Sea and Lake Ice Thickness and Age with GOES-R ABI and NPP/JPSS VIIRS

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Introduction

The cryosphere exists at all latitudes and in about one hundred countries. It has profound socio-economic value due to its role in water resources and its impact on transportation, fisheries, hunting, herding, and agriculture. Current spaceborne sensors have been used primarily for mapping ice extent and ice concentration, but more accurate, consistent, and detailed ice thickness and age data are also critical for a wide range of applications from climate modeling to operational uses such as shipping and hazard mitigation.

Here we describe the application of a thermodynamic model, called the One-dimensional Thermodynamic Ice Model (OTIM), to estimate sea and lake ice thickness and age with optical satellite imagery. The model was developed for use with the Geostationary Operational Environmental Satellite (GOES-R) Advanced Baseline Imager (ABI). A similar method is being used with the Visible/Infrared Imager Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (NPP) satellite.

Validation with in-situ ice thickness measurements from submarine sonar, mooring sites, and surface stations shows that the OTIM is capable of retrieving ice thickness up to three meters with an overall accuracy greater than 80%. OTIM ice age meets the required ABI accuracy of 80% and product precision of less than one ice age category.

There is an internationally accepted terminology for ice morphology and conditions, coordinated by the WMO. This terminology is used by the Canadian Ice Service as the basis for reporting ice conditions, and adopted here with minor modifications for classifying ice into different categories, i.e., ice age in terms of ice thickness.

A One-dimensional Thermodynamic Ice Model (OTIM)

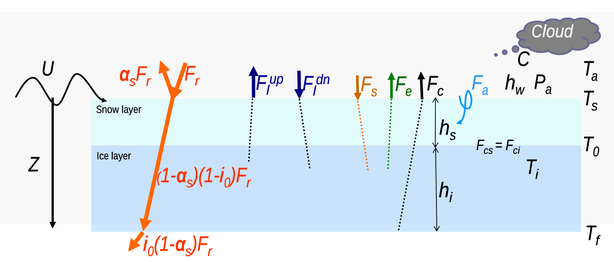
A One-dimensional Thermodynamic Ice Model (OTIM) was developed based on the surface energy balance at thermo-equilibrium state that contains all components of the surface energy budget to estimate ice thickness. The equation for energy conservation at the top of the surface (ice or snow) is

$$(1-\alpha_s)(1-i_0)F_r - F_l^{up} + F_l^{dn} + F_s + F_e + F_c = F_a(\alpha_s, T_s, U, h_i, C, h_s, \ldots)$$

where α_s is surface ice/snow broadband albedo, F_r is surface downward shortwave radiation, I_0 is shortwave radiation passing through the ice interior, F_l^{up} and F_l^{dn} are surface upward and downward longwave radiation, respectively. F_s, F_e, and F_c are surface turbulent sensible, latent, and conductive heat fluxes, F_a is the residual heat flux that contributes to melting at or near the surface (zero in the absence of a phase change). After parameterizations of thermal radiation (F_l^{up}, F_l^{dn}) and turbulent (sensible & latent) heat (F_s, F_e), ice thickness h_i becomes a function of 12 model controlling variables:

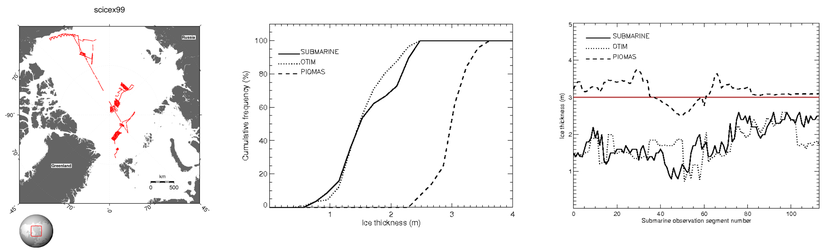
$$h_i = f(\alpha_s, i_0, F_r, T_s, T_i, T_a, P_a, h_w, U, C, h_s, F_a)$$

where T_s is surface skin (ice or snow) temperature, T_i is ice surface temperature, T_a is surface air temperature, P_a is surface air pressure, h_w is surface air relative humidity, U is surface wind speed, C is cloud amount, h_s is surface snow depth.

