High Resolution Remote Sensing of Ocean Wind and Wave Fields

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LONG-TERM GOALS

This project is part of a larger effort to use the high resolution capabilities of synthetic aperture radar to map variations in ocean surface wind and wave fields on spatial scales that are not currently resolved by other spaceborne systems such as scatterometers, radiometers, and altimeters.

OBJECTIVES

The objectives of this project are to refine the physical models that relate the wind and wave fields to quantities observable by synthetic aperture radar, and to develop procedures for inverting these models so as to estimate the wind speed and direction and the wave height spectrum from synthetic aperture radar data.

APPROACH

The technical approach in this project involves three types of models: (1) the two-scale electromagnetic scattering model, which relates the radar backscatter to the surface wave spectrum, (2) the wave action model, which describes the relationship between the surface wave spectrum and the near-surface wind field, and (3) atmospheric dynamical models that describe or constrain the spatial variations in the surface wind field. Linking the first two models allows a forward prediction of the synthetic aperture radar image for a prescribed wind field. However, it is possible, at least in principle, for two different wind fields to produce identical images, since the radar cross section is influenced by both the wind speed and direction. Our approach to resolving this ambiguity is to constrain the wind field, either by the use of atmospheric dynamical models or by means of auxiliary information supplied by other sensors (such as scatterometers or radiometers). These constraints will be incorporated into a formal inversion procedure in order to estimate the wind field from the synthetic aperture radar image.

WORK COMPLETED

Efforts during the first year of this project have focused on the implementation and enhancement of the forward prediction models. Technical improvements were made in the two-scale scattering model involving the slope integration procedure, and additional mechanisms were incorporated in order to predict the upwind-downwind asymmetry in the backscatter. An inversion procedure was developed to determine a form for the equilibrium wave spectrum that is consistent with the CMOD4 model

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14. ABSTRACT

This project is part of a larger effort to use the high resolution capabilities of synthetic aperture radar to map variations in ocean surface wind and wave fields on spatial scales that are not currently resolved by other spaceborne systems such as scatterometers, radiometers, and altimeters.

15. SUBJECT TERMS

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function, and a new time stepping procedure was implemented to solve the wave action equation in the presence of variable surface winds.

The complete inversion procedure has not yet been implemented, but some preliminary exercises have been done to test the feasibility of the resolving the wind speed/directional ambiguity by minimizing the vorticity of the resulting surface wind field. We also conducted a preliminary survey of Radarsat images collected over the Gulf of Alaska in order to find examples of the types of small-scale wind fields that may be amenable to the procedures developed in this project.

RESULTS

The relationship between the radar cross section and the surface wind speed and direction has been the subject of several empirical investigations, and perhaps the most detailed and authoritative result of these investigations is the CMOD4 model function derived by Stoffelen and Anderson (1997). Our first task has been to develop a physically based model that agrees with these empirical results in cases where the wind field is sufficiently uniform so that a state of equilibrium exists between the wind and wave fields. To that end we have derived a modified version of the two-scale scattering model and an equilibrium wave spectrum that is consistent with the CMOD4 model function.

One of the most important features of this model is the dependence of the radar cross section on the wind direction relative to the radar look direction. The largest part of this dependence is controlled by the angular distribution of the surface wave spectrum. However, there is also a slight asymmetry in this dependence, in the sense that the radar cross section is not exactly the same for upwind and downwind look directions. This effect may be caused by an asymmetry in the surface slope probability density function, as observed by Cox and Munk (1954), or by the modulation of short waves by longer gravity waves (Hara and Plant, 1994). The modulation of the short waves can be shown to be correlated with the large-scale surface slope, as represented by the equations

$$\left\langle f\,\eta_x \right\rangle = \tfrac{1}{2}\iint m_i\, k k_x\, S(k_x,k_y)\; dk_x dk_y \quad \text{and} \quad \left\langle f\,\eta_y \right\rangle = \tfrac{1}{2}\iint m_i\, k k_y\, S(k_x,k_y)\; dk_x dk_y$$

where f is the fractional modulation of the short wave spectral density, $m = m_r + i m_i$ is the dimensionless modulation transfer function, and $S(k_x,k_y)$ is the one-sided wave height spectrum. Thus, the expected value of the spectral modulation can be written as

