

VALIDATION OF GEOSAT ALTIMETER-DERIVED WIND SPEEDS AND SIGNIFICANT WAVE HEIGHTS USING BUOY DATA

GEOSAT radar altimeter-derived wind speeds and significant wave heights are compared with those measured by buoys in the National Data Buoy Center network. Measurements from a subset of 43 buoys moored in coastal regions and deep within the North Pacific, North Atlantic, and Gulf of Mexico were examined. Altimeter comparisons were obtained during the GEOSAT geodetic mission from May through August and October through December 1985. Only GEOSAT data within 150 kilometers of buoy locations were accessed, resulting in 1166 wind-speed and significant-wave-height pairs. An error analysis was performed to better understand the differences between altimeter- and buoy-derived results and to establish consistency between the two data sets. Four algorithms relating altimeter radar cross section to ocean-surface wind speed were investigated. Measurement goals for GEOSAT were 1.8 meters per second rms for wind speeds of 1 to 18 meters per second and 0.5 meter rms for significant wave height, or 10 percent, whichever was greater. These goals were met.

INTRODUCTION

Wind speed and direction over the world's oceans are required as inputs to meteorological and wave-forecasting models and are desirable inputs to ocean-circulation models. While winds are measured regularly and accurately over land areas, winds over the ocean are much more difficult to measure. The National Oceanic and Atmospheric Administration uses 2000 to 4000 reports per day from buoys and widely scattered ship reports. GEOSAT data in the reporting system add over 50,000 global values per day to that total, with the following potential benefits:

1. Improved tropical and extratropical storm analyses result in increased warning time for hurricanes and winter storms;
2. Improved initial conditions for regional, hemispheric, and global numerical models result in improved forecast accuracies;
3. A homogeneous, global set of wind and wave data that improves estimates of seasonal and annual variations for climate research;
4. Wind data for deriving wind-driven currents within the right time frames to produce yield predictions for improving fisheries management and increasing fish catches.

Radar remote sensing requires an understanding of the relationships between the signal the instrument is measuring and the physical characteristics of the medium

from which the signal backscatters. In many cases, these relationships can be established by quasi-empirical means with the aid of in-situ measurements. The determination of ocean wind speed and significant wave heights from GEOSAT radar altimeter measurements represents such a case.

Two parameters that can be derived from the altimeter measurements are ocean-surface wind speed and significant wave height. Wind speed is related to backscattered power, and significant wave height is determined from the slope of the leading edge of the returned pulse. Algorithms used to extract these parameters and the associated accuracies of these algorithms are addressed here.

We first describe results of a simulation conducted before the GEOSAT launch. We next show comparisons of wind and wave measurements with buoys, and then describe the errors inherent in any comparison of the two instruments.

VALIDATION APPROACH

Before the GEOSAT launch, computer simulations were performed to predict the number of expected comparisons and the time periods required to obtain enough samples for statistical confidence levels.¹ The simulations involved "flying" the altimeter over the buoy network and determining the number of times the altimeter ground tracks were within 150 kilometers of buoy locations and within 30 minutes of measurement.

Since the overflight of GEOSAT rarely coincides with either buoy measurement times or locations, there almost always exist temporal and spatial separations between paired GEOSAT and buoy observations. Because the buoys used in this study report every hour, time separations are never greater than 30 minutes. The validation

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strategy limits spatial separations to a maximum of 150 kilometers. Typical histograms of the number of potential comparison pairs as a function of these simulated time and space separations for a given buoy during April to June are shown in Figs. 1 and 2. Figure 3 shows the typical pattern of ground tracks laid down by GEOSAT within a 150-kilometer radius of a buoy over the same time period. The ordinates of Figs. 1 and 2 represent the number of altimeter/buoy comparisons within the indicated abscissa range and time separations, respectively. In Fig. 1, a "hit" represents the closest approach distance between the satellite subtrack and the buoy location. In Fig. 2, a hit represents any case for which the closest approach distance is within 150 kilometers. We note from Fig. 1 that for any given buoy, a relatively small percentage of the total number of hits occurs within 50 kilometers. We also note from Fig. 2 that the distribution of time separations is for the most part uniformly spread over the 30-minute period. The histograms of Figs. 1 and 2 further show relatively few satellite and buoy observations that coincide either in time or space

over a 90-day period. Ideally, comparisons should be made using only those data sets that are coincident in time and space.

The total number of hits corresponding to maximum separation distances of 50 and 150 kilometers is given in Table 1 for 43 buoy platforms located in different regions of the world. These were obtained for the period April through June. Table 2 gives similar information for those buoys that also measure wave height.

Buoys located at higher latitudes in the Pacific have slightly larger numbers of hits, and buoys in the Gulf of Mexico have somewhat fewer hits. If only buoy data taken within 50 kilometers of the GEOSAT ground track are used, the total number of observation pairs available for performance evaluation is about 1500 per year. If all GEOSAT observations within 150 kilometers of a buoy are used, the total increases to about 4000 per year. Experience with actual data sets has indicated that this total is significantly reduced, the dominant reason being the elimination of measurements made by buoys that are very close to land.

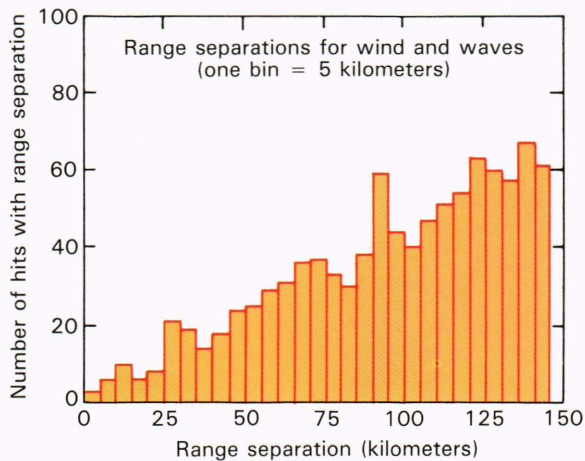


Figure 1—A histogram of hits for range separations between altimeter ground-track positions and buoy 44005 over a three-month period. A hit is defined as a ground-track buoy separation distance less than 150 kilometers.

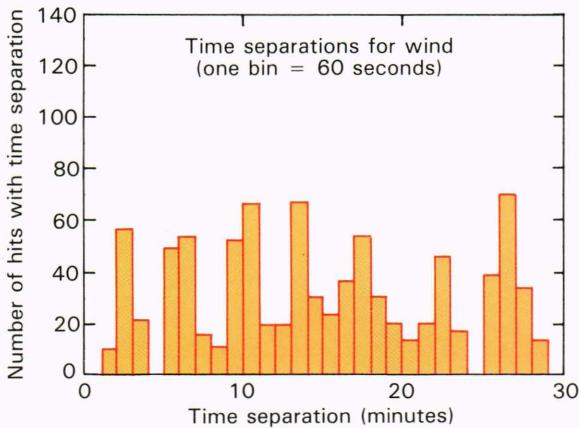


Figure 2—A histogram of time separations corresponding to altimeter hits over a three-month period for buoy 44005.

