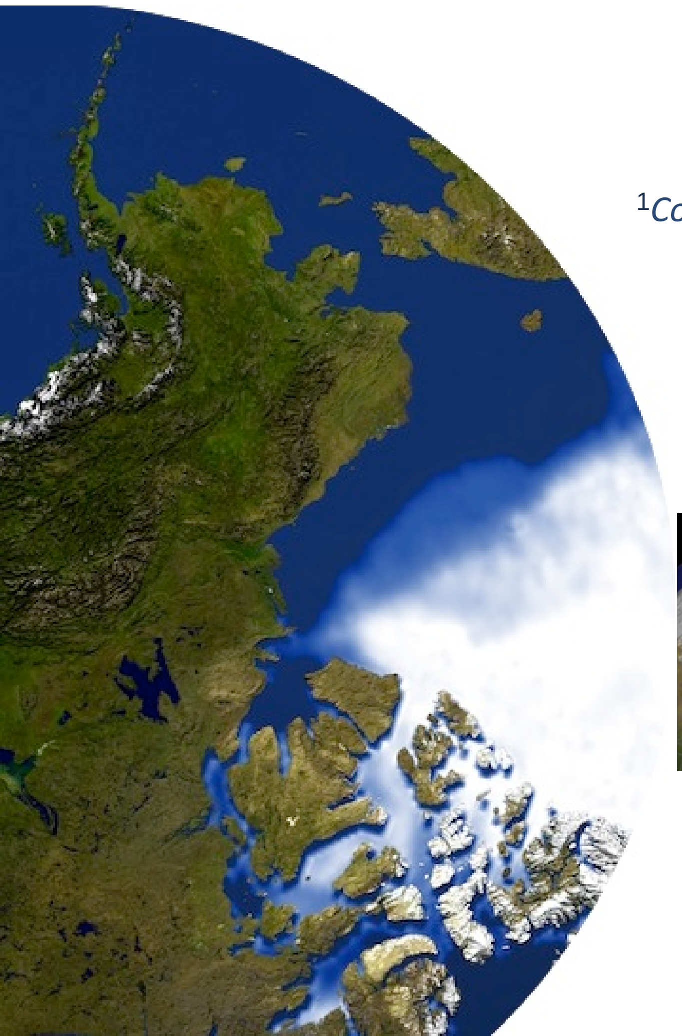
Sea Ice Thickness from Satellite



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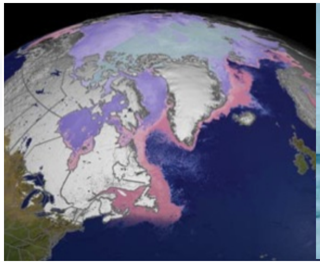
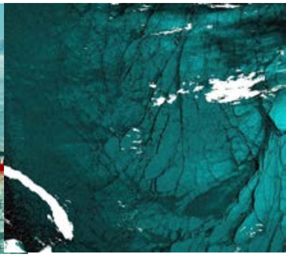
With input from Dan Baldwin and Mark Tschudi, CU-Boulder



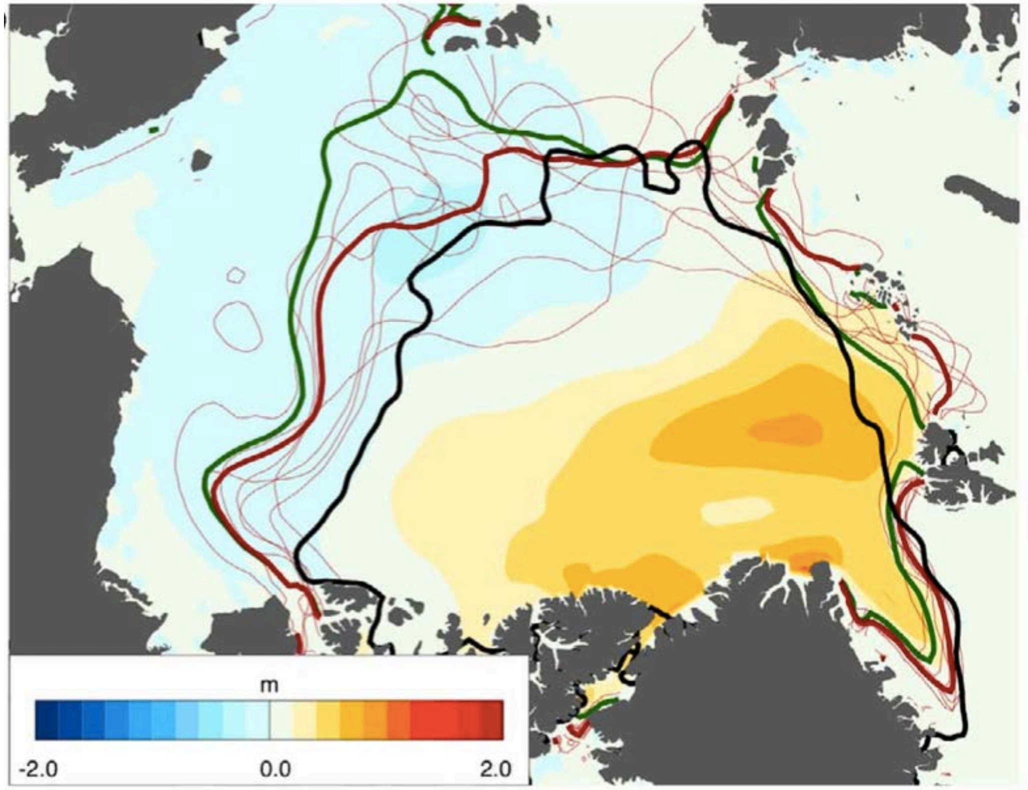



STAR JPSS 2015 Annual Science Team Meeting
24-28 August 2015, NCWCP, College Park, MD

Importance of Ice Thickness

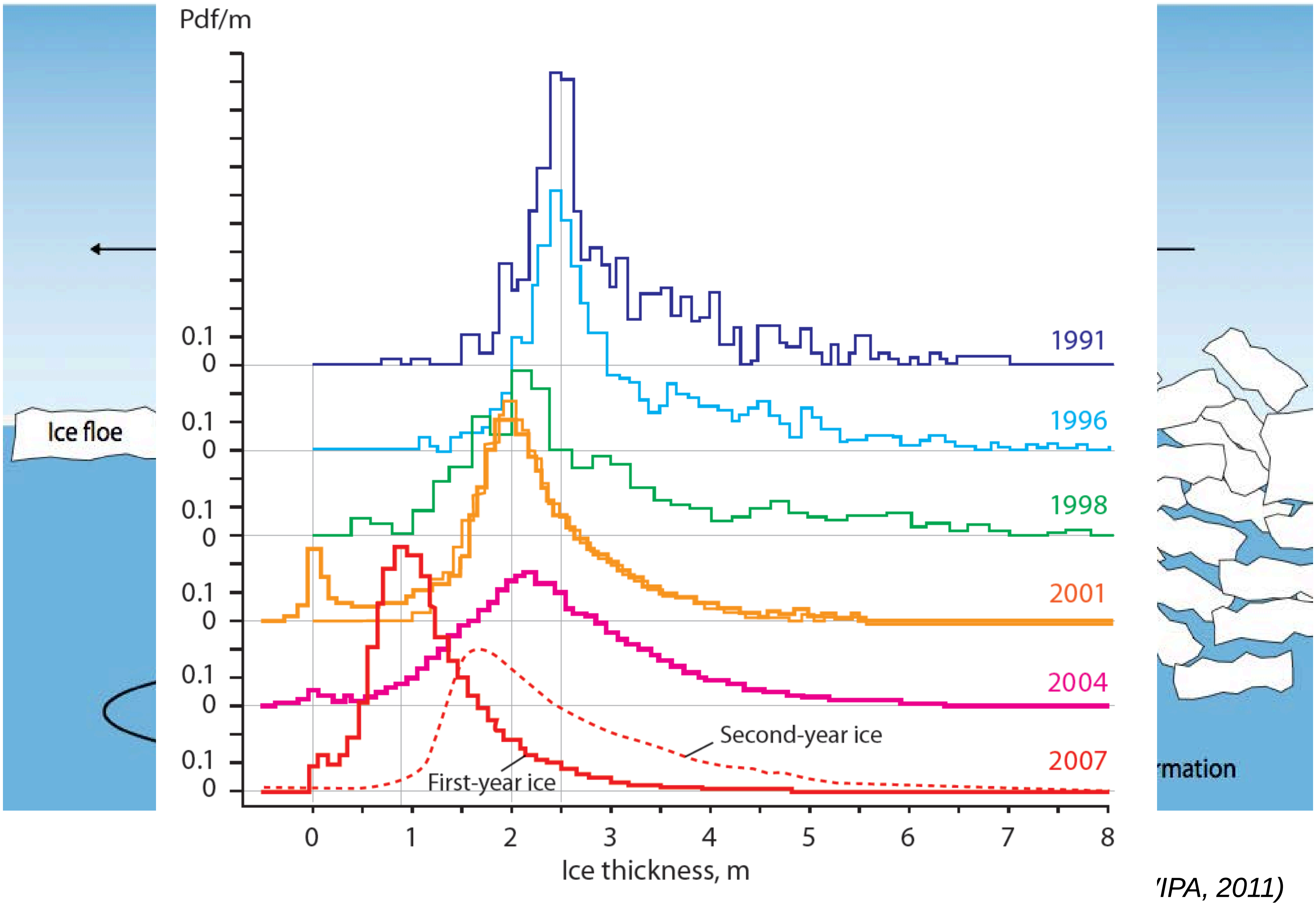
Thermodynamically and dynamically it is ice thickness, not ice extent, that is important. Thickness provides an integrated measure of changes in the energy balance. It is critical to navigation.