$$\hat{f} = a\eta_x + b\eta_y \quad \text{where} \quad a = \left\langle f\,\eta_x \right\rangle / \sigma_x^2 \quad \text{and} \quad b = \left\langle f\,\eta_y \right\rangle / \sigma_y^2 \ .$$

where σ_x^2 and σ_y^2 are the *x* and *y* components of the slope variance. This equation can be readily incorporated into the two-scale model. However, for this modulation to influence the mean radar cross section the slope probability density function must also be multiplied by the projected-area factor

$$a(\eta_x,\eta_y) = \max\{1-(\eta_x\cos\phi + \eta_y\sin\phi)\tan\theta,\, 0\}$$

where θ is the incidence angle and ϕ is the look direction relative to the *x*-axis (Chan and Fung, 1977). These expressions have been incorporated into our implementation of the two-scale model and found to produce an upwind-downwind asymmetry in the backscatter that is consistent with CMOD4 for reasonable values of the modulation transfer function.

Various forms for the short wave equilibrium spectrum have been proposed in recent years (Apel, 1994; Caudal and Hauser, 1996; Elfouhaily et al., 1997) which have similar features although they differ significantly in detail. We have chosen to represent the spectrum by the form

$$S(k,\phi) = S_{PM}(k,\phi)\,P(k)[1 + b_2(k)\cos 2(\phi - \phi_w)]$$

where $S_{PM}(k,\phi)$ is the Pierson-Moskowitz (1964) frequency spectrum converted into wavenumber space using the angular distribution proposed by Hasselmann *et al.* (1980) and the gravity-capillary dispersion relation, and the rational functions

$$P(k) = \frac{1 + p_1 k + p_2 k^2}{1 + p_3 k + p_4 k^2} \quad \text{and} \quad b_2(k) = \frac{p_5 k + p_6 k^2}{1 + p_1 k + p_2 k^2}$$

represent correction factors for the wavenumber and angular dependence at high wavenumbers. The parameters $p_1 \ldots p_6$ were selected using a Nelder-Mead optimization routine in order to replicate the CMOD4 model function as nearly as possible when used with the two-scale model described above. Cuts through the spectrum in the wind direction for various wind speeds are shown in Figure 1(a). The radar cross section values obtained using this spectrum in the two-scale model are compared with CMOD4 values for three incidence angles and wind speeds in Figures 1(b)-(d).