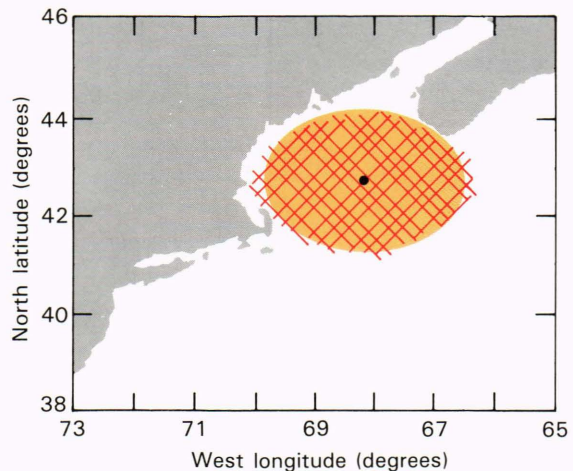


Figure 3—A map showing predicted ground tracks of the GEOSAT altimeter within a 150-kilometer distance from buoy 44005 over a three-month period.

Table 1—Number of GEOSAT/buoy data pairs for various buoy locations during the period April through June for measuring wind speed.

Region	Number of Buoys/ Platforms	Points of Closest Approach < 150 km	Points of Closest Approach < 50 km
North Pacific	19	515	178
North Atlantic	10	250	86
Great Lakes	7	192	72
Gulf of Mexico	6	139	48
Hawaii	1	53	17
Totals	43	1149	401

Table 2—Number of GEOSAT/buoy data pairs for various buoy locations during the period April through June for measuring significant wave height.

Region	Number of Buoys/ Platforms	Points of Closest Approach < 150 km	Points of Closest Approach < 50 km
North Pacific	19	515	178
North Atlantic	8	142	69
Great Lakes	7	192	72
Gulf of Mexico	5	139	48
Totals	39	988	367

THE BUOY NETWORK OF THE NATIONAL DATA BUOY CENTER

Figure 4 shows the locations of the 66 reporting stations in the National Data Buoy Center network of buoys covering the North Pacific, North Atlantic, Great Lakes, Gulf of Mexico, and Hawaii. Most are in coastal regions but 16 are located in the open ocean. Because of land effects on coastal waters and the nature of the wind fields there, stations close to land have not been used in the effort.

All buoys in the network measure wind speed and direction, atmospheric pressure, air temperature, and sea-surface temperature each hour. A subset of the buoys also makes hourly measurements of significant wave height, significant wave period, and, in some cases, wave spectra. However, within the hour, the times of measurement and the periods of integration differ for these measurements. Wave data that are averaged for 20 minutes

are reported at 29 minutes after the hour. Winds are averaged for 8.5 minutes starting at 40 minutes after the hour. On most buoys, anemometers are located 10 meters above mean sea level. For those buoys in which wind-speed measurements were made at other elevations, a boundary layer model was used to adjust the values to 10 meters before comparison.

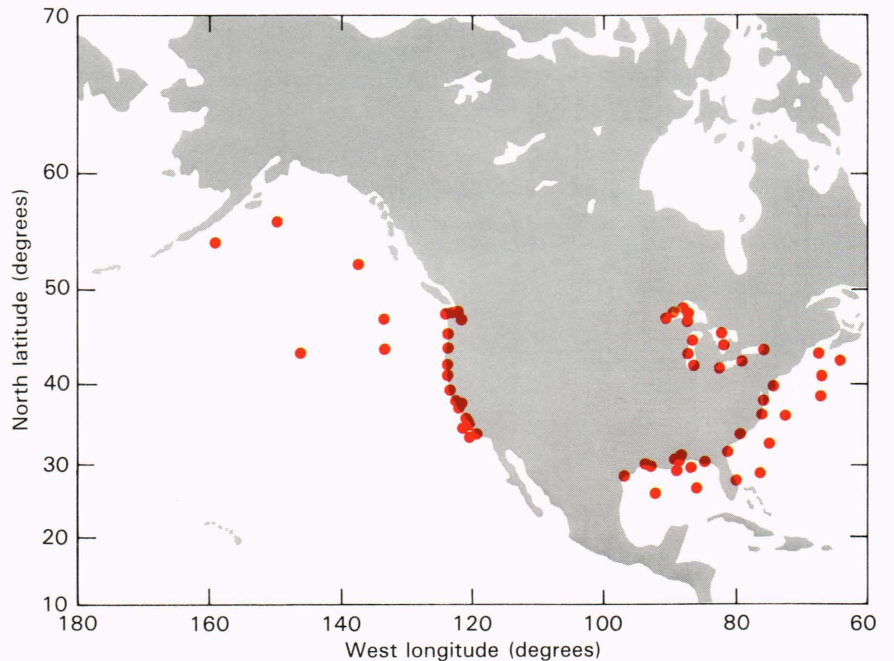
WIND-SPEED VALIDATION

Wind speed at the ocean surface is deduced from the altimeter-backscattered radar cross section. At nadir incidence angle, the energy backscattered from the ocean is directly proportional to the normal incidence Fresnel power-reflection coefficient and inversely proportional to the mean square slope of the low-pass-filtered version of the ocean surface.² The constant of proportionality in this relationship depends on the probability density of surface slopes. Cox and Munk³ measured this probability density and determined that there was a logarithmic relationship between density function and wind speed. As the winds increase, the surface slopes increase and the backscattered cross section decreases. This relationship between wind and σ^0 is based on an empirical probability density, although it does not necessarily hold at all wind speeds. The relationship is known to break down at low wind speeds when the slopes on the surface are low and the wave heights are equal to or shorter than the wavelength of the electromagnetic energy.⁴ Four algorithms that are used to infer surface wind speed from radar cross-section measurements are described below.

Brown's Algorithm

Brown et al.⁵ compared the normalized backscatter ocean cross section derived from the altimeter power measured on board the GEOS-3 satellite with wind

Figure 4—National Buoy Data Center buoy locations (shown as dots).



speeds derived from buoy measurements. In particular, 184 measurements of backscatter power were culled over an approximate three-year period; they correspond to measurements made during the “near” overflights of National Oceanic and Atmospheric Administration data buoys from which surface-wind speeds were obtained. Brown used buoy data from the North Atlantic and North Pacific taken within 1.5 hours and 150 kilometers of a GEOS-3 overpass. The resultant algorithm relating predicted wind speed to altimeter cross section is given in two stages. The first stage is given by

$$W_1 = \exp \left[\frac{10^{-(0.21 \times \sigma^0/10)} - B}{A} \right], \quad (1)$$

$$\begin{aligned} A = 0.080074 \quad B = -0.124651 & \text{ for } \sigma < 10.12, \\ A = 0.039893 \quad B = -0.031996 & \text{ for } 10.12 \leq \\ & \sigma \leq 10.9 \\ & \text{decibels,} \\ A = 0.01595 \quad B = 0.017215 & \text{ for } \sigma \geq 10.9 \\ & \text{decibels.} \end{aligned} \quad (2)$$

In Eq. 1, σ^0 is the altimeter-measured normalized backscatter cross section expressed in decibels relative to 1 square meter, and A and B assume the defined values. Here, W_1 represents the first estimate of the predicted wind speed. In comparing predicted and buoy-measured wind speeds, Brown et al. found the distribution of the difference values between buoy- and altimeter-measured wind speed to be skewed. To mitigate the skewness, a second-stage estimate of the predicted wind speed, W_2 , was given by

$$W_2 = \sum_{n=1}^5 a_n W_1^n, \quad W_1 \leq 16 \text{ meters per second,} \quad (3)$$

$$W_2 = W_1, \quad W_1 > 16 \text{ meters per second,} \quad (4)$$

$$\begin{aligned} \text{where } a_1 &= 2.087799, \\ a_2 &= -0.3649928, \\ a_3 &= 0.04062421, \\ a_4 &= -0.001904952, \text{ and} \\ a_5 &= 0.00003288189. \end{aligned} \quad (5)$$

Eqs. 1 and 3 together represent the resultant Brown et al. algorithm that corresponds to a wind-speed measurement at a height of 10 meters above the ocean surface (Fig. 5).

