Report on
Stochastic Analysis of Satellite-derived Arctic Sea Ice Information and Acceleration proposal to support N00014-02-1-0244

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Collaborator's Websites:
http://www.vims.cis.udel.edu:8888/ (UD VIMS web site)
http://www.crrel.usace.army.mil/sid/index.html (CRREL Snow and Ice Branch web site)
http://www.gi.alaska.edu/ (University of Alaska Fairbanks GI Institute)
http://www.asf.alaska.edu/ (Alaska SAR Facility)
http://www.pmel.noaa.gov/ (NOAA at PMEL in Seattle, WA)
Visualization Demonstration Websites:
http://www.cis.udel.edu/~lzhou/r1.html (hurricane visualization using GOES satellite)
http://www.udel.edu/Geography/Geiger/research.html (buoy visualization)

LONG-TERM GOALS

Sea-ice motion falls under the larger category of non-rigid motion analysis [Kambhamettu et al., 1994, 1998, 2002]. The interdisciplinary field of non-rigid motion involves the understanding of three basic types of materials, namely, continuous, piece-wise continuous, and discrete particle motion. Depending on the scale, each of these descriptions applies to sea ice. At the large (basin) scale, sea ice has traditionally been regarded as a non-rigid Newtonian continuum and at the small scale it is regarded as a collection of discrete particles/floes. While great progress has been made in understanding these two outer scales of sea ice, the intermediate (mesoscale) of piece-wise continuous sea-ice motion is particularly difficult because it goes beyond the limits of its scale with very narrow (i.e. small scale) crack-like features stretching thousands of kilometers (i.e. basin scale). The added complexity of sea ice as a solid material at the air-sea boundary interface makes sea ice a challenging material to study. Understanding such complex behavior involves an interdisciplinary approach through which many other fields can reap the benefits.

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14. ABSTRACT
Sea-ice motion falls under the larger category of non-rigid motion analysis [Kambhamettu et al., 1994 1998, 2002]. The interdisciplinary field of non-rigid motion involves the understanding of three basic types of materials, namely, continuous, piece-wise continuous, and discrete particle motion. Depending on the scale, each of these descriptions applies to sea ice. At the large (basin) scale, sea ice has traditionally been regarded as a non-rigid Newtonian continuum and at the small scale it is regarded as a collection of discrete particles/floes. While great progress has been made in understanding these two outer scales of sea ice, the intermediate (mesoscale) of piece-wise continuous sea-ice motion is particularly difficult because it goes beyond the limits of its scale with very narrow (i.e. small scale) crack-like features stretching thousands of kilometers (i.e. basin scale). The added complexity of sea ice as a solid material at the air-sea boundary interface makes sea ice a challenging material to study. Understanding such complex behavior involves an interdisciplinary approach through which many other fields can reap the benefits.

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Our long-term goal is therefore to gain an understanding of mesoscale sea-ice processes and their interplay with large and small scale processes within the hierarchy of air-ice-sea processes. Our approach is a cross-disciplinary one, which is ideally suited to advance basic principles in the scientific community at large.

OBJECTIVES

Originally intend goals:

1) provide measures for quality control of sea-ice motion products notably in regard to temporal-spatial variability and error propagation;
2) prepare three SAR-derived datasets in the Arctic (SIMI, Sheba, Buoys 2001/2002) for testing the validity of using motion-derived products as direct input to high-resolution models (especially PIPS); and
3) investigate a stochastic formulation for sea-ice models at scales of 10-300km.

APPROACH

The approach is to construct Lagrangian time series of coincident buoy and SAR-derived motion products from the SIMI, Sheba, and Beaufort 2001/2002 ONR field programs. Using a statistical approach, the local drift and deformation can be computed over these time frames to assess the impact of temporal and spatial scale on the determination of deformation values. Development of practical fields such as time series of continuous and discontinuous sea-ice motion (i.e., high-resolution lead-resolving fields) serve as a valuable tool for understanding the evolution of meso-scale processes. Once constructed, the time series will be used for analysis by this research group and eventually made available to the modeling community for case studies and data assimilation.

