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Corrected Spectra of Wind Speed and Significant Wave Height

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In a recent paper (Monaldo, 1988) I presented spatial spectra of wind speed and significant wave height (SWH) variance. The spectra were calculated from spatial variations of wind speed and SWH as measured by the Seasat and Geosat radar altimeters. It has recently come to my attention that these spectra were incorrectly calculated. The shape of the corrected wind speed variance spectra no longer agree with theoretical predictions by Thompson (1973). The expected differences between two altimeter wind speed or SWH measurements separated a given distance apart were calculated in the time domain and not by inverse Fourier transformation of the spectra. The expected differences given by Monaldo (1988) are therefore unaffected by the errors in the calculation of the SWH and wind speed spectra.

1. INTRODUCTION

There are many reasons why estimates of wind speed and significant wave height (SWH) made from a spaceborne radar altimeter will differ from in situ estimates obtained from buoys. These reasons, which were enumerated by *Monaldo* [1988], include (1) buoy instrumentation limitations, (2) temporal proximity, (3) spatial proximity, (4) sampling variability, (5) altimeter instrumentation noise, and (6) imperfections in the algorithms relating altimeter radar measurements to wind speed or SWH.

The third source of difference between altimeter and buoy estimates, spatial proximity, refers to the fact that when buoy and altimeter estimates are compared, they are rarely exactly colocated. Usually, there is some spatial separation between places in the ocean from which the estimates are obtained. For example, *Dobson et al.* [1987] compared buoy and altimeter wind speed and SWH estimates when the minimum spatial separation between the two fell within the windows of 50, 100, and 150 km. In general, the greater the spatial separation, the greater the expected difference between the buoy and altimeter wind speed and SWH estimates.

In an attempt to estimate the magnitude of this effect, the spatial variability of wind speed and SWH were examined by calculating the spatial spectra of Seasat and Geosat altimeter-derived estimates of wind speed and SWH. A coding error in the computer program which calculated these spectra has been found. In this brief correspondence, this error will be described, and the consequences of this error on the conclusions of *Monaldo* [1988] will be given.

2. CALCULATION OF SPECTRA

The spectra of wind speed and SWH variance from Seasat and Geosat altimeter measurements were obtained by first breaking up contiguous ground tracks of data into segments of 512 points. Each point in the segment represents a 1-s average of altimeter estimates of either wind speed or SWH. Given a ground track velocity of about 7 km/s, an entire segment represents about 3500 km of data. Any dropouts in the data were filled in by linear interpolation across the data gap. Segments with more than 10% bad data were discarded. Subsequently, the mean value of wind speed or SWH from each segment was subtracted out and a Fast Fourier Transform (FFT) computed. No window was applied to the data.

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To calculate the corresponding variance spectrum, the FFTs of the segments were to be squared and then normalized to the variance in the original segments. Unfortunately, the computer code incorrectly squared the FFTs twice. As a result, the variance spectra presented by *Monaldo* [1988] have a slope as a function of wave number that is too large.

For the case of wind speed, the spectra presented were represented as being proportional to k^{-3}, where k is wave number on spatial scales from 300 to 25 km. Although this previous value agreed with the theoretical predictions of *Thompson* [1973], it is not correct. The true slope is closer to -1.7. The reader is directed to *Freilich and Chelton* [1986] both for a discussion of predicted slopes of wind spectra and for spectra of vector wind components computed from Seasat scatterometer data.

In the case of SWH, the spectra given by *Monaldo* [1988] show a slope of -2. The true value is closer to -1.4. Figure 1 shows the average of 100 Seasat wind speed and SWH spectra, sampled from the whole globe, calculated correctly. Graber, in an unpublished manuscript, has recently performed an extensive spectral analysis of both Seasat and Geosat altimeter wind speed and SWH. The spectra shown in Figure 1 are of the same general character and exhibit the same slope as a function of wave number as given in Graber's unpublished manuscript. The reader is directed there for a comprehensive look at such spectra. His spectra are calculated for various geographical regions at various times of the year.

