

The quest for basin-scale estimates of sea ice thickness

ICESat



CryoSat



JPL

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7th ESA Earth Observation Summer School
ESRIN, Frascati, Italy
4-14 August 2014



QuikScat Ice Cover (Nov)

- Measurements of ice thickness
 - Submarine/other techniques
 - Satellites (radars and lidars)
- Arctic ice thickness and volume - Observations

Mean winter Ice Thickness: ~2.5-3 m

Winter Snow Thickness ~10-30 cm



Envisat

- Multi-year ice
- First year ice
- Open Water

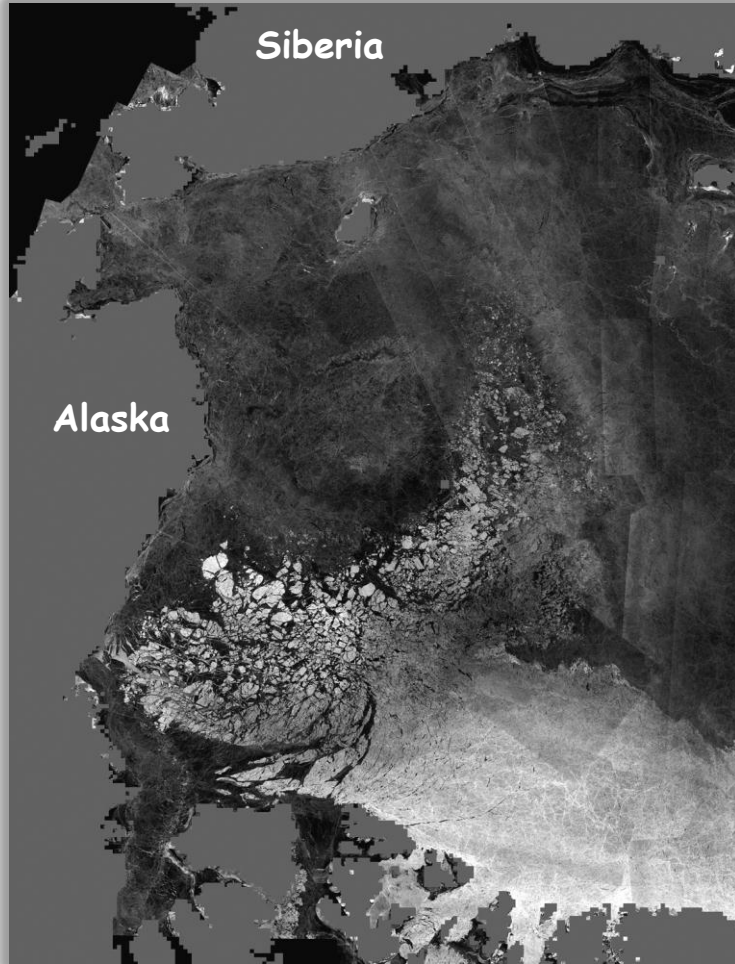
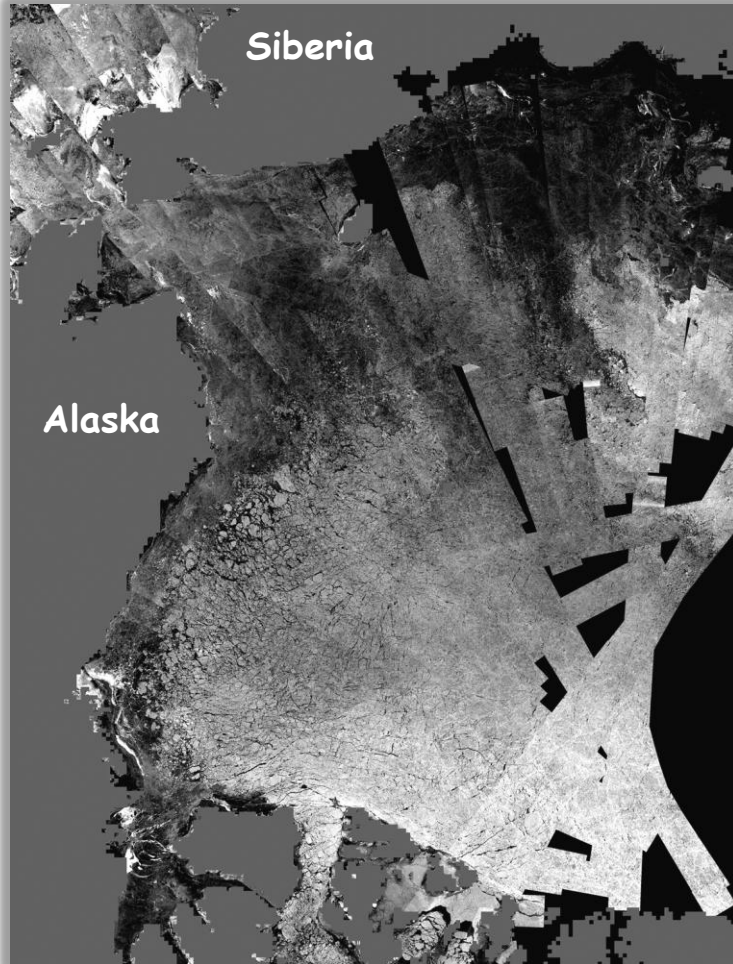
RADARSAT-1



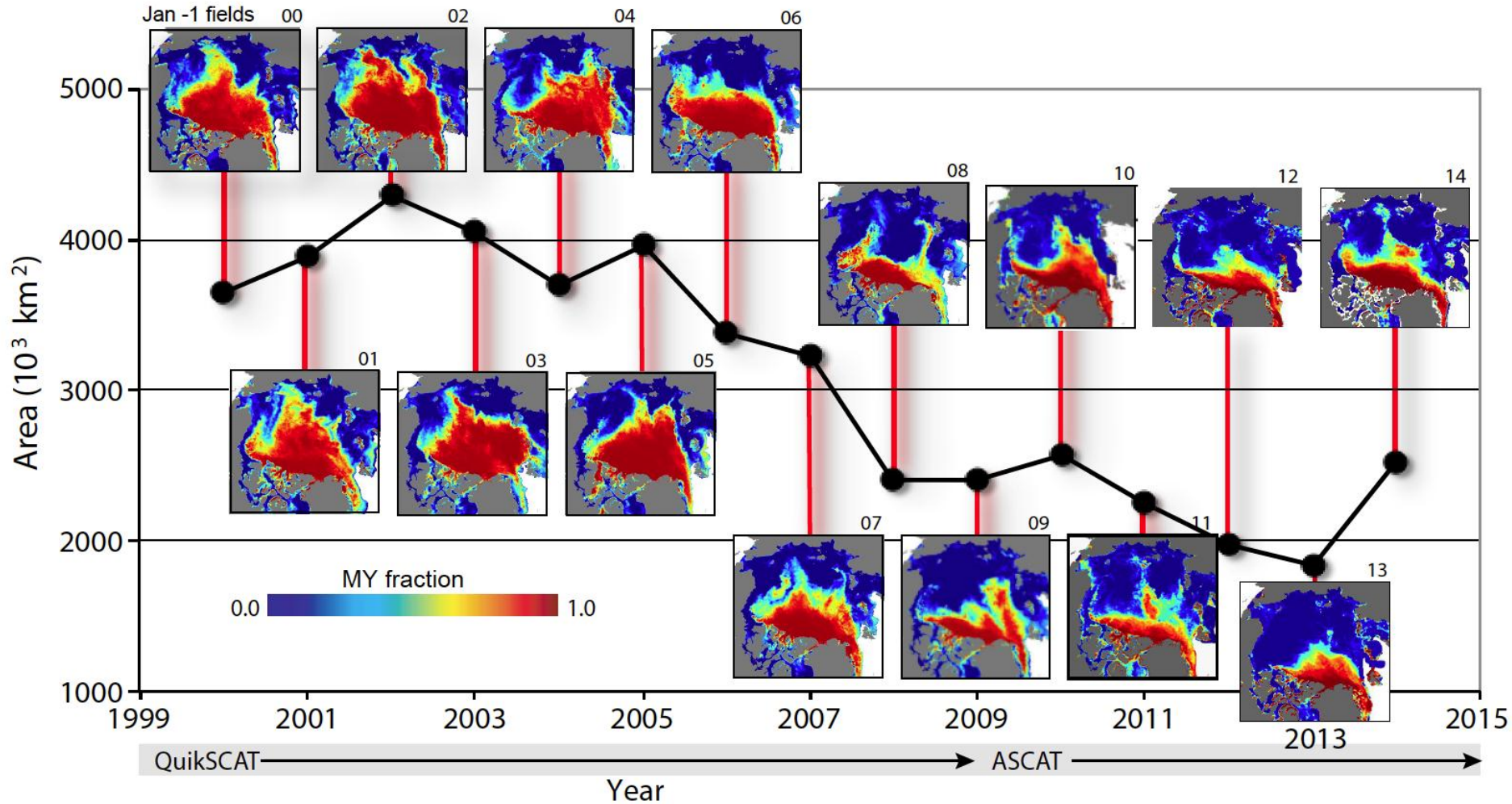
Feb 1993
ERS



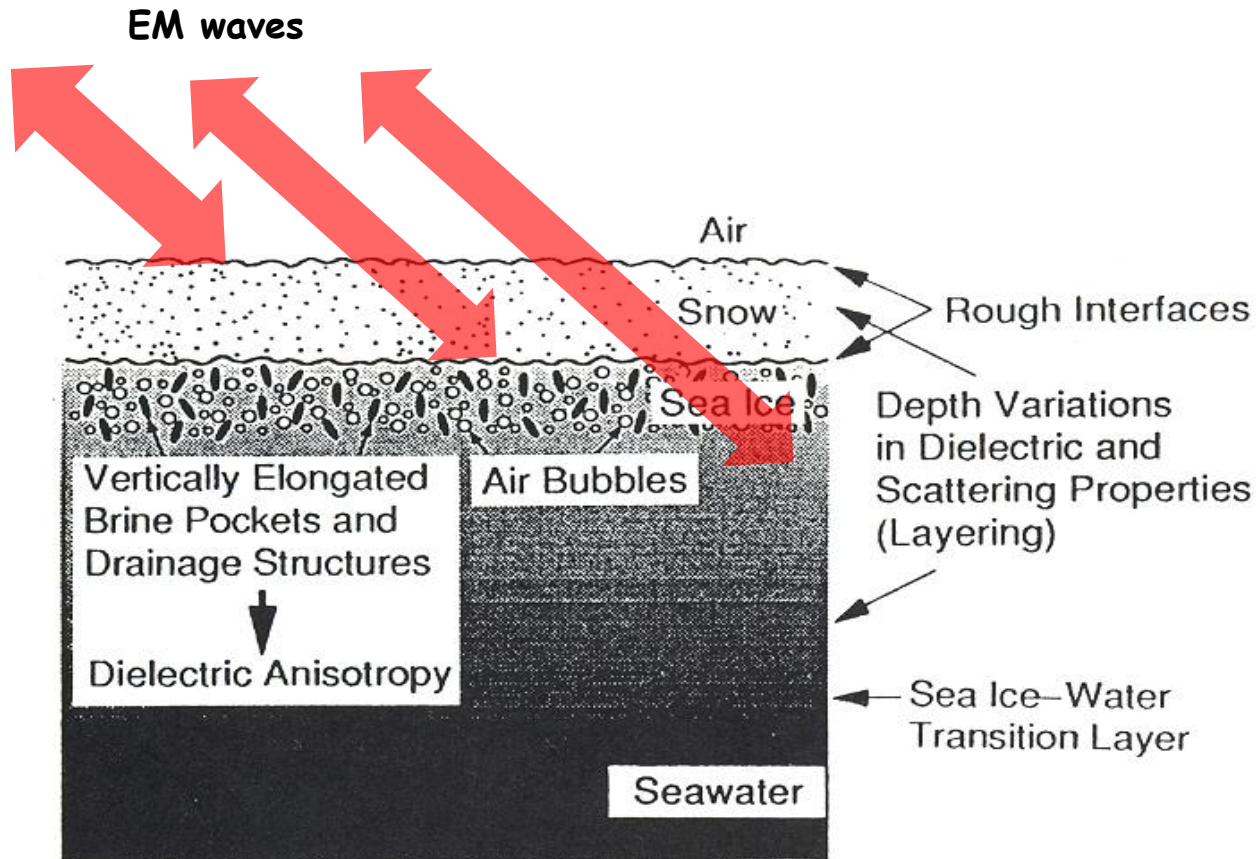
Feb 2008
RADARSAT



On the image, the thick multiyear ice is bright; the thinner first year ice is dark. The figure shows the great reduction in multiyear sea ice over a 15 year period. Alaska is to the upper left.



