Sea Ice Altimetry

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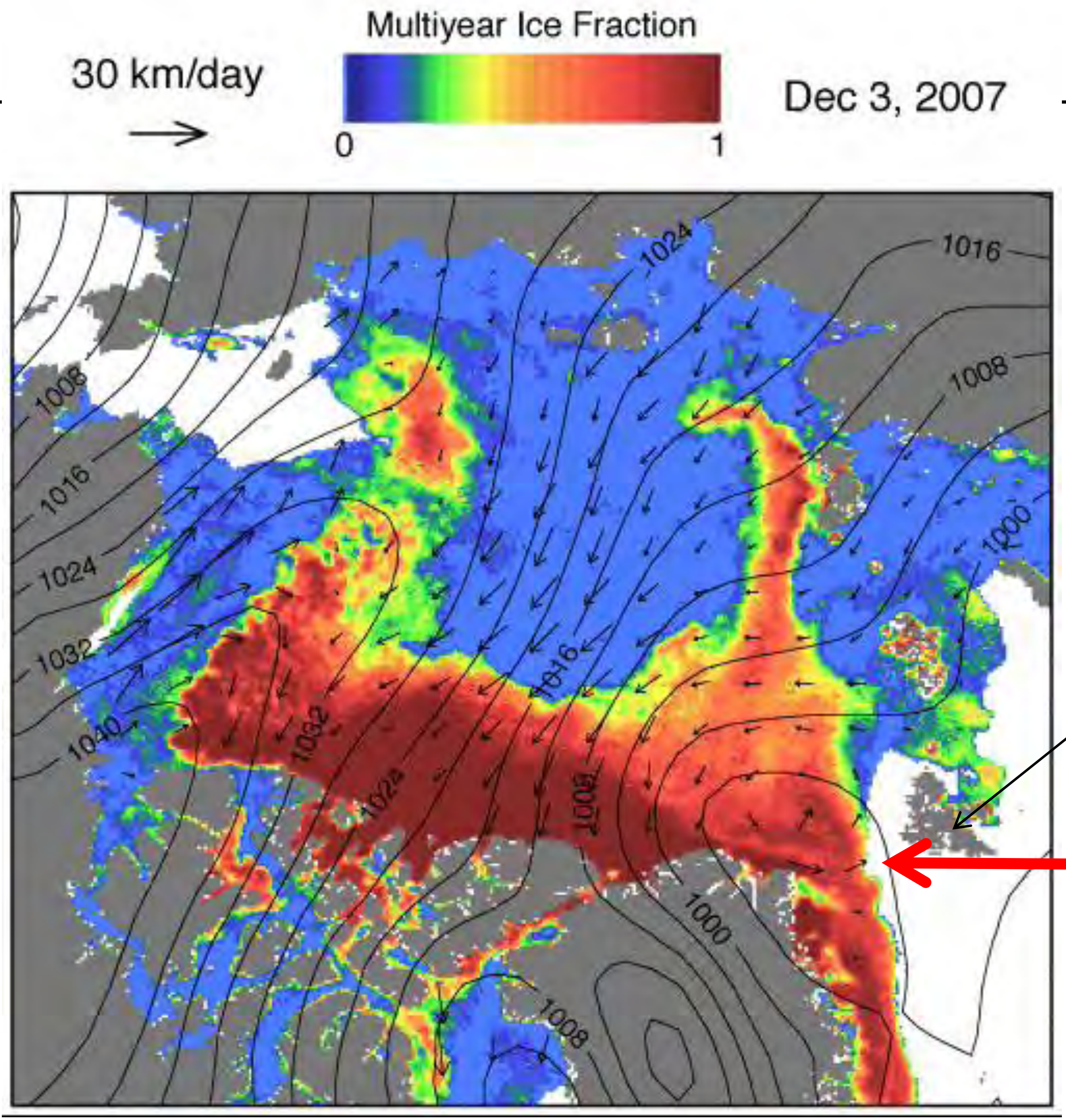
ESA Cryosphere Remote Sensing Training Course
11-16 June 2018
UNIS, University Centre in Svalbard
Longyearbyen, Svalbard



