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Intercalibration of wave and wind data from TOPEX/POSEIDON and moored buoys off the west coast of Canada

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Abstract. Significant wave height (SWH) and wind speed data from the merged geophysical data record (MGDR) of the TOPEX/POSEIDON satellite altimeters, for the first 47 cycles of satellite coverage (September 1992 to December 1993), are compared with measurements from an array of instrumented buoys moored along and off the west coast of Canada. SWH values from the satellite and buoys cover a range of 0.1 to 8 m, in one case exceeding 12 m. The comparison shows TOPEX waves, on average, low by 5% relative to the buoys, with rms scatter about the mean relation of 30 cm. For buoys lying within 10 km of the satellite tracks, this scatter is reduced to about 15 cm. TOPEX tracks pass sufficiently close to each of the buoys for the satellite altimeter to be used as a "transfer standard," showing a small difference between the two types of buoys in the array and occasional problems with the buoy measurements. A significant difference was found between the satellite and buoy wind speeds, with NASA altimeter winds being high by about 10% relative to the buoys. This can be explained by known factors affecting the buoy data. The small amount of POSEIDON data shows the winds in the MGDR to be 12% low compared with the buoys. The difference between POSEIDON and NASA altimeter winds is confirmed by computing large-area spatial averages over the Pacific Ocean. The rms scatter for wind speed about the best fit regression was near 2 m/s, reducing to 1.4 m/s when data were restricted to distances less than 10 km from deep water buoys. Atmospheric pressure values, inserted in the satellite data from a global weather model, were found to agree with buoy measurements to within about 1 mbar. Apart from the discrepancy in wind speeds, the results are consistent with both buoy and satellite data meeting or exceeding their design specifications. The effects of spatial variations of wave climate and changes in atmospheric stability are assessed. The comparison demonstrates how satellite and buoy observations can be used for mutual calibration and performance monitoring.

1. Introduction

Measurements of winds and waves over the ocean are important for modeling and forecasting of weather, ocean surface conditions, and ocean circulation. Recent new technology has provided two different but complementary sources of these data: moored, instrumented surface buoys that use sophisticated data processing and satellite communications and a series of satellites carrying radar altimeters whose precisions have improved steadily from 1974 (Skylab) to the present. The buoys provide continuous time series at locations of particular interest. The satellites measure along tracks that cover the world oceans in a time/space grid that is defined by the satellite's orbit. Accuracy specifications for buoy data are typically 5% for significant wave height (SWH) and 10% or 0.5 m/s for wind speed. Satellite measurements aim for lesser accuracies of 10% or 0.5 m in SWH and about ±2 m/s in wind speed.

Buoy measurements have the disadvantages that hull and mooring design and the low height of the anemometers above the sea can introduce errors, and the harsh environment can cause changes in sensor response or loss of data. Satellite data are limited by errors inherent in determining radar backscatter but have the advantage that all measurements are made with a single instrument carried in a relatively stable environment. If well calibrated, the data can be used to look for trends in ocean conditions during the satellite's lifetime and for variations among responses of different surface instruments.

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This paper presents the results of a comparison of wave and wind data from TOPEX/POSEIDON, the latest satellite to carry a precise radar altimeter, with data from a network of buoys that started operating during the years 1987 to 1993 off the west coast of Canada. The comparison covers the first 47 cycles (466 days or 1.3 years, September 1992 to December 1993) of the satellite mission. It was undertaken partly to validate the TOPEX/POSEIDON data in terms of the mean calibration of the buoy array and partly to check the relative responses of individual buoys, on average and as a function of time, using the satellite as a "transfer standard" and as a stable source of data.

The comparison makes use of the merged geophysical data record (MGDR), distributed by the NASA Jet Propulsion Laboratory (JPL) on compact disc (CD). Listed wind speeds need correction for changing altimeter calibration, as noted below. Properties of the satellite and buoy data are summarized in the next sections 2 and 3, and the method and results of the comparisons for wave height, wind speed, and atmospheric pressure are summarized in section 4. Section 5 summarizes the conclusions and discusses the accuracies and calibration problems in satellite and buoy data.

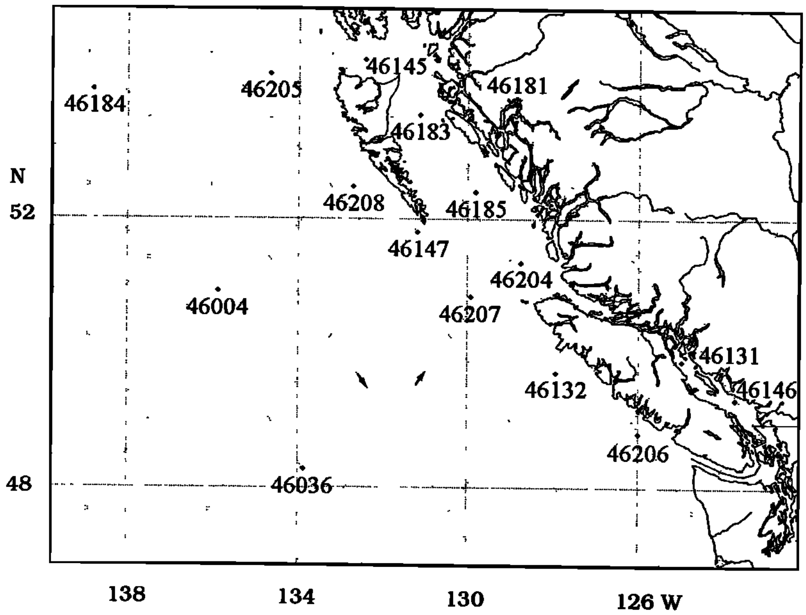

Figure 1. Locations of the moored Canadian west coast buoys identified by their World Meteorological Organization numbers. The dotted lines are the positions of measurements made at 1-s intervals by the TOPEX/POSEIDON satellite, showing the fixed pattern of tracks which is repeated at 10-day intervals.

2. TOPEX/POSEIDON Data

The TOPEX/POSEIDON satellite (hereinafter referred to as TOPEX), is a joint U.S./French project of NASA and Centre National d'Etudes Spatiales, the space agencies of the two countries. The satellite is designed to measure global ocean circulation and carries two altimeters, the dual K and C band NASA instrument and the single K band French POSEIDON instrument. It also carries a microwave radiometer for measuring atmospheric water vapor and liquid water and tracking equipment for accurately determining the position of the satellite.

The data used in the present comparison are the merged (NASA and POSEIDON combined) geophysical data records described by *Benada* [1993], with additional details given by *Callahan* [1993]. Each CD contains data from two cycles in binary records that list time, satellite position, altimeter data, and the required corrections at 1-s intervals for each of the 254 ascending and descending passes (half orbits) that make up a 9.916-day cycle.

The ground track is maintained constant from cycle to cycle to within 1 km of a fixed pattern (Figure 1). The center position of each 1-s average is recorded to an accuracy of better than 1 m.

The NASA and the POSEIDON altimeters share the same antenna and cannot operate simultaneously. The NASA altimeter is used for most passes. The POSEIDON instrument was used for occasional passes in early cycles, up to cycle 16, and for about 1 in every 10 complete cycles thereafter.

The values of SWH (in meters) and of wind speed (in meters per second) used in this comparison are those given in the MGDR. SWH values, as determined at both K and C bands, are listed for the NASA altimeter. The algorithm used is based on properties of the altimeter pulse shape [*Zieger et al.*, 1991]. K and C band sigma zero values and the resulting wind speed in meters per second are also listed. The conversion is based on the modified Chelton-Wentz algorithm, reported by *Witter and Chelton* [1991] and verified by *Freilich and Dunbar* [1993], with a −0.7-dbar correction applied to the sigma zero values to adapt the model function from the Geosat altimeter to TOPEX. Only K band sigma zeros are used in deriving wind speeds. The relation used is that for 19.5-m altitude winds from *Witter and Chelton* [1991], with a modification at low wind speeds to give a value of 0.7 m/s if the measured sigma zero is greater than 17 dbar.

Further corrections to the measured sigma zeros have since been calculated (reported by *Ebuchi and Kawamura* [1994]). The values used in the present comparison (P. S. Callahan, personal communication, 1994) reduce these corrections slightly. They now average 0.08 dbar (equivalent to 0.3 m/s) for the time period considered here.

Wave and wind measurements from a satellite altimeter are averages over circles directly beneath the satellite, having a diameter of 3.6 km for an SWH of 1 m, increasing to 9.6 km for 10 m [*Chelton et al.*, 1989]. Each pulse therefore averages over 10 to 70 km^2 of the sea surface. Averaging of many pulses over a 0.1-s period and further averaging to 1-s intervals increase this area further.