Why is older ice brighter? Scattering from different sea ice types



Layered random medium

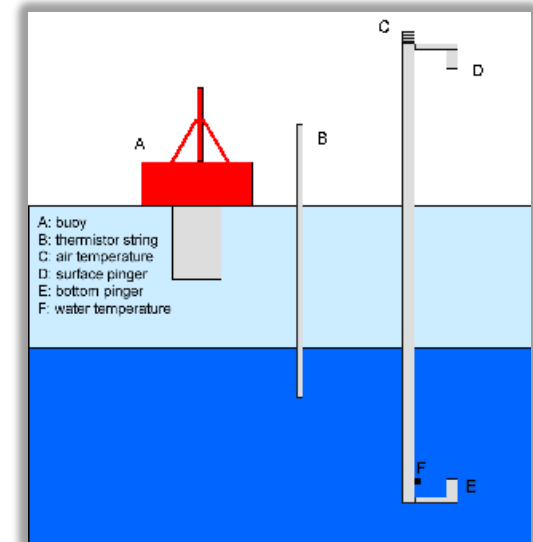
An aerial photograph of a vast, flat, wetland landscape. The terrain is a mosaic of light-colored, irregularly shaped water bodies and darker, textured mudflats. The water bodies vary in size and shape, some being small ponds and others larger, interconnected channels. The overall appearance is that of a complex, interconnected network of water and land. The text "Observational Technologies" is overlaid in the center of the image.

Observational Technologies



EM Pod

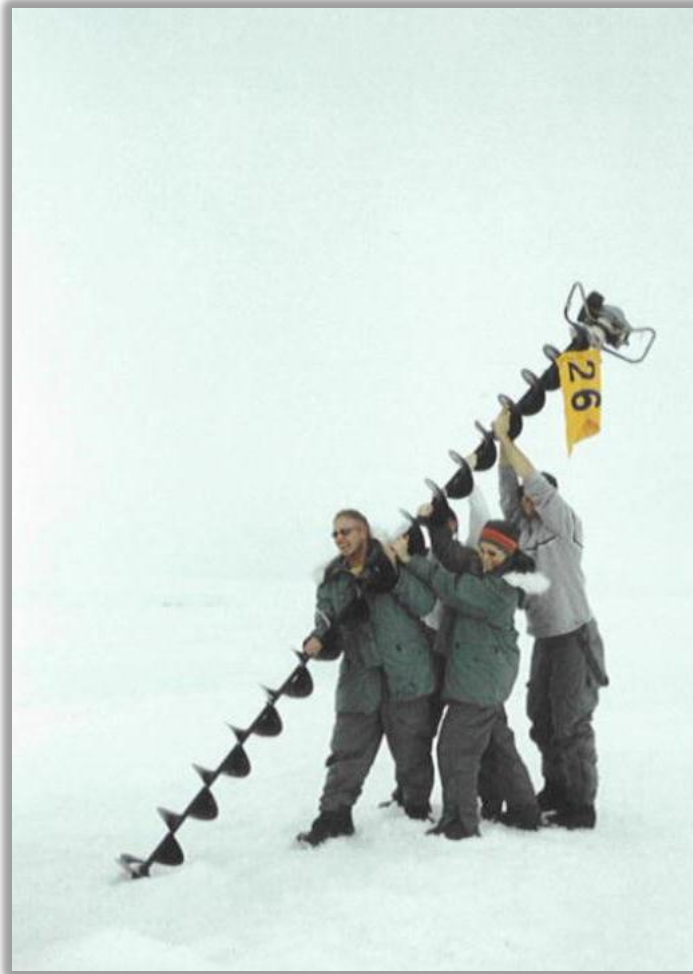
- At/above the surface
 - Coring and Drilling
 - EM induction
 - Ice Mass Balance Buoys
 - Wide-band ice penetrating radar
 - Airborne lidar or radar profilers for freeboard
- Below the surface
 - Moored upward looking sonars
 - Submarine sonars



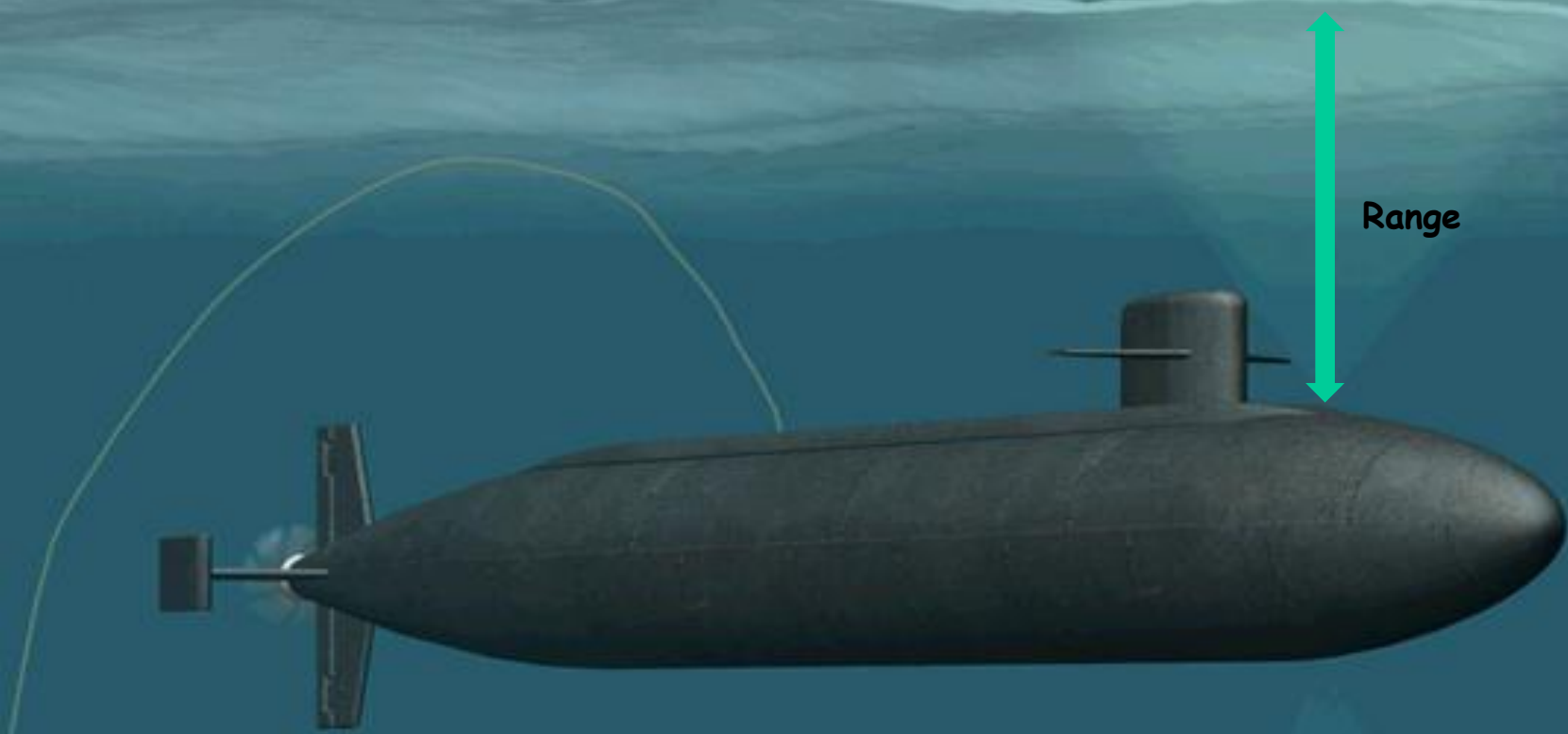
Ice Mass Balance Buoy

Sea Ice Coring-

Not the way to get a basin-scale picture
of the time-varying thickness field!