We are here

Fram Strait

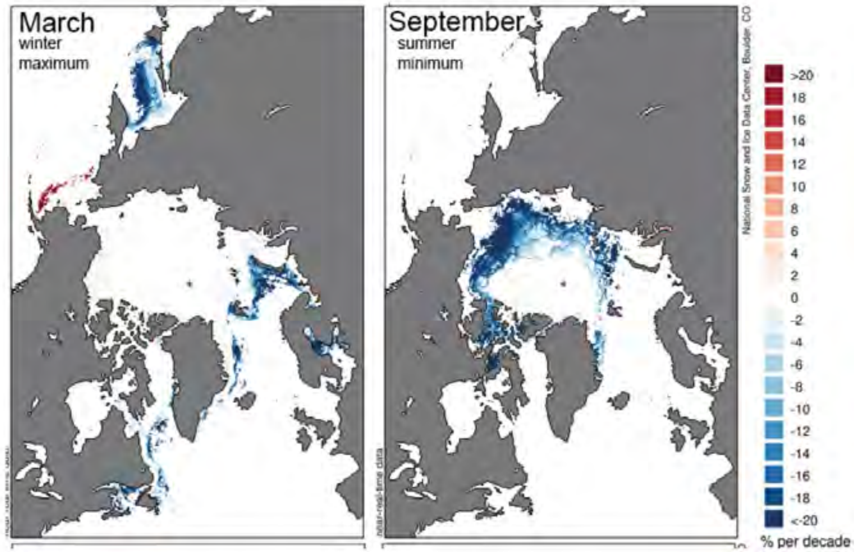
Topics

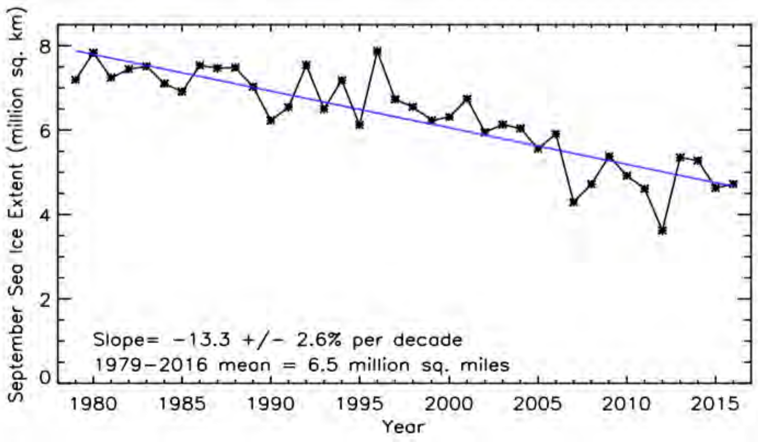
- Sea Ice Science
- Altimetry and sea ice thickness
- Technology
  - Lidars and Radars
- Some recent results