Through a NASA DAR proposal submitted in conjunction with these projects, Cathleen Geiger, Chandra Kambhamettu and their graduate student Mani Thomas have isolated roughly 200 sequential SAR scenes per experiment which are coincident with buoy arrays equipped with GPS and stress sensors. The development of a multi-scalar sea-ice motion tracking algorithm (down to 400 m resolution) has redirected the initially proposed work in a very positive way.

WORK COMPLETED

Tasks accomplished thus far.

1) Buoy trajectory data from three experiments are under analysis by Geiger with collaborative interaction between her and the NOAA/PMEL group (under Jim Overland) in Seattle, WA who collected these data.
2) A DAR plan has been submitted by Geiger and approved (as of September 19, 2002) for the reprocessing of the needed SAR images.
3) Animations and cataloguing of coincident time windows between buoys and SAR image pairs have been constructed using software developed by Geiger. This is to ensure proper identification of specific image pairs from an enormous archive catalog.
4) The isolation of about 200 sequential SAR scenes from each of the SIMI, Sheba and the Beaufort buoy project 2001/2002 via the Alaska ASF facility. Orders of those data are still underway but progressing in an organized and timely manner.
5) A multi-scalar motion tracking scheme has been developed by Mani Thomas under the guidance of C.A. Geiger, and C. Kambhamettu under NSF funding OPP9818645 and the projects herein. The

algorithm is in the process of being automated with documentation (completed technical report with peer-reviewed publication in preparation – see reference list).

6) Due to Geiger's new job change, contacts have been made at CRREL for eventual studies to combine the strain-rate analyses from this project with coincident stress measurements. These 3 field experiments are the first ever such opportunities to examine large- to meso-scale stress vs. strain-rate from in situ field measurements.

RESULTS

Using a phase correlation method to render sea-ice motion from ERS-1 test images in the Weddell Sea, we reconstruct velocity fields of sea-ice at very high resolution (max resolution 400m – order of magnitude greater than the standard RGPS products). We take advantage of the fundamental limitation of correlation, namely its inability to resolve regions of discontinuous motion, to produce fields of continuous and discontinuous motion and therefore the location of shear zones and/or leads (e.g., Figure 1).

A paper entitled "Delineation of continuous and discontinuous sea-ice motion at the mesoscale" currently in preparation will summarize the findings from this study. The paper will focus on the 3 objectives listed above. The case studies under preparation are scheduled to be completed by the end of project N00014-03-1-0045 in FY2004. The lack of continued funding for the PI under project N00014-02-1-0244 will limit the number of case studies to those which can be isolated and processed by the student funded under N00014-03-1-0045.

IMPACT/APPLICATIONS

We make use of a key limitation with correlation methods, namely, their inability to resolve regions of discontinuity [Vernon, 2001], to produce maps of correlation, which serve as templates for segmenting an image into continuous and discontinuous partitions (Figure 1). Further segmentation is accomplished by combining these results with information about the changes in velocity direction and magnitude to render a gridded field containing high resolution velocity vectors in continuous regions and locations of discontinuities. The results (as illustrated in the lower panel of Figure 2) are in a "model friendly" format, which modelers can use for direct comparisons (upper panel of Figure 2). Gridded products like this, over a Lagrangian sequence of buoy arrays, are the primary deliverables we intend through the ONR projects. The striking similarity in format between the two panels shown in Figure 2 further encourages detailed study towards the creation of a synthesized product between buoys, RGPS SAR images, and some type of model (like the CRREL DEM).

We have successfully developed and tested a collection of programs under PV-wave software, which read in the position of polar-orbiting satellite images coincident with particles tracked by GPS moving along the surface of the earth. The code extracts pairs of satellite images, which temporally and spatially match the moving particles. Output includes a sequence of animated images to check their coincidence with nearby surface particles and images for application in motion feature tracking. A tabulation of images is provided in a form which can be copied and pasted to a website for ordering the images. The graphical visualization and automated output allows for simple checks of the images with minimal introduction of human error. While such technology will advance the field of sea ice, there are many benefits of such searching algorithms in general military applications.