The spectra shown by *Monaldo* [1988] were not the primary focus of that paper; rather, they were used as means to estimate how the spatial variability of wind speed and SWH affect the comparison of spatially separated altimeter and buoy data. The expected difference between two altimeter estimates of wind speed or SWH separated by a given distance was computed from the autocorrelation functions of wind speed and SWH.

We can represent the spatial variations of wind speed and SWH measured by an altimeter as $u(x_i)$ and $h(x_i)$, respectively, where x_i is equal to $i\Delta x$. The value Δx is the distance between two adjacent altimeter measurements. The autocorrelation functions of wind speed and SWH as a function of x_m' equal to $m\Delta x$ can be calculated two different ways.

One way is to compute the inverse Fourier transform of the wind speed and SWH spectra. Specifically, if $S_u(k_l)$ and $S_{\mathrm{SWH}}(k_l)$, are the average wind speed and SWH variance spectra as a function of wave number ($k_l = l\Delta k$), then their autocorrelation functions for any x_m' are given by

$$\rho_u(x_m') = \Delta k \sum_{i=1}^{512} S_u(k_l)\exp\left(j2\pi \frac{x_m' k_l}{511\Delta x}\right) \qquad (1)$$

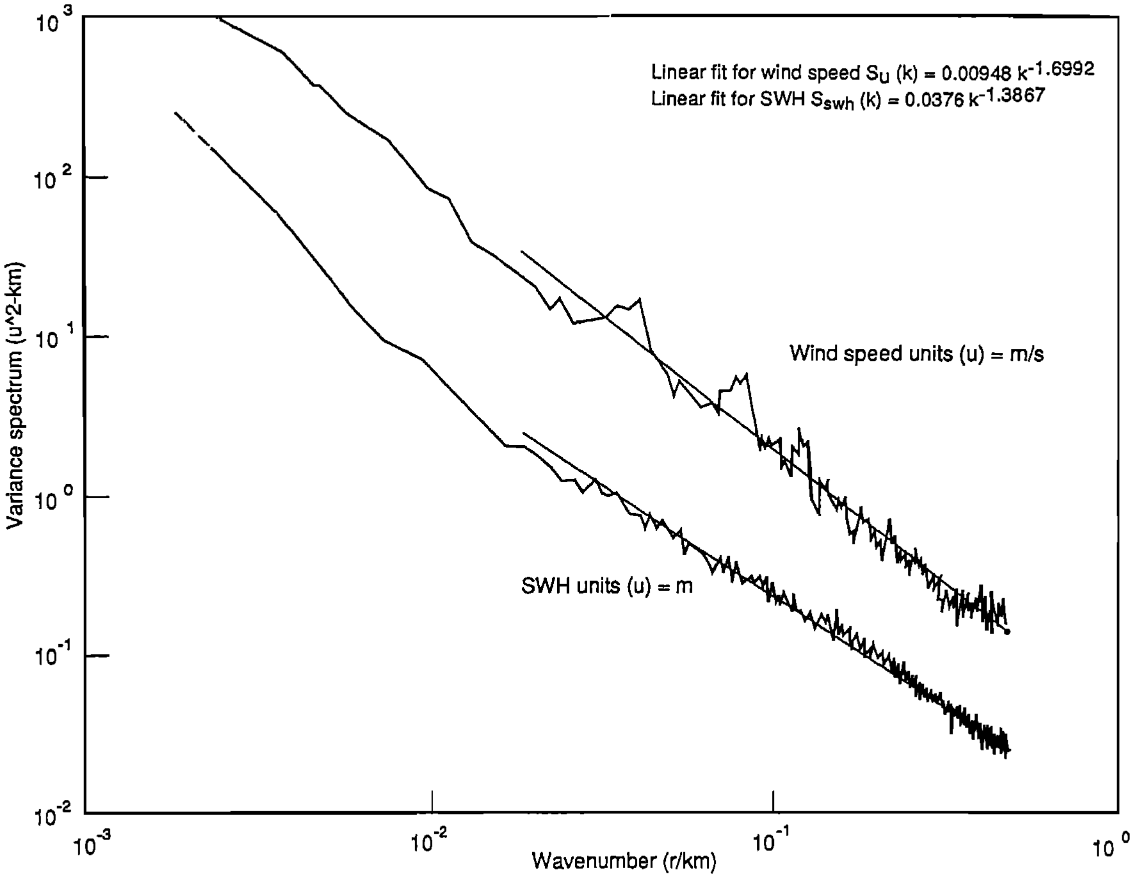

Fig. 1. The average wind speed and SWH variance spectra from 100 segments of Seasat altimeter data distributed over the globe. These spectra were computed without the coding error mentioned in the text. Note that the slope of the spectra as function of wave number is about a factor of 2 smaller than those shown by *Monaldo* [1988]. The straight lines are linear, least squares fits to the logarithm of the spectra as a function of the logarithm of wave number for wavelengths shorter than 300 km.

and

$$\rho_h(x_m') = \Delta k \sum_{l=1}^{512} S_{\mathrm{SWH}}(k_l)\exp\left(j2\pi \frac{x_m' k_l}{511\Delta x}\right) \tag{2}$$

respectively.

The second way is to compute the autocorrelation function directly from the spatial series of wind speed and SWH, using the equations

$$\rho_u(x_m') = \frac{512\Sigma_{i=0}^{\mathrm{MIN}(511,i+m)} u(x_i)u(x_i + x_m')}{\mathrm{MIN}(512,\ i + m + 1)\ \Sigma_{i=0}^{511} u(x_i)u(x_i)} \tag{3}$$

