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Research Article

Wave Observations from Central California: SeaSonde Systems and *In Situ* Wave Buoys

Regan M. Long,[1] Don Barrick,[1] John L. Largier,[2] and Newell Garfield[3]

[1] *CODAR Ocean Sensors Ltd., 1914 Plymouth St, Mountain View, CA 94043, USA*
[2] *Bodega Marine Laboratory, University of California, Davis, CA 95616, USA*
[3] *Romberg Tiburon Center, San Francisco State University, Tiburon, CA 94132, USA*

Correspondence should be addressed to Don Barrick, don@codar.com

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Wave data from five 12-13 MHz SeaSondes radars along the central California coast were analyzed to evaluate the utility of operational wave parameters, including significant wave height, period, and direction. Data from four *in situ* wave buoys served to verify SeaSonde data and independently corroborate wave variability. Hourly averaged measurements spanned distance is 150 km alongshore × 45 km offshore. Individual SeaSondes showed statistically insignificant variation over 27 km in range. Wave height inter-comparisons between regional buoys exhibit strong correlations, approximately 0.93, and RMS differences less than 50 cm over the region. SeaSonde-derived wave data were compared to nearby buoys over timescales from 15 to 26 months, and revealed wave height correlations $R = 0.85$–0.91 and mean RMS difference of 53 cm. Results showed that height RMS differences are a percentage of significant wave height, rather than being constant independent of sea state. Period and directions compared favorably among radars, buoys, and the CDIP model. Results presented here suggest that SeaSondes are a reliable source of wave information. Supported by buoy data, they also reveal minimal spatial variation in significant wave height, period, and direction in coastal waters from ∼45 km × ∼150 km in this region of the central California coast. Small differences are explained by sheltering from coastal promontories, and cutoff boundaries in the case of the radars.

1. Introduction

Several sea-state wave monitoring sensors, including four *in situ* wave buoys and five coastal ocean dynamics application radar (CODAR) high-frequency radars (HFRs) called SeaSondes, are currently deployed along the central California coast from Bodega Bay, CA, south to Half Moon Bay (Figure 1). In an effort to better characterize SeaSonde-derived wave parameters and their overall utility, we compared one to two year data sets with nearby *in situ* buoys. Seventeen sensor-to-sensor comparisons were conducted to provide an extensive look at the usefulness of the differing datasets and also provide interesting insights into the wave environment in this central California region extending 150 km from north to south and offshore to 45 km.

There are 130 coastal HF radars around the continental US operating in real time as part of the US IOOS national network. Their intended and primary outputs are surface current maps extending out as far as 200 km. Of these, 122 are CODAR SeaSondes—the design to be discussed herein as candidate for wave outputs. Wave data from SeaSondes are considered a secondary output that is available on many systems, but are not being used or displayed operationally on the national web servers (e.g., http://hfradar.ndbc.noaa.gov/). A motivation for this paper is examination of SeaSonde HF radar output wave parameters to assess their accuracy and utility as an augmentation to the offshore NOAA/NDBC buoy network (http://www.ndbc.noaa.gov/).

We have two goals: (1) to determine how well CODAR-derived wave height and period compare with nearby wave buoy data and (2) to characterize the spatial patterns of wave heights off central California as they apply to HF radar outputs.

2. Location and Instruments

2.1. CODAR, High-Frequency Radar—SeaSondes. Data from five land-based, 12-13 MHz SeaSondes located along the

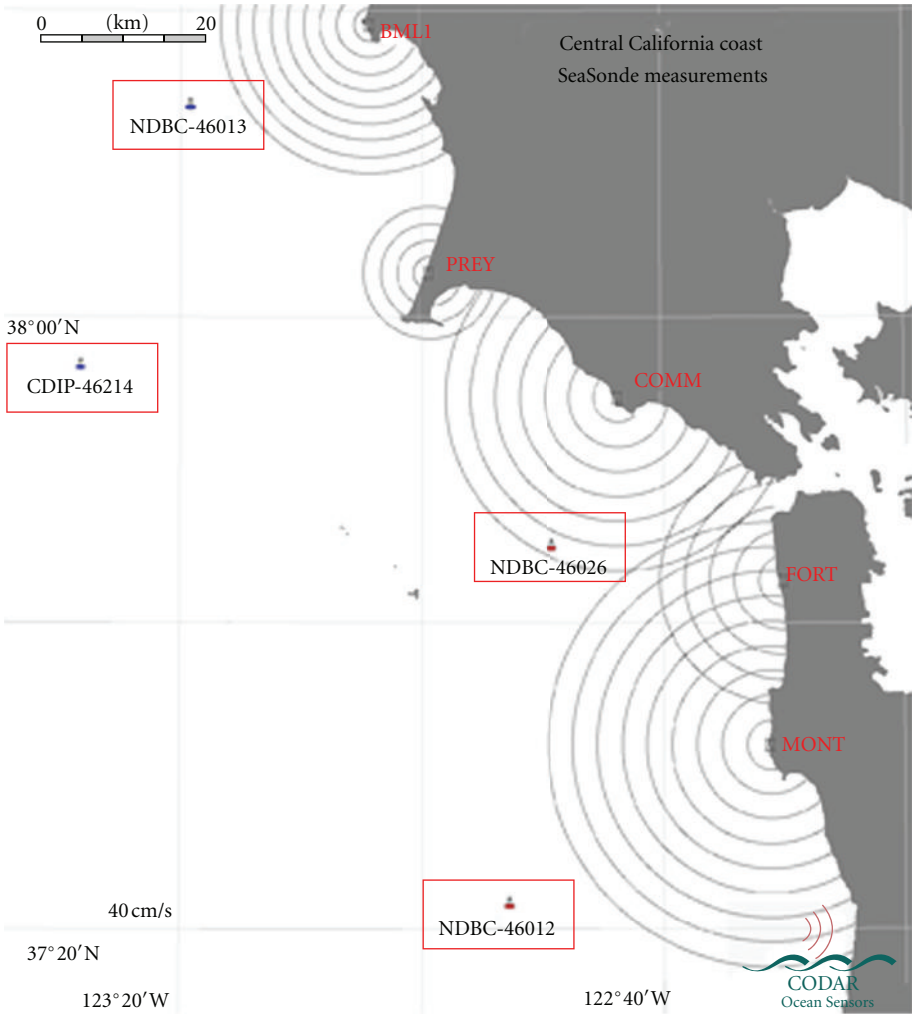

Figure 1: Location of SeaSondes and wave buoys located along the central California coast.

central California coast were used in this study (Figure 1): two SeaSonde systems were located north of Point Reyes, one at Bodega Marine Lab (BML1) and one at South Beach in the Point Reyes National Seashore (PREY); three SeaSondes systems were located south of Point Reyes: one near Bolinas, CA (COMM), one in San Francisco, CA (FORT), and one in Montara, CA (MONT). Data sets from these sites contributed with wave height, wave period, and wave direction spanning 26 months, from November 2005 to January 2008.

Land-based SeaSonde systems measure surface currents and sea-state wave conditions by transmitting radio waves over the ocean surface. Doppler-shifted return sea echo is used to extract surface current velocities from the dominant first-order Bragg peaks out to ~90–200 km offshore (Barrick et al., [1]). Each site observes flow moving toward or away from the radar, referred to as radial currents. By combining two or more radial vectors at a grid point, a total current vector is produced.

Additionally, each SeaSonde site can measure independent wave information, such as wave height, wave period, and wave direction if second-order sea echo is present (Barrick, [2, 3]). The second-order spectrum is used to extract wave information, such as significant wave height, wave period, and wave direction, by applying the Pierson-Moskowitz model to second-order spectra (see, Lipa and Nyden [8]). This is different from the Wyatt method [4] for phased-array radars. The Wyatt method, as well as our own earlier attempts, involves full mathematical inversion of the second-order echo spectrum; this was found to be considerably less robust than fitting a model with fewer parameters to the echo.

The SeaSondes used in this study (12-13 MHz systems) can measure a minimum wave height of 1 m and a maximum wave height of 8 m. If waves are sufficiently energetic, second-order spectra will provide wave estimates from the first few range cells. Wave data are collected from several annular range-cell rings, with width (w) and distance (R) from the radar (Figure 2). Wave parameters represent average conditions over this entire annular range ring. This means that the same Pierson-Moskowitz wave spectral model is assumed to apply independent of position around the ring, that is, the wave field is homogeneous. If in practice this assumption

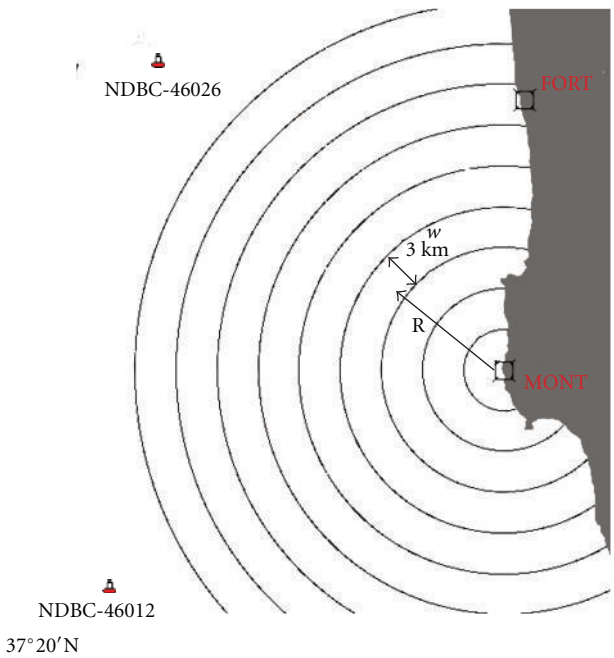

Figure 2: Schematic/closeup of SeaSonde range cells of width = 3 km.

does not apply within the time and space sampling considered here, then variations will be seen among range cells and among SeaSonde and buoy measurements. This is in fact the subject of this paper, and our results will show minimum variation, thereby justifying the use of this model for sea-state measurement purposes with SeaSondes.

The number of range cells collected for wave processing, wave data averaging, output options, coastline bearing angles, and the method of data output (i.e., average or median filter) are all parameters that are user selected and have been employed at each respective site for years. For example, BML1 and PREY significant wave height data were averaged onsite over 75 minutes and output hourly. COMM wave data were not averaged and output every 30 minutes. FORT and MONT wave data were also not averaged but output every 10 minutes.

The raw data used in this study are summarized in Table 1. The BML1 data set is the longest, spanning 26 months from November 2005 to January 2008, collecting wave data from 4 km to 18 km offshore. Montara has the largest range extent spanning from 6 km to 27 km offshore. Figure 1 shows range cells used for wave acquisition from each SeaSonde site.