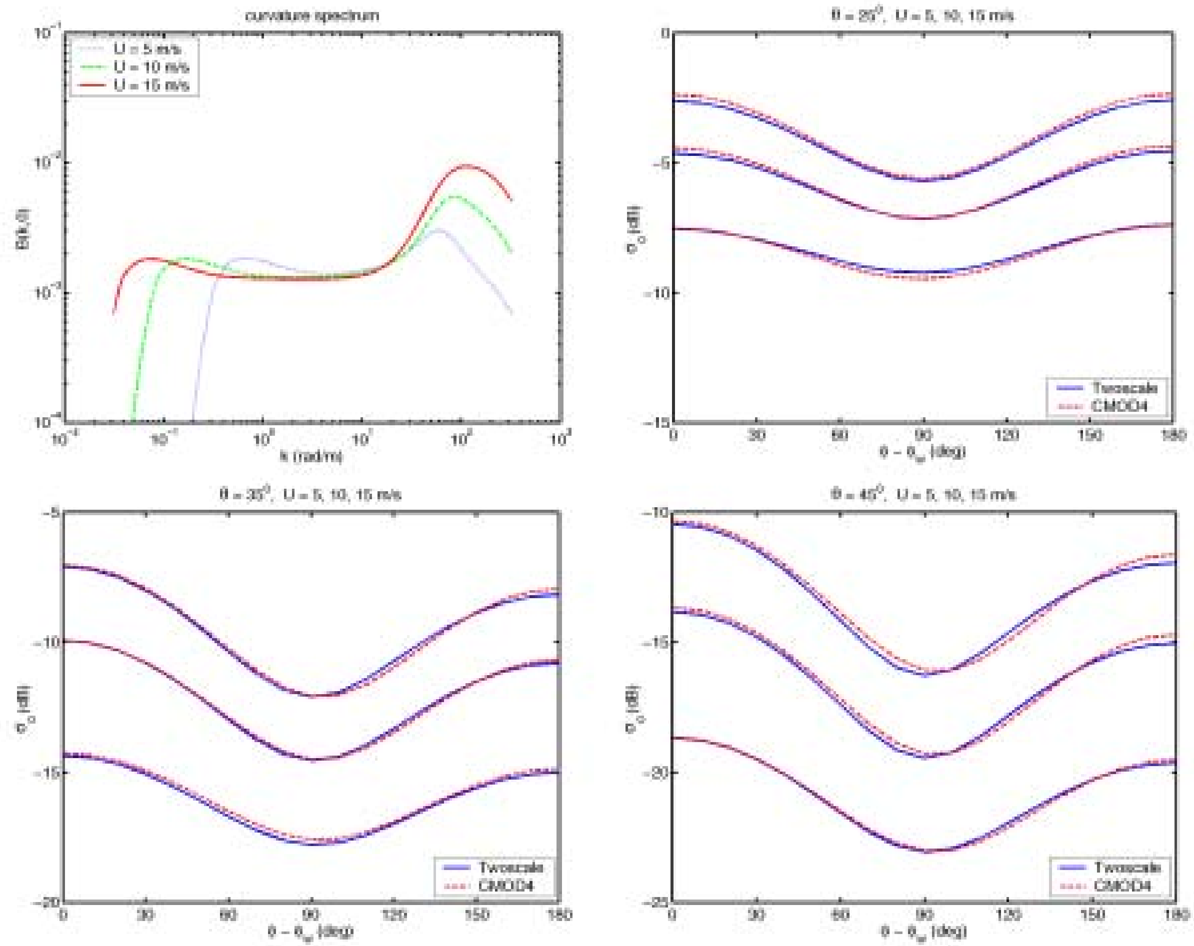

Figure 1. Derived wave spectrum (a) and comparison of radar cross section predicted by two-scale model with CMOD4 model function for (b) 25°, (c) 35° and (d) 45° incidence angles.

One type of small-scale wind feature observable by synthetic aperture radar is the precipitation-induced downdraft cell discussed by Atlas (1994). The impact of the precipitation itself may cause changes in the backscatter that are not described by the models developed in this project. Surrounding the rain shaft, however, there is typically a larger region that is impacted by the diverging wind field induced by the falling precipitation. An example of several such features is shown in Figure 2. This figure shows a portion of a Radarsat image collected on May 10, 1998 in the Gulf of Alaska at approximately 56° N 142°W. The region shown is about 200 km west of a strong wind front that was moving eastward at 30 km/hr, as inferred from a sequence of SSM/I images collected on May 9-10. Although the wind front itself was clearly visible on the SSM/I imagery, the rain cells behind it are not resolved by this sensor. The passage of the front is also evident in the wind measurements made by NOAA Buoy 46001 which is located about 250 km west of the image segment shown in Figure 2. These measurements also show variations in the wind speed and direction behind the front which may correspond to the passage of downdraft cells over the buoy.