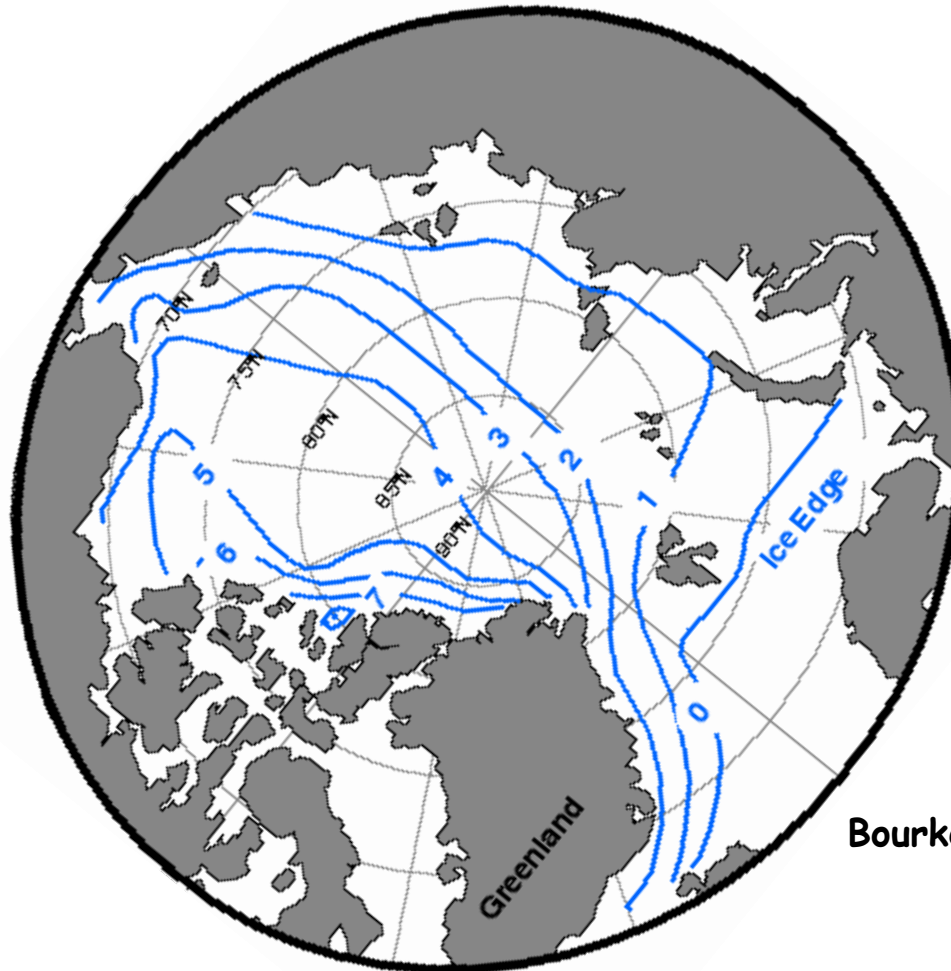
Ice Draft from submarine sonars



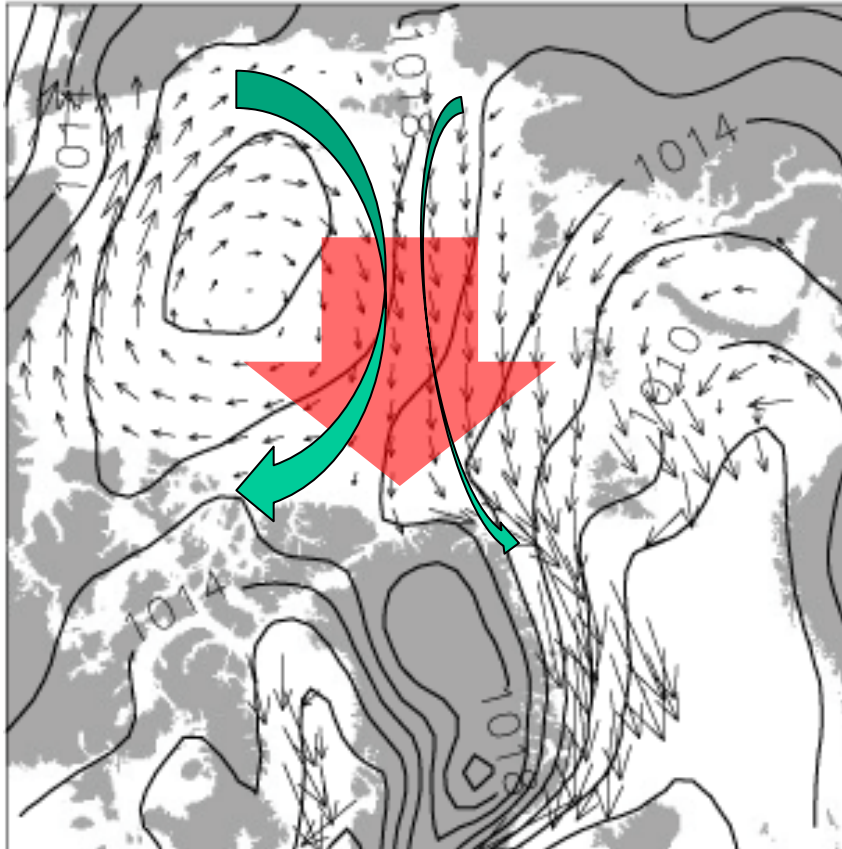
Range

SCICEX (Scientific Ice Expeditions)

Rough contour of Arctic ice draft from submarines



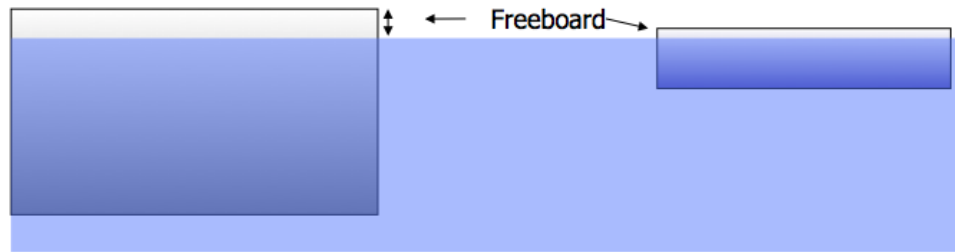
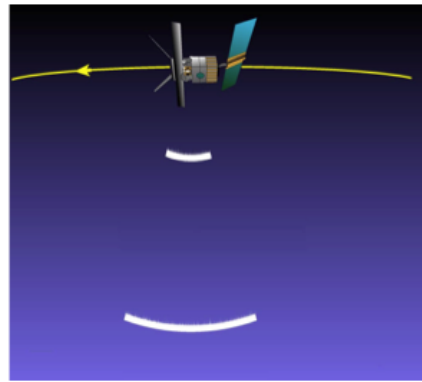
Bourke and McLaren (1992)



**Convergence north of
Ellesmere and Greenland**

Estimates are from Satellite Altimetry

$$h = \frac{ct}{2}$$



Measurement of freeboard from Space (Radar)

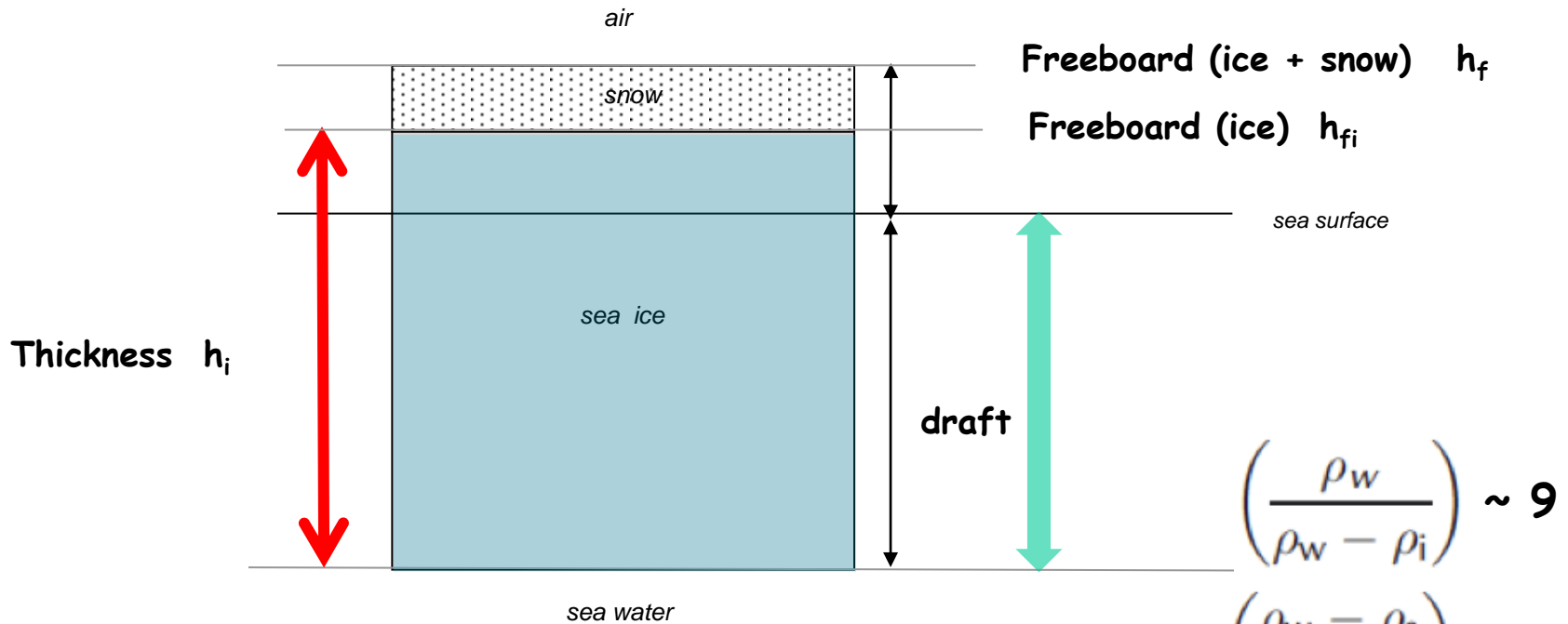


Ice Freeboard

Measurement of freeboard from Space (Lidar)



Total Freeboard



$$\left(\frac{\rho_w}{\rho_w - \rho_i} \right) \sim 9$$

$$\left(\frac{\rho_w - \rho_s}{\rho_w - \rho_i} \right) \sim 6$$

$$\left(\frac{\rho_s}{\rho_w - \rho_i} \right) \sim 3$$

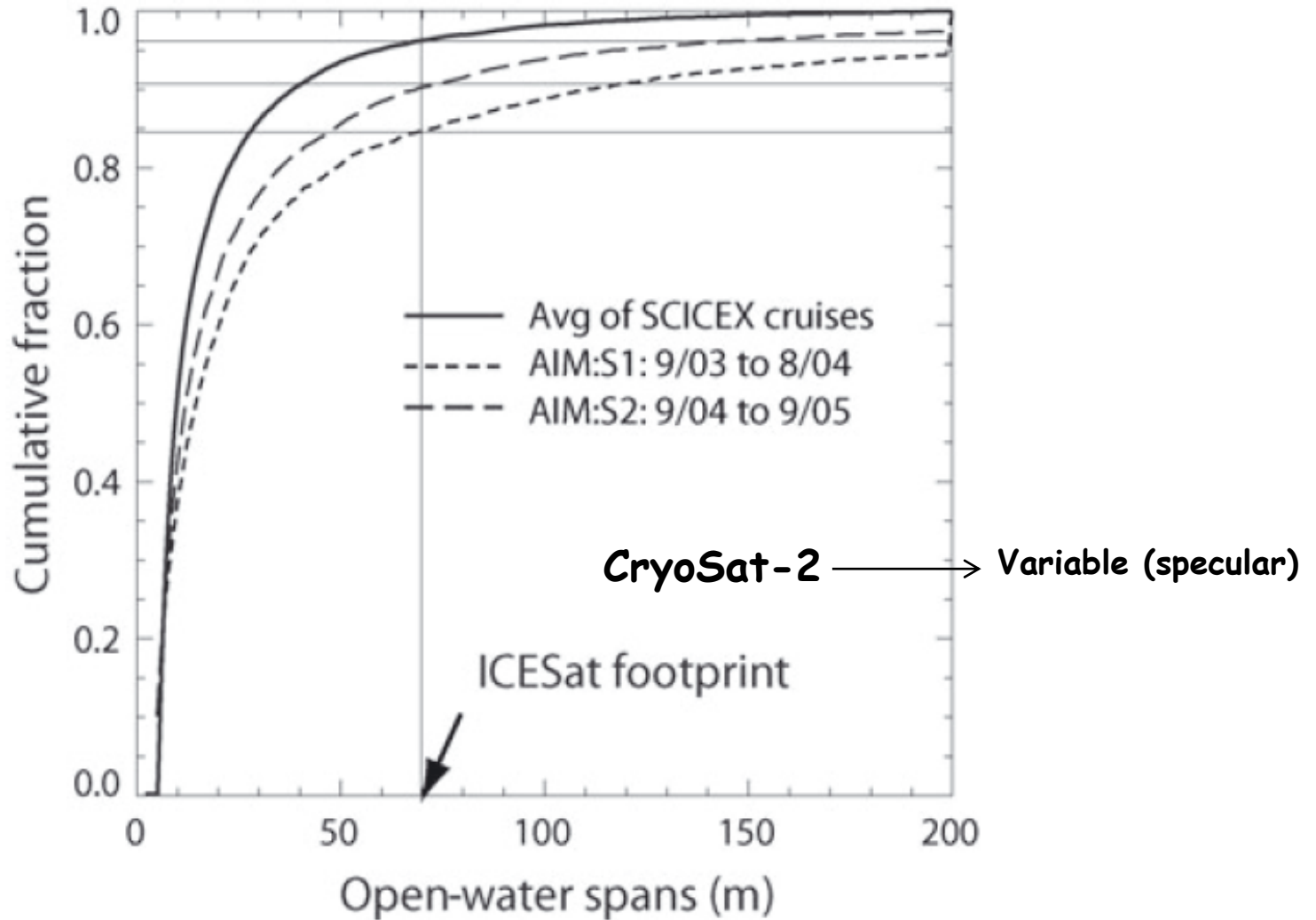
Isostatic Equilibrium

$$h_i = \left(\frac{\rho_w}{\rho_w - \rho_i} \right) h_f - \left(\frac{\rho_w - \rho_s}{\rho_w - \rho_i} \right) h_{fs} \quad (\text{lidar})$$

$$h_i = \left(\frac{\rho_w}{\rho_w - \rho_i} \right) h_{fi} + \left(\frac{\rho_s}{\rho_w - \rho_i} \right) h_{fs} \quad (\text{radar})$$

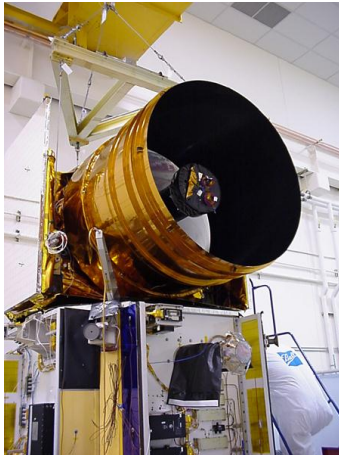


- Assumptions:
 - Isostatic equilibrium
 - Surface penetration
- Measurement (from altimeter)
 - Sea surface reference (need to resolve leads)
$$h_{ssh}(x, t) = h_g(x) + h_a(x, t) + h_T(x, t) + h_d(x, t) + O^2.$$
 - Elevation
 - Water density
- External input:
 - Snow loading (depth and density)



