EFFECTS OF ATMOSPHERIC WATER AND SURFACE WIND ON PASSIVE MICROWAVE RETRIEVALS OF SEA ICE CONCENTRATION: A SIMULATION STUDY

Dong-Bin Shin, Long S. Chiu[1] and Pablo Clemente-Colón[2]

Center for Earth Observing and Space Research, George Mason University, Fairfax, VA 22030 USA

[1]Data and Information Service Center, Code 602, Goddard Space Flight Center, Greenbelt, MD 20771 USA

[2]National Ice Center, NOAA Satellite Operations Facility, Suitland, MD 20746 USA

E-mail: dshin1@gmu.edu, lchiu@gmu.edu

ABSTRACT The atmospheric effects on the retrieval of sea ice concentration from passive microwave sensors are examined using simulated data typical for the Arctic summer. The simulation includes atmospheric contributions of cloud liquid water and water vapor and surface wind on surface emissivity on the microwave signatures. A plane parallel radiative transfer model is used to compute brightness temperatures at SSM/I frequencies over surfaces that contain open water, first-year (FY) ice and multi-year (MY) ice and their combinations. Synthetic retrievals in this study use the NASA Team (NT) algorithm for the estimation of sea ice concentrations. This study shows that if the satellite sensor's field of view is filled with only FY ice the retrieval is not much affected by the atmospheric conditions due to the high contrast between emission signals from FY ice surface and the signals from the atmosphere. Pure MY ice concentration is generally underestimated due to the low MY ice surface emissivity that results in the enhancement of emission signals from the atmospheric parameters. Simulation results in marginal ice areas also show that the atmospheric and surface effects tend to degrade the accuracy at low sea ice concentration. FY ice concentration is overestimated and MY ice concentration is underestimated in the presence of atmospheric water and surface wind at low ice concentration. In particular, our results suggest that strong surface wind is more important than atmospheric water in contributing to the retrieval errors of total ice concentrations over marginal ice zones.

KEY WORDS: Sea ice concentration, Atmospheric effect, NASA Team algorithm

1. INTRODUCTION

Remote sensing techniques are the most viable approach to monitoring global sea ice concentrations and their changes. However, uncertainties due to sampling, differences in sensor characteristics, surface types (ice, water, and snow) and the weather interference still pose a major challenge for ice change detection (Meier *et al.*, 2005). For examples, visible and infrared techniques provide high resolution retrievals. Their capability, however, is restricted to non-cloudy and daylight conditions (visible). Microwave radiometry provide almost all-weather monitoring, but their low spatial resolution limits their applicability to large scale monitoring. Active microwave monitoring by synthetic aperture radars provides detail monitoring capabilities even under cloudy conditions. However, the high acquisition cost prohibits their use in routine monitoring. The whole suite of remote sensors is needed for a comprehensive assessment of sea ice conditions.

A series of satellite-borne passive microwave sensors has been deployed or planned for monitoring sea ice conditions since the launch of the Electrically Scanning Microwave Radiometer onboard the NIMBUS-5 satellite (ESMR-5). Passive microwave retrievals of sea ice concentration, such as the Norsex (Svendsen *et al.*, 1983) and the NASA Team (NT) algorithm (Comiso *et al.*, 1997) are mostly based on the distinct difference of surface emissivities of ice-free water and the two major types of sea ice: first-year (FY) and multi-year (MY) ices. However, uncertainties such as atmospheric effects, variability of the surface emissivity, especially for MY ice and over marginal ice areas, and the existence of other ice types such as thin ice, melting ice and snow covered surface contribute to algorithm errors.

An assessment of the error contributions to the retrieval will aid sea ice analysts in the use of these remote sensing products in analyzing sea ice conditions. Error estimates are also important for the use of sea ice parameters in diagnostics studies and hypotheses testing of climate change scenarios. In this study we use radiative transfer modeling with atmospheric, surface, and sea ice models to understand the algorithm error sources in microwave retrieval of sea ice concentration. The advantages of such an approach are that individual errors may be examined separately and the validation of algorithms is easily carried out from synthetic retrievals. In the case when atmospheric conditions are available from in situ measurements or from other remote sensors, the atmospheric information can be incorporated into the retrieval to improve the sea ice retrieval.

