Eos, Transactions, American Geophysical Union, Vol. 78, No. 51, December 23, 1997, Pages 597, 602

Wind Observations From New Satellite and Research Vessels Agree

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An instrument designed to observe wind speeds and directions over the ocean surface has realized the promise suggested by the first spaceborne scatterometer on the SeaSAT satellite nearly 20 years ago. In 1996, NSCAT (NASA Scatterometer) rode into orbit on the Japanese satellite ADEOS and gathered 8.5 months of valuable wind data. NSCAT's unprecedented ability to determine wind speed and direction over 90% of the ice-free global water surface with a 25 km resolution in 2 days should have profound impacts on oceanographic and meteorological applications. Prior to these applications, however, the uncertainty of NSCAT data must be determined from calibration and validation with in-situ observations. Comparison of NSCAT wind speeds and direction to those observed from research vessels shows an extremely good match. The analysis suggests that NSCAT winds appear to be sufficiently accurate for use in forcing ocean models.

Gathering Wind Data

Wind observations from 3 ships provided 74 observations that were collocated with satellite observations, which covered a range of wind speeds (adjusted to the speed at a height of 10 m, U_{10}) from 2 to 20 m s^{-1}. The observation times are less than 20 min apart, and the locations are within 50 km of each other. Observations from research ships are often recorded at 1 min intervals; consequently, the satellite observations usually occur within 30 s of ship observations. Wind data observed from ships are converted to Earth-relative winds and averaged over the 6 min centered on the satellite observations. Only those averages from 3 or more observations are used in the comparison.

Using a boundary-layer model [*Clayson et al.*, 1996; *Bourassa et al.*, 1997], we adjusted averaged observed wind speeds to a height of 10 m, the height for which NSCAT was calibrated. Correction of the ship observations to correspond to an Earth-relative frame of reference and the standard height are critical because any errors in these in-situ speeds and directions will increase discrepancies between ship and satellite winds, which are used to assess the accuracy of the scatterometer winds. The World Ocean Circulation Experiment (WOCE) Data Assembly Center for surface meteorological data at Florida State University collects, checks, archives, and distributes surface meteorological data from international WOCE vessels, including data from nearly continuous recording systems. Analysts employ data-quality evaluation procedures to produce value-added data sets [*Smith et al.*, 1996]. If the reported winds are ship-relative rather than true winds (relative to the fixed Earth and true North), and if the necessary meteorological and navigational observations are available, then true winds can be calculated. Additional tests, based on the ship-relative wind direction, have been developed to flag observations likely to have been influenced by ship acceleration and flow distortion.

Aboard the polar-orbiting ADEOS satellite, NSCAT measured wind speeds from September 15, 1996, to June 30, 1997. The active microwave sensor measured return signals from 600 km wide swaths on both sides of the satellite. The resolution within the swaths was approximately 25 km. The microwaves were Bragg scattered by short water waves; the fraction of energy that returned to the satellite (backscatter) was a function of wind speed and wind direction. Each swath was sampled by fore, mid, and aft beams, each sampled from different directions. Wind speeds and directions were calculated where there were observations from all 3 of these beams. Among satellite remote sensors, only scatterometers can determine the wind direction—from the angle that is most likely to match the observed backscatter. The function describing the fit usually has multiple minima (ambiguities). Ideally, the best fit corresponds to the true direction of the wind, the next best fit is in approximately the opposite direction, and the next two minima are in directions roughly perpendicular to the wind direction. The process of selecting the direction from among the multiple minima is called ambiguity selection. Noise can change the quality of fit and thereby cause incorrect ambiguities (also known as aliases) to be chosen. The use of 3 antennas per swath improves the likelihood that the selected ambiguity is the correct direction. Ambiguity removal for NSCAT data is improved by using 2 combinations of beam polarizations with 1 antenna.

The optimal averaging period for the ship observations, which depends on wind speed, sea state, and the size of the NSCAT footprint, ranged between 3 and 20 min. Physical considerations included spatial and temporal scales for homogeneity of the ship and satellite observations, as well as previous sea states. Absolute values of differences in wind speed were calculated for each averaging period and for a set of wind speed bins. Within each speed bin, a mean and standard deviation in this mean were determined. The root mean square (rms) difference between the observations within each speed and averaging period bin is determined. The quality of the averaging period is shown by the rms difference minus the "mean rms difference for the averaging period," divided the uncertainty in the mean. Good averaging periods correspond to low values (relatively little spread from the mean), and poor averaging periods correspond to maxima (relatively large spreads from the mean; for graphics see http://www.coaps.fsu.edu/~bourassa/nscat_cv.html). For short averaging periods (10 min) 2 strong maxima (>2.5) occur at 8 and 10 min for moderate wind speeds (6 to 10 m s^{-1}). The differences in 12–15 m s^{-1} winds show strong minima at 5 and 7 min, and the 15–20 m s^{-1} have a minima at 8 min. A period of 6 min was chosen for the optimal averaging period in this study because it corresponds to a local minima for most speed bins and is not in the range of poor averaging times for the moderate wind speeds.