Sea Ice Science

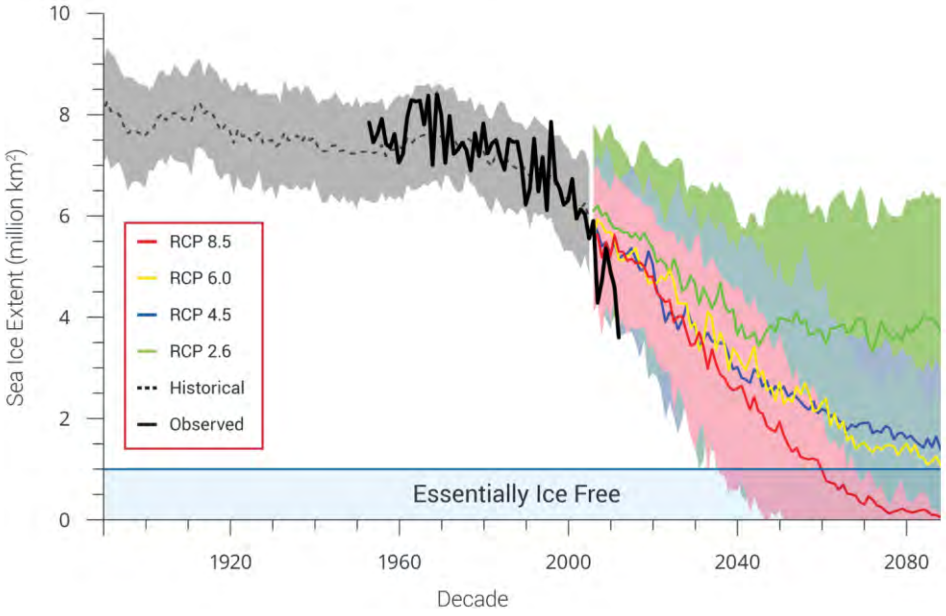
Trends in Arctic sea ice coverage

Observed trends



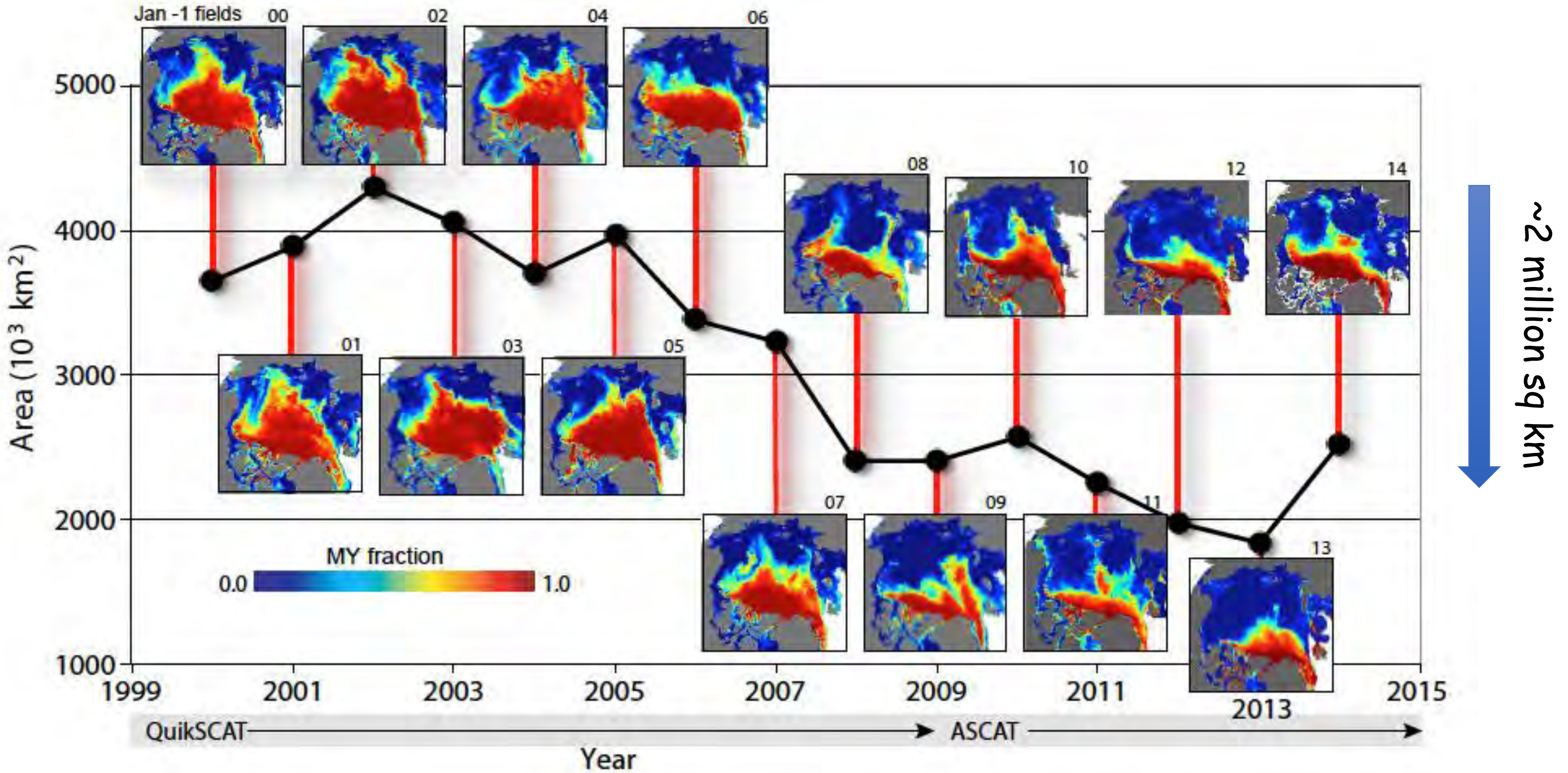


Projections for different Climate Pathways – Sept Extent



Ice-free Arctic in summer

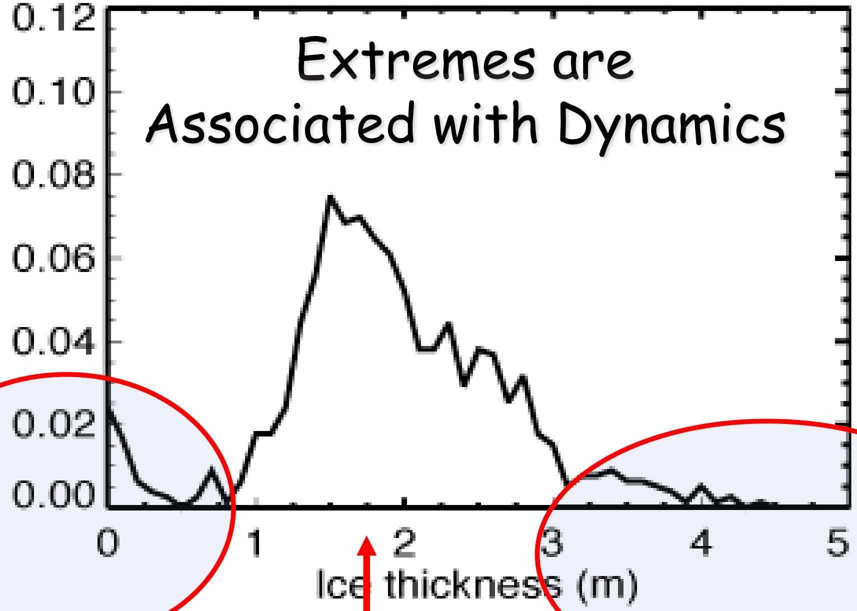
Decline in multiyear/thick sea ice coverage from scatterometers (1999-2014)



Sea ice thickness distribution:

Integrator of Thermodynamics and Dynamics

Sample thickness distribution: ~100 km transect



New Ice in fractures

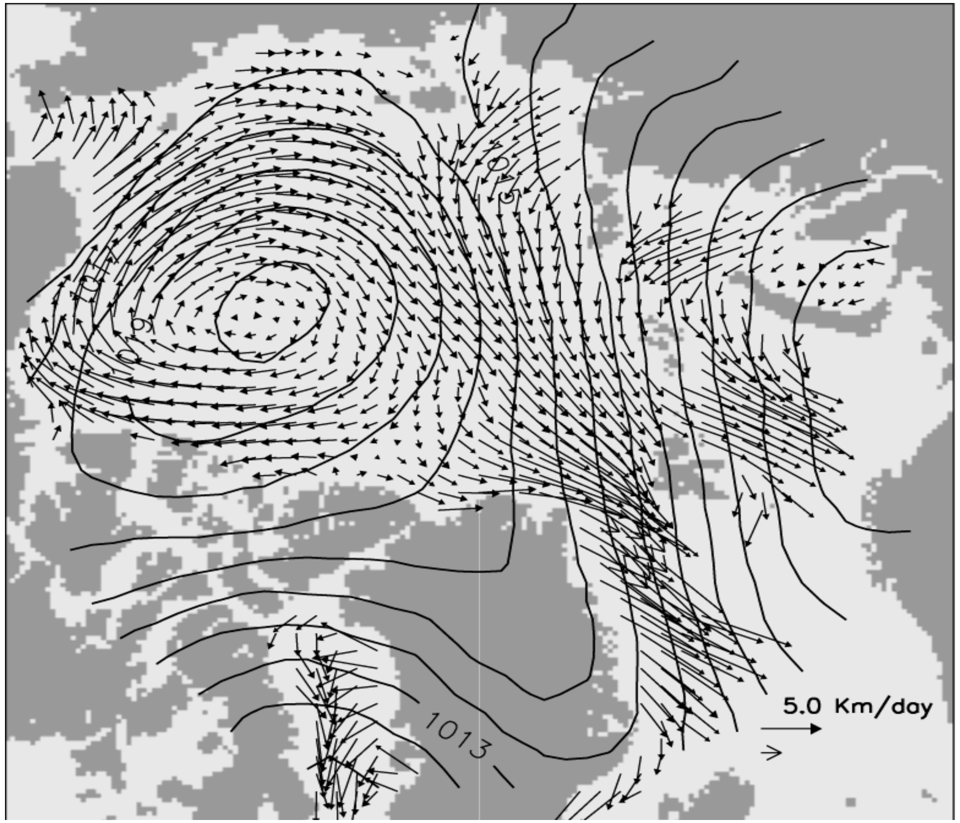
Limit of Seasonal Growth

Thick multiyear ice and Ridges

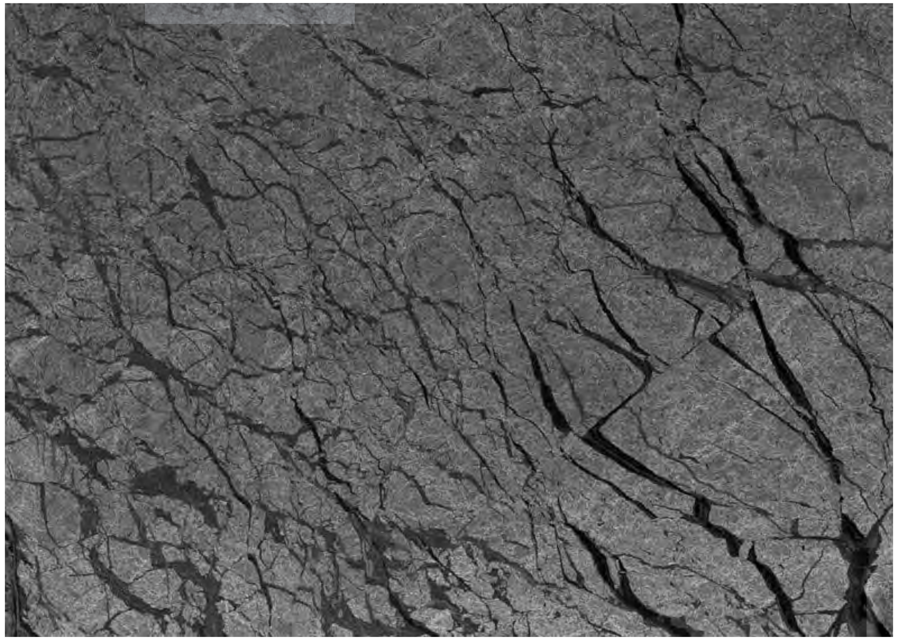
Uses: Monitoring changes; model assessment/validation; process studies; assimilation into models; initialization of forecasts.

Ice Drift (Different length scales)

2000 km

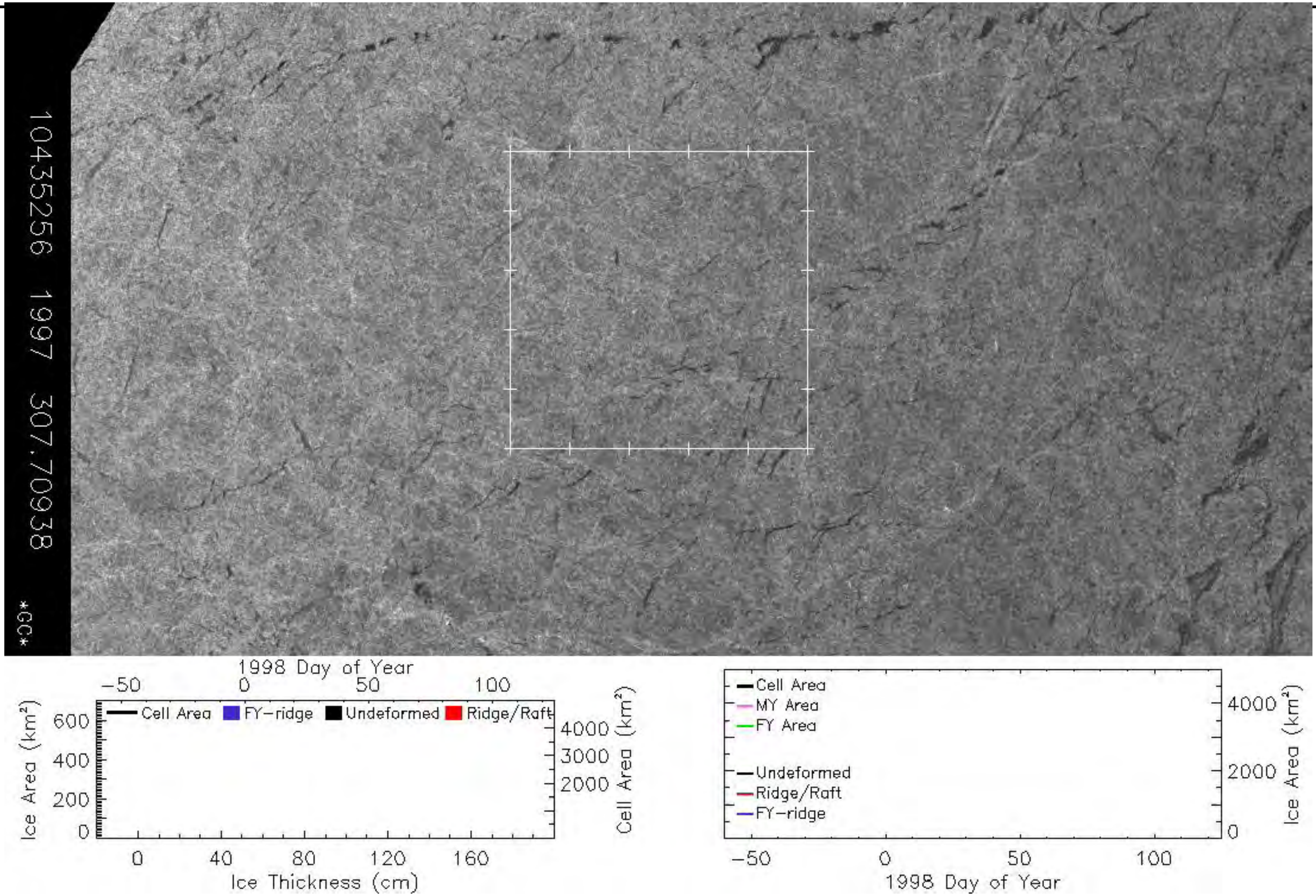


100 km



ICE is a SOLID!
All large scale 'gradients' are concentrated in cracks and fractures

