Spectral Density Composites for Aiding Hawaiian Southern Shore Surf Forecasts

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Abstract

Extra-tropical cyclones in the southern hemisphere create surf on southern shores of the Hawaiian Islands. A small percentage of episodes create hazardous conditions at harbor entrances, dangerous near shore currents, and if combined with a spring high tide, high wave run-up. The National Oceanic and Atmospheric Administration National Weather Service in Honolulu issues High Surf Advisories when heights are above the high season average and High Surf Warnings for exceptionally large episodes. The issuance of a warning sets into motion actions for the civil defense, select transportation and commercial sectors, and water safety personnel. Consequently, the forecasters need strong evidence prior to issuing a warning. One of the most important tools used for fine tuning a surf forecast is buoy data. Wave sensors on a buoy near the equator about 1300 nm south-southeast of Oahu provide roughly a two-day lead while a network of three buoys spread east to west within 17-19^{o}N south of the main Hawaiian Islands gives roughly a one-quarter to one-half day fore-warning before an event. To better understand the potential magnitude of an imminent swell, the spectral density as a function of wave period is analyzed. This study creates composite signatures for the spectral density based on historic cases of surf categorized by magnitude. These composites can be used as a guide to forecasters as future events unfold.

Introduction

The Hawaiian Islands are famous for large surf during winters on the northern shores (CALDWELL, 2005; AUCAN 2006). In contrast, the southern shores are well-known for gentle breakers, making Waikiki Beach on the southern shore of Oahu one of the world's most popular tourist destinations. On rare occasions, the usually balmy southern shores can receive exceptionally high breakers. An episode on June 18, 2003 resulted in 350 rescues and 600 assists by Honolulu City and County Water Safety Division lifeguards in the Waikiki and Ala Moana areas. A 16-foot boat was capsized by a breaker while exiting the Ala Wai Yacht Harbor, leading to a rescue and injuries. Subsequently, the harbor was officially closed to all traffic (LENT *et .al*., 2003).

For the 2003 case, the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) issued a High Surf Advisory-- but not a High

Surf Warning. In retrospect, a warning would have been more appropriate. Since the incident, attention has been focused on how to better anticipate such episodes.

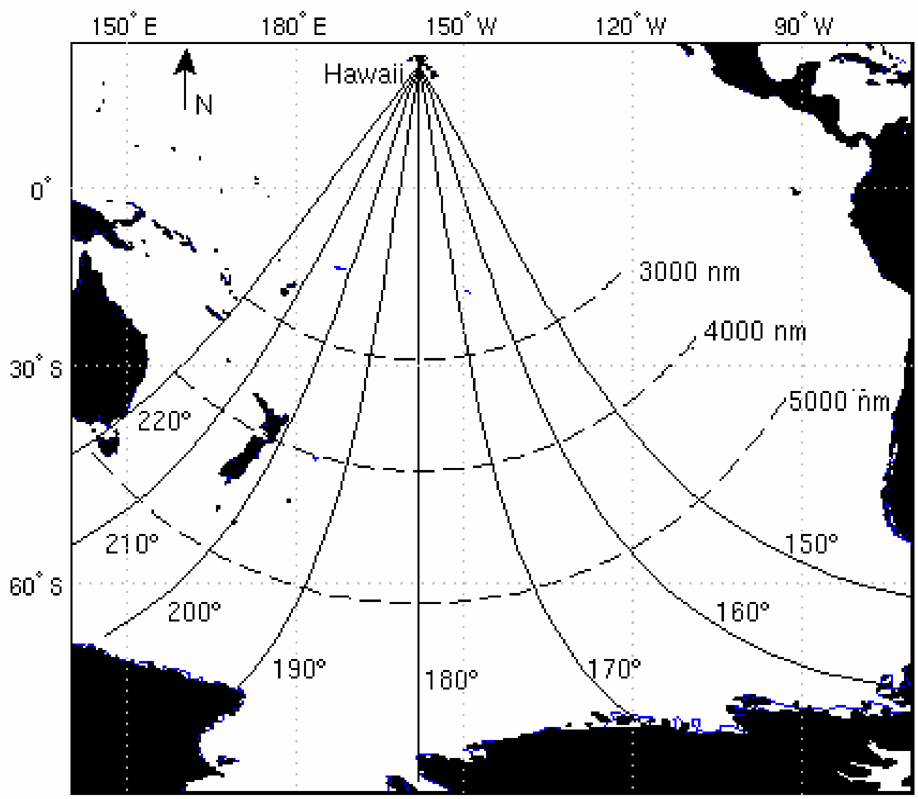

Figure 1. Great circle directional rays and distances relative to Hawaii.

One of the most objective ways to fine tune a surf forecast is through analysis of buoy measurements. A network of NOAA National Data Buoy Center (NDBC) buoys south of the Hawaiian Islands provide essential forewarning of imminent southerly swells. Typically, a forecaster uses the significant wave height and dominant period as the primary means of assessing the surf potential. However, the significant wave height can have a substantial contribution of short-period energy associated with the common fresh-to-strong (17 to 25 knots) trade winds, making for uncertainty in interpretation. This occurs because the short-period local seas alone create 2-3 m heights while remotely generated southern hemisphere long-period swell typically has heights from 0.5 - 2 m.

The buoys also record spectral density as a function of wave frequency. This allows a basis for comparison of the long-period energy among different swell episodes, and in turn, opens the door to more precise estimates of the potential magnitude of breakers.

