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On Using Significant Wave Height and Radar Cross Section to Improve Radar Altimeter Measurements of Wind Speed

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Wind blowing across the ocean surface generates small, centimeter scale roughness. The radar cross section (RCS) measured by spaceborne, nadir-looking altimeters operating at about 13.5 GHz is responsive to this roughness. Present altimeter algorithms use RCS to infer wind speed. We compare Geosat altimeter estimates of wind speed and nearly coincident estimates from NOAA data buoys to determine whether altimeter algorithms can be improved by using more of the information available from altimetry. We find that a marginal improvement in wind speed retrievals can be obtained by including additional RCS information and significant wave height in the retrieval algorithm. Perhaps most important, results also suggest that wind-wave growth is suppressed in the presence of preexisting ocean swell.

1. INTRODUCTION

Although the primary purpose of spaceborne radar altimeters has been the high precision measurement of the range between the satellite and the ocean surface to monitor both the Earth's geoid and sea height manifestations of ocean circulation, altimeters are also used to estimate wind speed and significant wave height (SWH). The high precision of altimeters, about 3 cm for Geosat [*Sailor and LeSchack*, 1987], necessitates pulse-limited radar systems. The modification of the return pulse from such a system provides a measure of wind speed and SWH.

Like the Skylab and Seasat altimeters, Geosat transmits pulses with a wavelength of 0.02 m. The measured radar cross section (RCS) of the ocean is sensitive to surface roughness on the scale of the radar wavelength and longer. Since the prevailing wind affects this roughness, wind speed is inferred from RCS [*Brown*, 1979].

SWH is estimated from the broadening of the return pulse. The return pulse from a flat surface exhibits a sharp leading edge. If ocean waves are present, the parts of the radar pulse reflecting from the crests have a shorter return-trip travel time than parts reflecting from troughs. The broader the return pulse, the larger the SWH [*Fedor et al.*, 1979].

The motivation behind this report is to determine if additional altimeter information, particularly SWH, can be used to improve altimeter wind speed retrievals.

Why might SWH be related to the altimeter wind speed retrieval? The answer lies in the physical link between buoy wind speed and RCS. A buoy estimates wind speed at a particular position by averaging wind speed measurements over a specified time period at a known height above the surface [*Gilhousen*, 1987]. Boundary-layer models are used to relate wind speed at a height to the wind just above the surface and a frictional wind speed u^*. The models are dependent upon the air-sea temperature difference and the roughness scales of the ocean [*LeBlond and Mysak*, 1978].

Frictional wind speed is a measure of the transfer of momentum from the wind to the ocean. A specific frictional wind speed acting upon the ocean for a sufficient period and over a sufficient area generates a fully developed wave height-variance spectrum. Several functional forms for this spectrum have been proposed [*Pierson and Moskowitz*, 1964; *Hasselmann et al.*, 1971]. There is particular controversy over the form of this spectrum at the high wave number end [*Bjerkaas and Riedel*, 1979; *Jackson*, 1987].

The height-variance spectrum provides the connection between wind speed and surface roughness. A geometric optics evaluation of the return from a nadir-looking altimeter predicts that RCS is proportional to the surface mean-squared-slope *MSS* [*Barrick*, 1968, 1974; *Brown*, 1978]. The larger the *MSS*, the rougher the surface, and the more electromagnetic energy is reflected away from nadir. Thus, the RCS is reduced. The wind-wave spectrum is the nexus between u^* and *MSS*.

If $S(k)$ is the wave height-variance spectrum as a function of wave number k, then the corresponding *MSS* of the surface is given by

$$MSS = \int_0^{k_{max}} k^2 S(k)dk \qquad (1)$$

where k_{max} is the diffraction limit of the radar. The value of k_{max} is on the order of $2\pi/\lambda_r$, where λ_r is the radar wavelength. Integration of this equation confirms that the relationship between *MSS* (and thus RCS) and u^* strongly depends on the functional form of the high wave number portion of the spectrum. Direct experimental confirmation of the general character of the *MSS*-to-wind-speed relationship has been made by *Cox and Munk* [1954], *Wu* [1972], and most recently by *Jackson* [1988].

