Remote Sens. Environ., 60, 357-384, 1997

Passive Microwave Algorithms for Sea Ice Concentration: A Comparison of Two Techniques

Josefino C. Comiso, Donald J. Cavalieri, Claire L. Parkinson, and Per Gloersen

Abstract

The most comprehensive large-scale characterization of the global sea ice cover so far has been provided by satellite passive microwave data. Accurate retrieval of ice concentrations from these data is important because of the sensitivity of surface flux (e.g., heat, salt, and water) calculations to small changes in the amount of open water (leads anal polynyas) within the polar ice packs. Two algorithms that have been used for deriving ice concentrations from multichannel data are compared. One is the NASA Team algorithm and the other is the Bootstrap algorithm, both of which were developed at NASA's Goddard Space Flight Center. The two algorithms use different channel combinations, reference brightness temperatures, weather filters, and techniques. Analyses are made to evaluate the sensitivity of algorithm results to variations of emissivity and temperature with space and time. To assess the difference in the performance of the two algorithms, analyses were performed with data from both hemispheres and for all seasons. The results show only small differences in the central Arctic in winter but larger disagreements in the seasonal regions and in summer. In some areas in the Antarctic, the Bootstrap technique shows ice concentrations higher than those of the Team algorithm by as much as 25%; whereas, in other areas, it shows ice concentrations lower by as much as 30%. The differences in the results are caused by temperature effects, emissivity effects, and tie point differences. The Team and the Bootstrap results were compared with available Landsat, advanced very high-resolution radiometer (AVHRR) and synthetic aperture radar (SAR) data. AVHRR, Landsat, and SAR data sets all yield higher concentrations than the passive microwave algorithms. Inconsistencies among results suggest the need for further validation studies.

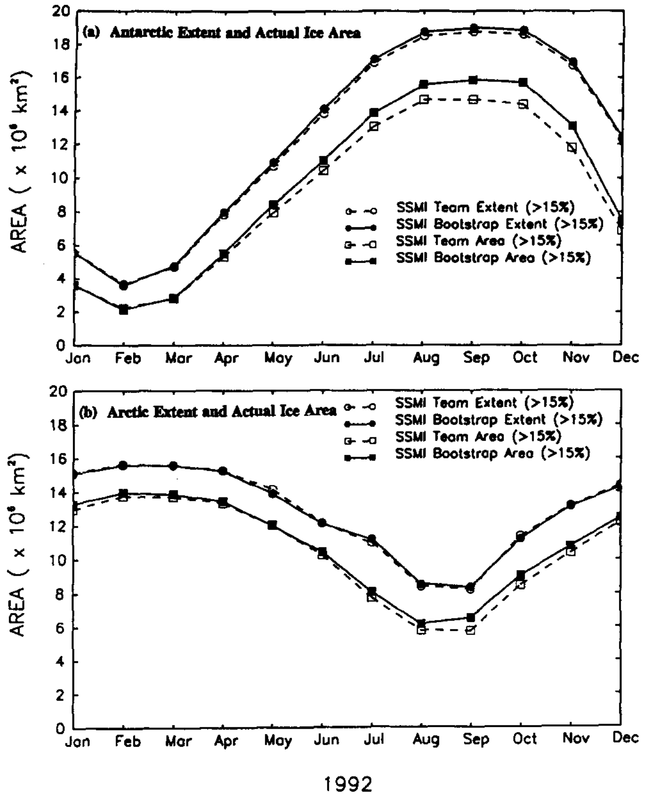

Figure 22. Comparison of monthly extent and actual ice areas derived from ice concentration maps generated by the Team and Bootstrap algorithms for the (a) Antarctic and (b) Arctic regions during 1992.

trations during the summer than those previously generated from the Bootstrap algorithm, are the ones currently in use.

DISCUSSION AND CONCLUSIONS

In this paper, a comparison of ice concentrations derived from the Team and Bootstrap algorithms has been made. Monthly maps over an annual cycle in 1992 were compared in both the Northern and the Southern Hemispheres. The results indicate some large differences in ice concentrations, in the inner pack, in the coastal regions, and in some marginal ice areas. In some areas of the Antarctic, the Bootstrap algorithm shows 10–35% higher values than does the Team algorithm. In others, the reverse is true, especially in the coastal regions along the continent. Similar but smaller discrepancies are observed in the seasonal sea ice zones of the Arctic. Results from other years also have been examined (e.g., 1988), and the patterns of differences are similar.