ICESat





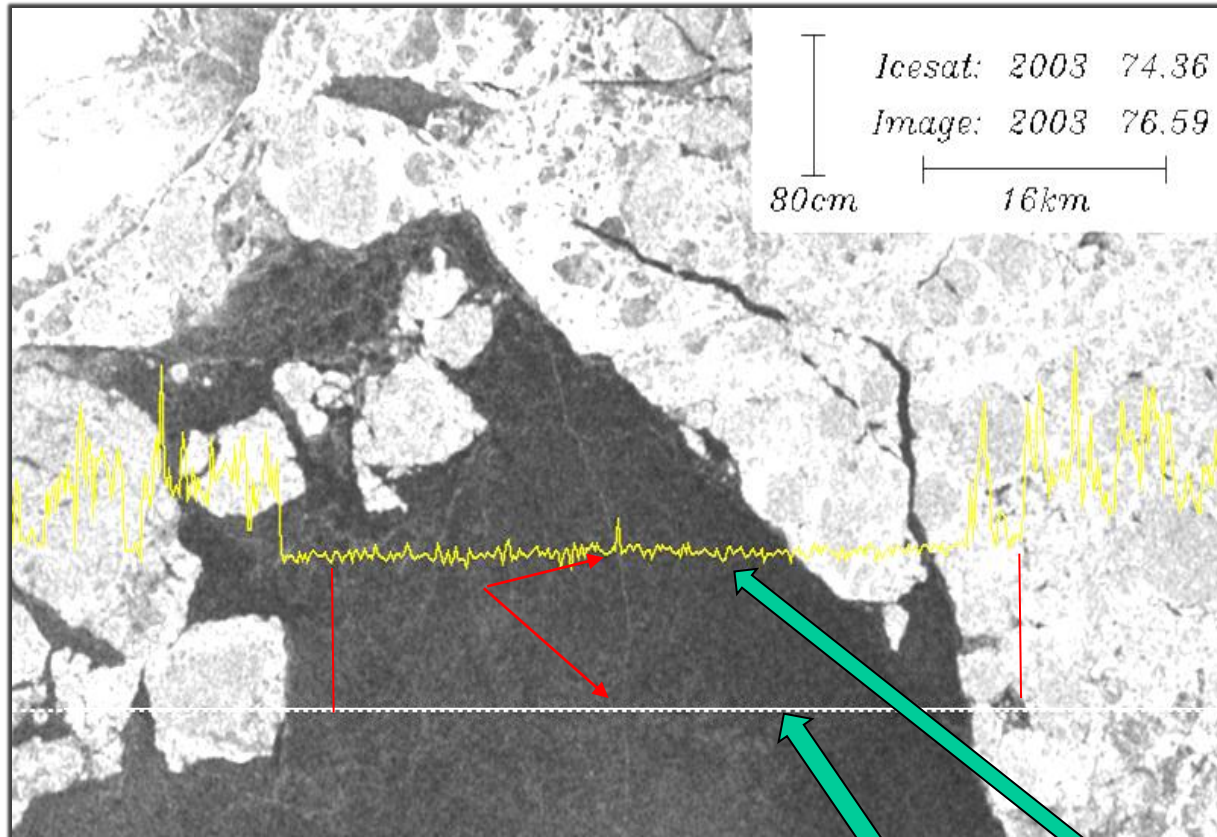
- Number of Lasers: 3 sets (at 1064 nm and 532 nm)
- Firing rate: 40 Hz (70 m on the ground; separation of ~170 m)
- Pulse width: 6 ns
- Telescope: 100 cm
- Digitizer rate: 1 ns
- Laser divergence angle (beam width: 70-110 urad)
- Predicted accuracy of surface elevation: 15 cm



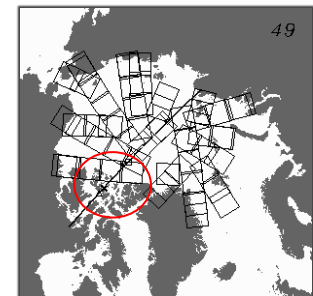
- ICESat
 - Inclination: 94 deg
 - Altitude: 600 km
 - Launched: Jan 2003
- Status:
 - Mission completion: 2009