and

$$\rho_h(x_m') = \frac{512\Sigma_{i=0}^{\mathrm{MIN}(511,i+m)} h(x_i)h(x_i + x_m')}{\mathrm{MIN}(512,\ i + m + 1)\ \Sigma_{i=0}^{511} h(x_i)h(x_i)} \tag{4}$$

respectively.

The results of these calculations for each of the segments can be averaged to yield the mean autocorrelation functions.

The autocorrelation functions used to generate the expected differences curves shown in Figures 11, 12, 15, and 16 of *Monaldo* [1988] were computed in the space domain and are therefore not subject to the errors found in the spectra shown in Figures 9, 10, 13, and 14 of the same paper. Hence the expected differences between altimeter and buoy estimates of wind speed and SWH given in Table 3 of *Monaldo* [1988] stand. Figure 2 is a graph of the autocorrelation functions computed directly from the data segments used to compute the spectra shown in Figure 1.

Figure 3 is plot of the expected differences between altimeter wind speed and SWH estimates separated a given distance apart as computed using the autocorrelation functions shown in Figure 2. These graphs are very similar to the one presented in Figures 11, 12, 15, and 16 of *Monaldo* [1988]. The expected difference curves were used by *Monaldo* [1988] to estimate the effect of spatial proximity on buoy and altimeter comparisons of wind speed and SWH. The values given in Table 3 of *Monaldo* [1988] are still valid in spite of the errors made in the calculation of the wind speed and SWH variance spectra.

It is worth mentioning here that the spatial autocorrelation functions given here and by *Monaldo* [1988] show a slower decorrelation with distance than those presented in Graber's unpublished manuscript. This difference, it turns out, is a result of a subtle difference calculation procedures.

In this correspondence and in the *Monaldo* [1988] paper, segments of 512 points were used to calculate spectra an autocorrelation functions. The mean wind speed and SWH were removed from each segment. Graber (1990) uses smaller segment lengths of 256 points from which the mean is removed. However, if a linear trend as well as mean is removed from the 512-point length

