# CONTINUOUS SEA ICE THICKNESS ESTIMATION USING A JOINT MODIS AND AMSR-E GUIDED VARIATIONAL MODEL

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**ABSTRACT**

Estimates of sea ice thickness are important for shipping and weather forecasting applications. Sea ice thickness can be estimated using data from the thermal channels on the Moderate Resolution Imaging Spectroradiometer (MODIS). However, using this data for studies of surface conditions is significantly hampered by cloud cover. This is particularly problematic for studies of the marginal ice zone, where atmospheric conditions often lead to persistent cloudy conditions. In this study a new method is proposed in which data from a passive microwave sensor is used to guide the estimation of surface temperature in cloud-covered regions. The impact of the method is verified by checking sea ice thickness values calculated using the guided surface temperature against values from operational sea ice charts.

***Index Terms—*** variational, sea ice, infrared

## 1. INTRODUCTION

An accurate estimate of sea ice thickness is important for navigation in ice-infested waters, for weather forecasting in ice-covered regions, and for understanding climate change. The thickness of thin ice has a critical impact on heat transfer between the atmosphere and ocean, and can impede ships in ice-infested waters. Sea ice thickness can be calculated using data from passive microwave and visual/infrared (VIS/IR) sensors [1, 2]. While estimates from passive microwave sensors are limited to very thin ice (less than 0.2m [1]) or thin ice (less than 0.5m [3]) and have coarse spatial resolution, estimates from VIS/IR sensors are finer resolution ($\approx$ 1km) and are valid for thicker ice (up to 1.8m [2]), with the limitation that this source of data cannot be used during cloudy conditions. The goal of the current study is to present a method that can provide sea ice thickness estimates during both clear-sky and partially cloudy conditions at higher resolutions by combining data from passive microwave and VIS/IR sensors to get the best of both worlds. This is accomplished via a multi-modality guided variational (MGV) model, which incorporates multiple imaging modalities (in this case, MODIS and multiple AMSR-E channels) to guide the estimation process. This approach is different from approaches which use adjacent temporal deduction, and fill in a cloudy pixel with the value from an image on a preceding day[4, 5]. A variational method has been used by for destriping MODIS images in [6], and for calculating a daily cloud-free image from MODIS in [7]. The method presented here is novel in the incorporation of multiple imaging modalities and additional spatial context within a variational framework.

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## 2. DATA

### 2.1. MODIS data

In this study the MOD29 ice surface temperature product prepared by the National Sea and Ice Data Services (NSIDC) was used [8]. This product contains swath data at 1km resolution in which each pixel has been screened for cloud contamination. To reduce the uncertainty associated with the surface albedo and shortwave radiation in the calculation of ice thickness, only nighttime images were selected [2].

### 2.2. AMSR-E data

In this study the brightness temperatures at 6.9GHz, 10.8GHz and 18.7GHz from the AMSR-E sensor are used. Higher frequencies were not used because of their sensitivity to the atmosphere. In the absence of atmospheric effects, the brightness temperatures measures the product of the emitting layer temperature and the surface emissivity, and was found to be correlated more strongly correlated with the MODIS surface temperature than polarization ratio. The ice concentration from AMSR-E was also used to initialize the surface temperature in cloudy regions. For this purpose the NSIDC L3 12.5km Sea Ice Concentration Product was used. This product calculates the ice concentration from the AMSR-E brightness temperatures using the Enhanced NASA Team 2 Algorithm (NT2).

### 2.3. Canadian Ice Service Sea Ice Analyses

The ice thickness values calculated from the surface temperature from the proposed MGV method are compared against

thickness values from daily ice charts produced by the Canadian Ice Service (CIS). The daily ice charts are prepared by trained ice forecasters who visually analyze a variety of near real-time data and relies to a large extent on RADARSAT Synthetic Aperture Radar (SAR) images. In the preparation of ice charts, the forecaster draws polygons of uniform ice conditions in terms of the total ice concentration and the relative mix of ice types. The ice types are defined according to their stage of development following World Meteorological Organization standards. To convert the ice chart data to mean ice thickness, the median thickness value associated with each ice type identified in a polygon was multiplied by the partial concentration of that ice type and the contributions from each thickness category in the polygon were summed.

