JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. C12, PAGES 25,015–25,024, DECEMBER 15, 1994

Comparison of TOPEX/POSEIDON σ_0 and significant wave height distributions to Geosat

Philip S. Callahan, Charles S. Morris, and S. Vincent Hsiao

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

Abstract. Monthly Ku band σ_0 and significant wave height (SWH) histograms from the NASA altimeter on the TOPEX/POSEIDON satellite are presented for January through June 1993 for three latitude bands between ±60 degrees. The data are compared to distributions from the Geosat mission for the same months in 1987–1989. Generally, the distributions agree quite well, although there are some seasonal/hemispherical differences. The σ_0 comparison reveals an overall bias between the two altimeters with the TOPEX σ_0 higher by about 0.7 dB, which is consistent with algorithm improvements for TOPEX. The SWH distributions show strong hemispherical/seasonal changes. The seasonal/hemispherical differences between TOPEX and Geosat are consistent for SWH and σ_0. The joint distribution of σ_0 and SWH is extremely stable from month to month. The typical SWH is independent of σ_0 for σ_0 greater than 11.3 dB. The minimum SWH grows exponentially with wind speed. This joint distribution may be useful for understanding electromagnetic bias in altimeter measurements. Finally, altimeter data are compared to buoy values from 21 overflights of the NASA verification site near Pt. Conception, California. Wave heights agree well with an RMS difference of only 0.2 m. Altimeter σ_0 values are compared to buoy wind speeds. The results are consistent with the −0.7 dB σ_0 offset from the histogram comparisons.

1. Introduction

Space borne altimeters provide very precise measurements of the range from the satellite to the sea surface. In the course of making this measurement, they also produce measurements of the significant wave height (SWH, the average height of the highest third of the waves) and the normalized radar backscatter cross section (σ_0). The way in which these quantities are determined from the altimeter waveform was originally described by *Brown* [1977] and more recently for Geosat and TOPEX by *Chelton et al.* [1989].

Because the SWH and σ_0 measurements are closely tied to the leading edge of the waveform where the range is measured, they provide diagnostic information about the accuracy of the calibration of the individual range gates and the overall system gain of the altimeter. Also, as σ_0 is sensitive to the off-nadir pointing of the altimeter, its correctness is a test not only of the altimeter hardware but also of the ground processing. Thus checking the accuracy and stability of these measurements is a useful adjunct to other altimeter calibration activities.

In what follows we will discuss only the NASA altimeter on the TOPEX/POSEIDON mission; we will refer to it simply as TOPEX. For SWH the TOPEX accuracy requirement is 0.5 m or 10%, whichever is greater. The geophysical data record (GDR) data resolution is 0.1 m. For σ_0 the TOPEX requirements are 0.25 dB precision and 1.0 dB absolute accuracy. The 0.25-dB precision requirement was interpreted by the altimeter builders as resolution, so the telemetry was quantized to this level. The quantization is smoothed somewhat by corrections for off-nadir pointing and sea state and for atmospheric absorption. The GDR resolution is 0.01 dB.

Paper number 94JC01759.
0148-0227/94/94JC-01759$05.00

SWH and σ_0 can be tested in two general ways for accuracy: statistically by comparison to previously measured global distributions and by comparison to buoys. The former method has the advantage of testing the altimeter over the entire range of global conditions. Because large numbers of points are included, relatively rare anomalies may be seen. The direct comparison of σ_0 data eliminates the need for a wind speed model function to relate altimeter σ_0 to wind speed for a comparison with buoys. On the other hand, in the statistical method there is no checking of individual values, so compensating errors could mask problems, and rare occurrences may be hidden in the mass of data. Because 3 years of Geosat data with their point calibration [*Dobson et al.*, 1987; *Carter et al.*, 1992] are available, it was felt that the statistical approach would be a good first test of the TOPEX altimeter. A small set of data from a buoy near the NASA verification site near Pt. Conception, California, was also used for a point comparison.

2. Data Investigation

2.1. Methodology

Histograms of Geosat and TOPEX SWH and σ_0 data were compared in the latitude bands $-60 \le$ latitude < -20, $-20 \le$ latitude ≤ 20, $20 <$ latitude ≤ 60 degrees for the months January through June. The cutoff latitude of 60 degrees was chosen in order that the two data sets have approximately an equal density of points with latitude. The three bands were