Sea ice thickness distribution:
Dynamics



Deformation of a Lagrangian parcel (or material element)

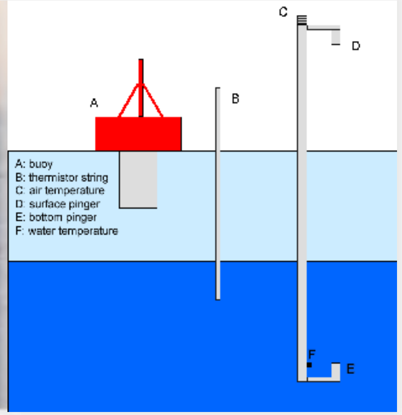
- 50x50 km initial dimension

- 6-months

- Divergence/Convergence

- Openings/Closings

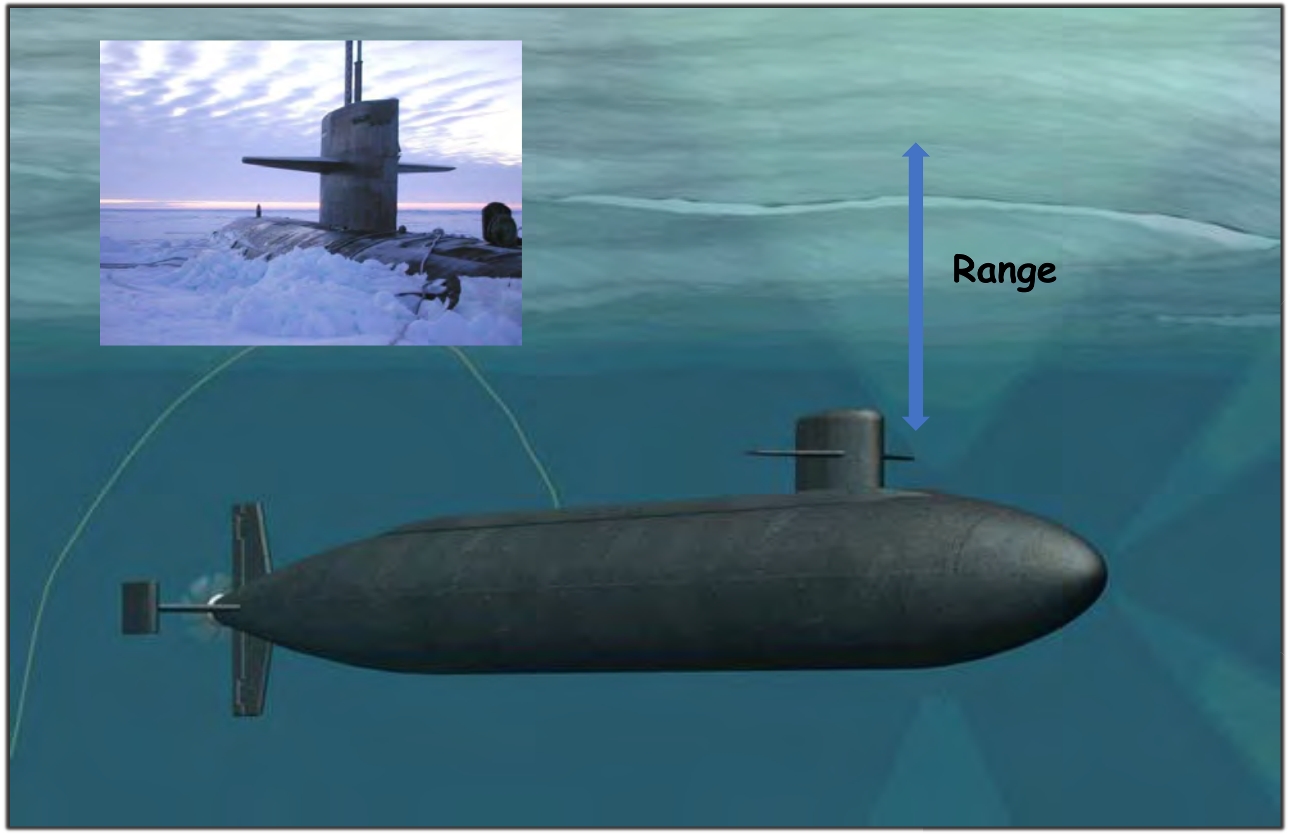
Ways of measuring ice thickness