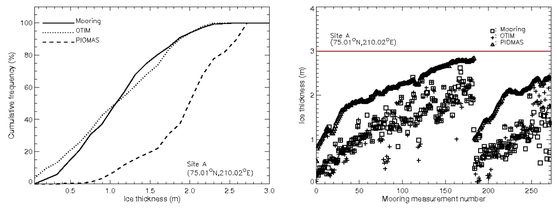


Based on the ice thickness, eight categories of ice "age" are defined: new, nilas (0.00~0.10 m), grey (0.10~0.15 m), grey-white (0.15~0.30 m), first-year thin (0.30~0.70 m), first-year medium (0.70~1.20 m), first-year thick (1.20~1.80 m), and older ice including second-year and multi-year ice (> 1.80 m). The current version of the OTIM was compared with the ice thickness measurements made by submarine and moored upward looking sonars during the Scientific Ice Expedition (SCICEX) and Beaufort Gyre Exploration Project (BGEP), Canadian meteorological stations over 2002~2004, and the simulated ice thickness data from Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS).

Validation and Verification

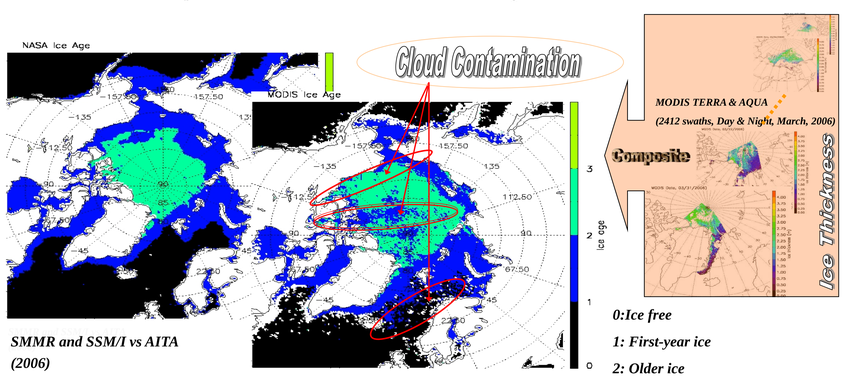


Submarine sonar data during the SCICEX experiment in 1999 was used for validation. The track is shown on the left. A comparison of the ice thickness cumulative frequency distribution from OTIM, PIOMAS, and submarine sonar, and the point-to-point comparison of the ice thickness from OTIM, PIOMAS, and submarine are shown in the middle and right figures. The OTIM ice thickness product was produced with AVHRR data. Overall OTIM uncertainty, expressed as the root mean square error, is 0.31 m with respect to the mean ice thickness of 1.80 m from submarine.



Mooring Location OTIM	Thickness mean (m)	Bias mean (m)	Bias absolute mean (m)
Site A (75°0.459' N, 149°58.669' W)	1.24	-0.02 (-1.2%)	0.19 (15.3%)
OTIM	1.22		
Site B (78°1.690' N, 149°49.288' W)	1.32	-0.15 (-11.4%)	0.29(21.9%)
OTIM	1.17		
Site C (76°59.252' N, 139°54.562' W)	1.32	-0.12 (-9.1%)	0.28 (21.2%)
OTIM	1.20		
ALL MOORING AVERAGE	1.29	-0.09 (-6.9%)	0.25 (19.4%)
OTIM AVERAGE	1.20		

Comparisons of the ice thickness cumulative frequency distribution (left) and point to point absolute values (middle) among OTIM retrievals with APP-x data, simulations from the PIOMAS model, and the ULS measurements at the mooring site A are shown above. The location information of three mooring sites over 2002-2004 and statistical comparison results are listed in the table on the righ.



OTIM derived ice age (middle) from a composite of Terra & Aqua MODIS data in March, 2006, and the ice age (left) derived from microwave ice concentration (NASA team algorithm) data using a tracking method over the year 2006. Inaccuracies in the MODIS cloud mask can severely affect the accuracy of ice thickness and age products.

Ice Age (OTIM vs Microwave)	
Statistics	Accuracy
Ice Free	D&N:93%, N:93%, D:~100%
First-year Ice	D&N:92%, N:92%, D:~100%
Older Ice	D&N:84%, N:84%, D:~100% *
All	D&N:89%, N:89%, D:~100%
Error Sources	1. Ice identification algorithm 2. Cloud mask/shadow detection 3. Relationship between thickness and age 4. Ice motion/Dynamic processes

