Applications of Synthetic Aperture Radar to Meteorology and Oceanography Command Operations

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LONG-TERM GOALS

Our long-term goal is to employ synthetic aperture radar (SAR) imagery of the sea surface as a marine meteorological research and forecasting tool. That is, we aim to use SAR to discover dynamical and morphological characteristics of microscale, mesoscale, and synoptic scale marine meteorological phenomena. We also aim to demonstrate how the fruits of our discovery can be used to aid marine meteorological analysts and forecasters.

OBJECTIVES

We propose to develop the software tools for portable, automated SAR-based analysis of the marine wind field with the objective of resolving intense mesoscale variability in the near-surface wind field.

We propose to develop a SAR-based system for automated verification of, and error-warning system for, mesoscale wind forecasts produced by numerical weather prediction (NWP) models. The emphasis will be on verification and error detection in those regions most challenging to mesoscale numerical weather prediction models—the near-shore zones adjacent to complex orography.

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14. ABSTRACT
Our long-term goal is to employ synthetic aperture radar (SAR) imagery of the sea surface as a marine meteorological research and forecasting tool. That is, we aim to use SAR to discover dynamical and morphological characteristics of microscale, mesoscale, and synoptic scale marine meteorological phenomena. We also aim to demonstrate how the fruits of our discovery can be used to aid marine meteorological analysts and forecasters

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We propose to empirically and theoretically investigate the phenomena responsible for the SAR-signature of convectively-driven squall / lull couplets. The analysis will include the forcing, structure, and predictability of these intense mesoscale variations in the near-surface wind field. The goal is to incrementally step towards improved NWP model and statistical forecasts of this phenomenon.
In the context of these objectives, we have outlined five tasks:

Task 1: Develop a highly portable, efficient, and verifiable CMOD 4/5 hybrid software system for SAR wind speed retrieval.

Task 2: Develop a fully automated system for mapping intense mesoscale variability in the near-surface wind field at sea.

Task 3: Determine the forcing, structure, and predictability of the convectively-driven open ocean squall / lull couplet features frequently seen on SAR imagery .

Task 4: Develop a SAR-based system for automated verification of, and error-warning system for, mesoscale wind forecasts produced by NWP models.

Task 5: Publish results in appropriate journals and present research at relevant conferences.

APPROACH

The basis of the proposed research is the approximately 35,000+ SAR wind speed image frames from the Bering Sea, Gulf of Alaska, East Coast of the United States, and the North Atlantic Ocean (from 1998 to present) contained in JHUAPL's image archive. This image data is provided at no cost by Dr. Winstead. This image archive has been used extensively by the PIs to study atmospheric phenomena in the Gulf of Alaska. In addition to previous ONR-funded research of Drs. Sikora and Young (N00014-06-10046 [Sikora] and N00014-04-10539 [Young]), Drs. Winstead and Young participated in an NSF-sponsored study of barrier jets in the Gulf of Alaska using SAR imagery. During the course of these research projects, a catalog of various imaged phenomena was generated by Drs. Sikora and Young (Stepp et al., 2007). This climatology documented a number of phenomena causing intense mesoscale variations in the near shore winds: gap flow exit jets (Figure 1), orographic gravity waves (Figure 2), island wakes (Figure 3). In the open ocean, the most intense wind speed variability was caused by quasi-circular squall / lull couplets (Figure 4), described in Young et al., (2007). The arrows seen within each SAR wind speed image are NWP model wind vectors. The approach described here is designed to automate the quantitative description of these intense mesoscale wind variations and lay the basis for forecasting them via a combination of numerical weather prediction and statistical post-processing.

The analytic foundation of the proposed SAR analyses is software to infer near-surface wind speed from SAR backscatter based on CMOD4 (Stoffelen and Anderson, 1997a, 1997b) and CMOD5 (Hersbach, 2007). Thus Task 1 was to use Dr. Winstead's expertise in CMOD and Dr. Young's expertise in software optimization, documentation, and testing to build a "technology transfer friendly" version of the existing JHUAPL CMOD system. The resulting Matlab software, including both CMOD4 and CMOD5, is available for public download from http://www.ems.psu.edu/~young/CMOD. The software is noteworthy in that it provides a fully documented testing and verification program, so that the user can both see how to implement calls to our CMOD functions and verify that the functions are working correctly on their system. To that end, the website also provides data files for system checkout and testing by users and a Word file documenting the system and its use. The outcome of Task 1 is summarized in Fisher et al.. (2007) and the documentation file on the website.