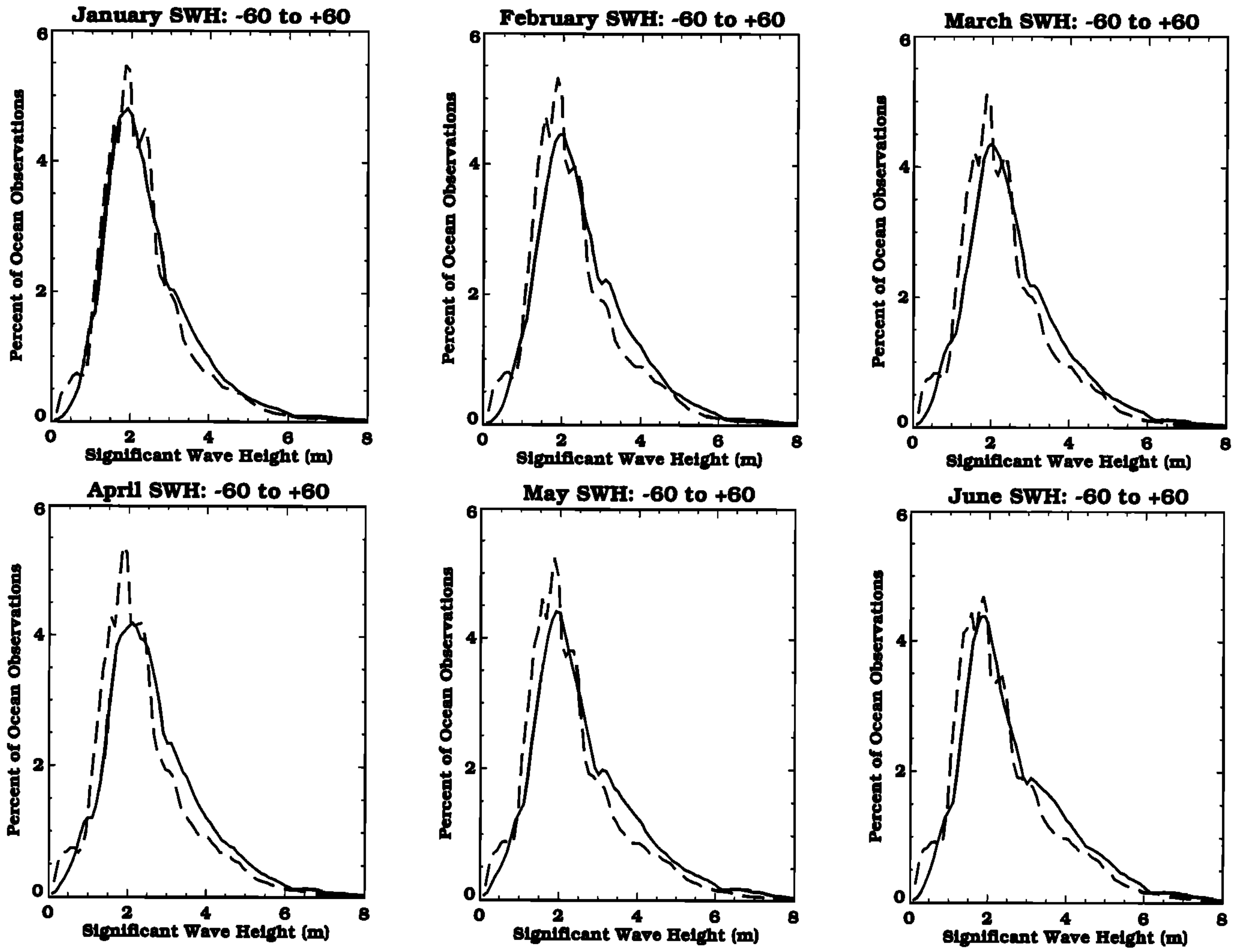

Figure 1. Global (±60 degrees) histograms of significant wave height for months January through June. Geosat data averaged over 1987–1989 (dashed); TOPEX data for 1993 (solid).

chosen to distinguish latitude and seasonal dependencies. The histogram interval was 0.1 m or decibel, respectively. No SWH values less than 0.1 m were counted. To allow for the fact that during the TOPEX/POSEIDON mission the Centre National d'Etudes Spatiales altimeter was on for part of each cycle for cycles 11 through 16 (January and February) and the difference in sampling of TOPEX and Geosat, the histograms are shown as the percentage of observations in each bin.

Monthly histograms of SWH and σ_0 for the months January through June were made from Geosat GDRs on CD-ROM [*Cheney et al.*, 1993] for the years 1987–1989. Only ocean data with good attitude determinations and sea surface height RMS less than 10 cm were used. It was found that the histograms for the 3 years were very similar, so they were combined for comparison with TOPEX. There are about 4 million points in each averaged monthly histogram.

Monthly histograms were also made from TOPEX GDRs [*Callahan*, 1992]. Only ocean data with the flags Alt_Bad1 = Alt_Bad2 = 0 and sea surface height RMS less than 10 cm were used. These flag settings ensure that only normal ocean data are included in the counts. For the months of January and February the typical number of TOPEX observations is 1.0 million, while for March through June it is about 1.3 million.

2.2. Significant Wave Height Distribution

Figure 1 shows the global (±60 degrees) SWH histograms by month for TOPEX and Geosat. No adjustment has been applied to these data. There is generally excellent agreement between the two altimeters and between the global distributions approximately 4 years apart, although there are indications of a slight shift to higher waves for TOPEX and fewer waves in the 0–0.5 and 1.5–2.0 m bands for TOPEX. The RMS difference between the distributions is a minimum (approximately 0.12%) for a relative shift of 0.2 m (two bins) in the sense of lowering (raising) TOPEX (Geosat). Matching the histograms at the 0.5% point at the high end shows an offset of 0.2 (January through April) to 0.3 m (May and June). At the low end, the obvious "bump" in the Geosat distribution makes matching unreliable.

The histograms have a Raleigh-like distribution similar to that of the global wind speeds [*Wentz et al.*, 1984]. A Rayleigh distribution with a width of 1.4 m, a scale factor of 0.09, and an offset from 0 wave height of 0.7 m fits the distributions with an RMS of about 0.3% over the 0- to 10-m

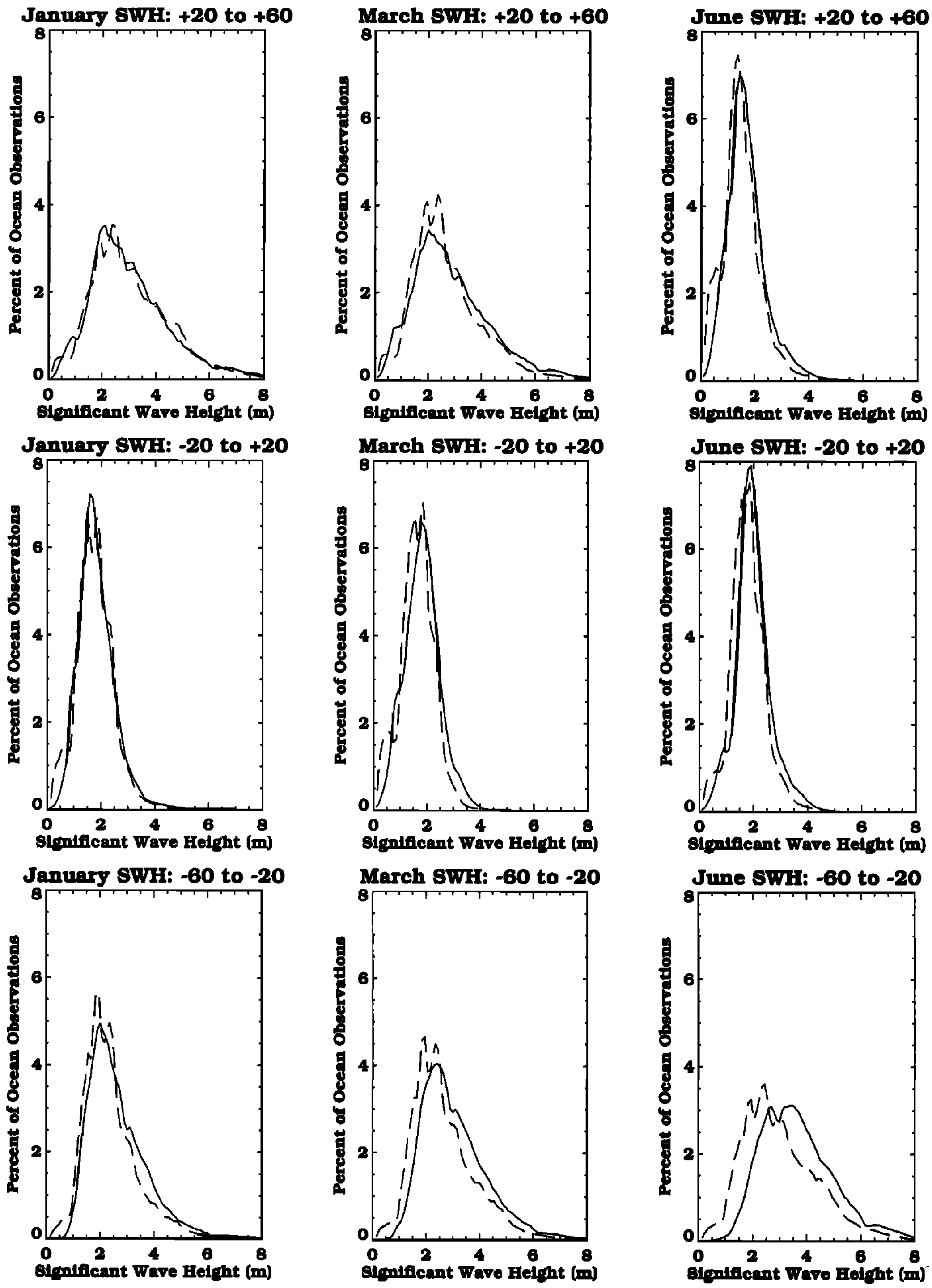

Figure 2. Histograms of significant wave height for months of January, March, and June for three latitude bands: north, 60 > latitude > 20; equatorial, 20 ≥ latitude ≥ −20; south, −20 > latitude > −60 degrees. Geosat data averaged over 1987–1989 (dashed); TOPEX data for 1993 (solid).

