IMPROVED RETRIEVAL OF SEA ICE THICKNESS FROM SMOS AND CRYOSAT-2

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ABSTRACT

We investigate the potential of a synergetic combination of data from ESA's SMOS and CryoSat-2 mission for sea ice thickness retrieval. SMOS and CryoSat-2 provide complementary information because of their different spatio-temporal sampling and resolution, and because of the complementary uncertainty due to the fundamental difference of the radiometric and altimetric measurement principle. The main limitations of the ice thickness retrieval depend on the emission e-folding depth and the vertical resolution of the effective radar pulse-length, respectively. It is shown that the combination of SMOS and CryoSat-2 considerably reduces the uncertainty with respect to the products derived from the single sensors. The RMS error is reduced from 76 to 66 cm and the squared correlation coefficient increases from 0.47 to 0.61 in comparison to validation data of NASA's Operation IceBridge campaign, 2013. Furthermore, we demonstrate the applicability of the Optimal Interpolation method for the generation of a combined product based on weekly CryoSat-2 averages.

1. INTRODUCTION

Sea ice is of great importance for the climate system both as an indicator for climate change and as a component that influences the interaction between ocean and the atmosphere as well as the global energy budget. The recent retreat of Arctic sea ice goes along with an increasing interest in Arctic shipping and the need for sea ice forecast systems. The European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) and CryoSat-2 missions provide novel data carrying information about the thickness of sea ice. In a pre-launch study the complementary nature of the uncertainties was predicted which now can be evaluated with the available measurements [1, 2]. The SMOS sensitivity to ice thickness is higher for thin ice, while CryoSat-2 exhibits a relative uncertainty higher for thin ice than for thick ice.

The SMOS payload is the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS) measuring for the first time globally the L-band brightness temperature at a range of incidence angles and at different polarizations. Electromagnetic radiation at L-band wavelengths (about 21 cm) emerge from deep inside the sea ice layer. The attenuation mainly depends on the relative brine volume which is a function of ice salinity and temperature. The penetration depth - or to be more precise, the emission e-folding depth - is up to 2 m for cold low-salinity sea ice and reduces to a few centimeters for saline sea ice at high temperatures. The potential to derive the ice thickness from L-band radiometry mainly depends on sea ice temperature and salinity. A sea ice thickness retrieval algorithm based on a combined thermodynamic and radiative transfer model has been used for the continuous operational production of a SMOS-based sea ice thickness data set from 2010 on [3]. The SMOS sea ice retrieval takes variations of ice temperature and ice salinity into account and corrects for the statistical thickness distribution function derived from high-resolution ice thickness measurements.

The ESA satellite altimeter CryoSat-2 is equipped with a Ku- band radar altimeter (SIRAL – Synthetic Aperture Interferometric Radar Altimeter). Its range retrieval enables the calculation of the sea-ice freeboard, which can be converted into sea-ice thickness, assuming hydrostatic equilibrium [4].

SMOS and CryoSat-2 are complementary in many different ways. In the following we focus on two main characteristics: firstly the accuracy of the ice thickness retrieval, and secondly, the difference in spatio-temporal resolution and sampling. We demonstrate the application of two methods for the generation of a combined product. We start with a simple weighted mean to show the reduction of the relative error for the combined ice thickness estimate based on monthly averaged data. In a second step we use the Optimal Interpolation (OI) method to fill the gaps of CryoSat-2 weekly averaged thickness products with the help of adjacent SMOS observations.

2. WEIGHTED MEAN OF SMOS AND CRYOSAT-2 SEA ICE THICKNESS

We compare the uncertainties of the SMOS and CryoSat-2 ice thickness retrieval with that resulting from a combination of both products using a weighted average. The weighted estimate is given as

$$x_{SYN} = \frac{\left(\frac{x_{SMOS}}{\sigma^2_{SMOS}} + \frac{x_{CS2}}{\sigma^2_{CS2}}\right)}{\left(\frac{1}{\sigma^2_{SMOS}} + \frac{1}{\sigma^2_{CS2}}\right)} \tag{1}$$

with variance

$$\sigma^2_{SYN} = \frac{1}{\left(\frac{1}{\sigma^2_{SMOS}} + \frac{1}{\sigma^2_{CS2}}\right)}. \tag{2}$$

The error of the weighted average is in general lower than the error of the single measurements. The example plot shown in Figure 1 suggests that the combination of both data sources leads to a considerable reduction of uncertainties when compared to the single products.

In order to prove the benefit of the added value through the weighted mean we compare the resulting combination with independent validation data. Figure 2 shows a comparison with NASA's Operation IceBridge (OIB) quicklook data [5]. It is evident for the thin ice area north of Barrow and Bank Island that the synergy of CryoSat-2 and SMOS agrees better with the validation data than the single products. The root-mean-square error reduces from 76 cm to 66 cm while the squared correlation coefficient increases from 0.47 to 0.61 when using the combined product instead of the single CryoSat-2 product in comparison to the validation data.

