THE WAVENUMBER SPECTRA OF SCATTEROMETER-DERIVED WINDS

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ABSTRACT

Spaceborne scatterometers are the only proven method for global all-weather measurement of vector winds at the ocean's surface. Such measurements are critical inputs in studies of oceanic circulation and air/sea interaction where the time variability of the surface wind field and the wind stress curl drive the ocean; hence, our interest in the spectrum of the surface wind field. In this paper we address the accuracy of scatterometer-derived winds using a frequency domain analysis and simulation.

While using simulation of SASS measurements to evaluate new methods of wind estimation from scatterometer measurements, the wavenumber spectra of the SASS-derived wind fields were observed to be accentuated relative to the input wind field. If similar accentuation occurs in winds estimated from actual scatterometer measurements, the wind spectrum will be overestimated, which may lead to erroneous inputs to ocean forcing models.

This paper reports the results of extensive simulations designed to test this observation. In these experiments actual SASS measurements of the normalized radar backscatter (σ^o) over an orbit (rev) were used as a template to generate simulated σ^o measurements. Pointwise wind estimation (traditional wind retrieval) of winds from the simulated σ^o measurements was then done with the ambiguity closest to the true wind selected as the unique wind vector estimate. For comparison, winds were also estimated using a new model-based approach. After wind retrieval, the spectra of the estimated wind fields were computed and compared to the input wind field. The high wavenumber portion of the spectra of the point-wise estimated winds was higher than the spectra of the true winds by an amount which depended on the wind speed variance. The model-based spectra exhibited a high degree of agreement with the true input spectra. We discuss the implications these results have for actual SASS data.

INTRODUCTION

From measurements of the normalized radar backscatter (σ^o) made by SASS, the near-surface wind over the ocean can be inferred using a geophysical model function relating σ^o and the vector wind, e.g., the Wentz geophysical model function [4]. Traditionally, a point-wise approach, in which only the σ^o measurements corresponding to a particular sample point are used to estimate the wind at that sample point, has been used to retrieve SASS winds. Since point-wise wind retrieval produces non-unique estimates of the wind vector, "ambiguity removal" must be used to select a unique wind vector estimate [5]. A new model-based approach to wind retrieval estimates the wind field over the entire swath by estimating the parameters of a model of the underlying wind field directly from the measurements of σ^o; the wind field estimate is computed from the estimated model parameters. This method generally produces more accurate estimates of the wind vector field [3].

Because the wind field model used in the model-based retrieval approach is based on simplified dynamics, it may smooth sharp fronts. To evaluate the effects of this smoothing, a frequency domain analysis approach is used. By using simulation, the ability of the scatterometer measurements and the retrieval scheme to accurately determine the wind field spectrum can be studied for both pointwise and model-based retrieval.

Various theories of wind turbulence inertial subranges in the wind give rise to slightly different power law predictions for the wind spectrum. Freilich and Chelton [1] first used Seasat Scatterometer (SASS) wind vector measurements to estimate the one-dimensional wavenumber spectra of oceanic surface winds over scales from 200 to 2200 km in several longitudinal bands. They found the spectra of the meridional (u) and zonal (v) wind components to be consistent with a power-law dependence on wavenumber of k^{-2} over scales of 200 to 2200 km. Crucial to this study is the ability of the scatterometer system (instrument and wind retrieval) to accurately determine the wind spectrum over these scales.

When comparing the estimated spectra of the point-wise and model-based wind fields derived from simulated σ^o measurements (in which the true wind field is known), it was determined that the point-wise retrieval method over estimated the wind wavenumber spectra at large wavenumbers (corresponding to scales less than 600 km). The model-based approach accurately estimated the wavenumber spectra. In this paper we explore these results and consider the implications these results have on wind estimation from actual SASS data. This paper is organized as follows: The simulation and spectrum computation method is first described. Then the results of a variety of experiments designed to quantify the spectral error are presented. Finally, we summarize our observations and discuss the implications of these observations.

SIMULATION APPROACH

To initially evaluate spectral estimation accuracy of SASS, we have adopted a simulation-based approach in which the true wind field is known. We can then compare the true wind spectra with the scatterometer-derived spectra. Because of the lack of wide area wind measurements with a resolution commensurate with the scatterometer measurement resolution (50 km), we have been forced to use simulated wind fields. These were generated from 1.875° resolution European Center for Medium-Scale Weather Forecasting (ECMWF) wind fields which were interpolated to 10 km resolution. Nondivergent, isotropic, small-scale variability with a spectrum consistent with ak^{-2} was then added. For a given 2000×2000 km region of the ECMWF wind field the value of a was selected to be consistent with the ECMWF wind field spectrum when adding the small-scale variability. Seven ECMWF fields were selected to span a wide range of meteorological conditions, including sharp fronts and small-scale cyclones. These wind fields have been used previously to evaluate and optimize point-wise retrieval for the NASA Scatterometer (NSCAT) [5]. While the simulated wind fields may not accurately model very small scale variations (e.g., small-scale fronts), in this study we are primarily interested in the *difference* between the input (true) wind field and the scatterometer-derived field. The results are only slightly dependent on the actual spectral shape.