range. The distributions peak just above 2 m with noticeable tails extending to wave heights of about 6 m. The average wave height is 2.7 m. Globally, about 1 to 3% (southern hemisphere winter) of the SWH values are greater than 6 m. Not shown in the figures are several hundred counts for heights greater than 8 m. By examining the counts one finds that the highest waves are about 12 to 14 m. There are 30–50 such counts per month. Surprisingly, although the histograms in Figure 2 show that on average the southern hemisphere has higher waves, the highest waves are somewhat more frequent and higher (up to 14 m versus 12 m) in the northern hemisphere winter than in the southern hemisphere winter. We speculate that this is because of higher wind speeds driven by the greater temperature contrasts in the northern hemisphere.

Figure 2 shows SWH histograms for January, March, and

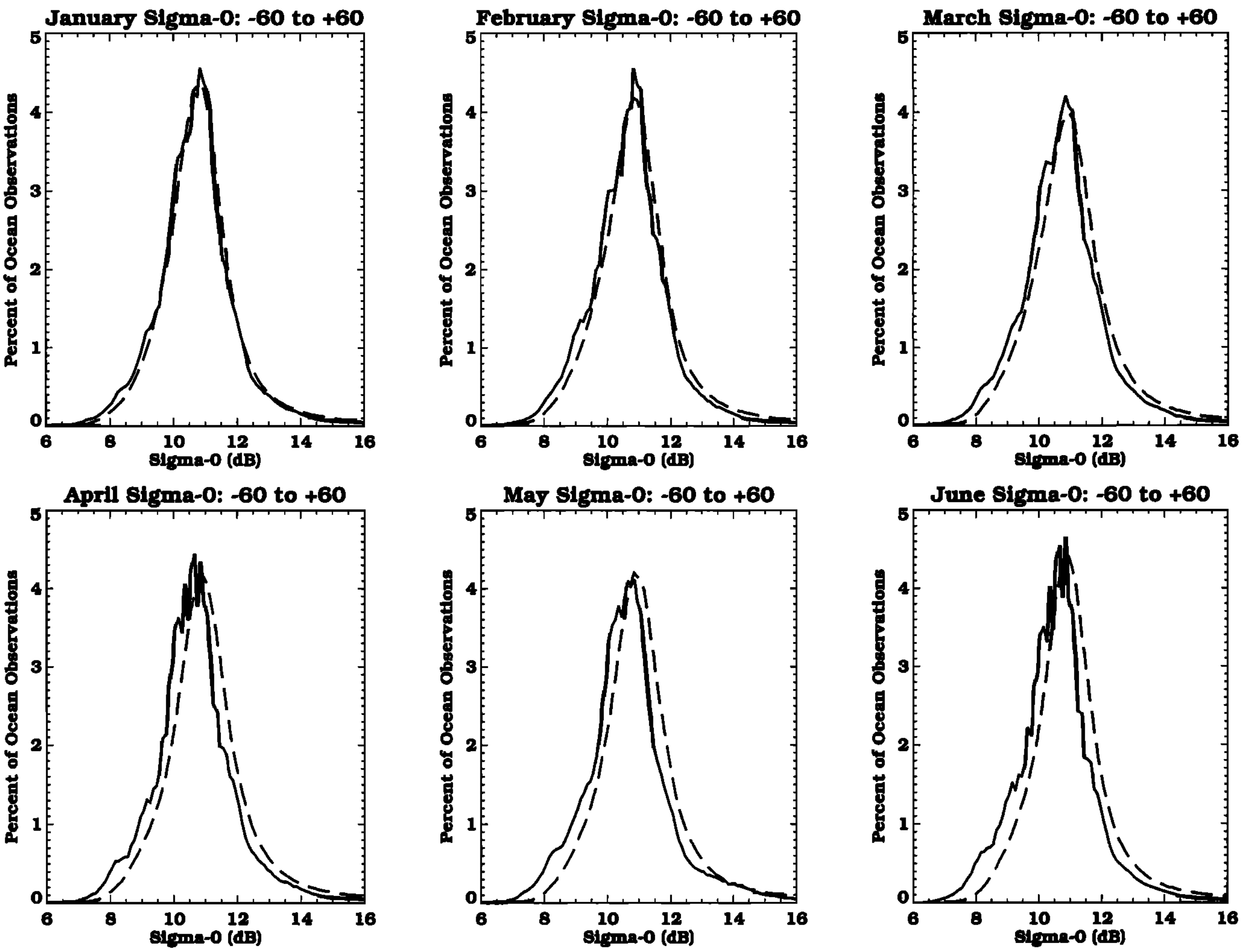

Figure 3. Global (±60 degrees) histograms of σ_0 for months January through June. Geosat data averaged over 1987–1989 (dashed); TOPEX data for 1993 (solid).

June for each of the three latitude bands. A seasonal/hemispheric dependence is immediately obvious, as is the benign character of the tropics (±20 degrees) both in terms of the maximum of the SWH distribution and month to month changes. As will be seen below, the trend to higher waves in the southern hemisphere winter of 1993 is consistent with the σ_0 or wind speed distribution. The southern hemisphere winter shows a shift of the entire distribution to higher waves by about 1 m resulting in a large increase in waves above 6 m. The southern hemisphere has almost no waves below 1 m for all months, while such waves are common in the tropics and northern hemisphere summer. The contrast between the global agreement and the southern hemisphere changes is an example of one of the possible problems with the statistical comparison if the data are not properly separated.

Aside from the generally good agreement between TOPEX and Geosat and the reasonable seasonal/hemispheric dependencies, several small features are obvious on the SWH histograms: Geosat has a sharp peak in the distribution between 1.5 and 2.0 m and a significant "bump" in the distribution below 1 m. TOPEX has dips in the counts at 3.0 m and 6.2 m. We believe that these are all instrumental effects and that the wave height distribution is basically smooth, especially near the peak. We do not know the details of the Geosat instrument or processing, but for TOPEX the features noted occur at altimeter gate index changes. (There are TOPEX gate index changes at approximately 0.9, 2.9, 6.2, and 13.0 m.) The dips are probably caused by incomplete or incorrect pointing angle/sea state corrections [*Hayne et al.*, this issue; *Callahan*, 1992] near gate index changes. It is likely that a similar effect causes the Geosat features.

2.3. The σ_0 Distribution

Figure 3 shows the monthly global (±60 degrees) σ_0 histograms for TOPEX and Geosat. The TOPEX data have had 0.7 dB subtracted from the σ_0 values found on the GDR. This offset was determined by minimizing the RMS difference between the TOPEX histograms for cycles 13 and 14 (January 20 through February 8, 1993) and Geosat data for the same period, assuming that year to year variations are small on a global basis. The offset is needed in order to allow use of the modified Chelton and Wentz (MCW) wind speed model function (WSMF) [*Witter and Chelton*, 1991] in TOPEX GDR production.

