MAPPING OF MESOSCALE AND SUBMESOSCALE WIND FIELDS USING SYNTHETIC APERTURE RADAR

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LONG-TERM GOAL

The long-term goal of this research effort is to investigate the possibility of obtaining quantitative information about the near-surface wind field and perhaps other parameters that characterize the Marine Atmospheric Boundary Layer (MABL) from an analysis of Synthetic Aperture Radar (SAR) imagery. Because of its potential for yielding such information at high horizontal resolution, this application of SAR would represent a significant advance over most scatterometer and passive microwave sensors that yield only coarse-resolution estimates of the wind field.

SCIENTIFIC OBJECTIVES

The major scientific objective of our research is to determine, by comparisons with more standard measurements and model predictions, if it is possible to extract detailed quantitative estimates of the near-surface wind field and perhaps various other parameters that characterize the MABL from SAR imagery. Because of the large footprint associated with conventional multiple-antenna scatterometers or passive microwave sensors, wind estimates in coastal regions are difficult to obtain. SAR, on the other hand, provides high-resolution imagery where various signatures associated with fluctuations in the MABL are commonly seen, especially in coastal waters. Moreover, because SAR can resolve the surface signatures of turbulence structures in the MABL, it may be possible to diagnose the surface layer stability and therefore even produce wind-speed estimates corrected for this important effect.

APPROACH

The first step in our approach to this complicated problem is the acquisition of a series of RADARSAT SAR overpasses over the coastal Atlantic along the eastern North American coast where the local meteorology can be characterized as well as possible by conventional methods. Precise calibration of the SAR imagery is, of course, critical. Next, we apply scatterometer-type algorithms for the wind extraction. Two important problems must be solved in this step: (a) An H-pol scatterometer algorithm must be developed, and (b) a reliable estimate of the wind direction (across the extent of the SAR image) must be obtained. Our approach to (a) is to convert existing V-pol scatterometer algorithms (e.g., CMOD4) to H-pol using experimental data as well as predictions of the polarization ratio from rough-surface scattering models. Our initial attempt at a

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solution for (b) will be to use wind-direction estimates from atmospheric models (e.g., from FNMOC) to specify the input for the wind inversion. The resulting wind field will then be compared with that obtained from other sensors until consistency (at the lower resolution of these sensors) is obtained. This procedure should provide a reliable estimate not only of the local wind field, but also of the wind-speed variance not currently available from standard low-resolution scatterometers and passive microwave sensors. We are also investigating as part of this study how the wind variance extracted from the SAR imagery in this way can provide information about the local MABL thickness and stability.

WORK COMPLETED

Completed works include the following:

1. We have acquired four sets of narrow ScanSAR (300 km swath) RADARSAT overpasses over the coastal Atlantic off the eastern U.S. on 12 overpasses between October 1996 and March 1997. This imagery was made available to us as part of the Canadian Space Agency’s Application Development and Research Opportunity program (ADRO);
2. Coincident with each of the four overpass sets, we have archived AVHRR imagery, routinely produced at JHU/APL, as well as a high spatial resolution (one-degree grid) wind and wave model analysis provided to us routinely every 6 hours by FNMOC. Furthermore, we have coordinated radio-sonde launches at points along the east coast beneath the relevant overpass to characterize the MABL for use in analysis of the SAR imagery;
3. Wind-field maps have been attempted for several of the overpasses where the wind direction, as predicted by the FNMOC model analysis, was nearly constant across the image swath. The resulting wind maps in most of these cases were in good agreement with measurements from NDBC buoys within the scene as well as with measurements from auxiliary wind sensors; and
4. A world-wide web site that highlights our four SAR data sets and the corresponding ancillary data is under construction. On this web site, we have accurately registered the ancillary fields discussed above with the SAR imagery. This allows one to easily observe the correlation between variations in these fields and features in the imagery. To view our RADARSAT data set on-line, open url: http://fermi.jhuapl.edu/sar/index.html, and click “RADARSAT.”

RESULTS

Figure 1 shows results of our initial attempt to extract wind information from the RADARSAT overpasses. This figure shows images of the U.S. mid-Atlantic region containing the FNMOC wind fields for the four highest-wind days (13 October 1996, 14 January, 17 January, and 6 March 1997) in our RADARSAT data set. The arrows in the maps represent the model wind direction on a 1° x 1° grid, while the gray-scale level gives the corresponding wind speed. Embedded into each of these images is our extracted wind-speed map computed from the SAR overpass on that day. The gray-scale level of the SAR wind-speed map is identical to that used for the FNMOC model winds so that comparisons between the two estimates can be easily made. Below, we discuss how the wind-speed maps were generated and present some of our observations concerning comparisons with the FNMOC model as well as local NDBC buoy measurements.

