Sea ice concentration estimates from satellite passive microwave radiometry and openings from SAR ice motion

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[1] Openings in the Arctic Ocean ice cover from small-scale sea ice motion fields are compared with open water fractions retrieved from satellite passive microwave observations. We find very little agreement between the results. Passive microwave retrieval algorithms seem to be insensitive to small areas of open-water in winter leads. Variability in the passive microwave retrievals is mostly due to anomalous and persistent regions of lower ice concentration where no openings are found. Between January and April of 1998, openings cover ~0.3 ± 0.1% of the total area within the perennial ice zone. This is smaller, in one instance ten times, than the open water fraction from the passive microwave retrievals. Previous bounds of open water coverage of the ice cover imposed on climate simulations based on uncertainties in passive microwave retrievals (±4 – 7%) are too high and the over-estimated open water fraction on model results should be re-examined. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 4207 Oceanography: General: Arctic and Antarctic oceanography; 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689)

1. Introduction

[2] Ice concentration is a measure of the ocean surface covered by sea ice within a specified area. Over the Arctic ice cover in winter, divergent motion controls the abundance of open water or exposed ocean surface and thin ice. Newly opened leads are sources of new ice growth, brine rejection to the ocean, and turbulent heat transfer from the ocean to the atmosphere. The rates of these climatologically important processes over these openings are significantly higher than areas covered by thicker ice.

[3] Gridded fields of SMMR (Scanning Multichannel Microwave Radiometer) and SSM/I (Special Sensor Microwave/Imager) ice concentration of the Arctic and Southern Oceans have provided a continuous record for more than 20 years [*Parkinson et al.*, 1987; *Zwally et al.*, 1987; *Gloersen et al.*, 1992]. The great strengths of the satellite passive microwave (PMW) ice concentration fields are their spatial coverage and the length of the data record. Due to the lack of ground truth, these ice concentration estimates have been validated against only a limited number of measurements from aircraft radars, aircraft radiometers, AVHRR (A Very High Resolution Radiometer) and Landsat imagery [*Steffen and Schweiger*, 1991; *Emery et al.*, 1994]. A summary of these validation results can be found in *Cavalieri* [1992]. The uncertainties in the ice concentration vary. In the winter Arctic and Antarctic, the uncertainties are approximately 7% with possible biases of similar magnitude.

[4] This paper examines the ice concentration retrievals of the winter ice cover using ice motion datasets produced by the RADARSAT Geophysical Processor System (RGPS). Openings along fracture zones, derived from time-sequential synthetic aperture radar (SAR) imagery, provide an unambiguous measure of the coverage and location of open water within the ice cover. The estimate is unique in that it does not depend on the calibration of the sensor or a thorough physical understanding of the ice signatures. Here, we use a 4-month winter dataset (January–April, 1998) that covers a large part of the Arctic Ocean. This represents one of the more spatially and temporally extensive examination of the PMW ice concentration estimates to date.

2. Data Sets and Approach

[5] Daily PMW ice concentration estimates used in our analysis are produced by two different algorithms: NASA-Team (NT) [*Cavalieri et al.*, 1984] and Bootstrap [*Comiso et al.*, 1997]. A discussion of the merits of the two approaches can be found in *Comiso et al.* [1997].

[6] Openings in the ice cover are estimated from the RGPS data set. The RGPS produces measurements of ice motion and deformation by using repeat surveys of Lagrangian elements or cells of sea ice in sequential RADARSAT SAR imagery [*Kwok and Cunningham*, in press]. Each initial cell dimension is 10 km on a side with the sampling interval between observations of nominally 3 days, but is ultimately dependent on data acquisition opportunities. Cell deformation and area changes are estimated using the motion of the polygon vertices defining the material element. As seen in the figures in this paper, the ice motion and deformation data cover a large part of the perennial ice zone of the Arctic Ocean. These fine-scale RGPS datasets, containing records of ice displacements and deformation, are available as routine products.