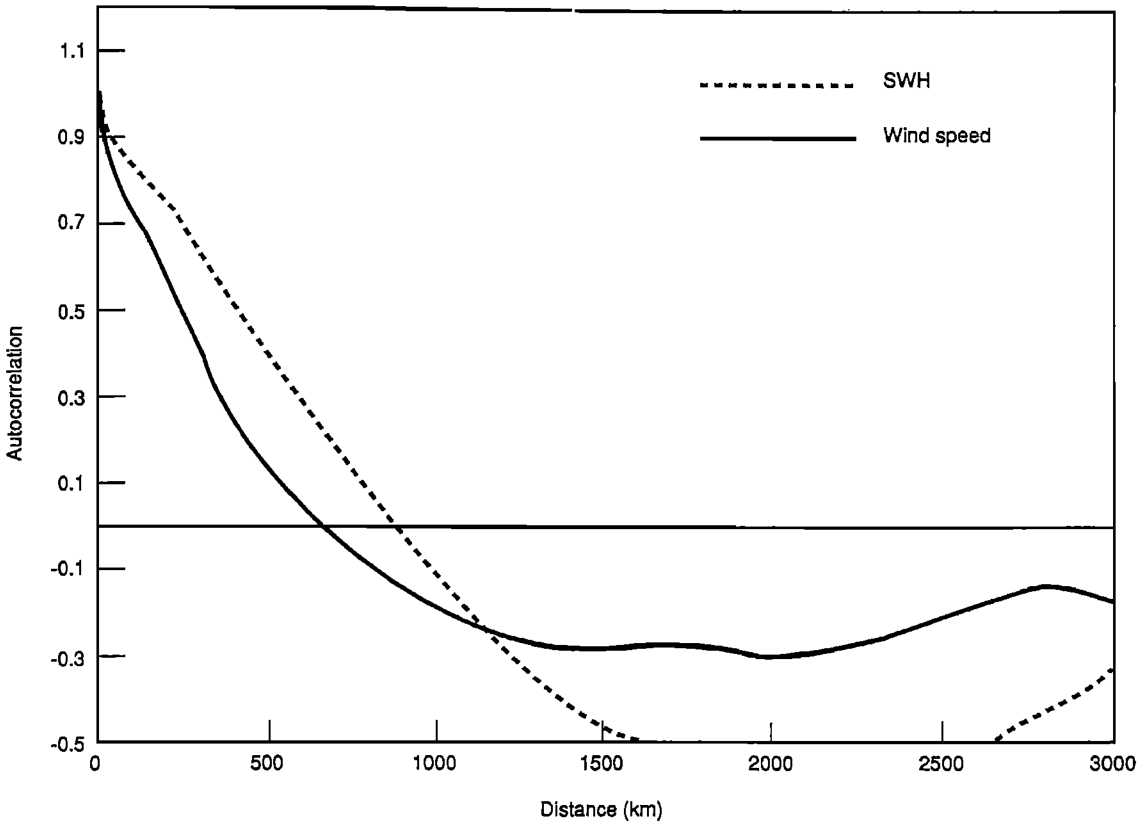

Fig. 2. The average autocorrelation function of wind speed and SWH computed from the same data base as was used for the spectra shown in Figure 1. These autocorrelation functions were computed in the space domain and not from the spectra.