We have applied the calibration procedure supplied to us by RADARSAT to convert the image pixel values to σ_0-values. At the time of our images in March 1997, the RADARSAT narrow ScanSAR beam mode had, in fact, not been declared officially calibrated although the calibration procedure clearly improved during the course of our collection period. Evidence for this improvement can be seen, for example, by noticing that the rather obvious level shift in the upper center of the 13 October SAR inlay becomes less apparent in the later images. The point to be emphasized here is that wind estimates from SAR, or any other sensor, can only be as accurate as the instrument's calibration.

To proceed further, we need to know a relationship between σ_0 and the local wind velocity; i.e., a scatterometer algorithm. A relatively well-tested scatterometer algorithm, CMOD4, developed for the V-pol, ERS-1 scatterometer already exists (1). Since RADARSAT operates at H-pol however, CMOD4 cannot be used directly. We have therefore modified the V-pol CMOD4 cross section, $s_0^V(U,q,f)$, for use at H-pol using the expression

$$s_0^H = s_0^V(U,q,f)\frac{\left(1.6 - sin^2 q\right)^2}{\left(1.6 + sin^2 q\right)^2}, \qquad (1)$$

where U is the wind speed, q is the incidence angle, f is the azimuth angle of the radar with respect to the wind direction, and s_0^H is the resulting H-pol cross section. The simple (empirical) polarization ratio used in (1) yields good agreement with measured H-pol cross sections for incidence angles between about 20° and 40° (Campell, et al., 1997). For specified values of q and f, we can now find U by inverting equation (1). The value of q is specified at each pixel in the RADARSAT image by the satellite geometry. How to specify the azimuth angle f is more difficult. For the wind maps shown in Figure 1, we have simply assumed a constant wind direction based on the FNMOC model analysis. It can be seen from the figure that this assumption is probably not too bad for the three later images where the wind is generally from the northwest. For the 13 October image, we have used a southwest wind for the inversion. One can see that this choice is reasonable for the northern portion of the SAR inlay. In the southern portion, the wind direction rotates around a (weak) high-pressure cell. In regions such as this where the wind direction is rapidly changing, the simple choice of constant wind direction must clearly be improved.

Comparison of the gray-level variations in the FNMOC wind speeds with those in our SAR wind-map inlays in Figure 1 show relatively good agreement in spite of the assumptions discussed above. The large-scale variations seen in the model analysis are generally reproduced quite nicely in the SAR wind maps. Note for example, the decreasing wind speed near the southern portion of each inlay, the "jet-like" structure in the 14 and 16 January inlays, and the increasing winds toward the east on 6 March. The wind speed extracted from the SAR shows generally good agreement with estimates from NDBC buoys located within the SAR swath (see our web site for buoy locations and their associated measurements). Also evident in the SAR inlays in Figure 1, especially on 14 and 17 January, are regions of high wind-speed variance resulting from the turbulence produced by an unstable MABL. Comparison with AVHRR imagery shows that the narrow dark band seen near the middle of the inlay on these days marks the north wall of the Gulf Stream. (Higher resolution versions of the SAR and AVHRR imagery are also available on our web site.) These findings give us confidence that the simplified wind-extraction procedure described above can produce reasonable wind values, and that improvements to the procedure are worth pursuing.

In the next version of our wind extraction implementation, we plan to use the FNMOC model analysis (or other sources) to directly define the wind direction at each SAR pixel. This procedure will better account for the problem of changing wind direction across the SAR swath mentioned above. Similarly, we plan to correct the extracted wind speeds for MABL stability using AVHRR, the FNMOC SST analysis, and the NORAPS air-temperature analysis. Clearly, there will be errors in the estimates whose magnitude will depend on knowledge of the "true" SAR wind algorithm, in particular on knowledge of the relative importance of the various "contaminating" influences, and the accuracy of their estimates. Nevertheless, with some skill, we expect that the accuracy of the resulting SAR wind estimates will exceed anything currently available in near-coastal regions, especially if nested within some of the other deep water fields.