2.2. In Situ Wave Buoys. Four wave buoys were located in the region of study, with mooring locations ranging from 20 km to 45 km offshore (Figure 1). Wave height and period data were collected from three, 3-meter discus buoys (46013, 46012, and 46026) operated and maintained by the National Data Buoy Center (NDBC), and a fourth Waverider buoy operated by Scripps Institution of Oceanography (as a part of the Coastal Data Information Program, CDIP). Quality-controlled, hourly averaged significant wave height, dominant period, and average period from June 2006 to December 2007 (17 months) were obtained from the National Data Buoy Center (NDBC) website for buoys 46013, 46026, and 46012 (http://www.ndbc.noaa.gov/), while only hourly significant wave height and dominant wave period were obtained from CDIP buoy, 46214. Directional wave data from three of the four buoys were either not available or incomplete from June 2006 to December 2007, and as such were not included in this study.

Buoy significant wave height measurements are described on the NDBC website as "an average of the highest one-third of all wave heights during a 20-minute sampling period" (http://www.ndbc.noaa.gov/measdes.shtml). Dominant wave period is described as "the period with the maximum wave energy," while NDBC computes the average period "as the square root of the ratio of the zeroth spectral moment to the second spectral moment." More information on how NDBC calculates the buoy measurements used in this study can be found here: http://www.ndbc.noaa.gov/wave.shtml.

Errors or uncertainties for NDBC buoy outputs are given on the above websites as ±20 cm for wave height; ±1 second for wave period; ±10° for wave direction. These are interpreted as standard deviations.

2.3. CDIP Near-Shore Model Data. Due to limited directional wave data from the buoys in this region, near-shore wave estimates for 2007 were obtained from a CDIP model, which is a work in progress based on a multibuoy extension of the spectral refraction modeling described in O'Reilly et al. [5]. It is worth noting that there are other models available for comparison (such as Wave Watch III and WAM); however, the CDIP near-shore refraction model data was readily available to us for the time span of our study. Model output was provided near SeaSonde locations at the 15 m isobath. The CDIP model swell (frequencies < 0.09 Hz) is obtained from CDIP buoy 46214 and 46042, while contributions to the local sea (frequencies > 0.09 Hz) are modeled from data at buoys within 150 km of the requested location. Buoys 46026 and 46214 (shown in Figure 1), and 46042 and 46236 (located near Monterey Bay, not shown in Figure 1), are used in this model approach.

2.4. What the Radar and Buoys Can and Cannot Measure. There are three types of observable wave information: (1) short-term spatial point measurements; (2) averages over a longer interval (e.g., an hour); (3) averages over a spatial area (e.g., across range rings defined by the radar parameters). The former are useful in studying rapidly changing conditions, as when a storm or front moves through and wave conditions change over fractions of an hour and distances of ~10 km. Wave buoys can output time series that contain this information (1), although the databases we accessed here, as noted, were hourly averaged samples (2). Useful HF radar data is presently restricted to hourly averages (2) and over spatial scales up to 40 km (3) (the latter based on the powers radiated by commercially available radars today).

Table 1: Summary of available wave data acquisition parameters.

Wave sensor	Data time span (months)	Raw onsite data output interval (minutes)	Wave data range from shore (km)	Onsite output method and interval
BML1 CODAR HFR	26	60	4–18	75-minute average
PREY CODAR HFR	16	60	4–8	75-minute average
COMM CODAR HFR	15	30	6–18	Hourly median filter
FORT CODAR HFR	14	10	6–15	Hourly median filter
MONT CODAR HFR	15	10	6–27	Hourly median filter
NDBC 46013	17	20	∼29	Hourly average
NDBC/CDIP 46214	23	20	∼60	Hourly average
NDBC 46026	17	20	∼26	Hourly average
NDBC 46012	18	20	∼42	Hourly average

This is true not only of CODAR SeaSondes, but also applies to phased array systems, where longer-term averaging is also required for stability (Wyatt et al., [6]). Hourly averages are quite adequate to measure predominant swell characteristics like those observed in the central California region (typically originating from the north and northwest). Swells have durations (time required to develop or change their energies) that exceed an hour; they also have fetches (distance over which they remain nearly constant) that exceed the spatial scales of HF radar measurements we consider herein (Kinsman [7]).

Therefore, short-term dynamics of storm events will not play a role in the results examined in this paper, because of the inherent spatial/temporal averaging. The spatial scales of, say, 40 km are commensurate with hourly averaging times. For example, typical Pacific waves with 12-s periods travel with deep-water group velocity 34 km/hr. Fetch considerations in an evolving storm also show that such waves require fetches and durations of many tens of kilometers and an hour or more to develop. Hence, we repeat that wave changes over short times and distances much less than 40 km are not considered herein.

3. Data Analysis Methods

Several data analyses were conducted to assess how SeaSonde wave data compare with buoy-derived wave height and period. First, we closely examined significant wave height from each individual SeaSonde to assess its own spatial variability and determine what data should be used to compare with the buoys. We then compared wave data from regional buoys and regional SeaSondes to establish if regional variability from different instruments exists. A regional wavefield "ground truth" is established from buoy-buoy comparisons, and then SeaSonde-to-buoy comparisons of wave height and period are conducted. These analyses are described in detail below.

3.1. Variability in Wave Height from SeaSondes and Buoys. Initial studies were conducted from each SeaSonde's significant wave height data set to determine if measured wave height varies over range from the radar. Each system has the capability to record wave height, period, and direction for multiple range cells (i.e., distances from the radar). Operational parameters set up on site by different radar operators determine which range cells had been used to extract wave parameters. In all five sites used in this study, multiple ranges were set to record wave parameters; however, ranges and data time spans vary from system to system (Table 1) due to different user settings.

Data were quality controlled (QC) and normalized prior to any analyses. A QC filter was first applied to both SeaSonde and buoy data, which removed raw flagged points (NaNs, 999s, etc.) and points exceeding a 1 m threshold change in less than an hour that can sometimes result from radio interference, physical environmental issues, and/or operator error. Table 2 shows initial number of points from each data set, and the number of points used in comparisons after the QC filter is applied.

In an effort to normalize the different raw SeaSonde data sets for comparison, all SeaSonde data were postprocessed with a 70-minute median running filter and output into median hourly values. The postprocessed median values were used in all comparisons.

The initial topic examined for all five SeaSonde sites was to determine if wave height measurements from SeaSondes vary from range cell to range cell. To do this, we calculated a "coefficient of variation" (CoV) over range for each hour of data collected. If CoV is close to zero, there is little deviation from the mean; if CoV is close to unity, there is significant deviation from the mean. First, a standard deviation of significant wave height measurements over range for each hour collected was calculated. Then, mean wave height over range was calculated for each hour. The standard deviation over range was then normalized by the mean over range, providing a CoV over range for each hour of data collected. CoV is used here to give a measure of whether height standard deviations (e.g., uncertainties) are a percentage of the mean, a fixed number, or a combination of both. In addition, a time average of the hourly standard deviations was calculated for each SeaSonde to give a sense of near-shore spatial variability in wave height from individual SeaSondes. [RMS differences among N time series of pairs of numbers are sometimes

Table 2: Spatial variation wave analysis results.

Wave sensor	No. of hourly points	No. of points after filter (hours)	Range (km)	% of points <50 cm variation over range	Mean standard deviation (cm)	Mean coefficient of variation
BML1	17,103	16,424	4–18	99%	19	0.09
PREY	11,550	11,550	4–8	98%	17	0.07
COMM	8,687	8,556	6–18	98%	20	0.10
FORT	9,403	8,952	6–15	95%	20	0.08
MONT	10,103	9,258	6–27	99%	20	0.09
All regional SeaSondes	4,634	4,634	150 km N/S 27 km E/W	85%	35	0.17
All regional buoys	9,884	9,884	100 km N/S 45 km E/W	89%	29	0.14

preferred when N is small (e.g., two or three). When N is larger, for example, in the case of time histories from multiple range cells from a radar, the standard deviation among the numbers themselves is the preferred, less cumbersome calculation. The latter can be shown to be identically equal to the RMS-difference standard deviation multiplied by the square root of two.]

In an effort to assess spatial variability over a larger region, we took time series of range-averaged significant wave height from each SeaSonde and conducted four regional SeaSonde-to-SeaSonde and five buoy-to-buoy comparisons. RMS differences, correlation coefficients, standard deviations, and mean differences were calculated to quantify spatial variability.

Regional spatial variability was also quantified by applying analyses used for the individual SeaSonde range cell-to-range cell comparisons to regional SeaSonde data and regional buoy data spanning 150 km from north to south and 45 km from east to west. A standard deviation and mean were calculated from the significant wave height collected over the region from all SeaSondes—and separately for all buoys—for each hour to produce the CoV over the larger domain; a mean standard deviation was calculated to summarize overall variability.

3.2. SeaSonde-Buoy Comparisons. To quantify how well SeaSonde wave data compare to *in situ* wave measurements from nearby buoys, we used direct comparison case studies between median-filtered wave height and period data from each SeaSonde site and the closest *in situ* wave buoy. The SeaSonde wave period—based on the centroid of the model fitted to the spectral data [8]—was compared both to the dominant and average wave period outputs from the buoys (where available) to determine which buoy period output correlated best with the SeaSonde wave period. Hence by its nature, the radar-derived period is different from buoy periods; the latter admit the possibility of sometimes measuring swell period separate from wind-wave period, where the radar cannot resolve these two at present. Wave direction was addressed; however, three of the four buoys did not have wave directional capability (or data readily available) at the time of our study. Hence, due to limited wave direction data, the 2007 annual mean SeaSonde wave direction from each site was compared to the 2007 median output from the CDIP near-shore model at the nearest 15-m isobath.

Six SeaSonde-to-buoy comparisons of wave height and period were conducted, each producing a correlation coefficient, RMS difference, mean difference, and standard deviation. Qualitative comparisons between the CDIP near-shore model and SeaSonde wave directions are derived from the calculated annual mean from each data set.

3.3. Interpreting Statistics. Statistics for differences tabulated in this paper have different meanings. *RMS difference* among sensors includes both the mean differences and their standard deviations, being the square root of the sum of their squares. These RMS differences can in general reflect: instrument biases; noise in the sensor measurement process; noise in the wave quantity to be measured that the sensors are unable to remove; and/or spatial variability in the wave field over the distances involved; we consider these further in this paper.

We use the word *bias* to mean a long time (>1 year) mean difference as seen between two sensors. Mean differences reflect sensor biases and/or natural differences or spatial variability in the wave field. Such mean differences will be explained as largely due to coastal cutoff and/or sheltering at the point of wave measurement by a coastal prominence further away, as discussed further in Section 5.

