical characteristics centered on January in the annual cycle of surf height and swell direction.

Future Work

The GC data set includes visual reports from other sites around Oahu. The series for the south shore begins in 1972.

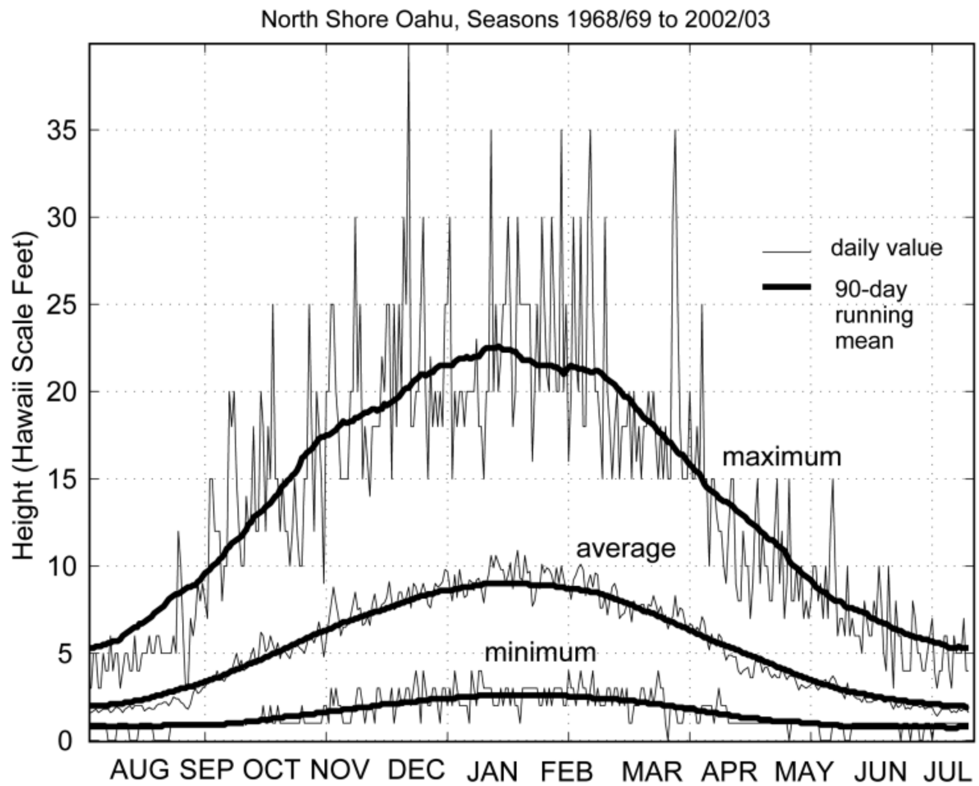

Figure 8. Annual variation of surf heights for the north shore of Oahu based on September 1968–May 2003, 35 years. The thin lines from top to bottom represent the daily maximum, average, and minimum of each calendar day, respectively. The thick lines are the running means based on plus or minus 45 days from the given calendar day.

Further tests for temporal consistency and uncertainty of these observations could be made, and surf climatological products could be produced.

The systematic errors among buoy 51001, the Waimea buoy, and the surf observations, as represented by varying regression numbers in Figures 5a, 5c, and 5d, are not well understood. For this study, fall through winter months dominated by long-period swell under light winds conditions were chosen. Another approach would be to utilize only the spectral data for wave periods longer than 11 seconds for all days.

Table 3. *Sample statistics for North Shore, Oahu, surf heights (Hawaii scale feet) based on August 1968–June 2003 daily visual surf observations.*

Month	Mean	Median	Standard Deviation	Average Maximum	Average Minimum
July	1.7	1.0	0.9	3.9	1.0
August	1.9	2.0	1.1	4.0	1.0
September	3.3	3.0	2.3	9.1	1.1
October	5.0	4.0	3.1	13.2	1.8
November	7.1	6.0	4.2	18.2	2.5
December	8.1	7.0	4.6	19.1	2.9
January	9.0	8.0	5.2	21.9	3.0
February	8.2	7.0	4.5	18.1	3.1
March	6.8	6.0	3.8	16.1	2.4
April	4.6	4.0	2.6	12.2	1.8
May	3.2	3.0	1.8	8.0	1.2
June	2.2	2.0	1.3	5.2	1.0
Average	5.3	4.4	2.9	12.4	1.9

This study showed the mean of the differences between the surf observations minus the Waimea buoy estimated breaker heights to be −0.65 m (−2.14 ft) with a correlation coefficient equal to 0.93. Since the buoy is only about 5 km from shore, the difference should ideally approach zero, and the correlation coefficient should become nearly 1.0. In order to achieve this goal, several considerations must be undertaken. First, target breaker heights must be designated such as the highest one-tenth and/or the significant wave height at the wave front location of greatest peakedness. Second, it would be necessary to translate the observations in Hawaii scale feet to wave front, trough-to-crest heights. This could be attempted with photographs or other line-of-sight techniques. Moreover, the buoy-estimated breaker heights must include refractive focusing. This would require high-resolution bathymetry for the regularly reported sites, such as Sunset Point and Waimea Bay. Other data sets could also be utilized. A short time series of pressure sensor data with 1-Hz samples from the surf zone at Waimea Bay in January 2002 during high-surf episodes are available. Detailed spectral wave models that include a variety of relevant physical processes (*e.g.,* wave refraction, diffraction, reflection, bottom friction, and so on) such as SWAN (Simulating WAves Nearshore) should be