## 3. METHODOLOGY

### 3.1. Calculation of surface temperature via multi-modality guided variational (MGV) model

The surface temperature is estimated in a spatially continuous manner using the MOD29 ice surface temperature product and the AMSR-E ice polarization ratios at four frequencies. Both the polarization ratios and the MODIS surface temperature are related to the sea ice thickness. To estimate the surface temperature the problem is first defined in the context of the given data measurements. Let $\underline{m_0}$ be a measurement vector denoting the sparse MODIS surface temperature data, and let $\underline{m_i}$ be a measurement vector denoting the sparse AMSR-E polarization ratio at the $i^{\text{th}}$ frequency (given four frequencies used, $i \in [1, 4]$). Therefore, one can define the joint forward measurement model for both MODIS and AMSR-E data as:

$$\begin{bmatrix} \underline{m_0} \\ \underline{m_1} \\ \vdots \\ \underline{m_3} \end{bmatrix} = \begin{bmatrix} C_0 \\ C_1 \\ \vdots \\ C_3 \end{bmatrix} \begin{bmatrix} \underline{z_0} \\ \underline{z_1} \\ \vdots \\ \underline{z_3} \end{bmatrix} \tag{1}$$

where $\underline{z_0}$ is the continuous ice temperature, $\underline{z_i}$ is the continuous polarization ratio based on the $i^{\text{th}}$ AMSR-E frequency used here, $C_0$ is the observation matrix that derives the measurements $\underline{m_0}$ from $\underline{z_0}$, and $C_i$ is the observation matrix that derives the measurements $\underline{m_i}$ from $\underline{z_i}$. As such, the observation matrices define the geo-locations at which the measurements are made by the imaging sensor. Therefore, the ice temperature estimation problem is effectively an inverse problem, where the goal is to estimate the unknown state $\underline{z_0}$ given known measurements $\underline{m_0}, \underline{m_1}, \ldots, \underline{m_3}$.

Since MODIS provides finer resolution data but cannot provide surface information under cloudy conditions, while AMSR-E is robust to cloudy conditions but provides lower resolution data, it is ideal to use of both data sources simultaneously. To accomplish this, we take advantage of the inherent relationship between variations in polarization ratio and ice surface temperature variations and introduce a multi-modality guided variational (MGV) model that utilizes the sparse measurements from both MODIS and AMSR-E (i.e., $\underline{z_0}, \underline{z_1}, \ldots, \underline{z_3}$) to compute a more robust and higher resolution estimate of surface temperature (denoted by $\underline{\hat{z}_0}$): where $\alpha$ and $\beta$ control the influence of the data fidelity and variational terms, respectively, $\lambda_s$ controls the contribution of local spatial proximity on guiding the solution process, and $\lambda_i$ controls the influence of local variations in $\underline{m_i}$ on guiding the solution process, $\underline{j}$ and $\underline{k}$ denote geo-locations, and $N(\underline{i})$ denotes a neigbhorhood around $\underline{i}$.

Eq. 2 is solved using an iterative gradient descent solver, with the initialization based on the MODIS ice surface temperature product for non-cloudy areas, but based on ice concentration (denoted by $IC$) from AMSR-E in cloudy areas according to $\underline{z_0} = 265^o K * IC + (1 - IC) * 274^o K$. In this implementation, $\beta = 1$, $\alpha = 0.7$, and $N(\underline{i})$ is a $7 \times 7$ neighborhood around geo-location $\underline{i}$ as it was found to provide reliable estimation performance.

### 3.2. Calculation of sea ice thickness from the surface temperature

The ice thickness is calculated from the surface temperature estimate $\underline{\hat{z}_0}$ following the method given by [2]. Briefly, an energy balance at the interface between the ice or snow and the atmosphere is applied. For nighttime conditions the energy balance is given by

$$F_l^{dn} - F_l^{up} + F_s + F_e + F_c = F_a, \tag{3}$$

where $F_l^{dn}$ is the downward longwave radiation, $F_l^{up}$ is the upward longwave radiation, $F_e$ is the latent heat flux, $F_s$ is the sensible heat flux, $F_c$ is the conductive heat flux and $F_a$ is the residual heat flux, which is heat transfer due to surface or lateral growth or melt. Full details regarding the heat flux equation and the parameterization of the terms in are given in [2] and references therein. The input to the energy balance equation is the surface temperature estimate $\underline{\hat{z}_0}$ and geophysical fields (windspeed, cloud fraction and surface pressure) from Environment Canada's Global Environmental Model. The geophysical fields are interpolated linearly to the observation times and bilinearly to the observation locations. In this study the snow density is specified as $200 kg/m^3$, which is representative of new snow conditions, the snow thickness parameterization from [2] and the air temperature is assumed to closely follow the surface temperature according to $T_a = T_s + \delta T$, where the temperature offset, $\delta T$ decreases with cloud fraction according to, $\delta T = 2.2 - 1.8 C_f$.