The NASA instrument output includes the rms scatter among the 0.1-s values used to compute the 1-s averages. In this sense, the altimeter SWH values have high statistical precision. Inspection of typical data shows the estimated rms error to vary from about 0.03 m rms for wave heights of 2 m or less, increasing to 0.05 m for an SWH of 5 m and 0.07 m for an SWH of 8 m. The statistical variations therefore amount to only about 3 cm or 1%, whichever is greater. Calculation of variations between consecutive 1-s averages confirms these low values. C band measurements have rms error values about 50% larger, still very much smaller than those considered acceptable from surface measurements. Although precision is high, accuracy needs to be confirmed by comparison with surface measurements, as reported here.

The rms difference between simultaneous SWH measure-

Table 1. Canada West Coast Moored Buoys

Station Name	WMO Number	Position		Water Depth, m	Number of Months	Ascending*		Descending	
		Latitude, °N	Longitude, °W			Path Number	Distance, km	Path Number	Distance, km
North Nomad	46184	53.933	138.803	3391	12	71	44	206	35
Middle Nomad	46004	50.938	135.865	3600	16	45	35	130	55
South Nomad	46036	48.297	133.856	3100	13	197	80	130	5
West Dixon	46205	54.167	134.667	2675	16	223	48	28	46
West Moresby	46208	52.500	132.700	2950	12	45	29	28	27
South Moresby	46147	51.822	131.201	2000	8	121	9	28	60
East Dellwood	46207	50.860	129.910	2125	16	197	14	28	66
South Brooks	46132	49.732	127.923	2040	3	19	16	28	107
La Perouse	46206	48.835	125.998	73	16	95	21	104	8
Central Dixon	46145	54.383	132.427	257	16	223	7	104	21
North Hecate	46183	53.567	131.140	58	16	45	30	104	37
South Hecate	46185	52.420	129.800	226	16	121	38	104	25
West Sea Otter	46204	51.375	128.745	224	16	197	17	104	11
Sentry Shoal	46131	49.907	124.985	16	15	...	...	...	...
Halibut Bank	46146	49.340	123.727	40	16	...	...	180	2
Nanakwa Shoal	46181	53.820	128.842	21	16	...	...	...	...

Canadian buoys are operated by Axys Environmental Consultants for Environment Canada and the Canadian Department of Fisheries and Oceans. WMO is World Meteorological Organization.
*Values are distances from TOPEX/POSEIDON ascending and descending paths. No data are given where lack of sufficient open water prevents the altimeters from acquiring usable data.

ments at C band and at K band was found to be 0.16 m, slightly higher than the above error values would suggest, but small enough that averaging the two values together would not significantly improve the comparison. This difference showed no apparent dependence on SWH up to an SWH of 12 m. Comparisons with buoys in this study show that C band data give a slightly larger rms scatter than K band. K band values were therefore emphasized in this paper.

Up to December 8, 1992, midway through cycle 8, the satellite was subject to attitude errors which may be sufficient to affect some of the results presented here [*Benada*, 1993]. Certainly, "outlying" points were encountered in some early cycles, but with no clearly greater frequency than in later data. In one case, noted below, outlying points in the SWH comparison in cycles 2 and 3 are traced to an apparent problem with one of the buoys.

3. Buoy Data

3.1. Buoy Positions and Measurements

The marine meteorological buoys are operated by Axys Environmental Consultants for Environment Canada and the Department of Fisheries and Oceans of the Canadian federal government. The positions of the 16 buoys in the west coast Canadian network are shown in Figure 1. The three offshore buoys are located about 400 km west of the British Columbia coast. Six inner buoys are in a line of exposed positions within 100 km of the coast, and an additional seven are located in more sheltered coastal waters, behind the Queen Charlotte Islands and Vancouver Island. For two of these buoys (46145 and 46146) the position used in the comparison had to be shifted along the TOPEX tracks to the nearest region of consistently valid satellite data. Two (46131 and 46181) are in areas with very limited open water, from which TOPEX is unable to collect any useful data. Only 46131 is considered further and only in the pressure comparison discussed below.

The three offshore buoys are of a 6-m "Nomad" type, weighing 10 t [*Wood and Wells*, 1988]; the remainder are 3-m discus buoys weighing 1.5 t [*Wood and Wells*, 1988; *Gilhousen*, 1987, *National Oceanic and Atmospheric Administration* (*NOAA*), 1985, 1987]. All are instrumented with dual anemometers at 5 m above the sea surface, thermistors for sea (1 m depth) and air temperature (3 m height), dual barometers, and an internal accelerometer for wave height measurement. All data are relayed hourly to users via the U.S. GOES and Canadian Anik satellites. The data used in this comparison are the vector average wind speed (meters per second) and the SWH (meters), as recorded from these satellite links.

The buoy names, World Meteorological Organization (WMO) identification numbers, and positions of the buoys are listed in Table 1, which also shows the water depth, the number of months for which data were collected in the study period, and the pass numbers with the minimum distances to TOPEX tracks. Data from the closest descending pass (from top left to bottom right in Figure 1) and from the closest ascending pass (from bottom left to top right) were used in this study. Minimum distances are less than 10 km in four cases and less than 40 km in 20 of the 28 cases. Satellite track separation is about 150 km. The maximum offset distance used is 107 km for the track passing offshore of buoy 46132. However, this buoy provided only 3 months of data in the 16-month study period. In the results presented below, data are separated by buoy, by groups of buoys, and by offset distance.

Buoy wave measurements are averages of 37 min of data collection. A first pressure measurement is made in the following minute. Winds are vector averages over the subsequent 10 min, and then a second pressure measurement is taken. Pressures are averages of the two measurements. Data are tagged with the time of transmission, which is 8 min after the end of the wind measurements. The time lags, of 13 min for wind and 36.5 min for waves, from the mean measurement times, are allowed for in this analysis.

Data are recorded at hourly intervals, giving a maximum time difference from a satellite overpass of 30 min. This time difference should have only a small effect on the comparison. Inspection of typical buoy data under moderately rough con-

Table 2. Relative Mean Wave Height and Wind Speeds Deduced From Monthly Averages Measured by Canadian West Coast Buoys, Expressed as Ratios to the Values for Buoy 46036

Station Name	WMO Number	Water Depth, m	Wind Speed Ratio	Number of Monthly Values	SWH Ratio	Number of Monthly Values
North Nomad	46184	3391	1.02 ± 0.02	52	0.99 ± 0.01	55
Middle Nomad	46004	3600	1.06 ± 0.01	46	1.05 ± 0.01	54
South Nomad	46036	3100	1.00	68	1.00	68
West Dixon	46205	2675	1.05 ± 0.02	42	0.93 ± 0.02	46
West Moresby	46208	2950	1.02 ± 0.03	22	1.03 ± 0.02	18
South Moresby	46147	2000	0.87 ± 0.04	8	0.95 ± 0.03	7
East Dellwood	46207	2125	0.94 ± 0.02	42	0.93 ± 0.01	47
South Brooks	46132	2040	0.96 ± 0.01	3	0.83 ± 0.02	3
La Perouse	46206	73	0.78 ± 0.02	49	0.74 ± 0.01	53
Central Dixon	46145	257	0.94 ± 0.02	33	0.57 ± 0.02	31
North Hecate	46183	58	0.96 ± 0.02	27	0.44 ± 0.01	30
South Hecate	46185	226	0.97 ± 0.02	39	0.65 ± 0.02	39
West Sea Otter	46204	224	0.91 ± 0.02	38	0.75 ± 0.01	48
Sentry Shoal	46131	16	0.61 ± 0.03	13	0.14 ± 0.01	15
Halibut Bank	46146	40	0.66 ± 0.02	21	0.14 ± 0.01	19
Nanakwa Shoal	46181	21	0.66 ± 0.03	40	0.12 ± 0.01	38

SWH is significant wave height. Ratios are the long-term averages and the rms errors in the long-term averages estimated from the individual monthly values. Also given is the number of monthly values included in the average.

ditions (SWH of 4 m) shows that differences in wave height, wind speed, and atmospheric pressure between consecutive samples have rms values of 0.25 m, 1.4 m/s, and 0.6 mbar rms, respectively. These differences are comparable to those found between buoy and TOPEX data (see below). However, the time interval in the comparisons will never be more than half this, and the linear interpolation used reduces the expected error further.

3.2. Buoy Intercomparisons

Monthly mean wave heights and wind speeds were computed as part of this study as a consistency check among the buoys. Means were computed for all months for which at least 300 hourly values were collected, over the full periods of available buoy data, and ratios were computed to the values for the southernmost outer buoy (46036) which was used as a reference. The ratios for both wind speed and SWH among the exposed buoys are stable enough to give a precision of a few percent for the mean values in Table 2 and show no appreciable seasonal cycle.