Surf Climatology

There are various sources of surf on southern shores of the Hawaiian Islands. Excluding regional trade winds which send mostly small, short-period surf to select east-facing exposures on the southern shores (AUCAN, 2006), extra-tropical cyclones in the southern hemisphere are the most frequent surf source (Figure 1). Tropical cyclones in the eastern and central north Pacific are an infrequent surf source (SCHROEDER, 1998). On rare occasions, tropical cyclonic activity in the southern hemisphere and the western Pacific produce surf for Hawaii's southern shores. Kona winds, which are excited by extra-tropical cyclones near the Hawaiian Islands and blow over the islands from the southeast to west, create mostly small, short-period surf a few times per year. Extra-tropical cyclones in the north Pacific beyond 500 nm from Hawaii create small to moderate, long-period surf for western exposures of the southern shores a few times each winter. MOBERLY and CHAMBERLAIN (1964) provide a schematic and summary of the various swell sources for the Hawaiian Islands. This paper only focuses on long-period swell from the southern hemisphere sources.

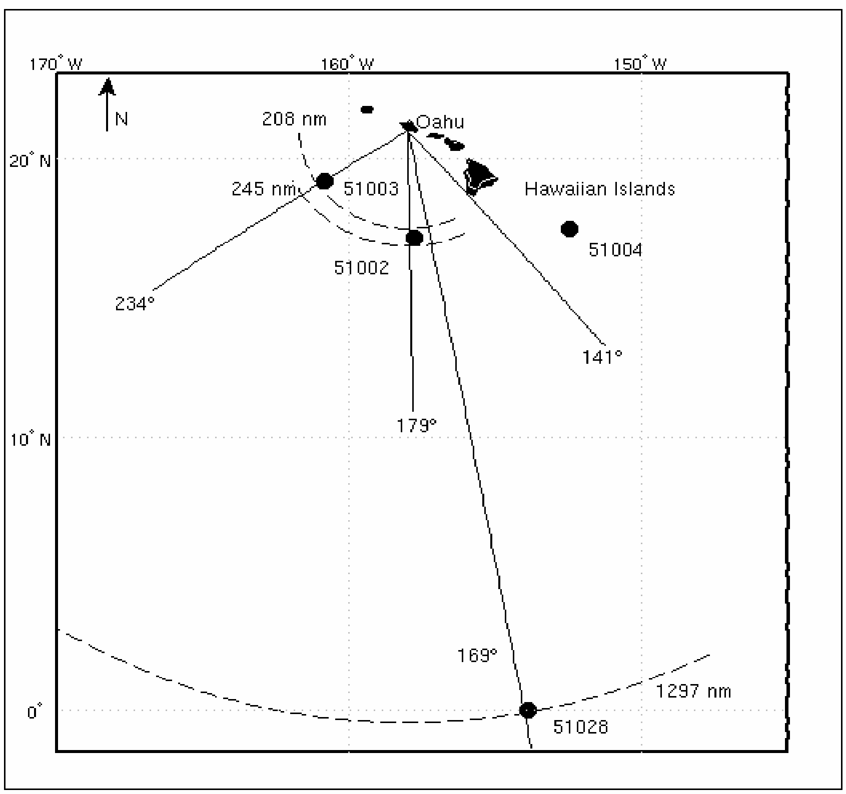

Figure 2. Great circle directional rays and distances relative to the entrance to the Ala Wai Yacht Harbor in Honolulu on the island of Oahu to the NDBC buoys and the shadow point on the Big Island of Hawaii.

For the south shore of Oahu, daily surf observations from Ala Moana Bowls, a popular surfing spot in Honolulu and a zone of high refraction, are available from 1973 to the present and form part of the Goddard-Caldwell (GC) database (CALDWELL, 2005). Each daily value nominally represents the average of the highest 10% ($H_{1/10th}$) of the breaker heights for the daylight hours of highest surf. The observations are made in Hawaii scale feet (Hsf) , a bias that underestimates by a factor of two the trough-to-crest height at the moment of maximum cresting for the highest portion of the shoreward side of the wave (CALDWELL and AUCAN, 2007). The estimate of this bias is based on photographic evidence and has a 20% margin of error.

	<3 Hsf (1.8m)		3 Hsf (1.8m)		4-5 Hsf (2.5-3m)		6-8 Hsf (3.5-5m)		> 9 Hsf (5m)	
Month	AV	SD	AV	SD	AV	SD	AV	SD	AV	SD
Jan	19	11	5	6	1	2	0	0	0	0
Feb	17	10	5	7	1	2	0	0	0	0
Mar	18	10	8	8	1	2	0	0	0	0
Apr	15	7	11	6	4	3	1	1	0	0
May	12	7	12	5	6	3	1	1	0	0
Jun	10	7	12	5	7	3	1	1	0	0
Jul	12	7	12	5	6	3	1	2	0	0
Aug	13	9	12	7	5	3	1	1	0	0
Sep	14	8	12	7	4	3	0	1	0	0
Oct	16	9	10	7	3	2	0	1	0	0
Nov	19	10	5	5	1	1	0	0	0	0
Dec	21	10	5	5	1	1	0	0	0	0

Table1. Average (AV) and standard deviations (SD) of the number of days of each height category for each month based on 1973-2006 surf observations.

A test of validity of the south shore surf observations was performed similar to the north shore set (CALDWELL, 2005). A comparison was made between the surf observations and the buoy-derived shoaling heights. For the north shore test, the significant wave height and dominant period of buoy 51001 were used. The results showed the north shore observations in the GC dataset to be temporally consistent with a root-mean square error of 15%, the magnitude of which increases with surf height. For the south shore comparison, the frequent fresh trade winds at non-directional buoys 51002 and 51003 (Figure 2) create a short-period contribution to the significant wave height. For comparison, the spectral energy density data for wave periods greater than 11 seconds were used via an integration routine using the same shoaling formula (KOMAR and GAUGHAN, 1973) and the same underlying assumptions as described in Caldwell (2005). Only the months of June-August were selected to eliminate the long-period swell generated by north Pacific extra-tropical storms. A plot (not shown) of the difference between the surf observations and the shoaling-only estimates shows temporal consistency in the south shore surf observation over 1985-2005.