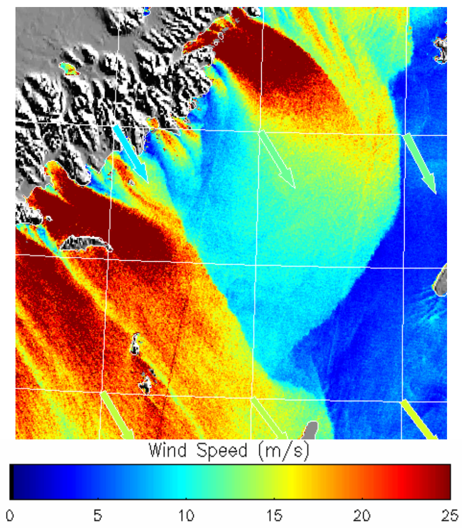

Figure 1. Radarsat-1 SAR wind speed image depicting the signature of gap flow exit jets forced stably-stratified flow through topography. The 600 m pixel image is 450 pixels by 450 pixels. The image was acquired off the coast of the Alaska Peninsula at 1635 UTC on 21 January 2006. (Provided courtesy of JHUAPL)

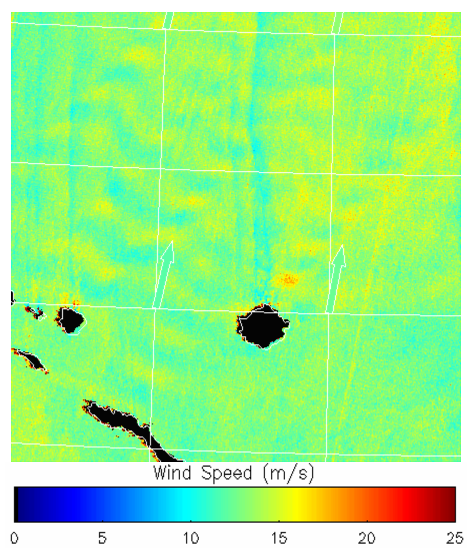

Figure 2. Radarsat-1 SAR wind speed image depicting the signature of gravity waves forced by stably stratified flow over mountainous islands. The 600 m pixel image is 450 pixels by 450 pixels. The image was acquired off the Aleutians at 1808 UTC on 28 February 2006. (Provided courtesy of JHUAPL)

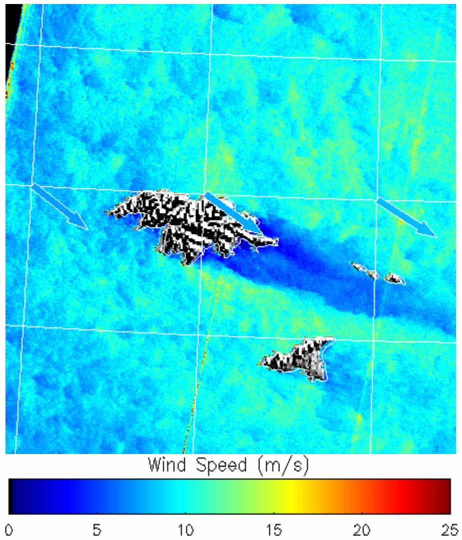

Figure 3. Radarsat-1 SAR wind speed image depicting the signature of a slow wake forced turbulent flow over a mountainous island. The 600 m pixel image is 450 pixels by 450 pixels. The image was acquired off Attu Island in the Aleutians at 1833 UTC on 30 March 2006. (Provided courtesy of JHUAPL)

