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SURFACE MARINE WIND RETRIEVAL IN NON–PRECIPITATING REGIONS

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Error estimates for the surface winds retrieved from Radarsat–1 synthetic aperture radar (SAR) backscatter cross section are derived using nonlinear regression. The SAR-wind relationship employed is the European Remote Sensing (ERS) C-Band model (CMOD) and the polarization ratio of Vachon and Dobson (2000). Non–precipitating regions of the SAR acquisitions obtained during the past 15 months along the east and west coasts of North America are considered. Bias and variance of the errors in backscatter cross section, relative to the wind errors of a high-resolution numerical model, are iteratively estimated in preparation for SAR data assimilation. An offline combination of these two data yields retrieved winds that are comparable to *in situ* observations from ships of opportunity and buoys. Assuming no errors in the latter observations, improvements over the model winds are quantified.

1. INTRODUCTION

Remote sensing offers the unprecedented opportunity to validate operational numerical weather prediction forecasts and ultimately to improve them in regions that are sparsely observed. Wind fields in coastal waters are highly variable on horizontal scales of a few kilometres and time scales of a few hours or less. This has important applications including search and rescue, forecasting the movement of sea and lake ice for marine transport, predicting the evolution of pollution episodes, and understanding marine ecosystems.

Forecasts that are made using the Global Environmental Multiscale (GEM) model are produced operationally at the Canadian Meteorological Centre on a 15-km grid and these are expected to be run over smaller windows at resolutions of about a kilometer. Such forecasts contain small–scale wind features that appear realistic, but evaluating the accuracy with which these features can be modeled and predicted with *in situ* observations would be prohibitively expensive. Advanced observational platforms, such as Radarsat–1, provide a high resolution reference. However, the SAR backscatter cross section depends not only on the wind field, but on other physical processes as well. In order to evaluate a model forecast, it is also necessary to gauge the accuracy of the SAR data and the marine winds derived from them.

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2. APPROACH

Errors in SAR and GEM data can be explicitly considered in terms of their regression equations. For SAR backscatter cross section ($\mathbf{y}$) and the GEM zonal and meridional wind components ($\mathbf{x}^b$), these can be written (in column matrix form) as

$$\begin{aligned} \mathbf{y} &= \alpha^{-1}[CMOD(\mathbf{x}) + \mathbf{e}_y] \qquad (1) \\ \mathbf{x}^b &= \mathbf{x} + \mathbf{e}_x, \end{aligned}$$

where the errors are $\mathbf{e}_y$ and $\mathbf{e}_x$. The parameter α depends linearly on incidence angle and permits bias in multi–beam SAR acquisitions (cf. Vachon et al. 1997; Beal et al. 2003) to be accounted for. The CMOD operator defines an empirical relationship between the wind field and the radar cross section (Hersbach 2003).

It is a function of the SAR beam incidence angle, wind speed, and wind direction (relative to the satellite look angle). This relationship has been tuned using the ERS C–band scatterometers, whose polarization is vertical for send and receive. Because the Radarsat SAR polarization is horizontal, we include a polarization correction following Vachon and Dobson (2000). SAR observation errors (both radiometric and geometric, with the latter including errors in incidence angle) are resolved in the $\mathbf{e}_y$ term, as are errors in CMOD and its polarization correction.

The regression equations are nonlinear owing to CMOD. Following Dowd et al. (2001), we derive from (2) a nonlinear cost function of the form

$$J = [\mathbf{x} - \mathbf{x}^b]^T \mathbf{B}^{-1} [\mathbf{x} - \mathbf{x}^b] + \quad (2)$$
$$[CMOD(\mathbf{x}) - \alpha\mathbf{y}]^T \mathbf{R}^{-1} [CMOD(\mathbf{x}) - \alpha\mathbf{y}].$$

Here, the **B** and **R** matricies are the error covariance matricies of the model winds and the SAR observations, respectively. The two terms on the rhs of the cost function are measures of the variance of the GEM and SAR errors, respectively (Seber and Wild 1989). Thus, a minimum of J represents a minimum variance estimate of the true wind field. This is obtained by varying the zonal and meridional wind components ($\mathbf{x}$). Derivatives of the CMOD operator with respect to $\mathbf{x}$ yield local gradients of J and an iterative search along the lines of steepest descent yields the desired wind field.

3. DATA

Radarsat–1 is a right–looking, C-band (5.6-cm) SAR with horizontal send and receive (HH) polarization. It operates in numerous beam modes at incidence angles between about 20° and 50°. All single–beam modes of interest have been radiometrically calibrated since mid–November 1999 (RSI 2000). We utilize both single–beam and ScanSAR modes, which combine two or more individual beams. At this stage, the resolution of the acquistions is reduced by an order of magnitude to 400 m, following Koch (2004). Radar cross section is masked over land and ice, as well as where the strongest (weakest) possible wind is less than 3 m s^{-1} (greater than 33 m s^{-1}) (cf. Fig. 1, rhs). ScanSAR beam seams are also masked. Most acquisitions considered in this study are near Nova Scotia and Newfoundland, where the satellite descends at approximately 1000 UTC and ascends at approximately 2100 UTC.