We use the word *noise* to denote a zero-mean random process that is Gaussian to lowest order. We show below that some noise in sensor differences—as reflected by the standard deviation of this difference—can be endemic to the parameter being measured. In other cases, it results from noise in the wave parameter as seen by different sensors, or by the same type of sensor at different locations. To lowest order, noisy sensor differences (i.e., large standard deviations) would not reflect a highly variable wave field; any such variability should not be zero mean. Rather, to the lowest order, mean difference, absent in any instrument biases, best reflects wave-field spatial variability.

We also calculate the *coefficient of variation* (CoV), which is the ratio of the standard deviation and the mean. This statistic is used to better define variance and dispersion of the wave field over range. It is specifically applied to study time series for wave height over range for individual SeaSondes

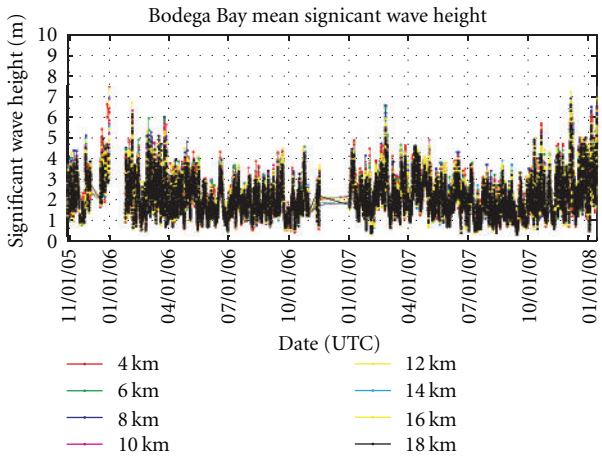

Figure 3: Multiple-range plot of wave height from range cells collecting wave data at BML1; different ranges are plotted in different colors.

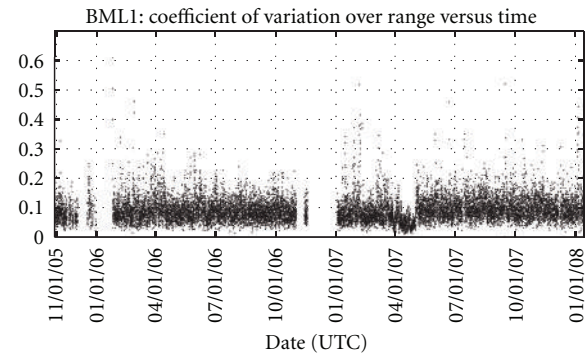

Figure 4: BML1 coefficient of variation (CoV) time series for significant wave height.

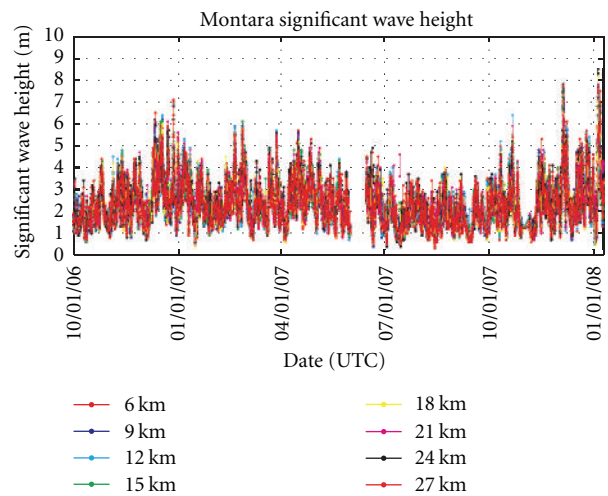

Figure 5: Multiple-range significant wave height history plot from Montara.

and regional buoy and SeaSonde wave outputs in addition to a mean standard deviation itself. A time series of the CoV will show any variability from hour to hour, while a mean CoV is also calculated to define the overall wave height dispersion for each data set.

For lack of space, we cannot show all cases including plots of time series, CoV, and scatter; however, we have highlighted noteable results for plotting and discussion. The mean statistics for all cases are calculated and included in our Tables 2–5.

4. Results

4.1. SeaSonde Range Cell-to-Range Cell Analyses. Years of individual SeaSonde wave data over range were analyzed and are presented in Table 2. In summary, all five SeaSondes report >95% of data points have less than 50 cm variation over range. Mean standard deviations over range do not exceed 20 cm. The mean coefficient of variation for all systems is lower than 0.10. Noteworthy details, results, and supporting figures are presented below.

4.1.1. BML1: November 2005–January 2008. Figure 3 shows significant wave-height time series plots for all range cells collecting wave data at BML1, representing the longest data set in this study. Standard deviations over range were calculated from significant wave height measurements for each hour over the 26-month data set to assess significant wave height variation over range. Of 16,424 QC-filtered hourly points analyzed, 99% of points show a standard deviation of less than 50 cm in wave height. The corresponding CoV was calculated from the time series and plotted in Figure 4. The mean CoV of 0.09 indicates low dispersion in significant wave height between 4 km and 18 km from the SeaSonde.

4.1.2. MONT: October 2006–January 2008. MONT produced the largest range of collected wave data. Wave parameters were collected in 3 km range cells, from 6 km to 27 km offshore, yielding parameters spanning 21 km; the time series plot of wave height over range is highlighted in Figure 5.

MONT wave height variability is remarkably low, with 99% of 9,258 QC-filtered hourly points showing less than 50 cm deviation, and a mean standard deviation of 20 cm. The CoV time series is shown in Figure 6 and used to calculate the mean CoV of 0.09.

4.1.3. PREY: September 2006–January 2008. The wave-height data set from PREY spans only 4 km, so there is expectedly little variation over range due to the restricted range. 98% of 11,550 points over 16 months show less than 50 cm change in significant wave height, yielding the mean standard deviation at 17 cm. The mean CoV is the lowest of all similar case studies at 0.07.

4.2. Regional SeaSonde Comparison Case Studies. Here, we present and discuss range-averaged results from four SeaSonde-to-SeaSonde comparisons of significant wave

Table 3: SeaSonde-to-SeaSonde comparison results.

SeaSonde systems	No. of points	Wave height				Wave period				Wave direction
		R	RMSD (cm)	MD (cm)	SD (cm)	R	RMSD (s)	MD (s)	SD (s)	MD (°)
MONT versus PREY	7,642	0.89	50	−21	45	0.86	.82	−0.16	0.81	−34
MONT versus FORT	7,182	0.89	52	−15	50	0.88	1.15	−0.80	0.83	21
BML1 versus PREY	9,912	0.88	54	−26	47	0.82	1.08	−0.56	0.92	−14
BML1 versus MONT	7,060	0.86	43	−8	42	0.83	1.07	−0.53	0.93	23
Mean	7,949	0.88	50	−17.5	46	0.85	1.03	±0.51	0.87	±23

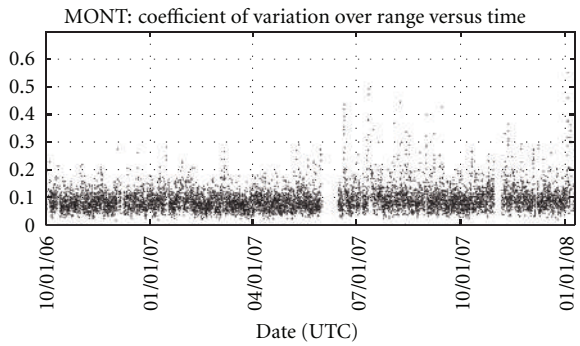

Figure 6: MONT coefficient of variation (CoV) time-series for significant wave height.

height, wave period, and wave direction, as well as regional summary results from all SeaSondes shown in Table 3. In summary, mean R for wave height and period across all four comparisons are 0.88 and 0.86, respectively. The mean wave height and wave period RMS difference are 50 cm and 1.03 s. Scatterplots from all SeaSonde-SeaSonde case studies are shown in Figure 7; results from comparisons of all regional, range-averaged SeaSondes are shown in Table 3. Notable comparisons, results, and supporting figures are presented below.

4.2.1. MONT versus FORT, November 2006–December 2007. MONT and FORT both face west and are separated by 20 km; FORT collects wave data from 6 km to 15 km and Montara collects wave data from 6 km to 27 km. We expect results to be somewhat similar between these two sites due to their close proximity and similar field of view.

Range averages of wave height were compared as scatter plots (Figure 7). Results detailed here—and shown in Table 3—reveal strong agreement with a significant wave height correlation coefficient of 0.89 and 52 cm RMS difference from 7,182 hours of compared data. Wave periods from these sites were also well correlated, yielding $R = 0.88$ and an RMS difference of 1.15 s. The mean difference in wave direction is 21°—possibly due to sheltering of FORT from dominant northwesterly swell—and will be discussed in Section 5.

4.2.2. BML1 versus MONT: June 2006–December 2007. MONT and BML1 are separated by 100 km, giving the largest distance comparison in these SeaSonde-SeaSonde investigations. 7,060 hourly points, spanning 13 months, were used in this case study. Results from the comparison yield positive wave height correlation and the lowest RMS difference of all HFR comparisons, $R = 0.86$ and 43 cm, respectively. Clear correlation is visually evident in the scatter plot in Figure 7.

4.2.3. All CODAR Sites, November 2006–December 2007. Range-averaged wave heights from all five SeaSonde sites were compared to assess regional wave-height variability (Figure 8). Wave data from the five sites span from ∼100 km north to south, and from ∼4 km to 27 km offshore. From November 2006 to December 2007, there were 4,634 matching hourly points between all five sites.

The regional standard deviation over range was calculated for each hour of collected data. Results from this comparison show that 85% of matched points vary less than ±50 cm over the region, with a mean standard deviation of 35 cm. When we normalize the standard deviation time series by a regional mean, we get a CoV of 0.17, indicating low dispersion in wave height over the region. These results indicate that significant wave height—averaged over the time and space scales employed by these sensors—varies little in these coastal waters.

4.3. Regional Buoy-to-Buoy Comparison Case Studies. To further validate and understand our SeaSonde comparison results, we utilized wave data from four *in situ* wave buoys located along the coast in this region: NDBC 46013, CDIP 46214, NDBC 46026, and NDBC 46012. We conducted five buoy-to-buoy comparisons to determine if *in situ* buoys observed the same regional wave height variability over the region as found with SeaSonde wave height comparison results. Comparison results presented in Table 4 corroborate the SeaSonde results, revealing slightly higher R for all buoy comparisons (mean of 0.94), and the same overall mean RMS difference of 50 cm. Average period output was not available from all buoys, so only a dominant period comparison was possible for most matchups. In general, dominant period comparisons yield larger RMS differences, indicating this is a noisy parameter and will be discussed more in Section 5. Notable comparisons are highlighted below.