2. SIMULATED DATA AND MODELS

In general, the microwave brightness temperature of a pixel for non-precipitating atmosphere is dependent on the surface temperature and the surface emissivity and is affected by atmospheric cloud liquid water and water vapor. The emissivity of FY ice is quite distinct from that of open water and MY ice. The emissivity of MY ice is non-unique or distributed, as the melting and refreezing processes change the brine and air contents of the MY ice, hence the inclusion of air contents can decreases the emissivity due to volume scattering. The microwave surface emissivity of open water is generally a function of the surface temperature, salinity, and the surface roughness.

In order to investigate the effect of atmospheric and surface variability on the estimation of sea ice concentration over various surface types, non-precipitating atmospheric profiles are generated along with surface variables. The simulated geophysical variables are intended to cover the climatological variability of the Arctic environments for a specific season (summer) as used in Markus and Cavalieri (2000). The surface temperatures of open water and sea ice are set to 271 K and 268 K, respectively. Then 300 atmospheric profiles including cloud liquid water and water vapor profiles are generated. The columnar cloud liquid water content (CLW) ranges 0 - 0.3 kg/m^2 and the columnar water vapor content (WV) varies from 1.5 mm to 8.1 mm at 271 K and 1.2 - 6.4 mm at 268 K, with a lapse rate of 6 K / km. The surface wind speed (WS) ranges 0 - 34 m/sec and the simulation are performed at 2 m/sec intervals (18 wind speed intervals). Each wind speed is applied to a set of cloud liquid water and water vapor profiles giving 5400 data sets (300 profiles x 18 wind speeds = 5400).

The microwave signatures from these profiles on top of three surface types (open water, FY ice and MY ice) and their combinations are computed. For simplicity, the calculations are performed for sea ice concentrations of 0, 20, 40, 60, 80, 90, 95, and 100 %. The simulated data can be used for testing various sea ice algorithms. The NASA Team (NT) algorithm (Comiso *et al.*, 1997) with weather filter is chosen for the current study. Microwave brightness temperatures (T_B) at the frequencies of SSM/I are computed using a one-dimensional plane parallel Eddington model (Kummerow, 1993). The SSM/I has five frequency channels at 19.35, 37.0, 22.24 and 85.5 GHz with horizontal and vertical polarizations (only vertical polarization at 22.24 GHz) and views the atmosphere at an Earth incidence angle of 53.1°. The surface emissivities of FY and MY ice and the tie points used are similar to those used in the NT sea ice algorithm for the Northern Hemisphere (Markus and Cavalieri, 2000). The tie points of these surfaces are defined by the T_B observed through a relatively cloud free (for open water) and calm sea surface (for 100% ice cover). The emissivity for a given incidence angle and polarization is computed. We also computed the wind-roughened sea surface emissivity based on Wilheit's (1979) model.

As in Comiso *et al.* (1997), the T_Bs for the sensor's field of view (FOV), which consists of three surface types, are obtained from a linear combination of T_Bs at each of three surfaces:

$$T_B = T_{B\_w}F_w + T_{B\_FY}F_{FY} + T_{B\_MY}F_{MY} \qquad (1)$$

where the subscripts, $_{w,\ FY}$ and $_{MY}$ denote three ocean surface types: open water, first-year (FY) ice and multi-year (MY) ice, respectively and the fractions of each surface are indicated by F_w, F_{FY} and F_{MY}. The sum of the fractions is unity.