The physical link between RCS and buoy wind speed can be affected by SWH in two ways. (1) The ocean waves present at a location are the combination of locally generated wind waves and waves generated elsewhere which have propagated into the area. The result is a larger *MSS* than could be expected purely on the basis on the local wind. For such a case, wind speeds would be overpredicted. (2) There is evidence from wave tank [*Donelan*, 1987; *Wu*, 1977] and field [*DeLeonibus*, 1971; *Geernart et al.*, 1986] studies which suggest that preexisting waves can reduce the input of wind energy to the surface, altering the expected wind-wave spectrum. The altimeter-estimated wind speed, in this case, would be lower than the buoy wind speed. The two effects are thus in opposite directions. Given this background, we hypothesize that residual differences between buoy- and altimeter-estimated winds might be a function of SWH.

2. REGRESSION ANALYSIS

The approach taken here for the incorporation of additional parameters into the altimeter wind speed algorithm is one of multiple linear regression. The perfect buoy versus altimeter wind speed

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relationship is linear with slope 1, no offset, and minimum residuals. The addition of new variables to the regression model is beneficial if the residuals are reduced by a statistically significant amount [*Draper and Smith*, 1981].

We start by defining the wind speed estimated by buoys to be y, the dependent variable. We further define x_1, the first independent variable, to be the wind speed predicted from the altimeter RCS measurement using either the smoothed-Brown (SB) [*Goldhirsh and Dobson*, 1985] or the *Chelton and Wentz* [1986] (CW) algorithm. The buoy wind speed is then predicted by the equation

$$y = a_0 + a_1 x_1 \tag{2}$$

where a_0 and a_1 are chosen to minimize the residual differences between buoy winds and those estimated from the linear model. It is important to recognize that x_1 is the wind speed calculated from the algorithms as specified by their originators. The wind speed estimated from the right-hand side of (2) is the result of multiplying the algorithm prediction by a constant and adding a bias, i.e., fine-tuning either the smoothed-Brown (u_{SB}) or Chelton-Wentz (u_{CW}) wind speed prediction.

The model is extended to include an additional variable x_2, (for example, SWH as measured by the altimeter), as shown:

$$y = a_0 + a_1 x_1 + a_2 x_2 \tag{3}$$

The coefficients a_i are selected by linear regression. If the residuals are reduced by a statistically significant amount, then the addition of this extra variable is concluded to improve altimeter performance.

The data base used here consists of a set of 236 pairs of buoy and Geosat altimeter wind speed estimates. The buoy estimates were obtained from a network of operational buoys maintained by the National Data Buoy Center of NOAA. All buoy wind speed estimates are the result of 8.5-min averages and are normalized to a height of 10 m above the surface. The maximum spatial and temporal separations between buoy and altimeter estimates allowed are 50 km and 30 min, respectively. Any single RCS measurement used to generate a single wind speed estimate is the mean RCS calculated over 5 s of altimeter pulses. During culling to reach the 236 comparison pairs, a number of potential pairs were excluded because of the proximity of the altimeter measurement to land or for other obvious errors [*Dobson et al.*, 1987].

We considered separately the addition of three different parameters as a second independent variable in (3): RCS, SWH, and "excess SWH". Even though the SB and CW algorithms are based on RCS, if they do not exhaust the information content of RCS, there may be some residual correlation between buoy-altimeter wind speed residuals and RCS. RCS is thus the first additional variable to be examined.

The reasons for suspecting that SWH might affect the wind speed retrieval algorithm were discussed earlier. Additionally, we considered "excess SWH", defined here as the portion of the altimeter-estimated SWH in excess of what is expected on the basis of the altimeter-estimated wind speed and the Pierson-Moskowitz wind-wave spectrum. Although this spectrum is not universally accepted or even believed to be universally applicable by those who accept it, *Mognard et al.* [1983] successfully used this parameter to identify the presence of swell in a wind-wave sea. The presence of such swell may partially explain the differences between altimeter and buoy wind speed estimates.