4.3.1. Nearshore Buoys: NDBC 46013 versus NDBC 46026, June 2006–December 2007. This comparison was between the two near-shore buoys in the region: NDBC 46013 and 46026, separated by 69 km. Buoy 46013 is located 28 km west of Bodega Bay and moored near the 127 m isobath;

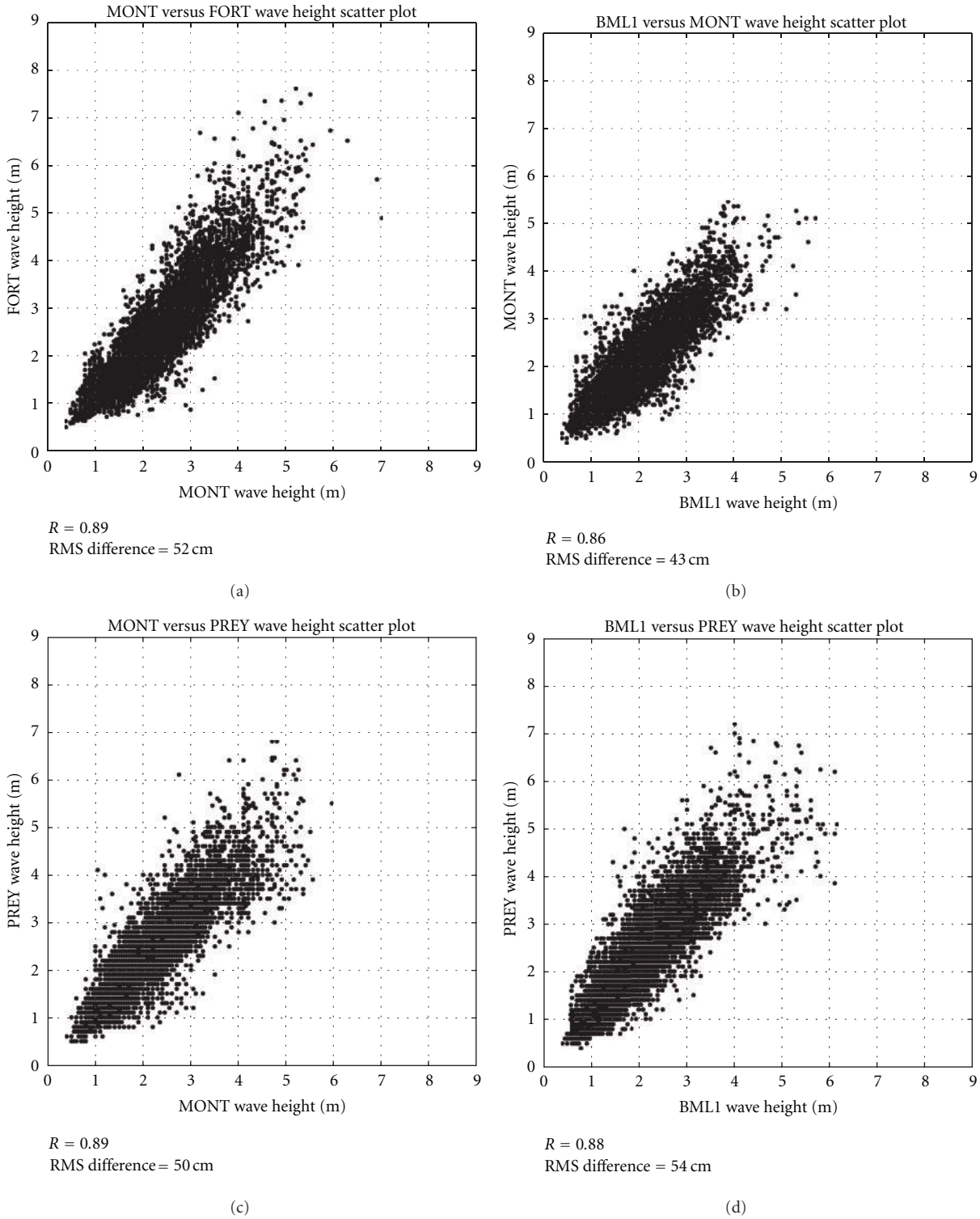

Figure 7: Scatterplots of SeaSonde-SeaSonde significant wave height comparisons.

the NDBC buoy 46026 is located 27 km west of San Francisco and moored near the 50 m isobath (Figure 1).

Matched hourly wave height and period were compared between the two buoys from June 2006 to November 2007 (Figure 9). One can see a general trend of slightly higher wave heights reported from 46013, likely due to its unsheltered position farther offshore. However, the wave-height comparison correlation coefficient from 12,537 matched points reveals one of the highest correlations of significant wave height in our study at 0.94. This case study also

Table 4: Buoy-to-buoy comparison results.

In-situ buoys	No. of points	Wave height				Dominant wave period				Average wave period			
		R	RMSD(cm)	MD (cm)	SD (cm)	R	RMSD (s)	MD (s)	SD (s)	R	RMSD (s)	MD (s)	SD(s)
46013 versus 46026	12,330	0.94	42	28	31	0.74	2.27	−0.31	2.25	0.90	0.66	0.01	0.66
46214 versus 46012	14,052	0.93	42	−17	38	0.73	2.25	0.13	2.25	X	X	X	X
46026 versus 46214	10,916	0.93	69	−55	41	0.69	2.41	−0.12	2.41	X	X	X	X
46013 versus 46214	14,592	0.94	46	−29	36	0.71	2.35	−0.35	2.32	X	X	X	X
46026 versus 46012	12,537	0.94	49	36	33	0.74	2.11	0.21	2.22	0.92	0.90	0.69	0.58
Mean	12,885	0.936	50	±33	36	0.72	2.28	±0.22	2.29	0.91	0.78	0.35	0.62

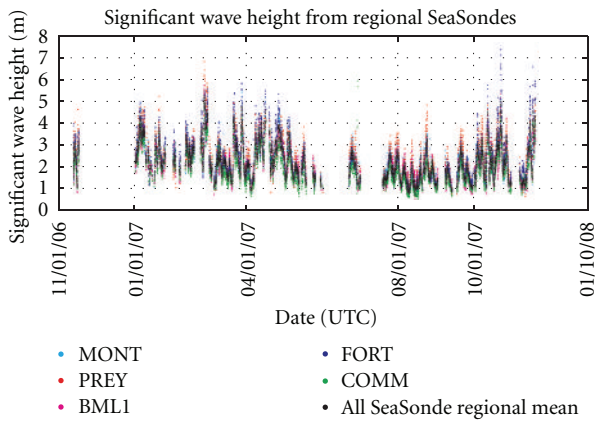

Figure 8: Significant wave height from regional SeaSondes.

yielded the lowest RMS difference and standard deviation in the study, 42 cm and 31 cm, respectively. Average wave period comparisons were positive, yielding $R = 0.90$ and RMS difference of 0.66 seconds. These well-correlated buoy-buoy results substantiate little wave height variability in the regions north and south of Point Reyes in near-shore regions (Figure 9), but slight differences in wave height are potentially due to sheltering and will be discussed further in Section 5.

4.3.2. Near and Offshore Buoys: CDIP 46214 versus NDBC 46026, June 2006–November 2007. The farthest offshore buoy wave height and dominant wave period (from CDIP 46214) were compared to wave data from NDBC 46026—the buoy moored closest to shore (Figure 1); these two are 61 km apart.

Figure 10 highlights the 15-month time series of data (10,916 hourly points) used in this wave height comparison. This buoy-buoy comparison reveals the highest wave height RMS difference (69 cm), highest mean difference (−55 cm) and highest standard deviation (41 cm) of all buoy-to-buoy comparison case studies. These values indicate potential sheltering at 46026 of waves from the northwest, which we will address in Section 5.

4.3.3. All Buoys, June 2006–November 2007. Wave heights from all four *in situ* wave buoys were compared to better evaluate variability over the region from ∼100 km north to south, and 25 km–45 km offshore. For this comparison, we used a similar method as for the regional SeaSonde case studies and calculated a standard deviation of time-matched, wave heights from the four buoys. From June 2006 to November 2007, there were 9,884 matching points (13.5

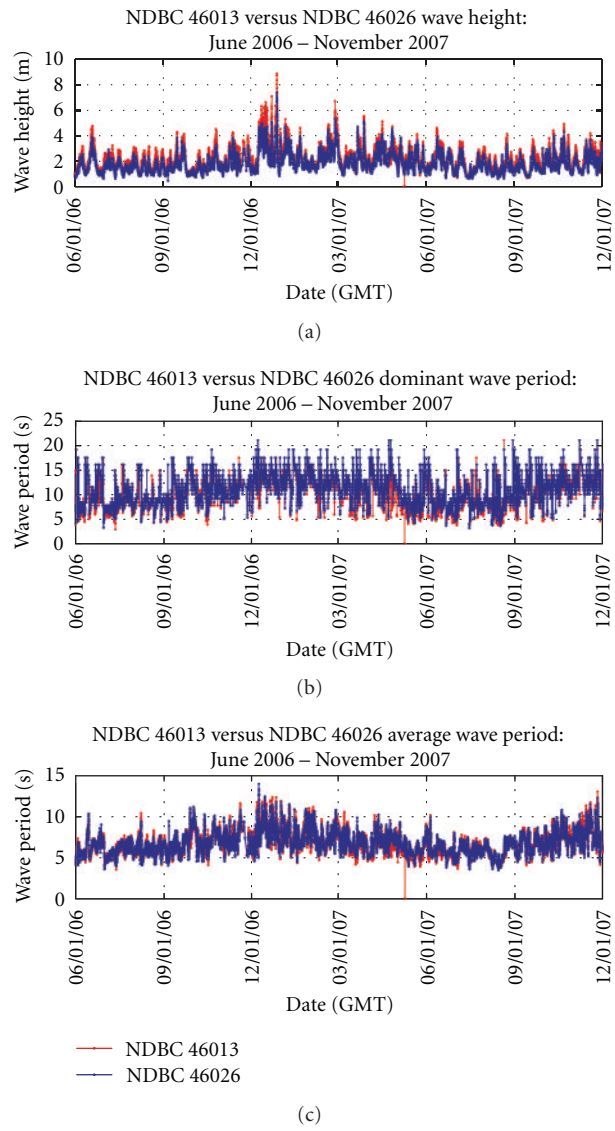

Figure 9: Near-shore buoy comparison plot: NDBC 46013 versus NDBC 46026.