Lidar Precision

Reflectance used for ice-water discrimination



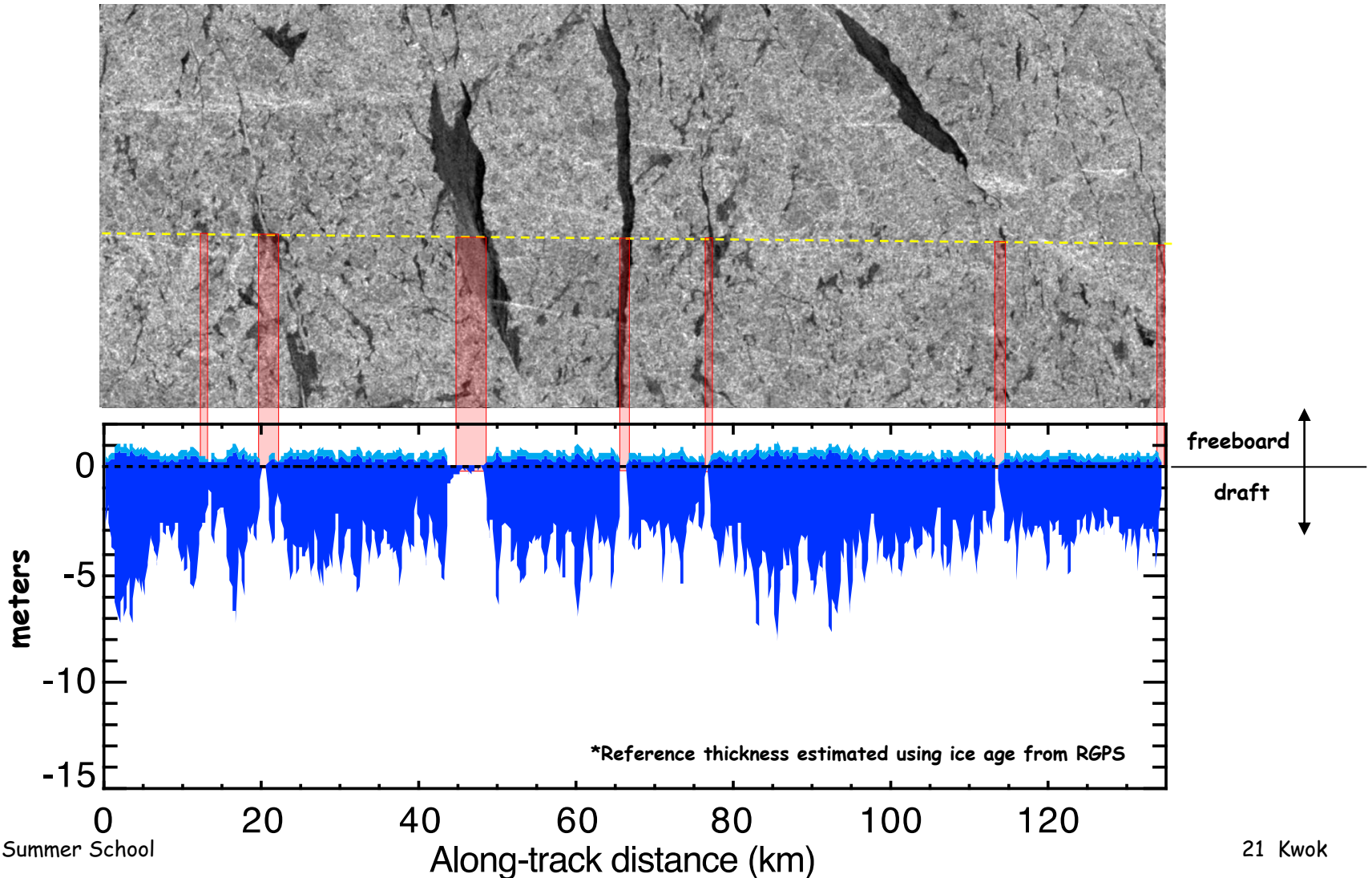
- At 10 km -
 - ~1.5 - 2 cm

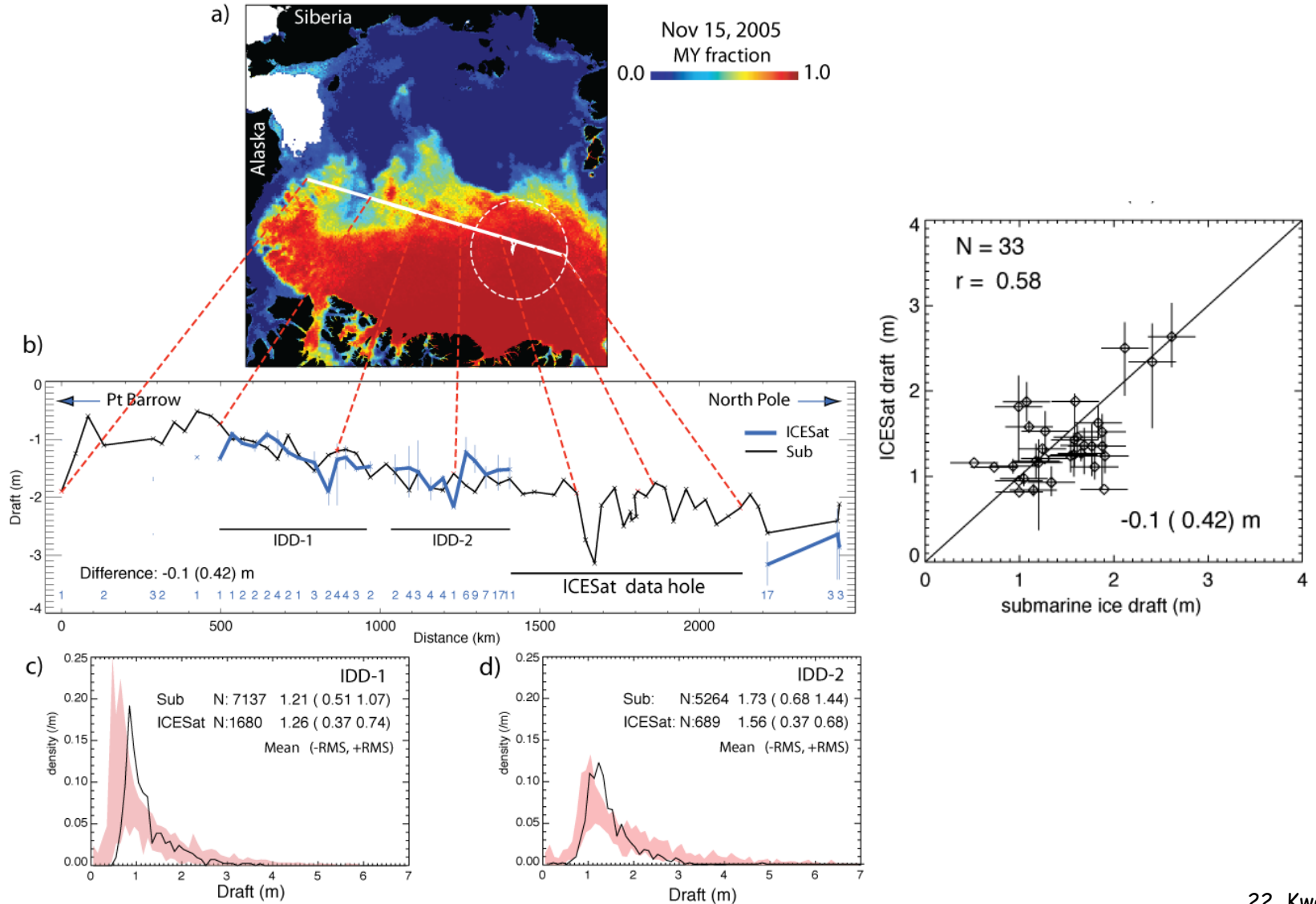


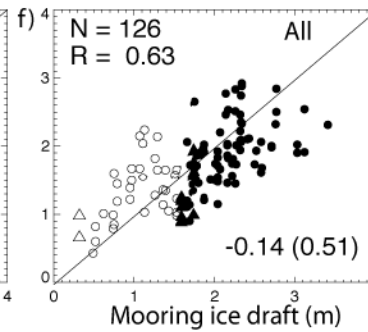
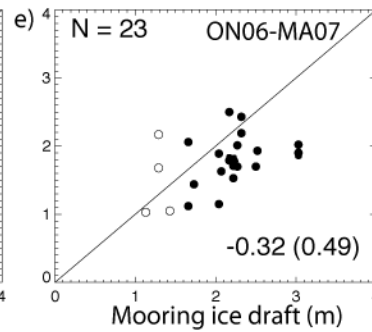
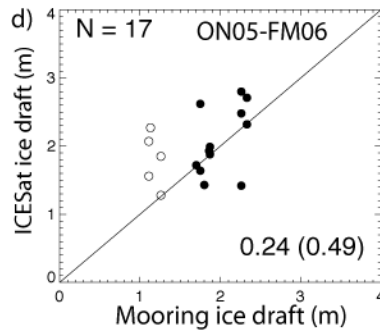
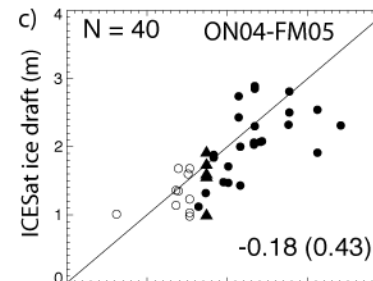
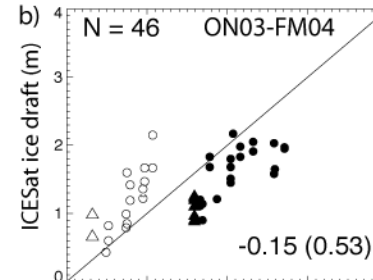
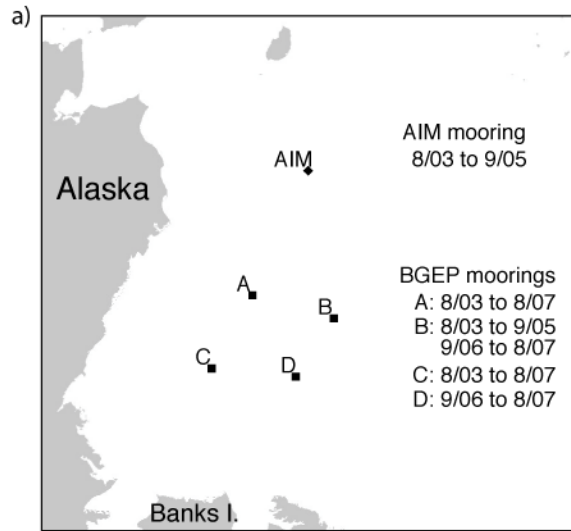
ICESat Elevation Profile

ICESat Track

ICESat track on RADARSAT image

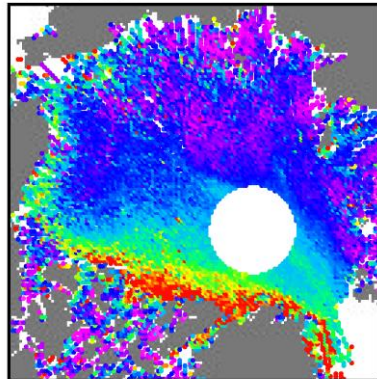




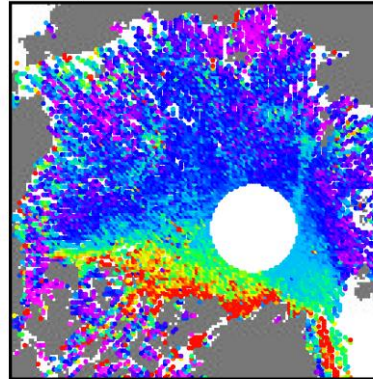


ICESat Thickness Estimates

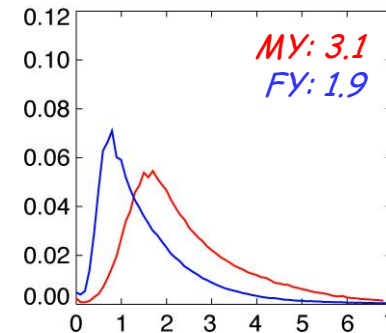
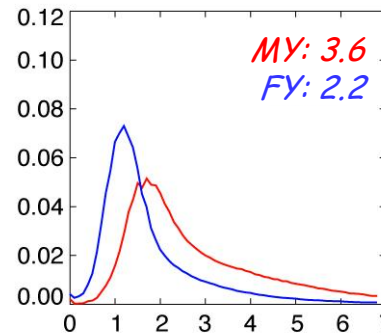
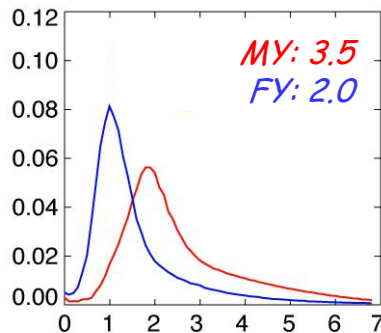
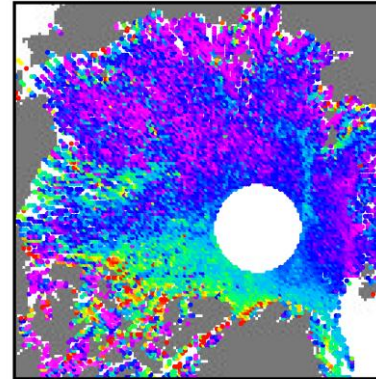
Feb-Mar 06



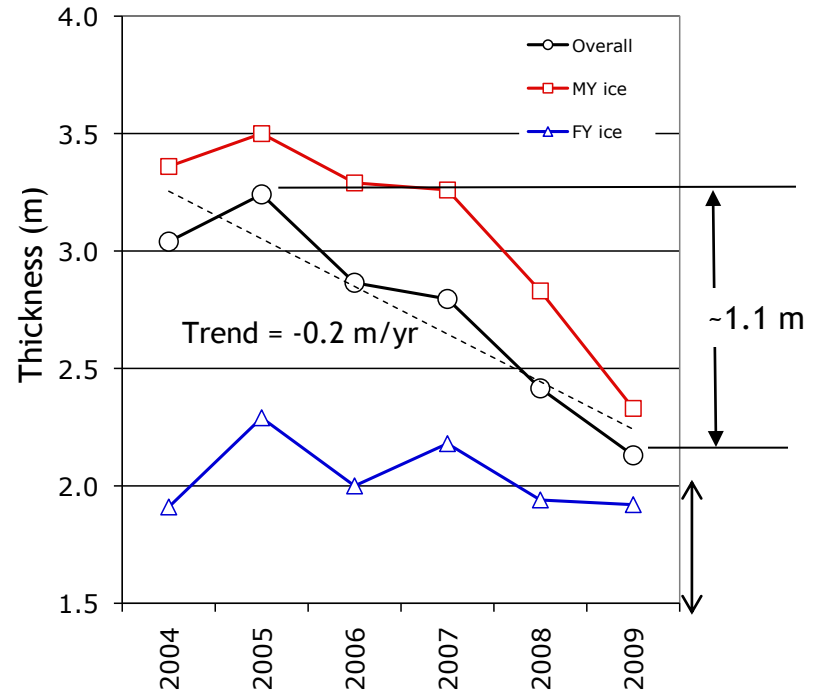
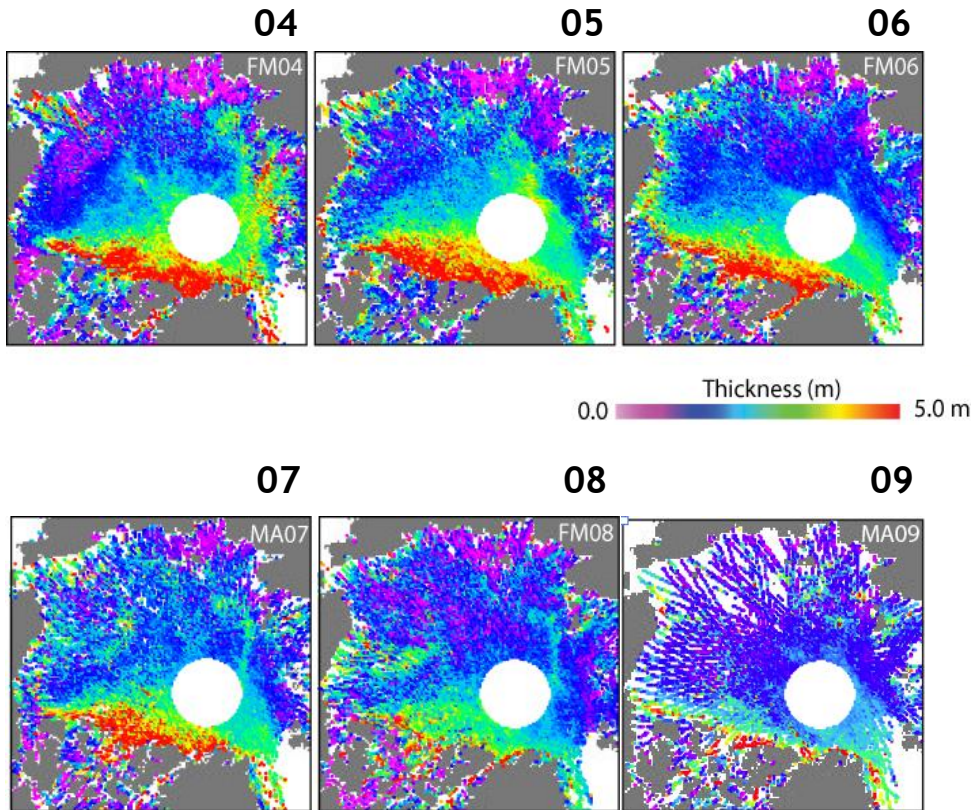
Mar-Apr 07