The Chelton and McCabe Algorithm

In applying the Brown algorithm to the Seasat database, Chelton and McCabe⁶ demonstrated that the algorithm produced a multimodal wind-speed distribution. They attributed its form to discontinuities in the slope of the wind-speed algorithm at 10.12 and 10.9 decibels.

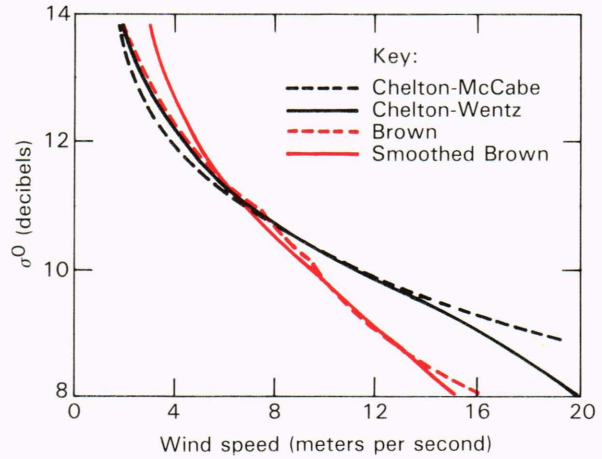


Figure 5—A comparison of algorithms relating altimeter-derived radar cross section with surface wind speeds.

Because there are no physical reasons for a multimodal distribution, they developed another algorithm given by

$$W = 10 \left[\left(\frac{\sigma}{10} - G \right) / H \right], \quad (6)$$

where

$$G = 1.502 \text{ and } H = -0.468, \quad (7)$$

and where σ^0 (the radar cross section) and W are expressed in decibels and meters per second, respectively. The values of G and H in Eq. 6 were estimated by using a regression analysis corresponding to 96 days of Seasat measurements. The values of σ^0 were derived from the Seasat altimeter, and wind speeds were estimated from off-nadir vertically polarized scatterometer returns. Both time and spatial averaging were performed within gridded regions defined by 2-degree latitude by 6-degree longitude intervals. Only data between the latitudes of 65°N and 55°S were included and only data for distances greater than 200 kilometers from land were used. Within each grid, cross sections and wind speeds were averaged in both time and space over the 96-day period; hence, each of the 1947 grids within which data existed provided a single averaged data point of scatterometer-estimated wind speed and altimeter-derived radar cross section (Fig. 5).

The Goldhirsh and Dobson Algorithm

In an attempt to eliminate the effects of discontinuities in wind-speed slope (with cross section) intrinsic to the Brown algorithm, Goldhirsh and Dobson⁷ fitted a fifth-degree polynomial to the original Brown data (184 points). The fit produced a smooth function that was nearly identical to the original algorithm but it produced no multimodal distribution. The derivation, the smoothed Brown algorithm, was considered to be a temporary solution to the problems associated with the Brown algorithm. When a larger GEOSAT/buoy database becomes available, at-

tempts to improve the algorithm will be made. The smoothed Brown algorithm is given by (Fig. 5)

$$W = \sum_{n=0}^5 a_n \sigma^n, \quad \sigma^0 < 15 \text{ decibels}, \quad (8)$$

where

$$\begin{aligned} a_0 &= -15.383, \\ a_1 &= 16.077, \\ a_2 &= -2.305, \\ a_3 &= 0.09896, \\ a_4 &= 0.00018, \\ a_5 &= -0.00006414. \end{aligned} \quad (9)$$

The condition $\sigma^0 < 15$ decibels implies that the algorithm is restricted to wind-speed values greater than 2 meters per second.

The Chelton and Wentz Algorithm

Chelton and Wentz⁸ noted several weaknesses in the wind-speed model function derived from Seasat data as proposed by Chelton and McCabe.⁶ A fundamental problem was that the scatterometer wind-speed algorithm was flawed. In addition, temporal and spatial averaging over a 2- by 6-degree grid resulted in scatterometer wind speeds limited to the 4- to 14-meter-per-second range. Furthermore, since the spatial (2- by 6-degree) and temporal (three-month-period) averages were rather large, performance of the algorithm for individual measurements was uncertain. Hence, Chelton and Wentz developed a new algorithm based on measurements of the Seasat altimeter radar cross section averaged in 50-kilometer bins in the along-track direction. These averaged values were then compared with wind speeds estimated from the nearest 100-kilometer-binned scatterometer-determined wind speeds (150 to 250 kilometers from nadir). In that way, 241,000 comparisons of radar cross sections at nadir versus scatterometer wind speeds ranging from 150 to 250 kilometers off nadir were obtained. The resultant algorithm is in the form of a tabulation over the range of radar cross sections from 8 to 19.6 decibels and wind speeds from 21 to 0.01 meters per second. The tabulation is given in Ref. 9 and is plotted in Fig. 5.

WIND-SPEED VALIDATION

The wind-speed measurement goal of the GEOSAT altimeter was specified as 1.8 meters per second rms for wind speeds over the range of 1 to 18 meters per second.⁹ One of the objectives of the validation effort was to assess whether the GEOSAT altimeter-derived wind speeds met that goal.

The GEOSAT Database

The raw GEOSAT database is received in the form of a Sensor Data Record and is combined with an ephemeris to create a Geophysical Data Record in which all instrument corrections are incorporated. One-second

averages of radar cross section and significant wave height were extracted from the Geophysical Data Record corresponding to ground tracks within 150 kilometers of 43 buoys.

In that effort, data were compiled over two periods totaling seven months—May through August and October through December 1985. The overall derived database was culled, and hits were removed on the basis of the following criteria: (a) the close proximity of buoy stations to land, (b) flagged significant-wave-height data errors on the Sensor Data Record, (c) obvious buoy data errors, (d) altimeter-height data-error flags, and (e) erratic changes of radar cross section. The resulting database after culling consisted of 1166 satellite/buoy data pairs. A subset of these measurements consisted of 698 hits corresponding to 13 open-ocean buoys, i.e., buoys located at least 40 kilometers from the nearest shoreline. These data were also stratified according to region, altimeter pointing angle, altimeter track/buoy separation distance, number of cross sections averaged, and the variability of measured cross sections in the averaging interval. Stratification by region should establish whether some areas are more suitable for comparison than others. Pointing-angle changes could play a significant role in the determination of radar cross sections, especially for calm sea conditions when the specular component is diminished in the backscatter direction as the pointing angle moves off nadir. The separation distance and averaging interval determine the spatial scales over which comparisons are valid. Radar cross-section variability is important because it indicates the homogeneity of the wind field and helps to identify those times when rain is present in the measuring area. Table 3 presents the stratification parameters used to compare altimeter and buoy data. Item 4 of the table corresponds to either a 5- or 10-point average in the cross section around the minimum range, where each “point” represents a 1-second time interval constituting a 7-kilometer ground-track distance interval. Item 5 corresponds to two levels of rms fluctuations over the averaging interval.

