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

Richard Danielson[1], Michael Dowd[2], and Harold Ritchie[1,3]
[1]Oceanography, Dalhousie University, Halifax, Nova Scotia
[2]Mathematics and Statistics, Dalhousie University, Halifax, Nova Scotia
[3]Environment Canada, Dartmouth, Nova Scotia

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 by coherent wind structures at the surface with various spatial scales above a few meters. 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 relative errors in synthetic aperture radar (SAR) wind information, with the expectation that data assimilation tests will subsequently explore their impact on forecasts. A nonlinear regression approach is employed in which these errors are postulated. These postulates are then used to construct analyses with minimum error variance from SAR acquistions and Global Environmental Multiscale (GEM) model forecasts. Two SAR–wind relationships are considered here. The first is the European Remote Sensing (ERS) C-Band model with the Radarsat-1 polarization correction of 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 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 **x** is an estimate of the true wind field, the standard regression form for the SAR and GEM data and their errors (**e**) is

$$\begin{pmatrix} \mathbf{y}_s \\ \mathbf{d}_s \\ \mathbf{x}_g \end{pmatrix} = \begin{pmatrix} \mathbf{c}(\mathbf{x}) \\ \mathbf{d}(\mathbf{x}) \\ \mathbf{x} \end{pmatrix} + \begin{pmatrix} \mathbf{e}_s \\ \mathbf{e}_d \\ \mathbf{e}_g \end{pmatrix}. \tag{1}$$

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 **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 is obtained by minimization of a cost function J. Given the above equation, the corresponding cost function is

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

The analysis **x** that minimizes J is thus a function of the postulated SAR backscatter, SAR gradient, and GEM error covariance matrices (**R**, **D**, and **B**, respectively). We treat the GEM wind errors

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Corresponding author email: rick.danielson@phys.ocean.dal.ca

as homogeneous and isotropic streamfunction and velocity potential errors, following Daley (1991), with fixed along- and cross-flow variance of 5 $\mathrm{m}^2\ \mathrm{s}^{-2}$ (the diagonal elements of $\mathbf{B}$) and spatial covariance that decays exponentially with a length scale of 350 km. For the SAR acquistion illustrated in Fig. 1, we postulate that the SAR backscatter error variance is 1.5% of the SAR backscatter itself (Portabella et al. 2002) and the covariance decays with a length scale of 15 km. The directional errors are simply assigned a variance of 0.1, which corresponds to placing high confidence in the gradient calculation as an indication of wind direction.

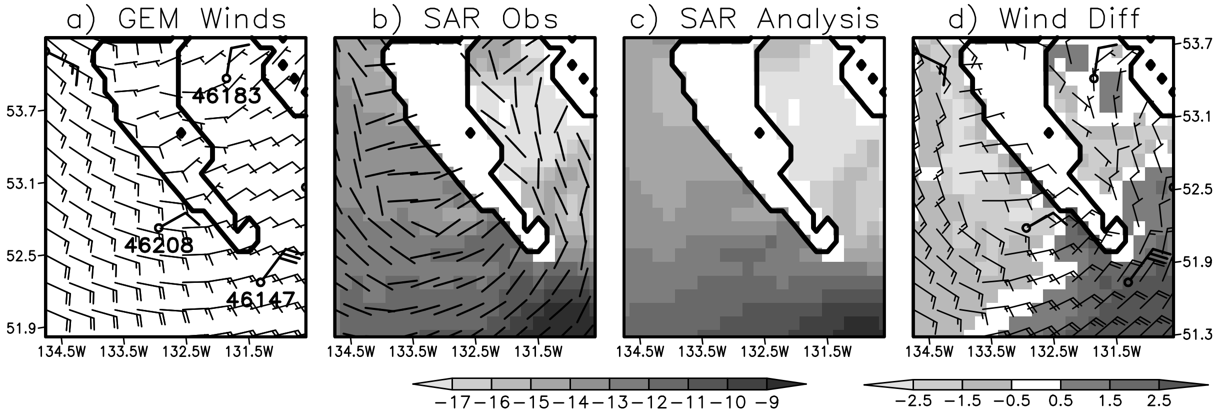

Figure 1: Surface wind analysis near the Queen Charlotte Islands on December 12, 2004: a) GEM model winds with four buoy observations, b) SAR backscatter with its range dependence removed and wind streak direction obtained following Koch (2004), c) the retrieved backscatter $\mathbf{c}(\mathbf{x})$ that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

Buoy observations that are vertically adjusted to the 10-m reference level (Walmsley 1988) and available within 30 minutes of Radarsat overpass have been used to tune our SAR error covariances. Figure 1b reveals the wind directions obtained from gradients in SAR backscatter at 400-m resolution are quite consistent with the buoys, which implies that the former should be weighted strongly. The resulting wind speeds also more consistent with buoys than the GEM forcast: the analyzed winds are slower than the GEM winds to the west and faster to the southeast.

Further comparison of analyses and buoy observations (not shown) suggests that the SAR error variance may be about 1.5% of SAR backscatter and have a length scale of about 15 km, which is much less than the resolution of scatterometer data (which is not considered to have spatial error covariance). One caveat here 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 limit their accuracy (Stoffelen 1998).

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