The ratios are consistent with expected wind and wave climate on the coast and show no clear evidence of calibration differences among the buoys. Table 2 shows equal mean SWH and wind speed at buoys 46036 and 46184, with a 5% ± 1% increase at 46004, located between them. This variation is significant when compared with the expected statistical 1 to 2% variation in the means but is comparable to the expected calibration errors. The three buoys close to the west coast of the Queen Charlotte Islands and the next buoy (46207) to the southeast all show ratios (to buoy 46036 values) in the range 0.87 to 1.03 for winds and waves. The low relative wind speed at buoy 46147 may indicate a calibration error of about 10% but is derived from a short data record of only 8 months. The two buoys off Vancouver Island show an apparent drop in wave height (ratio of 0.83) but not in wind speed at 46132 (based on 3 months of data) and a drop by 0.78 and 0.74 in waves and wind, respectively, at 46206, the only exposed station in shallow water. Buoys in more sheltered water show similar wind (0.91 to 0.97) but lower waves (0.44 to 0.75) in Hecate Strait and Queen Charlotte Sound and lower winds (0.61 and 0.66) and much lower waves (0.14) for buoys 46131 and 46146 in Georgia Strait.

4. Satellite/Buoy Data Comparisons

The closest ascending and descending passes of TOPEX data were searched for each buoy during each of the first 47 cycles of satellite coverage (September 1992 to December 1993). Software was written to automatically select the nearest satellite data point to the buoy location, and the time, distance of separation, and wave, wind, and pressure data were extracted, together with quality flags. The small variation between consecutive TOPEX data points indicates that averaging of several points would not significantly improve the comparison. The list of TOPEX data was then used as input to a second program which searched the buoy data for time coincidences, adding data collected at the two times, before and after the satellite overpass. Results were then compared using standard spreadsheet software.

4.1. Wave Data

4.1.1. Data comparisons. SWH values from the NASA K band altimeter were compared for each buoy separately, and results of regression analyses are listed in Table 3. Results are grouped to reflect the locations of the buoys as follows: the three outer, the six inner exposed, and the five sheltered buoys. Combined results are also shown for the inner and outer groups, compared with the NASA K band and C band altimeters and with the (K band) POSEIDON altimeter.

The maximum potential number of comparison data points for each buoy is 94 (two passes for each of 47 cycles). This was reduced to between 13 and 82, primarily by missing buoy data, with a smaller number of cases where poor quality buoy or satellite data were flagged or where satellite passes were missed.

For the buoys in exposed (inner and outer) locations, SWH

Table 3. Comparison of SWH Values Measured by the TOPEX/POSEIDON Satellite With Those Measured by the West Coast Canadian Moored Buoys

	Number of Observations	Rms Scatter	Intercept, m	Slope	Slope With Zero Intercept
46184	47	0.37	0.12 ± 0.05	0.94 ± 0.03	0.97 ± 0.01
46004	64	0.28	−0.04 ± 0.07	0.93 ± 0.03	0.92 ± 0.01
46036	63	0.35	0.13 ± 0.07	0.88 ± 0.03	0.92 ± 0.01
Three outer buoys					
NASA K band	174	0.35	0.03 ± 0.03	0.93 ± 0.02	0.94 ± 0.01
NASA C band	174	0.36	0.12 ± 0.05	0.91 ± 0.02	0.94 ± 0.01
POSEIDON	9	0.44	−0.43 ± 0.40	1.08 ± 0.19	0.97 ± 0.04
46205	56	0.31	0.43 ± 0.07	0.87 ± 0.03	0.99 ± 0.02
46208	36	0.31	0.24 ± 0.08	0.84 ± 0.03	0.90 ± 0.02
46147	39	0.22	0.33 ± 0.07	0.86 ± 0.03	0.98 ± 0.02
46207	62	0.31	0.38 ± 0.07	0.90 ± 0.03	1.00 ± 0.01
46132	11	0.22	0.67 ± 0.11	0.85 ± 0.05	1.04 ± 0.03
46206*	31	0.21	0.22 ± 0.05	0.96 ± 0.03	1.03 ± 0.01
Six inner buoys					
NASA K band	235	0.30	0.36 ± 0.03	0.88 ± 0.01	0.98 ± 0.01
NASA C band	235	0.33	0.38 ± 0.05	0.88 ± 0.02	1.00 ± 0.01
POSEIDON	22	0.32	0.18 ± 0.15	0.95 ± 0.09	1.01 ± 0.02
46145	62	0.60	0.40 ± 0.18	1.14 ± 0.08	1.31 ± 0.04
46183	57	0.41	0.31 ± 0.09	0.74 ± 0.05	0.87 ± 0.04
46185	80	0.29	0.21 ± 0.04	0.78 ± 0.02	0.85 ± 0.01
46204	68	0.28	0.13 ± 0.06	0.97 ± 0.03	1.01 ± 0.01
46146	27	0.24	0.39 ± 0.08	0.69 ± 0.17	1.33 ± 0.12

Results are shown of regression analyses using data from individual buoys (by WMO numbers) and for groups of inner and outer buoys.
*Data are up to May 1993.

varied typically over the range 1 to 7 m. Satellite and buoy data showed high correlation, with most regression line slopes close to, but slightly less than 1.0. The results for the north Nomad buoy 46184 shown in Figure 2 are typical of the offshore buoys. A single observation for this buoy is unusual in that it was collected in extremely rough conditions. The satellite measured an SWH of 12.5 m at 0549 UT on December 14, 1992, and the buoy (44 km off track) measured 12.8 m at 0552 UT. For the validation of both buoy and satellite measurements, it is gratifying to see close agreement up to such high values of SWH.

The best fit line to the data has a slope of 0.97 and no

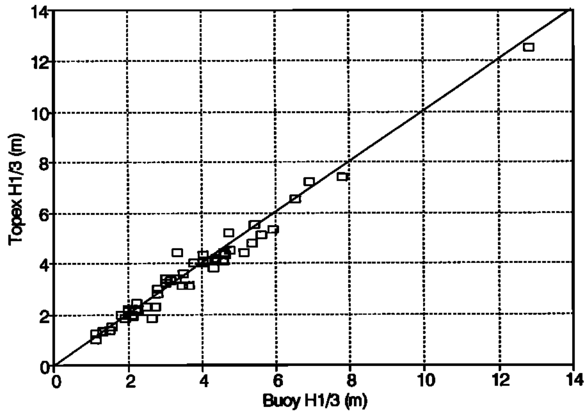

Figure 2. Comparison of significant wave height (SWH) values measured by the NASA altimeter on TOPEX and those measured by buoy 46184. The observations include an observation of extremely high waves during a storm in December 1992, which gave the highest SWH value so far measured by the buoys. Points should lie on the solid line for perfect agreement. Regression results for these points are included in Table 3.

significant offset at zero buoy wave height. Scatter about this line is smaller at lower wave heights, where wave fields may be expected to be more uniform, and increases in rougher conditions, as might be expected for smaller-scale (200 to 400 km) weather systems.

Table 3 shows that the regression analysis gives consistent results for the three offshore buoys. The zero offset is very small, and the slopes are 0.97, 0.92, and 0.92. The fit for the combined data for the three outer buoys gives a slope of 0.94 ± 0.01, showing that TOPEX is measuring 6% low with respect to the buoys.

The six inner buoys also show consistent results (Table 3), but with an apparent difference from the outer buoys. The offset value at zero buoy wave height for the best fit to the combined data from six inner buoys appears significant at 0.36 ± 0.03 m. The combined plot is shown in Figure 3. The regression line slope is 0.88. The offset and the low slope are confirmed by the data from each of the buoys separately. The combined effect of the slope and the offset is to give a mean slope near 1.00 when the intercept is constrained to be zero.

The five buoys in more sheltered water showed results mostly consistent with the inner set, but with additional effects interpretable as due to local variations in wave climate. Comparisons for buoys 46145 and 46146 are shifted from the closest positions by 17 and 61 km, respectively, to avoid areas where TOPEX data were flagged as invalid. Slopes of about 1.3 for these buoys are therefore probably due to wave climate differences rather than to calibration problems. Also, for buoy 46146, in the sheltered waters of the Strait of Georgia, wave heights never exceeded 1.4 m.