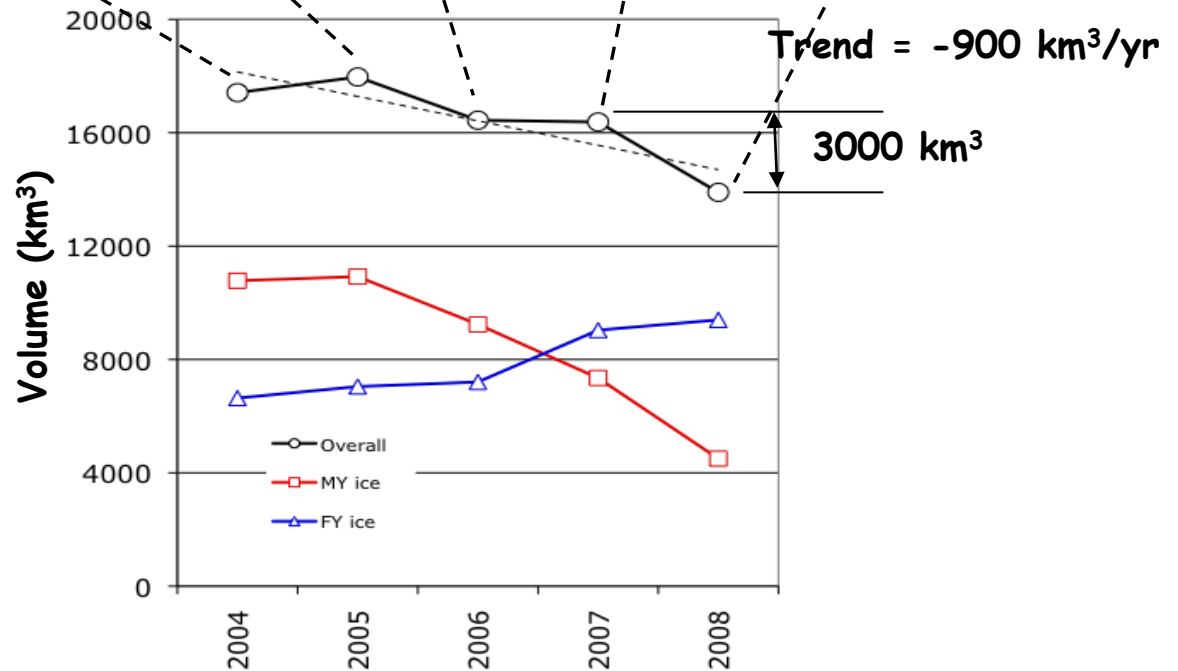
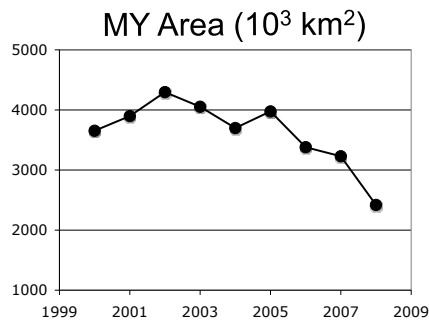
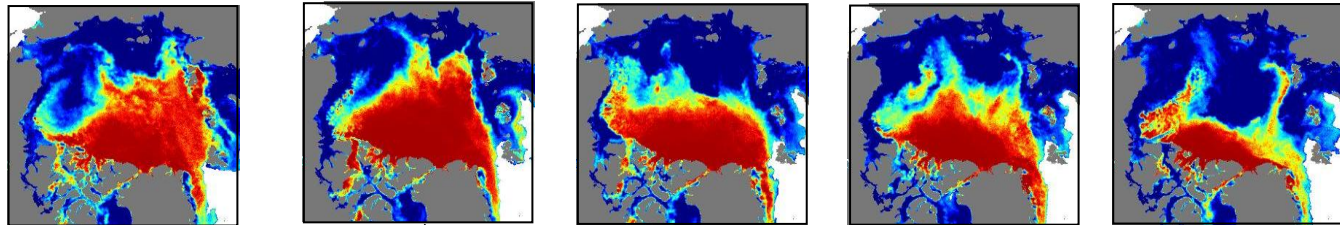
Feb-Mar 08



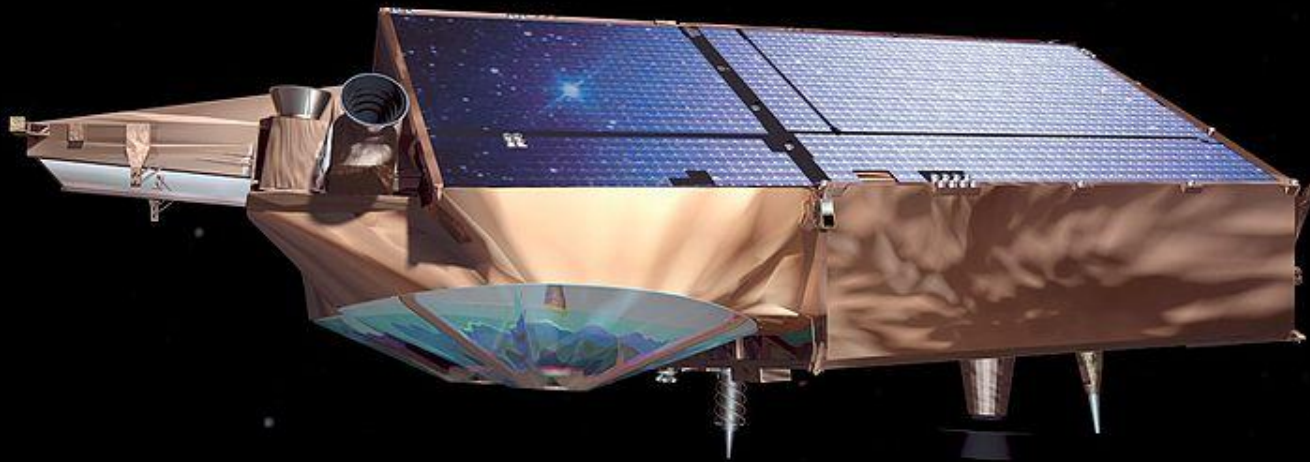
(Kwok, 2008)