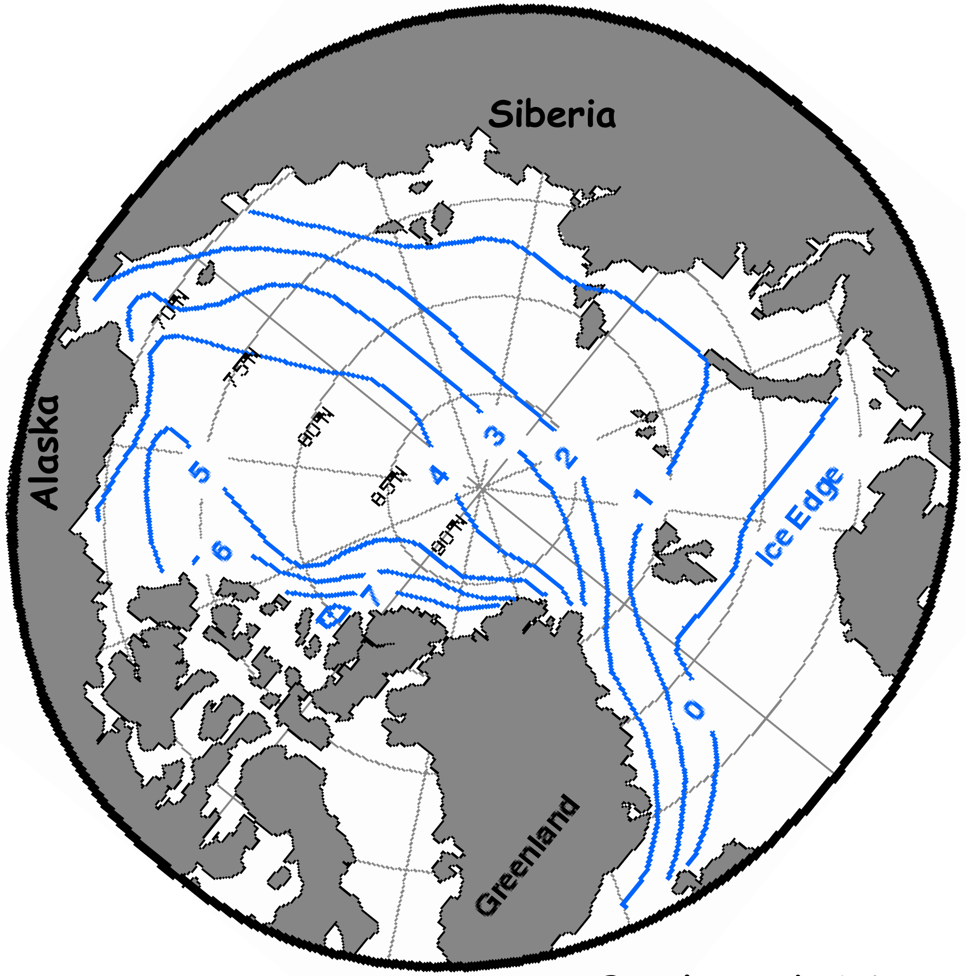
But, difficult to get a basin-scale picture…

Rough map of Arctic ice draft from US Navy submarines

Ice Draft from submarine sonars

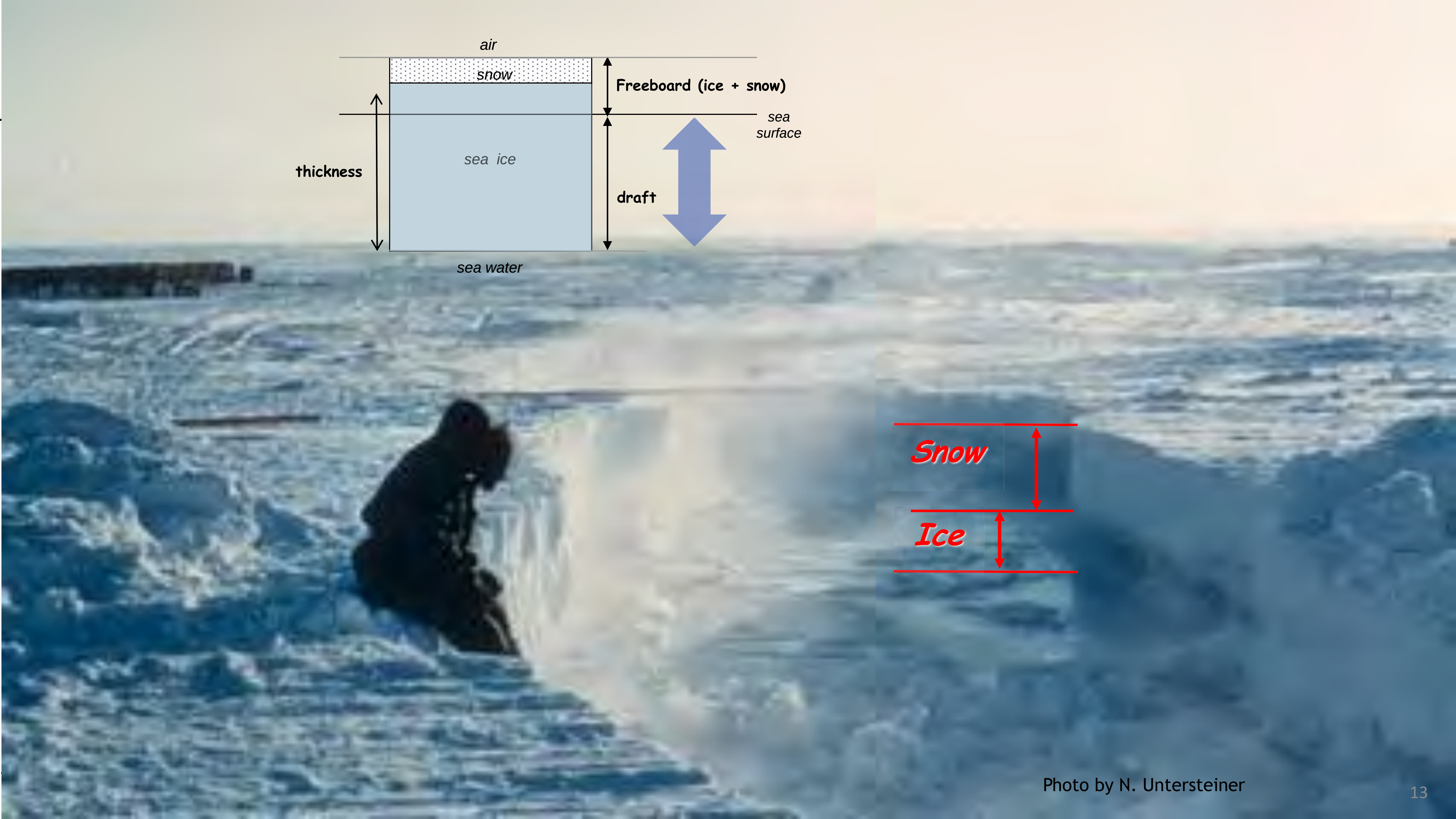


SCICEX (Scientific Ice Expeditions)



Bourke and McLaren (1992)