Two differences between the TOPEX and Geosat calculations of σ_0 explain the offset, and thus the TOPEX and

Geosat altimeters are in excellent agreement in measuring σ_0. First, TOPEX used a round Earth correction in the σ_0 calculation [*Callahan*, 1992] which was not used for Geosat (D. W. Hancock III, Geosat σ_0 calculation, private communication, 1994). Geosat σ_0 was calculated with the same algorithm as for Seasat and an adjustment was made to align the Geosat and Seasat distributions. Note that this contradicts *Chelton et al.* [1989]. The round Earth formulation results in σ_0 values larger by 0.8 dB for TOPEX. If this correction were applied to Geosat, the change would be 0.5 dB at the Geosat altitude, accounting for 0.5 dB of the offset. Second, while both Geosat and TOPEX σ_0 values were corrected for pointing angle and instrumental effects, the TOPEX values had an additional correction for atmospheric absorption applied. The atmospheric σ_0 correction mainly depends on the amount of liquid water in the line of sight as determined by the TOPEX microwave radiometer, although it also includes absorption by dry air and water vapor. The minimum atmospheric absorption correction is about 0.2 dB, the maximum for data without the "rain flag" set is about 0.6 dB, and the global average is about 0.30 to 0.35 dB. Combining these two processing differences results in TOPEX σ_0 values being larger than Geosat's by about 0.7 to 0.9 dB.

With the offset applied the TOPEX and Geosat data show generally excellent agreement for January through March, followed by a shift for the last 3 months. Some of the agreement in January and February could be attributed to the offset determination using cycles 13 and 14, but that process used only 10 days of data from each month. Because of the limited amount of data and time span, the original offset determination could be in error by 0.2 dB. A change of 0.2 dB corresponds to a wind speed change of about 0.5 m/s for winds of 5 to 15 m/s [*Monaldo*, 1988]. Minimizing the RMS difference between the distributions, both for the entire distribution and only for values greater than 10 dB, one finds that the estimated offset changes from about −0.7 in January to −0.4 in June. Comparing the distributions at the 0.5% points (near 9 and 13 dB) gives the same result. Part of this change can be accounted for by recently introduced calibration data (D. W. Hancock III, TOPEX σ_0 calibration, private communication, 1994) which show a σ_0 drift relative to the beginning of the mission of 0.1 dB in February to 0.25 dB at the end of June. With the calibration included the offset is relatively stable at −0.7 to −0.6 dB. This shows the utility of global statistical data for calibration monitoring.

Figure 4 shows σ_0 histograms for January, March, and June for each of the three latitude bands. A seasonal/hemispheric dependence is again immediately obvious. Also apparent is the benign character of the tropics (±20 degrees) both in terms of maximum wind speed (minimum σ_0 about 8.5 dB except in January) and month to month changes. TOPEX and Geosat agree well in all three bands in January. In March there is an excess of low σ_0 values in the northern and southern hemispheres for TOPEX. Finally, the southern hemisphere winter of 1993 shows both a higher wind speed for the peak of the distribution (shifted from about 11 dB (7 m/s) to less than 10 dB (11 m/s)) as well as a broader distribution with a significant tail extending below 8 dB. These shifts are large compared to the calibration changes of 0.1 to 0.2 dB.

The data in Figure 4 support both the good agreement between the two altimeters and the need to separate data in order to detect seasonal/hemispheric effects. Data in Figures 2 and 4 are quite consistent in showing that the northern hemisphere and tropics were very similar between the Geosat mission and 1993, while the southern hemisphere winter of 1993 was apparently very windy, resulting in larger wave heights. Examination of wind speed maps for 1987–1989 [*Halpern et al.*, 1991, 1992a, 1992b] and 1993 (D. Halpern, 1993 ERS 1 wind speed observations, private communication, 1994) shows good qualitative agreement with these observations. In particular, the southern hemisphere in June 1993 had much higher wind speeds than the average for 1987–1989, although it is comparable to 1989 alone. All months and bands (except for the shift in TOPEX in the south in June) show similarly shaped distributions with long tails extending above 13 dB. This is related to the difficulty in determining a WSMF for low wind speeds (<3 m/s), that is, at low wind speeds the backscatter is not well correlated with wind speed.

One notable feature in the TOPEX σ_0 histograms is the rapid fluctuations in the counts, particularly near the peak of the distribution. One possible explanation is that this is caused by the quantization of the telemetry to 0.25 dB. Because of the excellent pointing, the pointing angle/sea state corrections to σ_0 are fairly small (<0.2 dB) so that the quantization is not erased by this globally random correction.

2.4. Joint σ_0—SWH Distribution

Altimeter σ_0 values show large variations for low wind speeds (<3 m/s) which makes determining wind speed model functions difficult in this regime [*Freilich and Dunbar*, 1993; *Witter and Chelton*, 1991]. A possible distinguishing variable in this situation could be the wave height. As shown by discussions of TOPEX and POSEIDON data (this issue), the exact form of the electromagnetic bias (EMB) correction to altimeter range measurements remains controversial. The observed joint distribution of σ_0 and wave height may show different regimes of wind and waves which could have different EMB.

Figure 5 shows the joint SWH-σ_0 distribution for the TOPEX data from January through June 1993. Distributions were generated for each month and were found to be so similar that they were combined. The 0.7-dB offset discussed above has not been removed from σ_0. The bin size is 0.25 in each coordinate. The contours are in percent of the total observations (more than 7 million). The peak of the distribution (2%) is at 11.1 dB (corresponding to 10.4 dB in Figures 3 and 4) and 2.1 m, similar to the individual σ_0 and SWH histograms. The similarity of all features of the distribution from month to month was somewhat surprising in light of the seasonal changes found in the separate SWH and σ_0 histograms.

There are several striking features of the distribution. First, the maximum ridge of the distribution makes a very sharp bend from its steep downward slope to a nearly constant SWH (1.6 m) for σ_0 greater than 11.3 dB. Second, the lower edge of the distribution rises very steeply from a σ_0 of about 11.3 dB. Third, there is an upper limit to the SWH which declines monotonically as σ_0 increases.