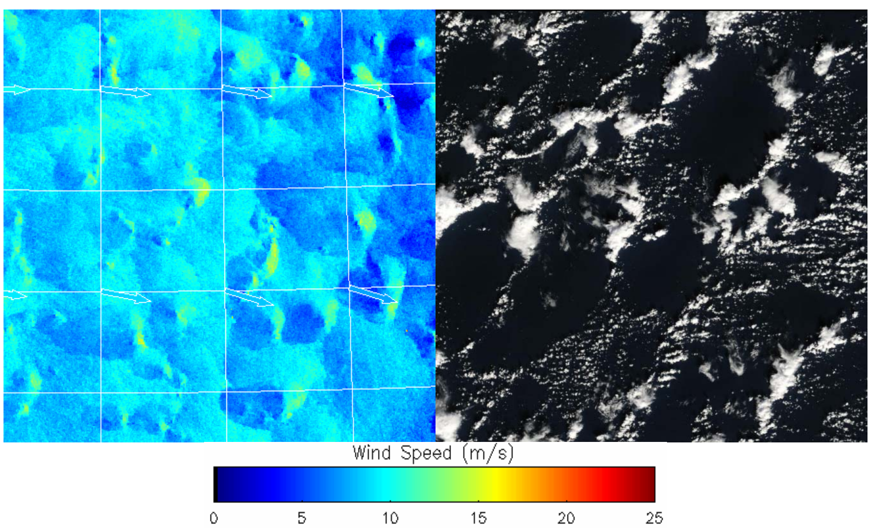

Figure 4. On the left is a Radarsat-1 SAR wind speed image depicting the quasi-circular signatures of convectively-driven open ocean squall / lull couplets. The 600 m pixel image is 450 pixels by 450 pixels. The image was acquired over the Gulf of Alaska at 0301 UTC on 8 November 2006. The near-surface wind speed varies by a factor of two across the couplets (13 to 6.5 m/s). (Provided courtesy of JHUAPL) On the right is the closest corresponding MODIS image, a Terra satellite image of the region at 1955 UTC on 7 November 2006. The 250 m pixel image is 900 pixels by 900 pixels. It shows open-cell mesoscale cellular convection with a scale similar to the SAR signatures. (Provided courtesy of NASA)

The other foundation of the proposed SAR analysis is the ability to distinguish sharp-edged mesoscale variability of the wind speed field from the smooth background gradient imposed by synoptic scale weather systems. This task (Task 2) is being approached as a digital filtering problem and objective analysis problem. In the first approach, application of a conventional high-pass two-dimensional digital filter (Oppenheim and Shafer, 1989) to the SAR wind speed image yields the perturbation wind field directly. In the second approach, in contrast, the perturbation wind field is obtained indirectly. First, a low-resolution objective analysis (Kalnay, 2003) is made of the SAR-derived wind speed field and then this smooth field is subtracted from the wind speed image to yield the perturbation wind field. Both approaches are being tested and their relationship and relative merits evaluated. We anticipate developing a tool box from which the end user can choose either method. Once a perturbation wind field is obtained, gust intensity (i.e., the standard deviation of the wind field) is mapped via a statistical procedure to yield a product more suitable to end-user needs. Gust intensity is computed statistically for an array of overlapping pixel-blocks, each large enough to provide a representative sample of the mesoscale phenomena responsible. The resulting gust intensity statistics are then objectively analyzed back to the original grid, yielding a smooth map of gust intensity. This procedure is loosely based on the aircraft turbulence data analysis procedure developed by Young et al., (2000). We are currently preparing a corresponding invited refereed article to appear in 2008.