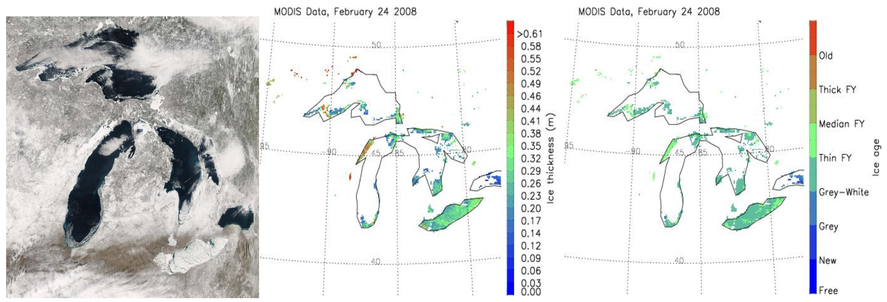
Note: Number in each cell stands for the number of pixels that belong to the ice age category difference corresponding to NASA and OTIM ice age classifications used to do statistics, i.e., accuracy and precision in ice age classification.

Ice Age Difference (OTIM vs Microwave)			
	No Difference	1 Category Difference	2 Category Difference
	(D&N:49820) (N:49822) (D:34774)	(D&N:7154) (N:7146) (D:30)	(D&N:52) (N:52) (D:0)
Precision	(D&N:0.34 Category) (N:0.34 Category) (D:0.03 Category) *		

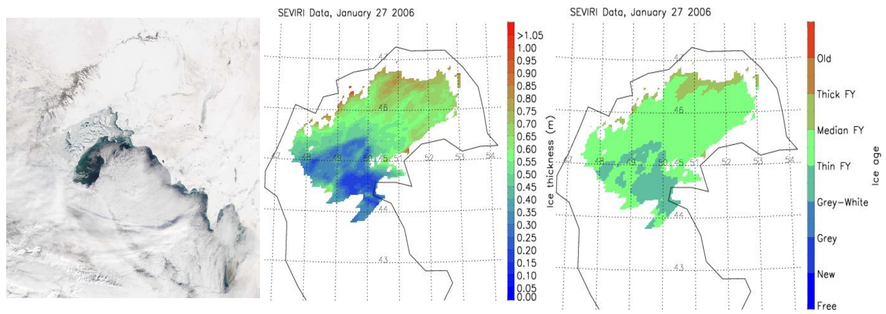
* D&N: Day (bright) and night (dark) pixels; D: Daytime (bright) pixels only; N: Nighttime (dark) pixels only.

The statistical comparison results between OTIM and microwave derived ice age products in terms of the product accuracy (left) and the product precision (right). Microwave ice age products were derived by using a in-time tracking method over the year 2006 with the microwave ice concentration product.

Testing with GOES-R ABI Proxy Data

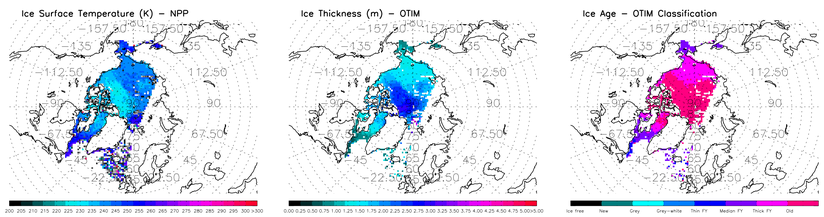


MODIS Aqua true colour image (left) on February 24, 2008 over Great Lakes, retrieved ice thickness (middle) in meters, and ice age (right).



MODIS true color image (left) over the Caspian Sea on January 27, 2006 and the corresponding sea ice thickness (middle) in meters, and sea ice age (right) from SEVIRI data on the same day.

Testing with NPP/JPSS VIIRS Data



VIIRS ice surface temperature (left), OTIM ice thickness (middle) based on VIIRS ice surface temperature, and ice age (right) derived from VIIRS ice surface temperature data on March 4 ,2012 for the Arctic region.

Conclusions and Perspectives

- GOES-R ABI Sea & Lake Ice Age Product is produced using a in-house developed One-dimensional Thermodynamic Ice Model (OTIM).
- The Sea & Lake Ice Age Product uses MODIS, SEVIRI, and AVHRR data as proxy and is validated against Upward Looking Sonar (ULS) measurements from submarine and mooring sites, stations observations, and microwave data to demonstrate that the Ice Age algorithm meets product requirements of 80% correct accuracy and less than one category precision.
- VIIRS data have been also applied to the OTIM to generate ice thickness and age products. Compared with VIIRS ice age product from Northrop Grumman (NG) algorithm, it shows better and more correct ice age classification
- The OTIM will be further modified to improve the accuracy, in particular, for daytime retrievals, with more validation data becoming available, e.g., NASA IceBridge data.