Errors associated with each algorithm have been assessed. The sensitivity in the determination of ice concentration resulting from fluctuations in temperature and emissivity has been discussed. The key issue is how well each algorithm handles these fluctuations. Temperature fluctuations are handled by the Team algorithm better than the Bootstrap algorithm. Interestingly, some of the patterns in the monthly maps of the differences (Fig. 7) are similar to the patterns in the temperature maps in Gloersen et al. (1992). Low snow-ice interface temperatures would cause an underestimate in ice concentration by the Bootstrap algorithm, whereas high ice temperatures would cause an overestimate. However, in areas of the Antarctic where large discrepancies occur between the two algorithms, in situ measurements of snow/ice interface temperatures indicate an average of $-6°$ C with a standard deviation of only about 2° C (Comiso et al., 1989).

Two case studies presented suggest that temperature is not the only cause of the discrepancies in the results. In these studies, the Bootstrap algorithm results are on average about 10% higher than the Team algorithm results, and analysis of Landsat, AVHRR, SAR, and aircraft photography indicate even higher ice concentrations than the Bootstrap values. If the Landsat and SAR values are correct, possible explanations for the differences are subsurface effects, such as ice layers in the snow or near the ice surface or the presence of new and young ice types. Each of these effects would affect the horizontally polarized radiances more than the vertically polarized radiances. The problem of new ice has been addressed elsewhere for Arctic seasonal sea ice zones (Cavalieri, 1994; Wensnahan et al., 1993).

For global climate studies, it is important to examine differences in sea ice extents, actual area, and their trends as produced by the two algorithms. Estimates of ice extent from either algorithm can be done with relatively high precision because of the large contrast in emissivity between ice and ocean at 19 or 37 GHz. However, the ice edge is usually the scene of stormy weather conditions, and the locations of the ice edge as inferred from the Team and Bootstrap algorithms are not always consistent, because of different weather filter–ocean masking techniques. The ice extents and ice areas derived from both algorithms in both hemispheres are shown in Figure 22. In the Antarctic, the difference in the 15% ice extent is as large as 0.2×10^6 km^2 (about 1%), whereas the maximum difference in actual ice area is about 1.2×10^6 km^2 (about 7.5%). In the Arctic, the corresponding values are 0.2×10^6 and 0.8×10^6 km^2, respectively. The differences in ice extents may originate in part from the differences in the weather filter–ocean masks. The differences in ice concentration within the pack make a substantial difference in the estimates of ice area. A better understanding of the differences between the two algorithms would eventually lead to more accurate ice concentrations, which would improve estimates of heat, radiation, and salinity fluxes in the polar regions.

We conclude that there is a need for further validation studies, especially in areas where there are large discrepancies in ice concentrations derived from the two algorithms. The focus should be on studying spatial variations in emissivity and temperature that may cause the large differences between the Bootstrap and the Team values in the Antarctic regions and in the peripheral seas in the Arctic. Even in the central Arctic region where the agreement is best, differences of a few percent should be resolved. Because of the large discrepancy between the two algorithms, a re-examination of the selected algorithm tie points is warranted. Our preliminary analysis shows that adjustments of tie points can make the results from the two algorithms more similar but there are substantial differences in the frequency distributions of ice concentration. For now, users should be aware of the strengths and weaknesses of each algorithm and be able to choose the one best suited to the research being undertaken.

We wish to thank Drs. J. Zwally, C. Koblinsky, T. Busalacchi, and R. Thomas for useful suggestions and discussions. Further, we appreciate the help of Rico Allegrino, of Hughes STX, and Larry Stocks, of Caelum Inc., in programming. This paper was supported by the Cryospheric Processes Program at NASA Headquarters.

REFERENCES

Cavalieri, D. J. (1994), A passive microwave technique for mapping new and young sea ice in seasonal sea ice zones. *J. Geophys. Res.* 99(C6):12,561–12,572.

Cavalieri, D. J., Crawford, J., Drinkwater, M., Emery, W. J., Eppler, D. T., Farmer, L. D., Goodberlet, M., Jentz, R., Milman, A., Swift, C., Wackerman, C., and Weaver, R. L., (1992), NASA sea ice validation program for the DMSP SSM/I: final report. NASA TM 104559.