[7] For this analysis, we select the winter months of January through April of 1998. Our approach is to compare the gridded openings computed from RGPS ice motion with the open water fraction from the PMW ice concentration fields. For ease of comparison, the grid spacing of RGPS data is matched to that of the PMW dataset i.e. 25 km. The uncertainty in the openings computed over a 25 km grid cell is ~0.6% and is due to errors in the tracking of ice features in SAR imagery. This uncertainty is reduced (by $0.6\%/\sqrt{N}$) when area change over a larger number of cells (N) are considered. The openings from RGPS ice motion represent the net increase in area of grid elements over the sampling interval. Hence, the age of the ice in the openings could be between 0 to 3-days old. Higher frequency openings and closings are missed due to under-sampling of the ice motion. In the comparisons, we expect openings found in the RGPS data to be indicated as higher open water fraction (lower ice concentration) in one or all of the daily PMW analyses spanning the RGPS sampling period, and that there should be substantial correspondence between their spatial patterns as openings are localized along linear fracture zones.

3. Results and Discussion

[8] Over the period, we compared 36 gridded fields of 3-day RGPS openings with 108 daily ice concentration fields. We find very little agreement between the spatial distribution of open water areas in the PMW fields and the RGPS openings. Here, we

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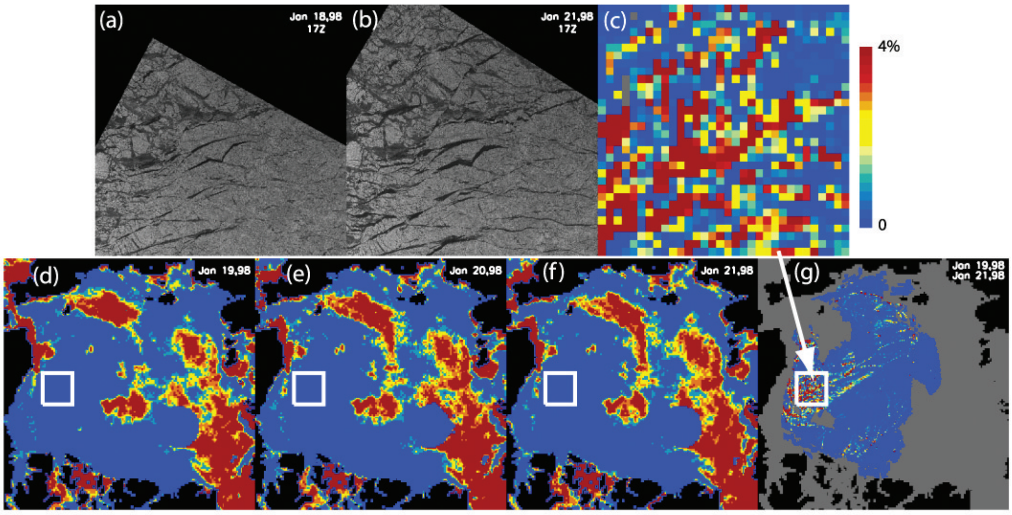

Figure 1. Comparison of openings derived from RGPS ice motion with passive microwave open water estimates. RADARSAT imagery on (a) Jan 18 and (b) Jan 21, 1998. (c) Average daily openings from RGPS ice motion. (d), (e), and (f) show the three daily fields (Jan 19 through Jan 21) of open water fraction derived from passive microwave data. (g) Gridded field of RGPS openings over a larger domain. (RADARSAT images ©CSA 2001).

examine in more detail the two scenarios of disagreement: openings with no detected open water, and detected open water with no openings. One would tend to decrease open water fraction while the other would have an opposite effect. Figures 1 and 2 illustrate the differences for two time periods at two length scales. One scale is closer to that of the scale of lead openings in the Arctic and the other a synoptic scale encompassing most of the basin.

[9] Figure 1 shows an example where fairly significant openings (>10% increase in area over the 25 km grid elements) of the ice cover seen in successive RADARSAT imagery are not detected in any of the daily PMW analyses. Similarly, at the larger scale the PMW analyses do not show any increases in open water fraction along other lead openings in the RGPS data. In fact, outside the white box we find no spatial agreement between the PMW open water fraction and RGPS openings. The same discrepancies can be seen in Figures 2 and 3, and throughout the fields (not shown here) that we have examined.