Ship and Satellite Winds Agree

Seventy-four collocations with wind speeds ranging from 2 to 20 m s^{-1} met all of the quality-control criteria for collocation and the lack of flow distortion. Collocations of the 3 research vessels and the satellite covered a

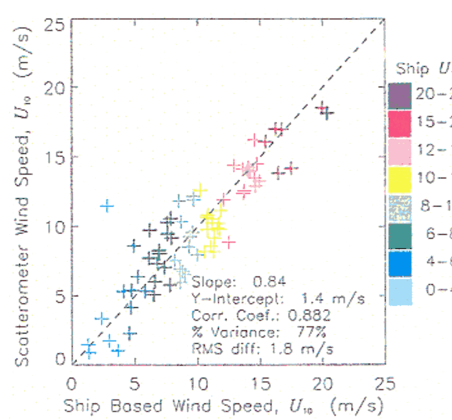

Fig. 1. NSCAT versus ship wind speed. The green dashed line indicates a perfect fit.

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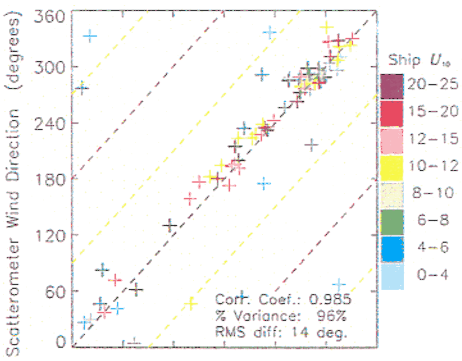

research vessel wind observations [personal communication., *R. Atlas and V. Zlotnicki*, 1997]. A similar problem is found in the Global Telecommunications System (GTS) reports from research vessels [personal communication, *V. Zlotnicki*, 1997].

Scatterometers determine wind direction as well as the wind speed. In Figure 2, a plot of scatterometer wind directions versus ship wind directions, shows a close match. Points close to the green line indicate a good fit, and the red lines indicate reversed wind directions. The rms difference in correctly selected ambiguities is 14° (well under NSCAT's design specifications of 20°). Comparisons against other in-situ wind observations showed that approximately 90% of NSCAT wind directions have the correct ambiguity selection. The rms differences in wind speed and direction are shown in Figure 3 as a function of ship observed wind speed. For U_{10}>6 m s^{-1}, the chance of an incorrect alias is small; this chance decreases as the wind speed increases. The rms difference for wind speed is large for U_{10}<4 m s^{-1}; however, the rms values for U_{10}>4 m s^{-1} is near 1.6 m s^{-1}.

The problems at low wind speed could be due to the comparison of a large scale average to a local average. At these wind speeds, boundary-layer convection and large eddies can cause large differences in surface wind within a few tens of km (the scale of the NSCAT footprint). For such conditions, the NSCAT winds are likely to be more representative of the average winds in the NSCAT footprint. Figure 4 shows the impact of NSCAT observational errors on monthly average winds in a comparison of NSCAT derived pseudo-stress (the product of wind speed and the vector wind) to the Florida State University (FSU) pseudo-stress fields [*Stricherz et al.*, 1993] for the Indian Ocean. FSU pseudo-stresses are often used to force ocean models, which is expected to be a common application of the NSCAT observations. The pseudo-stress vector is defined as a (UW, VW), where U and V are the east-west and north-south components of the wind, and W is the speed. All NSCAT wind observations were adjusted to a 20 m height, converted to pseudo-stress and binned in 1° boxes (the FSU pseudo-stress field is routinely constructed in a similar manner). The FSU product, which is based on only in-situ data, is the result of a variational objective analysis technique [*Legler et al.*, 1989]. The pseudo-stress is vector-averaged; therefore, winds with incorrect ambiguity selections are averaged with winds with correctly selected ambiguities, resulting in slower average NSCAT winds and errors in directions.

