INTEGRATED RETRIEVAL OF SURFACE AND ATMOSPHERIC PARAMETERS OVER THE ARCTIC FROM AMSR-E SATELLITE MICROWAVE RADIOMETER DATA USING INVERSE METHODS

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ABSTRACT

We present a method for the retrieval of atmospheric and surface parameters (namely, surface wind speed, total water vapor, cloud liquid water, surface temperature, ice concentration, multiyear ice fraction) over the Arctic Ocean from brightness temperature measurements by the spaceborne microwave radiometer AMSR-E (Advanced Microwave Scanning Radiometer for EOS) on the satellite Aqua. We use an inverse method, with a forward model based on a fast radiative transfer for AMSR-E over open ocean which we have extended by including the possibility of ice-covered or partly ice-covered sea, using new data on sea ice emissivity at AMSR-E frequencies. The method performs reasonably well and can even retrieve cloud liquid water over ice, and ice concentration in the marginal ice zone in cloudy and humid conditions.

Index Terms— Microwave radiometry, polar regions, sea ice, cloud liquid water

1. INTRODUCTION

The polar regions are notorious for insufficient data on the state of the surface and atmosphere because of too few direct observations. Therefore, satellite remote sensing of surface and atmospheric parameters in polar regions is essential for understanding and predicting weather and climate.

Here we try to address some issues in microwave remote sensing of polar regions, namely the retrieval of sea ice concentrations near the ice margin, and the retrieval of cloud liquid water over potentially ice-covered seas. Near the sea ice margin, the atmosphere has a large influence on the retrieval of the sea ice concentration from satellite microwave radiometer data as there, atmospheric humidity is usually

much higher than in the center of sea-ice covered regions, far away from open water. At the same time, retrieval of atmospheric parameters such as humidity or cloud liquid water over polar regions is challenging as the contribution from the surface to the signal received by the sensor is highly variable (because of variable sea ice cover) and often poorly known. In particular, the retrieval of cloud liquid water over sea ice was not possible in the past.

Our main idea is to use inverse methods in order to simultaneously retrieve sea ice and atmospheric parameters from data of the sensor AMSR-E (Advanced Microwave Scanning Radiometer for EOS) on board the satellite Aqua of the NASA (National Aeronautics and Space Administration). We currently use ten out of the twelve channels of AMSR-E, i.e., those at 6.93, 10.65, 18.7, 23.8, and 36.5 GHz, at both horizontal and vertical polarization. The spatial resolution of the channels is between about 50 km (at 6.93 GHz) and 15 km (at 36.5 GHz), and the polar regions are covered at least once daily.

2. RETRIEVAL METHOD

The inverse method we use for the retrieval is the “optimal estimation method” (maximum a posteriori likelihood) [1, 2, 3]. At its core is the forward model that is to be inverted.

2.1. Forward model

The forward model that translates the state variables (ice and atmospheric parameters) into AMSR-E brightness temperatures is based on the fast radiative transfer model for AMSR-E over ocean by Wentz and Meissner [4]. As this model is originally only for open water, we had to extend it by including the possibility of ice-covered or partly ice-covered sea. This means that two terms in the original forward model have to be modified: the term describing thermal emission by the ocean surface, and the term describing scattering or reflection

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of downwelling radiation by the surface. The thermal emission by a surface of mixed open water (OW), first-year ice (FYI), and multiyear ice (MYI) is written as

$$T_{B,S} = C_{ow}E_{ow}T_{ow} + C_{fyi}E_{fyi}T_{fyi} + C_{myi}E_{myi}T_{myi} \quad (1)$$

where $C_{..}$ denotes the fraction covered by open water, first-year ice or multiyear ice (and $C_{ow} + C_{fyi} + C_{myi} = 1$), $E_{..}$ denotes the respective emissivities, and $T_{..}$ the surface temperatures. For the reflection and scattering of downwelling radiation, we use an effective reflectivity combined in a similar way:

$$R_{eff} = 1 - E_{eff} = 1 - (C_{ow}E_{ow} + C_{fyi}E_{fyi} + C_{myi}E_{myi}) \quad (2)$$

The emissivities of sea ice which are then needed are based on monthly average values empirically retrieved with the method described by [5, 6]. We linearly interpolate (in time) between the monthly average emissivities.

2.2. Inverse method

The effect of the forward model can be written as

$$T_A = F(p) + e \quad (3)$$

where T_A is the vector of ten AMSR-E brightness temperatures, F is the forward model, p the state vector containing surface wind speed, total water vapor (TWV), cloud liquid water (CLW), surface temperature of open water, surface temperature of ice, ice concentration, and multiyear ice fraction, and e is the error of the measured brightness temperatures.

In order to apply the optimal estimation method, we further need the a priori state, p_0 , and the a priori covariance S_p . The a priori ice concentrations are determined directly from the brightness temperatures (NASA Team algorithm), and the a priori surface temperatures are determined from the brightness temperatures using ice concentration and the new ice emissivities estimates. The a priori values of the other parameters are climatological means derived from meteorological analysis data (ECMWF). We also need the error covariance matrix S_e of T_A which is a diagonal matrix containing the radiometric error of the AMSR-E channels.