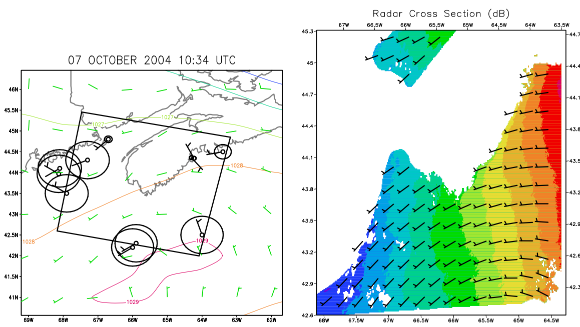

Figure 1: SAR acquisition near Nova Scotia: left panel) GEM model winds (green barbs at 110-km intervals) and ship/buoy observations (black barbs) with their regions of validity encircled. right panel) Radarsat–1 radar cross section and retrieved winds (black barbs at 20-km intervals) within the box shown on the left. Note that backscatter is masked over land and where winds are weak.

The physical basis of the relationship between ocean surface wind and radar cross section involves groups of capillary waves that vary with the near–surface wind and produce Bragg scattering when illuminated by C–band radars. The SAR backscatter may also be sensitive to precipitation (Braun et al. 2002, 2005). Although such processes are nominally accounted for in a statistical sense by CMOD, it is not clear how precipitation impacts the polarization ratio correction of Vachon and Dobson (2000). Co–polarized C–band SAR may be either damped or enhanced owing to precipiation (depending in part on incidence angle and drop–size distribution). Thus, such regions are identified using GEM precipitation fields and the corresponding SAR data are masked. Finally, both CMOD and wind directions defined by the GEM model are used to remove the incidence angle dependence of the SAR data in regions of non–precipitation (a reference angle of 30° is employed).

The resolution of the operational GEM regional analyses of the Canadian Meteorological Centre (Laroche et al. 1999) increased from 24 km to 15 km in May 2004. Winds are extrapolated downward from the lowest model sigma level to 10 m above the surface. We then interpolate model data linearly to the transit time of the SAR acquistion and to the 1-km SAR grid, where wind retrieval is performed. Note that analysis quality is degraded somewhat by interpolating in time and no information is gained in interpolating to a finer spatial resolution.

To validate our retrieved winds, we make use of observations by buoys and ships of opportunity. Anemometer and thermometer heights for buoys are widely available (e.g., www.ndbc.noaa.gov), whereas ship observation heights are obtained from WMO Pub. 47 (Kent et al. 2005). If stability can be calculated, winds that are measured from ships and buoys are vertically adjusted to 10 m following Walmsley (1988). A logarithmic profile is otherwise used and winds that are visually estimated from ships are adjusted following Thomas et al. (2005). Finally, each observation is assigned a circular region of validity from 5 km to 50 km in radius, depending on its proximity to land (Fig. 1, lhs). Observations that occur within 90 minutes of a SAR acquisition and whose region of validity overlaps with this acquisition and are considered collocated in the overlap.

4. RESULTS

Following Portabella et al. (2002), the model wind error variance (diagonal elements of the **B** matrix) are set to 3 $m^2\ s^{-2}$. Off–diagonal elements of both the **B** and **R** matricies follow an exponential decay with a length scale of 150 km. The magnitude of the elements of the SAR error covariance matrix (**R**) is then varied. A minimum criteria is defined by the difference between the retrieved and *in situ* winds at all triple collocations. Specifically, we minimize the vector RMS and wind component standard deviation of these differences. Wind speed distributions corresponding to this minimum are shown in Fig. 2. For convenience, the ship and buoy observations are assumed to be the reference (cf. Stoffelen 1998). Figure 2d,e thus depict the model and retrieved wind errors, respectively. We find that the retrieved wind variance is reduced by 0.1 $m^2\ s^{-2}$. Corresponding values for the radar backscatter error distributions are also reduced, as expected.

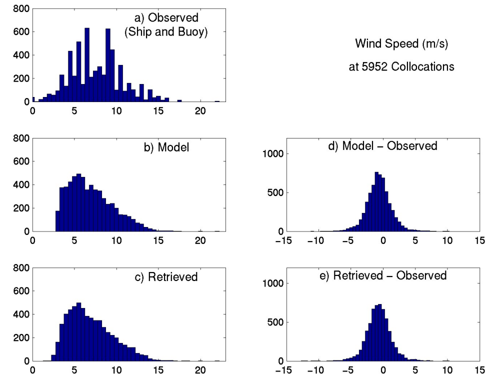

Figure 2: Wind speed distributions for 5952 triple collocations: a) observed by ships and buoys, b) modelled operationally by GEM, c) retrieved by 2D-Var, d) model minus observed, and e) retrieved minus observed. Abscissa is wind speed in m s^{-1} and ordinate is number of occurrences in 1 m s^{-1} bins.

5. SUMMARY

The direct retrieval of a vector wind field from scalar SAR observations is generally an underdetermined problem (Portabella et al. 2002). We have instead employed the GEM model winds as a background field and, using nonlinear regression, have attempted to improve the GEM winds. Much effort has already been invested in the calibration CMOD for scatterometer wind retrieval, but errors inherent in SAR wind retrieval are not as well known. Considering their much higher resolution, however, it may become worthwhile to incorporate SAR measurements into coastal data assimilation systems. Our results suggest that there is wind information that is not already present in high–resolution models and work is ongoing to refine our error estimates (specifically, the matricies **B** and **R**). Objective and statistically based methods of estimating scatterometer data errors (e.g., Stoffelen 1998) are also expected to be useful in the context of SAR marine wind retrieval.

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