[10] Open water areas are generally found in leads along linear fracture zones in the winter pack [*Kwok*, in press]. It is possible that the winter freezing rate is so high that open water areas may not be adequately sampled by SSM/I overpasses. Since thin ice has an emissivity signature that lie between the values of open water and those of thicker ice [*Grenfell et al.*, 1992], the signature of growing ice would quickly depart from that of open water. Also, due to the size of the radiometer footprints of tens of kilometers, retrieval procedures may not be sensitive to the mixture of ice and open water based on their unique signatures. The accurate detection of open water areas is thus limited by their fractional coverage of an SSM/I grid cell and their contribution to the observed microwave signature. Ice motion and geolocation uncertainties cause smearing of open water signatures in the daily gridded brightness temperature composites produced using a drop-in-the-bucket binning procedure. The results demonstrate a general lack of sensitivity of the

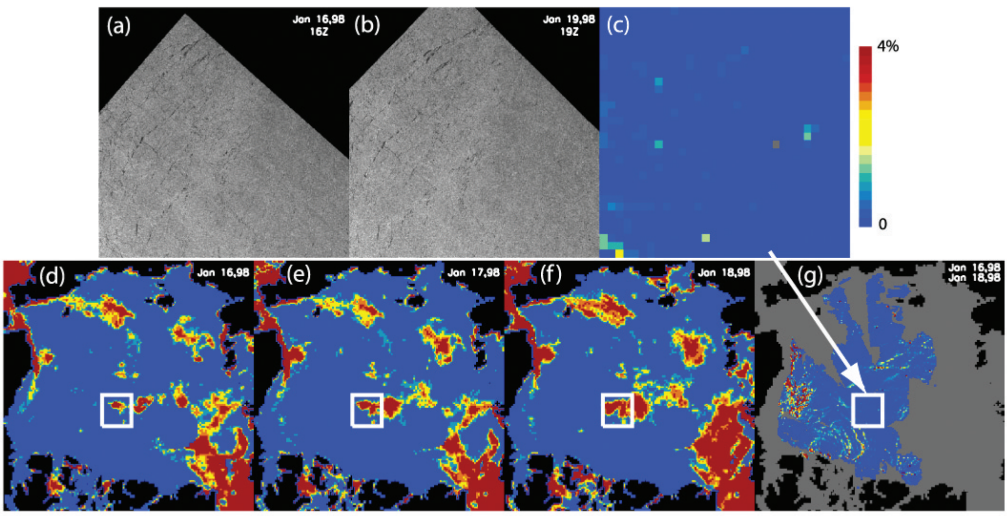

Figure 2. Same as Figure 1 except over a different period — Jan 16 and Jan 18, 1998. (RADARSAT images ©CSA 2001).