To generate the simulated σ^o measurements from actual SASS measurements, randomly selected ascending SASS orbits (revs) pass-

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ing over the Pacific were used as templates. The actual σ^o measurement was replaced by a simulated σ^o measurement which was computed using the actual SASS σ^o measurement geometry, the simulated wind field, and the Wentz geophysical model function. Monte Carlo noise, with a noise variance computed from the actual α, β, and γ parameters of the K_p equation and the simulated σ^o, was added to the simulated σ^o measurements. Multiple realizations of the Monte Carlo noise were generated for each true wind field and for each orbit template. Each true wind field was observed with several orbit templates.

Pointwise estimation (traditional wind retrieval) of winds from the simulated σ^o measurements was then done on a 50 km grid by "binning" the σ^o measurements into the grid and using only the measurements which fell into each grid element to retrieve the wind for that element. The ambiguity closest to the true wind was selected as the unique wind vector estimate; thus, the pointwise wind vector estimate represents ideal ambiguity removal, i.e., the best that can be done with pointwise retrieval.

For comparison, winds were are also estimated using the model-based approach. The wind field model is based on the geostrophic approximation and simplistic assumptions about the wind field vorticity and divergence, but includes ageostrophic winds [2]. In model-based estimation, the wind field model parameters are estimated directly from the scatterometer measurements of the radar backscatter of the ocean's surface using maximum-likelihood (ML) principles. The wind field estimate is then computed from the estimated model parameters. For this experiment, the initial value for ML optimization was determined from the pointwise wind estimate [3]. A 2nd order parameterized boundary condition (PBC) model was used [2].

After wind retrieval, the one-dimensional (in the along-track direction) spectra of the u and v components of estimated wind fields were computed using an approach similar to Freilich and Chelton [1] but using the 50 km resolution winds. The one-dimensional spectra were separately computed in 5 regions defined by the latitude bands given in Table 1. Within a given latitude band, an along-track sequence of u and v components of the wind was extracted for each 50 km cross-track bin. Data gaps of a single missing wind vector were filled using linear interpolation. Sequences with longer gaps or containing land were discarded. To precisely compare the spectra, only cell sequences in which both pointwise and model-based estimates were valid were used (the model-based retrieval method has fewer gaps). The spectral estimates were averaged over rev, realization, and true wind field to provide an "expected" scatterometer measurement capability.

RESULTS AND OBSERVATIONS

A sample result (for region 1) is shown in Fig. 1. We note the approximately k^{-2} rolloff of the true wind component spectra. As evident, the pointwise wind estimates overestimate the high wavenumber portion of the spectra relative to the spectra of the true winds for both the u and v components of the wind field, with a "knee" in the spectra; the pointwise spectra follow the true spectra closely for wavenumbers less than $k \approx 10^{-2}$ but are nearly flat for $k > 10^{-2}$ (corresponding to scales less than 630 km). The spectra of the model-based winds, however, exhibit a high degree of agreement with the true input spectra.

Several of the other study regions had a larger wind speed variance, resulting in higher-level spectra for the true wind field. The pointwise wind spectra were always larger than the true for all regions; however, for the regions with a much higher wind speed variance, the pointwise spectra deviated only slightly from the slope of the true wind field spectra. This pattern did not depend on which revs (i.e., the orbital sampling geometry) were used to generate the simulated measurements. The pattern varied little for different Monte Carlo realizations. Some variation with the true wind fields used was noted, although this could be attributed to the differences in the wind variance and was consistent with the following hypothesis.

On the basis of these observations, and the results of the experiments which follow, we postulate that the observational noise ("communication K_p") results in a spectral "noise floor." The noise floor introduces high frequency noise into the pointwise winds, causing the pointwise winds to overestimate the spectra for high wavenumbers. In addition, when the true component spectrum drops below a threshold value, the corresponding spectrum of the pointwise winds becomes fixed at the threshold value and does not reflect the true wind spectrum.