$$\underline{\hat{z}_0} = \text{argmin}_{\underline{\hat{z}_0}} \left[ \alpha \left\| \underline{m_0} - C_0 \underline{\hat{z}_0} \right\|_2 + \beta \sum_{\underline{j}} \sum_{\underline{k} \in N(\underline{j})} exp(-\lambda_s \left\| \underline{j} - \underline{k} \right\|_2) \sum_{i=0}^{3} exp(-\lambda_i \left\| \left\{ C_i^{-1} \underline{m_i} \right\} (\underline{j}) - \left\{ C_i^{-1} \underline{m_i} \right\} (\underline{k}) \right\|_2) \left| \underline{\hat{z}_0}(\underline{j}) - \underline{\hat{z}_0}(\underline{k}) \right| \right] \tag{2}$$

## 4. RESULTS

Ice thickness was calculated from the MODIS ice surface temperature and the MGV ice surface temperature every day for the month of January 2007. Results are shown in Figure 1 for January 24, 2007. The surface temperature from MODIS is shown in Figure 1a), with the surface temperature estimate obtained from the MGV method shown in Figure 1c). We can see the MGV method provides reasonable surface temperate estimates in small cloudy patches over the ice and open water, which are guided in part by the AMSR-E brightness temperature (shown in Figure 1b) for 10.8 GHz) and the surrounding MODIS data. The ice thickness calculated from the MGV surface temperature estimate is shown in Figure 1d).

These derived thicknesses were compared with the CIS ice charts by averaging all values within a distance of half of the spacing between chart values at the ice chart thickness location. The thickness values were then binned into ice thickness categories. The absolute differences between the ice thickness estimates and the ice charts are given in Table 1. We can see that when the MGV method is used the sea ice thickness values are in closer agreement with the ice charts. This is particularly true for the two categories that contain the thinnest ice, which are also those that are most negatively impacted by the presence of unmasked clouds. The comparison here is given only for thin ice, because this is the ice in the verification domain is predominantly thin at this time of year (99% of the ice chart thickness values are less than 0.3m in thickness).

| | MODIS swath data | MGV |
|---|---|---|
| $0 \leq \text{h}_{chart} \leq 0.1$ | 0.154 | 0.142 |
| $0.1 \leq \text{h}_{chart} \leq 0.15$ | 0.143 | 0.0736 |
| $0.15 \leq \text{h}_{chart} \leq 0.30$ | 0.0920 | 0.0909 |

**Table 1**. Differences between ice thickness calculated using only MODIS surface temperature product vs. the ice thickness estimate using MGV, and ice charts from the Canadian Ice Service for the month of January, 2007.

## 5. CONCLUSIONS

The preliminary results presented here indicate that using MGV provides a continuous surface temperature estimate, which can be used to calculate sea ice thickness in both clear and partially cloudy situations. The sea ice thickness estimated using MGV is in better agreement with data from ice charts than when the MODIS surface temperature product is solely used.

## 6. REFERENCES


[1] K. Iwamoto, K.I. Ohshima, T. Tamura, and S. Nihashi, "Estimation of thin ice thickness from AMSR-E data in the Chukchi Sea," *International Journal of Remote Sensing*, vol. 34, no. 2, pp. 468–489, 2013.

[2] X. Wang, J.R. Key, and Y. Liu, "A thermodynamic model for estimating sea and lake ice thickness with optical satellite data," *Journal of Geophysical Research*, vol. 115, pp. C12035, 2010.

[3] L. Kaleschke, X. Tian-Kunze, N. Maab, M. Makynen, and M. Drusch, "Sea ice thickness retrieval from SMOS brightness temperatures during the arctic freeze-up period," *Geophysical Research Letters*, vol. in press, 2012.

[4] D.K. Hall, Riggs G.A., J.L. Foster, and S.V Kumar, "Development and evaluation of a cloud-gap-filled MODIS daily snow-cover product," *Remote Sensing of Environment*, vol. 114, pp. 496–503, 2010.

[5] Y. Gao, H. Xie, T. Yao, and C. Xue, "Integrated assessment on multi-temporal and mult-sensor combinations for reducing cloud obscuration of MODIS snow cover products of the Pacidic Northwest USA," *Remote Sensing of Environment*, vol. 114, pp. 1662–1675, 2010.

[6] Bouali M. and S Ladjal, "Toward optimal destriping of MODIS data using a unidirectional variational model," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 49, no. 8, pp. 2924–2935, 2011.