Limitations: Cloud cover

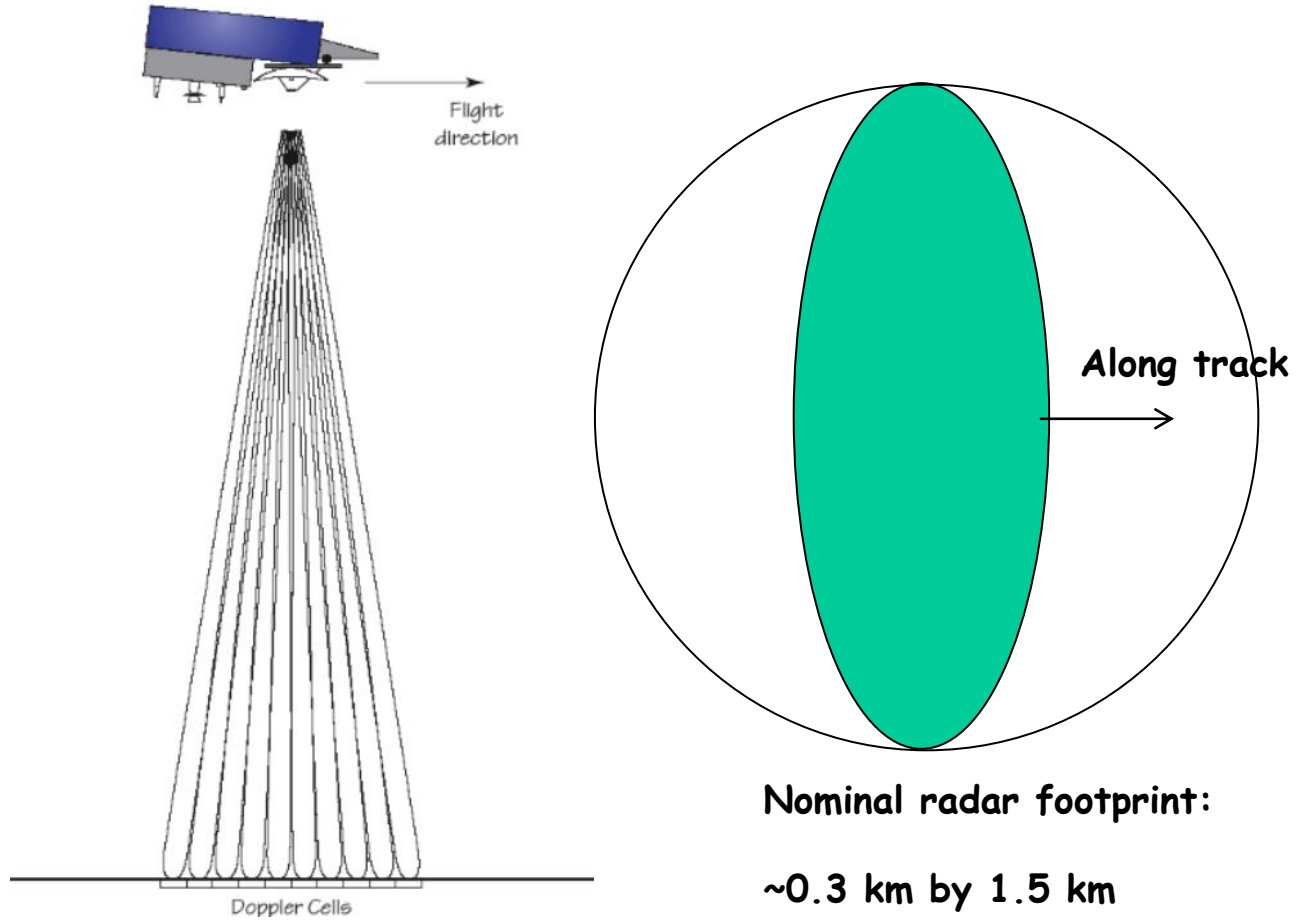


CryoSat-2

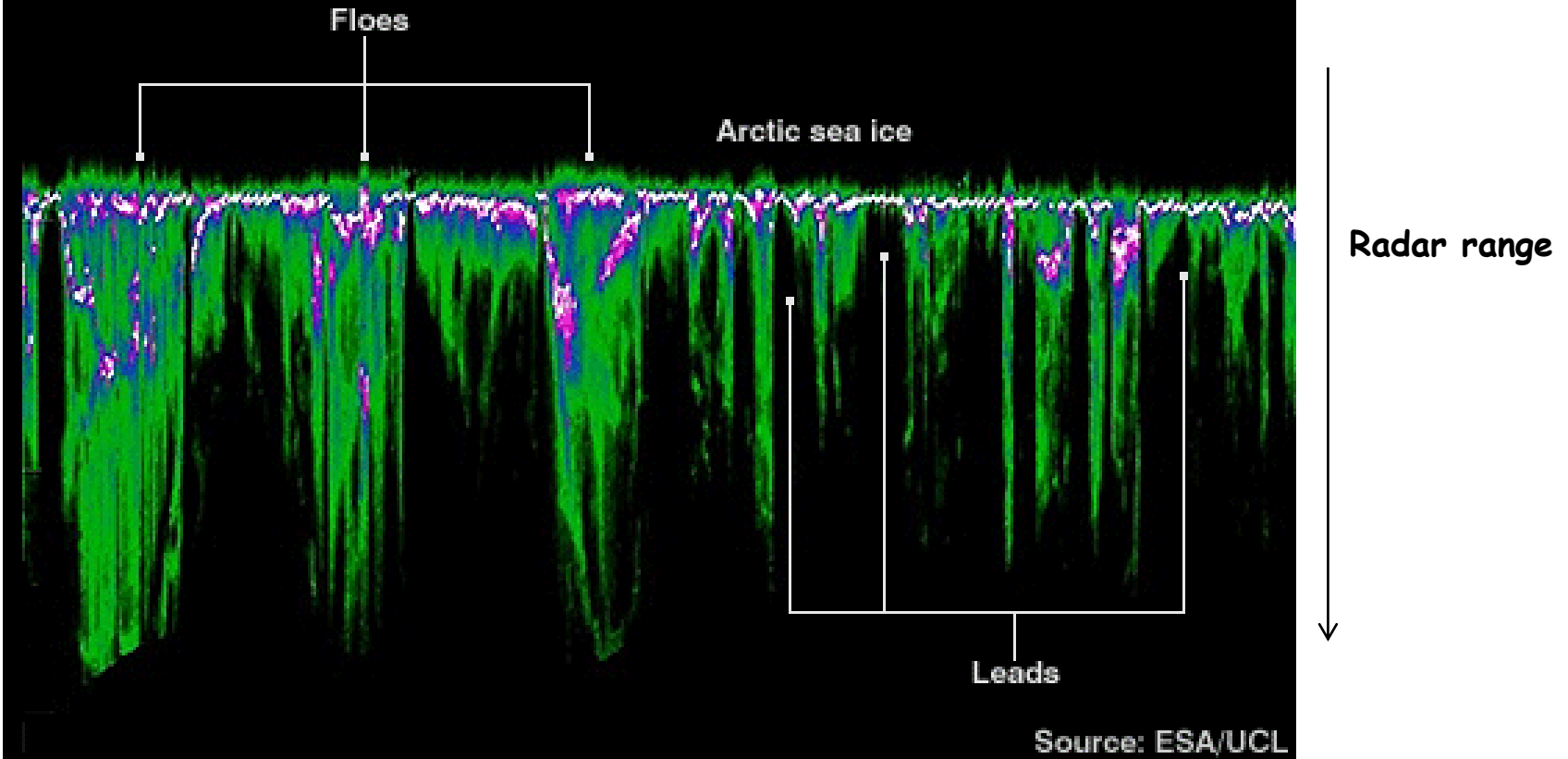


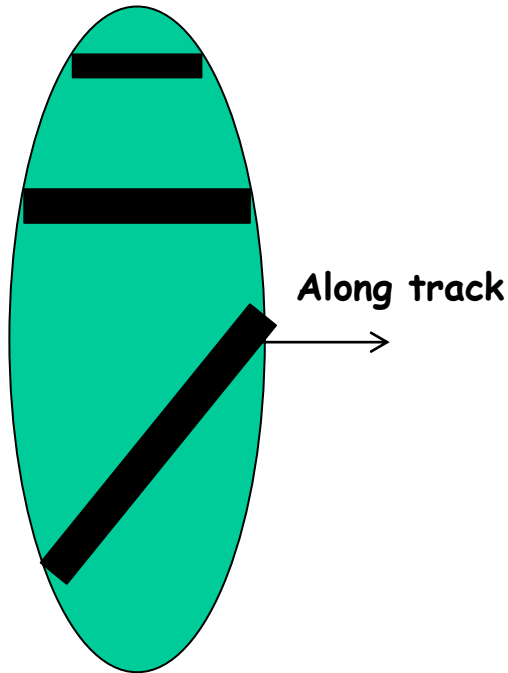


- Radar: 13.575 GHz
- Pulse repetition frequency: 18.181 kHz in SAR and SIN mode
- **Pulse Bandwidth: 320 MHz** (Range resolution: 46.8 cm)
- Burst duration (in SAR): 85.7 Hz
- Pulse width: 44.8 us
- Antenna: 2 reflectors - 1.2 by 1.1 m (15 km footprint)
- Range sampling (in SAR): 0.2342 m
- (beam width: 70-110 urad)
- Predicted accuracy of surface elevation: 15 cm
- **Pulse limited footprint: 313 by 1670 m**
- CryoSat-2
 - Inclination: 92 deg
 - Altitude: 717 km
 - Launched: Apr 2010
 - Status: Mission: on-going



CRYOSAT-2: Data from Arctic Ocean

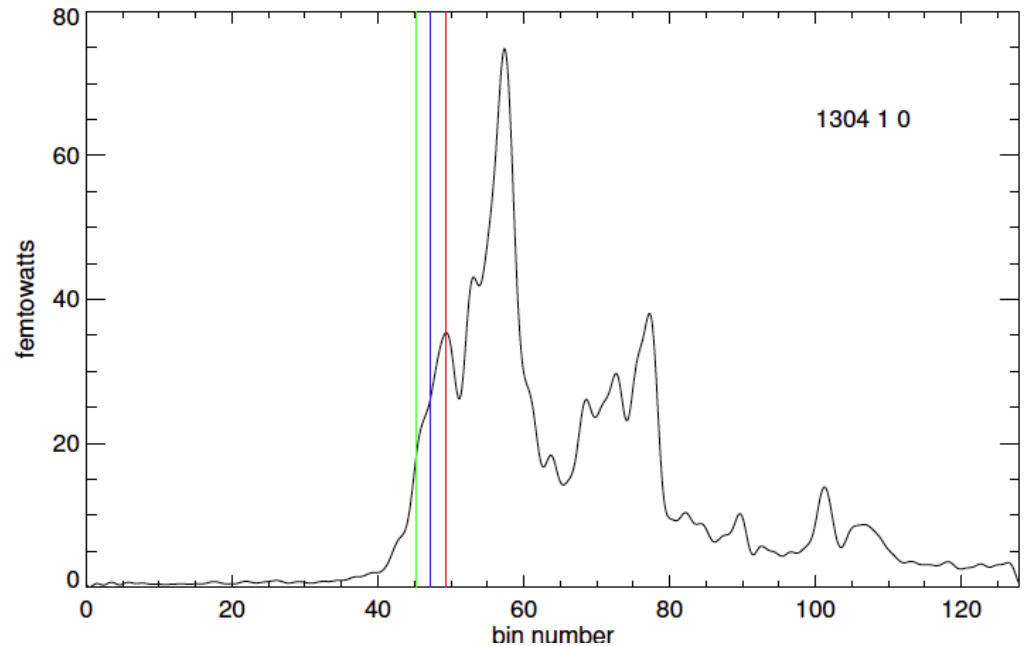




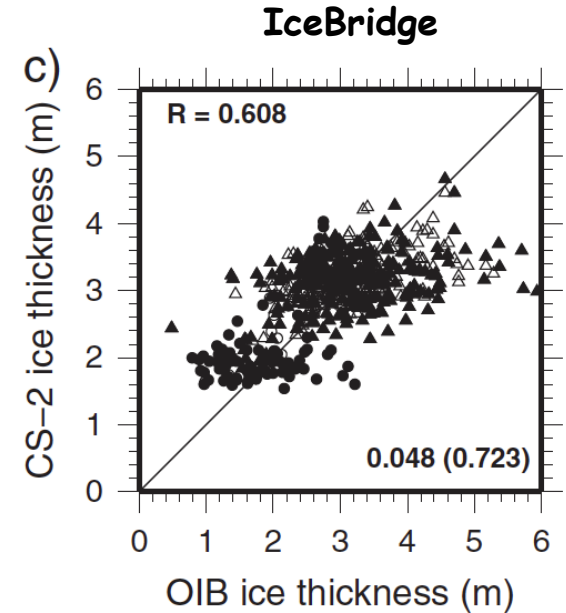
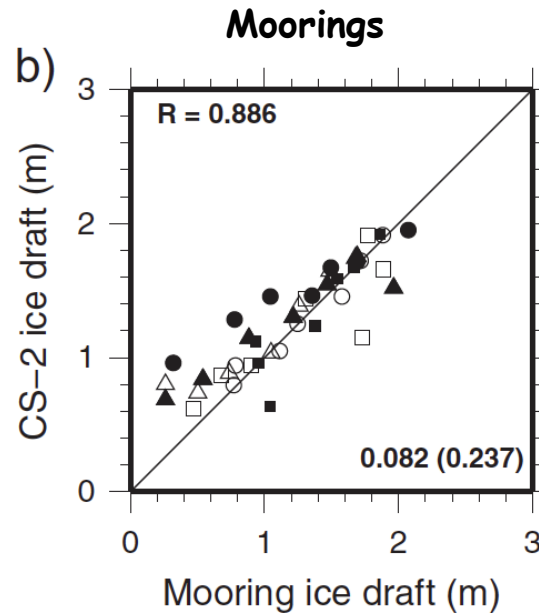
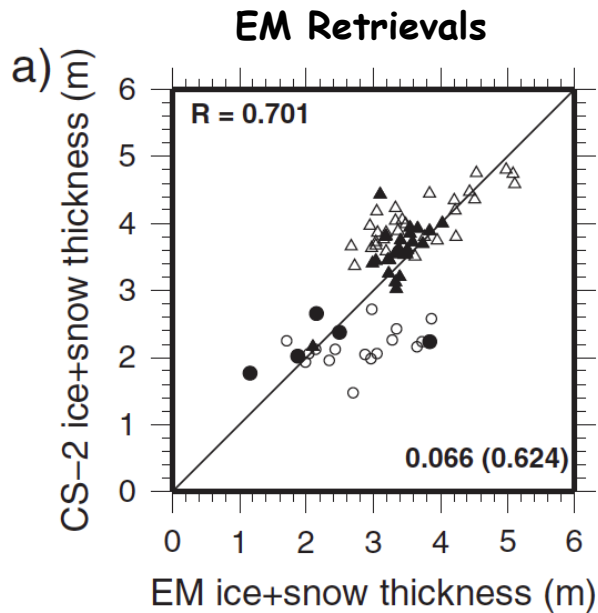
Nominal radar footprint:

~0.3 km by 1.5 km

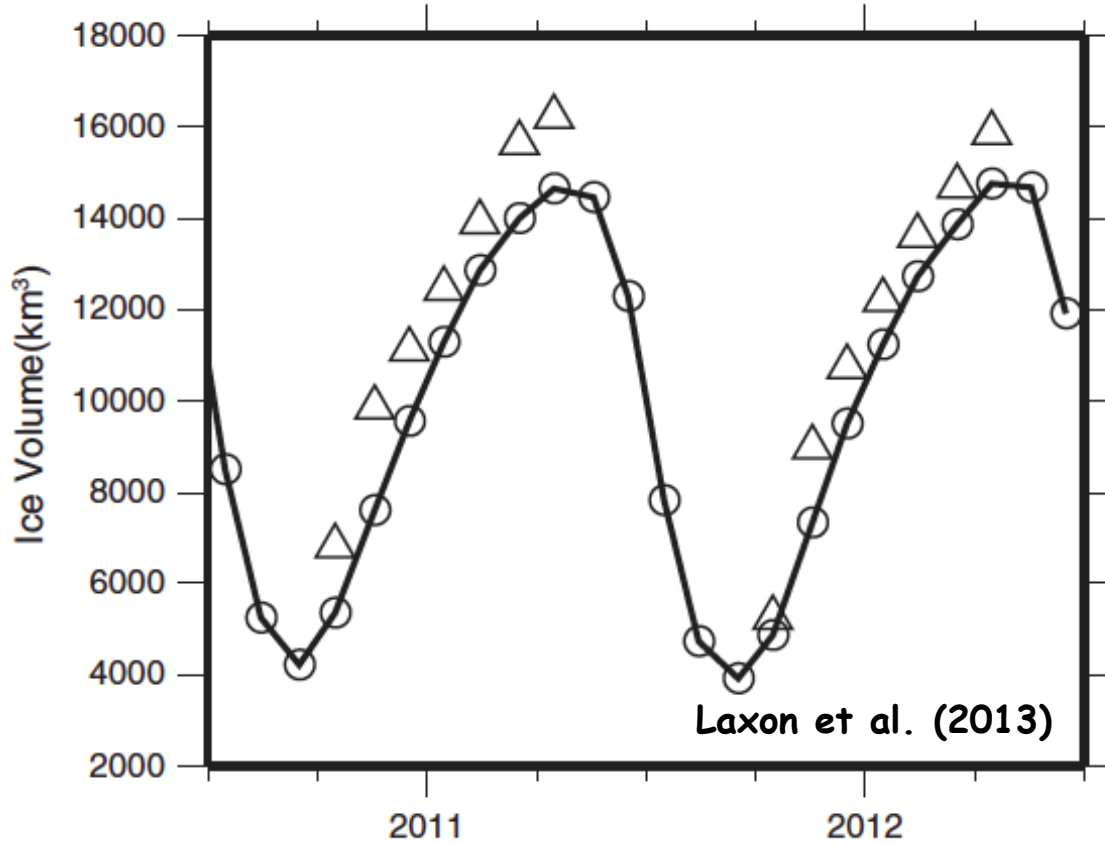
A CryoSat-2 return



Use character of the first return to identify open water returns



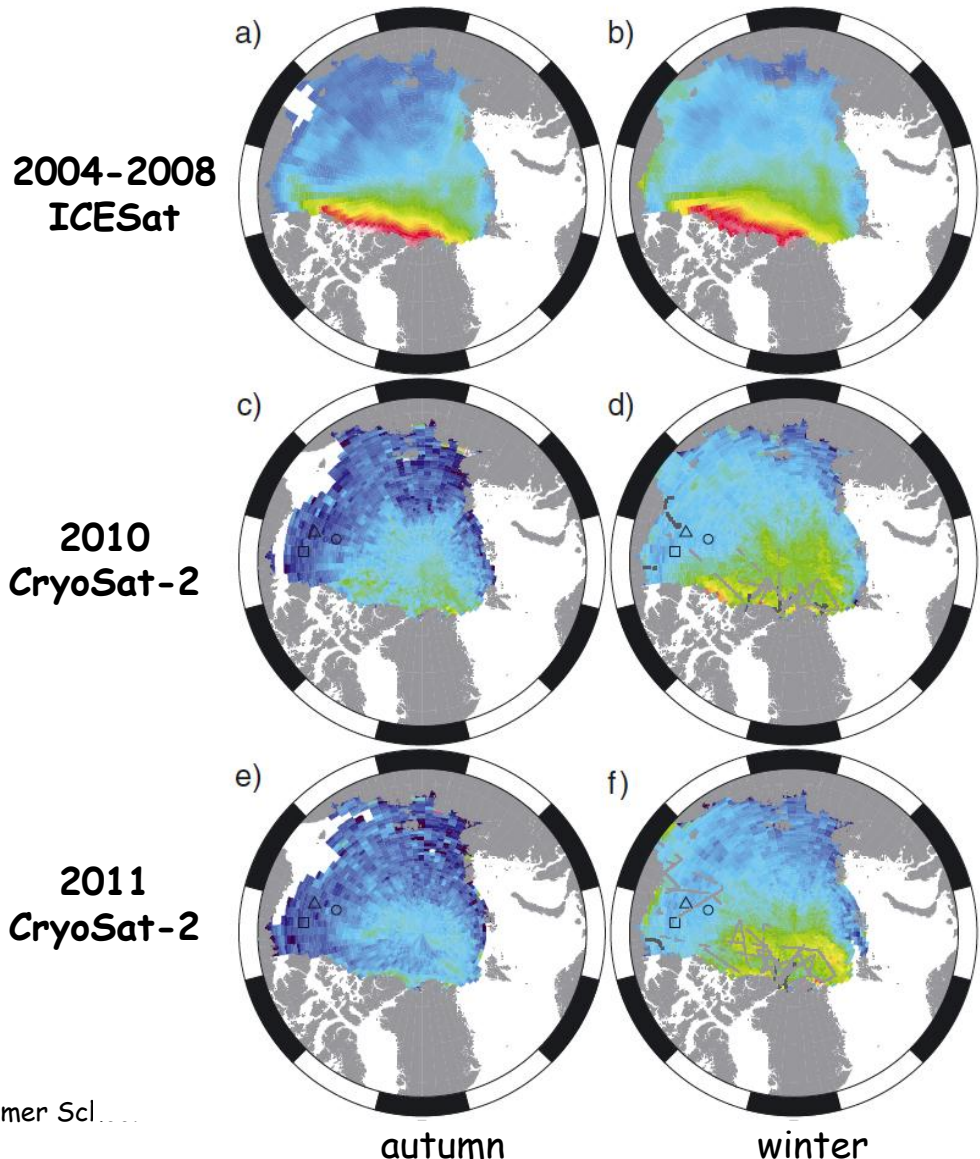
Laxon et al. (2013)



Laxon et al. (2013)

Triangle: CS-2

Circle: Coupled ice ocean model

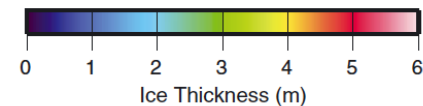


ICESat



CS-2

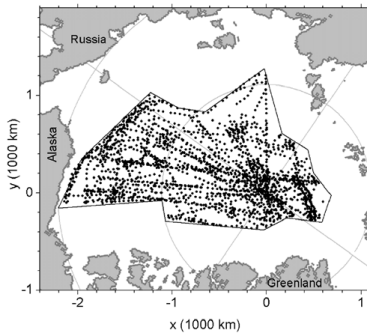
Between the ICESat and CryoSat-2 periods, the autumn volume declined by 4291 km^3 and the winter volume by 1479 km^3



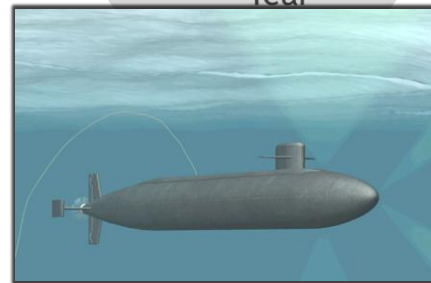
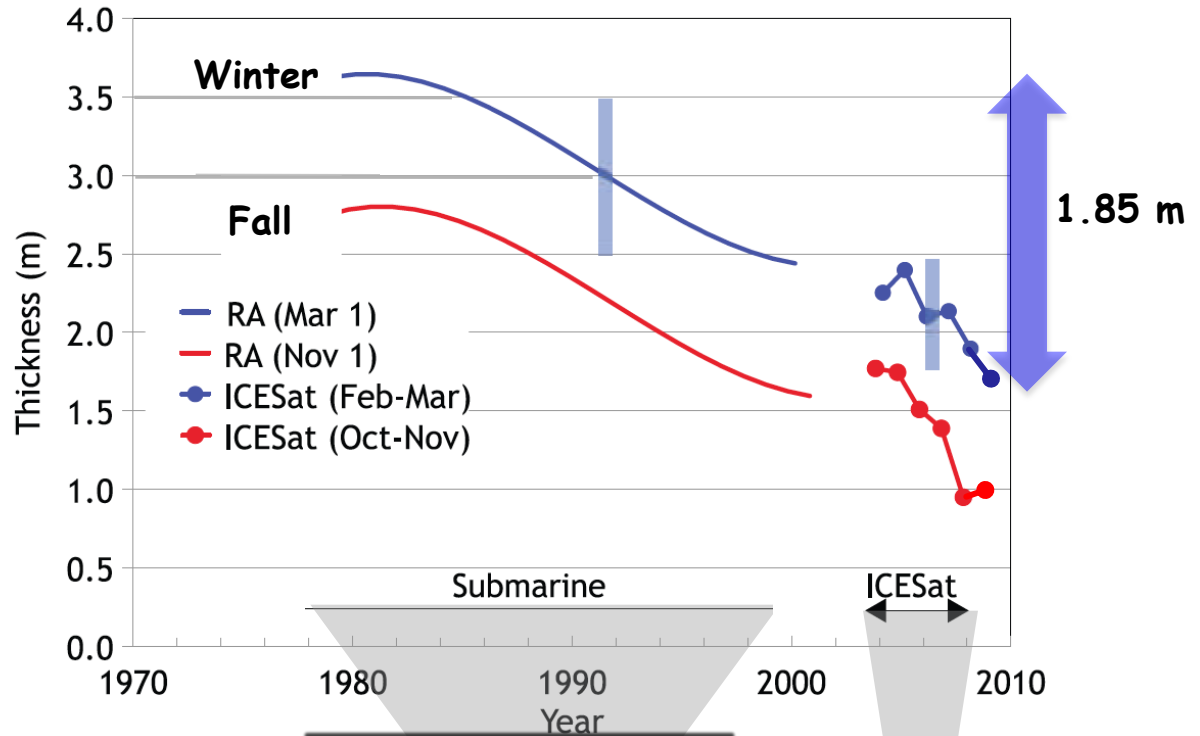


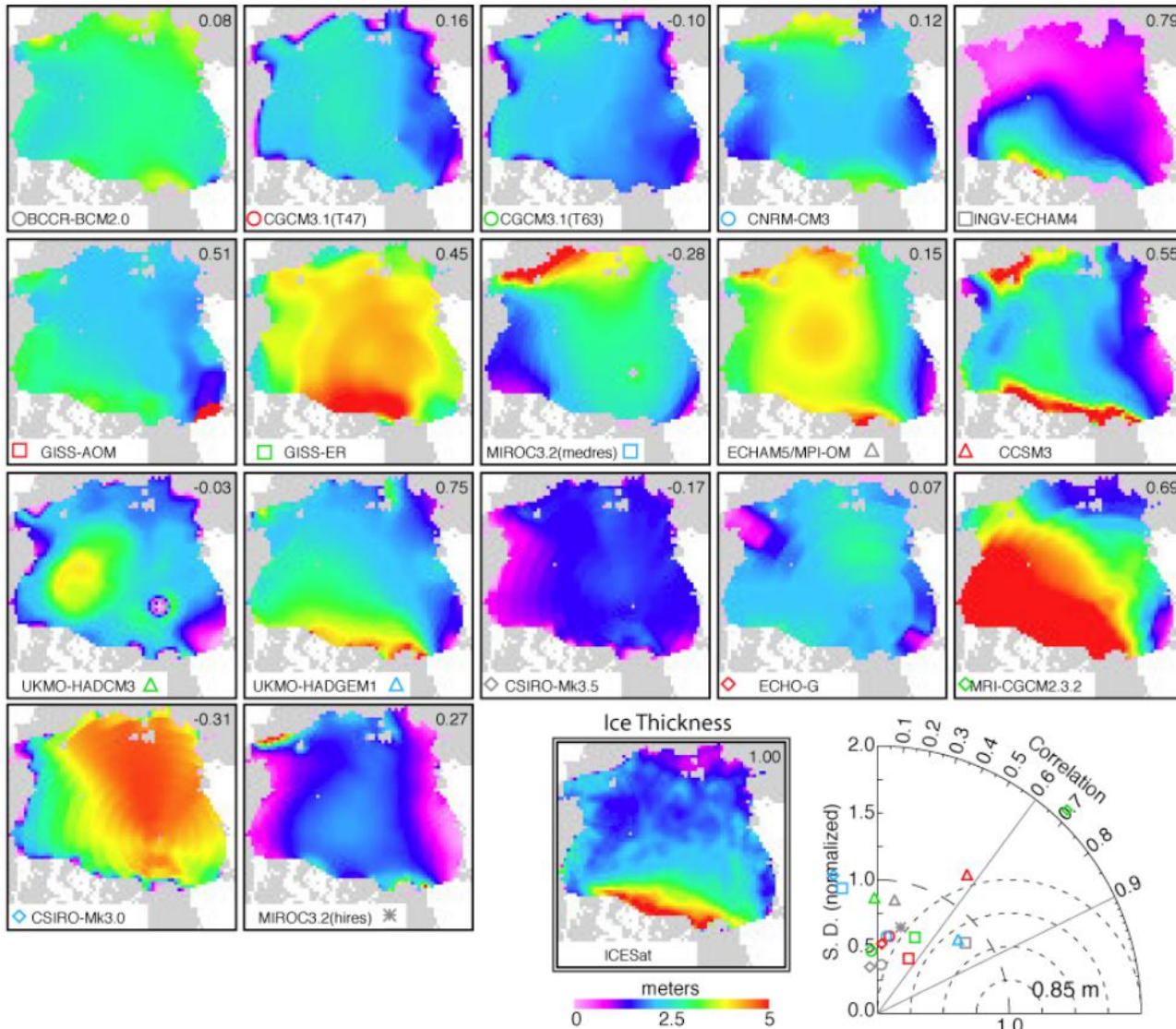
Integrating and reporting the observations

Decline in sea ice thickness from submarine and ICESat records: 1978 - 2009



Note: Submarine estimates based on regression of available ice draft from US Navy submarines





Kwok, 2011

An aerial photograph showing a vast expanse of sea ice. The ice is broken up into numerous irregular, interconnected floes of varying sizes, creating a complex, porous pattern. The open water channels between the floes are a light, milky blue color, contrasting with the darker, textured surface of the ice. The overall appearance is that of a fragmented and thinning ice cover.

**What about the
Antarctic sea ice cover?**

-
- Historical Records of ice draft from Submarines
 - Ice Types from Satellites
 - Ice Freeboard/Thickness from Satellites
 - There are several platforms that are capable of measuring freeboard from space: ICESat, CryoSat-2 (Nov 09), ICESat-2 (~2014)
 - Ice Thickness and Volume
 - Finally, we have a method to estimate the basin-scale pattern of ice thickness of the Arctic Ocean and observe its seasonal and interannual variability
 - First time that we can say, with some certainty, the total ice volume of the Arctic Ocean sea ice (overall heat and mass balance)



QUESTIONS?