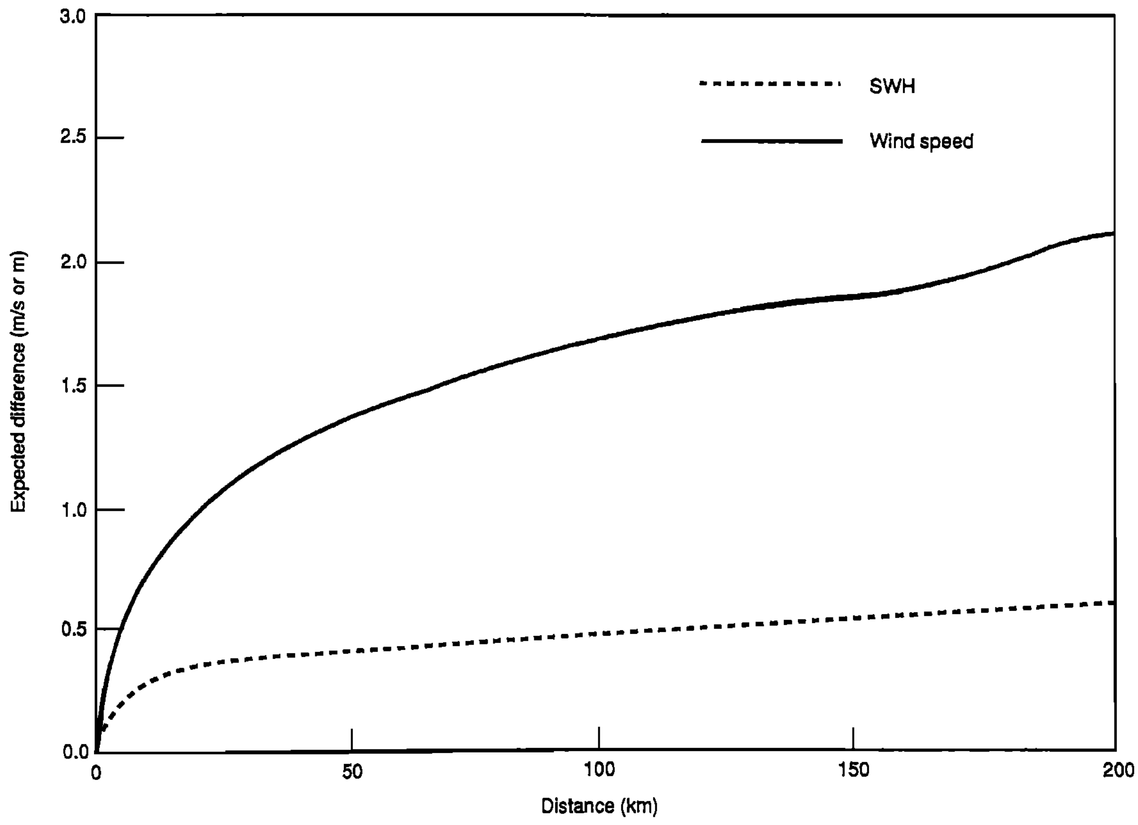

Fig. 3. The expected difference between two altimeter wind speed or altimeter measurements separated by a given difference. These curveswere calculated from the autocorrelation functions displayed in Figure 2. These are consistent with Figures 11 and 15 of *Monaldo* [1988].

segments before calculation of the autocorrelation function, the resulting autocorrelation functions more closely resemble those from the 256-point segments.

The original purpose of *Monaldo* [1988] was to use the autocorrelation function to estimate the expected difference between measurements taken a given distance apart. When comparing measurements made between an altimeter and, for example, a buoy, it is not possible to remove a trend from the local wind speed or SWH field. Therefore the method of computing the autocorrelation functions used here and by *Monaldo* [1988] are more appropriate for addressing the question of spatial proximity in buoy-altimeter comparisons.

In addition, it is interesting to note that *Dobson et al.* [1987] found that the root-mean-square (rms) deviation between buoy and Geosat altimeter wind speed measurements, when the measurements were separated by at most 50 km, was between 1.7 m/s and 1.9 m/s. The predicted rms difference from *Monaldo* [1988] was 1.8 m/s. Of that total, 1.0 m/s was estimated to be due to effect of spatial proximity. Using the more rapid decorrelation function given by Graber (1990) would result in a contribution of 1.5 m/s from spatial proximity, and the total expected rms difference between altimeter-buoy comparison would grow to 2.1 m/s. This value is higher, but not inconsistent with the observations of *Dobson et al.* [1987]

In summary, because of a computational error the wind speed and SWH variance spectra given by *Monaldo* [1988] exhibit too steep a slope as a function of wave number. The reader is directed to Graber (1990) for a complete set of computationally correct spectra. However, because the autocorrelation functions were computed from the original data and not through the wind speed and SWH spectra, the error in the spectra did not propagate through to the estimation of the expected difference in two measurements of wind speed and SWH separated by a given distance. The table of expected difference between buoy and altimeter measurements of wind speed and SWH given by *Monaldo* [1988, Table 3] remains essentially unaffected.

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