To test this hypothesis we conducted a series of experiments in which we modified the wind speed variance (true wind spectra level) and the K_p of the σ^o measurements. The wind speed variance was modified by multiplying the true wind fields by a constant A and processing the modified fields as before. The resulting fields exhibited higher or lower wind speed variance but had precisely the same spectral shape. Values of A from 0.2 to 2.0 were considered, though at the extremes many wind speeds fell outside of the range (0.5 to 50 m/s) of the geophysical model function, resulting in gaps in the component sequences. The K_p level was modified by multiplying the SASS α, β, and γ parameters by a constant B. Values of B from zero to 10 were considered. *In all cases, the model-based spectra closely matched the true spectra, with only a small deviation for large B.*

As A was increased (which increased the true wind spectra levels), the difference between the true and pointwise spectra grew smaller (see Fig. 2). However, the deviation from the true spectra to nearly flat spectra was still observed at approximately the same threshold, or noise floor level. As A was further increased, the true spectra rose above the threshold level and the pointwise spectra more closely matched the rolloff of the true spectra. As A was decreased (which decreased the levels of the true spectra), the relative difference between the true and pointwise spectra increased. The deviation of the pointwise spectra from the true spectra was observed at the same threshold level. Regions which previously did not exhibit this effect (their true spectra were originally above the threshold), did as the true spectra fell below the threshold.

The case for which $B = 0$ corresponds to a noise-free scatterometer system. For $B = 0$, the point-wise spectra closely matches the true spectra (see Fig. 3). As B is increased, the apparent "threshold" level at which the pointwise spectra deviates from the true spectral shape also increased. For sufficiently large B, all regions exhibited the effect. For a given increment in B the largest change in difference between the pointwise and true spectra at large wavenumbers occurred for small values of B.

COMMENTS

Our results imply that due to noise in the σ^o measurements, there is a "noise floor" in the spectra of the components of the pointwise-estimated wind. The threshold of this "noise floor" is primarily dependent upon the K_p of the σ^o measurements. This "noise floor" effect is evident in regions which have a wind speed variance below the threshold. We also observed that improving the σ^o measurement K_p results in reduced errors in the pointwise retrieved wind spectra. The noise-floor effect was not observed in the model-based winds, which accurately represented the true component spectra.

These observations are based only on simulation, which may not accurately model the full system. For example, we have not included geophysical modelling error in our simulation. In addition, actual SASS σ^o measurements appear to exhibit more variability than quantified by the predicted σ^o measurement K_p. Further, we have assumed that the true wind wavenumber spectrum rolls off like k^{-2} for scales down to 50 km. This may not be true for the smaller scales. However, if the "noise floor" threshold effect also occurs in pointwise wind retrieval from actual SASS measurements, the retrieved winds may overestimate the small-scale variability.

Unfortunately, it is difficult to determine if this effect occurs in actual pointwise retrieved winds. One approach is to examine the spectra of the actual retrieved winds to search for a "knee" in the spectrum curve. This was not observed in [1]. A second approach is to compare the spectra of model-based and pointwise retrieved winds. Our preliminary results, based on two weeks of SASS data, show a good comparison between the spectra of the two retrieval approaches. Both these observations are to be expected if the actual time-averaged wind variance is above the noise threshold. However, specific regions of low wind variance have yet to be examined in detail. Because there is insufficient ground truth to compute the "true" wind spectra, a comprehensive analysis is difficult.

We note that the simulation approach used in this paper is unable to evaluate the performance of the model-based method in the presence of sharp, small-scale fronts since these were not contained in the simulated wind fields; however, some frontal smoothing at scales <150 km is discernable when actual SASS pointwise and model-based retrieved winds are compared.

CONCLUSION

We have used simulation to compare the wind retrieval accuracy of the traditional pointwise and model-based methods of wind retrieval. We observed that pointwise retrieval often overestimated the high wavenumber wind spectrum. Further, a K_p-dependent noise floor threshold effect was observed which may affect the accuracy of the wind spectrum inferred from the pointwise wind estimates. This effect was not observed in the model-based retrieved winds, which fit the true wind field spectra closely, implying that the model-based approach is more noise-tolerant than pointwise retrieval. This is reasonable since, in effect, the model-based approach assimilates all σ^o measurements over a wide area into the wind field to estimate the wind field over the area. Thus, the model-based approach acts as a σ^o noise filter. This may permit reductions in the size and weight of future scatterometer instruments by reducing the requirements on the SNR of the σ^o measurements, permitting smaller transmitters, antennas, etc.