While little work has been done on assimilating ice thickness in models, indications are that doing so would improve ice forecasts.

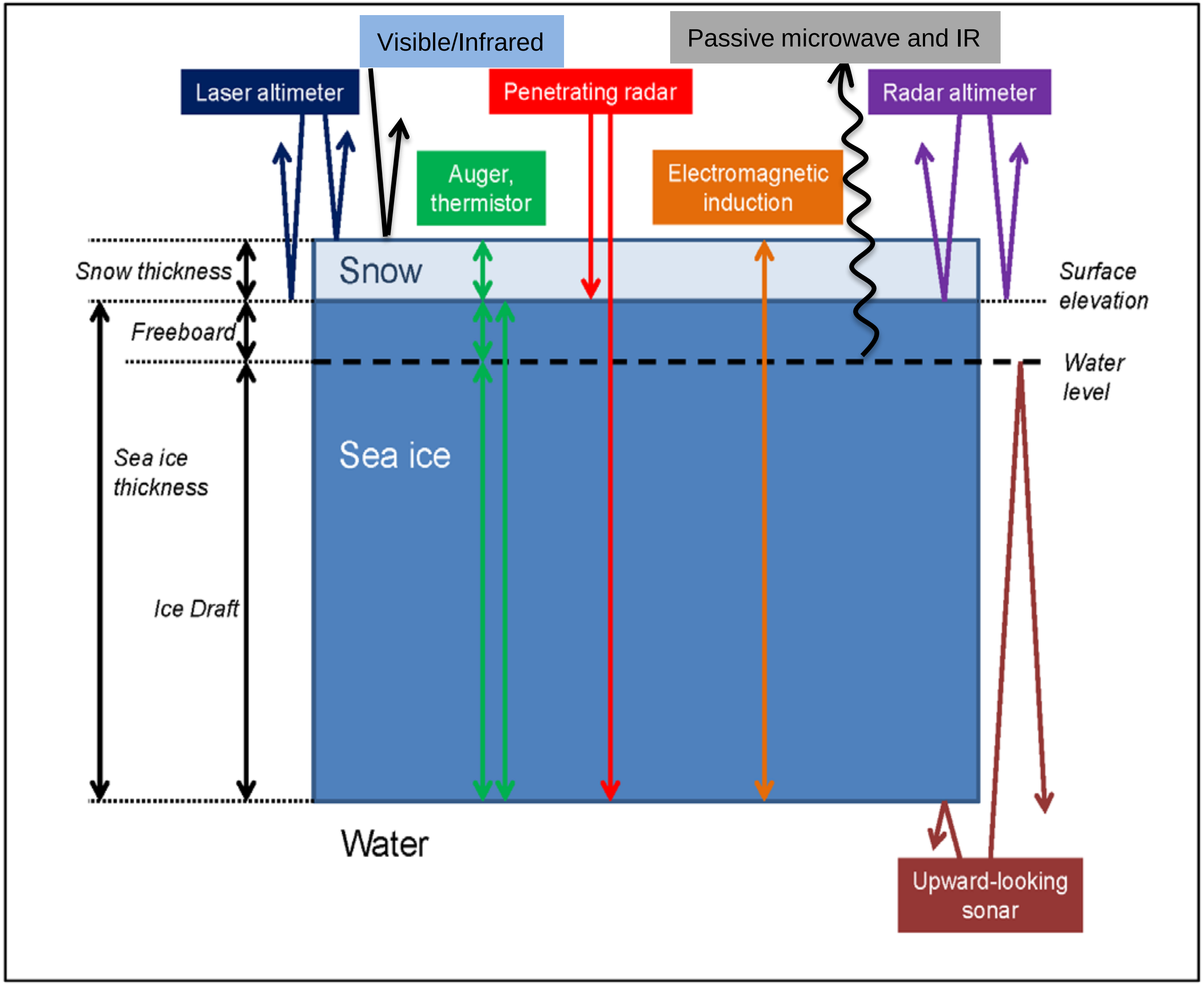


The difference in mean ice thickness for September between the corrected and the control runs of the PIOMAS model, where corrected runs use IceBridge and SIZONet ice thicknesses to correct the initial thickness field. The thin red lines are the ice extent (0.15 ice concentration) lines for each of the corrected ensemble members and the thick red line is the mean for the ensemble. The thick green line is the mean of the ensemble of control runs and the black line is the observed September mean ice extent. From Lindsay et al. (2012)

Processes That Affect Ice Thickness



Measuring Ice Thickness



(adapted from Meier et al., 2014)

Sea Ice Characterization EDR L1RD Requirements

Sea Ice Characterization Requirements from L1RD version 2.9

Note that because the percentage of N/Y ice is, on the annual average, very small, the 70% probability of correct typing of both classes together could be met by simply labeling all ice pixels as “Other Ice”!

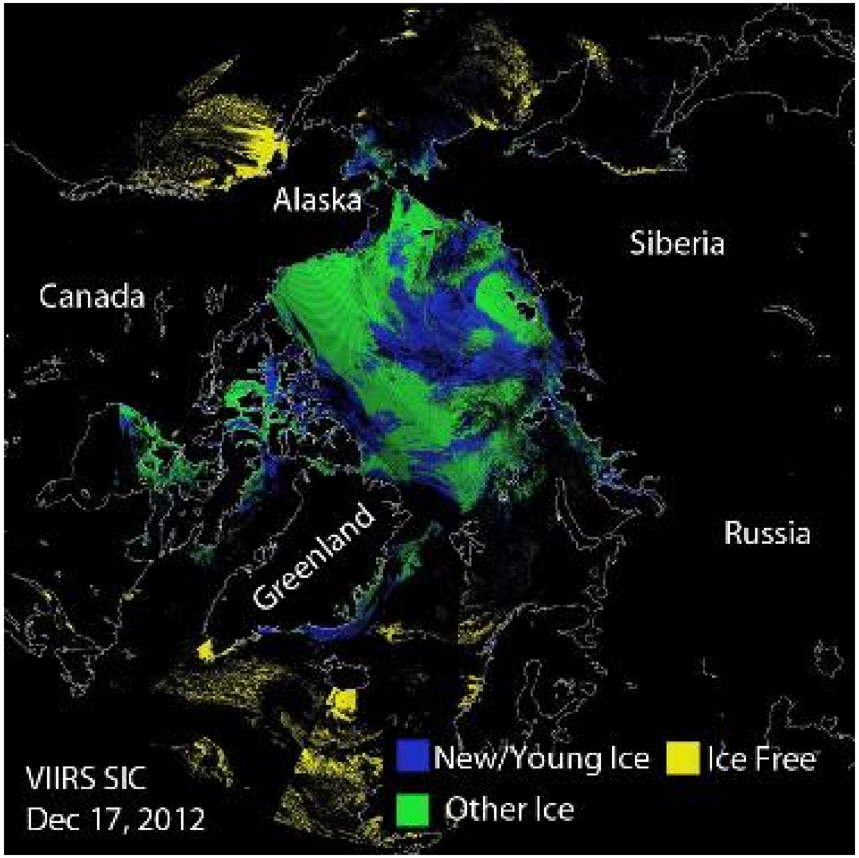
f. Refresh	At least 90% coverage of the global every 24 hours (monthly average)	6 hrs
g. Geographic coverage	All Ice-covered regions of the global ocean	All Ice-covered regions of the global ocean

Notes:
1. VIIRS produces a sea ice concentration IP in clear sky conditions, which is provided as an input to the ice surface temperature calculation

Summary of VIIRS Sea Ice Characterization EDR

- The VIIRS Sea Characterization EDR (Ice Age) consists of ice classifications for *Ice Free*, *New/Young* and *Other Ice* at VIIRS moderate spatial resolution (750m @ nadir), for both day and night, over oceans poleward of 36°N and 50°S latitude.