Figure 4 shows the plot for buoy 46185, for which the low slope of 0.84 suggests that TOPEX measurements were consistently taken in calmer water. The buoy is located to the east of the center of Queen Charlotte Sound. Satellite measure-

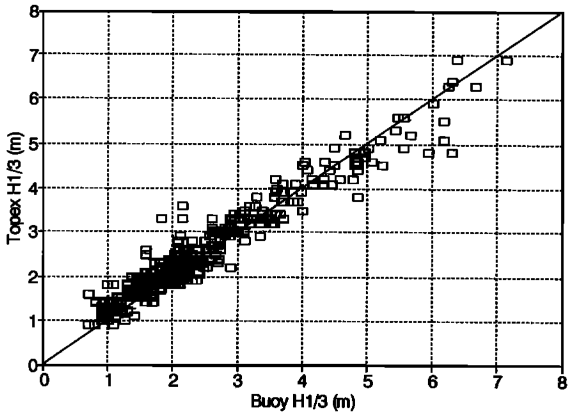

Figure 3. Comparison of SWH values measured by the NASA altimeter on TOPEX and those measured by the six "inner" buoys located in exposed positions close to the coast. TOPEX measurements are slightly but significantly higher at low SWH and lower at high SWH. Points should lie on the solid line for perfect agreement. Regression results for these points are included in Table 3.

ments are sampled at two locations (of minimum buoy to satellite track distance) about 30 km farther west. The plot for buoy 46183 has a similar form, with slope less than 1.00, again showing lower wave heights to the west. This buoy is in the middle of Hecate Strait, and the area to the west is closer to the coast of the Queen Charlotte Islands. Buoy 46204 is located closer to the two satellite tracks used in the comparison. The regression shows much better agreement, with the slope close to 1.00.

4.1.2. TOPEX/buoy mean relation. In general, the results show extremely good agreement between the buoys and the TOPEX satellite, roughly consistent with the accuracies planned for each system. For TOPEX this was ±10% or +0.5 m (rms), whichever is greater. Calibration accuracy of the buoy accelerometer sensors, using a procedure where they are driven at different rates round a 2-m-diameter vertical circle, is estimated to be about ±5% (Axys Environmental Consultants, personal communication, 1994).

NASA altimeter waves appear to be 6 ± 1% low compared with the outer buoys. The small amount of POSEIDON data available suggests accuracy and calibration similar to that of the NASA instrument, with satellite measurements 3 ± 4% low (Table 3).

The results of comparisons with the inner buoys show a significant difference in response, with an intercept of 0.36 ± 0.03 m at zero buoy SWH and a mean regression line slope of 0.88 ± 0.01. There is insufficient POSEIDON data to confirm the two different buoy responses.

This response of the inner buoy group is similar to that found by *Ebuchi and Kawamura* [1994] in a comparison of TOPEX SWH data with values from three, 10-m-diameter buoys near Japan. Their amount of data and range of wave heights are less than in the present comparison, and the scatter in the data is rather larger, as would be expected from their less frequent (3 hourly) sampling. They show a mean intercept of 0.30 m and a mean slope (not quoted, but deduced from *Ebuchi and Kawamura* [1994, Figure 5]) of 0.93.

A similar effect is evident in the results of *Dobson et al.* [1987] for comparison of buoy data with Geosat wave heights. They used data from 43 U.S. buoys, of which about two thirds are close to the coast, but made no separation between nearshore and offshore buoys. *Cotton and Carter* [1994] also find this effect (intercept of 0.17 m, slope of 0.92 m) in a comparison of monthly mean values in boxes 2° square centered on buoy positions. In the following two sections it is shown that this intercept/slope difference in the present data set could be due to differences in buoy design, but it appears better explained as an effect of spatially varying wave climate nearshore.

4.1.3. Differences in buoy hulls and sensors. Two different types of buoy response in the present comparison might be expected, since the three outer buoys have a different hull shape and also accelerometer design from the others. However, previous studies have found only small differences in response between the two types of buoys. [*NOAA*, 1985, 1987]. With a single exception (buoy 46206) both the inner and the outer groups of buoys are moored in deep water (2000 m or deeper), eliminating water depth as a possible cause of the difference.

The three outer buoys are equipped with gimbal systems, designed to keep their accelerometers vertical as the buoy rolls and pitches. Others are 3-m discus buoys, each with a strapped-down accelerometer that will only measure true vertical motion when the buoy is not tipped. The response difference is consistent with the discus buoys underestimating the SWH of a low wave field and overestimating the SWH of a high one. Both differences could be explained by errors due to a strapped-down accelerometer that tilts with the buoy. At low SWH, less than the full vertical motion is sensed by an accelerometer that is, on average, tilted. At high SWH a tilted accelerometer could also sense strong horizontal motions due to breaking waves. A combination of these two effects could explain the observed intercept. However, *Gilhousen* [1987] reports tilts of less than 10° for this type of buoy, too small to give a significant error, and no such intercept has been measured. The sensors used in the comparison of *Ebuchi and Kawamura* [1994] are also of this strapped-down accelerometer type.

Differences could also be due to the difference in hull design. A comparison in which both types of hull were outfitted with strapped-down accelerometers [*NOAA*, 1987] showed mean SWH values over a 4-month period differing by 5%, with No-

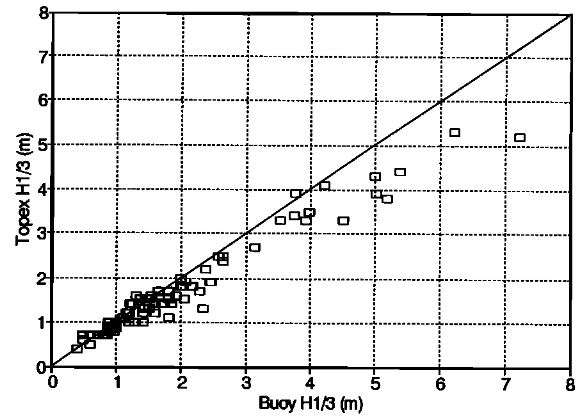

Figure 4. Comparison of SWH values measured by the NASA altimeter on TOPEX and those measured by buoy 46185 located east of the Queen Charlotte Islands. Points should lie on the solid line for perfect agreement. Regression results for these points are included in Table 3. The relatively higher buoy values can be ascribed to a spatial variation in wave climate.

Table 4. Comparisons of NASA Altimeter K Band and Buoy SWH Values, Showing the Effect of Reducing the Maximum Distance Between the Locations of Satellite and Buoy Measurements from 107 km to 20 and 10 km

	Number of Observations	Rms Scatter	Intercept, m	Slope	Slope With Zero Intercept
Three outer	174	0.35	0.03 ± 0.03	0.93 ± 0.02	0.94 ± 0.01
46036, <10 km*	30	0.14	−0.11 ± 0.05	1.00 ± 0.02	0.97 ± 0.01
46036, >70 km	32	0.35	0.18 ± 0.08	0.83 ± 0.03	0.88 ± 0.02
Six inner	235	0.30	0.36 ± 0.03	0.88 ± 0.01	0.98 ± 0.01
Inner, 20–107 km	159	0.33	0.43 ± 0.07	0.85 ± 0.02	0.98 ± 0.01
Inner, <20 km	76	0.21	0.21 ± 0.07	0.93 ± 0.02	0.99 ± 0.01
Inner, <10 km	28	0.15	0.05 ± 0.11	0.99 ± 0.03	1.00 ± 0.01
46147, May–Sept. 1993, <10 km	14	0.14	−0.04 ± 0.13	1.06 ± 0.07	1.04 ± 0.02
46147, from Oct. 1993, <10 km	6	0.12	0.18 ± 0.24	0.89 ± 0.08	0.95 ± 0.02
46206, to May 1993, <10 km	16	0.16	0.10 ± 0.12	0.98 ± 0.04	1.02 ± 0.01

*One point has been omitted from the analysis, as discussed in text.

mad higher. In Table 3 a higher response by Nomad buoys would reduce the slope for the outer buoy comparison relative to that for combined data from the six inner buoys. A difference of this amount is indeed observed. Since only mean SWH values are given in the NOAA report, the differences in slope and intercept found here cannot be checked.

In one case in the present data set, the different buoy responses can be tested at the same location. As part of a storm wave study, the discus buoy that was first installed in May 1993 as 46147 was replaced by a Nomad buoy in October 1993. Results using only data from the track that passed within 10 km of this buoy, separated before and after October 1993, are listed in Table 4. Unfortunately, the discus buoy deployment covered only spring and summer months (May to September) in 1993, with SWH values at the times of TOPEX overpasses ranging from 0.9 to 2.8 m, whereas the range for the Nomad data acquired in October to December covered 1.8 to 5.8 m. The amount of data is also small. The separate "intercept" and "slope" values for the two time periods in Table 4 show the opposite change to that noted above, with the Nomad buoy showing the larger intercept and the smaller slope, but with low statistical significance. Forcing the intercept to zero gives a slope for the Nomad deployment of 0.95 ± 0.02 and for the discus deployment of 1.04 ± 0.02, again showing a higher Nomad response.

4.1.4. Spatially varying wave climate. The effect of slight spatial variations in wave climate over the 10- to 100-km distances used in the comparisons has been referred to above and is shown in Figure 4. Such variations can explain slope values different from 1.00 in the last column of Table 3, but a variation that is systematically dependent on wave height is needed to explain the offset/slope response of the inner buoys. Such an effect is unlikely offshore but could occur due to differing swell and wind wave properties, near the coast.