3. SYNTHETIC RETRIEVALS

We investigate the sea ice retrieval errors due to atmospheric and surface wind effects. The NASA Team (NT) algorithm is used for retrieval. The polarization ratio (PR) at 19 GHz and the spectral gradient ratio (GR) between 37 GHz and 19 GHz for a satellite sensor's FOV in the NT algorithm are defined as follows:

$$PR = (T_{B\_19V} - T_{B\_19H}) / (T_{B\_19V} + T_{B\_19H}), \qquad (2)$$

$$GR = (T_{B\_37V} - T_{B\_19V}) / (T_{B\_37V} + T_{B\_19V}) \qquad (3)$$

where the subscripts $_V$ and $_H$ indicate vertical and horizontal polarizations, respectively. The definitions of PR and GR and the assumption that the observed T_B for each pixel are linear combinations of the T_Bs at different surfaces (Eq. 1) can be used to solve for the FY and MY ice concentrations. Following (Comiso *et al.*, 1997), the concentrations of FY and MY ice, C_{FY} and C_{MY} are computed from Eq. (1) as follows,

$$C_{FY} = (a_0 + a_1PR + a_2GR + a_3\,PR\cdot GR)/D \qquad (4)$$

$$C_{MY} = (b_0 + b_1PR + b_2GR + b_3\,PR\cdot GR)/D \qquad (5)$$

where

$$D = c_0 + c_1PR + c_2GR + c_3\,PR\cdot GR \qquad (6)$$

The coefficients, a_i, b_i, and c_i (i=0, 1, 2, 3) are computed from the tie points. Three surface types are considered: a) FY ice and open water (OW), b) MY ice and OW, and c) FY ice + MY ice + OW. In case c), equal amounts of FY and MY ice are introduced. The total ice concentration (C_T) is the sum of the FY and MY ice concentrations ($C_T = C_{FY} + C_{MY}$) and $F_{FY} = F_{MY} = ½\,F_T$. Atmospheric and surface wind effects are then included by imposing variability of atmospheric and surface parameters in the range and intervals specified in the previous section.

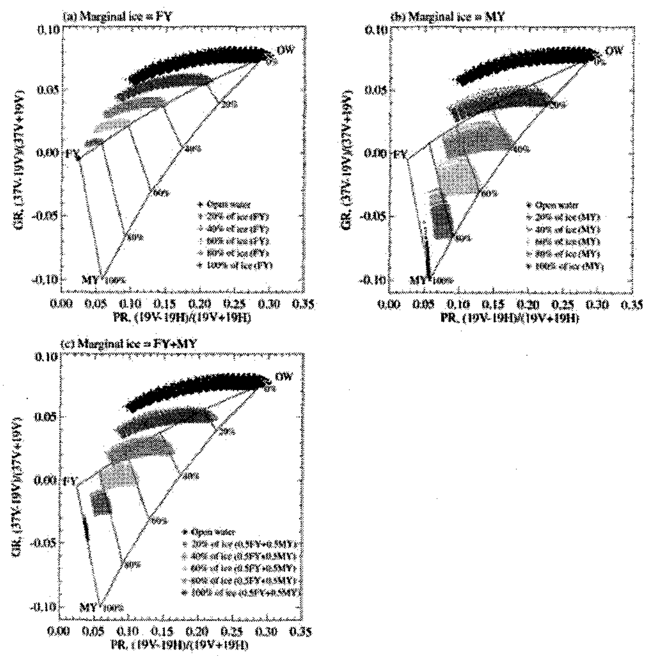

Figure 1. Scatter plots of the spectral gradient ratio (GR) versus the polarization ratio (PR) for the three different surface types: (a) open water (OW) and FY ice, (b) for OW and MY ice and (c) OW, FY and MY ices. The fractions of ices are indicated by different colors. The triangle for ice concentration retrieval is superimposed. The lines of total ice concentrations are shown in 20% intervals.

Figure 1 shows the scatter plots of PR and GR corresponding to the three combinations of surface types. The tie points for OW, FY and MY ice and curves of the fraction of FY and MY ice at 20% intervals are indicated. Simulation results for different fractions of sea ice are colored differently. In the case of FY ice retrieval, Fig. 1(a) again shows that the changes of PR and GR due to WV and CLW are small while WS decreases PR significantly. Since the dominant effect of WS is to decrease PR, the scatters are moved outside of the retrieval triangle formed by the tie points of OW, 100% FY and 100% MY ice. The scatters resulting from the atmospheric effects decreases as the fraction of FY ice increases. This is due to the high contrast between the emissivity of the FY ice and OW which overwhelms the atmospheric contributions. In the second case of MY ice, Fig. 1(b) shows the scatter is larger than that for the corresponding FY ice. The lower contrast of emissivities between the MY ice and OW enhances the atmospheric effects. The wind effects moves the scatter points toward more ice concentration areas in the retrieval triangle, hence large errors in retrieval errors are incurred. For a combination of OW, FY and MY ice (the third case, Fig. 1(c)), the scatter is somewhere in between the first and second cases.