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Region Number	Latitude Range	Longitude Range
1	−45° to −25° N	160° to 280° E
2	−25° to −5° N	160° to 280° E
3	+5° to +25° N	140° to 250° E
4	+25° to +45° N	150° to 230° E
5	−5° to +5° N	150° to 280° E

Table 1: Region definitions

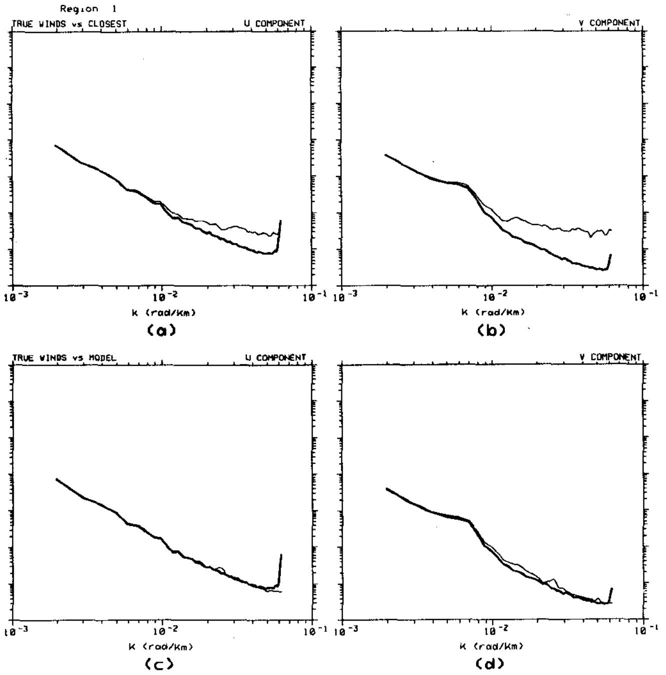

Figure 1. Plots comparing the along-track spectra of the components of the true and retrieved wind fields for Region 1. The true spectrum is shown as a dark line (generally lower than the retrieved) while the retrieved is shown as a thin line. In this and other plots, the vertical scale is arbitrary. a) u component pointwise. b) v component pointwise. c) u component model-based. d) v component model-based.

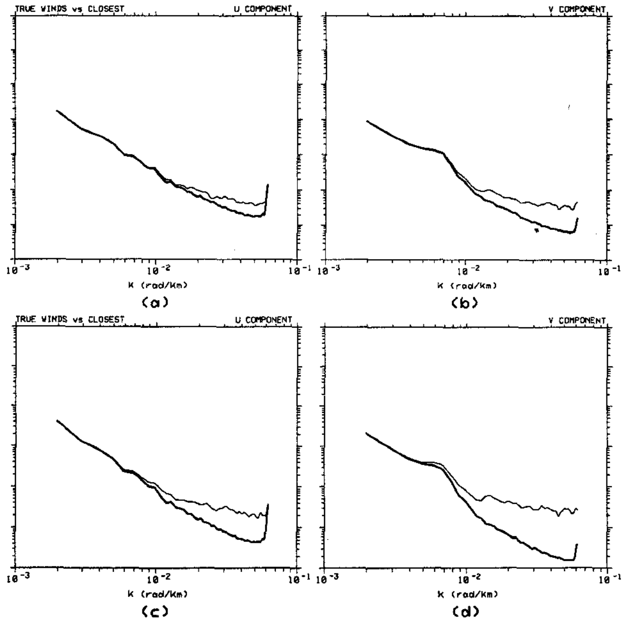

Figure 2. $B = 1$. a) & b) $A = 1.5$; c) & d) $A = 0.75$.

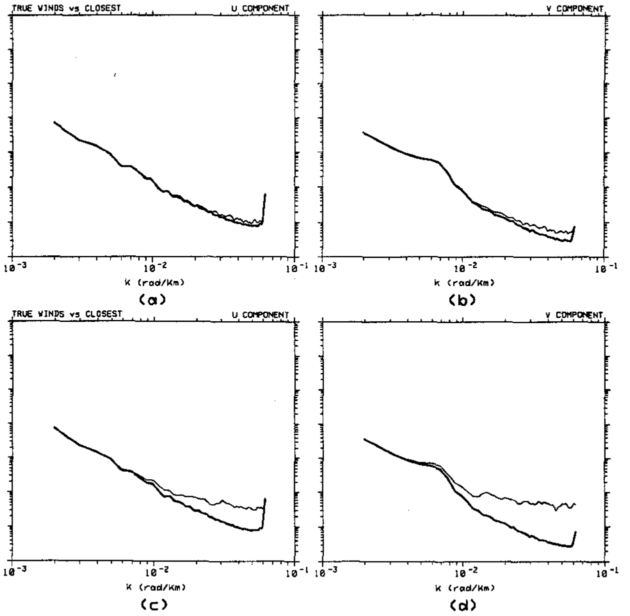

Figure 3. $A = 1$. a) & b) $B = 0$; c) & d) $B = 2$.

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