Any effects of wave climate variations on the results in Table 3 should be reduced when the comparisons are limited to smaller distances than the maximum 107 km. Table 4 shows that the offset and slope observed for the inner buoys do indeed go to 0 and 1, respectively, when the maximum comparison distance is reduced. Table 4 also shows the results of comparisons for the inner six buoys when the data are split between comparison distances greater than and less than 20 km. A comparison for less than 10 km is also shown. The intercept values reduce monotonically with the distance used in the comparison, and the corresponding slopes approach 1.00 (middle block of entries in Table 4). Data in Tables 3 and 4 show that the change in intercept and slope is not due to differences among the buoys used in the comparisons.

This result shows that wave climate variation must be affecting the comparison but gives no explanation of the mechanism. The wave climate pattern has to vary with wave height. For the inner buoys the TOPEX tracks tend to be offshore from the buoys. When larger comparison distances are included, TOPEX appears to measure higher than the buoys at low SWH. Perhaps swell predominates in these conditions and is less nearshore. At higher SWH the difference is reduced or changes sign. Similar effects are apparent in data presented by *Ebuchi and Kawamura* [1994] and *Dobson et al.* [1987], but without a comparison over smaller distances for these data sets, a similar cause cannot be demonstrated. *Cotton and Carter* [1994] use only offshore buoys, but their method of averaging may tend to increase the effect of wave climate variations.

4.1.5. Scatter about the mean TOPEX/buoy relations. Average scatter about the regression line in Figure 2 amounts to 0.37 m rms. Scatter for the combined data from the outer three buoys is 0.35 m and for the inner six, 0.30 m (Table 3). This is close to the value of 0.36 m found by *Dobson et al.* [1987] for comparison of U.S. buoys with Geosat data, with a maximum distance of 50 km, and less than the value of 0.51 m found by *Ebuchi and Kawamura* [1994] from comparisons of Japanese buoys with TOPEX, with a maximum distance of 100 km (though the 3-hour buoy sampling interval may explain the higher scatter in this case). Table 4 shows that scatter in the present comparison is reduced when satellite/buoy distances are restricted to less than the maximum 107 km. For the inner buoys, using 20 km reduces the scatter to 0.21 m. For 10 km it is 0.15 km.

Figure 5 shows the wave height comparison for 31 measurements from one of the outer buoys, the south Nomad buoy 46036, for which the satellite track passed less than 4 km away. With the exception of a single point, the scatter about a mean regression line through zero (excluding this point) is only 0.14 m rms. The line slope is 0.96. The single point, for which SWH values disagree by more than 1 m, is from December 1992, during a period of rapid but not unusual wave growth measured at the buoy of about 0.5 m SWH per hour. About 80 min after the overpass the buoy SWH had increased to the value

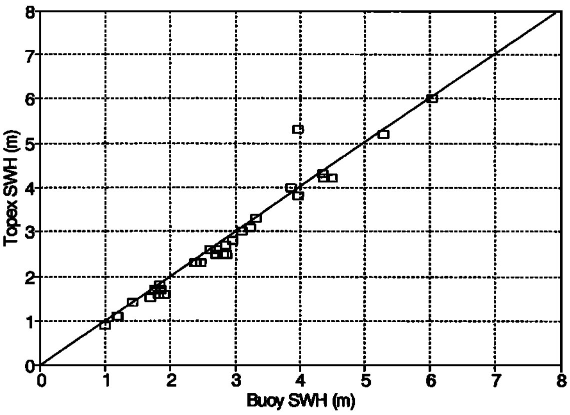

Figure 5. Comparison of SWH values measured by the NASA altimeter on TOPEX and those measured by buoy 46036 using only TOPEX data collected within 10 km of the buoy. Points should lie on the solid line for perfect agreement. Regression results for these points (omitting the single outlying point, as discussed in the text) are included in Table 4.

indicated by TOPEX. The TOPEX data showed a constant value of 5.3 m over a length of about 30 km along track.

Such a disagreement could be due to data quality problems on the satellite or the buoy, though no such problem was flagged. Measured satellite attitude was 0.1° from vertical, well within the acceptable range. The disagreement can also be interpreted as a real variation of wave properties with position, though the data imply a very small space scale for a significant change in SWH. Table 4 shows that, apart from this single point, data from all three buoys giving comparisons over distances less than 10 km give scatter values near 0.15 m. *Callahan et al.* [1994] show scatter of 0.17 m for 21 passes exactly over a buoy.

For Geosat/buoy comparisons, *Monaldo* [1988] predicted scatter of about 0.4 m rms, due to rms errors of 0.26 m from the buoy sensors, 0.03 m from the altimeter, and 0.30 m due to a maximum comparison distance of 50 km. While this total is close to that observed for most buoy comparisons in Table 3, results using smaller comparison distances show the buoys to be more precise than Monaldo assumed.

4.1.6. Buoy problems. In two cases this comparison showed temporary problems with data from certain buoys. For buoy 46208 the ratios to buoy 46036 of 14 monthly mean wave heights are 1.03 ± 0.08 for data collected in 1991 and 1993 but dip to 0.89, 0.79, 0.61, 0.59, 0.74, and 0.96 for the months of June to November 1992, respectively. This apparent drop in buoy sensitivity was clearly visible in the comparison with satellite data. In the plot similar to Figure 2 for buoy 46208, four outlying points at low wave height corresponded to the buoy measuring lower SWH by a factor 0.60 to 0.65 compared with the NASA altimeter. The points were from TOPEX cycles 2 and 3 in early October 1992. Attitude errors were about 0.3°, near the threshold for problems to occur [*Benada*, 1993]. However, apparent underestimates of SWH by a factor 0.6 were noted in the "Buoy Status Reports" (R. Mclaren, personal communication, 1994) during routine data checks. These errors were not flagged in the archived digital data. The sensor has since been replaced.

Buoy 46206 also showed a smaller, but longer-term drop in apparent sensitivity, to about 0.80 during 1993 in the comparison with TOPEX. This was confirmed, though with lower precision, using the monthly means of the buoy data. However, this drop or that noted above for buoy 46208 could be a real property of the wave climate, and some nearby comparison data are needed to confirm the buoy calibration. In this case, TOPEX provided these data, without the problem being otherwise noted. The problem was traced to a sensor with a calibration error of 15% being installed in May 1993 (Axys Environmental Consultants, personal communication, 1994). Data from buoy 46206 after April 1993 are excluded from Tables 3 and 4.

4.2. Wind Data

4.2.1. TOPEX/buoy mean relations (NASA altimeter). Comparisons for wind speeds were carried out in a similar way to those for wave heights. Buoy winds were increased by a factor 1.12 [*Smith*, 1988] to allow for the difference between the 19.5-m reference height of the TOPEX winds and the 5-m buoy observations (see below). TOPEX winds were corrected according to sigma zero corrections released by JPL (P. S. Callahan, personal communication, 1994).

Figure 6 shows the combined data from the three outer buoys compared with NASA altimeter measurements. The TOPEX winds are consistently high compared with the buoys by about 10% (regression line shown as dashed in Figure 6). Buoy wind speeds were typically in the range 2 to 15 m/s, with occasional observations up to 21 m/s. The few outlying points at low wind speed appear to correspond to reliable measurements from both buoys and satellite. The modified Chelton-Wentz model function [*Witter and Chelton*, 1991], which is used to convert radar measurements to wind speed, increases in slope at low winds. This would tend to increase the relative accuracy of low wind measurements. The scatter is ascribed to spatial variability and atmospheric stability effects, as discussed below.

Table 5 shows the results of the regression analyses carried out on data from all buoys. Calculated intercept values are made variable by the outlying points at low wind speeds. Constraining the intercept to zero gives regression line slopes close

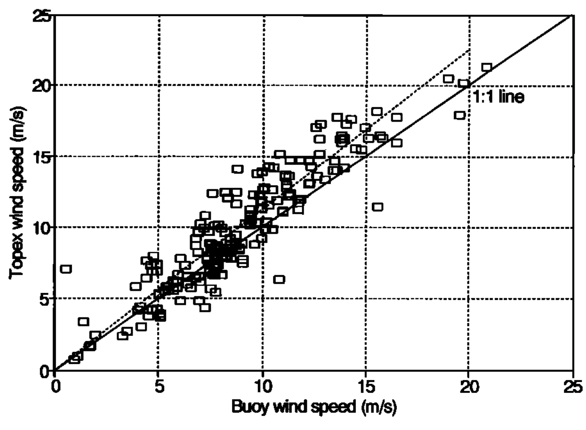

Figure 6. Comparison of wind speed values measured by the NASA altimeter on TOPEX and those measured by the three "outer" buoys located about 400 km west of the coast. Points should lie on the solid line for perfect agreement. Regression results for these points are included in Table 5. The dotted line shows the best fit to the data (forced through zero) and indicates a calibration (slope) difference of 10% (NASA altimeter high).