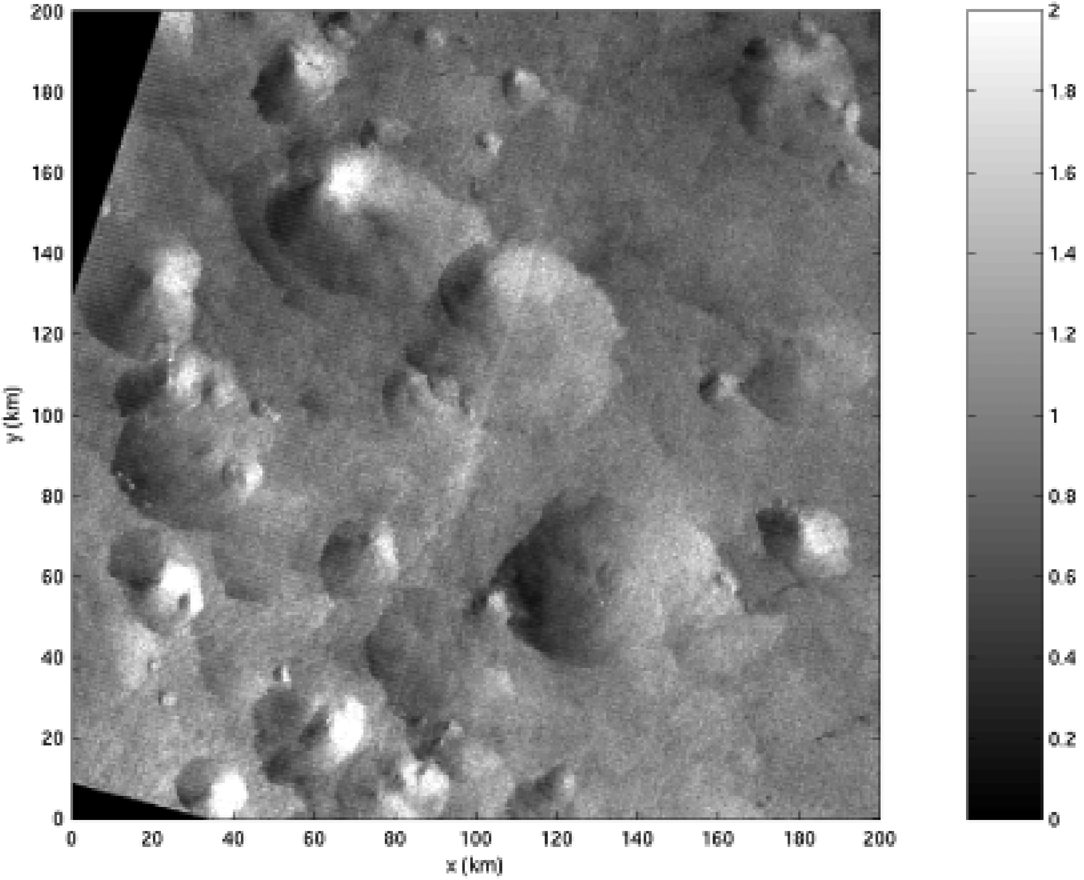

Figure 2. Portion of Radarsat image collected at 15:43 GMT on 5/10/98, showing downdraft cells. [Downdrafts appear as circular features with brighter returns on the sides facing the direction in which the cells are being advected by ambient winds, and darker returns on their trailing edges.]

In attempting to extract quantitative information from images such as shown in Figure 2 we are confronted by two problems: the first is the wind speed/directional ambiguity mentioned earlier, and the second is the possibility that the wave spectrum may not be in equilibrium with the wind, in which case empirical model functions such as CMOD4 would not be applicable. One possible means of resolving the wind speed/directional ambiguity is to assume that the vorticity of the horizontal wind field is zero, and use this condition to select the wind speed and direction at each grid point so as to agree with the observed radar cross section and also to produce the minimum vorticity. In order to evaluate the feasibility of this approach, we have implemented a procedure to minimize the vorticity of the wind field obtained by inverting a model function for the radar cross section. This exercise produced encouraging results but does not represent a complete solution, because the model function may not be applicable due to non-equilibrium conditions. Our next step will be to run the wave action model for this case to determine whether the equilibrium assumption is valid or whether a complete inversion of the wave action equation is required.

IMPACT/APPLICATIONS

Small-scale wind fields such as those shown in Figure 2 can have an important impact on naval operations, but are difficult to predict in advance. Therefore, an observational capability such as that under development in this project may prove to be useful operationally, provided that real-time imagery is available.

TRANSITIONS

The methodologies described in this report are still in the process of development. If successful we will pursue possibilities for transition to naval meteorological research and/or operational programs.

RELATED PROJECTS

This project is closely related to work being done in the NOAA Office of Research and Applications under the Alaska SAR Demonstration Project (http://orbit-net.nesdis.noaa.gov/orad/sar/index.html) Other research efforts have focused on the inference of wind directions from large-scale structures in SAR images (Wackerman, *et al*, 1996; Fetterer *et al*, 1998; Horstmann *et al*, 2000) and on combining synthetic aperture radar images with model-generated wind directions (Monaldo *et al*, 2001).

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PUBLICATIONS

Lyzenga, D.R., Unconstrained inversion of wave height spectra from SAR images, *IEEE Trans. Geoscience and Remote Sensing 40*, 261-270, 2002.