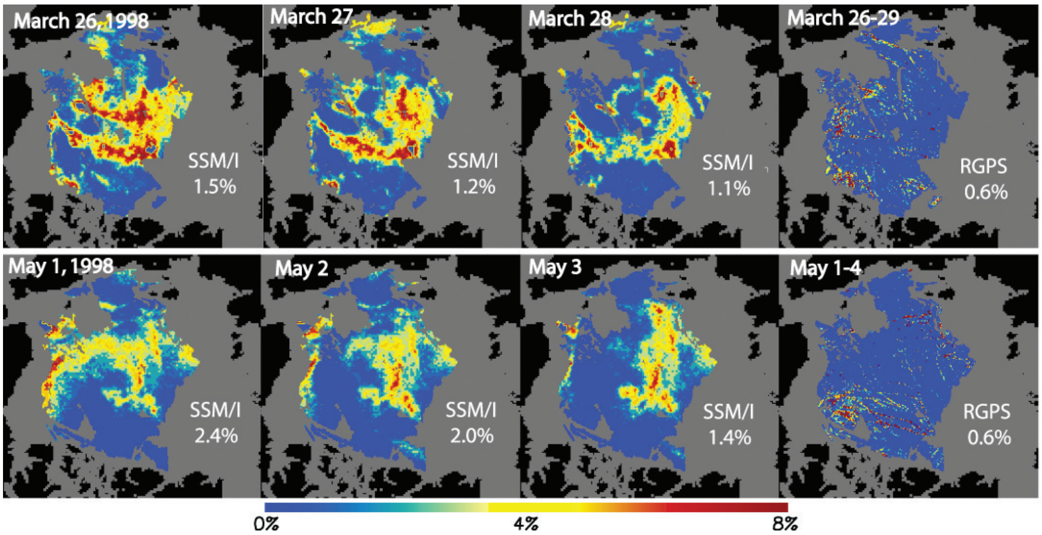

Figure 3. Two examples of persistent areas with significant open water fractions, in March and May, when no net openings can be found in the RGPS ice motion fields. The three daily passive microwave derived fields coincident with the 3-day RGPS opening estimates are shown. Areas with no RGPS observations over the period are masked out.

PMW algorithms to small areas of open water within the winter pack.

[11] The white box in Figure 2 shows an area where no openings are indicated yet open water is detected by the PMW algorithms. Within the box, no deformation and open water signature are evident in the RADARSAT imagery. In fact, the anomalous areas of increased open water fraction are persistent over the period. Similarly, outside the box there is no correspondence between the PMW open water fraction and the spatial pattern of RGPS openings. Persistent areas with open water detected by the PMW retrieval procedures are evident. Again, the same discrepancies described here can be seen in Figures 1 and 3, and throughout the fields that we have examined. These areas of persistent lower ice concentration have been noted by *Gloersen et al.* [1992]. Low-level clouds at the inversion height were suggested as a possible cause of such anomalies [*Steffen et al.*, 1992].

[12] We believe that these anomalous regions are not areas with open water for the following reasons. First, as mentioned earlier, we expect open water to be detected in linear rather than blob-like features seen here. Second, the persistence and the extent of these features are disturbing, as one does not expect open water production in the Arctic Ocean without any associated regional deformation. The possibility of ice-melt to form areas of open water in the central Arctic in winter at this scale is unlikely and has never been observed. As these anomalies seem stationary, we speculate that these anomalies as expressions of snow and ice surfaces modified by passing weather systems. To illustrate the pervasiveness of these anomalies, we show two additional examples of such anomalies from the end of March and early May that do not have corresponding openings computed from the ice motion fields. They cover large regions of the Arctic Ocean.

[13] The variability of total open water fraction in the PMW fields is explained almost entirely by the higher open water fractions in these anomalous regions. This is evident in the four examples shown here as well as the fields not shown. In any case, a comparison of the differences between the average ice concentration from the two PMW retrieval algorithms with the RGPS openings over the four winter months of 1998 is shown in Figure 4. Except for the large divergent event in January of 1998, the RGPS openings generally stayed below 0.5% of the total area with a slight negative trend over the remainder of the winter. We attribute the negative trend to the increase in ice strength as a result of a thicker ice cover after a winter of deformation and growth. The bootstrap and NT algorithms overestimate the open water fraction by 0.7 and 1.4%, respectively. These are well within the expected uncertainties in the PMW ice concentration retrievals and seem small relative to the overall ice concentration. However, these uncertainties are quite high from the point of view of open water coverage as winter heat and brine flux are much higher, in certain cases two orders of magnitude, in these areas. Thus, even though open water coverage is small, the integrated heat and brine flux could be a significant portion of the total budget. Figure 5 shows the over-estimation of the open water areas over the four months as a factor relative to the RGPS openings. The PMW algorithms overestimate the open water area by an average factor of 3–5, and in one instance almost 10 times that of the RGPS estimates. In

