

Final Report for
Sea Ice Kinematics and Thickness from RGPS: Observations and Theory
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The RADARSAT Geophysical Processor System (RGPS) has produced a wealth of data on Arctic sea ice motion, deformation, and thickness with broad geographical coverage and good temporal resolution. These data provide unprecedented spatial detail of the structure and evolution of the sea ice cover. The broad purpose of this study was to take advantage of the strengths of the RGPS data set to investigate sea ice kinematics and thickness, which affect the climate through their influence on ice production, ridging, and transport (i.e. mass balance); heat flux to the atmosphere; and structure of the upper ocean mixed layer. The objectives of this study were to: (1) Explain the relationship between the discontinuous motion of the ice cover and the large-scale, smooth wind field that drives the ice; (2) Characterize the sea ice deformation in the Arctic at different temporal and spatial scales, and compare it with deformation predicted by a state-of-the-art ice/ocean model; and (3) Compare RGPS-derived sea ice thickness with other data, and investigate the thinning of the Arctic sea ice cover as seen in ULS data obtained by U.S. Navy submarines.

In the course of pursuing objective (2) above, we became acquainted with the work of three French geophysicists in Grenoble who study fracture and deformation of materials on a wide range of spatial scales. They were interested in the RGPS data because of its wide spatial coverage, high resolution, and the richness of the patterns in the sea ice. We were interested to learn about their new methods of analysis. Thus in 2002 we obtained travel funds from NSF (through International Opportunities for Scientists and Engineers) to collaborate with the French team. We (Stern, Lindsay, and Rothrock) spent a week in June 2002 at the Laboratoire de Glaciologie in Grenoble. We explained the intricacies of the RGPS data to the French team, and they taught us new analysis techniques for examining spatial structure in the data. They visited us in Seattle in April 2003, and we began to write a joint paper, which resulted in Marsan et al. [2004]. Our continuing collaboration has widened the exposure of RGPS data to an international audience, and provides an interesting link to other areas of geophysics.

We briefly review the results of our work below, separated into the topics of sea ice deformation and sea ice thickness. This is followed by a list of publications, meetings and presentations, and other activities supported under this grant. We are attaching to this report copies of all the listed publications. Finally, we would like to point out our "community service" to NASA through our involvement with the ASF User Working Group and the RGPS Science Working Group, as evidenced in the list of meetings and presentations below.

Sea Ice Deformation

In Moritz and Stern [2001] we looked at the relationship between the geostrophic wind and sea ice deformation. Assuming that most of the deformation is concentrated in active leads that open, close, and slide (shear), while the rest of the pack ice is relatively rigid, we identified a set of active leads and computed the jump in the ice velocity vector across each lead. We found that the velocity jumps had a standard deviation of about 1 km/day parallel to the lead and 0.3 km/day perpendicular to the lead – i.e. roughly three times as much sliding as opening or closing. We derived a formula relating the orientation of the velocity jump vector to the principal axis of strain rate in the ice, which was found to be nearly aligned with that of the wind. These results are relevant to new efforts to develop anisotropic sea ice models in which the orientation of leads is important.

Lindsay and Stern [2003] made a detailed study of the accuracy of RGPS ice motion and deformation products. Because of the novelty of the data sets and their complex temporal and spatial sampling characteristics, this study was necessary to establish the reliability of the RGPS products. Errors in the computed RGPS ice motion are due to tracking errors (from the cross-correlation of SAR image patches), and geolocation errors. The tracking errors were found to have a standard deviation of 100 meters, or one SAR image pixel. Comparison of RGPS trajectories with those from drifting buoys showed that RGPS displacement errors (including geolocation errors) over the typical three-day sampling interval were on the order of 300 meters. This is extremely accurate – far better than ice motion derived from tracking AVHRR or SSM/I images. Errors in the RGPS-derived sea ice deformation arise from tracking errors and from the approximation of the boundary of a material element (or cell) by only four points. The second type of error is larger than the first, with the total error standard deviation being about 3.5% for a typical 10-km RGPS cell. While this is relatively large compared to typical deformation rates, aggregation of cells reduces the error substantially (at the expense of spatial resolution). This confirms the validity of using RGPS products to assess the sea ice deformation computed by models.

Lindsay et al. [2003] compared sea ice velocity and deformation estimates from RGPS with those from a state-of-the-art ice-ocean model. The model was run in two modes: with assimilation of ice velocity data from buoys and SSM/I (designated DA for data assimilation), and without data assimilation (designated MO for model only). The wintertime correlation of RGPS and model ice velocity increased from 63% (MO) to 95% (DA), and the correlation of RGPS and model ice deformation increased from 15% (MO) to 63% (DA). This was the first time it had been possible to compare model ice deformation with an independent data set in such detail. The distribution functions (probability densities) of ice deformation were also compared. The model-only case had too many grid cells with small deformation (compared to RGPS), while the data-assimilation case seemed to overcompensate, resulting in a distribution with a heavy tail (too many grid cells with large deformation). The RGPS data sets were thus used to quantify the improvement in the model deformation as a result of assimilating ice velocity data, and to suggest areas where the model could be improved.