In the culling process, a detailed characterization of each hit was obtained through a series of plots as shown in Fig. 6. Figure 6(a) shows a plot of the buoy position (■) and the GEOSAT ground track. When land is in the area displayed, its boundaries are also indicated. Shown in Fig. 6(b) is significant wave height as measured over a 24-hour period for the day of the comparison. The colored circles in this figure indicate the air-sea temperature difference (in degrees centigrade) at the ocean surface as measured by the buoys (right-hand scale). The wind speed (colored squares) and wind gust (▲) over a 24-hour period are given in Fig. 6(c). Figure 6(d) and 6(e) give the altimeter-measured significant wave height and radar cross section as a function of range between the buoy and ground track. In the descending-pass example shown, the range starts at near 150 kilometers, reaches a minimum of 37 kilometers, and then increases again. Parameters listed in Fig. 6 correspond to the time of minimum range and represent the following: radar cross section (5-point average); wind speed from the

Table 3—Stratification parameters for comparing altimeter and buoy data.

1. Regions	
Open Pacific	
Coastal Pacific	
Open Atlantic	
Coastal Atlantic	
Gulf of Mexico	
Equatorial Pacific	
All regions	
Open ocean	
2. Antenna angle off vertical (degrees)	
0–0.50	
0–0.75	
0–1.00	
3. Range between buoy and altimeter subtrack (kilometers)	
0–50	
0–100	
0–150	
4. Number of radar cross section measurements averaged*	
Five 1-second measurements	
Ten 1-second measurements	
5. Standard deviation of radar cross section over averaging area for cases listed under item 4 (decibels)	
0.5	
1.0	

*The spatial equivalent of 1-second measurements of radar cross section is 7 kilometers along track.

smoothed Brown algorithm; wind speed from the Chelton-Wentz algorithm; buoy wind speed; GEOSAT significant wave height; buoy significant wave height; buoy number; Julian day; air-sea temperature difference; hour of altimeter pass; minimum range between buoy and altimeter subtrack; and altimeter attitude angle. Numbers to the right of these parameters represent the difference between buoy and altimeter measurements; e.g., “hour (GMT, min)” indicates that the altimeter passed at 1100 hours and that there was a 22-minute difference in time between the two measurements. Composite figures of this type were prepared for the 1166 data pairs to aid in the assessment of the temporal and spatial behavior of the wind and wave fields.

Radar Cross-Section Statistics

The global distribution of radar cross sections was obtained for two three-month periods to determine its consistency and to compare it with Seasat altimeter distributions. The distribution for October through December 1985 is shown in Fig. 7. With a bin size of 0.2 decibel,

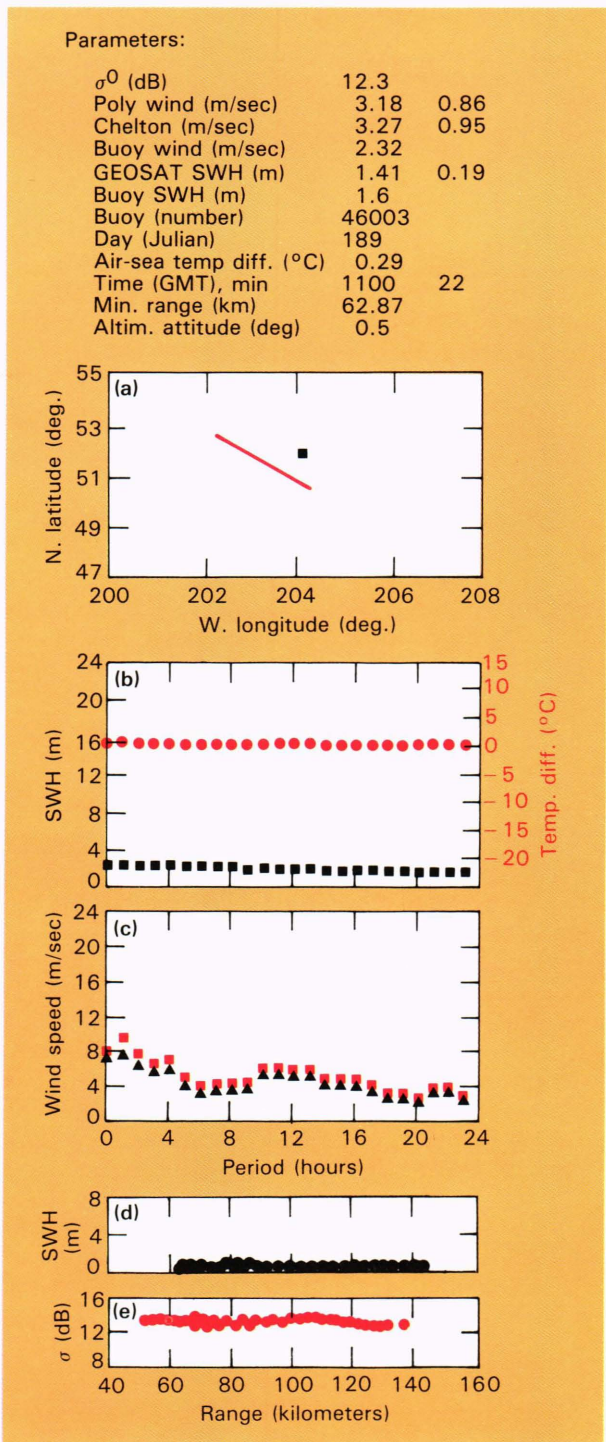


Figure 6—A series of plots describing the temporal and spatial behavior of buoy and altimeter data. A summary of pertinent data at the top of the figure includes a second column denoting the difference between buoy- and altimeter-derived measurements. (SWH is significant wave height.)

the distribution peaks at 10.9 decibels with a mean of 10.9 decibels and a standard deviation of 0.9 decibel. The global distribution from the Seasat mission had a mean of 10.8 decibels.

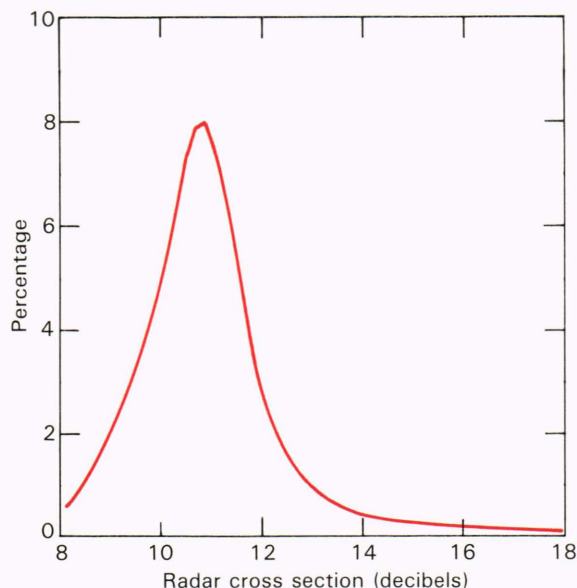


Figure 7—The distribution of GEOSAT altimeter-derived radar cross section for October through December 1985. The distribution peaks at 10.9 decibels, has a mean of 10.9 decibels, and has a standard deviation of 0.9 decibel. Seasat had a mean of 10.8 decibels.