Figure 6 is a plot of the main features of the SWH-σ_0 distribution against wind speed. The minimum and maximum wave height envelopes were measured arbitrarily at the 0.01% contour. The wind speed was determined from σ_0 by

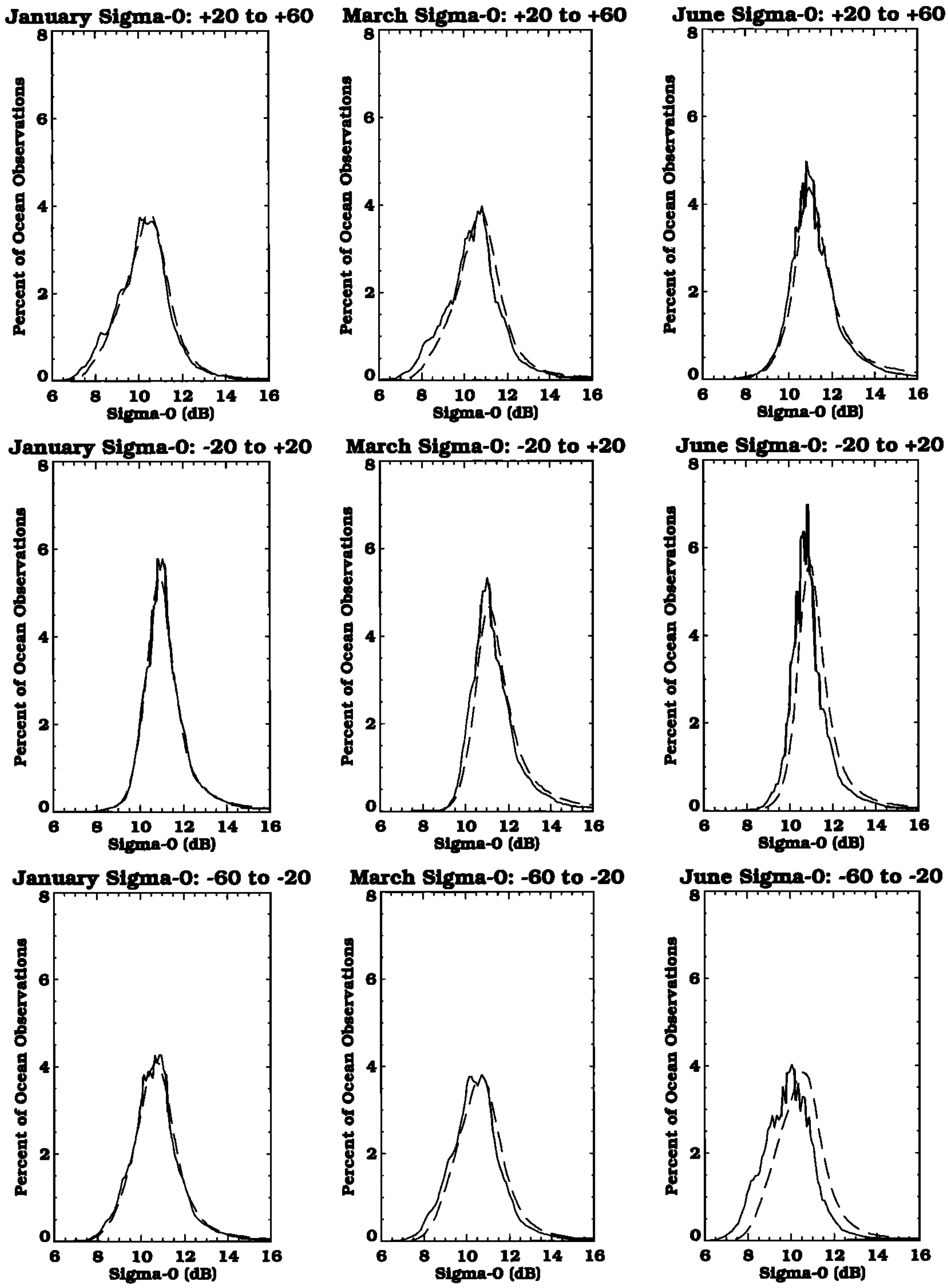

Figure 4. Histograms of σ_0 for months of January, March, and June for three latitude bands: north, $60 >$ latitude > 20; equatorial, $20 \geq$ latitude ≥ -20; south, $-20 >$ latitude > -60 degrees. Geosat data averaged over 1987–1989 (dashed); TOPEX data for 1993 (solid).

subtracting the 0.7 dB bias and then using the MCW WSMF [*Witter and Chelton*, 1991], except that adjusted σ_0 values less than 7.0 dB were all assigned a wind speed of 21.73 m/s. In addition to the data, Figure 6 shows functions that may represent the ridge and the minimum wave height. The sloping part of the ridge of the distribution above 8 m/s (MCW $\sigma_0 < 10.7$ dB) is well represented by a power law in wind speed with exponent 1.6. This is significantly less than the exponent of 2.0 for a "fully developed sea" from the Pierson-Moskowitz spectrum [*Pierson and Moskowitz*, 1964]. The lower envelope of the distribution is well represented by an exponential in wind speed with a wind speed scale of 5.4 m/s. Finally, the upper envelope shows approximately a square root dependence on wind speed (not shown).

These features suggest the following interpretations: The

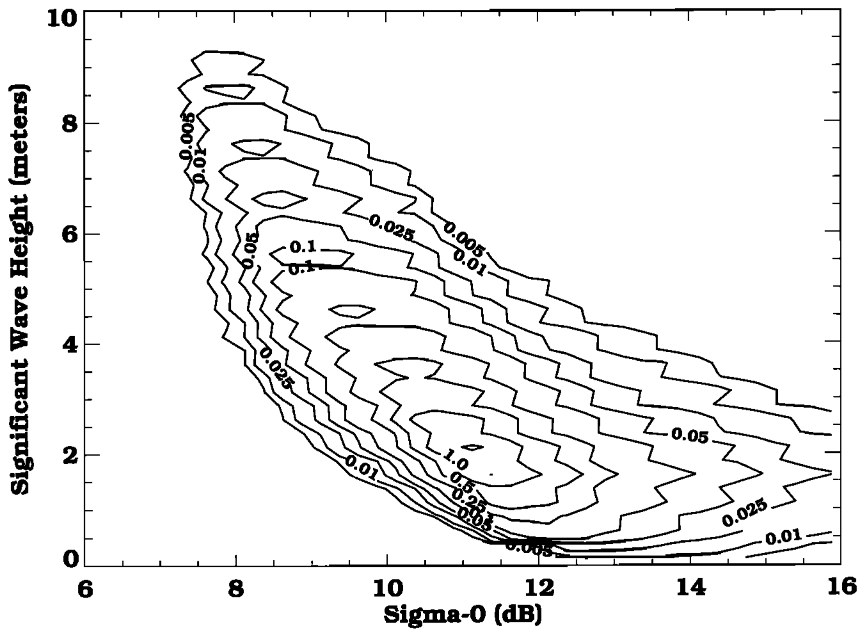

Figure 5. Joint distribution of TOPEX GDR significant wave height and σ_0 (no offset applied) for months January through June 1993. Contours are percent of total data, approximately 7 million points.

ridge of the distribution for SWH > 4 m represents the typical situation where winds and waves are approaching equilibrium. Based on formulae in the literature, several quantities may be calculated from parameters of the distribution. Along the ridge, the pseudo wave age of *Fu and Glazman* [1991] is constant at a value slightly less than the nominal for waves above 6 m, rises slowly to the nominal for waves from 6 to 4 m, and then climbs rapidly for lower SWH. *Ebuchi et al.* [1992] compare formulae from Joint North Sea Wave Project (JONSWAP) and Wilson to wave growth with fetch in the Sea of Japan. They find that the formula of Wilson gives a good fit to the data. That formula gives a nearly constant fetch of about 800 km for waves above 4 m, but the fetches grow to about 1200 km for the lower waves. The Wilson formula does not work for winds below 6 m/s where the observed distribution has flattened at