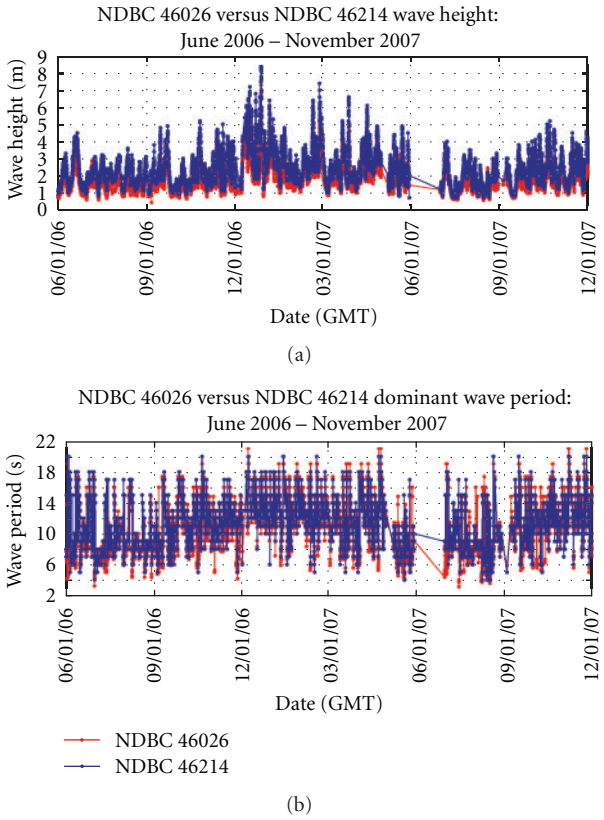

Figure 10: Near-shore versus offshore buoy significant waveheight comparison plot: NDBC 46214 versus NDBC 46026.

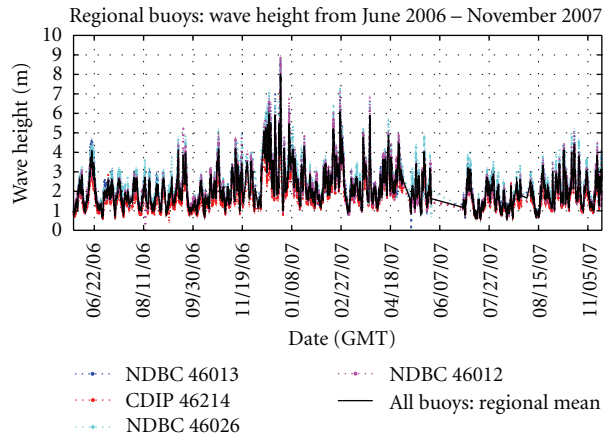

Figure 11: Regional buoy wave height comparison plot; all buoys and regional mean.

months) between all four sites used in the comparison (Figure 11).

Results from this comparison show that 89% of matched points vary less than ±50 cm over the regional buoy domain (Table 2). The mean standard deviation was 29 cm, similar to the regional SeaSonde mean standard deviation of 35 cm. When we calculate a regional mean of significant wave height to obtain the CoV, we find 0.14, indicating low dispersion of wave height over the region.

4.4. SeaSonde-to-Buoy Comparison Case Studies. Six SeaSonde-to-buoy comparisons were conducted to analyze correlation, RMS difference, mean difference, and standard deviation of wave height and wave period. The SeaSonde's centroid period was compared to both the buoy parameters of dominant and average period where available. All results are summarized in Table 5 and Figures 12–14. Figure 12 shows wave height scatter plots from all SeaSonde-buoy comparisons. Annual mean wave direction comparisons from the CDIP near-shore model and SeaSonde results are shown in Figure 16. Details and supporting figures of the specific comparisons are discussed below.

4.4.1. BML1 versus NDBC 46013, November 2005–January 2008. 14,808 time-matched hourly points were used in the comparisons of significant wave height and period over a 26-month timeframe. Wave height comparison results here reveal positive correlation ($R = 0.87$), while the RMS difference of 47 cm, mean difference of 9 cm, and standard deviation of 46 cm are some of the lowest statistical values in all SeaSonde-buoy case studies.

4.4.2. PREY versus NDBC 46013: August 2006–January 2008. Wave data from the PREY system were compared to data from nearby NDBC buoy 46013. Figure 13 shows the 10,954 matched hourly points of wave height and period used to in this comparison. The wave height results of $R = 0.90$ and RMS difference of 48 cm reveal similar characteristics to the buoy-to-buoy comparison case study results described in Section 4.3 and the MONT versus 46026 comparison case study described below.

4.4.3. COMM versus NDBC 46026: October 2006–January 2008. The shortest comparison case study was between COMM and 46026 with 8,388 matching hourly points. However, it is the only case where the buoy lies within the SeaSonde range.

This unique case study reveals positive correlation in significant wave height ($R = 0.86$), the lowest significant wave height RMS difference of 46 cm, and lowest mean difference (6 cm) of all SeaSonde-to-buoy significant wave height case studies. Wave period comparison results were on par with other SeaSonde-buoy results, yielding correlations of 0.61 and 0.74 for dominant and average periods, respectively, and associated RMS differences were 2.86 s and 3.39 s.

4.4.4. MONT versus NDBC 46026 and NDBC 46012, October 2006–January 2008. Two NDBC buoys were in the general vicinity of the MONT SeaSonde: NDBC 46026 located about 17 km northeast of the Gulf of the Farallones and nearly 36 km northwest of MONT, and NDBC buoy 46012 located 37 km southwest of MONT (refer to Figure 1). MONT wave data were separately compared to each buoy. Matching hourly points (9,999) with 46026 spanned nearly 15 months from October 2006 through January 2008 (shown

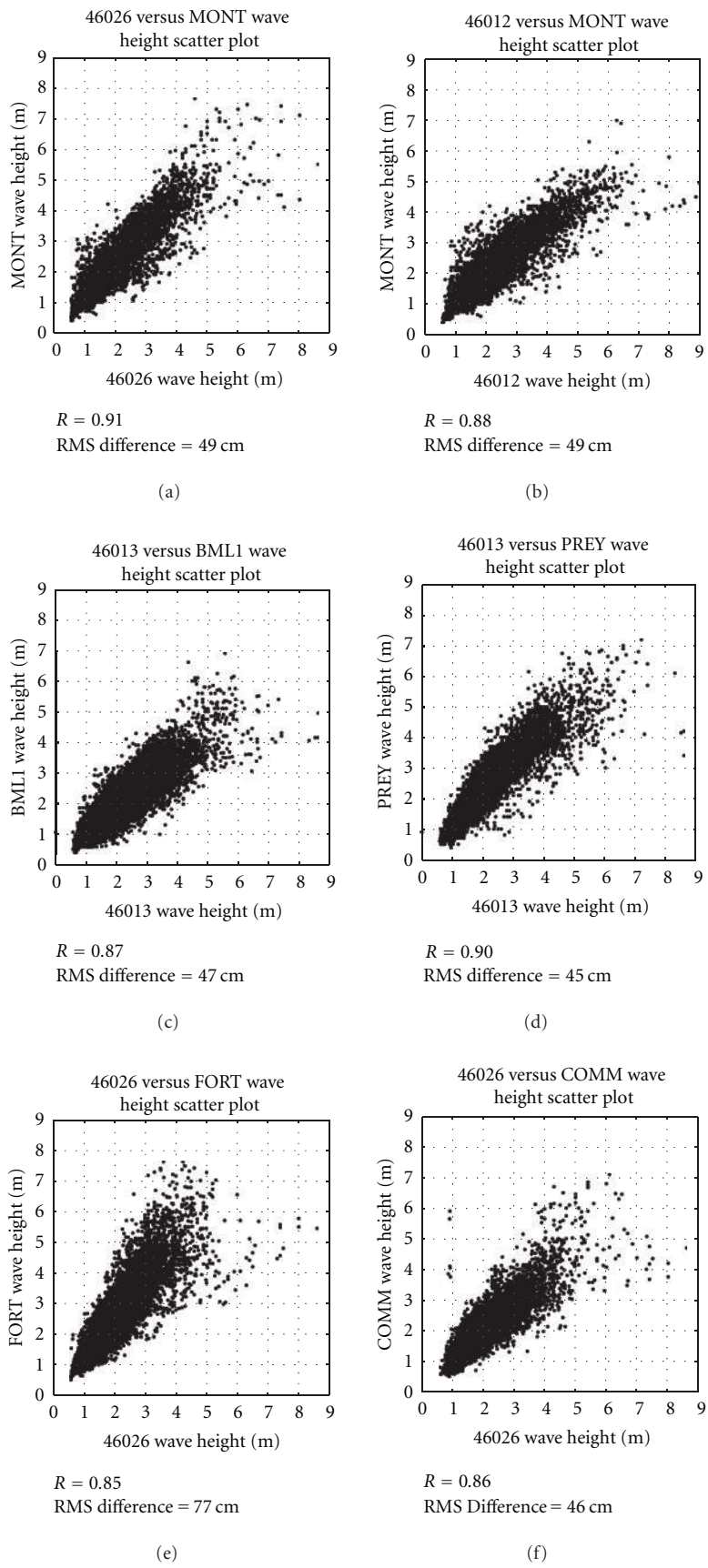

Figure 12: Scatter plots of all SeaSonde-buoy wave-height comparisons.

Table 5: SeaSonde-to-Buoy comparison results.

Wave Sensor	No. of points	Wave height				Dominant Wave Period				Average Wave Period			
		R	RMSD (cm)	MD (cm)	SD (cm)	R	RMSD (s)	MD (s)	SD (s)	R	RMSD (s)	MD (s)	SD (s)
BML1 versus 46013	14,808	0.87	47	9	46	0.61	2.81	1.37	2.46	0.75	2.89	−2.67	1.05
PREY versus 46013	10,954	0.90	49	−20	45	0.59	2.71	1.06	2.49	0.75	3.25	−3.09	1.03
COMM versus 46026	8,388	0.86	46	6	46	0.61	2.86	1.48	2.45	0.74	3.39	−3.28	1.17
FORT versus 46026	8,846	0.85	77	−47	61	0.59	2.67	0.86	2.52	0.69	3.96	−3.73	1.32
MONT versus 46026	9,999	0.91	49	−27	40	0.56	3.05	1.66	2.55	0.79	3.11	−2.94	0.99
MONT versus 46012	8,718	0.88	49	9	48	0.61	2.87	1.57	2.39	0.82	2.48	−2.31	0.91
Mean	10,286	0.88	53	±20	48	0.59	2.83	1.33	2.48	0.77	3.18	±2.68	1.08

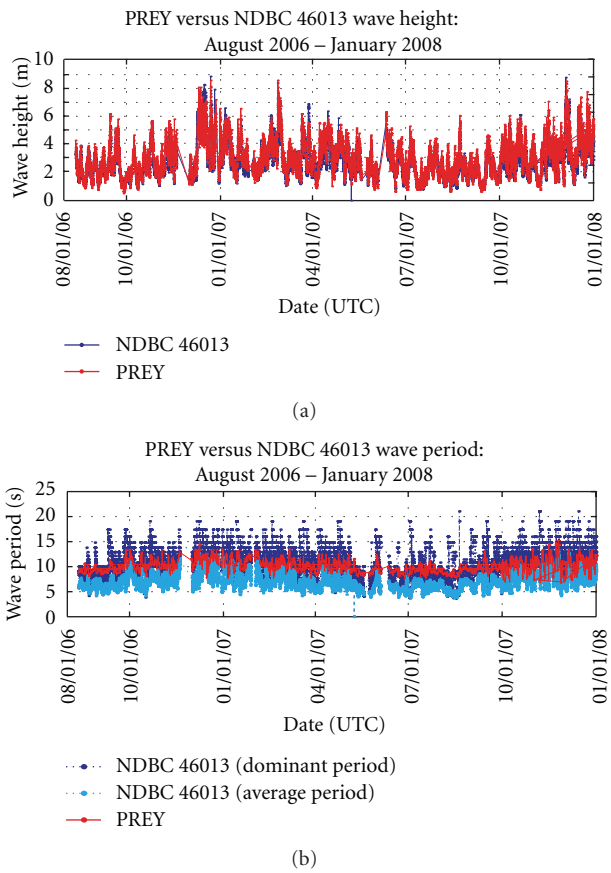

Figure 13: PREY versus NDBC 46013 wave height and period.