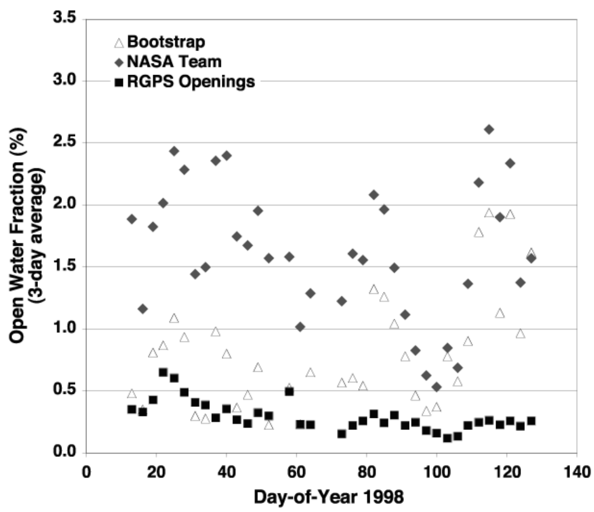

Figure 4. Comparison of four months of open water fraction estimates from the Bootstrap and Team algorithms with ice motion derived openings computed within the RGPS domain. Areas without RGPS observations are not used.

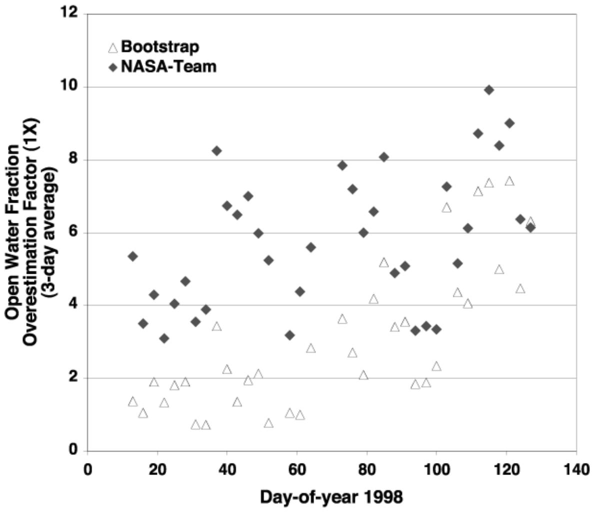

Figure 5. Overestimation open water fraction compared to the openings derived from RGPS ice motion.

general, the variability of the NT retrievals is much higher than that of the bootstrap.

4. Conclusions

[14] We have compared over a four month period, at near basin scale, the PMW open water fraction estimates with RGPS openings within the winter pack. We find very little agreement between the spatial distribution of open water areas in the PMW fields and the RGPS openings. As discussed above, the PMW algorithms as they presently stand do not seem to be sensitive to open water in linear fracture zones in the winter ice cover. The variability of total open water fraction in the PMW fields is explained almost entirely by the higher open water coverage, incorrectly retrieved, in regions with persistent lower ice concentration. We emphasize that this verifies the level of uncertainty, supported by previous studies, in the PMW open water retrievals. But even though the PMW ice concentration estimates are well within the expected uncertainties and seem small relative to the total ice concentration, this nevertheless leads to over-estimates in the open water coverage of the Arctic Ocean ice cover. From the perspective of heat and brine flux, the average overestimate of 3–5 times the open water coverage is significant. Possible causes of these uncertainties are suggested but at this time there are no adequate in-situ or remote-sensing data for comprehensive understanding of their radiometric or geometric origins. The results here also suggest potential issues with the algorithms closer to the ice edge due to signature variability and ice dynamics.

[15] The RGPS openings from January to April of 1998 indicate a winter ice cover with very low open water coverage (0.3%) and even lower variability (0.1%). Therefore, to monitor the fraction and the variability of open water within the winter Arctic Ocean ice pack requires algorithm performance close to these levels. Current retrieval algorithms seem well-suited for monitoring the ice edge where large contrasts in ice concentration are found. Within the winter pack, the current approaches seem inadequate as the uncertainties are too high. Previous bounds of open water coverage of the ice cover imposed on climate simulations [*Parkinson et al.*, 2001] based on uncertainties of current passive microwave retrieval algorithms (±4 − 7%) could be too high and the impact of lower ice concentration on the model results should be re-examined.