Convectively-driven squall / lull couplets at sea are not generally resolved by operational NWP models except when clusters of thunderstorms are involved. Yet such couplets are frequently observed in SAR imagery, even when no thunderstorms are present. Thus, other convective phenomena that are not correctly resolved in current NWP models must be responsible for this phenomenon. Comparison of MODIS Terra and Aqua 250 m resolution visible satellite imagery with SAR wind speed imagery suggests that the quasi-circular couplets may be caused by the surface outflow of precipitation-driven downdrafts from shallow, non-thunderstorm convection (Young et al., 2007; Fisher 2007). Such non-thunderstorm couplet cases seem to be particularly common in mid- to high-latitude non-frontal synoptic settings in which towering cumulus or open-cell mesoscale cellular convection is observed. The JHUAPL SAR image archive has been mined for squall / lull couplet cases of this sort (Stepp et al., 2007) and the corresponding MODIS imagery examined. This comparison was conducted primarily for the Gulf of Alaska region because of improved coverage by both satellites at higher latitudes. SAR and MODIS multi-spectral imagery were used to verify the hypothesis that couplets of scale less than about 10 km are associated with isolated precipitating towering cumulus while those on scales of 10 to 100 km are associated with precipitating towering cumulus organized into open-cell mesoscale cellular convection. Also documented using MODIS were the cloud depth and microphysical characteristics necessary for the initiation of couplet-generating precipitation-driven downdrafts. We went on to investigate their occurrence and orientation as a function of the mean lower-tropospheric stability and wind profiles. The open cell convection occur during cold air outbreaks, with the squalls oriented perpendicular to the low level wind (i.e., propagating downwind) and occurring at the downwind edge of the downdraft outflow. This work lays the foundation for future developments in the statistical post-processing of NWP model output to yield forecasts of these unresolved non-thunderstorm convective squall / lull couplets. The work described above corresponds to Task 3.

Warning of mesoscale wind speed variability in the near-shore region is both complicated by the numerous orographically generated mesoscale flows discussed above and aided by the partial resolution of these phenomena by mesoscale NWP models. Task 4 thus focuses on using SAR to verify whether or not the NWP model forecasts valid at the SAR observation time are resolving the observed mesoscale wind speed variability, both near-shore and for the open ocean. Thus, SAR will provide warning of ongoing events and information about how well the operational NWP model forecasts will capture future events of that type. The first stage in this analysis involves using model-derived wind directions to obtain a SAR wind speed analysis from the backscatter image. The second stage is a direct comparison between the SAR wind speed analysis and the modeled wind speed field. If the two agree, then the model is resolving the current flow well and can be expected to do so during similar synoptic situations in the future. In contrast, if the SAR and modeled wind speed fields disagree, either the model wind directions are wrong (causing SAR wind speed errors) or the model is failing to resolve the wind speed field correctly. In either case, the model is known to be doing a poor job of resolving the wind field. This is expected to be a particular problem near mountainous coasts where meteorologically significant gaps can frequently be only a few km across, requiring grids an order of magnitude finer than are now used in operational NWP models to fully resolve the flow field.

WORK COMPLETED

Task 1: Technology transfer friendly software has been developed to infer near-surface wind speed from SAR backscatter based on CMOD4 and CMOD5. An evaluation of wind speed retrieval skill for CMOD4 and CMOD5 for a geographic region with intense mesoscale variability, the Gulf of Alaska, has been completed.

Task 2: Prototype of a fully automated system for mapping intense mesoscale variability in the near-surface wind field at sea has been developed.

Task 3: Observational study focused on determining the forcing, structure, and predictability of the convectively-driven open ocean squall / lull couplet features frequently seen on SAR imagery has been completed.

Task 4: Work not yet addressed.

Task 5: See publication list below.

RESULTS

Task 1: CMOD4 and CMOD5 functions in Matlab have been released for public use along with full documentation, test data, and performance statistics for a geographic region of intense mesoscale variability. The performance of SAR wind speed retrieval in this challenging environment was excellent when compared with direct measurements from three Navy Oceanographic Meteorological Automatic Device (NOMAD) buoys. Both of the commonly used SAR wind speed retrieval models, CMOD4 and CMOD5, performed well although there was some wind speed bias. It is unknown whether this bias was caused by a SAR wind speed retrieval error or a buoy error since buoys are known to underestimate winds as wind speed and, thus, sea state increase. There was little impact on the comparisons after correcting the buoy-derived wind speeds for surface layer stability. The comparisons were also insensitive to the choice of wind direction source, buoy observations or NOGAPS model analyses. It is concluded that useful wind speeds can be derived from SAR backscatter and global model wind directions even in proximity to mountainous coastlines.