IMPACT/APPLICATION

As discussed briefly above, SAR has the potential to overcome some of the inherent limitations of conventional scatterometry. We expect our approach for mapping mesoscale and submesoscale wind fields using synthetic aperture radar will not only provide more information on a higher resolution than do existing algorithms, but will also allow diagnoses to be performed much closer to strong discontinuities such as coasts and ocean current boundaries. Furthermore, remote measurements of the small-scale structure in the wind field i.e., the wind-speed variance, which are only possible with high-resolution SARs, can provide an indication of the atmospheric stability and possibly even quantitative estimates of the stability parameter.

RELATED PROJECTS

The work described above is part of an on-going effort in collaboration with meteorologists at The Pennsylvania State University.

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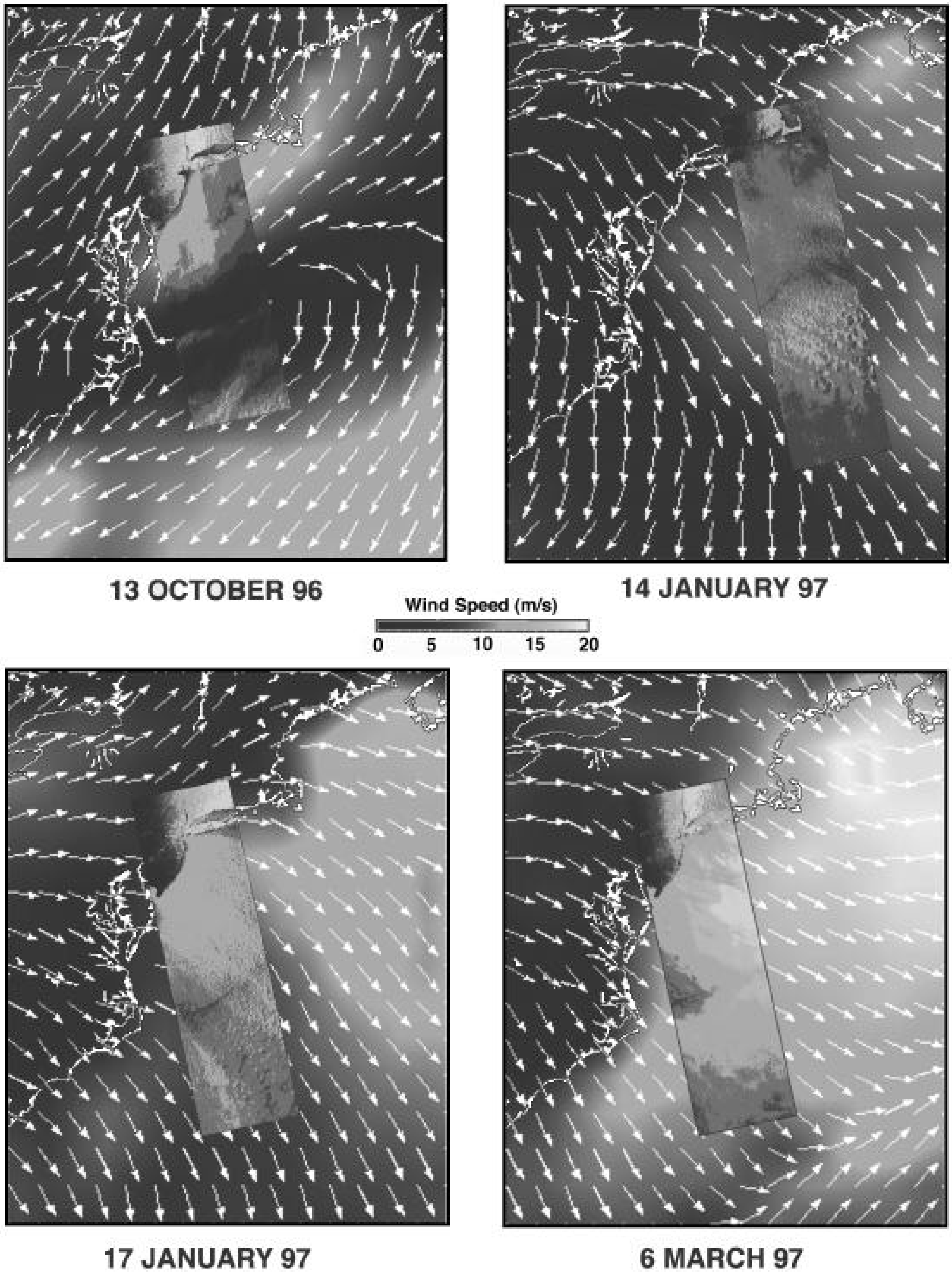

FIGURE 1
RADARSAT WIND ESTIMATES EMBEDDED IN FNMOC MODEL FIELDS