Cavalieri, D. J., Crawford, J. P., Drinkwater, M. R., Eppler, D. T., Farmer, L. D., Jentz, R. R., Wackerman, C. C. (1991), Aircraft active and passive microwave validations of sea ice concentrations from the DMSP SSM/I. *J. Geophys. Res.* 96:21,989–22,008.

Cavalieri, D. J., Gloersen, P., and Campbell, W. J. (1984), Determination of sea ice parameters with the Nimbus 7 SMMR. *J. Geophys. Res.* 89:5355–5369.

Cavalieri, D. J., St. Germain, K. M., and Swift, C. T. (1995), Reduction of weather effects in the calculation of sea ice concentration with the DMSP SSM/I. *J. Glaciol.* 41(139):455–464.

Comiso, J. C. (1983), Sea ice effective microwave emissivities from satellite passive microwave and infrared observations. *J. Geophys. Res.* 88:7686–7704.

Comiso, J. C. (1986), Characteristics of Arctic winter sea ice from satellite multispectral microwave observations. *J. Geophys. Res.* 91:975–994.

Comiso, J. C. (1990), Arctic multiyear ice classification and summer ice cover using passive microwave satellite data. *J. Geophys. Res.* 95:13,411–13,422.

Comiso, J. C. (1995), SSM/I ice concentrations using the Bootstrap algorithm. *NASA Report* 1380.

Comiso, J. C., Ackley, S. F., and Gordon, A. L. (1984), Antarctic sea ice microwave signatures and their correlation with in-situ ice observations. *J. Geophys. Res.* 89:(C1):662–672.

Comiso, J. C., Grenfell, T. C., Bell, D. L., Lange, M. A., and Ackley, S. F. (1989), Passive microwave in situ observations of winter Weddell Sea ice. *J. Geophy. Res.* 94(C8):10,891–10,905.

Comiso, J. C., Grenfell, T. C., Lange, M., Lohanick, A. W., Moore, R. K., and Wadhams, P. (1992), Microwave remote sensing of the southern ocean ice cover, In *Microwave Remote Sensing of Sea Ice* (F. Carsey, Ed.), American Geophysical Union, Washington, DC, pp. 243–259.

Comiso, J. C., and Kwok, R. (1996), The Arctic sea ice cover from satellite observations. *J. Geophys. Res.* 101(C-12): 28397–28416.

Comiso, J. C., and Sullivan, C. W. (1986), Satellite microwave and in-situ observations of the Weddell Sea ice cover and its marginal ice zone. *J. Geophys. Res.* 91(C8):9663–9681.

Comiso, J. C., Wadhams, P., Krabill, W., Swift, R., Crawford, J., and Tucker, W., III (1991), Top/bottom multisensor remote sensing of Arctic sea ice. *J. Geophy. Res.* 96(C2): 2693–2711.

Emery, W. J., Fowler, C., Maslanik, J. (1994), Arctic sea ice concentrations from special sensor microwave imager and advanced very high resolution radiometer satellite data. *J. Geophys. Res.* 99(C9):18,329–18,342.

Eppler, D., Anderson, M. R., Cavalieri, D. J., Comiso, J. C., Farmer, L. D., Garrity, C., Gloersen, P., Grenfell, T., Hallikainen, M., Lohanick, A. W., Mätzler, C., Melloh, R. A., Rubinstein, I., Swift, C. T., and Garrity, C. (1992), Passive microwave signatures of sea ice. In *Microwave Remote Sensing of Sea Ice* (Frank Carsey, Ed.), American Geophysical Union, Washington, DC, pp. 47–71.

Gloersen, P., Campbell, W., Cavalieri, D., Comiso, J., Parkinson, C., and Zwally, H. J. (1992), Arctic and Antarctic sea ice, 1978–1987: satellie passive microwave observations and analysis. *NASA* Special Publication No. 511.

Gloersen, P., and Cavalieri, D. J. (1986), Reduction of weather effects in the calculation of sea ice concentration from microwave radiances. *J. Geophys. Res.* 91(C3):3913–3919.