The solution is found by iteration with the Gauss-Newton method [3], using the linearized forward model (i.e., its derivative):

$$M = \frac{\partial F(p)}{\partial p} \quad (4)$$

Then the iteration of the state vector is

$$p_{n+1} = p_n + \hat{S}_n^{-1} (M_n^T S_e^{-1} [T_A - F(p_n)] + S_p^{-1} [p_0 - p_n]) \quad (5)$$

where $M_n = M(p_n)$, and

$$\hat{S}_n = (S_p^{-1} + M_n^T S_e^{-1} M_n)^{-1} \quad (6)$$

is the covariance matrix of the state vector p_n , also called the a posteriori covariance matrix. We use two convergence tests, checking the condition

$$d^2 = (p_{n+1} - p_n)^T \hat{S}_n^{-1} (p_{n+1} - p_n) < 7 \quad (7)$$

where the threshold value of 7 is the dimensionality of the state vector (see [3]), and checking for a minimum of

$$\Delta = \|T_A - F(p_n)\| \quad (8)$$

Convergence is usually reached after less than 10 iterations.

Then, p_n contains the retrieved parameters, and $\hat{S}_n$ contains the variances (diagonal elements) and covariances (off-diagonal elements) of the retrieved parameters. The square root of the variances, i.e., the standard deviations of the retrieved parameters, are a measure of their uncertainty.

A possible source of problems is that several parameters of the state vector, namely wind speed, TWV and CLW, are constrained to be positive but can easily become negative during the iteration. Resetting them explicitly to avoid problems with the forward model physics can, in turn, cause bad convergence. This can be resolved by replacing the three parameters (wind speed, TWV and CLW) by their logarithm. As this will make the forward model too non-linear for the Gauss-Newton method, the Levenberg-Marquardt method has to be used instead, which is computationally not much more expensive when implemented in the way suggested in [3].

3. RESULTS

The retrieval method can produce fields (swath by swath) of wind speed, total water vapor, cloud liquid water, sea surface temperature, ice surface temperature, total sea ice concentration, and multiyear ice fraction. A preliminary version of the retrieval method has been running at DTU (Denmark's Technical University) at a resolution of 12.5 km, with daily coverage of the Arctic in near real time, see <http://www.seaice.dk>.

Figure 1 shows an example of the retrieved maps of cloud liquid water (CLW) and its uncertainty (standard deviation), for 20 March, 2008. Typical uncertainty (standard deviation) over sea ice in winter is 0.05-0.2 mm for CLW, which can reach the same magnitude as the signal. The algorithm works fine over the ocean, where the signal-to-noise ratio is larger. While CLW (and total water vapor) retrievals are continuous over the ice edge, the contour of the sea ice covered areas clearly shines through in the corresponding uncertainty maps, reflecting the fact that the precision of the atmospheric retrievals over sea ice is largely reduced by the higher surface contribution in the satellite signal.

Figure 2 shows the total ice concentration and its uncertainty for the same day as above. The optimal estimation algorithm derives reliable ice concentrations even north of Scotland where there is substantial cloud cover and strong wind

Fig. 1. Cloud liquid water (left) and its uncertainty (right) retrieved from AMSR-E, 20 March, 2008. Scale, left: blue is 0 mm, white is 0.3 mm; right: blue is 0 mm, red is 0.1 mm

(not shown), and at the same time it allows direct estimation of the uncertainty in the ice parameter retrieval.

4. CONCLUSION AND OUTLOOK

The data from AMSR-E can be used to improve monitoring atmospheric and surface parameters in polar regions, namely sea ice concentration, multiyear ice fraction, total water vapor and cloud liquid water. The results show further that the sea ice concentration can be retrieved near the ice margin even in very cloudy and humid conditions, yet, however, with reduced accuracy. Furthermore, retrieval of cloud liquid water works not only over open water, but also over sea ice, albeit with greatly reduced accuracy.

In order to improve the performance of the retrieval, we plan to use AMSR-E brightness temperatures that have been spatially resampled in order to harmonize the different resolution (i.e., antenna footprint sizes) at the different frequencies.

This will also make incorporating the 89 GHz channels possible. Using meteorological analysis data for the a priori state and covariance instead of climatological means is expected to improve performance, too, in particular, to reduce the uncertainty of the results. Finally, replacing some parameters by their logarithm and using the Levenberg-Marquardt instead of the Gauss-Newton method, as discussed in Section 2.2, seems promising. A much more challenging idea is to model sea ice and snow emissivity in parallel to the emissivity retrieval, as proper emissivity models can ultimately help the integrated retrieval of sea ice and atmospheric parameters.

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Fig. 2. Total ice concentration (left) and its uncertainty (right) retrieved from AMSR-E, 20 March, 2008. Scale, left: blue is 0%, green is about 40%, red is 100%; right: blue is 0%, green is 5%

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