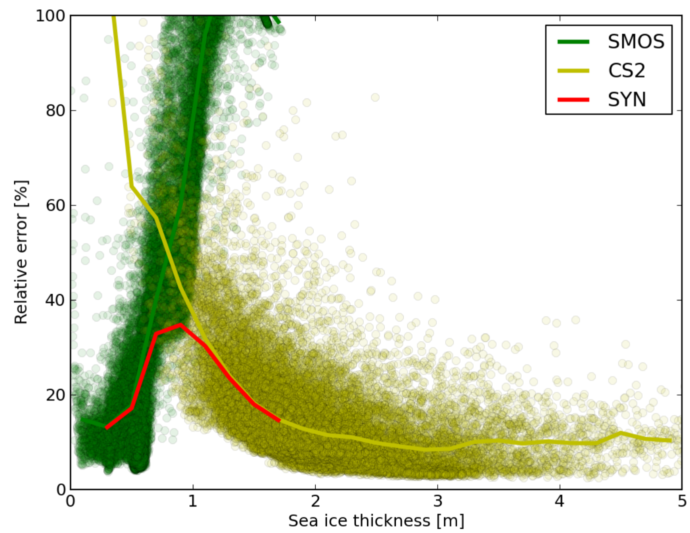

Fig. 1. Example error characteristic of SMOS and CryoSat ice thickness retrieval from SMOS (Algorithm II*) and CryoSat2 (AWI-retracked) with uncertainties from data products. The green and yellow lines have been calculated over 20 cm bins and respresent the single product relative errors. The red line gives the relative error of the combined product as inferred using Eq. 2

3. OPTIMAL INTERPOLATION FOR THE GENERATION OF WEEKLY COMBINED PRODUCTS

Optimal Interpolation is a sequential data assimilation scheme for practical operational implementation [6]. The basic optimal interpolation equation is:

$$x_a = x_b + W[y_o - H(x_b)], \tag{3}$$

where x_a is the analysis field, representing the merged sea-ice thickness product. x_b represents the background field, y_o the observational data and H an operator that transforms the background field data to the observation space. Here we specifically use bilinear interpolation to retrieve background values at each observational data point. As observational data we use CryoSat-2 weekly means (see Figure 3) and mid-week SMOS daily sea-ice thickness estimates. For the initial background field the CryoSat-2 monthly mean of the previous month is used. Then, we subsequently use x_a as x_b for the following week. The weight matrix W is retrieved by the background error covariance B in the observation space, multiplied by the inverted total error covariance matrix:

$$W = BH^T(R + HBH^T)^{-1}, \tag{4}$$

where R represents the error covariances of the observations. We use a Gaussian function of the form

$$b(d) = \exp(-d^2/cl^2), \tag{5}$$

to model the background error covariance matrix B, where d is the distance between the data points and the analysis grid point. Thus, the impact of a data point decreases with increasing distance. We additionally use a correlation length cl = 100 km, which alters this impact. For the observation error covariances we additionally add the SMOS and CryoSat-2 thickness variances, obtained from the product uncertainties. Finally a radius of influence of 100 km is applied to consider only data points in the vicinity of the analysis grid point. Figure 3 shows the merged weekly product (x_a), starting the 1st week of January 2014.

4. CONCLUSIONS

We have demonstrated the clear benefit of the combined use of SMOS and CryoSat-2 data for the estimation of ice thickness. The uncertainty of the thickness estimation is considerably reduced when compared to the single products. The weighted mean is a robust approach when applied with monthly mean data. Using the Optimal Interpolation method is a reasonable approach to generate combined products from the weekly averaged CryoSat-2 and the daily averaged SMOS thickness.

5. ACKNOWLEDGEMENTS

Thanks to ESA (contracts 4000101476/10/NL/CT, 4000112022/14/I-AM) and DFG (EXC177) for funding.