The tie points for each surface are usually obtained from mean atmospheric profiles. Given the assumed uniform distributions (in terms of vertically integrated amount) of our simulated data, the tie points corresponding to simulated atmospheric profile data with the highest 10 % of PR for OW and the lowest 10 % of GR for the FY and MY ices are used. The tie point values computed herein is close to the values given in Comiso *et al.*(1997). The weather filter in NT (Comiso *et al.*, 1997) to reduce spurious sea ice concentrations over open water is included, i.e. for FOVs with GR values greater than 0.05, sea ice concentrations for the FOVs are set to zero.

The three cases as described in Fig. 1 are used for synthetic retrievals by the NT algorithm. We then examine the relative sensitivity of atmospheric parameters and surface wind on sea ice concentration estimates. Figure 2 shows the retrieved FY and MY ice concentrations (C_{FY} and C_{MY}) as a function of CLW by keeping WS at 0 m/sec for FY and MY ice, respectively. Figure 2c and 2d show the retrieval as a function of WS by keeping CLW = 0 kg/m^2. In all cases, WV is fixed at 2 mm. In the absence of WS, the NT algorithm overestimates the FY ice and underestimates the MY ice. The estimation error seems to be relatively unrelated to the ice concentration. In the case of zero CLW, the errors in the retrieval of FY ice increase substantially as a function of WS and ice concentration and the overestimation of FY ice is a nonlinear function of surface wind. For MY ice, the underestimates are less dramatic and show a strong dependency on sea ice concentration (more sensitive to the low sea ice concentrations). It can thus be inferred that the surface wind effect on the retrieval error is greater than that due to cloud liquid water within the typical ranges of these parameters. The weather filter (GR < 0.05) automatically sets FY concentrations of 20% or less to 0% (Fig. 2a), but at WS greater than about 22 m/s, the radiometric signatures are increased beyond the limit of the weather filter, resulting in the huge overestimation of FY ice fraction (Fig. 2c).

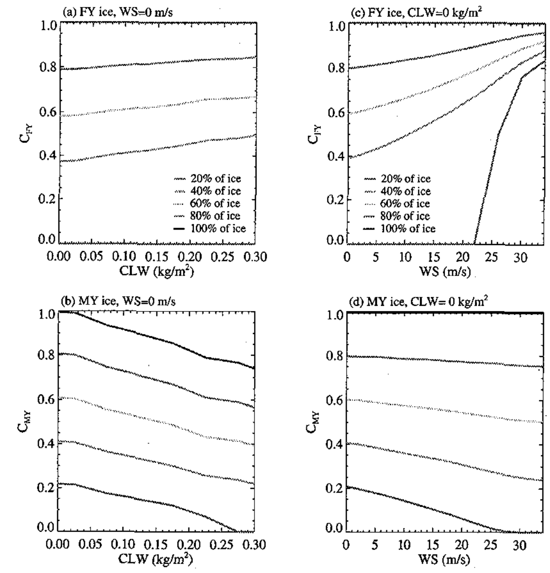

Figure 2. FY and MY ice concentrations (C_{FY}, C_{MY}) for each surface type as a function of columnar cloud liquid water content (CLW) when surface wind speed (WS) is 0 m/s (left column) and as a function of WS when CLW is 0 kg/m2 (right column). The columnar water vapor content (WV) is fixed at 2 mm for both the cases. Colors indicate the fractions of ices as before.