Altimeter and Buoy Wind-Speed Comparisons

Figure 8 presents comparisons between GEOSAT altimeter-derived wind speeds and buoy wind speeds for the Brown, smoothed Brown, Chelton-McCabe, and Chelton-Wentz algorithms using all buoys (121 comparisons). The solid lines represent the perfect-agreement case and the ± 2 -meter-per-second cases. The data shown here are for a maximum range separation of 50 kilometers with 5-point averaging and an attitude restricted to less than 0.75 degree. The Brown and smoothed Brown algorithms (Fig. 8a and 8b) gave the smallest rms difference of 1.7 meters per second between buoy and altimeter measurements. These compare with 3.1 and 2.3 meters per second for the Chelton-McCabe (Fig. 8c) and Chelton-Wentz (Fig. 8d) algorithms, respectively. There appears to be an overestimation of wind speeds by both Chelton algorithms as evidenced by the means of 1.8 and 1.3 meters per second, compared to means of 0.3 and 0.5 meter per second for the other two algorithms. Very few high wind speeds were measured from buoys; they are required to truly establish the best algorithm. Several data points in Figs. 8c and 8d are not shown because they correspond to predicted wind speeds larger than the scale maximum of 20 meters per second.

Algorithm comparison results for range and attitude stratifications for both the “all buoys” and “open-ocean” ocean buoy cases (43 and 13, respectively) are summarized in Table 4. Comparisons of the mean difference wind speed and the rms difference (GEOSAT versus buoy-derived) are listed for the four algorithms mentioned above. The smallest rms differences (*) for each of the algorithms occur for range intervals of 50 kilometers or smaller. When all buoys are considered,

the best accuracy occurs when the altimeter pointing has an attitude within 0.75 degree. The open-ocean buoys do not show a strong dependence with attitude within 1 degree. In every stratification indicated, the Brown and smoothed Brown algorithms do better than the others. While ranges of 150 kilometers may be too large to assure homogeneity over an area, reducing the range to 50 kilometers severely limits the number of data points and hence introduces smaller confidence levels pertaining to the results.

VALIDATION OF SIGNIFICANT WAVE HEIGHT

The GEOSAT significant-wave-height measurement goal was set at ± 0.5 meter or 10 percent.⁹ Based on comparisons of GEOSAT-derived radar altimeter and buoy data, that goal has been met. Figure 9 shows GEOSAT/buoy significant wave heights for a shorter distance than 50 kilometers. These data are for the 43 open-ocean buoys and constitute 116 comparisons. The rms difference is 0.49 meter with a mean deviation of 0.36 meter. The rms wave-height deviations were between 0.4 and 0.8 meter for the range of off-nadir angles and range separations shown in Table 4. Mean differences are generally around +0.4 meter, indicating that the GEOSAT significant wave height is lower than the buoy level by that amount. The global distribution of significant wave heights for May is shown in Fig. 10. The mean and standard deviation of the distribution are 2.4 meters and 0.6 meter, respectively.

EXPECTED DIFFERENCES IN ALTIMETER-BUOY COMPARISONS

In comparing altimeter-derived wind speed and significant wave height with buoy estimates, it is important to establish self-consistency between the comparisons and the expected uncertainty. The following discussion focuses on five distinct error sources that will cause altimeter and buoy estimates of wind speed and significant wave height to differ: (a) buoy instrument inaccuracies, (b) temporal separation, (c) spatial separation, (d) time and area averaging, and (e) altimeter-related errors. Reference will be made to Fig. 11 describing individual sources of differences as a function of wind speed.^{10,11}

Buoy Instrumentation

The instrument error associated with buoy estimates of wind speed or significant wave height will contribute to the observed differences with altimeter estimates. Anemometers mounted on board the National Data Buoy Center network of operational buoys are specified to an rms accuracy of 0.5 meter per second or 10 percent of wind speed, whichever is greater.¹² Intercomparisons of wind-speed measurements from twin anemometers located on single buoys are consistent with these specifications. In an effort by Monaldo,¹⁰ wind speeds measured by dual anemometer systems on four buoys were examined over a one-month period, and rms differences between the pairs of anemometers on each buoy were