Table 5. Comparison of Wind Speeds Measured by the TOPEX/POSEIDON Satellite With Those Measured by the West Coast Canadian Moored Buoys and Corrected to a 19.5-m Reference Height

	Number of Observations	Rms Scatter	Intercept, m/s	Slope	Slope With Zero Intercept
46184	47	2.03	1.14 ± 0.95	1.03 ± 0.08	1.13 ± 0.03
46004	64	1.32	0.45 ± 0.44	1.05 ± 0.04	1.09 ± 0.02
46036	63	1.89	0.36 ± 0.47	1.05 ± 0.07	1.09 ± 0.02
46036, <10 km	31	1.35	−1.39 ± 0.80	1.28 ± 0.08	1.12 ± 0.03
46036, >70 km	32	2.19	1.45 ± 0.77	0.92 ± 0.10	1.06 ± 0.04
Three outer buoys					
NASA	174	1.75	0.48 ± 0.34	1.06 ± 0.04	1.10 ± 0.01
POSEIDON*	8	0.90	−1.06 ± 0.45	0.94 ± 0.08	0.85 ± 0.03
46205	56	2.15	1.67 ± 0.70	1.04 ± 0.08	1.12 ± 0.03
46208	40	2.88	2.48 ± 0.86	0.85 ± 0.11	1.10 ± 0.06
46147	39	2.22	0.75 ± 0.80	0.98 ± 0.12	1.09 ± 0.05
46207	62	2.10	1.38 ± 0.63	0.99 ± 0.07	1.13 ± 0.03
46132	11	1.54	2.05 ± 0.77	0.94 ± 0.12	1.14 ± 0.06
46206	70	1.88	0.00 ± 0.53	1.02 ± 0.05	1.02 ± 0.03
Nine inner and outer buoys					
NASA	452	2.05	0.73 ± 0.23	1.03 ± 0.02	1.10 ± 0.01
POSEIDON*	31	1.58	0.07 ± 0.42	0.88 ± 0.07	0.88 ± 0.03
46145	62	3.01	0.99 ± 0.87	0.93 ± 0.11	1.05 ± 0.05
46183	57	2.50	−0.77 ± 0.64	0.97 ± 0.08	0.90 ± 0.04
46185	80	1.95	−0.19 ± 0.42	1.02 ± 0.05	1.00 ± 0.02
46204	68	2.24	0.54 ± 0.50	0.99 ± 0.06	1.04 ± 0.03
46146	29	1.86	−0.42 ± 0.63	0.87 ± 0.11	0.81 ± 0.05
NASA,† <20 km	195	2.02	−0.06 ± 0.39	1.06 ± 0.04	1.06 ± 0.02
NASA, <10 km	84	1.76	−0.54 ± 0.43	1.11 ± 0.05	1.04 ± 0.02
NASA, <10 km, deep	43	1.36	−1.05 ± 0.55	1.23 ± 0.07	1.11 ± 0.03

Results shown are from regression analyses.
*One point has been omitted from an analysis of these data (see Figure 9).
†Data from buoys 46145 and 46146 were excluded. Four deep water and two shallow water buoys that meet the distance criterion were used for the <20 km analysis; two deep and two shallow buoys were used for the <10 km analysis; and only two deep water buoys were used for the "<10 km deep" analysis.

to 1.10 for comparison of the NASA altimeter with all exposed buoys and a mean slope of 1.10 ± 0.01 for the combined data from nine of these buoys.

Figure 7 shows the comparison when data are restricted to those from the TOPEX track that passes within 4 km of buoy 46036. The reduction in scatter is not as marked as in the case of wave heights. The 10% difference between TOPEX and buoy winds remains the same. Figure 8 shows the comparison for a larger amount of data from six different buoys, including some nearshore, for which distances were restricted to 20 km. Scatter is comparable to Figure 6. This gives a slightly lower mean slope (1.06 ± 0.02). Outlying points at A, B, and C in Figure 8 are discussed below. The 0.7 m/s minimum altimeter wind speed (see section 2) is apparent in the bottom left of Figure 8.

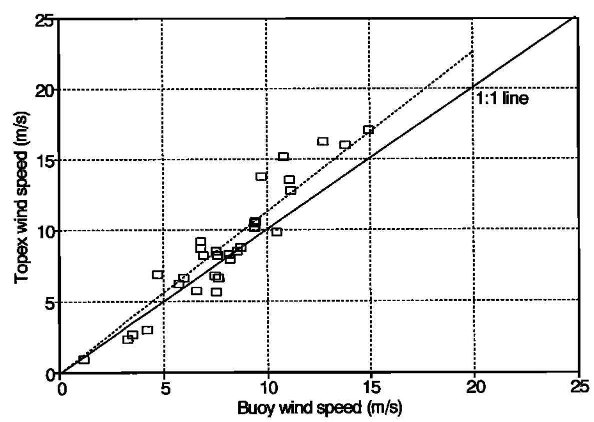

Figure 7. Comparison of wind speed values measured by the NASA altimeter on TOPEX and those measured by buoy 46036 using only data for which TOPEX measured within 10 km of the buoy. Points should lie on the solid line for perfect agreement. The dotted line shows the best fit to the data (forced through zero) and indicates a calibration (slope) difference of 10% (NASA altimeter high).

Dobson et al. [1987, Figure 11] show a 20% overestimate in Geosat wind speed using the Chelton-Wentz algorithm, which was greatly reduced when the modified Chelton-Wentz algorithm was introduced by *Witter and Chelton* [1991]. Neither study gives the value of the mean calibration difference, but that remaining in the work by *Witter and Chelton* [1991] appears less than 10%. *Ebuchi and Kawamura* [1994, Figure 3] show good agreement (less than 5% difference, but no error estimate given) between the mean calibrations of their buoy winds and TOPEX using the modified Chelton-Wentz algorithm for a 10-m reference height. They apply a 3% correction to allow for the 7.5-m height of the buoy anemometers. *Callahan et al.* [1994] show wind speed comparison, giving a slope of 0.96 ± 0.04 (intercept forced to zero) from 21 NASA altimeter passes exactly over a buoy. Of the three TOPEX comparisons, only the Canadian buoys measure low with respect to corrected data from the NASA altimeter.

4.2.2. TOPEX/buoy mean relations (POSEIDON altimeter). The much smaller amount of data from the POSEIDON altimeter gives a slope of 0.88 ± 0.03 (Figure 9 and Table 5). One point plotted in Figure 9, corresponding to a large dis-

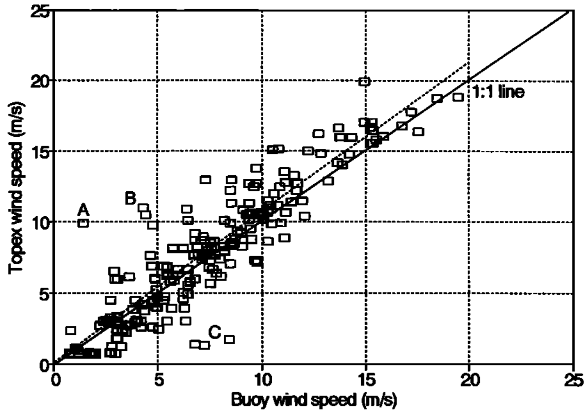

Figure 8. Comparison of wind speed values measured by the NASA altimeter on TOPEX and by buoys giving distance differences of less than 20 km. Data from buoys 46145 and 46146 were not used. Outlying points at A, B, and C are discussed in the text. Cluster C appears to indicate the effect of atmospheric stability when air temperature significantly exceeds surface water temperature. Points should lie on the solid line for perfect agreement. Regression results for these data are included in Table 5. The dotted line shows the best fit to the data (forced through zero) and indicates a calibration (slope) difference of 6% (NASA altimeter high).

crepancy in (low) wind speeds, is excluded from the regression analysis results in Table 5. Even with the small amount of data available, there is a significant, 25% difference between this value and the 1.10 ± 0.01 found for the NASA altimeter.

Any calibration difference between the two instruments will affect all TOPEX wind measurements and should show up in values of mean winds averaged over large areas. After cycle 16 all measurements in a cycle were made with only one or the other instrument. To check on the apparent calibration difference, mean winds were calculated from the MGDR for 5° ranges of latitude from 50°S to 50°N in the longitude range 180 to 230°E. This covers a large, open area of the central and eastern Pacific Ocean. The average wind speeds show large dips at POSEIDON cycles 20, 31, and 41 compared with the results from the NASA altimeter in other cycles. Overall mean wind was 7.44 ± 0.50 m/s. The mean of the three POSEIDON cycles was 5.65 ± 0.52 m/s, 31% lower.