[7] Q. Xia, X. Gao, W. Chu, and S. Sorooshian, "Estimation of daily cloud-free, snow-covered areas from MODIS based on variational interpolation," *Water Resources Research*, vol. 48, pp. W09523, 2012.

[8] D. K. Hall, Riggs G. A., and V. V. Salomonson, "MODIS/Terra Sea Ice Extent 5-min L2 Swath 1km V005, [January 10-January13, 2009], Boulder, Colorado USA: National Snow and Ice Data Center.," 2007.

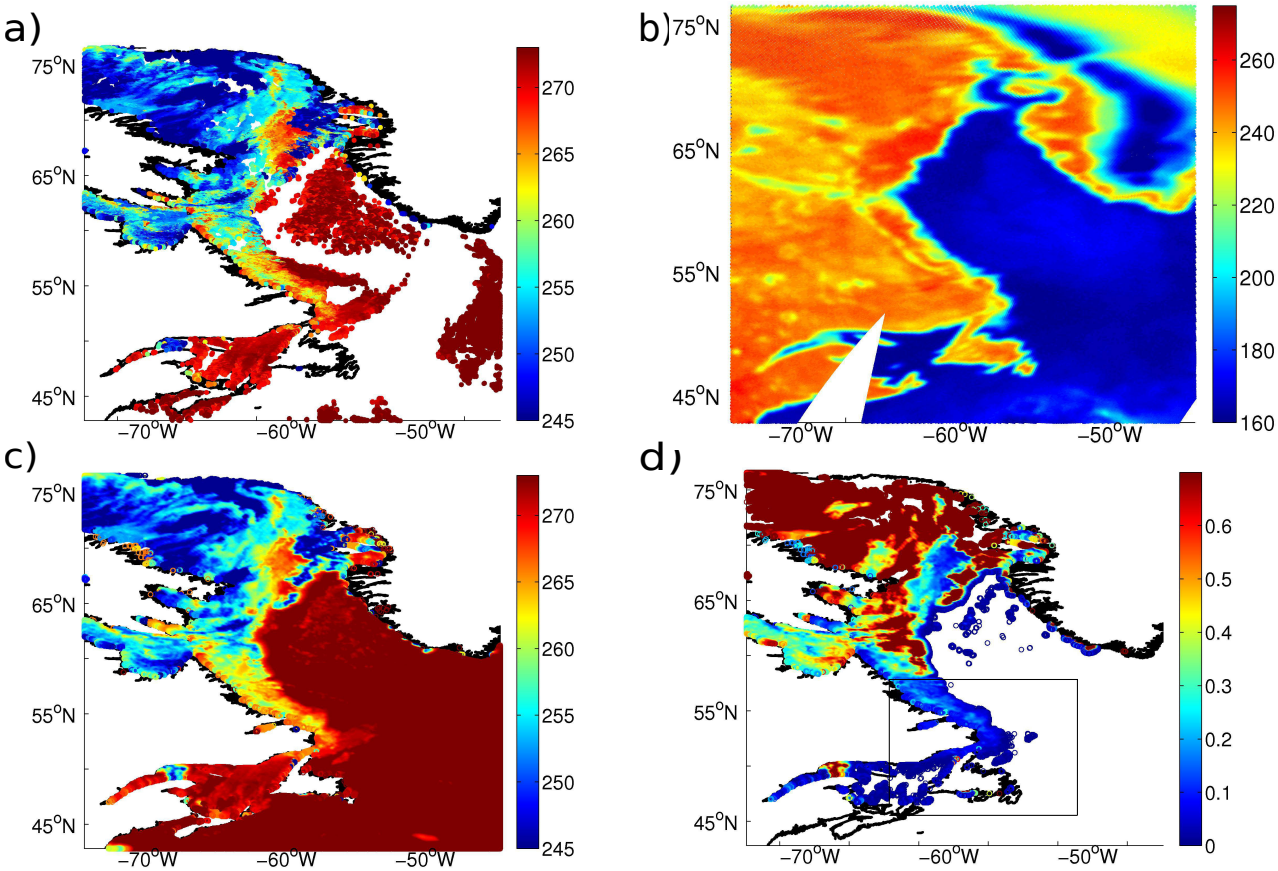


**Fig. 1**. Conditions for January 24th, 2007; a) Surface temperature using only MODIS, white areas over the ocean are cloud; b) Brightness temperature from AMSR-E 10.8 GHz channel (two swaths). c) MGV ice surface temperature estimate; d) Sea ice thickness calculated from the image in panel (c). Ice thickness values are only calculated for temperatures in the range of 241K-271K. The boxed area in panel (d) indicates the area covered by the CIS ice chart.