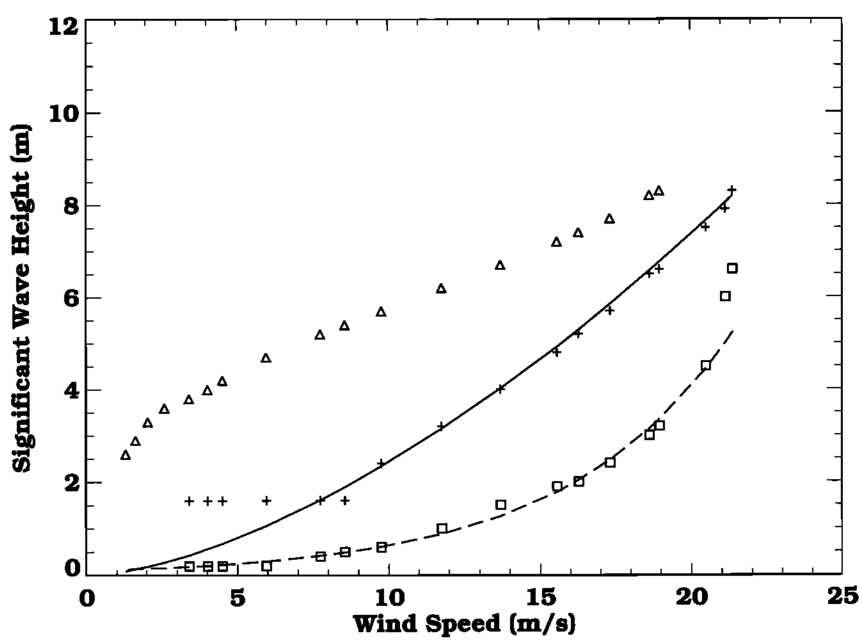

Figure 6. Main features of TOPEX joint significant wave height versus σ_0 distribution plotted against wind speed. TOPEX σ_0 -0.7 dB used in model function. Maximum SWH (triangles); ridge of distribution (pluses) with best fit line of exponent 1.6 (solid line); minimum SWH (squares) with best fit exponential with scale of 5.4 m/s (dashed line).

SWH = 1.6 m. The JONSWAP formula of fetch proportional to SWH^2/U^2, where U is wind speed, gives fetches decreasing monotonically from about 500 km for the highest waves to only about 150 km where the distribution flattens. Rapidly growing fetches are then required to produce 1.6-m waves for wind speeds below 6–8 m/s. Computing duration as fetch divided by the speed of the dominant waves [*Glazman and Pilorz*, 1990], one finds, using the JONSWAP formula, that the duration is nearly constant at about 6 hours for waves along the ridge above 2 m. The Wilson fetches give durations of about 12 hours for waves above 4 m, with rapidly increasing durations for lower waves. In light of this discussion the observation that along the ridge SWH rises more slowly with wind speed than the fully developed U^2 relationship probably shows that most of the waves are fetch- or duration-limited.

The lower envelope of the distribution shows the very rapid growth of SWH as wind increases and suggests that this minimum wave height is achieved in very short time. The pseudo wave age for the lower envelope is significantly lower than for the ridge and declines monotonically from higher to lower wave heights. The JONSWAP fetches for these waves are only 50 to 300 km, much less than for the ridge. Finally, the upper envelope of the distribution and the near constancy of SWH along the ridge of the distribution for wind speeds below 8 m/s shows the importance of swell in low wind speed regions. One may speculate that for wind speeds less than about 6 m/s (MCW $\sigma_0 > 11.3$ dB) nearly all the waves higher than 1.6 m are swell. Such regions should have a much lower EMB for a given SWH than developing or fully developed seas. Waves below the ridge are developing and may have higher than normal EMB. Thus this diagram could lead to a new EMB algorithm in which the relationship of the observed SWH and wind speed to this distribution is used to select different coefficients for swell, fully developed or developing seas. The distribution does not appear to offer insight into the large spread of σ_0 at low wind speeds.

2.5. Buoy Comparisons

The National Data Buoy Center buoy 46051, San Miguel, is located approximately 1 km northwest of the NASA verification site at Texaco's Platform Harvest near Pt. Conception, California. The buoy sits in over 200 m of water about 12 km from the coast. Installed just prior to the TOPEX/POSEIDON launch, the San Miguel buoy provides standard buoy measurements of wind speed, atmospheric pressure, air and sea temperature, and significant wave height. After cycle 29 the buoy suffered a complete instrument failure.

Dobson et al. [1987] and *Monaldo* [1988] concluded that buoy SWH measurement error can be considered negligible, while buoy wind speed measurements have an accuracy of approximately 0.8 m/s. Spatial separation was noted as a significant source of error in comparing buoys to remote sensing observations. Although the number of data points is limited for the comparison (21), it has the advantage that the buoy is in the altimeter footprint. Buoy SWH and wind speed estimates are available once per hour and are given to 0.1 m and 0.1 m/s, respectively, in the near real time synoptic format. The wind speeds used are the extrapolated 19.5 m values. Buoy data were interpolated to the time of the TOPEX overflight.

Table 1. Altimeter and Buoy Data for TOPEX Overflights of NASA Verification Site

Cycle	GDR σ_0	GDR SWH	Buoy Wind Speed	Buoy SWH	Model Altimeter Wind Speed	Wind Speed Altimeter-Buoy
2	13.5	2.2	2.2	1.9	2.62	0.42
3	14.3	1.3	3.0	1.4	1.79	−1.21
5	11.1	2.7	6.8	2.8	9.06	2.26
7	10.2	2.8	12.7	2.8	12.98	0.28
8	11.5	2.0	4.7	1.8	7.42	2.72
10	13.0	1.7	4.8	1.9	3.40	−1.40
11	12.3	1.8	5.7	1.8	5.07	−0.63
13	12.4	3.1	5.6	3.0	4.78	−0.82
15	12.0	2.7	5.2	3.0	5.96	0.76
17	11.5	2.8	7.0	2.8	7.76	0.76
18	12.1	1.9	6.8	1.9	5.63	−1.17
19	11.3	2.8	8.8	2.7	8.55	−0.25
21	10.45	3.5	11.3	3.4	11.96	0.66
22	11.55	1.3	8.4	1.6	7.56	−0.84
23	10.85	3.2	9.4	3.2	10.36	0.96
24	12.95	2.0	5.6	1.8	3.52	−2.08
25	13.35	2.5	5.0	2.3	2.76	−2.24
26	13.05	1.3	4.4	1.2	3.32	−1.08
27	11.75	2.6	7.9	2.5	6.80	−1.10
28	16.15	1.8	2.6	1.6	0.87	−1.73
29	10.75	2.6	12.9	2.6	10.78	−2.12

Altimeter wind speed obtained from modified Chelton and Wentz model function after removing offset of 0.7 dB from the GDR σ_0 and adding calibration corrections of +0.1 dB for cycles 15–19, +0.15 dB for cycles 21–28, and +0.25 dB for cycle 29.