The 34-year time series of Ala Moana Bowls observations in the GC database was analyzed for better understanding of the surf climatology. The surf on the southern shores has a high season during April through October (Figure 3). Every calendar day of the year has had heights greater than the high season average (~3 Hsf or 1.8m) as well as days near nil. The largest surf, 15 Hsf (9 m), in the 34 year time series occurred on September 11, 1992 and was generated by Hurricane Iniki. There is low confidence in the accuracy of this visual observation due to the storminess of the surf. The highest surf, 12 Hsf (7 m), from the southern hemisphere extra-tropical source was on June 13, 1995. The average high season heights (3 Hsf or 1.8m) are relatively low because the frequency of occurrence of above average heights is low (Table 1). On days of 3 Hsf (1.8m) in the GC database, except for the impact zone for locations of high refraction, breakers are benign along most stretches of the coast with safe swimming conditions.

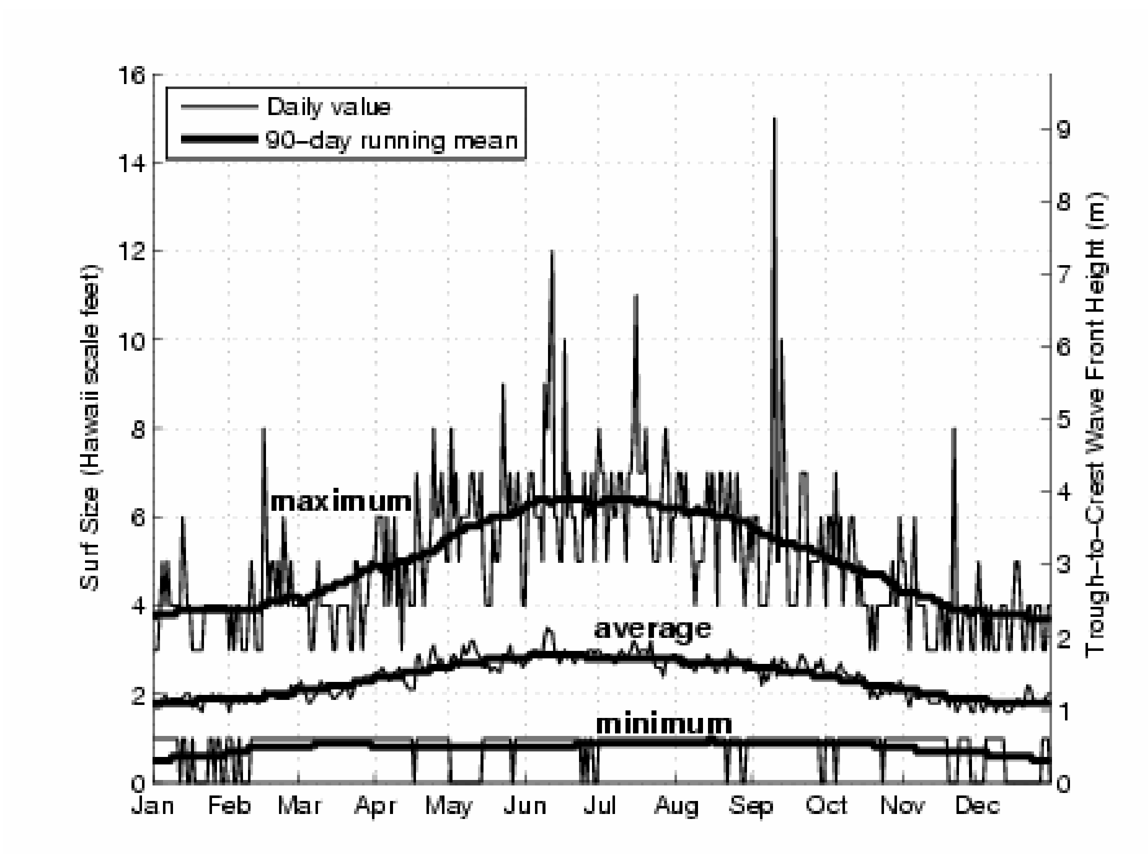

Figure 3. Annual cycle of surf heights based on the Goddard-Caldwell south shore Oahu database, 1973-2006.

The number of days of surf heights in select size categories shows inter-annual variability (Figure 4). The **extreme** episodes (> 8 Hsf or 5m) occur once every four years on average. **Large** heights (6-8 Hsf or 3.5-5m) happen on average five days per year but not necessarily every year. With a low tide and 6 Hsf heights, the entrance to the Ala Wai Yacht Harbor entrance receives breakers, creating hazards for navigation. During spring high tides, the entrance begins to have combers when the heights reach roughly 8 Hsf. With heights in the 6-8 Hsf category, exceptionally strong breakers and near shore currents necessitate an increase in Honolulu City and County lifeguards. Surf heights reach **commonly high** levels of 4-5 Hsf (2.5-3m) on average 39 days per year. Such heights cause strong breakers and currents in the impact zone for locations of high refraction while other areas require caution for marginally strong breakers and currents.

Southern hemisphere extra-tropical storms are strongest during the austral fall, winter, and spring, occur primarily between 35-65 ^{o}S, and are typically steered eastward by the circumpolar jet stream. The wave shadow from the dense network of islands and New Zealand in the southwest Pacific keeps Hawaiian surf from 200-220 ^{o} (Figure 1) mostly near or below the high seasonal average (3 Hsf or 1.8m). The common easterly storm track in the "roaring 40s" sends the highest swaths of swell east of the Hawaiian Islands toward the Americas, although angular spreading of swell trains brings about 12 days per month of seasonally average heights during May-September (Table 1).