Altimetry and sea ice thickness


air
snow
Freeboard (ice + snow)
sea
surface
thickness
sea ice
draft
sea water
Snow
Ice
Photo by N. Untersteiner

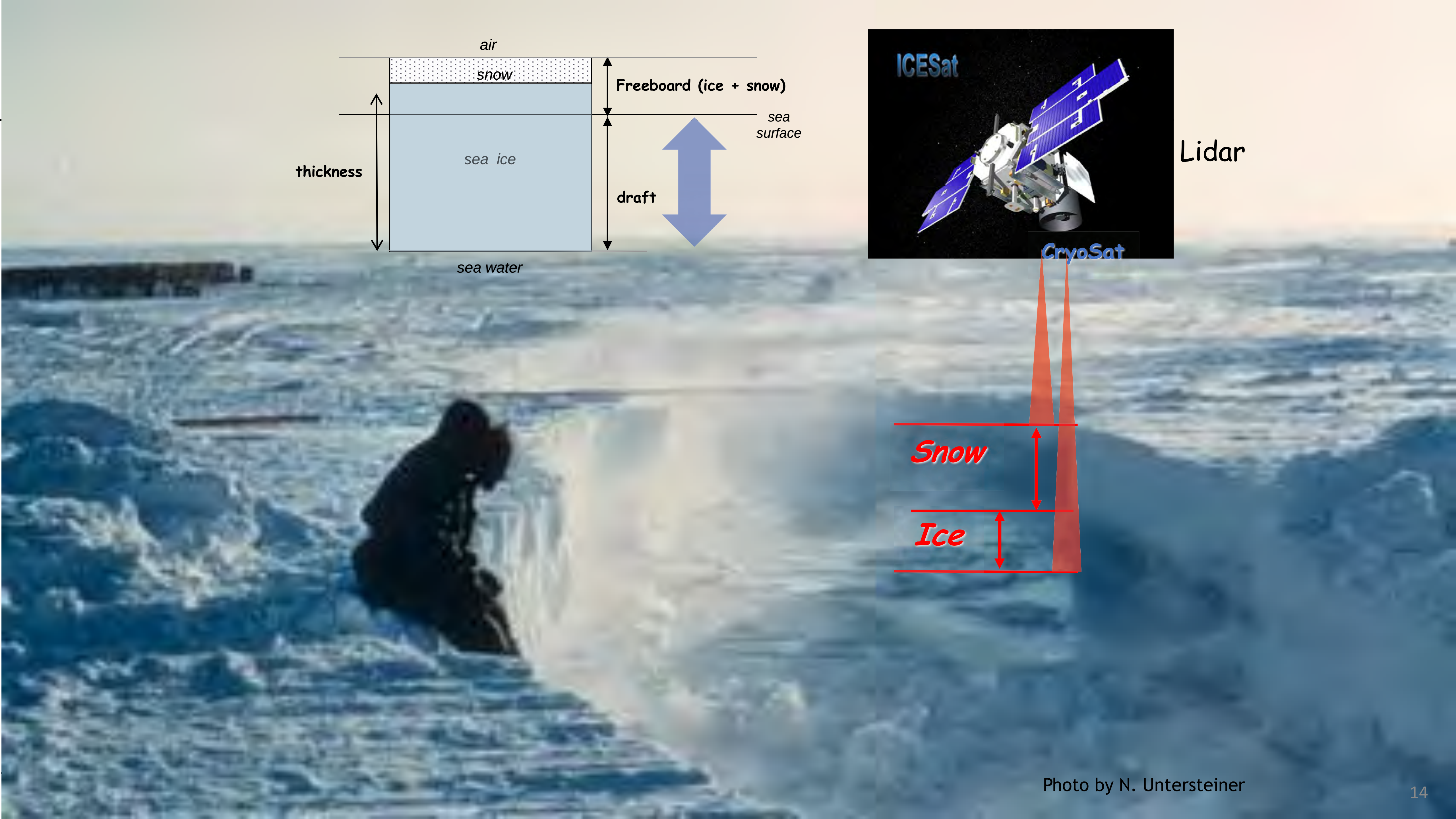
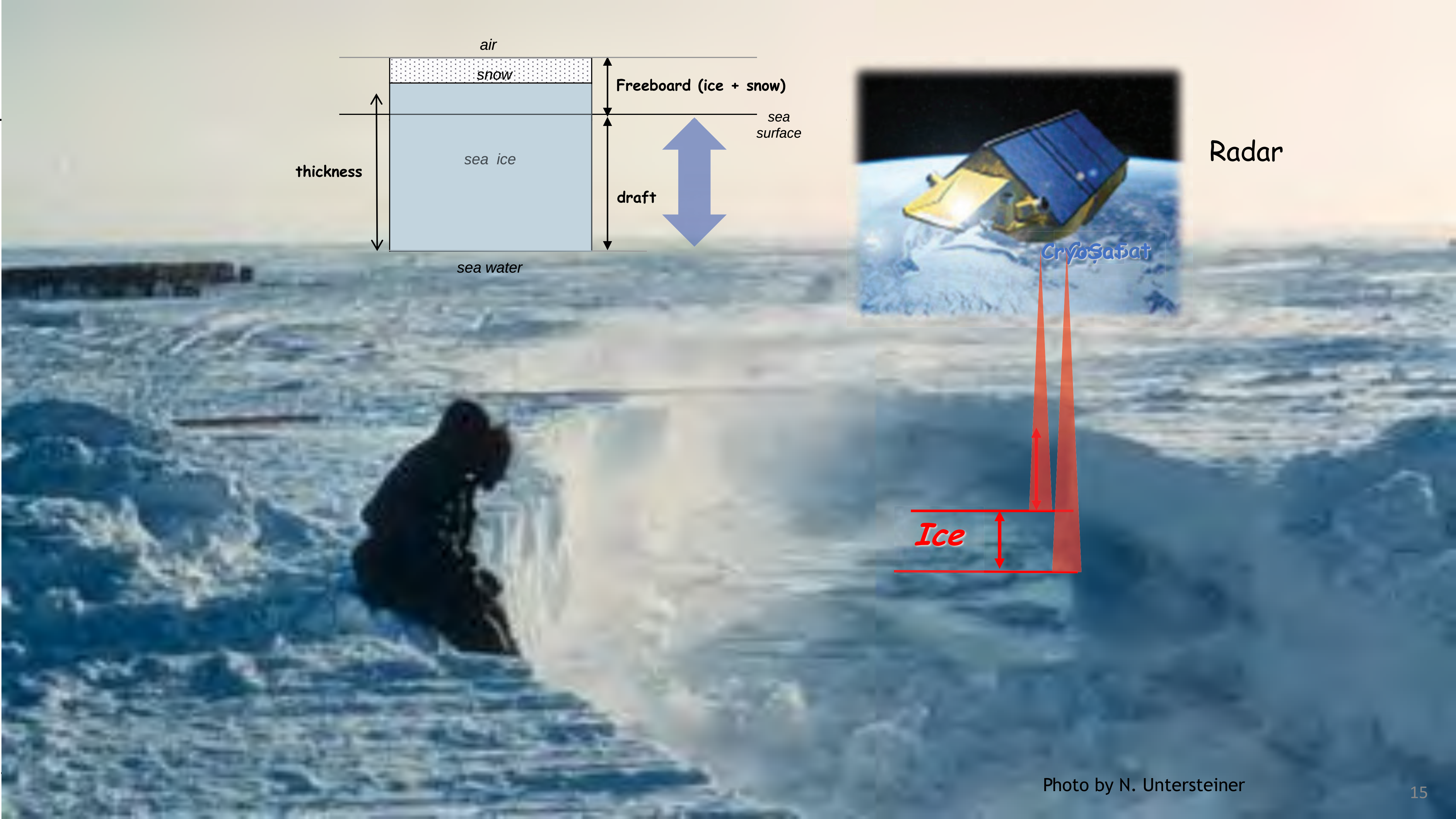