This confirms the calibration difference found in the comparison with buoy measurements. From inspection of the MGDR it appears that the 0.7-dbar correction has been applied to data from the NASA altimeter but not POSEIDON. The revised calibration reduces the 0.7 dbar to about 0.6 dbar, equivalent to an increase in average wind speed of about 2 m/s, enough to remove this discrepancy.

Clearly, an improvement of the MGDR wind speed data set is needed before it can be used as a uniformly calibrated source of wind speed values. At present, the most immediate application of wind speeds from the two altimeters is to use them separately as inputs to two different empirical algorithms to correct electromagnetic bias on sea surface height measurements. For this, a consistent calibration is less necessary.

4.2.3. Scatter about the mean relations. Scatter about the mean regression lines using all data for each buoy, as shown in Table 5, is in the range 1.1 to 2.9 m/s, with the exception of buoy 46145 (rms scatter of 3.0 m/s), for which buoy and satellite measurement locations are from areas with different exposures to offshore conditions, as noted above. Scatter from the combined data for the three outer buoys and the NASA altimeter is 1.75 m/s, increasing to 2.09 m/s when inner buoys are included. Scatter for the POSEIDON data compared with outer buoys is less (0.9 m/s) when one point is excluded, but only eight data points then remain. Including the six inner buoys increases this scatter to 1.58 m/s.

These rms scatter values are comparable to the 2.2 m/s reported by *Dobson et al.* [1987] from a comparison of Geosat altimeter winds with buoy data for a maximum separation distance of 50 km and to the 1.9 m/s reported by *Witter and Chelton* [1991] when these same data were converted using the modified Chelton-Wentz model function. Dobson et al. found only a very small reduction in scatter (2.1 m/s compared with 2.2 m/s) when deep water buoys alone were used but report no comparisons for distances limited to less than 50 km. *Ebuchi and Kawamura* [1994] reported a similar rms scatter of 1.85 m/s for a maximum comparison distance of 100 km. *Gilhousen* [1987] presents data from pairs of buoys that show scatter of 1.3 m/s due to a separation of 40 km and 1.7 m/s at 109 km.

When the distance for the comparisons is restricted to 20 km (Figure 8), the scatter is almost unaffected at 2.02 m/s (Table 5). Further reduction of the distance limit to 10 km gives a drop, to 1.76 m/s. When data from shallow water buoys are excluded, the scatter drops to 1.36 m/s. *Ebuchi and Kawamura* [1994] report a drop in scatter for smaller comparison distances, in their case to 1.23 m/s rms at 50 km. Their three buoys are all more than 300 km from the coasts of major land masses. *Callahan et al.* [1994] show scatter of 1.41 m/s for 21 passes over a buoy nearshore.

The low scatter (1.36 m/s rms) at small comparison distances in deep water indicates that when real wind speed changes with distance are at least partially removed, the NASA instrument is giving a precision considerably better than the 2 m/s accuracy planned for TOPEX, without making any allowance for errors in the buoy measurements. These results are comparable to

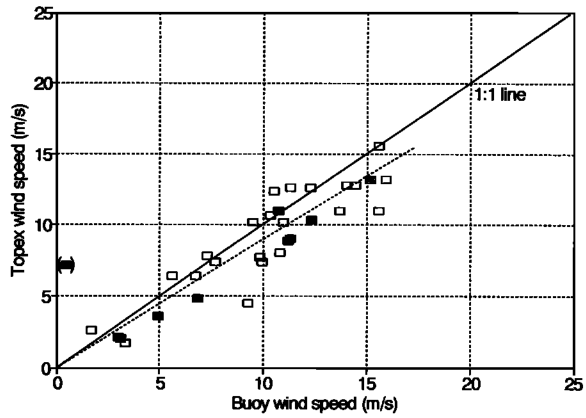

Figure 9. Comparison of wind speed values measured by the POSEIDON altimeter on TOPEX and those measured by the three outer buoys (stippled squares) and the six inner buoys (open squares). Points should lie on the solid line for perfect agreement. Regression results for these points, with the exclusion of the point in parentheses, are given in Table 5. The dotted line shows the best fit to the data (forced through zero) and indicates a calibration (slope) difference of 12% (POSEIDON low). There appears to be a 25% difference between the POSEIDON and NASA altimeter winds in the merged geophysical data record.

Monaldo's [1988] predictions for Geosat/buoy comparisons of 1.8 m/s scatter due to 0.9 m/s from the buoy, 1.2 m/s from the altimeter, and 1.0 m/s from using a maximum comparison distance of 50 km. At zero distance the predicted scatter would therefore be 1.5 m/s.

A large contribution to the scatter about the mean regression line in Figure 8 is made by outlying points at low wind speeds. Four points at A and B correspond to high TOPEX and low buoy winds measured by three different buoys (46204, 46206, and 46207) on four different TOPEX cycles (1, 17, 21, and 45). Two of these buoys are in shallow water near the coast, where smaller-scale variations in wind speed may have affected the comparisons. However, a similar point in Figure 9 (POSEIDON data) is from the offshore buoy 46004.

Similar points were found in the comparison for buoy 46208, giving the high scatter listed in Table 5. Five outlying points were all measured in July, four in 1992 and one in 1993. Omitting these points reduces the rms scatter for this buoy to 1.65 m/s, comparable to values for other buoys, and reduces the scatter for nine buoys combined from 2.09 to 1.92 m/s.

4.2.4. Wind shear and the effects of atmospheric stability. Variation of wind speed with height affects both the mean wind comparison and the scatter of individual measurements that may be affected by unusual stability conditions. The buoy anemometers are at about 5 m height above the water. TOPEX wind speeds are deduced from the microwave backscatter of the surface (sigma zero), which is controlled by small-scale roughness. On average, the modified Chelton-Wentz [*Witter and Chelton*, 1991] algorithm relates this to wind at 19.5 m, as noted above. Expected differences between measurements at these two heights are given by *Smith* [1988] as about 12% (TOPEX high) for neutral conditions (equal air and sea surface temperatures). This correction has been applied to the buoy data. For stable conditions (air warmer) the difference can be greater, especially at low wind speeds, but remains less than 22% for wind speeds above 8 m/s and air-sea temperature differences less than 3°C.

Both air and sea temperatures are measured by the buoys, so that the effect of atmospheric stability on this comparison can be assessed. The mean air-sea temperature difference was −0.7°C (air colder), with about 1/3 of the differences in the range 0 to −1°C. Thus most data were collected in slightly unstable conditions. Using a mean temperature difference of −0.7°C reduces the expected wind speed difference from 12% to about 11%. Weighting the factors given by *Smith* [1988] with the observed distribution of temperature differences for the whole data set leaves the difference unchanged at 12%.

Occasional periods of stable conditions under low wind do appear to cause significant errors. The three points at C in Figure 8 are from three different buoys and two different TOPEX passes showing buoy winds in the range 6 to 10 m/s and TOPEX winds less than 2 m/s. All three measurements were made on May 13, 1993. Data from four other buoys (for which distance differences were greater than 20 km, so that they were omitted from this sample) also showed a similar effect on this same day. Temperature measurements made on the buoy show that these satellite overpasses occurred during one of the relatively rare periods when air temperature was more than a degree warmer than water temperature.

These buoy wind speeds were in the range 6 to 10 m/s. Corresponding altimeter measurements gave about 1/4 of this amount. The mean relations given by *Smith* [1988] show that an air-sea temperature difference of 5 to 10° is needed to produce such a large speed difference, whereas the buoy measurements indicated differences of only about 1.5°. An adjustment of Smith's plots is needed, since these assume that air temperatures are measured at 10 m height, whereas the thermistors on the 3-m buoys are only 3 m above the water. However, even at the largest temperature difference of 10°C (air warmer) the observed wind speed of 8 m/s limits this correction to about 2°, insufficient to explain this discrepancy.

Still, the coincidence of unusual stable conditions with the large wind speed differences in Figure 8 appears significant. Buoy measurements show that air temperatures exceed water temperatures by over 1° in only about 5% of the hourly observations and 1.5° in only 2%. Also, buoy winds must exceed 5 m/s for the difference to appear significant in Figure 8.

4.2.5. Other possible sources of error. Buoy winds may be significantly in error in high wave conditions due to disturbance of the near-surface wind field by wave crests or to tilting of the anemometer. Vector average wind speeds would give a lower reading if wind direction (but not speed) is modulated by waves.

Gilhousen [1987] has reported that buoy wind speeds tend to be lower than those measured on an adjacent platform. He ascribed this to the difference between vector and scalar averaging, which in his study amounted to 7% (vector averaging lower). This would explain most of the 10% discrepancy found here. The Canadian buoys used in this study, at present, measure vector averages. Software on the buoys is being altered to record both scalar and vector averages. The storm wave study at buoy 46147 [*Skey et al.*, 1993], referred to above, is designed to investigate this further.