Table 4. *Monthly averaged number of days with heights (Hawaii scale feet) within select size brackets based on August 1968–June 2003. Bracket overlaps due to course resolution of daily visual surf observations. Ave. denotes average; SD denotes standard deviation.*

	<3		3–5		5–7		6–9		8–12		11–15		14–18		17–25		23–29		30+	
	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD	Ave.	SD
July	26	4	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	23	5	8	5	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	13	5	13	5	4	2	2	2	1	2	0	1	0	0	0	0	0	0	0	0
October	4	4	17	4	9	3	7	3	4	2	1	1	1	1	0	1	0	0	0	0
November	1	2	12	4	10	3	11	3	7	3	3	2	2	2	1	1	0	1	0	0
December	1	1	10	3	11	3	11	3	10	3	4	2	3	2	2	2	0	0	0	0
January	0	1	8	4	9	3	11	3	10	3	5	2	5	3	3	2	1	1	0	0
February	0	1	8	4	9	3	11	2	10	3	4	2	3	3	1	2	0	0	0	1
March	1	1	13	4	11	3	11	3	8	3	3	2	2	2	1	1	0	0	0	0
April	5	4	17	4	8	3	6	3	3	3	1	1	0	1	0	0	0	0	0	0
May	13	6	16	6	4	3	3	2	1	1	0	0	0	0	0	0	0	0	0	0
June	21	5	9	5	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0

used to augment the understanding of these complex relationships.

Once a formula is derived that optimally estimates breaker heights for specific reefs based on the nearby open-ocean swell characteristics, the public could be better informed of current conditions at intervals of buoy data availability. Furthermore, formulas could be developed to best fit the relationship between swell characteristics at the remote buoy 51001 and the surf of the north shore of Oahu. Since this buoy is nondirectional, it would require some assessment by experienced forecasters to estimate the dominant swell direction and its directional spread based on knowledge of the storm characteristics and use of wave model output. These activities would lead to an improvement in the accuracy of

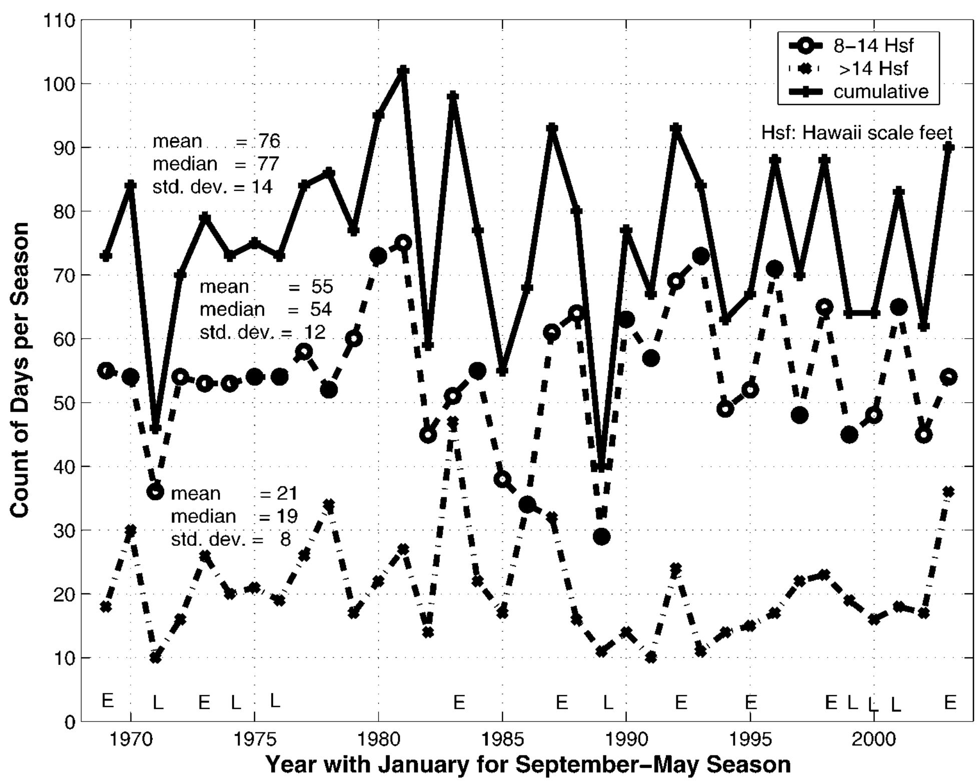

Figure 9. Year-to-year variations of the number of high-surf days for a given season, defined as September 1–May 31. The 8–14 Hawaii scale feet (Hsf) range was chosen because that would represent high-surf days when Sunset Point was the primary reporting location. Once the surf heights approach 15 Hsf or higher, Waimea Bay is the primary reporting location. The year on the ordinate axis refers to the second half of the season. For example, 1970 represents the season from September 1969 through May 1970. La Niña (L) and El Niño (E) years, based on Smith and Sardeshmukh (2000), are noted above the ordinate axis.

surf forecasts and therefore enhance coastal planning and safety.

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