  - New or Young ice is discriminated from thicker ice (Other Ice) by a threshold ice thickness of 30 cm. Discrimination of New/Young ice from thicker ice is achieved by two algorithms: (1) Energy balance at night and (2) reflectance during the day.
  - Heritage: There is no operational visible/IR heritage. AVHRR research heritage (Comiso and Massom 1994, Yu and Rothrock 1996 and Wang et al. 2010).



Summary of VIIRS Sea Characterization EDR (Ice Age) Algorithm Overview

Reflectance Threshold Branch (Day Region Algorithm)

- Input ice tie point reflectance (I1, I2), VCM IP, AOT IP
- Input granulated NCEP gridded precipitable water, total ozone fields
- Obtain snow depth for each ice thickness bin obtained from climatology modeled snow depth/ice thickness LUT
- Retrieve ice thickness from sea ice reflectance LUT using ice tie point reflectances, modeled snow depth, AOT, precipitable water, and solar and satellite view geometry
- Classify by comparing retrieved ice thickness to 30 cm ice thickness threshold

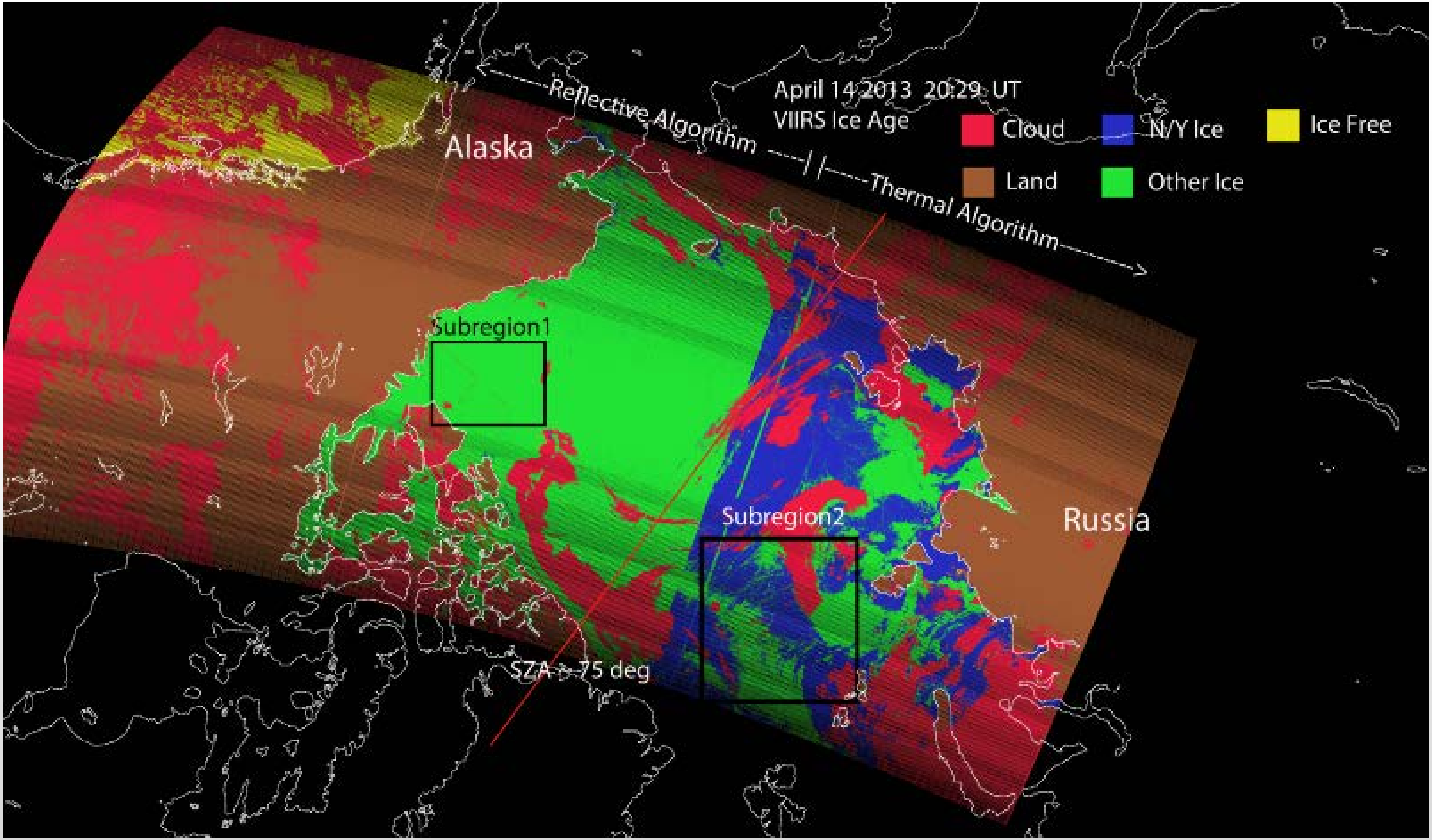
Energy Balance Branch (Terminator and Night Region Algorithm)

- Input Ice Temperature Tie Point IP
- Input granulated NCEP gridded surface fields (surface pressure, surface air temp, specific humidity, etc.)
- Compute snow depth for 30cm ice thickness threshold from heat/energy balance
- Classify by comparing computed and climatology LUT snow accumulation for a 30 cm ice thickness threshold

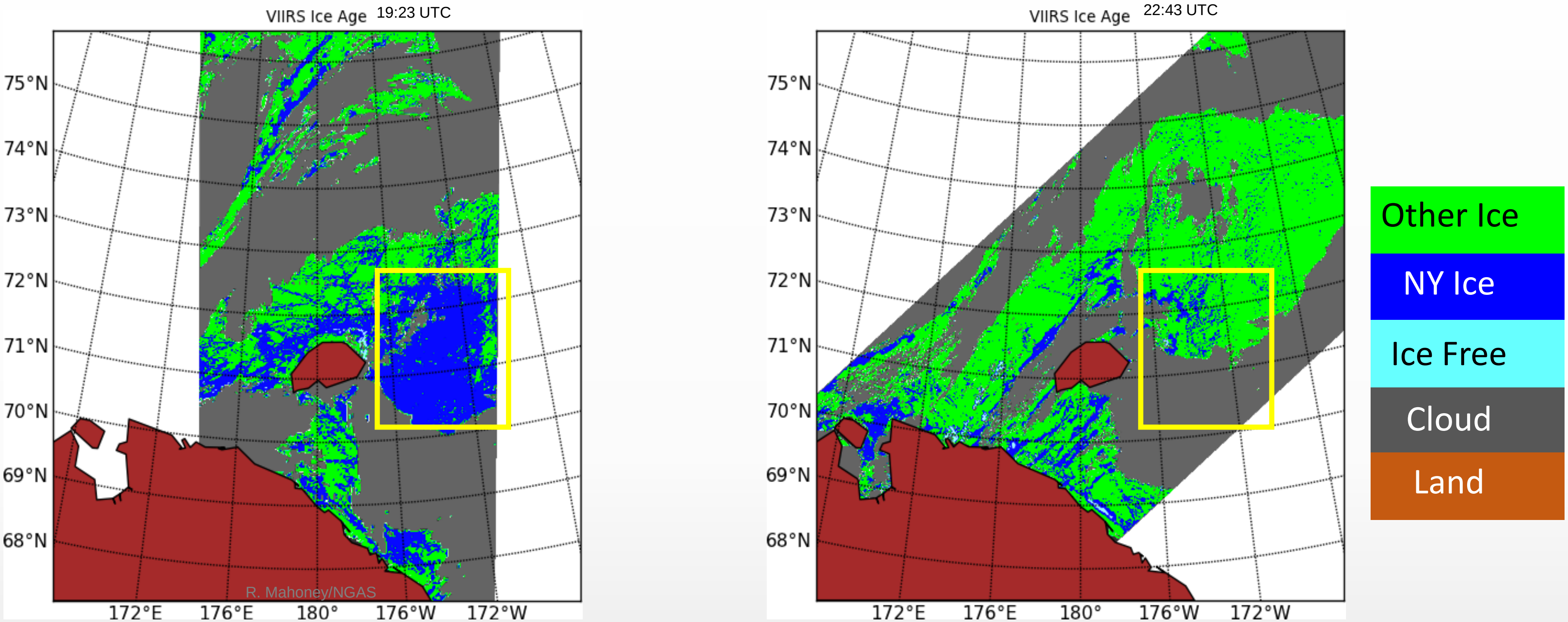
The Snow-Depth-Ice Thickness Climatology LUT contains:

- predicted snow accumulation depths for modeled ice thickness threshold growth times based on monthly climatology surface air temperatures and precipitation rates

Problem: Day-Night Differences



Problem: Orbit-to-Orbit Misclassification of NY and Other Ice



Region near Wrangle Island showed significant amounts of sea ice that were correctly classified as thicker “Other Ice” in 22:43 UTC orbit scene (right) being misclassified as NY in the 19:23 UTC orbit scene (left). The yellow boxed region shows a broad region of misclassified NY ice in the 19:23 scene.

SDR RGBs, ice tie point reflectance, modeled sea ice reflectance, modeled snow accumulation depth, internally computed ice thickness and other inputs were examined and compared in order to determine the cause for the misclassification.

Summary of VIIRS Sea Ice Characterization Status

The Sea Ice Characterization EDR has considerable performance challenges. Misclassification of ice was observed to occur for the following categories of conditions:

- Day regions:
  - bias towards misclassification of Other Ice as NY in regions with 1) large values of climatology snow depth, 2) high satellite view zenith angle and regions with 3) low reflectance due to melting ice and 4) cloud shadows
- Night regions
  - reversals of ice age classification
- Terminator regions
  - frequent, broad misclassification of Other Ice as NY and reversals of classification
  - Ice classification discontinuities are most evident and frequent where the algorithm transitions from the day reflectance based algorithm to the night energy balance based algorithm

Solutions to these problems are illusive, so another approach was pursued: the One-dimensional Thermodynamic Ice Model (OTIM) that was developed for GOES-R.

One-dimensional Thermodynamic Ice Model (OTIM) (Wang et al., 2010)

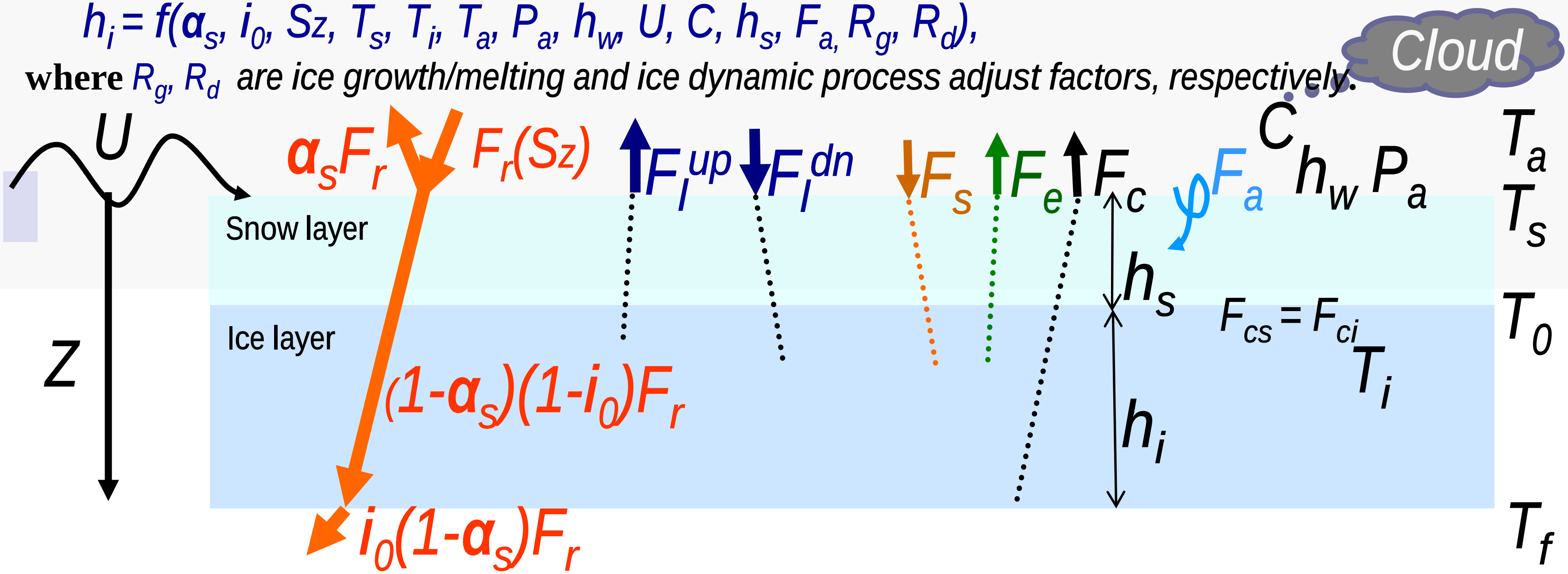
Based on the surface energy budget at thermo-equilibrium state, the fundamental equation is

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

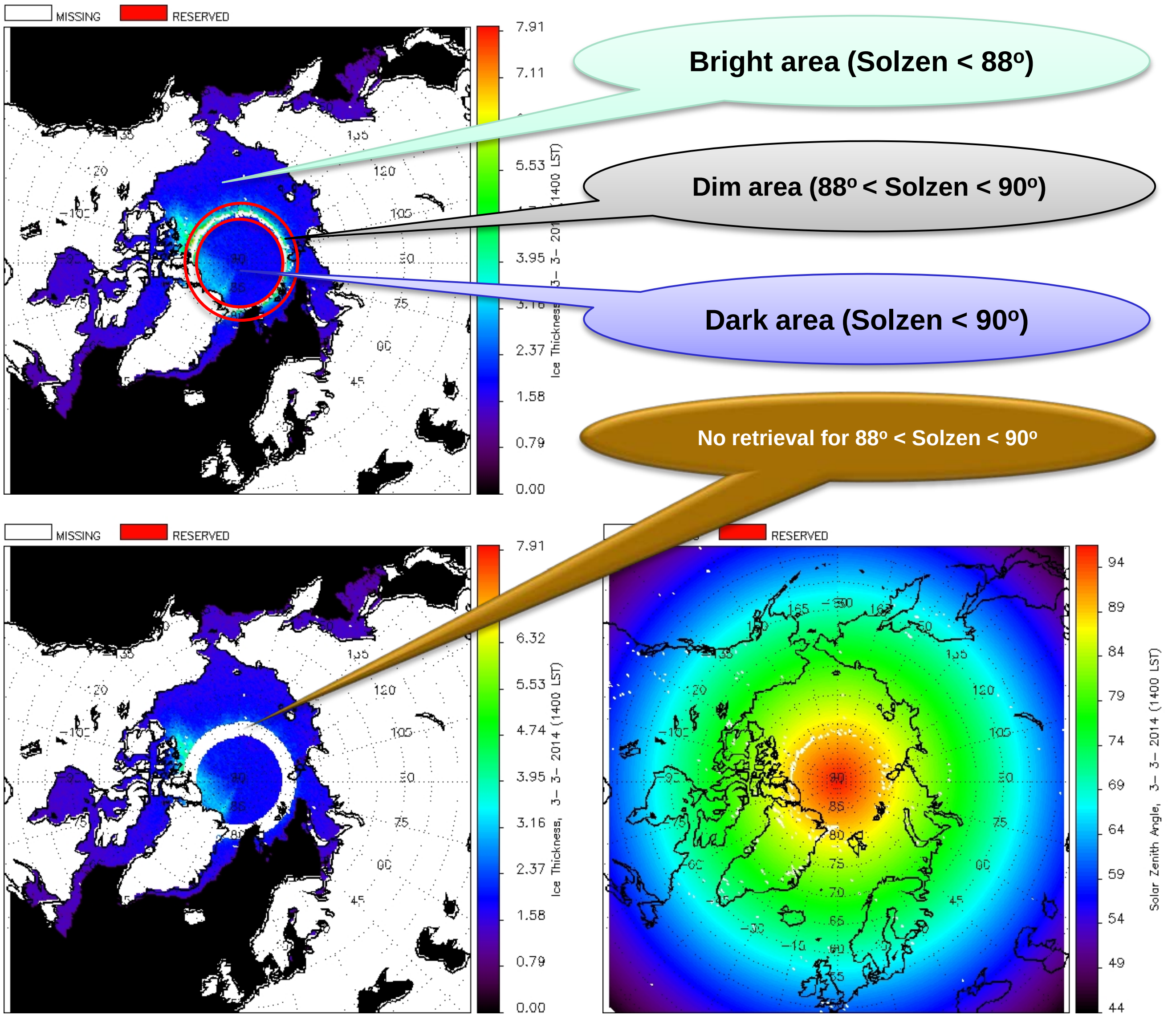
After parameterizations of thermal radiation (F_r, F_l^{up}, F_l^{dn}) and turbulent (sensible & latent) heat (F_s, F_e), ice thickness *hi* becomes a function of 11 model controlling variables plus two factors:

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

where R_g, R_d *are ice growth/melting and ice dynamic process adjust factors, respectively.*



Consistency - OTIM daytime and nighttime algorithms

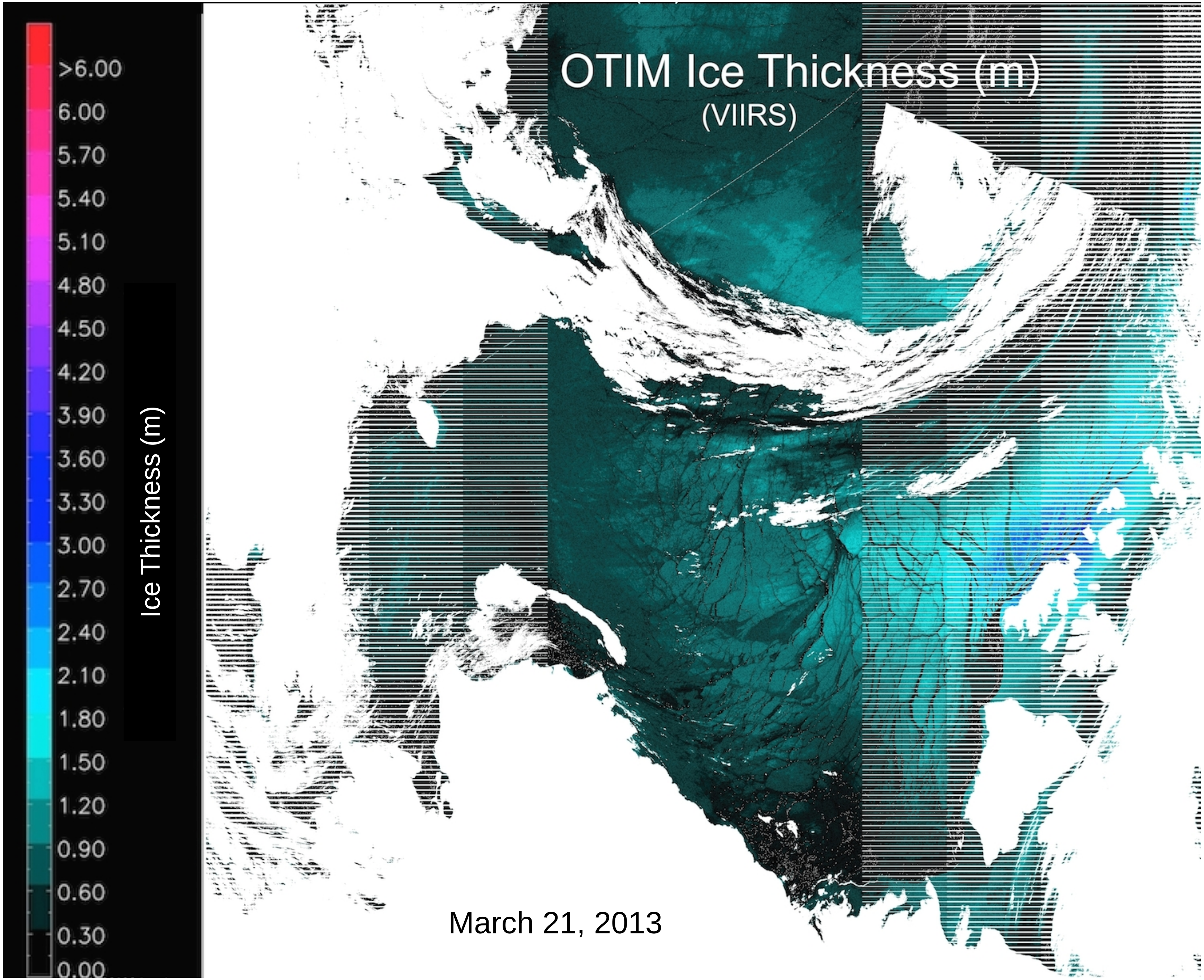


Sea ice thickness on March 3, 2014 at 14:00 LST (white solid ring indicating dim area with solar zenith angle between 88 and 90 degrees)

Solar zenith angle on March 3, 2014 at 14:00 LST

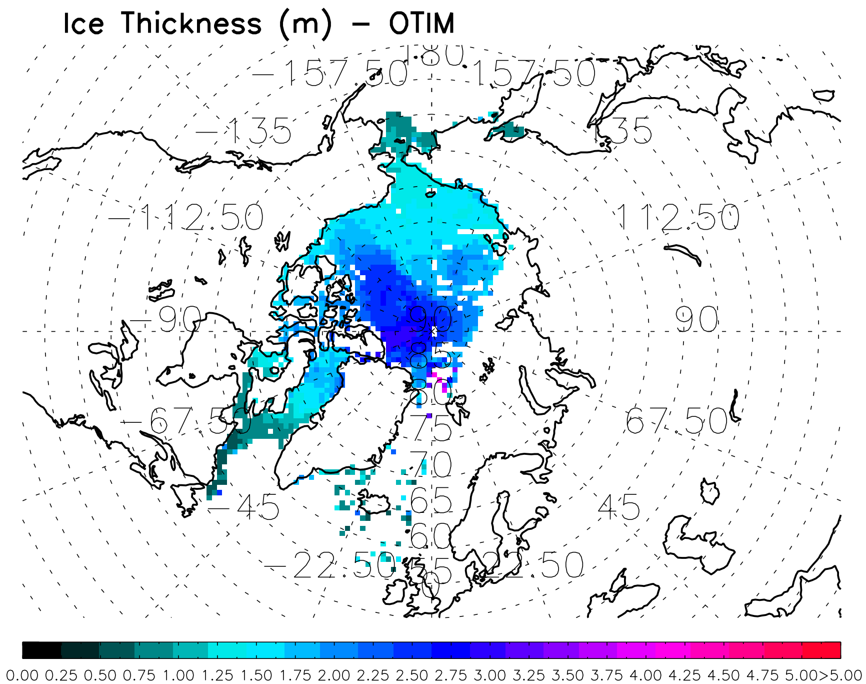
(APP-x 25 km data products)

Though the algorithms in OTIM for retrieving daytime and nighttime ice thickness are different because of solar radiation involved in daytime retrieval, their retrieved ice thickness is very consistent in value except that dim area where solar zenith angle between 88 ~ 90 degrees has poor retrieved ice thickness because of poor cloud and surface albedo retrievals.