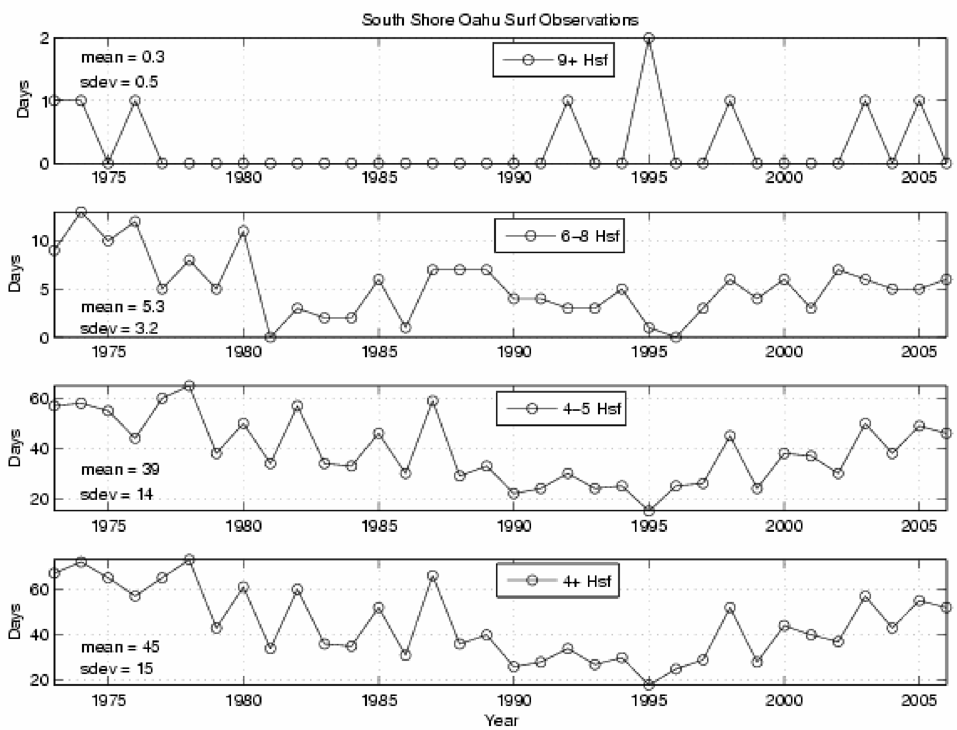

Figure 4. Year-to-year variations of the number of days of surf per year in the surf height categories from top to bottom, respectively: **extreme** (>8 Hsf or 5 m), **large** (6-8 Hsf or 3.5-5m), **commonly high** (4-5 Hsf or2.5-3m), and commonly high or greater. The mean and standard deviation (sdev) of each are given.

Most high surf arrives in Hawaii from a distance between 3,500 to 5,000 nm away out of 170-200 ^{o} (Figure 1). In this directional band, the highest episodes occur when the storms have wind speeds of severe gales (41-47 knots) or greater and the storm trajectory has a more northerly component, which allows a longer fetch length and duration for the directional band aimed at Hawaii. Such a "trapped" or "captured" fetch occurs when the motion of a weather system has a similar speed and direction to the batch of growing seas. With gale to storm speeds, building seas have dominant periods of 13-16 seconds; thus, a captured fetch occurs when the storm track speed is roughly 500 nm per day. For the typical source 4,000 nm away from Hawaii, the travel time for 20, 17, and 14 second wave energy is approximately 6, 7, and 8 days, respectively. High surf in Hawaii out of 150-170 ^{o} from southern hemisphere sources is rare, although seasonally average heights (3 Hsf or 1.8m) do occur several times per season. Swell generated in the directional band east of 140 ^{o} is blocked on Oahu by the Big Island (Figure 2).

a) 51028

PERIOD (sec)	TIME (hr)	cos10 (hr)	cos20 (hr)	cos30 (hr)	cos40 (hr)	cos60 (hr)
11	77.8	76.6	73.1	67.4	59.6	38.9
14	61.1	60.2	57.4	52.9	46.8	30.6
17	50.3	49.6	47.3	43.6	38.6	25.2
20	42.8	42.1	40.2	37.0	32.8	21.4
25	34.2	33.7	32.2	29.6	26.2	17.1

b) 51002

PERIOD (sec)	TIME (hr)	cos10 (hr)	cos20 (hr)	cos30 (hr)	cos40 (hr)	cos60 (hr)
11	14.7	14.5	13.8	12.7	11.3	7.3
14	11.5	11.4	10.8	10.0	8.8	5.8
17	9.5	9.4	8.9	8.2	7.3	4.8
20	8.1	8.0	7.6	7.0	6.2	4.0
25	6.5	6.4	6.1	5.6	5.0	3.2

c) 51003

PERIOD (sec)	TIME (hr)	cos10 (hr)	cos20 (hr)	cos30 (hr)	cos40 (hr)	cos60 (hr)
11	12.7	12.5	11.9	11.0	9.7	6.4
14	10.0	9.8	9.4	8.7	7.7	5.0
17	8.2	8.1	7.7	7.1	6.3	4.1
20	7.0	6.9	6.6	6.1	5.4	3.5
25	5.6	5.5	5.3	4.8	4.3	2.8

Table 2. Travel times (hours) from NDBC buoys to Oahu as a function of wave period (seconds) and direction. In the table header, "cos10" refers to cosine of 10^{o}, etc. To approximate the angle between an incident swell and the directional ray of a buoy relative to Oahu, refer to Figure 2.