The Japanese buoys used by *Ebuchi and Kawamura* [1994] measure scalar averages of wind speed. U.S. buoys were converted from vector averaging to scalar averaging during the period 1988 to 1991. The winds reported by *Callahan et al.* [1994] and *Ebuchi and Kawamura* [1994] will therefore tend to be higher by this 7%.

4.3. Pressure Data

Although atmospheric pressure is not measured by TOPEX instruments, values are added to all data records for correction of altimeter ranges and provide a convenient way of verifying the calibration of the barometers on each buoy and of validating the pressure data itself. Pressure values in the TOPEX data are derived from global weather observations and models compiled by the European Centre for Medium-Range Weather Forecasts (ECMWF). It should be noted that some of the observations will be from these same buoys, but a larger amount of data is expected from nearby shore stations, which would dilute the buoys' contributions.

Atmospheric pressure values are inserted in the satellite data in the form of corrections to the range measured by the satellite due to the propagation delay experienced by the microwave radiation in passing twice through the atmosphere. This delay is equivalent to an apparent range increase of about 2.3 m for the entire atmosphere at a mean surface pressure of 1013 mbar. A change in the surface pressure of 1 mbar causes an apparent range change of 2.7 mm. Range corrections are given in the TOPEX data to 1 mm precision, equivalent to about 0.4 mbar.

Figure 10 shows the results of the comparison using data from all buoys. The mean regression line has a slope of 0.97 and shows a mean offset between the two data sets of only 0.1 mbar at 1015 mbar. Scatter about the line is 1.0 mbar rms. A

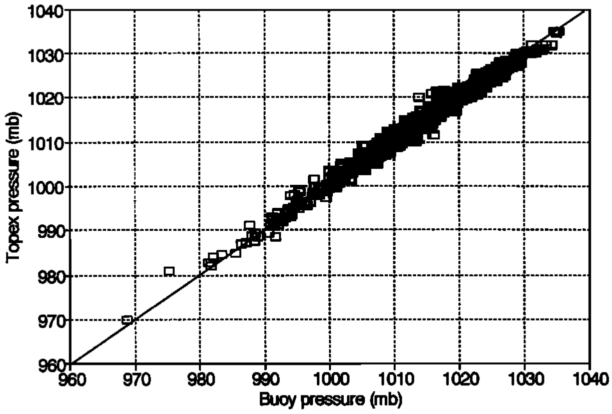

Figure 10. Comparison of surface atmospheric pressure values, as included in the TOPEX data set, and those measured by the moored Canadian west coast buoys. Points should lie on the solid line for perfect agreement. Regression results for these points and for each buoy separately are given in Table 6.

slope of slightly less than 1.0 might be expected due to the spatial smoothing that is applied to the pressure data in compiling a global data set. This smoothing would tend to raise or "fill in" small regions of low pressure and reduce the peaks of highs and would therefore reduce the slope of the regression line. This line corresponds to an overestimate of low pressures at 975 mbar by 1.2 mbar and an underestimate of highs at 1040 mbar by 0.4 mb.

Results of the regressions for individual buoys are shown in Table 6. ECMWF surface pressures are found to agree with buoy measurements to within 1 mbar rms. Data for individual buoys show small mean offsets of between −0.4 and +0.5 mbar, with largest offsets for the two buoys, 46131 and 46146, in the Strait of Georgia. These buoys also show anomalously low regression slopes of 0.90 and 0.91, respectively, nearly 10% below that required for agreement. They experience a relatively low range of pressure variations. These and three other buoys showing regression slopes below 0.95 all lie in the southern part of the study area. Calibration errors of 10% in the barometers seem large, but the calculated slopes apply only to pressure offsets from the mean, which is about 1015 mbar. A 10% error therefore results in pressure errors of less than 1 mbar for most of the data. It is possible that these apparent errors are the result of smoothing of extreme readings in the global maps, as noted above.

Table 6. Comparison of Atmospheric Pressure Values Derived From a Global Weather Model and Included in the TOPEX Data With Those Measured by the West Coast Canadian Moored Buoys

WMO Number	Number of Observations	Rms Scatter	Offset, mbar	Slope
46184	52	1.31	−0.37 ± 0.18	0.98 ± 0.01
46004	71	0.77	0.20 ± 0.09	0.98 ± 0.01
46036	68	1.07	−0.15 ± 0.13	0.95 ± 0.01
46205	71	1.18	0.35 ± 0.15	0.96 ± 0.01
46208	49	0.57	0.04 ± 0.08	0.97 ± 0.01
46147	43	0.77	0.02 ± 0.12	0.98 ± 0.02
46207	74	0.85	0.12 ± 0.10	0.99 ± 0.01
46132	14	1.24	0.11 ± 0.34	0.93 ± 0.03
46206	83	0.65	0.35 ± 0.08	0.94 ± 0.01
46145	81	1.11	−0.22 ± 0.14	1.00 ± 0.01
46183	79	1.03	0.09 ± 0.13	0.99 ± 0.01
46185	90	0.83	−0.02 ± 0.09	0.98 ± 0.01
46204	75	0.79	−0.05 ± 0.09	0.97 ± 0.01
46131	37	0.94	0.53 ± 0.15	0.90 ± 0.03
46146	74	1.10	0.52 ± 0.19	0.91 ± 0.02
Total	961	1.00	0.11 ± 0.03	0.97 ± 0.00

Results are from regression analyses.

5. Conclusions

Agreement between TOPEX and buoy SWH values are good enough to suggest that both systems are achieving their accuracy goals. A small (about 5%) calibration difference between the two types of buoys may need to be corrected. An additional difference between the mean satellite/buoy relationships for the outer and inner buoy groups disappears when comparisons are limited to distances less than 10 km. Similar satellite/buoy relationships to those found here for the inner buoys are apparent in the comparisons reported by *Dobson et al.* [1987] and *Ebuchi and Kawamura* [1994]. In both cases the minimum comparison distance was 50 km, and no separation was made between coastal and offshore buoy locations. *Ebuchi and Kawamura* [1994] report a mean overestimate of TOPEX SWH by 0.3 m. The present study suggests this should be reevaluated using only data with smaller distances between buoy and satellite measurements. *Callahan et al.* [1994] present data from 21 TOPEX passes over a buoy, giving an intercept of 0.08 ± 0.20 m and a slope of 0.98 ± 0.06, covering a relatively small range of SWH, but tending to confirm the present conclusion.

The present comparison shows NASA altimeter winds high by 10% and POSEIDON winds low by 12%. This NASA/POSEIDON difference is also evident in average wind speeds computed over large areas and needs to be resolved. Users of the MGDR data set need to be aware that the winds speeds refer to 19.5 m height and need additional corrections for calibration adjustments made after the data were released.

The Canadian west coast buoy array appears to be measuring wind speeds about 10% low compared with the NASA altimeter, the U.S. buoy [*Callahan et al.*, 1994], and three Japanese buoys [*Ebuchi and Kawamura*, 1994]. The results of *Gilhousen* [1987] suggest that a 7% underestimate of wind speed by buoys should be expected because of the vector wind speed averages used.

The scatter of points about the mean regression lines for wave heights goes down from 0.35 to 0.15 m as the maximum comparison distance is reduced from 100 to 10 km. The scatter for wind speeds is close to the ±2 m/s expected for TOPEX when comparisons out to 100 km are used but is considerably lower (1.36 m/s) when this distance is reduced to 10 km and data are restricted to those from deep water buoys. Some of the systematic error and remaining scatter may be due to buoy errors in measuring wind close to the sea surface at a height comparable to that of waves, and some may be due to the indirect nature of the satellite measurement, which should relate more directly to wind stress. The effect of air-sea temperature difference is apparent in one event in the data.

The above conclusions show the importance of using only the smallest possible distances when validating sensor performance. For validating the altimeters, the west coast Canadian buoy array provides comparisons over distances of less than 10 km. For validating individual buoys in the array, data from distances up to at least 46 km (Table 1) need to be used.

Although altimeter winds are limited in coverage and lack of directional information compared with scatterometer winds, the present comparison shows them to be precise enough to be useful for a variety of regional and large-scale studies. It is recommended that the above mentioned satellite calibration problem be resolved as soon as possible.

Apart from uncertainties associated with the wind speed difference, this comparison also confirms the high quality of data from the buoys off the west coast of Canada. Gaps in the buoy data records point to the problems of maintaining stations in the harsh ocean environment. The comparison with satellite data also shows temporary problems in buoy calibration. Ongoing research is directed at reducing these.

Near a given location, satellite observations are distributed much more sparsely in time than data from a suitably placed buoy, but in space, satellites provide "global" coverage in the diagonal ground track pattern, part of which is shown in Figure 1. TOPEX can therefore be used as a transfer standard between buoy arrays anywhere in the world. The only limits to this are contamination of satellite data by nearby land, which can be subtle, as shown here, and the latitude coverage of TOPEX, which extends to 66° north and south.

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