Complementary to the above, we have developed a multi-scalar motion feature tracking system. The system development is complete and is under testing to provide high resolution (4x4 pixel) motion vectors from microwave imagery containing discontinuous materials in 2D and 3D. The output is provided in a "model friendly" format as an array containing the velocity vectors and a mask (series of zeros and ones) to identify the location of the discontinuities. Currently, motion vector products of sea ice are available down to a resolution of about 5 km. This new system will provide results down to a resolution of 400 m (an order of magnitude improvement) with an uncertainty assigned to each individual vector as opposed to an average value as is currently available.

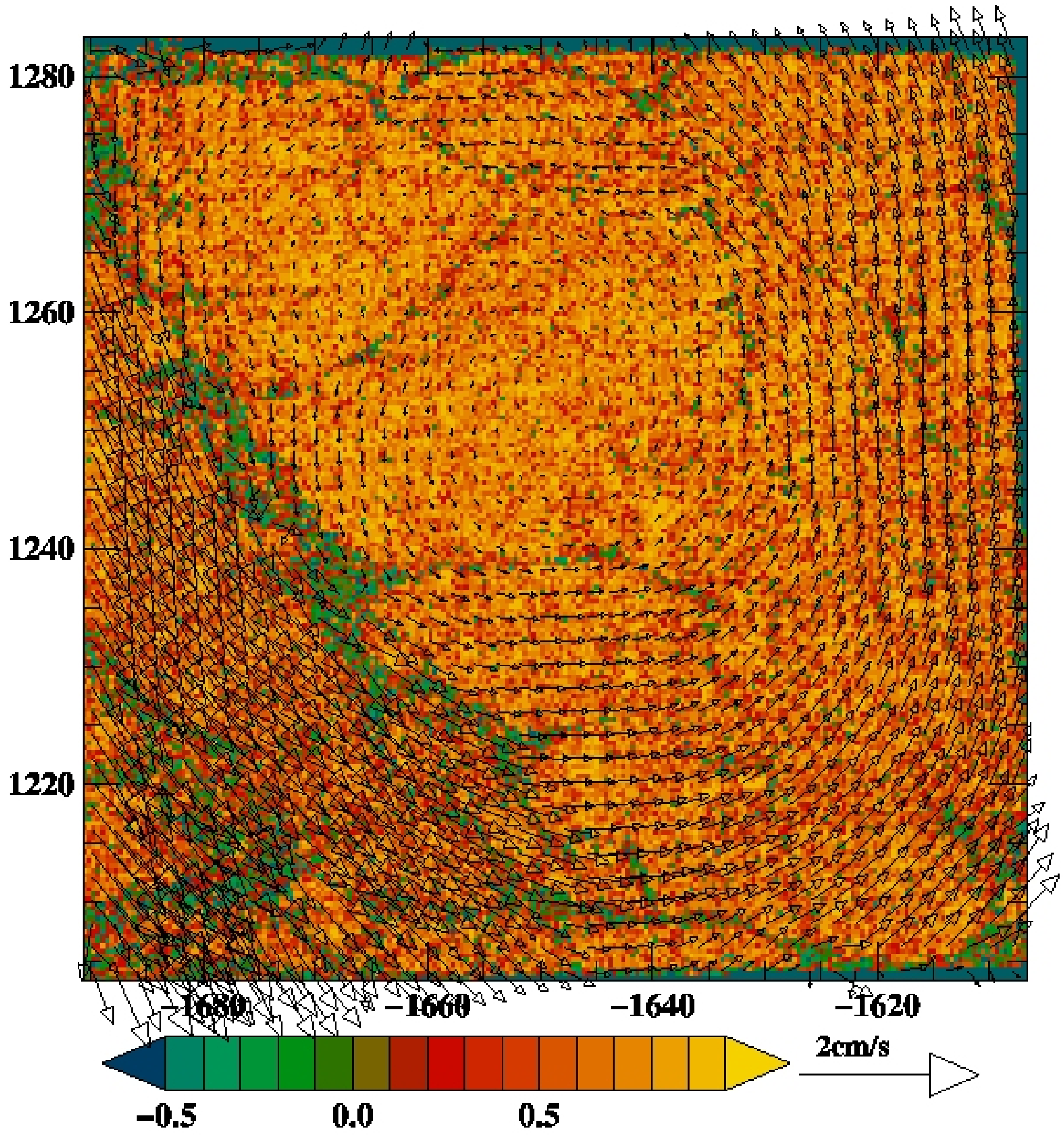

Figure 1: SAR-derived differential motion vectors and associated correlation coefficient (colored boxes). Motion resolved at a scale of 400m with every 5th vector shown. The correlation is lowest in regions of discontinuous ice motion.