Altimeter SWH and σ_0 values were interpolated to the location of the platform from 1-s GDR data, with the exception of cycles 2 and 3. During these early cycles, the satellite's attitude was suspect immediately over the platform. The values adopted for these cycles are representative values within a few seconds of the platform. A summary of the buoy and altimeter data is given in Table 1.

Figure 7a displays a direct comparison between the TOPEX altimeter and San Miguel buoy SWH. The agreement is excellent with an RMS of 0.17 m and a mean offset of −0.03 m, which is not significant. The RMS agreement is impressive given that the SWH values only have a precision of 0.1 m. Although the range of SWH sampled in this evaluation is only between 1.0 and 3.5 m, this range covers the majority of SWH values encountered in the ocean. The difference (buoy − TOPEX) by cycle is given in Figure 7b. Given the RMS of 0.17 m no significant trend with time is apparent, although the last seven points are all ≤0. The result found here is different than that of *Ebuchi and Kawamura* [1994] who find a bias of −0.3 m (buoy − TOPEX) between buoys around Japan and TOPEX SWH for 90 observations within 1 hour and 100 km. Nearly one quarter of their data are for SWH < 1 m for which we have no sample. The resolution of this discrepancy will require further investigation (see section 3).

Figure 7c shows wind speed obtained from TOPEX σ_0 values from Table 1 and the difference between the altimeter and buoy plotted against buoy wind speed. There is a bias of −0.4 m/s and an RMS of 1.4 m/s. It should be noted that *Witter and Chelton* [1991] found that Geosat with the MCW gave wind speeds high relative to buoys by 0.45 m/s. There is no trend with time, except that all of the residuals in May and June are less than −1 m/s. If one plots the wind speed

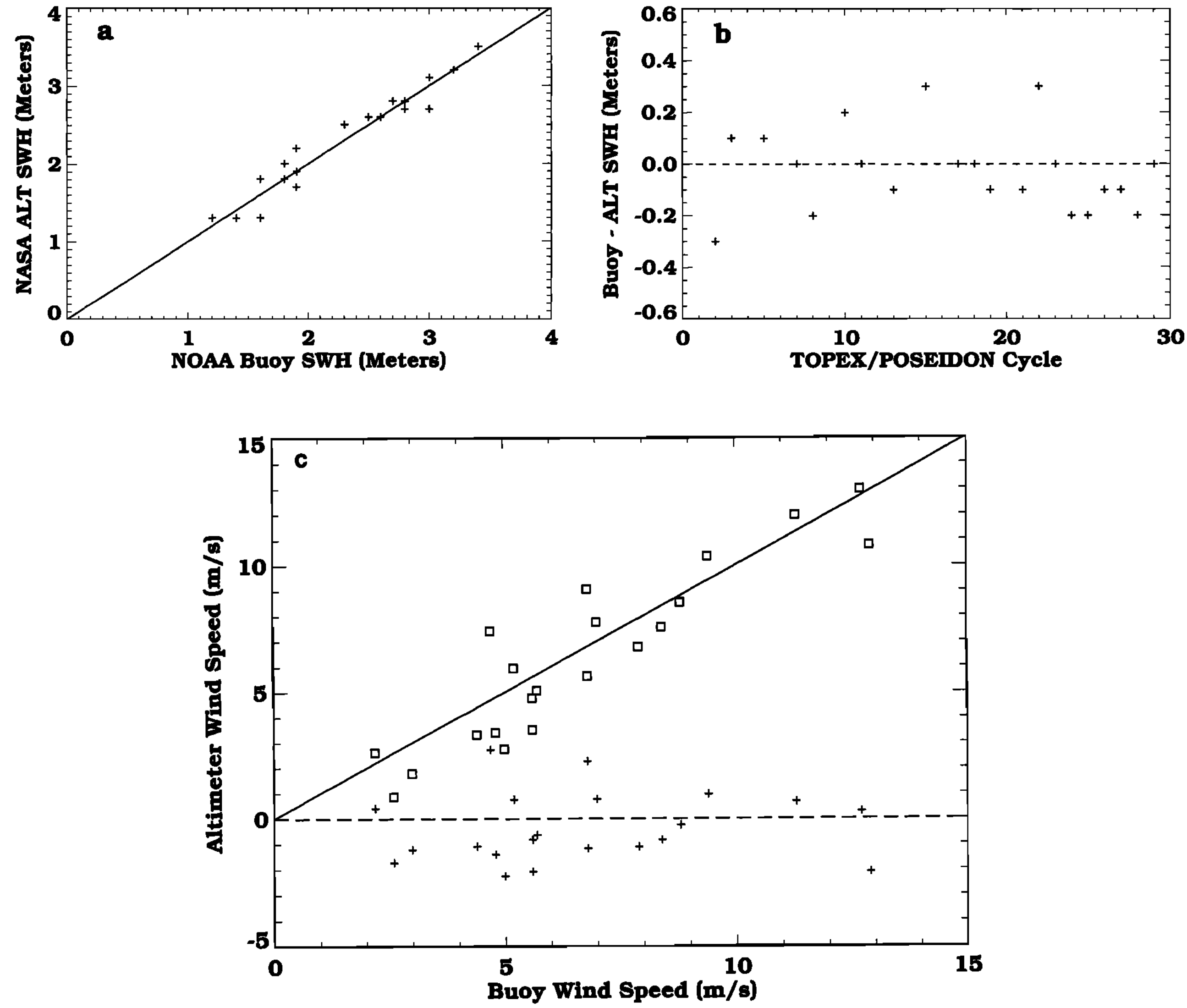

Figure 7. (a) TOPEX altimeter SWH versus buoy SWH at NASA verification site. (b) Difference of altimeter and buoy SWH versus cycle. (c) Altimeter wind speed (squares) and altimeter-buoy wind speed (pluses) versus buoy wind speed. Calibrated TOPEX σ_0 -0.7 dB used in model function.

residuals against SWH, one finds only two positive residuals for SWH < 2.6 m (13 total points) and only two negative for SWH > 2.6 m (8 points). Thus the negative residuals may be related to wave height as opposed to a strictly temporal trend. Given the small number of points here and the fact that the environment near the coast may be different than the open ocean, these data are not inconsistent with the offset determined from the global histograms.

3. Discussion and Conclusions

Monthly histograms of SWH and σ_0 from January to June 1993 from TOPEX have been compared to the average of the same months for 1987–1989 from Geosat globally and separated into northern, equatorial, and southern latitude bands.

The SWH distributions compare well with an offset for TOPEX of 0 to -0.2 m (i.e., lowering TOPEX or raising Geosat). Raising Geosat SWH would be consistent with the results of *Carter et al.* [1992], although not with *Dobson et al.* [1987]. Lowering TOPEX would be consistent with *Ebuchi and Kawamura* [1994], although not with overflights of the buoy at the NASA verification site reported here. These four results are from buoy comparisons. Note that only one of the suggested adjustments can be made. The evidence still supports the conclusion that the SWH estimates obtained by the NASA altimeter are well within the project specification of 0.5 m.