Task 2: Preliminary analysis of the mathematics of digital filtering and objective analysis shows that the two approaches are broadly equivalent. In high-pass filtering a low-pass filtered (i.e., smoothed) image is subtracted from the original to yield the gust data. Similarly, in objective analysis, a weighting function is used to produce a smoothed image for subtraction from the original. Thus, the two differ primarily in the choice of weight matrix (a.k.a. filter matrix). Experimentation with classical algorithms for digital image enhancement (i.e., high-pass filtering) revealed that the each of the two broad classes of enhancement filters corresponds to one of the two broad glasses of mesoscale wind variability. Edge enhancement filters are appropriate for the detection of elongated zones of wind speed gradient, such are those along fronts, barrier jets, and gap flow exit jets. Likewise, two-dimensional de-blurring filters are appropriate for distinguishing convective squalls. Some filtering techniques, such as the local entropy algorithm, are suitable for quantifying both types of wind speed variability. The key element in the choice of filtering method is the user's operational weather sensitivity. Thus, different filtering and mapping techniques will be required to support naval operations that are sensitive to squalls while others are more suited to mapping the sharp wind gradients associated with more linear mesoscale phenomena.

Task 3: Examination of Moderate Resolution Imaging Spectroradiometer (MODIS) imagery, meteorological analyses, and numerical weather prediction model forecasts for a collection of 24 open-cell convection cases in the Gulf of Alaska revealed that squall-and-lull patterns observed within corresponding SAR-derived wind speed images resulted from downdraft momentum transfer and spreading associated with the deep precipitating convection along the cells' leading (i.e., downwind) edges. In addition, this analysis suggested a new conceptual model of open cell convection. MODIS imagery revealed that the open cell convection is composed primarily of cumulus humulus and cumulus congestus clouds, with cloud shadow measurements yielding a factor-of-three variation in cloud top height between the highest clouds (those on the leading or downwind edge of the cells) and the more shallow clouds along the sides and rear of the cells (Figure 4). The MODIS imagery also revealed that the tallest clouds typically contain ice, which suggests that the Bergeron process plays a role in the precipitation-driven downdrafts that cause the wind squalls seen in SAR-derived wind speed imagery. Individual squall-and-lull features have an elliptical boundary with an arc-shaped squall along the feature's downwind edge, with wind speed decreasing gradually across the feature to its upwind edge.

Task 4: Work not yet addressed.

Task 5: See publication list below

IMPACT/APPLICATIONS

The completed research of Tasks 1 and 2 fulfill ONR objectives by working towards the automated integration of standard meteorological NWP model output and SAR data with the goal of providing high-resolution analyses of near-surface wind speed, direction, and gust intensity in *in situ* data-sparse regions over the ocean, including the littoral zone. Moreover, observational results associated with Task 3 will lead to improved forecasts of the same variables.

TRANSITIONS

None

RELATED PROJECTS

Dr. Sikora is collaborating with Dr. Winstead and National Weather Service Weather Forecast Office Juneau meteorologists on a NOAA-funded project to study the meteorological uses of SAR in the small inlets and mountain gaps that riddle the southeast coast of Alaska. The project goal is to determine the accuracy of SAR gap flow wind speeds under various synoptic scale situations (i.e., develop an error climatology) and to assess the impact of improved wind directions in these critical locations. This NOAA-funded project is closely aligned with Task 4.

Dr. Winstead and the JHU/APL team has applied for funding from NASA to standardize and distribute all SAR wind data archived to date at APL. This will include all imagery from Radarsat-1, ERS-1, and EnviSAT. If this project is funded, we will be able to offer to the naval community a standardized wind product with tools for accessing the data. We plan to make these data products compatible with the software generated for this project making future study of the near-surface wind field from SAR easier.

Dr. Young is part of a Penn State and NCAR team addressing the mesoscale modeling of the mesoscale wind variability caused by spatial variations in cloud cover and soil moisture. Many of the implications of this over-land work are equally applicable to the circulations driven by sea surface temperature variations. Dr. Young has focused on the fluid dynamic similarity theories for such buoyantly-driven mesoscale phenomena, including gravity currents, solenoidal circulations, and convection.

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PUBLICATIONS

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