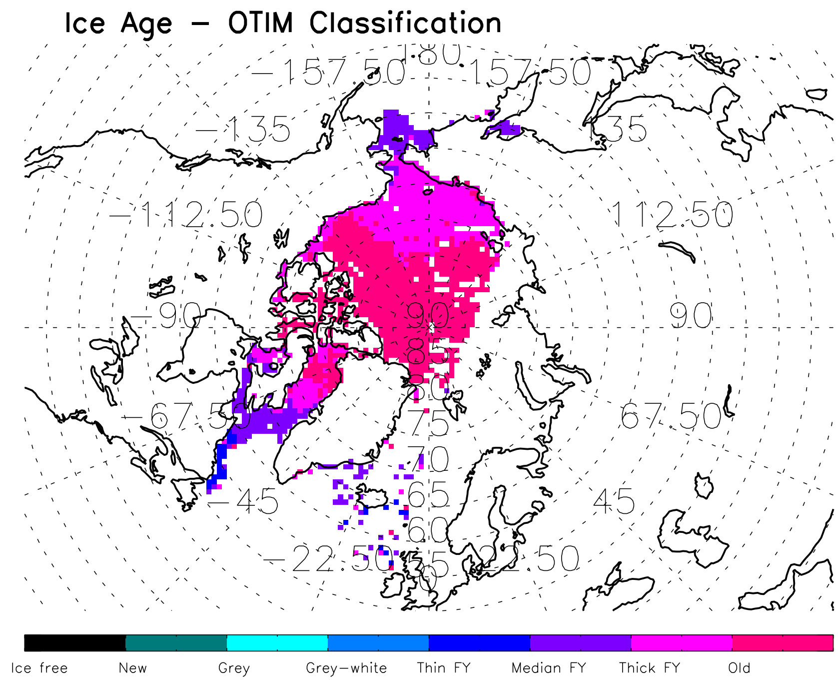

OTIM Ice Thickness (m)
(VIIRS)
Ice Thickness (m)
>6.00
6.00
5.70
5.40
5.10
4.80
4.50
4.20
3.90
3.60
3.30
3.00
2.70
2.40
2.10
1.80
1.50
1.20
0.90
0.60
0.30
0.00
March 21, 2013

Large Scale VIIRS Ice Thickness

Ice Thickness

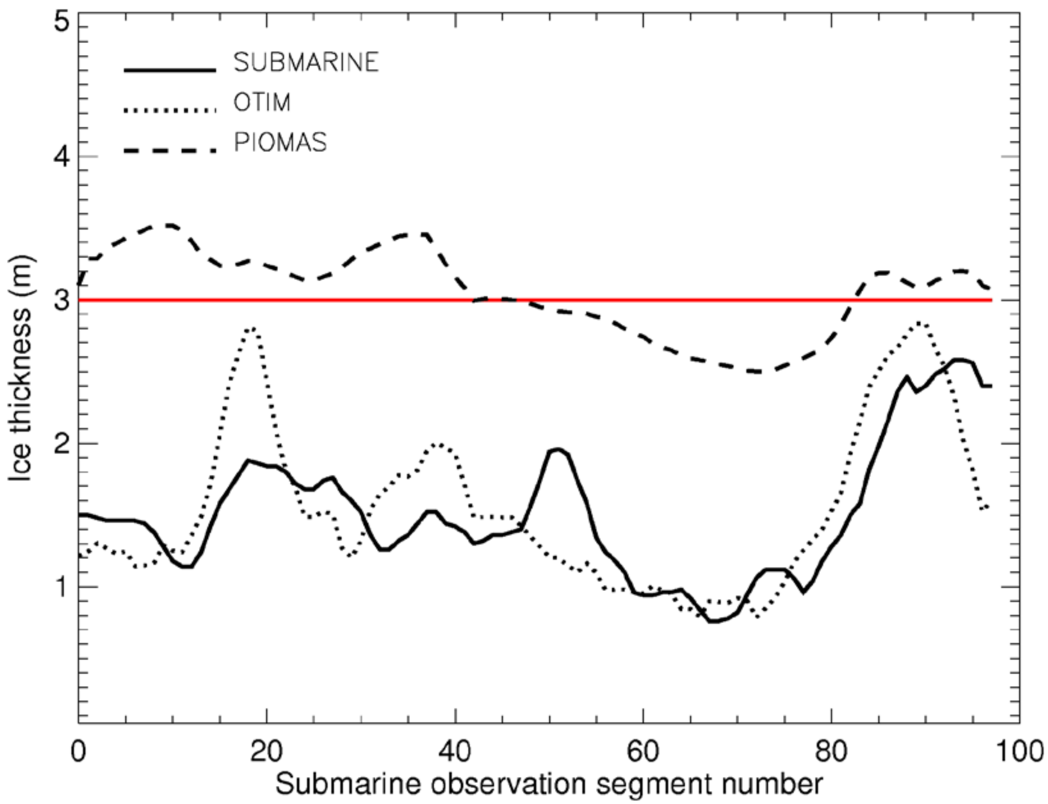


Ice Age



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

Comparison of APP-x and Submarine ULS



Comparisons of ice thickness retrieved by OTIM with APP-x data, measured by submarine, and simulated by PIOMAS alone the submarine track segments.

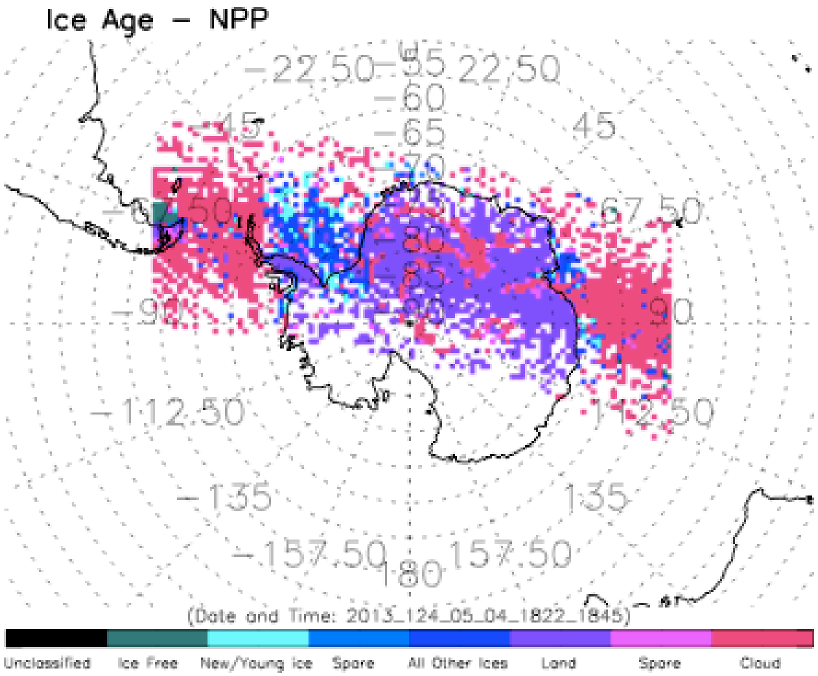
	OTIM	Submarine
Thickness Mean (m)	1.55	1.51
Bias (m)	0.04	
RMS difference (m)	0.52	

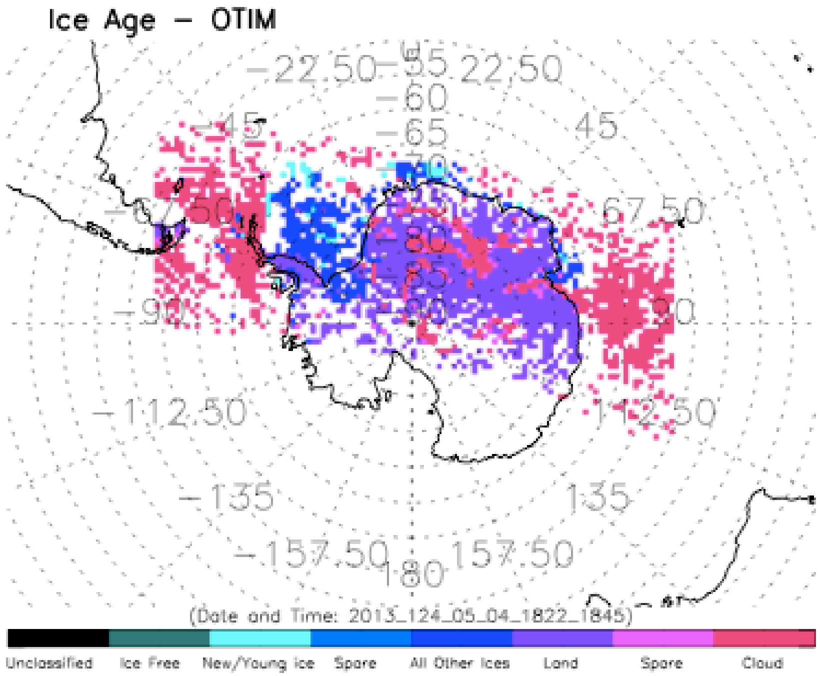
OTIM (w/AVHRR) and Surface Measurements

	OTIM ALERT LT1	OTIM ALERT YLT	OTIM CAMBRIDGE BAY YCB	OTIM CORAL HARBOUR YZS	OTIM EUREKA WEU	OTIM HALL BEACH YUX	OTIM RESOLUTE YRB	OTIM YELLOWKNIFE YZF
Thickness Mean (m)	1.52 1.09	1.59 1.09	1.51 1.44	1.04 1.20	1.59 1.22	1.18 1.41	1.63 1.38	0.95 0.98
Bias Mean (m)	0.43	0.50	0.07	-0.16	0.37	-0.23	0.25	-0.03
Bias Standard Deviation (m)	0.52	0.39	0.97	0.62	0.52	0.68	0.50	0.58
OTIM Ice Age	Ice free water, new/fresh, grey, grey-white, first year thin, first year medium, first year thick, and multi-year ice.							
EDR Requirements	Distinguish between ice free, new/fresh ice, and all other ice.							