Gloersen, P., Nordberg, W., Schmugge, T. J., Wilheit, T. T., and Campbell, W. J. (1973), Microwave signatures of first-year and multiyear sea ice. *J. Geophys. Res.* 78:3564–3572.

Grenfell, T. C., Comiso, J. C., Lange, M. A., Eicken, H., and Wenshahan, M. R. (1994), Passive microwave observations of the Weddell Sea during austral winter and early spring. *J. Geophys. Res.* 99(C5):9,995–10,010.

Martin, S., Holt, B., Cavalieri, D. J., Squire, V., (1987), Shuttle imaging radar B (SIR-B) Weddel sea ice observations: a comparison of SIR-B and Scanning Multichannel Radiometer ice concentrations. *J. Geophys. Res.* 92:7173–7180.

Matzler, C., Ramseier, R. O., and Svendsen, E. (1984), Polarization effects in sea ice signatures. *IEEE J. Oceanic Eng.* OE-9:333–338.

Parkinson, C. L., Comiso, J. C., Zwally, H. J., Cavalieri, D. J., Gloersen, P., and Campbell, W. J. (1987), Arctic sea ice 1973–1976 from satellite passive microwave observations. *NASA* Special Publication No. 489.

Rothrock, D. A., Thomas, D. R., Thorndike, A. S. (1988), Principal component analysis of satellite passive microwave data over sea ice. *J. Geophys. Res.* 93:2321–2332.

Rubinstein, E., Nazarenko, D. M., and Tam, S., (1994), Passive Microwave Systems. In *Remote Sensing of Ice and Icebergs*

(M. Lewis, K. Raney, and J. R. Rossiter, Eds.) Wiley, New York, pp. 177–258.

Steffen, K., Cavalieri, D. J., Comiso, J. C., St. Germain, K., Gloersen, P., Key, J., and Rubinstein, I. (1992), The estimation of geophysical parameters using passive microwave algorithms. In *Microwave Remote Sensing of Sea Ice* (F. Carsey, Ed.), American Geophysical Union, Washington, DC, pp. 201–231.

Steffen, K., and Schweiger, A. (1991), NASA team algorithm for sea ice concentration retrieval from the defense meteorological satellite program special sensor microwave imager: comparison with Landsat imagery. *J. Geophys. Res.* 96(12):21,971–21,987.

Svendsen, E., Kloster, K., Farrelly, B., Johannessen, O. M., Johannessen, J. A., Campbell, W. J., Gloersen, P., Cavalieri, D., and Matzler, C. (1983), Norwegian remote sensing experiment: evaluation of the Nimbus 7 scanning multichannel microwave radiometer for sea ice research. *J. Geophys. Res.* 88:2781–2792.

Swift, C. T., Fedor, L. S., and Ramseier, R. O. (1985), An algorithm to measure sea ice concentration with microwave radiometers. *J. Geophys. Res.* 90:1087–1099.

Thomas, D. R., and Rothrock, D. A. (1993), The Arctic Ocean ice balance: a Kalman smoother estimate. *J. Geophys. Res.* 98(C6):10,053–10,067.

Tucker, W. B., III, Perovich, D. K., Gow, A. J., Weeks, W. F., and Drinkwater, M. R. (1992), Physical properties of sea ice relevant to remote sensing. In *Microwave Remote Sensing of Sea Ice* (F. Carsey, Ed.), American Geophysical Union, Washington, DC, pp. 9–28.

Wadhams, P., Lange, M. A., and Ackley, S. F. (1987), The ice thickness distribution across the Atlantic section of the Antarctic ocean in midwinter. *J. Geophys. Res.* 92(C13):14,535–14,552.

Wensnahan, M., Maykut, G. A., Grenfell, T. C., and Winebrenner, D. P. (1993), Passive microwave remote sensing of thin sea ice using principal component analysis. *J. Geophys. Res.* 98:12,453–12,468.

Wilheit, T. T., Nordberg, W., Blinn, J., Campbell, W., and Edgerton, A. (1972), Aircraft measurements of microwave emission from Arctic sea ice. *Remote Sens. Environ.* 2: 129–139.

Zwally, H. J., Comiso, J. C., Parkinson, C. L., Campbell, W. J., Carsey, F. D., and Gloersen, P. (1983), Antarctic sea ice, 1973–1976: satellite passive microwave observations. *NASA* Special Publication No. 459.