Analysis

The purpose of this study is to provide a tool to improve surf forecasts for southern shores of Hawaii from the most frequent high swell source: extra-tropical cyclones in the southern hemisphere. The signatures in the spectral energy density measured by buoys south of Hawaii (Figure 2) during high surf episodes are studied for episodes in the size categories as defined above: extreme, large, and commonly high. Buoy 51004 was excluded in the analysis because it is well east of Oahu. Buoys 51002 and 51003 are more directly upstream of Oahu for the dominant swell directional band of 170-200^o. The buoy data were acquired from the NOAA National Oceanographic Data Center (NODC). The series for buoys 51002 and 51003 begin in 1984 and for 51028, in 1997.

The travel time of swell energy from the buoys to Oahu varies with wave period and direction (Table 2). This information was taken into account while analyzing the data. The elevated wave energy of an episode typically has a maximum over an 18-36 hour period. For this study, time series graphs of the long-period wave energy were studied (Figure 5), and the 36-hour time segment of highest values corresponding to the surf episode on Oahu was estimated subjectively. Data over this single 36-hour interval per episode were selected for further analysis.

For all events, episodes were selected only if there was not significant long period energy from non-southern hemisphere sources, such as extra-tropical or tropical storms in the north Pacific. This screening is particularly important for buoys 51002 and 51003, which do not have directional wave sensors. Buoy 51028 does provide directional wave information. The north shore observations in the GC database were inspected for extra-tropical north Pacific swell. Episodes were dismissed if such swell could add sufficient energy to the buoy data. The number of accepted episodes in the extreme, large, and commonly high categories was 3, 10, and 9, respectively (Table 3).

The spectral density is provided as a function of wave frequency bands of fixed width. The central frequency of each band is defined in the data set and the inverse gives an approximate wave period. This paper uses these nominal wave periods associated with each frequency band in the plots and discussion.

The resolution (interval width) of the buoy wave spectra data changed (Table 3). Originally, the interval width was of lower resolution of 0.01 Hz and partitioned the energy at the wave periods of 13, 14, 17, 20, and 25 seconds for the long-period domain. During 2002-2004, each buoy was upgraded to a higher resolution in frequency interval width to 0.005 Hz and gave output at 13, 14, 15, 16, 17, 19, 21, and 24 seconds. The selected episodes of each surf height category were separated into lower and higher resolution groups.

For the extreme surf category, only one high resolution episode was available; thus, the spectral density at 14 and 17 seconds were used and the 15 and 16 second bands were ignored. The 19- and 21-second values were averaged together and grouped with the 20 second low resolution set. The 24-second high resolution readings were included with the 25-second low resolution values.

For the extreme and large surf size categories, the data were analyzed over wave period range of 14-25 seconds, since these type episodes are characterized by long period energy. For the commonly high category, the 13 second data are included. Since the

a) Extreme						
Date	Height		Direction	Available		
yyyy mm dd	(Hsf)	(m)		51028	51002	51003
1995 06 13	12	7.3	SSW	N	N	LR
1998 06 12	9	5.5	SSW	LR	LR	LR
2003 06 18	10	6.1	SSW	LR	LR	LR
2005 09 14	10	6.1	S	HR	E	E

b) Large						
Date	Height		Direction	Available		
yyyy mm dd	(Hsf)	(m)		51028	51002	51003
2000 06 04	7	4.3	S	LR	N	LR
2000 08 21	7	4.3	SSW	LR	LR	LR
2001 07 19	7	4.3	SSW	LR	LR	LR
2002 04 29	7	4.3	S	LR	LR	LR
2002 05 12	7	4.3	S	LR	LR	LR
2004 07 16	8	4.9	SSW	HR	HR	LR
2005 05 05	6	3.7	SSW	HR	HR	HR
2005 06 10	7	4.3	SSW	HR	HR	HR
2006 06 02	6	3.7	S	HR	HR	HR
2006 08 01	6	3.7	SSW	HR	HR	HR

c) Commonly high						
Date	Height		Direction	Available		
yyyy mm dd	(Hsf)	(m)		51028	51002	51003
2000 09 01	5	3.0	S	LR	LR	LR
2001 04 14	5	3.0	SSW	LR	LR	LR
2001 06 11	5	3.0	SSW	LR	LR	LR
2002 08 19	4	2.4	SSW	LR	LR	LR
2003 07 03	5	3.0	SSW	LR	LR	LR
2003 07 29	4	2.4	SSW	LR	LR	LR
2005 06 18	5	3.0	S	HR	HR	HR
2006 06 22	4	2.4	S	HR	HR	HR
2006 08 24	4	2.4	SSW	HR	HR	HR

Table 3. Dates of episodes of each surf height category used in this study. “Height” refers to visual surf observations, which were made in Hawaii scale (Hsf) and estimated in meters (m). The incident swell directions were either south (S) or south-southwest (SSW). NDBC data availability is also given. “N” refers to data not available. “E” means the data were excluded due to contamination by non-southern hemisphere sources of long period swell. “LR” denotes low resolution and “HR” high resolution spectral density interval width.

southern hemisphere source zone is so far away, energy in wave period bands less than 13 seconds arrive 1-3 days after the episode maximum and give way to surf near the high season average or less.

The energy (spectral density) values in each frequency (period) band have high hour to hour variability. As a result, two subsets were formed: the average of the highest three (H3) hours and the average of the highest 12 (H12) hours of each wave period over the 36-hour time segment. These subsets emphasize nominally the maximum (H3) and average (H12) highest values during the peak of the episode. H3 and H12 values were calculated for each episode at all available buoys.