Ice Thickness and Age
IDPS and NDE (OTIM) Comparison

Sea ice age categories from VIIRS sea ice age classification (left) and OTIM ice thickness converted to the same categories (right) on May 4, 2013 over the Arctic.





Ice Thickness and Age
IDPS and NDE (OTIM) Comparison

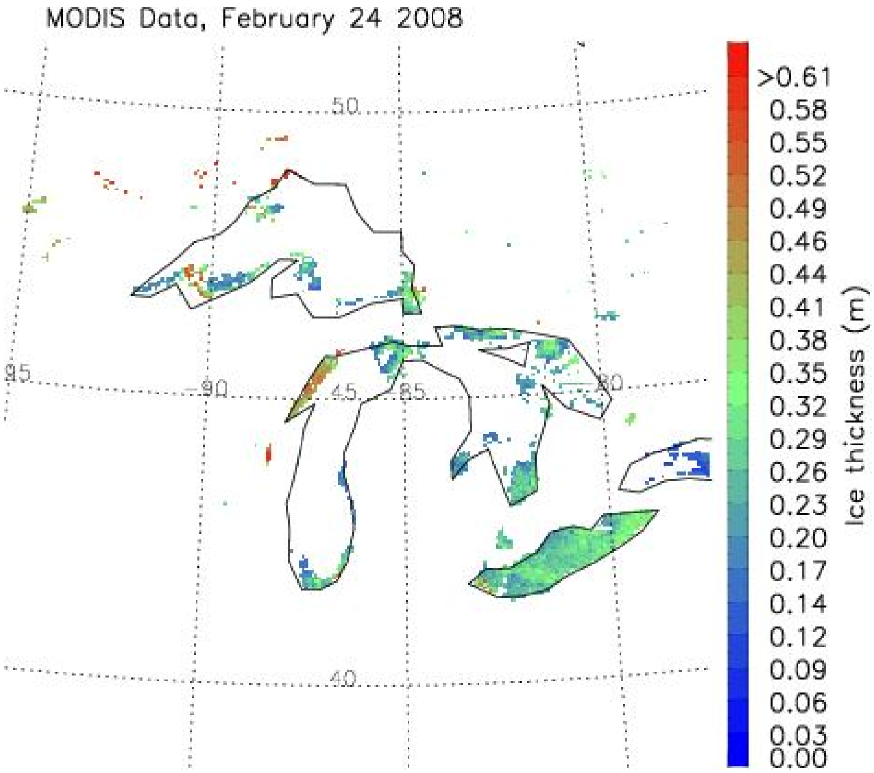
Statistics for figure on previous slide:

Percentage in each ice age category from VIIRS and OTIM for May 4, 2013 case.

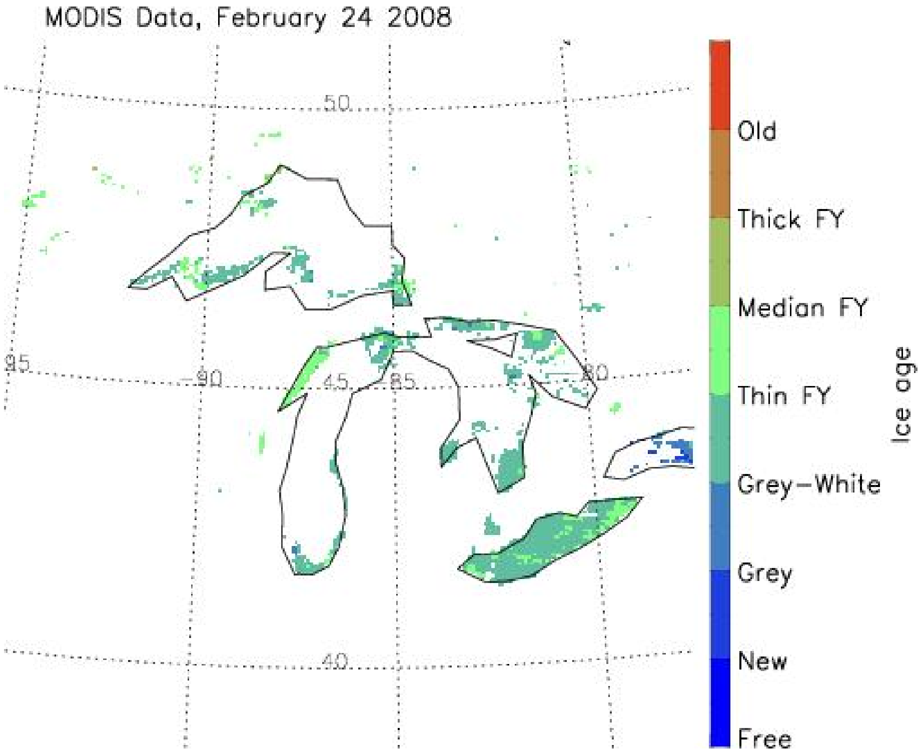
Categories	VIIRS ice age	OTIM ice age	Difference (VIIRS-OTIM)
Day and night time:			
Ice free	13	24	-11
New/Young ice	52	9	43
Other ice	35	67	-32
Daytime:			
Ice free	27	50	-23
New/Young ice	53	3	50
Other ice	20	47	-27
Nighttime:			
Ice free	10	20	-10
New/Young ice	52	10	42
Other ice	38	70	-32

Ice Thickness and Age: Great Lakes!

Ice Thickness



Ice Age



Estimated ice thickness (left) and ice age categories (right) based on MODIS data on February 24, 2008.

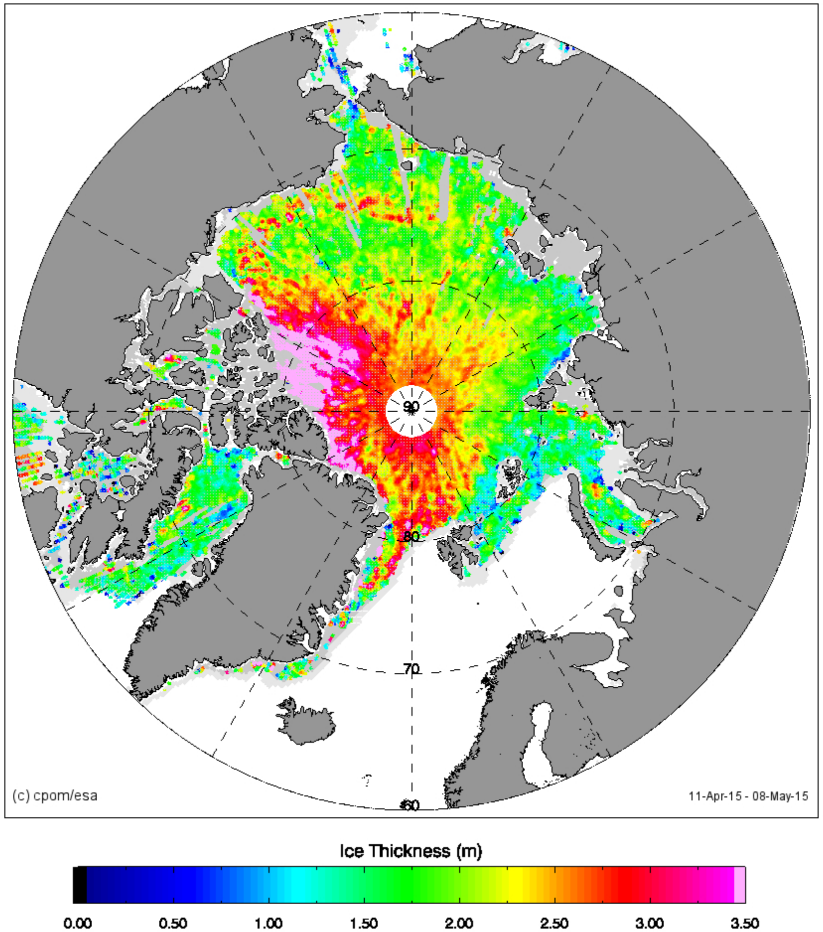
Satellite-Derived Ice Thickness Products