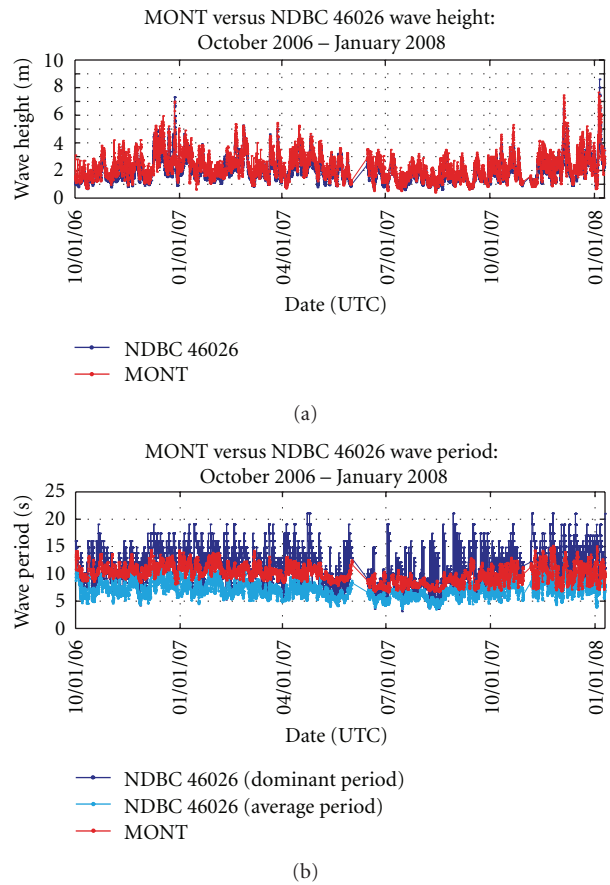

Figure 14: MONT versus NDBC 46026 wave height and period.

in Figure 14), while matching points (8,718) with 46012 spanned 14 months from October 2006 to November 2007.

MONT wave heights compared with 46026 yielded best results of all SeaSonde-buoy comparisons with $R = 0.91$, standard deviation of 40 cm, and RMS difference of 49 cm. Period correlations between MONT and 46026 were slightly lower, yielding 0.56 and 0.79 for respective dominant and average comparisons, with RMS differences of 3.04 and 3.11 seconds. These slightly less impressive results for periods could be due to 46026's more sheltered environment near the Gulf of the Farallones, while MONT is located on a headland with more exposure to longer-period, northwesterly swell.

Figure 15 shows a detailed plot of regional buoys and the widely separated MONT and PREY SeaSondes, all observing significant wave events in winter and summer, 2007. We see good correlation among all SeaSonde-derived wave data and nearby *in situ* buoys in SeaSonde-to-buoy comparison case studies (summarized in Table 5).

4.4.5. Wave Direction From CDIP Near-Shore Model and SeaSondes, 2007–2008. Mean annual wave direction was calculated from near-shore model wave results obtained from CDIP buoys at the 15 m isobath located immediately offshore from the SeaSonde locations (see Figure 16). Annual mean

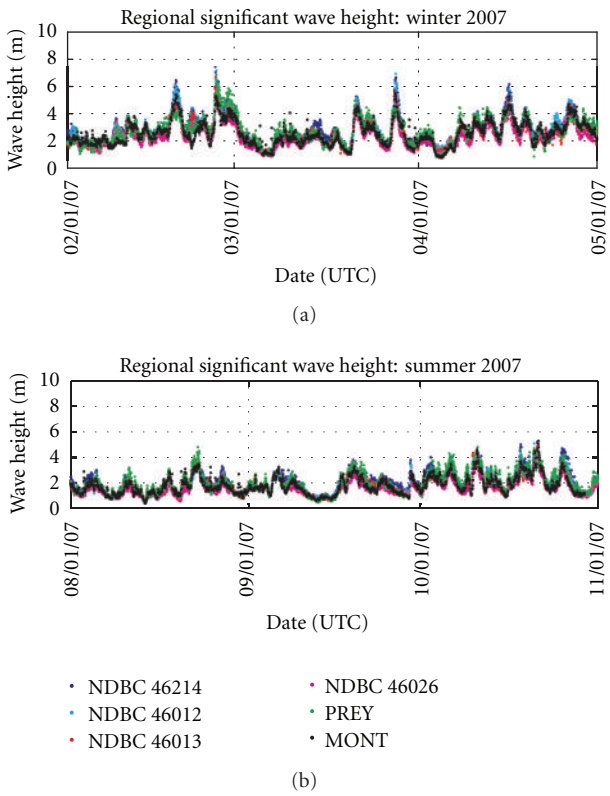

Figure 15: Regional buoy versus regional SeaSonde seasonal wave height comparison plot; top shows winter 2007 and bottom shows summer 2007.

wave directions from the CDIP near-shore model closely match annual mean wave directions from MONT, COMM, PREY, and FORT. Differences between the model output and these SeaSondes are between 3° and 14°. The model output least correlates with the annual mean direction from BML1 where the CDIP model outputs 245° for the annual mean direction near BML1, while the SeaSonde measures 281°. This difference of 36° is explained by near-shore, wave refraction/diffraction (discussed further in the Section 5) near the 15 m isobath. This wave direction refraction is not observed by the SeaSonde system since the 15 m isobath is within a few hundred meters from shore, where SeaSondes do not collect wave data.

5. Discussion

In this section, we interpret data presented in the *Results* subsections and draw some conclusions from our study. We first address how well SeaSonde-derived wave data compare with nearby wave buoy data. Then, we set this in perspective by examining the spatial variation in wave heights off central California.

5.1. Validation of SeaSonde-Derived Wave Data. Comparing wave data obtained from SeaSondes and buoys helps us gain a better understanding of instrument variability *vis-à-vis* spatial variability in wave height over the region. By analyzing long-term results presented here, we can typify the wave field in this region using different sensors and determine the reliability of the measurements. Results from comparisons among buoys, SeaSondes, and SeaSondes-to-buoys are discussed below.

5.1.1. Buoy-to-Buoy Comparisons. Moored wave buoys have been widely accepted as reliable devices for ocean sea-state measurements. NDBC and CDIP operate a wide network of buoys moored near-shore and offshore in the northern/central California region, as well as around the world. Four wave buoys located in our region of study are used as "candidates for sea truth" when analyzing sea state in the region. Therefore, one important comparison was to first determine if wave measurements among closely and distantly spaced buoys—both offshore and along shore—revealed similar sea-state results, with data averaged over an hour and time scales spanning greater than one year.

Sea-state wave-height comparison results between all buoys—near-shore, offshore, and distantly separated buoys—revealed strong correlation ($R > 0.90$) over timescales spanning more than one year. Comparisons between near shore buoys (46013 & 46026), located less than 25 km from shore, and then between offshore buoys (46214 & 46012), located 50–75 km from shore, have the lowest RMS differences and lowest mean differences. The higher RMS differences and mean differences of the buoy comparisons occur when comparing a near-shore buoy to an offshore buoy (46026 versus 46214, 46026 versus 46012, and 46013 versus 46214), although the "higher" RMS differences are all below 70 cm. There is a slightly higher correlation and less variability when comparing buoys located within a similar distance from shore, which is consistent with natural sea-state processes. Overall, all buoy-to-buoy correlations are strong ($R > 0.90$), RMS differences are low (<70 cm), but overall mean difference is slightly higher (MD > ±33 cm). When the buoy errors reported on the NDBC website are included (standard deviation 20 cm—http://www.ndbc.noaa.gov/), their contribution suggests that two buoys side by side could see RMS differences of 28 cm, based on the fact that they making independent measurements and their errors are uncorrelated (i.e., the square root of the sum of the squares of 20 cm).

These findings show that the buoys discussed here, located within 100 km of shore, are indeed consistent (within the reported buoy errors themselves discussed above) over the region and provide an accurate source for sea-state measurements and can serve as "candidates for sea truth" when comparing to other wave sensors.

5.1.2. SeaSonde-to-SeaSonde Comparisons. All SeaSonde-SeaSonde comparison case studies revealed very similar results, with R between 0.86 and 0.89 and RMS differences between 43 and 54 cm. Naturally, some local and temporal variability exists, but these long-term, summarized results are very similar to buoy-to-buoy and SeaSonde-to-buoy comparisons discussed later. Specifically, mean RMS difference is exactly the same as calculated for buoy-buoy comparisons (50 cm), and the average mean difference and