The σ_0 data show generally excellent agreement with a -0.7-dB offset for the TOPEX σ_0, except for the southern hemisphere winter. The -0.7 dB can be traced to algorithm improvements. All data show the expected seasonal/hemispheric changes. The differences between TOPEX and Geosat for the southern hemisphere winter of 1993 are consistent between SWH and σ_0 with TOPEX showing higher SWH and lower σ_0 (higher wind speed). External data qualitatively confirm the higher winds.

The TOPEX σ_0 data were compared to a small sample of buoy data from the NASA verification site. The wind speed comparison also supports the statistical comparison with an offset of about −0.7 dB in σ_0. We conclude that TOPEX is measuring σ_0 values equivalent to Geosat's to within about 0.2 dB. It should be remembered that the TOPEX σ_0 values come from an improved algorithm and include atmospheric correction; hence they are more accurate representations of the radar cross section. The −0.7 dB offset is needed in order to use existing wind speed model functions (e.g., modified Chelton-Wentz).

Some features of the TOPEX SWH and σ_0 distributions are related to known altimeter effects and suggest improvements for future altimeters. The σ_0 automatic gain control should be quantized to 0.1 dB or less in the original telemetry instead of 0.25 dB used by TOPEX. Pointing angle/sea state corrections must rectify all changes which occur at internal altimeter gate changes. The ability to see the overall calibration, instrument effects, and seasonal variations shows the utility of the statistical comparison method used here for sensor verification. It also shows that it is important to separate the data in order that seasonal or geographic changes can be separated from instrument effects. The seasonal/latitude variations found indicate that at least 1 year of global data should be used to establish a WSMF.

The joint distribution of SWH and σ_0 has three main features which may help in understanding the electromagnetic bias in altimetry. The most notable feature is that along the ridge of the distribution SWH grows with wind speed to the 1.6 power for wind speeds greater than about 8 m/s, but SWH is constant at about 1.6 m for winds less than 8 m/s. Below about 6 m/s, most of the waves are probably swell. There is a lower envelope to the distribution where SWH grows exponentially with wind speed. The waves between the lower envelope and the ridge are presumably developing rapidly. The fact that the power law index for the ridge is less than 2 indicates that the waves there are not fully developed in this typical condition. These different wind-wave regimes should be expected to have different EMB. Separating the correction by regime should help to understand the effect and lead to lower scatter in the corrected data.

Acknowledgment. This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with National Aeronautics and Space Administration.

References

Brown, G. S., The average impulse response of a rough surface and its applications, *IEEE Trans. Antennas Propag.*, *AP-25*, 67–74, 1977.

Callahan, P. S., TOPEX GDR users handbook, *Rep. JPL D-8944*, Jet Propul. Lab., Pasadena, Calif., 1992.

Carter, D. J. T., P. G. Challenor, and M. A. Srokosz, An assessment of Geosat wave height and wind speed measurements, *J. Geophys. Res.*, *97*, 11,383–11,392, 1992.

Chelton, D. B., E. J. Walsh, and J. L. MacArthur, Pulse compression and sea level tracking in satellite altimetry, *J. Atmos. Oceanic Technol.*, *6*, 407–438, 1989.

Cheney, R. E., N. S. Doyle, B. C. Douglas, R. W. Agreen, L. L. Miller, E. L. Timmerman, and D. C. McAdoo, The complete Geosat altimeter GDR handbook, *NOAA Manual NOS-NGS-7*, Natl. Oceanic and Atmos. Admin., Silver Spring, Md., 1993.

Dobson, E., F. Monaldo, J. Goldhirsh, and J. Wilkerson, Validation of Geosat altimeter-derived wind speeds and significant wave heights using buoy data, *J. Geophys. Res.*, *92*, 10,719–10,731, 1987.

Ebuchi, N., and H. Kawamura, Validation of wind speeds and significant wave heights observed by the TOPEX altimeter around Japan, *J. Oceanogr.*, *50*, 479–487, 1994.

Ebuchi, N., H. Kawamura, and Y. Toba, Growth of wind waves with fetch observed by the Geosat altimeter in the Japan Sea under winter monsoon, *J. Geophys. Res.*, *97*, 809–819, 1992.

Freilich, M. H., and R. S. Dunbar, Derivation of satellite wind model functions using operational surface wind analyses: An altimeter example, *J. Geophys. Res.*, *98*, 14,633–14,649, 1993.

Fu, L.-L., and R. E. Glazman, The effect of the degree of wave development on the sea state bias in altimeter measurements, *J. Geophys. Res.*, *96*, 829–834, 1991.

Glazman, R. E., and S. H. Pilorz, Effect of sea maturity on satellite altimeter measurements, *J. Geophys. Res.*, *95*, 2857–2870, 1990.

Halpern, D., V. Zlotnicki, J. Newman, O. Brown, and F. Wentz, An atlas of monthly mean distributions of Geosat sea surface height, SSMI surface wind speed, AVHRR/2 sea surface temperature, and ECMWF surface wind components during 1988, *JPL Publ. 91-8*, Jet Propul. Lab., Pasadena, Calif., Feb. 1991.

Halpern, D., V. Zlotnicki, J. Newman, D. Dixon, O. Brown, and F. Wentz, An atlas of monthly mean distributions of Geosat sea surface height, SSMI surface wind speed, AVHRR/2 sea surface temperature, and ECMWF surface wind components during 1987, *JPL Publ. 92-3*, Jet Propul. Lab., Pasadena, Calif., Jan. 1992a.

Halpern, D., W. Knauss, O. Brown, and F. Wentz, An atlas of monthly mean distributions of SSMI surface wind speed, ARGOS buoy drift, AVHRR/2 sea surface temperature, and ECMWF surface wind components during 1989, *JPL Publ. 92-17*, Jet Propul. Lab., Pasadena, Calif., July 1992b.

Hayne, G. S., D. W. Hancock III, C. L. Purdy, and P. S. Callahan, The corrections for significant wave height and attitude effects in the TOPEX radar altimeter, *J. Geophys. Res.*, this issue.

Monaldo, F., Expected difference between buoy and radar altimeter estimates of wind speed and significant wave height and their implications on buoy-altimeter comparisons, *J. Geophys. Res.*, *93*, 2285–2302, 1988.

Pierson, W. J., and L. Moskowitz, A proposed spectral form for fully developed wind seas based on the similarity theory of S. A. Kitaigorodsky, *J. Geophys. Res.*, *69*, 5181–5190, 1964.

Wentz, F. J., S. Peteherych, L. A. Thomas, A model function for ocean radar cross section at 14.6 GHz, *J. Geophys. Res.*, *89*, 3689–3704, 1984.

Witter, D. L., and D. B. Chelton, A Geosat altimeter wind speed algorithm and a method for altimeter wind speed algorithm development, *J. Geophys. Res.*, *96*, 8853–8861, 1991.

P. S. Callahan, S. V. Hsiao, and C. S. Morris, M.S. 300-319, Jet Propulsion Laboratory, Pasadena, CA 91109-8099. (e-mail: P.CALLAHAN/OMNET psc@purim.jpl.nasa.gov)

(Received November 12, 1993; revised June 30, 1994; accepted June 30, 1994.)