3. RESULTS AND CONCLUSIONS

Even given perfect altimeter algorithms, buoy and altimeter wind speeds will necessarily differ. The reasons for these differences are associated with the disparate manner with which buoys and altimeters sample the temporally and spatially varying wind field and the fact that the comparisons are rarely made at precisely the same time and place. In addition, both measurements are encumbered with inherent instrumental limitations [*Monaldo*, 1988]. Since these factors will cause the differences between buoy and altimeter winds to be randomly distributed, it is possible that the inclusion of an additional variable in a multiple linear regression model will fortuitously reduce residuals. We must be careful to distinguish flukes from statistically significant reductions in residuals.

Table 1 lists the a_i coefficients, the resulting residual mean-squared-differences, and the F value resulting from the multiple linear regressions. The F value is used in an analysis-of-variance test to assess the confidence with which we may conclude that the inclusion of an additional variable results in a statistically significant reduction of residuals. These confidence levels, rounded to the nearest 1%, are also given in Table 1. A listing of 100% indicates that the confidence level is greater than 99.5%. Note that the most significant improvement in residuals results from the simple multiplication by a constant and addition of a bias to the u_{SB} and u_{CW} wind speeds. After this fine-tuning the two algorithms have statistically equivalent residuals.

The addition of RCS to the linear regression model using u_{SB} reduces residuals by 2%. While small, the F value of 4.69 suggests a 99% certainty that the improvement is statistically significant. By contrast, the addition of RCS in a regression with u_{CW} has an F value of only 0.38. The addition of a term linear in RCS does not improve the CW algorithm.

Both the SB and CW algorithms exhibit some improvement by the inclusion of SWH as an additional parameter. The F values of 1.63 and 1.45, suggest that there is a greater than 75% (80%

TABLE 1. Linear Regression Results

x_1	x_2	a_0	a_1	a_2	Residuals, m^2/s^2	F Value	Confidence Level
					8.115		
u_{SB}	None	1.050	0.882	None	4.035	236.65	100%
u_{SB}	RCS	−31.563	1.851	2.368 m s^{-1} dB^{-1}	3.972	4.69	99%
u_{SB}	SWH	1.148	0.817	1.193 s^{-1}	4.024	1.63	80%
u_{SB}	Excess SWH	1.118	0.870	0.217 s^{-1}	4.047	0.29	17%
u_{CW}	None	2.838	0.577	None	4.004	242.29	100%
u_{CW}	RCS	− 2.567	0.687	0.418 m s^{-1} dB^{-1}	4.014	0.38	32%
u_{CW}	SWH	2.806	0.537	0.182 s^{-1}	3.996	1.45	76%
u_{CW}	Excess SWH	3.123	0.527	0.156 s^{-1}	3.964	3.36	98%

for SB, 76% for CW) certainty that the associated reduction in residuals is statistically significant. Although these levels of confidence are not particularly high, it would seem prudent not to discount the effect of SWH on wind speed retrievals. However, one would be justified in refusing to alter present wind speed algorithms without substantially greater confidence levels. A larger sample of buoy-altimeter comparisons would be more conclusive.

Using excess SWH as an additional parameter in a multiple linear regression seems to have far more impact when paired with u_{CW} than with u_{SB}. The reduction in residuals resulting from using excess SWH in conjunction with u_{SB} is both small and statistically insignificant. However, when used in conjunction with u_{CW}, the reduction in residuals is statistically significant to the 98% level. The a_2 coefficients calculated by least-squares regression for the cases when u_{SB} is paired with SWH and when u_{CW} is paired with excess SWH are positive. This suggests that the greater the SWH or excess SWH, the more wind speed is underpredicted by using either u_{SB} or u_{CW} wind speeds alone. This result, perhaps the most significant contribution of this paper, is consistent with the observation that wave growth is suppressed in the presence of preexisting swell. Furthermore, this result is associated with 80% and 76% confidence levels when SWH is paired with u_{SB} and u_{CW}, respectively, and 98% when excess SWH is paired with u_{CW}.

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