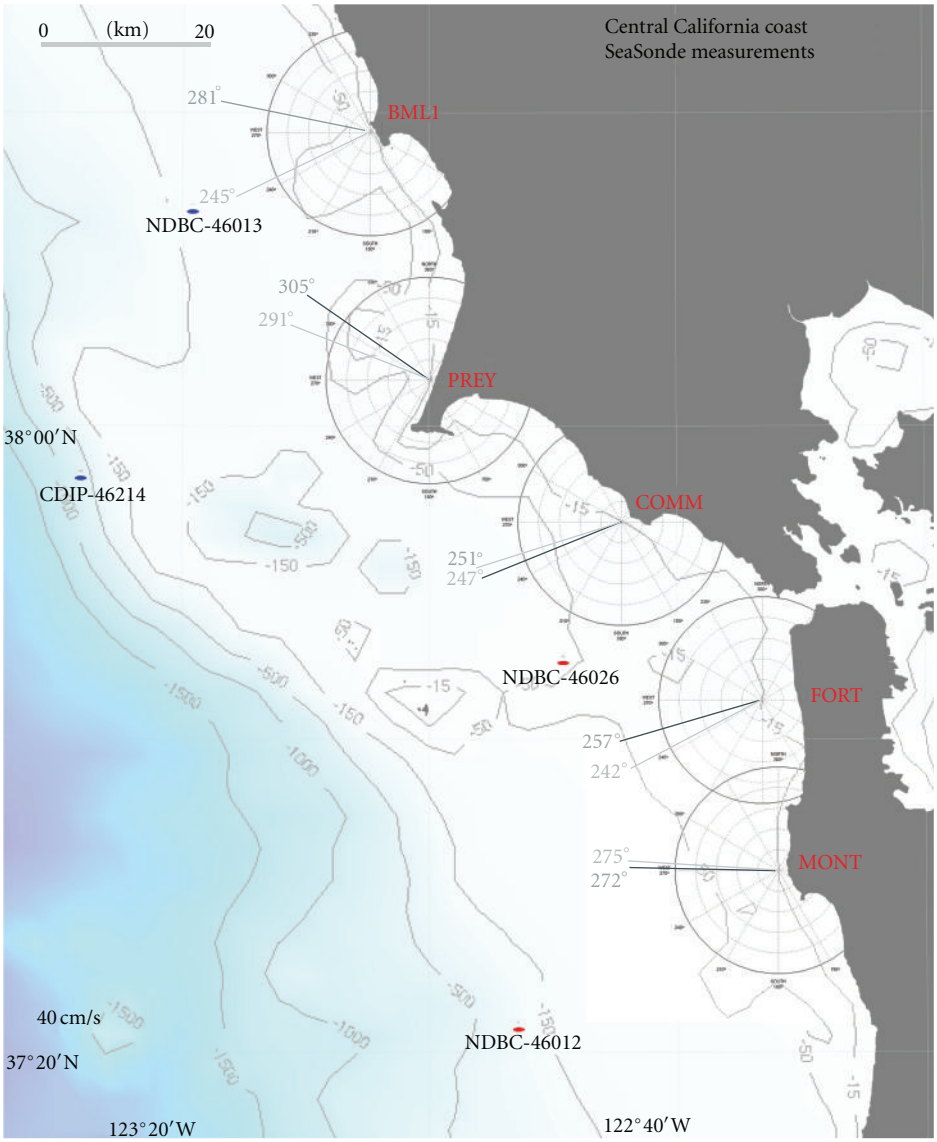

Figure 16: Annual mean wave directions for 2007 calculated from SeaSonde wave data (dark grey) and near-shore CDIP model annual mean wave direction results (light grey).

overall mean standard deviations are also close to buoy-buoy and SeaSonde-buoy comparisons. All case studies show the same trends for events in significant wave height over both long time scales and shorter time scales, all of which quantitatively justify the argument that the observational network of SeaSondes and buoys is independently measuring the regional sea state accurately.

5.1.3. Seasonde and Buoy Range Comparisons. The bottom two rows of Table 2 summarize regional spatial variation from all SeaSondes and buoys, respectively. We took the range average from each SeaSonde data set (used in SeaSonde-to-buoy comparisons) and averaged all sites together for a "regional CODAR" wave height data set to compute a regional SeaSonde significant wave height mean. This regional SeaSonde average of wave height from all five systems comprised 4,634 hourly points, of which 85% of points varied less than 50 cm over the region. The same was done for the buoy data; all four buoy datasets were averaged over the region to produce a "regional buoy" wave height average. We found that 89% of 9,884 matched buoy points show less than 50 cm variation over the region.

Together, these wave-height versus distance offshore comparisons of SeaSonde and buoy data show that the wave height varies little within 3 km–45 km. We discuss this finding in further detail in Section 5.2.

5.1.4. Seasonde-to-Buoy Comparisons. With buoys established as "candidates for sea truth." we can begin to interpret and compare wave data obtained from land-based SeaSondes to buoys. Inherently, SeaSondes measure waves in a different way than buoys. Wave buoys give a point measurement,

while SeaSondes give wave data averaged over range rings; wave buoys measure waves by moving with the waves on the ocean, while SeaSondes derive the wave information from backscattered sea echo over kilometer-scale areas. However, despite these differing methodologies, we have shown here that SeaSonde wave measurements correlate very well with nearby buoy measurements on hourly averaged time scales.

SeaSonde wave heights from individual sites were compared to nearby regional buoys discussed in Sections 3 and 4 (see Table 5). The best comparisons resulted from the PREY versus 46013 comparison and MONT versus 46026—the first being one of the longest SeaSonde-to-buoy comparisons in our study, and the second having the largest span of SeaSonde wave data coverage. These studies revealed correlation coefficients equal to or greater than 0.90 and RMS differences below 50 cm.

The worst comparison was between FORT and 46026, giving $R = 0.85$, and the only RMS difference greater than 49 cm. This comparison yielded the lowest overall correlation coefficient, and the highest RMS difference, mean difference and standard deviation of all SeaSonde-buoy comparisons. These results are still acceptable, given the duration of the comparison, and are similar to results reported from the 46026 versus 46214 buoy case study.

The MONT site was compared to a near-shore buoy (46026) and an offshore buoy (46012) to determine if comparison results differed similarly to near-shore versus offshore buoy-to-buoy comparisons. Both comparisons revealed strong correlation and low RMS differences. The only notable difference between these comparisons—and the FORT versus 46026 comparison—is the larger negative mean difference between the SeaSondes and 46026. This larger negative mean difference indicates overall lower significant wave heights from 46026. The lower wave heights at 46026, and thus higher negative mean differences, is due to sheltering of 46026 by Point Reyes. We make a point to address slight differences in height due to sheltering in Section 5.2.1, as its affect is apparent in our results throughout this study.

The COMM versus 46026 case study was particularly interesting because the buoy was located within the radar coverage area. One might conclude that this case study would reveal the best comparison results given the data sets are collocated. We do see the lowest significant wave height RMS and mean difference; however, all other comparison parameters for wave height and period do not stand out as better amongst the other SeaSonde-buoy comparisons. Thus, in this instance, there does not seem to be compelling evidence in this study that collocation of instruments provides any additional comparison accuracy. An additional study could be conducted with multiple buoys within a radar's footprint to more solidly determine these conclusions.

Results of all six SeaSonde-to-buoy comparisons yielded strong wave height correlations, low RMS differences, mean differences, and standard deviations. Overall, mean RMS difference results from SeaSonde-to-buoy comparisons are on the same order as buoy-to-buoy comparisons, yielding 53 cm and 50 cm, respectively. Mean differences are lower overall in SeaSonde-to-buoy comparisons, yielding an average mean difference of ±20 cm, compared to the average mean difference of ±33 cm for buoy-to-buoy comparisons. The mean SeaSonde-to-buoy correlation ($R = 0.88$) is slightly lower than the mean buoy-to-buoy correlation ($R = 0.94$), but all correlations are positive. Further, we expect that SeaSonde-to-buoy comparisons would reveal slightly lower correlations than buoy-to-buoy and SeaSonde-to-SeaSonde comparison case studies due to the inherent nature of their different measurement methodologies. Hence, this perhaps reveals a real sensor measurement difference that should be inspected in a different study.

5.1.5. Interpretation of Wave Periods among SenSors. It must be emphasized that there are three definitions of periods at play within these buoy/SeaSonde comparisons. Buoys output dominant period, which is the inverse of the frequency of the maximum in the wave-height spectrum; some buoys also output an average period, defined "as the square root of the ratio of the zeroth spectral moment to the second spectral moment." SeaSondes output a period that represents the centroid of the model being fitted to the second-order Doppler spectrum. This is expected to be a more stable period estimator than the buoy dominant or peak period, which is a noisy estimator as shown in our comparisons among buoys because the centroid represents a fit of the smooth spectral model to the entire wave spectrum. The buoy average period is a stable estimator, like our centroid. They are different because the average favors higher wave frequencies. The SeaSonde centroid model fit does not adequately represent the situation where both swell and wind waves are present, which the buoy methods do in some cases. Wave spectra available from some buoys allow clear analysis and separation of swell and wind waves when they both are present. The centroid period is expected to always fall between the two buoy period estimators. Let us see how these expectations are borne out by the measurements.

In SeaSonde-to-buoy comparisons, the SeaSonde's centroid period indeed falls in all cases between the buoy's dominant and average period. This is seen in Table 5 by comparing mean differences.

The buoy dominant period estimator is seen to be such a noisy parameter as to render its use for any purpose questionable. Comparing among buoys in Table 4 shows that its standard deviation among the four buoys is about 2.3 seconds. Because dominant period is always longer than the average period from buoys, it sometimes represents swell when swell is present. However, its utility as a precise parameter is cast in doubt by its large statistical uncertainties. Compare this to the mean differences among buoy dominant periods, which is 10% of its standard deviations and RMS differences. That this dominant period measurement is noisy is not surprising. The spectral energy in the frequency bins near the peak region has variances equal to their means—they are chi-squared random variables with two degrees of freedom. Barrick [9] has developed statistics for tracking the peak of these fluctuating frequency bins and showed it to be a noisy quantity unless averaged. Thus, this dominant period noisiness is reflected in the RMS and standard deviations between radar and buoy comparisons, rendering

them relatively meaningless beyond the mean differences, which indeed are useful.

The SeaSonde centroid period is a less noisy indicator, as seen from its standard deviations in Table 3, which average about 1 second. Meaningful inferences about sheltering effects on period from the data are not possible based on our present analyses, with a single number representing the entire wave spectrum. Physical principles dictate that waves of lower frequency and longer wavelength/period (whether water or electromagnetic waves) diffract more and are sheltered less than higher-frequency, shorter-wavelength ones. We recommend a future study of sheltering based on wave period, as it should see such effects among the buoy and SeaSonde locations.

5.2. Spatial Variation of Wavefields and Dependence on Coastal Influences. Having thoroughly evaluated results presented from buoy-buoy, SeaSonde-SeaSonde, and SeaSonde-buoy comparisons, we find that comparison results reveal exceptionally well-correlated significant wave-height events from multiple sensors spanning 100 km from north to south and 45 km east-to-west over time periods greater than one year. In general, this indicates that this coastal region exhibits minimal spatial variation in wave height and period. The remaining discussion focuses on those points of variability observed from the results obtained in this study.

By spatial variation, we mean the statistically significant variation of wave parameters over some distance. Because HF radar data samples represent measurements over cells at least 2-3 km in size, they constitute a statistical average over areas of this size; unlike buoys, HF radars cannot see individual waves. Therefore, spatial variability, as we use the term, extends beyond the 2-3 km radar cell span and implies an hourly time sampling.

We suggest four sources of spatial variation in the wavefield that one can encounter over tens of kilometers. (1) Fetch: wind wave development requires a given distance, called fetch, related to its speed and time duration to achieve full development. Over shorter spans than the "fetch," the wave height can vary spatially. (2) Shallow water: when waves move into shallow coastal waters, their direction, wavelength, and ultimately their height change. (3) Sheltering or diffraction: coastal promontories can partially block or change the down-field wave parameters from what they would have been in the promontories' absence. (4) Strong horizontal current shears: parameters of waves propagating across such strong shears will change.