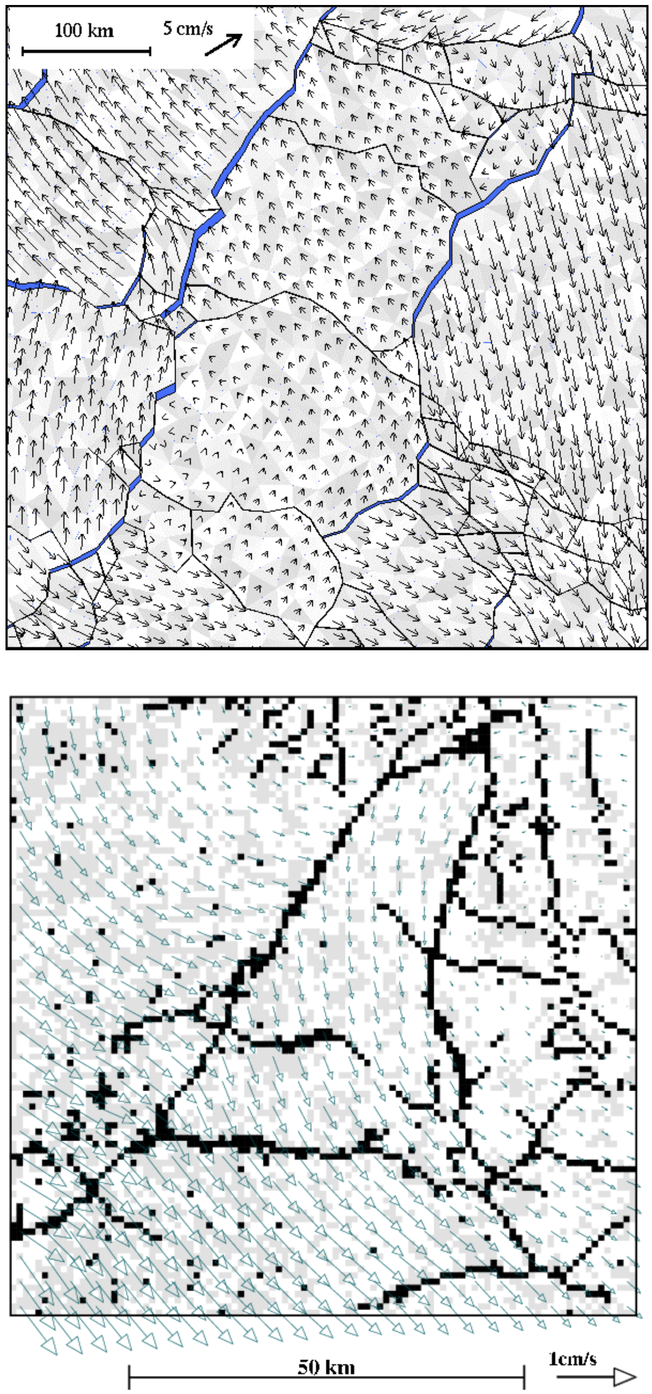

Figure 2: Upper panel shows results from a 500 x 500 km^2 section of the CRREL DEM model with grey and white model elements shown. Black lines indicate boundaries and blue is for open water. The model output is from January 20, 1998 over the SHEBA camp.

Lower panel is a composite of differential motion vectors rendered from 75x75 km^2 subsection of a RADARSAT image pair taken January 14 and 17, 1998 in close proximity to the SHEBA camp. Grey and white pixels represent regions of high correlation motion between images. Black regions are a composite of gradients in velocity magnitude and direction and low correlation. Every 4th velocity vector is shown.

