

Marine Wind Analysis with the Benefit of Radarsat-1 Synthetic Aperture Radar

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ABSTRACT

A nonlinear regression approach is employed to construct a surface wind analysis from a synthetic aperture radar (SAR) acquisition off the west coast of North America and a collocated operational marine wind forecast. The analysis is iteratively constructed using a cost function that minimizes discrepancies with the wind forecast, the SAR backscatter, and wind directions that are inferred from the backscatter gradients. The relative importance of these discrepancies is defined by three corresponding error covariance matrices and an independent set of buoy observations is used to postulate their precise definition.

Keywords: Surface wind estimation, synthetic aperture radar, nonlinear regression, data assimilation

1 INTRODUCTION

It is well known that remote sensing can lead to improved marine forecasts in regions that are otherwise poorly observed. Atmospheric upper level and boundary layer processes are often manifested at the surface by coherent wind stress structures on various spatial scales greater than a few meters. These, in turn, produce corresponding variations in the growth of capillary waves and other surface roughness elements. Although the footprint of these structures can be observed using, for example, space-based scatterometers (with O[10-km] resolution) and synthetic aperture radars (with O[10-m] resolution), this type of information is often underutilized when analyzing marine winds. The objective of this work is to estimate the errors in synthetic aperture radar (SAR) wind information, with the expectation that data assimilation tests will subsequently explore their impact on forecasts.

2 ANALYSIS APPROACH

A nonlinear regression approach is employed in which the relative errors in SAR data are postulated. These postulates are used to construct analyses with minimum error variance using SAR acquisitions and Global Environmental Multiscale (GEM) model forecasts. Two SAR-wind relationships are considered. The first is the European Remote Sensing (ERS) C-Band model with the Radarsat-1 polarization correction of [1] Vachon and Dobson (2000) (and we denote the composite function by c below). This provides an estimate of SAR backscatter given wind speed and direction. The second is based on the proposition that SAR acquisitions resolve coherent wind streak patterns at O[100-m] scales that can be used to determine wind direction. This 180°-ambiguous wind direction (which we multiply by two, modulus 360°, and denote by a unit vector \mathbf{d}_s below) is derived from the local SAR backscatter gradient following [2] Koch (2004).

Errors in SAR and GEM data are expected to be indicative of the proper composition of a surface wind analysis in the least-squares sense. If \mathbf{x} is an estimate of the true wind field, the standard regression form for the SAR and GEM data and their errors (\mathbf{e}) is

$$\begin{bmatrix} \mathbf{y}_s \\ \mathbf{d}_s \\ \mathbf{x}_g \end{bmatrix} = \begin{bmatrix} \mathbf{c}(\mathbf{x}) \\ \mathbf{d}(\mathbf{x}) \\ \mathbf{x} \end{bmatrix} + \begin{bmatrix} \mathbf{e}_s \\ \mathbf{e}_d \\ \mathbf{e}_g \end{bmatrix}, \quad (1)$$

Here, each term is a column matrix of dimension $5N$ (for a SAR scene with N valid observations). The lhs term contains the SAR radar cross section (\mathbf{y}_s), the two components of the unit vector pointing at twice the angle of the observed wind streaks (\mathbf{d}_s), and the two components of the GEM model winds (\mathbf{x}_g). The first term on the rhs involves \mathbf{d} , which provides a unit vector at each analysis location that points at twice the angle of the estimated true wind vector. The second term on the rhs contains errors in the SAR backscatter (\mathbf{e}_s), in the use of SAR gradients to estimate wind direction (\mathbf{e}_d), and in the GEM wind components (\mathbf{e}_g). We define vectors by their cross-track (u) and along-track (v) components and express radar cross section in decibels.

An estimate of the true wind field with minimum error variance can be obtained by minimizing a cost function J . Given the above equation, for which we assume negligible covariance among the three types of errors, the corresponding cost function is

$$J = \|\mathbf{y}_s - \mathbf{c}(\mathbf{x})\|_{\mathbf{R}^{-1}}^2 + \|\mathbf{d}_s - \mathbf{d}(\mathbf{x})\|_{\mathbf{D}^{-1}}^2 + \|\mathbf{x}_g - \mathbf{x}\|_{\mathbf{B}^{-1}}^2. \quad (2)$$

The analysis \mathbf{x} that minimizes J is thus a function of the postulated SAR backscatter, SAR gradient, and GEM error covariance matrices (\mathbf{R} , \mathbf{D} , and \mathbf{B} , respectively). It is convenient to parameterize these matrices in terms of simple functions of only a few variables. We treat all errors as homogeneous and isotropic, with covariance that falls off exponentially with a given length scale. The GEM wind errors are specified in terms of streamfunction and velocity potential errors, following [3] Daley (1991). They have fixed along- and cross-flow variance of $5 \text{ m}^2\text{s}^{-2}$ (the diagonal elements of \mathbf{B}) and spatial covariance with a length scale of 350 km. The SAR backscatter errors are assumed to be a fraction of the SAR backscatter itself, following [4] Portabella et al. (2002), but because we also consider SAR error covariances, we normalize the backscatter to an incidence angle of 30° . This normalization is accomplished by multiplying radar cross section by a quadratic function of incidence angle (note the lack of range dependence in Fig. 1b,c). Variances are postulated to be between less than 1% and 31% of the normalized backscatter and covariances fall off with a length scale of between 0 km and 155 km. The SAR wind streak error variances are assumed to be between 0.1 and infinite (where the $\mathbf{d}_s - \mathbf{d}$ term contributes nothing to J). For simplicity, we neglect the error covariance in the directional information.