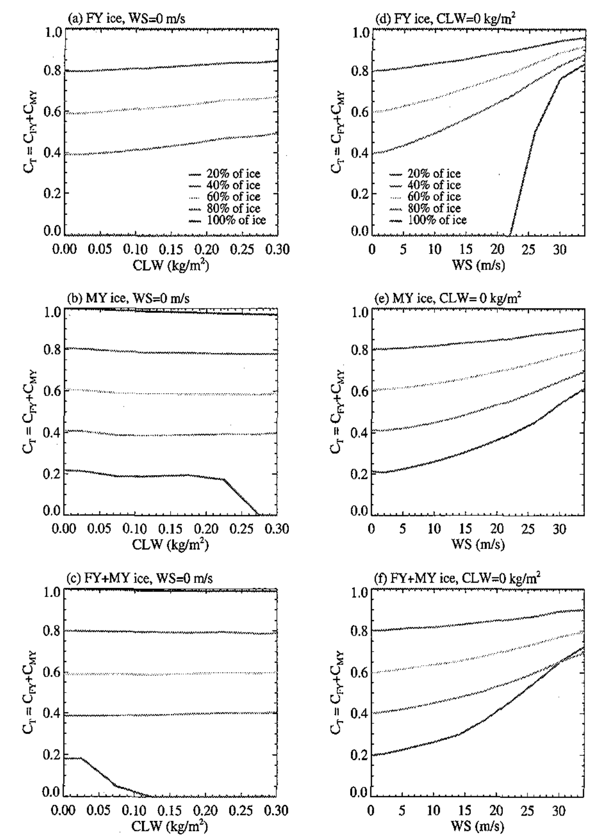

Figure 3. Same as Fig. 2 but for total ice concentrations (C_T) for the three different surface types.

Figure 3 shows the retrieved total ice concentrations (C_T) as a function of CLW and WS for different ice fractions and surface types. The left columns (Fig. 3a-c) shows retrieved C_T as a function of CLW when WS is zero (calm surface). The right columns (Fig. 3d-f) show retrieved C_T as a function of WS when CLW is zero, i.e. clear atmosphere. The WV is again fixed at 2 mm. For FY ice and WS = 0 m/s (Fig. 3a), the retrieved sea ice concentration increases with increasing CLW for ice concentration between 0.4 and 0.8, but CLW does not affect the estimates for 100% of ice. At 0.2 FY ice, no sea ice is retrieved, due mainly to the use of the weather filter (C_T=0 if GR>0.05). For MY ice (Fig. 3b) and FY+MY ice (Fig. 3c), the retrieval errors are small. Due to the application of the GR cutoff value, there is also noticeable underestimation of C_T when CLW is greater than 0.23 kg/m^2 for MY ice and no sea ice is retrieved for CLW > 0.12 kg/m^2 for FY+MY ice combination. The variability of WV appears to affect the retrievals in the similar way as found in the CLW case, but its effect is much less pronounced than that of CLW (results not shown here). Figures 3d-f show the effect of surface wind on sea ice concentration retrievals. In the presence of high wind, more sea ice is retrieved for ice concentration in excess of 0.2. This is probably due to the reduced polarization resulting from the wind-driven foam which covers the ocean surface in a way independent of polarization. Note also that no sea ice is retrieved when the ice fraction is less than 0.2 and WS is less than 22 m/s (Fig. 3d). This is again attributed to the weather filter. At high wind speed (WS > 22 m/s), the total sea ice concentration is substantially overestimated. If we compare the left and the right columns of Fig. 3, it can be seen that the sea ice retrieval is more sensitive to WS than CLW (or WV) within the range of variabilities of these parameters.

4. DISCUSSIONS

Synthetic retrievals using the NT algorithm based on the simulated data show overestimations of FY ice concentration due to the atmospheric water and greater overestimation due to surface wind. MY ice concentrations are underestimated due to the presence of atmospheric water at all sea ice concentrations and for surface wind at low ice concentrations. The overestimate of FY and underestimate for MY ice concentrations reduces the error in the total sea ice concentration in the retrieval. This result is consistent with the previous works (Maslanik, 1992; Oelke, 1997). This study, however, demonstrates the strong effect of surface wind in contributing to the retrieval error of total ice concentrations especially over low marginal ice areas, and has only received little attention in previous studies. Moreover, our sensitivity study shows that the errors due to surface wind depend nonlinearly on sea ice concentration and surface wind shows a stronger effect on retrieval than cloud liquid water. These results can be compared to that of Maslanik (1992) who showed the error in ice concentration estimates is linearly related to surface wind and is smaller than the effect due to liquid water.