[16] The Advanced Microwave Scanning Radiometer (AMSR) planned for the NASA's Aqua and the Japanese ADEOS II satellite will provide higher resolution and sensor performance. It is anticipated that planned validation efforts will provide a more complete characterization of the ice concentration retrieval approaches. The openings derived from SAR ice motion can provide a readily available dataset for validation of the ice concentration retrieval results.

[17] **Acknowledgments.** The SSM/I data are provided by World Data Center A for Glaciology/National Snow and Ice Data Center, University of Colorado, Boulder, CO. The RGPS products are available at the following website (URL: http:: //www-radar.jpl.nasa.gov/rgps/radarsat.html). RADARSAT images were processed at the Alaska SAR Facility, Fairbanks, AK. I wish to thank G. F. Cunningham for his software support during this study. R. Kwok performed this work at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

References

Cavalieri, D. J., P. Gloersen, and W. J. Campbell, Determination of sea ice parameters from Nimbus 7 SMMR, *J. Geophys. Res.*, *89*(D4), 5355–5369, 1984.
Cavalieri, D. J., The validation of geophysical products using multisensor data, in *Microwave Remote Sensing of Sea Ice*, edited by F. D. Carsey, American Geophysical Union, Washington, D. C., 233–242, 1992.
Comiso, J. C., D. J. Cavalieri, C. L. Parkinson, and P. Gloersen, Passive microwave algorithms for sea ice concentration: A comparison of two techniques, *Remote Sens Environ.*, *60*, 357–384, 1997.
Emery, W. J., C. Fowler, and J. Maslanik, Arctic sea ice concentration from special sensor microwave imager and advanced very high resolution radiometer satellite data, *J. Geophys. Res.*, *99*, 18,329–18,342, 1994.
Gloersen, P., W. J. Campbell, D. J. Cavalieri, J. C. Comiso, C. L. Parkinson, and H. J. Zwally, *Arctic and Antarctic Sea Ice, 1978–1987: Satellite Passive-Microwave Observations and Analysis*, National Aeronautics and Space Administration, SP-511, 1992.
Grenfell, T. C., D. J. Cavalieri, J. C. Comiso, M. R. Drinkwater, R. G. Onstott, I. Rubenstien, K. Steffen, and D. P. Winebrenner, Consideration of microwaver remote sensing of thin ice, in *Microwave Remote Sensing of Sea Ice*, edited by F. D. Carsey, American Geophysical Union, Washington, D. C., 291–301, 1992.
Kwok, R., Deformation of the Arctic Ocean sea ice cover: November 1996 through April 1997, in *Scaling Laws in Ice Mechanics and Dynamics*, edited by J. Dempsey, Kluwer Academic, in press.
Kwok, R., and G. F. Cunningham, Seasonal ice area and volume production in the Arctic Ocean: November 1996 through May 1997, *J. Geophys. Res.*, in press.
Kwok, R., D. A. Rothrock, H. L. Stern, and G. F. Cunningham, Determination of Ice Age using Lagrangian Observations of Ice Motion, *IEEE Trans. Geosci. Remote Sens.*, *33*(2), 392–400, 1995.
Parkinson, C. L., D. Rind, R. J. Healy, and D. G. Martinson, The impact of sea ice concentration accuracies on climate model simulations with GISS GCM, *J. Clim.*, *14*, 2606–2623, 2001.
Steffen, K., and A. Schweiger, NASA team algorithm for sea ice concentration retrieval from Defense Meteorological Satellite Program Special Sensor Microwave Imager: Comparison with Landsat satellite imagery, *J. Geophys. Res.*, *96*, 21,971–21,987, 1991.
Steffen, K., J. Comiso, K. St. Gemain, P. Gloersen, J. Key, and I. Rubenstein, The estimation of geophysical parameters using passive microwave algorithms, in *Microwave Remote Sensing of Sea Ice*, edited by F. D. Carsey, American Geophysical Union, Washington, D. C., 201–228, 1992.

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