Of the four sources above, only sheltering (3) is a likely source of spatial variation in onshore-propagating wave parameters seen over these distances off the California coast, for the following reasons.

(i) Fetch for onshore, higher waves described in (1) above will be much greater than the 100 km distances studied here; fetch relationships were well establishedduring the period of World War II by Pierson, Neuman, and James as summarized in Kinsman [7].

(ii) Shallow water off California (and most other coastal locations), as it can affect a high-frequency (HF) radar, would cause changes within the closest 3 km strip off the coast. For this and other reasons, we exclude the closest range cell from analysis here. Beyond the very first range cell, the shallow water therefore cannot produce observable variability.

(iii) Strong horizontal shears, sufficient to change wave properties, are a very rare occurrence and usually appear in well-known locations. For example, the Gulf Stream flow east of Florida is an example of such wave-changing shears; steep waves in the Columbia River mouth are an example on the west coast.

5.2.1. Sheltering Effects on Wave Height Variability by Coastal Features. There are two effects that might cause variation of onshore wave heights seen by radars at different locations: blockage by promontories within the path of waves traveling toward the radar and local cutoff due to the tangent to the coastline at the radar site itself (i.e., HF signals do not propagate over land). For a buoy, only the first effect could come into play. Neither of these effects can be calculated precisely quantitatively. The "shadow" from a promontory is always fuzzy as, for example, it is well known that longer swells will diffract better around coastal prominences into areas not along the line-of-wave propagation. Hence, we can at best allow for the possibility of some blockage and then see if the wave height variations observed are consistent with physical expectations. *It should be noted that for this part of the west coast, the strongest waves on average emanate from the northwest (NW) to NNW* (the northwesterly winds at these latitudes as well as the significant North Pacific storms explain these dominant wave directions). With this knowledge, let us look at the sensor-to-sensor mean wave height difference variations. In all cases, about 9,000 or more observations were used for each comparison case. Results came from Table 3. See Figure 1 or Figure 16 with respect to sheltering effects discussed below.

(i) SeaSonde Comparison Case Studies. (a) BML1 versus PREY: Point Reyes has a clear view to the north and NW, while BML1 is cut off by local coastline angles clockwise from NNW. Hence, Pt. Reyes should in general see slightly higher wave heights than BML1. The mean wave height difference is −26 cm, with Pt. Reyes giving the slightly higher average wave heights, as expected.

(b) MONT versus PREY: Montara sits south of Point Reyes. Both the coastline angle at Point Reyes and the sheltering of Montara by the protrusion of Pt. Reyes suggest that the latter should see higher wave heights. Indeed, Pt. Reyes sees (on average) 21 cm higher wave heights than Montara.

(ii) Buoy Comparison Case Studies. Of the five buoy comparisons conducted in this study, we focus on the two that have the largest mean differences (Table 4).

(a) 46026 versus 46214: the latter is farthest out to sea and farthest north. Hence, it should see higher waves. The mean difference is −55 cm and indeed shows higher waves on average at 46214. Since 10,916

observations were used in this comparison, this result is statistically significant (i.e., random error in a sample of 10,000 would be the reciprocal of the square root of this number: 1% of the −55 cm mean difference).

(b) 46012 versus 46026: the latter is more sheltered by waves from the NNW by the protrusion of Point Reyes. As expected, the latter sees average wave heights that are 36 cm lower than those from 46012, that is less sheltered. 12,537 measurements were used.

(iii) Overall RMS Difference Comparisons. Recall that RMS difference includes both the mean difference plus its standard deviation. Overall, mean buoy-buoy, SeaSonde-buoy, and SeaSonde-SeaSonde RMS differences are, respectively, 50 cm, 53 cm, and 50 cm. Differences among these are minimal—on the order of 5 cm. It is therefore difficult to make a case that the buoys are significantly more accurate than radars, or *vice versa*. Or, that the spatial variation inherent in these sensor measurements at different points within a 100 km span along and out from the coast is statistically meaningful, especially when the sheltering and coastline blockages discussed above are taken into account.

5.2.2. Sheltering Effects on Seasonde and CDIP Mean Directional Differences. Because not all of the buoys provided wave direction at the time of this study, we employ the SeaSonde-SeaSonde comparisons of Table 3 and comparisons of mean annual wave direction results from the CDIP near-shore model to discuss the meaning of measured differences in terms of sheltering and coastline angles.

The statistics presented in Table 3 represent thousands of measurements spanning all seasons well beyond a year, and hence mean direction comparisons give an overall, "all-period" behavior, rather than specific case studies that might focus on individual long-period, storm events.

In the summaries of the statistics in Table 3, we do not calculate nor provide standard deviations for direction measurements. This is a meaningless quantity when applied to direction, unlike the mean directional difference itself. The reason is that when the wave energy/height tends to zero, wave directional difference increases, becoming indeterminate. This is comparable to the increasing, random directional fluctuation of a weather vane when the wind speed drops to zero.

(i) SeaSonde Comparison Case Studies. Both BML1 and PREY sites are north of the sheltering effects seen by the sites south of Pt. Reyes. Hence, the only reason for real differences might be the local coastline angles at the radar sites that limit their view. In that respect, BML1 has a coastline angle of 335°, while PREY's is 020°. Thus, PREY should see waves with an average direction closer to north, that are cut off from BML1's view; indeed it does, with a mean difference between the two of −14°.

All sites south of Point Reyes (i.e., FORT and MONT) suffer sheltering due to the protrusion of Point Reyes to the west, cutting off waves from the NW. The cutoff of FORT by Point Reyes is about 305°, while MONT —further south—is cut off at about 320°. Despite MONT and BML1 having the same local coastline angle of 335°, MONT is predominately sheltered from northwesterly swell due to Point Reyes. Indeed, BML1 sees waves on average that are 23° closer to north than does MONT, due to this sheltering effect on MONT by Point Reyes.

PREY, on the other hand, sees much further to the north than does BML1 and MONT (coastline angles, resp. are 020° and 335°). But the sheltering of MONT by PREY further blocks waves that it can see. Hence, the mean difference is even greater, −34°, coinciding with our expectations that these two sites (PREY and MONT) should have the greatest reason why the former should see waves more from the NW, NNW, and N—contributing to its directional bias to the north, as well as higher wave heights as discussed and compared earlier. Finally, even though both MONT and FORT are sheltered by waves from the NW, FORT is more sheltered (320° for FORT compared to 305° for MONT). But, in addition, MONT's local coastline angle (335°) also favors waves further to the north than does FORT's (305° coastline angle). These two effects compound, to give a mean difference of 21°, with MONT seeing more waves approaching from the north.

Conclusions drawn above are further confirmed with near-shore modeled wave data provided from the CDIP model (Figure 16), discussed below.

(ii) CDIP Near-Shore Model Wave Direction Comparisons. Annual mean wave directions for 2007 from the CDIP model show that indeed, as predicted, wave direction is observed to originate from the north and northwest, but wave directions vary locally from location to location due to coastal protrusions.

The CDIP model annual mean wave direction output near PREY is 291°, which shows that it is more exposed to dominant northwesterly swell; whereas the annual mean CDIP wave directions output near COMM and FORT are 251° and 242°, respectively. These latter two locations are clearly protected from more northerly swells, so the annual means reveal waves approaching more from the southwest, as one might expect due to coastal protrusions. SeaSonde-derived annual wave direction means from COMM and MONT differ from CDIP model mean wave directions at the nearby 15-m isobath by only 1-2°. PREY and FORT also agree well with the CDIP model annual means, with annual wave directional differences of 14°.

The annual mean wave direction calculated from SeaSonde wave data at BML1 is 297°, which sees the dominating northwesterly swell at its relatively unprotected shoreline. However, the CDIP model results show a mean wave direction of 245° at the 15-m isobath. This large mean direction disagreement between the two datasets at this location is explainable by considering fundamental near-shore wave dynamics. The disagreement is likely attributed to the closeness of the 15 m isobath to shore. At this location, the 15 m isobath is located only 450 m from the shoreline. As waves approach shore, refraction orients the longer wave trains to

approach shore in an orthogonal orientation to the isobath. Thus, in this location, it makes sense that the SeaSonde, measuring waves much further out, from 4 km to 18 km offshore, where sea waves are not yet significantly affected by bottom wave refraction, obtains a more northwesterly orientation of 297° for wave direction. While at the same time, the CDIP model produces very near-shore wave direction results revealing a south westerly wave direction orientation of 245°, which is nearly a perfect orthogonal orientation to the 15 m isobath, located 450 m from shore. This also lends strong credence to the ability of the CDIP wave model to correctly account for shallow-water refraction in its predictions. As one would expect in a sea-state region with minimal spatial variability, wave directions from the CDIP model at near-shore locations closely resemble annual mean wave directions calculated from SeaSonde wave data. We have shown here that the only variation between the two data sets occurs when waves approach very near shore, where shallow-water wave effects dominate, with the SeaSonde excluding this region from its analysis because it is too close to the radar.

5.3. Interpretation of CoV (Coefficient of Variation). Statistical fluctuation of wave parameters, in particular significant wave height, is of interest in assessing the nature of sensor or measurement errors. For instance, when comparing differences among the same or different sensors at the same time, are the RMS differences or standard deviations constant? Or, do they depend on the mean wave height being measured? This might be of concern in a product specification, that is, whether to describe accuracy in terms of wave height (e.g., 30 cm) or in terms of a percentage of wave height.

The results presented here in figures and tables suggest that it is a percentage fluctuation. It is statistically the same among the different instruments (buoys, radars), as well as among different range cells from the same radar. More important, hourly time series of CoV (standard deviation divided by mean) show essentially no correlation with the actual significant wave height (refer to Table 2, and compare Figures 3, 4, 5, and 6). Thus, going forward, a percentage of wave height is the more appropriate descriptor of the random fluctuation (noisiness) for significant wave height.

6. Conclusions

In this analysis of unprecedented depth and scope of wave data from SeaSondes, buoys, and model directional wave data in the central California region spanning over up to 2.5 years, we have accomplished two goals: (1) we have presented strong evidence that SeaSonde-derived wave data should be considered a reliable and practical enhancement to wave data provided by point-measurement wave buoys, especially near shore, and where SeaSondes are already in use; (2) we have concluded that the wave height is only minimally variable from 3 km to 45 km off the central California coast. These findings are supported by summary statistics—for both radars and buoys—the mean spatial standard deviation in wave height being less than 35 cm, with a mean coefficient of variation less than 0.17 over the 150 × 45 km regions spanned by radars and buoys.

Further, with the long-duration SeaSonde and CDIP model wave direction data sets, we have helped confirm both the SeaSonde and CDIP model's abilities to report wave direction near shore, and that coastal protrusions affect local long-wave direction.

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