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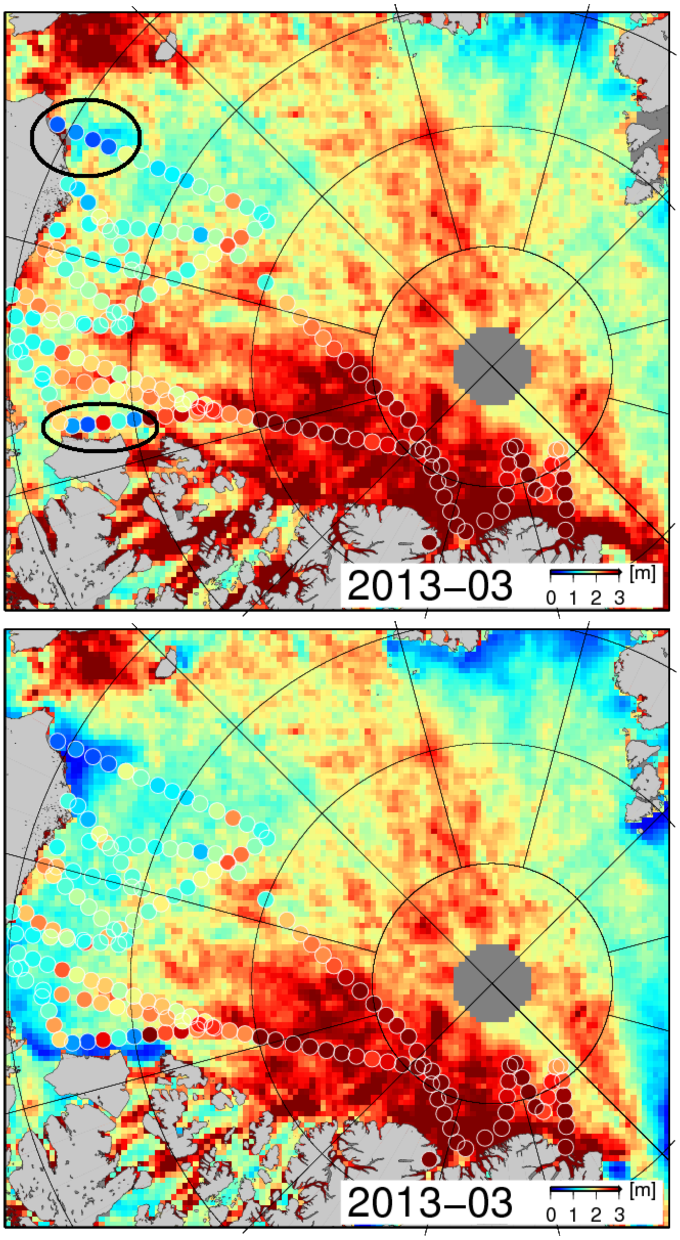

Fig. 2. CryoSat-2 (top) and CryoSat-2+SMOS synergy (bottom) together with sea ice thickness from NASA's IceBridge quicklook data averaged over ∼70km lags (colored circles). The black ellipse shows thin ice areas where SMOS considerably improves the thickness retrieval. The agreement with NASA's IceBridge measurements improves for the thin ice areas due to the added value of SMOS. Monthly averages March 2013.

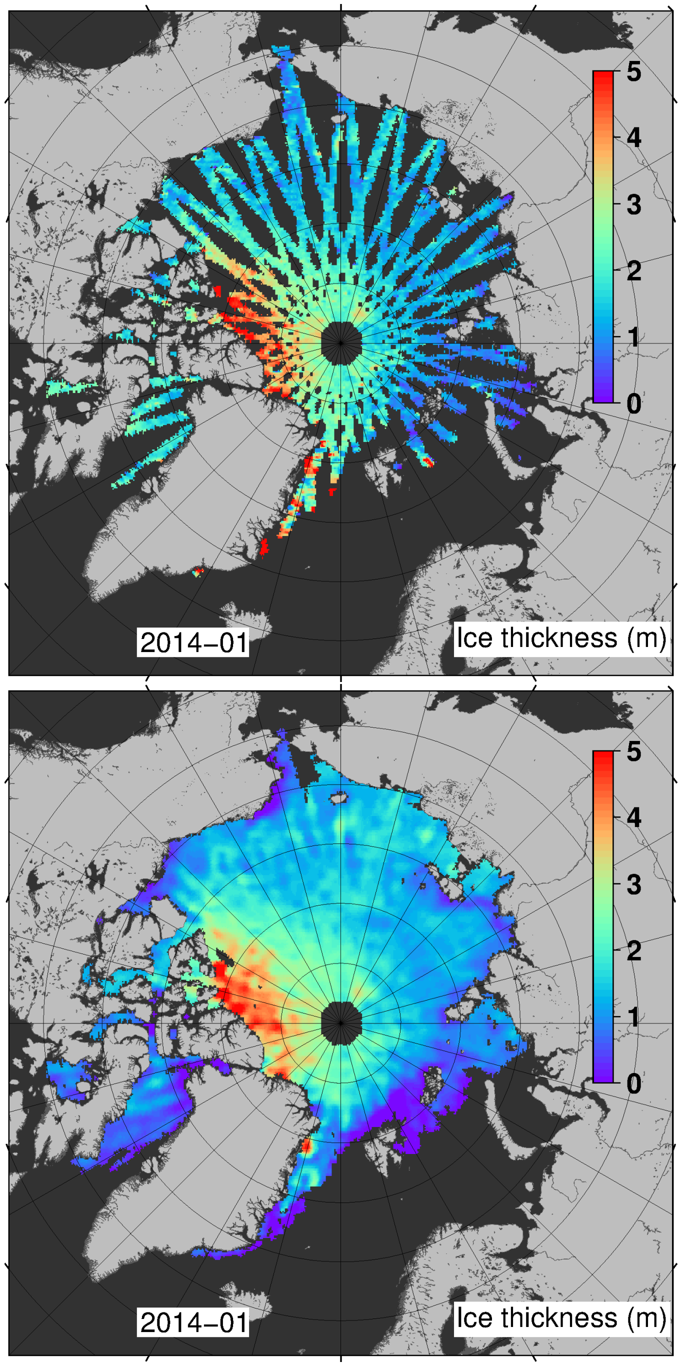

Fig. 3. Weekly CryoSat-2 thickness retrieval (left) and weekly CryoSat-2 and SMOS OI-fusion product (right)