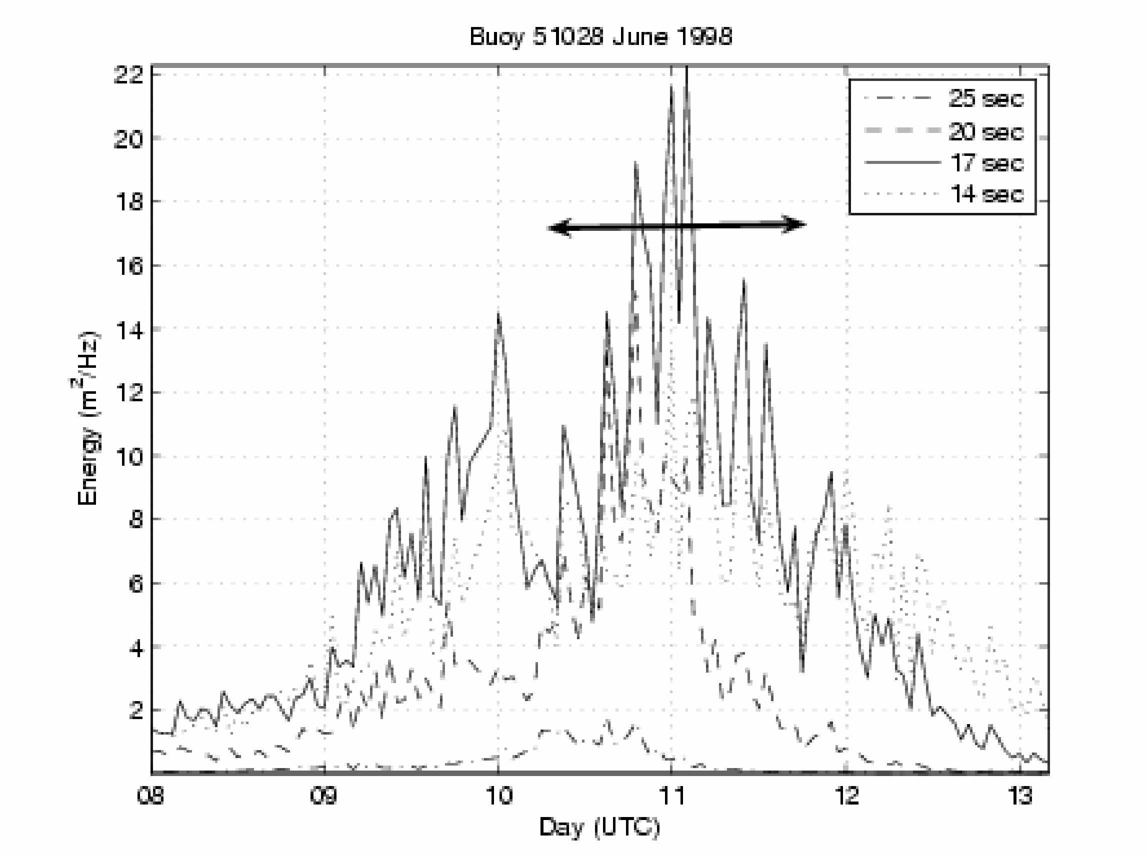

Figure 5. 8-12 June, 1998 NDBC buoy 51028 spectral density (energy). The double arrow denotes a 36-hour period chosen as the episode maximum.

Separately for the H3 and H12 sets, the final composites are made by averaging each wave period group individually across all episodes of each category size and for each area (buoy 51028 and together buoys 51002 and 51003). The standard deviation as a function of wave period is calculated to better understand the variability. An example for one set of composites is given in Figure 6. The composites include averages for wave period bands common to both the low and high resolution interval widths (13, 14, and 17 seconds).