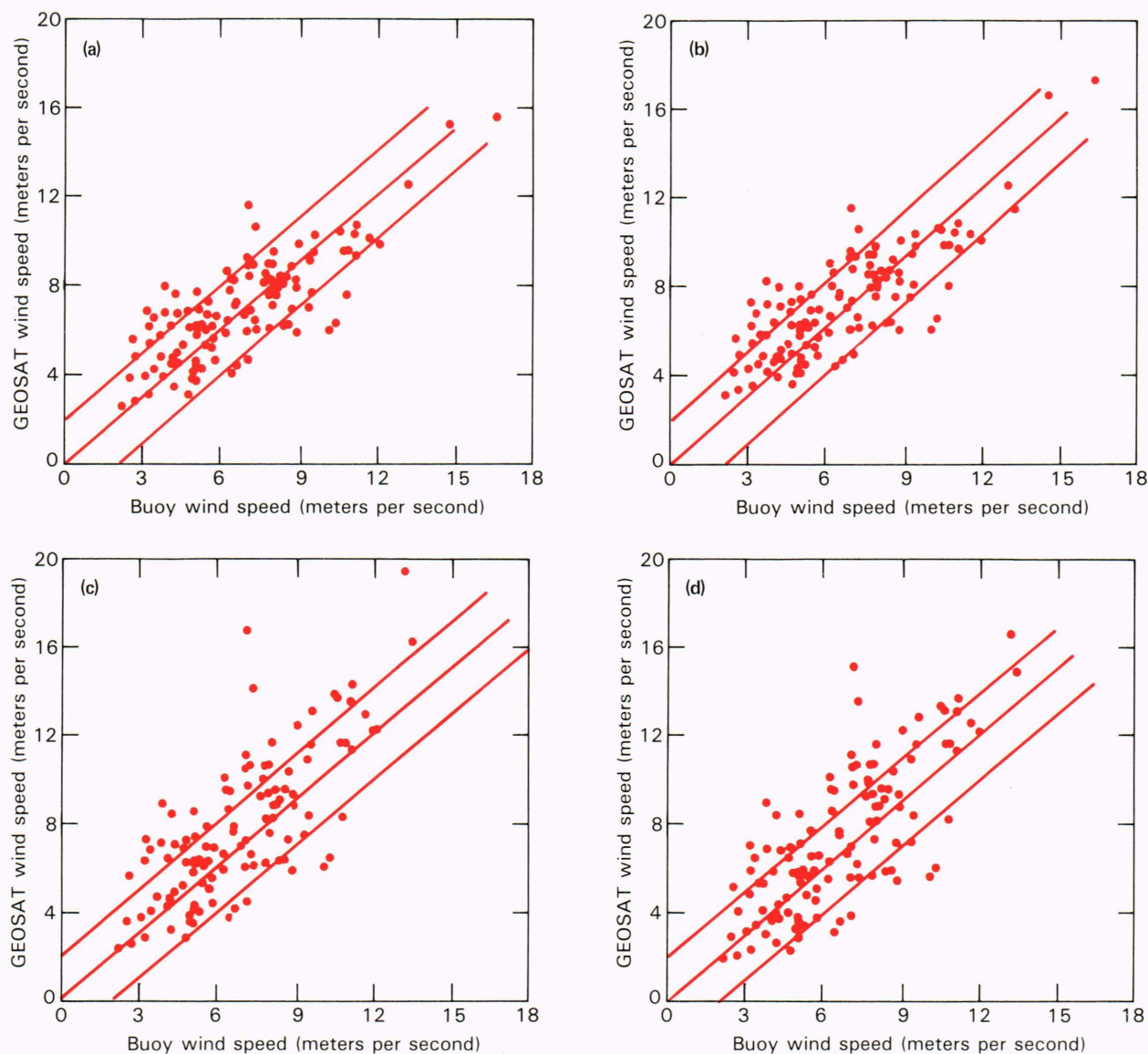


Figure 8—Wind speeds derived using GEOSAT altimeter data and (a) the Brown et al. algorithm⁵ (rms deviation 1.7 meters per second), (b) the smoothed Brown algorithm⁷ (rms deviation 1.7 meters per second), (c) the Chelton-McCabe algorithm⁶ (rms deviation 3.1 meters per second), and (d) the Chelton-Wentz algorithm⁸ (rms deviation 2.3 meters per second). In each case, the separation distance is within 50 kilometers, the altitude is within 0.75 degree, and the number of GEOSAT/buoy comparisons is 121 using 43 buoys.

found to be 0.48, 0.72, 0.49, and 0.6 meter per second. These comparisons are important in that altimeters cannot be expected to agree with buoy measurements any better than anemometers on the same buoy can be expected to agree with each other. Using the National Data Buoy Center buoy accuracy specifications and a global average ocean wind speed of 8.0 meters per second, altimeter and buoy estimates of wind speed can be expected to differ by 0.8 meter per second (Fig. 11) because of accuracy limitations on the buoy estimate of wind speed.

The accuracy of buoy estimates of significant wave heights is somewhat more difficult to specify. A dedicated experiment comparing wave heights measured by an operational National Data Buoy Center buoy with those

measured by a Waverider Analyzer Satellite Communicator buoy, which is considered a measurement standard, indicates rms differences in the estimation of wave heights of about 7 percent.¹³ This difference is shown below to be consistent with sampling variability errors. The instrument error associated with buoy measurement of significant wave heights may therefore be considered negligible.

Temporal Separation

In order to obtain a reasonably large number of altimeter-buoy comparisons, a temporal window of acceptability is established, for example, a window wherein altimeter-buoy comparisons made within one hour of each oth-

Table 4—Summary of mean and rms wind-speed errors stratified as a function of antenna pointing and closest approach range. Four algorithms are considered.

Off Vertical (deg)	Range (km)	Points (no.)	Smoothed Brown		Chelton-Wentz		Brown		Chelton-McCabe	
			Mean (m/sec)	rms (m/sec)	Mean (m/sec)	rms (m/sec)	Mean (m/sec)	rms (m/sec)	Mean (m/sec)	rms (m/sec)
All buoys (43)										
1.0	50	192	0.1	1.9	0.7	2.4*	0.3	2.0	1.1	2.8
	100	428	0.2	2.2	0.8	2.8	0.4	2.2	1.1	3.1
	150	682	0.4	2.3	1.0	3.0	0.6	2.3	1.4	3.3
0.75	50	121	0.3	1.7*	0.8	2.2	0.5	1.7*	1.2	2.8
	100	269	0.3	2.1	0.9	2.7	0.6	2.1	1.2	3.0
	150	443	0.4	2.2	1.0	2.9	0.7	2.2	1.4	3.2
0.5	50	61	0.4	1.7*	0.9	2.2*	0.6	1.7*	1.2	2.3
	100	150	0.5	2.1	1.1	2.7	0.7	2.0	1.4	2.9
	150	248	0.6	2.2	1.1	2.9	0.8	2.2	1.4	2.9
Open-ocean buoys (13)										
1.0	50	98	0.3	1.7	1.1	2.0	0.5	1.7	1.2	2.0
	100	209	0.3	2.0	1.0	2.6	0.5	2.0	1.2	2.6
	150	320	0.5	2.1	1.2	2.7	0.7	2.1	1.4	2.8
0.75	50	61	0.4	1.5*	0.9	1.9*	0.6	1.5*	1.1	1.9
	100	135	0.5	1.9	1.1	2.5	0.7	1.9	1.3	2.5
	150	207	0.7	2.0	1.2	2.6	0.9	2.0	1.5	2.8
0.5	50	31	0.3	1.6	0.9	2.1	0.8	1.7	1.1	2.1
	100	80	0.5	2.1	1.1	2.8	0.7	2.1	1.3	2.8
	150	125	0.6	2.2	1.3	2.9	0.8	2.3	1.5	2.9

*Minimum rms for the indicated category.

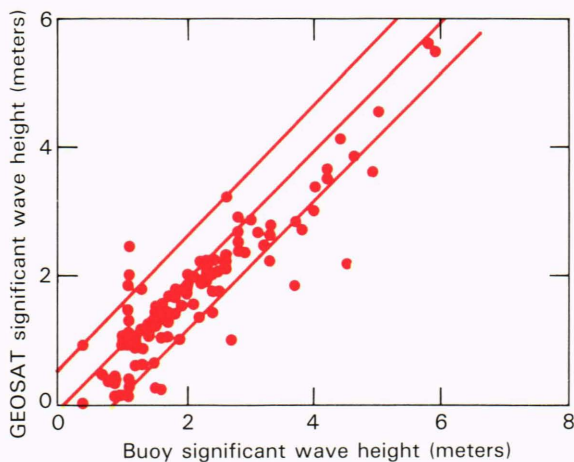


Figure 9—GEOSAT altimeter-derived significant wave heights compared with buoy measurements for a distance separation within 50 kilometers. Comparisons were made using 43 open-ocean buoys (116 data points). The rms deviation is 0.49 meter with a mean deviation of 0.36 meter.

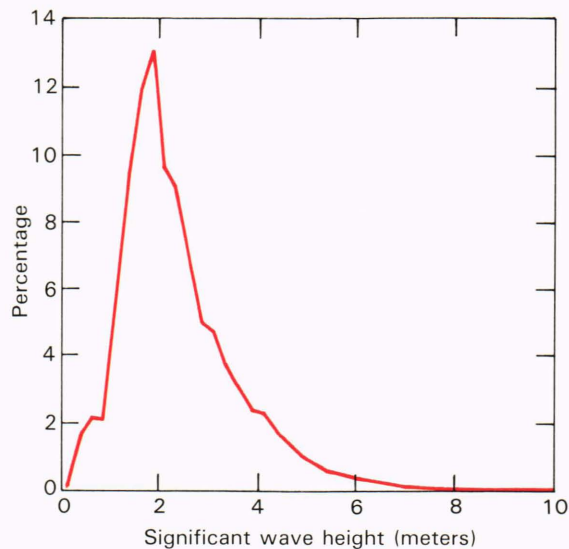


Figure 10—Global distribution of significant wave heights for May 1985. Bin size is 0.25 meters. The mean significant wave height is 2.4 meters and the standard deviation is 0.6 meter.

er are acceptable in the comparison data set. The farther apart in time two measurements are made, the larger the

difference that can be expected between the two measurements. Establishing smaller windows of acceptability re-