It is now possible to estimate ice thickness from space using a variety of techniques:

- **The One-dimensional Thermodynamic Ice Model (OTIM) is an energy budget approach for estimating sea and lake ice thickness with visible, near-infrared, and infrared satellite data from sensors such as the Advanced Very High Resolution Radiometer (AVHRR), the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Visible Infrared Imaging Radiometer Suite (VIIRS) – APP-x and MPP-x (*Wang et al., 2010*).**
- **Laser and radar altimeter data from the ICESat and CryoSat-2 satellites estimate ice thickness from ice elevation (freeboard) – ICESat, CryoSat-2, and IceBridge (*Kwok et al., 2009; Laxon et al., 2013; Kurtz et al., 2013).***
- **Another method employs low-frequency passive microwave data from the Soil Moisture and Ocean Salinity (SMOS) mission (*Tian-Kunze et al., 2014*).**
- **Arctic sea ice thickness has also been modeled with Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) (*Zhang and Rothrock, 2003*).**

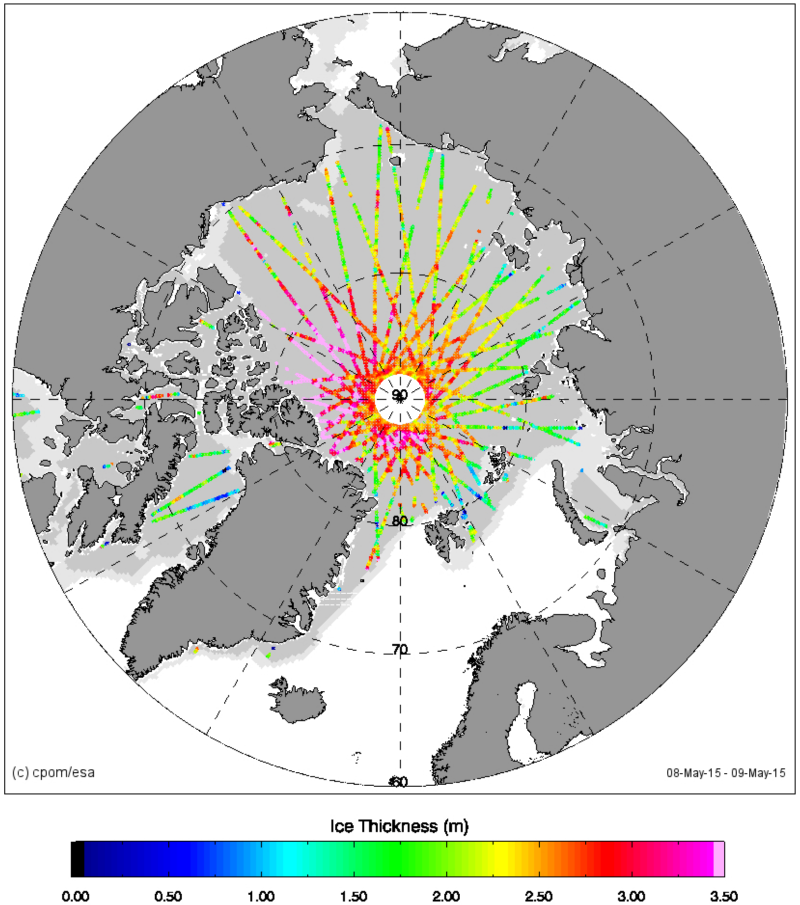
Thanks to: Ron Kwok, Jinlun Zhang, the National Snow and Ice Data Center (NSIDC), the Alfred Wegener Institute, and the University of Hamburg for providing sea ice thickness data from ICESat, PIOMAS, IceBridge, CryoSat-2, and SMOS.

CryoSat-2 Sea Ice Thickness (ESA)



Left: 28-day composite

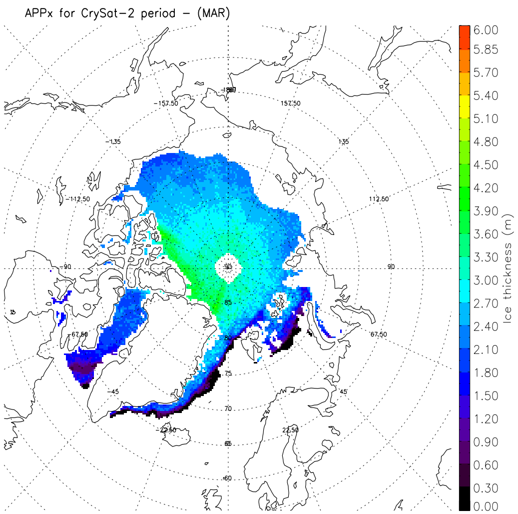
Below: 2-day composite



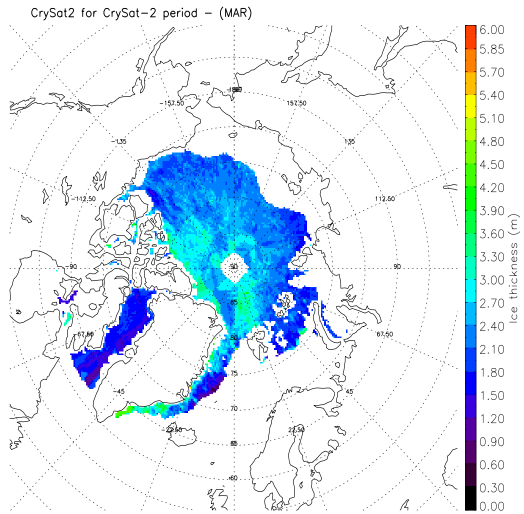
Intercomparison for CryoSat-2 Period

(01/2011 - 03/2013, March)

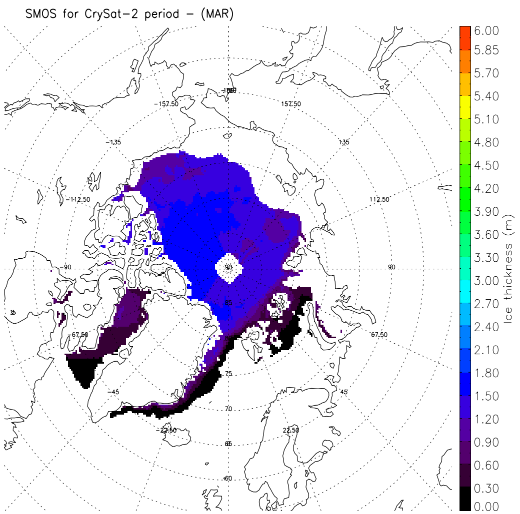
APP-x



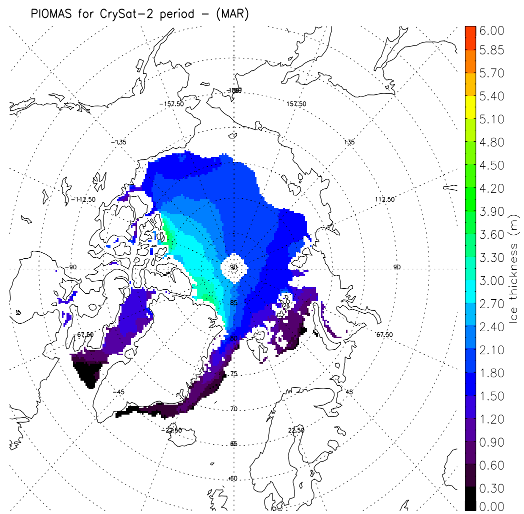
CryoSat-2



SMOS



PIOMAS



APP-x - PIOMAS: Bias=0.51 m

CryoSat-2 – PIOMAS: Bias=0.57 m

SMOS – PIOMAS: Bias=-0.43m