3 ANALYSIS EXAMPLE

The example chosen to illustrate our analysis technique is of an offshore wind event of moderate strength on the west coast of Canada. The observed SAR backscatter (Fig. 1b, after having been smoothed to 12.8-km resolution and then normalized to a 30° incidence angle) appears to confirm both the buoy observations and GEM forecast of stronger winds to the south (Fig. 1a). Although there are numerous discrepancies between the buoy observations and the GEM winds, SAR observations may help to reconcile these. For instance, the wind directions revealed by the SAR gradient calculation (Fig. 1b) are more consistent with the buoy observations. Also, there appears to be a wind shadow that is indicated by the low backscatter near buoy 46208 that the GEM wind forecast does not resolve. Here, only buoy observations within 30 minutes of Radarsat overpass are considered and these are vertically adjusted to the 10-m reference level, following [5] Walmsley (1988).

Buoy observations are used as an independent reference for postulating what the SAR error covariances should be in this case. After tuning the covariances, the analyzed wind directions (Fig. 1d) are more consistent with the buoys than the GEM directions. The wind shadow to the west and strong increase in wind speed to the south of the Queen Charlotte Islands are resolved in the analysis as well. The postulated SAR backscatter error variance that is used to produce this analysis is 1.5% of the SAR backscatter, with a covariance length scale of 15 km. The directional error variance is 0.1, which corresponds to placing high confidence in the local SAR gradients as an indication of wind direction.

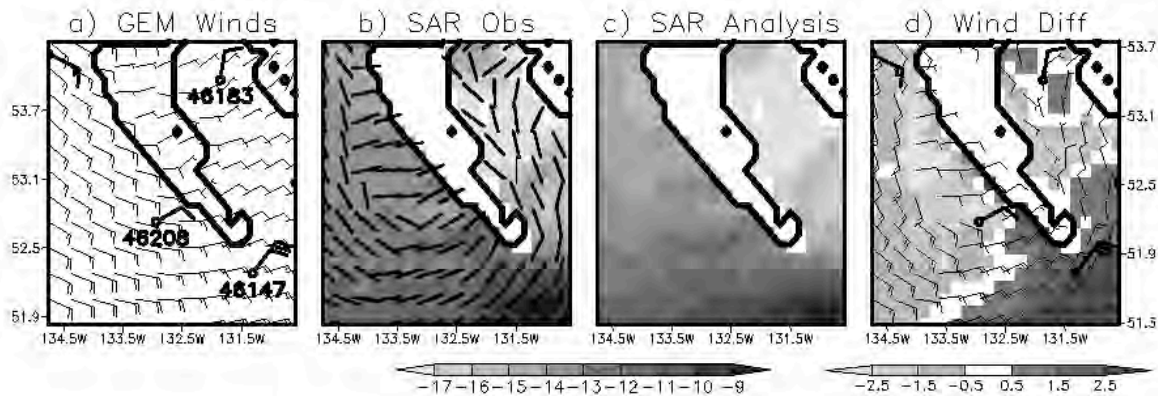


Figure 1. Surface wind analysis at 12.8-km resolution near the Queen Charlotte Islands at 15:08 UTC 12 December, 2004: a) GEM model winds with four buoy observations, b) SAR backscatter with its range dependence removed and wind streak direction obtained following Koch (2004), c) the retrieved backscatter $c(x)$ that minimizes J , and d) the corresponding wind analysis (barbs) along with analysis minus GEM wind speed differences (shaded).

4 CONCLUSIONS AND FUTURE WORK

Information extracted from a SAR acquisition can be used to modify a short-term operational model forecast of the surface wind so that better agreement is obtained with *in situ* observations. By employing the same nonlinear regression approach, comparisons between multiple analyses and collocated buoy observations may confirm that the SAR wind information, when it is available, should generally be weighted strongly and have a nonzero, but relatively short length scale. (Any SAR error length scale that is less than the resolution of a scatterometer would be consistent with the assumption that scatterometer errors have little spatial covariance.) An important caveat is that our postulated SAR errors are predicated on the assumption that the buoy observations can be used as a reference. Although this is expected to yield a good preliminary error estimate, buoy errors may ultimately limit their accuracy (cf. [6] Stoffelen 1998).

ACKNOWLEDGMENTS

This research has been sponsored by the Canadian Space Agency and hosted by the Oceanography Department of Dalhousie University. The SAR scene was obtained from the Gatineau office of MacDonald Dettwiler and Associates Ltd. and acquired through the Integrated Satellite Tracking of Oil Polluters (ISTOP) program of Environment Canada. John Wolfe, originally of the Canadian Centre for Remote Sensing, kindly provided code to calculate radar cross section. Land masks were derived using the Generic Mapping Tools software package (gmt.soest.hawaii.edu). Luc Fillion and Mark Buehner of Environment Canada provided assistance with the cost function minimization. Bridget Thomas of Environment Canada is thanked for providing algorithms to vertically adjust buoy wind observations, which were obtained from the Pacific-Yukon regional archives of Environment Canada.

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