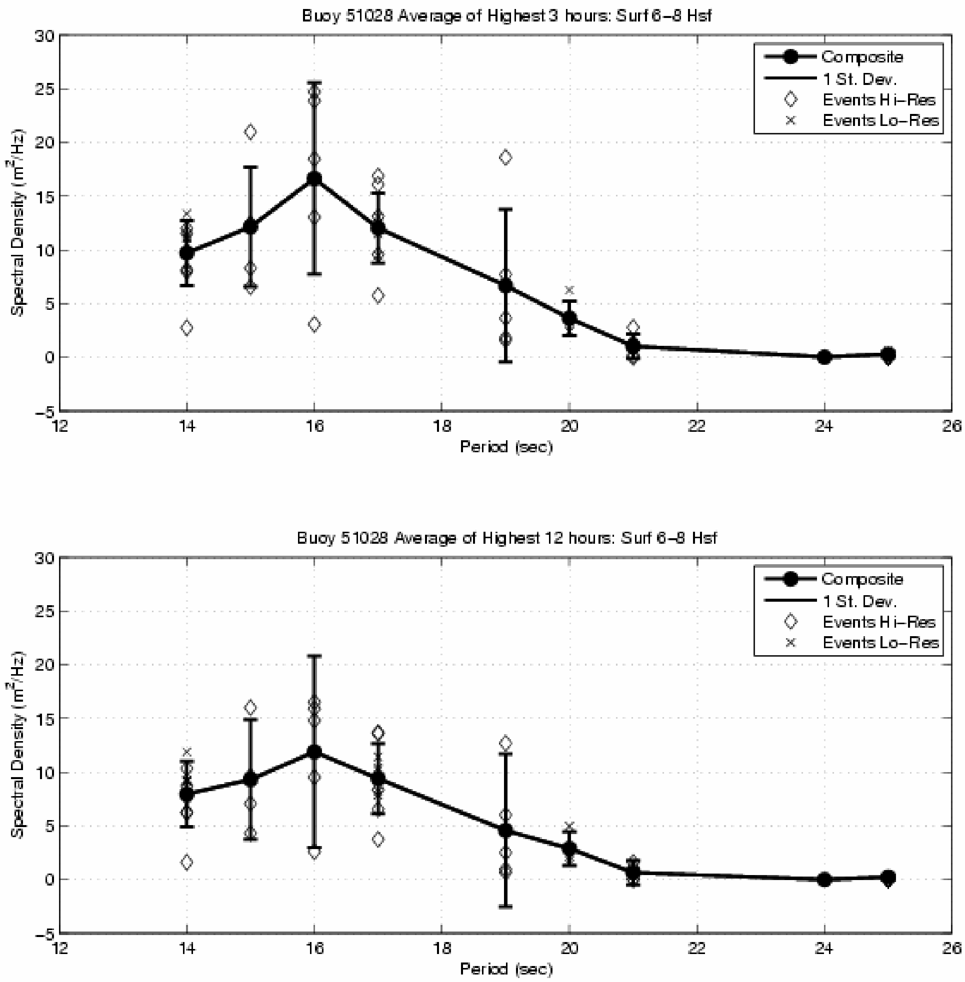

Figure 6. Buoy 51028 composite spectral density signature for the H3 (top panel) and H12 sets (bottom panel) for surf episodes in the large (6-8 Hsf or 3.5-5m) size category. The variability as a function of wave period is depicted with bars denoting ± one standard deviation. Individual episodes are grouped based on use of low or high resolution interval widths and denoted with symbols.

For buoys 51002 and 51003, the data are averaged together as a function of wave period. The buoys are roughly 200 nm apart (Figure 2). Typically one buoy measures mildly more energetic long period wave energy than the other, depending on whether the primary swath of swell is situated more east or west of the buoys. Over many episodes, such subtleties average out.

Conclusions

The composite spectral density signatures as a function of wave period for the H3 and H12 groups of each size category are presented for buoy 51028 (Figure 7) and the

51002 and 51003 buoy pair (Figure 8). The magnitude of the energy of each category is typical one-half to two-thirds less in the area of buoys 51002 and 51003 relative to buoy 51028, a reflection of the wave energy loss during travel of nearly 1000 nm. As would be expected, the spectral density is greater and is centered on longer wave periods as the surf size increases.

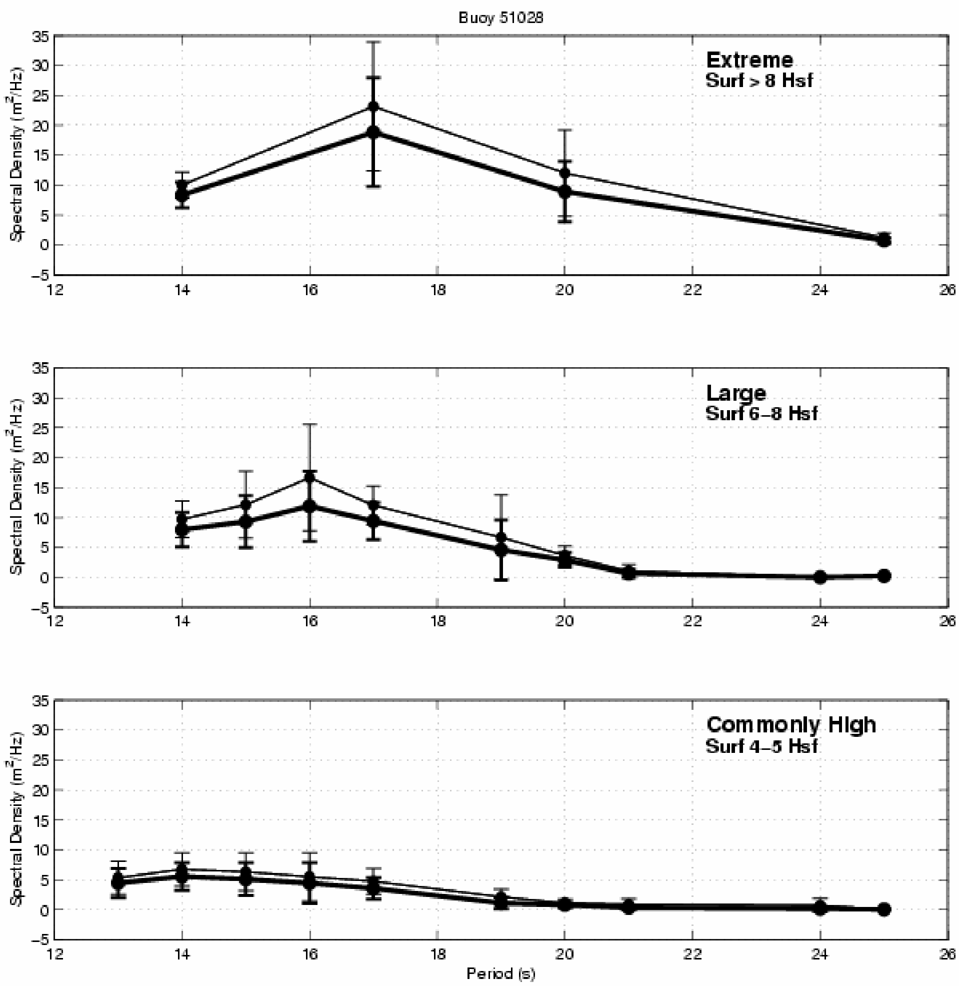

Figure 7. Buoy 51028 composite mean and standard deviation for extreme, large, and commonly high surf categories for the H3 (thin lines) and H12 (thick lines).