In computing our ensemble, the vertical distributions of each parameter are not uniform but their integrated amounts (columnar cloud liquid water and columnar water vapor contents) and surface wind are assumed to have a uniform distribution (at discrete intervals). This assumption is used for its simplicity in our study since our aim is to understand the impact of these variables on the microwave signature for retrieval. However, the atmospheric variables have different distributions temporally and regionally. In addition, they are correlated. For example, in frontal zones, strong surface wind tends to be associated with increase cloudiness and water vapor. In order to compute the retrieval statistics that are appropriate for the specific period and region, more realistic distributions of the atmospheric variables must be used.

Other major uncertainties, such as the ice surface temperature, especially for MY ice, and snow conditions, will also affect microwave retrieval. Sea ice parameters, such as sea ice surface temperature recently derived from the Moderate Resolution Interferometer Spectroradiometer (MODIS) (Hall *et al.*, 2004) and atmospheric profiles derived from the Atmospheric Infrared Sounder/ Atmospheric Microwave Sounding Unit/ Humidity Sounding from Brazil (AIRS/AMSU/HSB) (Aunmann *et al.*, 2003) package will provide additional information to narrow down the errors in microwave sea ice retrieval. The additional atmospheric and surface information can be easily incorporated into our simulation models and radiative transfer computations to aid sea ice analysts in the interpretation of sea ice products from microwave sensors.

REFERENCES

Maslanik J. A., 1992: Effects of weather on the retrieval of sea ice concentration and ice type from passive microwave data. Int. J. Remote Sen., 13, 37-54

Oelke C., 1997: Atmospheric signatures in sea-ice concentration estimates from passive microwaves: modeled and observed. Int. J. Remote Sen., 18, 1113-1136.

Meier W., M. Marquis, M Kaminski, and R. Weaver, 2005: NASA EOS sensors demonstrate potential for multiparameter studies of arctic sea ice. Eos Trans., AGU, 85(46), 481.

Svendsen, S., K. Kloster, O. Johannessen, J. Johannessen, W. Campbell, P. Gloersen, F. D. Cavalieri, and C. Matzler, 1983: Norwegian remote sensing experiment: evaluation of the NIMBUS 7 Scanning Microwave Radiometer for sea ice research, J. Geophys. Res., 88, 2718-2791.

Comiso, J. C., D. J. Cavalieri, C. L. Parkinson, and P. Gloersen, 1997: Passive microwave algorithms for sea ice concentration – A comparison of two techniques. Remote Sens. Environ., 60, 357-384.

Markus, T., and D. J. Cavalieri, 2000: An enhancement of the NASA team sea ice algorithm. IEEE Trans. Geosci. Remote Sens., 38, 1387-1398.

Kummerow, C., 1993: On the accuracy of the Eddington approximation for radiative transfer in the microwave frequencies. J. Geophys. Res., 98, 2757-2765.

Wilheit, T. T., 1979: A model for the microwave emissivity of the ocean's surface as a function of wind speed. IEEE Trans. Geosci. Electron., 17, 244-249.

Hall D., J. R. Key, K. A. Casey, G. A. Riggs, and D. J. Cavalieri, 2004: Sea ice surface temperature product from MODIS. IEEE Trans. Geosci. Remote Sens., 42, 1076-1087.

Aunmann, H., H., M. Chahine, C. Gautier, M. Goldberg, E. Kalnay, L. McMillin, H. Revercomb, P. Resenkranz, W. Smith, D. Staelin, L. Strow, and J. Susskind, 2003: AIRS/AMSU/HSB on the Aqua Mission: design, science objectives, data products, and processing systems, IEEE Trans. Geosci. Remote Sens., 41 (2) 253-264.