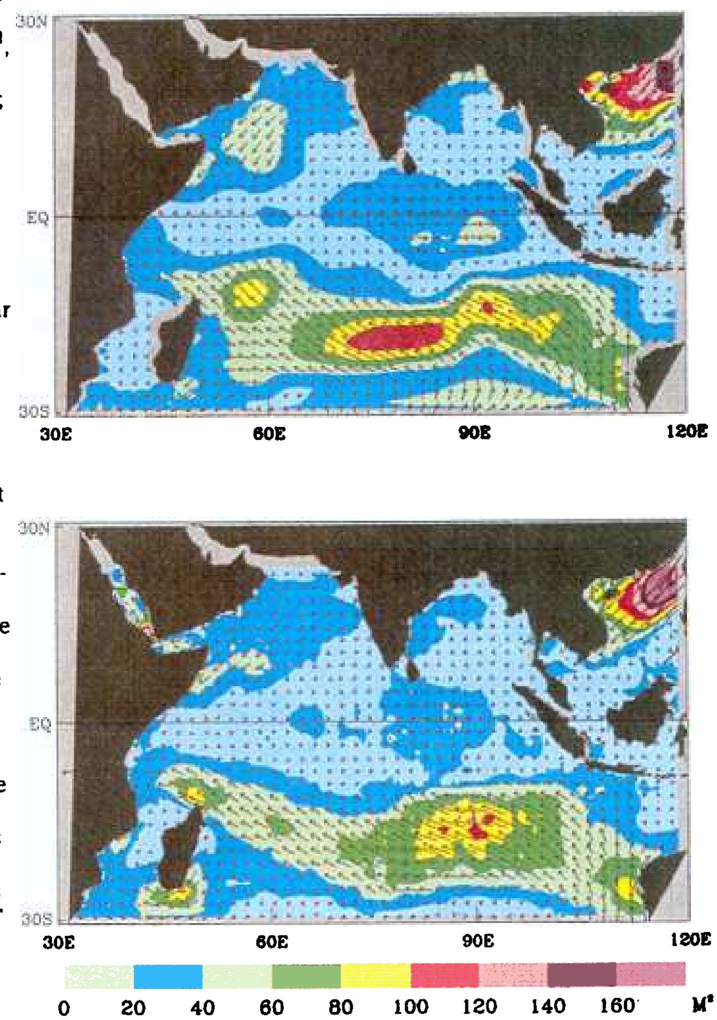

Fig. 4. Mean pseudo-stress (UW, where U is wind vector, and W is the scalar wind speed) during Nov. 1996 for (a) NSCAT winds, and (b) Florida State University (FSU) winds. The arrows indicate the direction of the psuedostress, and the contours indicate the pseudo-stress magnitude. The data are binned on a 1° grid, but vectors are drawn every 2° for convenience.

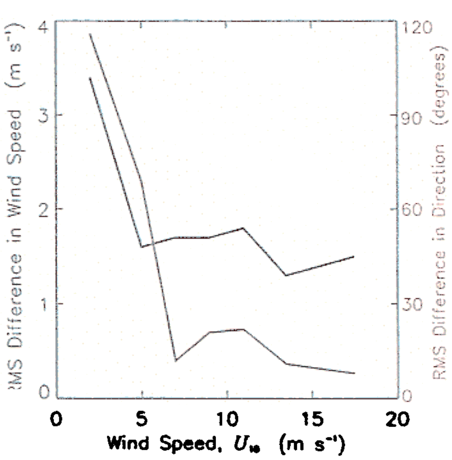

Fig. 3. Root mean square differences in NSCAT and ship observed wind speed and direction as a function of ship observed wind speed.

The high wind speed regions have similar patterns and magnitudes. The NSCAT field is more detailed in the southern Indian Ocean, which is a region sparse in ship observations. In low wind speed regions, such as the Arabian Sea, the patterns and the magnitudes are similar, indicating that the ambiguity selection problem does not result in a severe degradation of monthly averaged winds.

Conclusions

High temporal resolution, quality-controlled wind observations from research vessels provide surface truth to evaluate the accuracy of NSCAT winds. Ambiguity selection is highly effective for $U_{10} > 6$ m s^{-1}. Monthly averaged pseudo-stress based on NSCAT winds is a good match to in-situ (FSU) pseudo-stress, indicating that the ambiguity selection difficulties for low wind speeds do not result in large errors in monthly mean fields. NSCAT worked well within the instrument's design specifications of 2 m s^{-1} uncertainty in speed, and 20° in the direction of correctly chosen aliases: the differences in comparisons to high quality in-situ observations are 1.6 m s^{-1} and 13° for $U_{10} > 4$ m s^{-1}. The rms differences in speed and direction decrease as the wind speed increases. These differences overestimate uncertainty in the satellite observations: the values include contributions from uncertainty in in-situ observations, and variation within the scatterometer's observational footprint. Future generations of scatterometers will have smaller footprints, which will reduce the differences due to variation within the footprint. The accuracy and coverage of NSCAT's wind observations are unprecedented.

These calibration/validation results indicate that NSCAT winds are suitably accurate to identify and closely locate atmospheric phenomena such as fronts and storms. The sampling rate is sufficiently rapid to study the daily evolution of storms and large scale weather patterns such as those of El Niño. Satellite observations are extremely useful in areas where there are sparse surface observations, such as the tropics and the southern hemisphere. The accuracy as well as spatial and temporal coverage of NSCAT exceeds previous satellites, making this type of observation ideal for forcing ocean circulation models. NSCAT observations, and those of future scatterometer missions, will be extremely useful in studies of the evolution of atmospheric and ocean circulations.

Acknowledgements

We thank Barrie Walden and Lane Abrams for providing observations from the R/V *Knorr*; Niel M. Bogue and Mike Realander for providing observations from the R/V *Thompson*; Kieran Jacka and Gordon Keith for providing observations from the RSV *Aurora Australis*; and Shawn Smith, Dan Gilmore, and Jiraporn Whalley for performing quality-control measures on the ship data. Funding for this project is from the NASA JPL NSCAT Project (contracts 957649 and 980646) and WOCE (NSF grant 9314515). COAPS receives its base funding from ONR's Secretary of Navy Grant to Dr. James J. O'Brien.

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