Many physical phenomena have been observed to obey power-law scaling relationships. A power law such as $y = ax^p$ implies that there is no natural or inherent scale in the system – re-scaling x and y still gives an exponent p in the new system. With our French colleagues, Jerome Weiss and David Marsan, we conducted a scaling analysis of the deformation of Arctic sea ice using RGPS data [Marsan et al., 2004]. We found that the mean wintertime deformation is related to the scale over which it is computed according to a power law with exponent -0.20 . In summer the exponent drops to -0.45 . This quantifies the fact that in conditions closer to free drift the deformation is more localized. The localization also increases at smaller scales. Finally, the distribution of deformation as a function of scale can be characterized as log-normally multifractal. This means that the moments of the distribution all obey power laws, with a particular relationship among the exponents. This leads to a mathematical method by which the deformation may be extrapolated to smaller scales, allowing (for example) sub-grid scale parameterization of deformation in models.

Sea Ice Thickness

Yu and Lindsay [2003] compared the thin end of the sea ice thickness distribution obtained from RGPS and from AVHRR imagery. RGPS computes the sea ice thickness by keeping track of cell areas – positive area changes initiate the growth of new ice based on freezing-degree days, and negative area changes imply ridging. The AVHRR method combines the surface temperature from the satellite with a thermodynamic model. Despite the differences in the two methods, good agreement between the thin ice distributions was obtained in areas containing large leads. One drawback of the AVHRR method is its inability to detect leads narrower than 1 km. On the other hand, the RGPS data probably underestimates ice production because of its three-day sampling interval. It is possible that a merged RGPS/AVHRR product could provide improved estimates of thin ice.

A dramatic thinning of Arctic sea ice was reported by Rothrock et al. in 1999. Their results were based on the mean thickness of sea ice as computed from ULS data obtained by U.S. Navy submarines. Yu et al. [2004] expanded on this work by using more submarine data and examining the whole ice thickness distribution. They found a doubling of the fractional coverage of thin ice (< 1 meter) – from 13% to 26% – between the early period (1958-1970) and the later period (1993-1997). The overall loss of ice volume was about 32%, consisting mostly of ridged ice (> 4 meters). These changes are attributed to increased ice export through Fram Strait (correlated with the Arctic Oscillation) and the generally warmer Arctic air temperatures of the 1990s.

Reviewed publications supported in whole or in part by this grant (copies attached)

Marsan, D., H. Stern, R. Lindsay, and J. Weiss, 2004. Scale Dependence and Localization of the Deformation of Arctic Sea Ice, *Phys. Rev. Lett.*, 93, 17, doi:10.1103/PhysRevLett.93.178501.

Yu, Y., G. A. Maykut, and D. A. Rothrock, 2004. Changes in the thickness distribution of Arctic sea ice between 1958-1970 and 1993-1997, *J. Geophys. Res.*, 109, C08004, doi:10.1029/2003JC001982.

Lindsay, R. W., J. Zhang, and D. A. Rothrock, 2003. Sea Ice Deformation Rates from Satellite Measurements and in a Model, *Atmosphere-Ocean*, 41 (1) 35-47.

Yu, Y., and R. W. Lindsay, 2003. Comparison of thin ice thickness distributions derived from RADARSAT Geophysical Processor System and advanced very high resolution radiometer data sets, *J. Geophys. Res.*, 108(C12), 3387, doi:10.1029/2002JC001319.

Lindsay, R. W., and H. L. Stern, 2003. The RADARSAT Geophysical Processor System: Quality of Sea Ice Trajectory and Deformation Estimates, *J. Atmos. Ocean. Tech.*, 20, 1333-1347.

Moritz, R. E., and H. L. Stern, 2001. Relationships between geostrophic winds, ice strain rates and the piecewise rigid motions of pack ice, in "IUTAM Symposium on Scaling Laws in Ice Mechanics and Ice Dynamics", J. P. Dempsey and H. H. Shen (editors), pp. 335-348, Kluwer Academic Publishers, The Netherlands.

Meetings and Presentations

October 8-9, 2001. We hosted a meeting of the ASF User Working Group. Stern was chairperson of the group.

October 10-11, 2001. We hosted a meeting of the RGPS Science Working Group. Stern was secretary, and Lindsay gave a talk on RGPS/model comparisons of ice deformation.

June, 2002. Lindsay gave a talk on the RGPS at the Laboratoire de Glaciologie, Université Joseph Fourier, Grenoble, France. Stern gave a talk on Arctic research at the same institution, and also at the Université de Savoie in Chambéry.

October 28-29, 2002. We hosted a meeting of the ASF User Working Group. Stern was chairperson of the group.

January, 2003. Lindsay attended the AMS Polar Meteorology and Oceanography meeting in Hyannis, MA. and gave a talk.

April 30 – May 1, 2003. We hosted a meeting of the RGPS Science Working Group. Stern was secretary, and he gave a talk on the joint work with his French colleagues.

November 19-20, 2003. Stern attended a meeting of the ASF User Working Group in Fairbanks. He was chairperson of the group.

January 23, 2004. Moritz gave a talk about his work on sea ice deformation for the Atmospheric Sciences colloquium, University of Washington.

Other activities supported by this grant

Lindsay used the RGPS products to make data sets of monthly averaged, regularly gridded sea ice motion and deformation, for use by the Arctic Ocean Model Intercomparison Project (AOMIP). The data sets are on a 160-km grid and cover the period from November 1996 to April 2000. They are available on his web site (<http://psc.apl.washington.edu/lindsay/#RGPS>) under “Derived data sets”.