The standard deviation increases with the magnitude of the spectral density. There is significant variability amongst the similar-sized episodes in the dominant wave period bands. However, the magnitude of the mean for each size category is sufficiently different so that the one-standard deviation bar marginally overlaps the mean of the neighboring size categories.

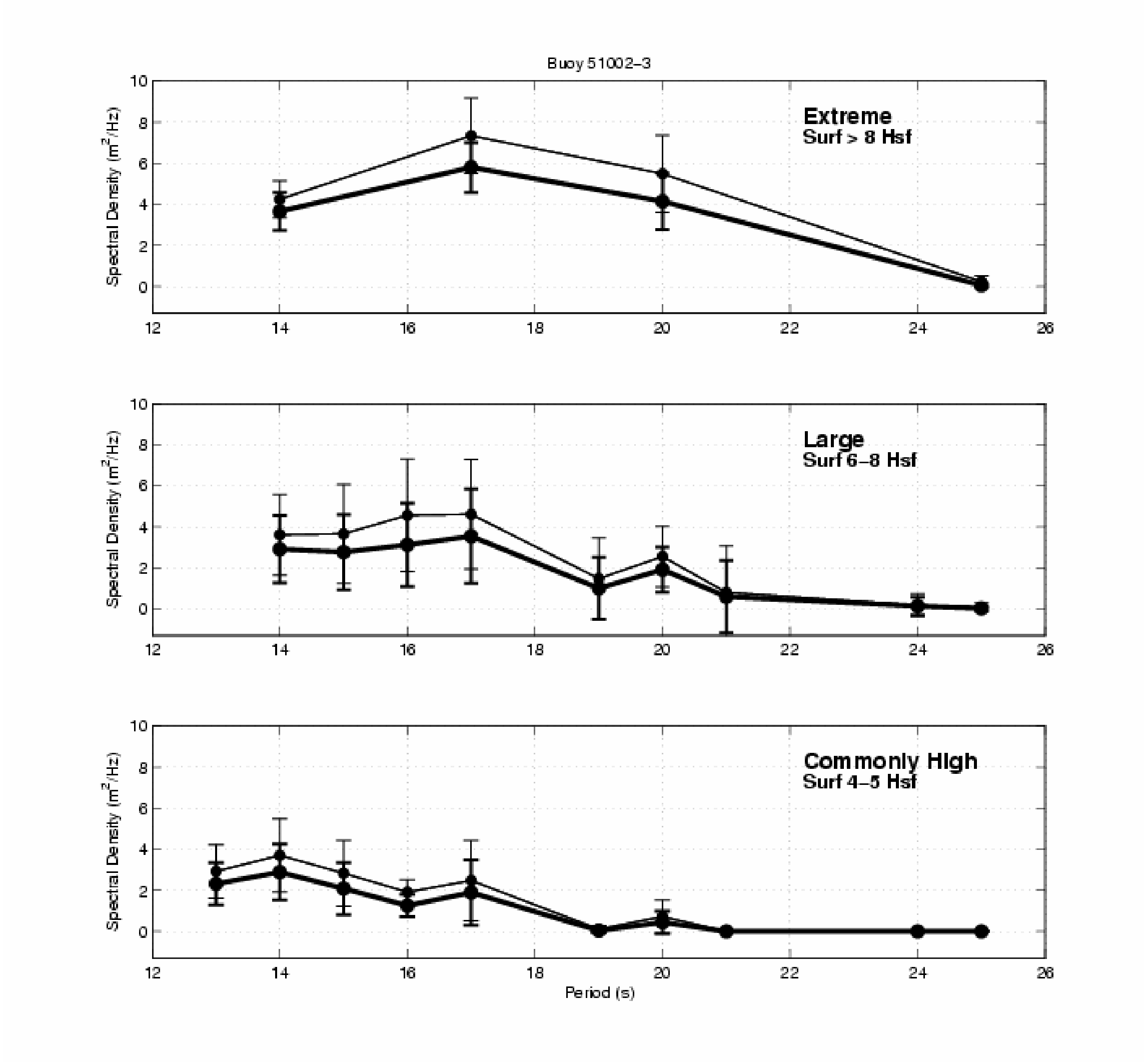

Figure 8. Like Figure 7 except this is a composite of the buoy pair 51002 and 51003.

For the buoy 51002 and 51003 pair, the large and commonly high composite signatures show minimums at 19 and 21 seconds for the former and 16, 19, and 21 seconds for the latter, respectively. This is likely due to the episodes with the high resolution interval widths (13, 14, 15, 16, 17, 19, 21, and 24 seconds) being marginally lower on average to the episodes of low resolution interval width (13,14, 17, 20, and 25 seconds) (Table 3). In future work as more episodes become available, the signature would likely have a smoother shape.

Buoy data are one of the most important aids in surf forecasting. These composite signatures provide guidance in estimating imminent surf on the southern shores of Hawaii from southern hemisphere extra-tropical storm sources. As new episodes unfold, the freshly measured spectral density data can be compared to the composite signatures for estimation of surf magnitude. The H3 and H12 curves allow a focus on the maximum and the average highest spectral density values, respectively. The standard deviation bars as a function of wave period define the variability about the mean.

In the future, these composites can be refined as more episodes become available in the buoy records. This technique could be applied to other areas with long buoy records and exposure to southern hemisphere swell such as Southern California. A similar composite could also be derived based on buoy 51001 for the north shores of Hawaii, although such events would have to be carefully analyzed by direction, since there is a significant shadow for incident directions south of 295^{o} and because the more northerly the direction, the greater the possibility of discrepancies in swell energy between the buoy location and Hawaii. Such a composite at buoy 51001 would work well for directions between 305-330^{o}, the dominant direction during the high season.

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