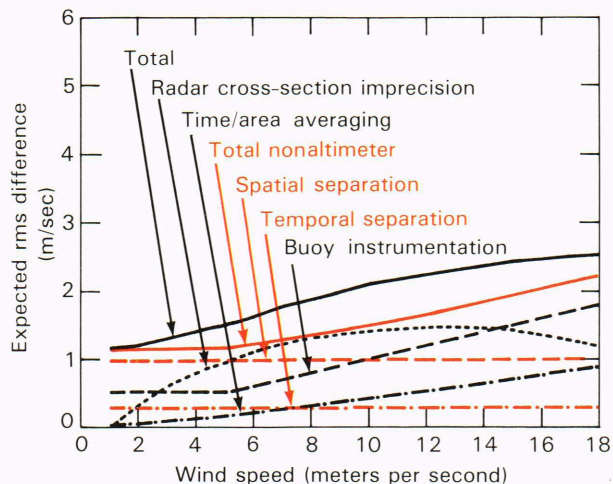


Figure 11—Plots of rms deviations versus wind speed for indicated error sources.

duces this error, but at the cost of having fewer comparisons available.

To estimate the magnitude of the expected difference between two measurements separated in time, several temporal buoy records from open-ocean buoys were examined that provided hourly wind-speed and significant wind height estimates for monthly periods. Since buoy measurements of wind speed and significant wave height are made hourly, the maximum temporal separation between a buoy and an altimeter estimate of wind speed and significant wave height is 30 minutes, with an average separation of 15 minutes. The examination of temporal buoy records indicated that the average separation of 15 minutes in buoy and altimeter estimates would cause a 0.3-meter-per-second rms difference in wind speed and a 0.1-meter rms difference in significant wave height.¹⁰

Spatial Separation

The effects of spatial separations are similar to those of temporal separations. In order to increase the number of available altimeter–buoy comparisons, altimeter and buoy measurements of wind speed and significant wave height separated by less than the spatial window of acceptability are included in the comparison data set. For example, a window of 50 kilometers would mean that every altimeter and buoy measurement comparison having a spatial separation of less than 50 kilometers that additionally falls within the temporal acceptability window is included in the comparison data set. The larger the spatial window of acceptability, the larger the number of comparisons available. Unfortunately, the larger that window, the greater the differences in buoy and altimeter measurements associated purely with the fact that the measurements are not coincident.

To estimate the effect of the spatial variability of wind and wave fields, we examined a global representation of approximately 500 Seasat and 500 GEOSAT-altimeter-derived wind-speed and significant-wave-height data

records of 3500 kilometers in length. Using the logic that we cannot expect the altimeter and buoy to agree when their measurements are separated by a certain distance any more than we can expect the altimeter estimates to agree with each other when separated by the same distance, we estimated the expected differences due to spatial separation. A 20-kilometer window of acceptability with an average separation of 14 kilometers resulted in expected differences of 0.5 meter per second in wind speed and 0.2 meter in significant wave height. Using a 50-kilometer window and an average separation of 35 kilometers resulted in expected differences of 1.0 meter per second in wind speed and 0.3 meter in significant wave height.¹⁰

Time and Area Averaging

The altimeter estimates of wind speed and significant wave height (SWH in the examples below) are the result of spatial averaging; at a given instant of time, the altimeter estimate of radar cross section is an average over a footprint diameter given by^{14,15}

$$D = 2[H c \Upsilon_e]^{1/2}, \quad (10)$$

where H is the height of the satellite (e.g., 800 kilometers) and c is the velocity of light. The parameter Υ_e is the effective pulse width given by

$$\Upsilon_e = [(N \Upsilon_0)^2 + \Upsilon_{\text{SWH}}^2]^{1/2}, \quad (11)$$

where Υ_0 is the effective chirped pulse width (e.g., 3.125 nanoseconds) and N is $1/2$ the number of sampled gates in the averaging interval (e.g., 24), and

$$\Upsilon_{\text{SWH}} = \left(\frac{\text{SWH}}{c} \right) \quad (12)$$

The estimate Υ_{SWH} is the additional contribution of the pulse width caused by ocean waves having a given significant wave height. Assuming a nominal significant wave height of 2.5 meters and the indicated GEOSAT values (given within parentheses specified above), we arrive at an effective footprint diameter of 8.5 kilometers associated with the instantaneous radar cross-section measurement. Averaging 5 and 10 seconds of altimeter data (as was done here) produces a resolution swath 35 and 70 kilometers long, respectively.

Pierson¹¹ and Donelan and Pierson¹⁶ have investigated the relationship between spatial and temporal averaging of wind speed and significant wave height, respectively. Their results suggest that the sampling variability associated with an area average is very small. Most of the differences between altimeter and buoy estimates of wind speed and significant wave height associated with sampling variability are the result of limited time averages. The 8.5-minute average of buoy wind speed is expected to result in sampling variability of roughly 0.3 meter per second in rms difference when compared with the altimeter spatial average.¹¹

Donelan and Pierson¹⁶ estimate that a 20-minute average of significant wave height would result in an 8 percent sampling variability. For a typical ocean significant wave height of 3 meters, this would imply an rms difference of 0.24 meter of sampling variability. We mentioned above that comparisons of significant wave heights estimated by buoys 100 meters apart exhibit roughly a 7 percent difference. This is consistent with the Pierson and Donelan prediction.

In Table 5, we summarize the above error sources and the corresponding rms values for both wind speed and significant wave heights. The bottom row gives the combined rms levels (the square root of the sum of the squares). We note overall uncertainties of 1 to 1.3 meters per second for wind speeds and 0.4 to 0.5 meter for significant wave heights. One should not expect to obtain rms differences smaller than these levels in comparing altimeter-derived and buoy measurements. It should, however, be stressed that these error sources do not include altimeter performance uncertainties as described below.

Altimeter Instrument-Related Errors

Fundamental error sources are also related to the accuracy with which the desired radar-signal characteristics can be measured. These characteristics are radar cross section for determining wind speed, and signature slope for determining significant wave height; given an uncertainty in the radar cross section and an algorithm that is assumed to be “true,” corresponding error values in the wind speed may be derived. A family of curves for various uncertainties in the measurements of altimeter cross sections is plotted in Fig. 12. The vertical scale represents wind-speed error and the abscissa represents true wind speed. The smoothed Brown algorithm was used in determining curves. The nominal uncertainty in measuring radar cross section is estimated to be 0.5 decibel.¹⁴ Assuming this figure and the global average ocean wind speed of 8 meters per second, the expected

error in wind speed caused by inaccuracy in the radar cross section is observed to be 1.2 meters per second.

The altimeter estimate of significant wave height is derived from the return pulse shape. Limitations on the ability of the altimeter to reconstruct the return pulse shape will cause errors in the significant wave height estimate. The return waveform is sampled discretely in “range bins.” Calibration errors for the range bins will cause errors in pulse reconstruction. In addition, Rayleigh fading noise corrupts the return pulse shape. That noise is unrelated to instrument problems but is caused by the random constructive and destructive interference of coherent radar signals reflecting off a rough surface. Generally, many waveforms have to be averaged to make good estimates of the return pulse shape. Nonetheless, errors in significant wave height associated with the inability to reconstruct exactly the return pulse shape are small. The noise levels of altimeter significant wave height measurement have been estimated at 0.03 meter.¹⁰

An additional, but coupled, error source also pertains to the uncertainty in the algorithm itself. It is apparent from Fig. 5 that the selection of the Chelton-Wentz algorithm in the determination of wind-speed errors of the type plotted in Fig. 11 leads to larger errors at higher wind speeds.