TRANSITION

Integration of projects into a new work environment at CRREL: The task of creating an effective high-temporal, high-spatial composite using *in-situ* instrumentation and satellite imagery remains an unsolved problem for any geophysical system. Using sea ice as a surrogate for an arbitrary collection of objects one can extrapolate the technology developed here to the general principle of moving particle behavior (i.e. tanks, guerrilla troops, non-stationary geophysical features). With military strategies shifting from a relatively stationary battle theater to a dynamic, highly mobile battlespace environment, more tactics must evolve from a co-moving (Lagrangian) frame of reference. In such an environment, "snap-shots" of information from isolated satellite images or isolated recon crews yields limited, if not flawed, interpretations due to critical gaps in the information. An integrated approach must be built on the strength of each technology with redundancies in the different resources for cross-checking. Hence, the simple exercise of characterizing the motion of ice floes subject to known and unknown constraints may prove useful in the development of new strategies within battlespace environment.

RELATED PROJECTS

NSF9818645: Investigation of tidal aliasing and climate scale processes in sea ice and their influence on oceanic-atmospheric heat/mass/momentum balances using stochastic methods, satellite-derived products, and *in-situ* buoy arrays. 1998-2001 with no-cost extension to September 2002. Analysis using coincident buoy and SAR-derived motion products to look at the temporal-spatial coupling of sea-ice processes in the western Weddell Sea. Two relevant publications listed in references.

RELEVANT REFERENCES

Geiger, C. A., M. Thomas, and C. Kambhamettu, Delineation of continuous and discontinuous sea-ice motion, manuscript in preparation to *Journal of Geophysical Research*, 2003.

Geiger, C.A., and M. Drinkwater, Consideration of tidal motion and other high frequency forcing in the western Weddell Sea: SAR and buoy comparison of sea ice from ISW 1992, submitted to *Journal of Geophysical Research*, 2003.

Geiger, C.A., and M.R. Drinkwater, Impact of temporal-spatio resolution on sea-ice drift and deformation, IUTAM Symposium on *Scaling Laws in Ice Mechanics and Ice Dynamics*, (eds.) J.P. Dempsey and H.H. Shen, Kluwer Academic Publishers, Netherlands, 407-416, 2001.

Kambhamettu, C., D. B. Goldgof, D. Terzopoulos and T. S. Huang, *Nonrigid Motion Analysis*, Handbook of PRIP: Computer vision, eds. Tzay Young, Vol II, pp 405-430, 1994. (also appeared in *Deformable Models in Medical Image Analysis*, edited by Ajit Singh et al., 1998.)

Kambhamettu, C., D. Goldgof, M. He, and P. Laskov, 3D Nonrigid Motion Analysis Under Small Deformations, Image and Vision Computing Journal (IVC), in press, 2002.

Kambhamettu, C. and D. B. Goldgof, Left ventricle wall motion tracking using curvature properties, *SPIE: Biomedical Image Processing*, 1450:311-322, 1992.

Kambhamettu, C. and D. B. Goldgof, Point correspondence recovery in nonrigid motion. *Proceedings of IEEE conference on Computer Vision and Pattern Recognition*, pages 222-227, June 1992.

Kambhamettu, C. and D. B. Goldgof, Curvature-based approach to point correspondence recovery in conformal nonrigid motion, *Computer Vision, Graphics and Image Processing: Image Understanding*, 60(1):26-43, July 1994.

Kambhamettu, C., D. B. Goldgof, and M. He, Determination of motion parameters and estimation of point correspondences in small nonrigid deformations, *Proceedings of IEEE conference on Computer Vision and Pattern Recognition*, pages 943-946, June 1994.

Kambhamettu, C., D.B. Goldgof, D. Terzopoulos, and T.S. Huang, Nonrigid motion analysis, In *Handbook of Pattern Recognition and Image Processing: Computer Vision*, pages 405-430, 1994.

Thomas, M., Phase correlation based global and local motion estimation, VIMS Technical Report, University of Delaware, 41 pps, 2003.

Vernon, D., Instantaneous optical flow, Chapter 7 in *Fourier Vision: Segmentation and Velocity Measurements using the Fourier Transform*, Kluwer Academic Publishers, 125, 2001.