CONCLUSIONS

Seven months of altimeter-derived radar cross sections and significant wave heights obtained from the GEOSAT geodetic mission have been compared to measurements from buoys operated by the National Data Buoy Center. The comparisons demonstrate that for off-nadir angles of up to 1 degree, over the measured wind-speed range, the Brown and smoothed Brown algorithms give the lowest rms and mean differences between the two sets of measurements for all ranges. The other algorithms considered were those of Chelton and Wentz and Chelton and McCabe. Questions remain concerning the perfor-

Table 5—Summary of rms error differences between altimeter-derived and buoy-measured wind speeds and significant wave heights.

Source of Error	Wind Speed (m/sec)	SWH (m)
Buoy instrument	0.8	—
Temporal separation	0.3	0.1
Spatial separation	0.5*–1.0†	0.2*–0.3†
Sampling variability (time vs. area averaging)	0.3	0.24
Overall rms	0.1–1.3	0.4–0.5

*20-kilometer space window

†50-kilometer space window

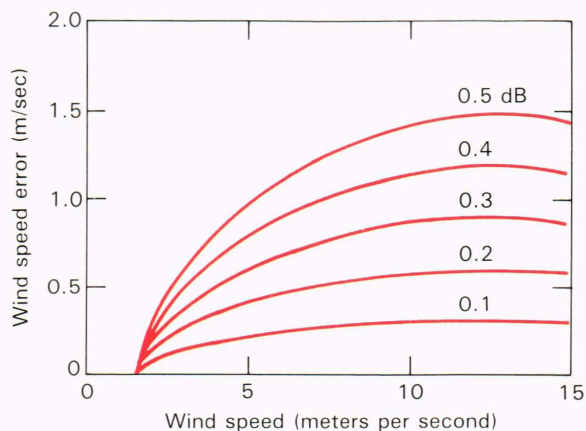


Figure 12—A family of curves showing wind-speed errors resulting from various levels of radar cross-section uncertainties assuming the smoothed Brown algorithm.¹⁰

mances of the algorithms at wind speeds greater than 14 meters per second because of insufficient high wind-speed values in the seven-month data set.

The above discussion of error budget analysis demonstrated that within a 50-kilometer range spacing between the buoy and altimeter subtrack, an expected wind-speed difference of 1.3 meters per second between the altimeter and the in-situ measurement may be expected. This difference is exclusive of any altimeter instrument or algorithm errors. A nominal 1.2-meter-per-second error may, in addition, be expected due to a 0.5-decibel uncertainty in the radar cross section. Combining these two errors results in an overall 1.8-meter-per-second error exclusive of any algorithm uncertainty (Table 5; Fig. 11). When comparing the altimeter-derived wind speed with buoy values for ranges within 50 kilometers (attitude of less than 0.75 degree) using the Brown or smoothed Brown algorithms, a 1.7-meter-per-second rms uncertainty was obtained. The error analysis is thus observed to be consistent with measurements, and the altimeter is therefore performing within measurement goals with regard to the measurement of wind speed (i.e., 1.8-meter-per-second rms).³

The error analysis also suggested a 0.5-meter uncertainty in the measurement of significant wave height that is consistent with the altimeter- versus buoy-derived significant-wave-height uncertainty that was shown to be 0.49 meter (Fig. 9). Hence, the altimeter-derived measurement of significant wave height has also been demonstrated to be performing within its measurement goal (0.5-meter rms or 10 percent of significant wave height).

REFERENCES

¹ E. B. Dobson and J. Goldhirsh, *Determination of Closest Approach Statistics Associated with the GEOSAT Altimeter Ground Track and the NDBC Buoy Network*, Vols. 1 and 2, JHU/APL S1R85U-004 (1985).

- ² G. S. Brown, "Backscattering from a Gaussian Distributed Perfectly Conducting, Rough Surface," *IEEE Trans. Antennas Propagat.* **26**, 472-482 (1978).
- ³ C. Cox and W. Munk, "Statistics of the Sea Surface Derived from Sun Glitter," *J. Mar. Res.* **13**, 198-227 (1954).
- ⁴ G. S. Brown, "Estimation of Surface Winds Using Satellite-Borne Radar Measurements at Normal Incidence," *J. Geophys. Res.* **84**, 3974-3978 (1979).
- ⁵ G. S. Brown, H. R. Stanley, and N. A. Roy, "The Wind Speed Measurement Capability of Spaceborne Radar Altimeters," *IEEE J. Oceanic Eng.* **6** (1981).
- ⁶ D. B. Chelton and P. J. McCabe, "A Review of Satellite Altimeter Measurement of Sea Surface Wind Speed: With a Proposed New Algorithm," *J. Geophys. Res.* **90**, 4707-4720 (1985).
- ⁷ J. Goldhirsh and E. B. Dobson, *A Recommended Algorithm for the Determination of Ocean Surface Wind Speed Using a Satellite-Borne Radar Altimeter*, JHU/APL S1R85U-005 (Mar 1985).
- ⁸ D. B. Chelton and F. J. Wentz, "Further Development of an Improved Altimeter Wind Speed Algorithm," *J. Geophys. Res.* **91** (1986).
- ⁹ W. E. Fraim, S. C. Jones, C. C. Kilgus, and J. L. MacArthur, "Navy GEOSAT Mission Radar Altimeter Satellite Program," *Monitoring Earth's Ocean, Land, and Atmosphere from Space—Sensors, Systems and Applications*, Vol. 97, in *Progress in Astronautics and Aeronautics Series*, A. Schnapf, ed., AIAA, pp. 440-463 (1985).
- ¹⁰ F. M. Monaldo, *Expected Differences in the Comparison of Wind Speed and Significant Wave Height by Spaceborne Radar Altimeters*, JHU/APL S1R86U-017 (1986).
- ¹¹ W. J. Pierson, Jr., "The Measurement of Synoptic Scale Wind Over the Ocean," *J. Geophys. Res.* **88**, 1683-1708 (1983).
- ¹² D. B. Gilhousen, "An Accuracy Statement for Meteorological Measurements Obtained from NDBC Moored Buoys," in *Proc. MDS '86 Marine Data Systems Int. Symp.*, pp. 198-204 (Apr 1986).
- ¹³ K. E. Steele and M. D. Earle, "The Status of Data Produced by NDBC Wave Data Analyzer Systems," in *Proc. OCEANS '79*, IEEE (1979).
- ¹⁴ J. L. MacArthur, *Seasat-A Radar Altimeter Design Description*, JHU/APL SDO-5232 (1978).
- ¹⁵ E. J. Walsh, E. A. Uliana, and B. S. Yaplee, "Ocean Wave Heights Measured by a High Resolution Pulse-Limited Radar Altimeter," *Bound.-Lay. Meteorol.* **13**, 263-276 (1978).
- ¹⁶ M. Donelan and W. J. Pierson, Jr., "The Sampling Variability of Spectra of Wind Generated Waves," *J. Geophys. Res.* **88**, 4381-4392 (1983).

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