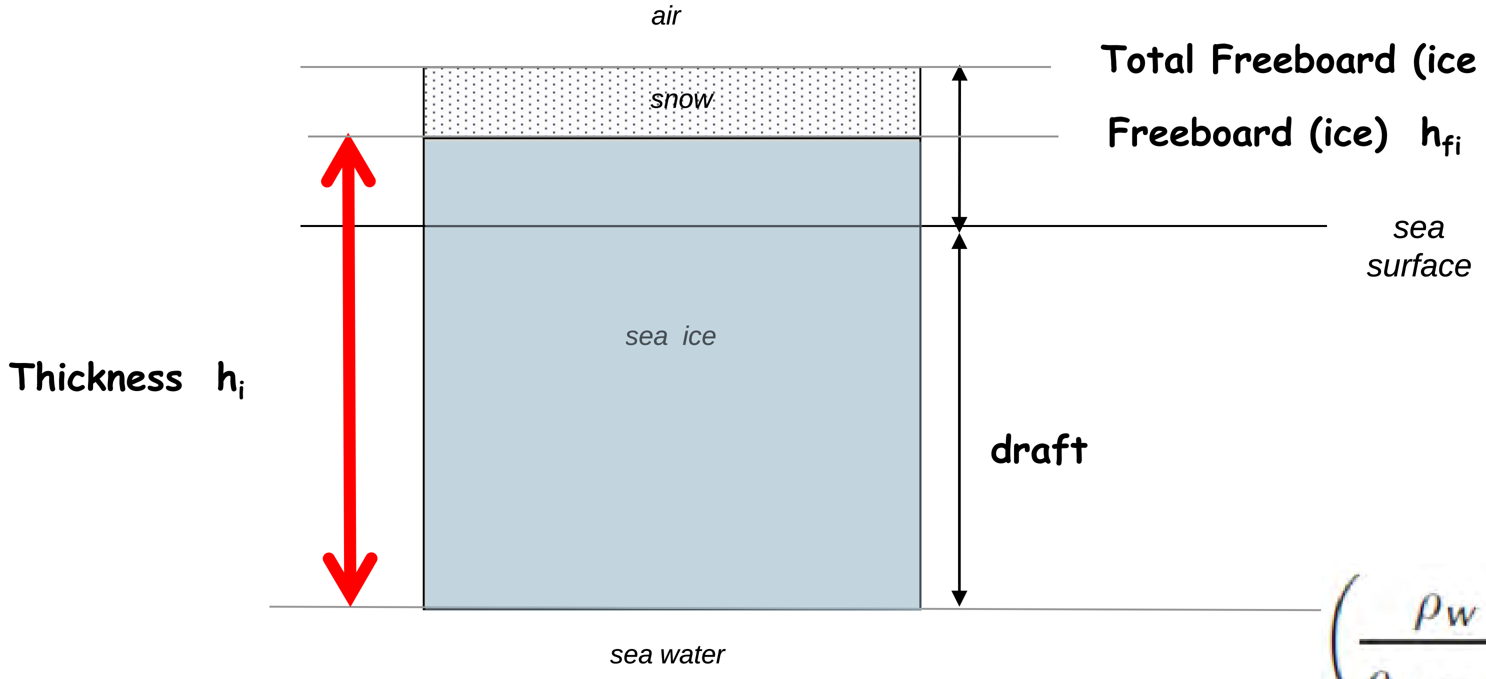


Photo by N. Untersteiner


air
snow
Freeboard (ice + snow)
sea
surface
thickness
sea ice
draft
sea water
Radar
CryoSat
Ice
Photo by N. Untersteiner

Freeboard, Snow depth, Ice Draft and Thickness



Hydrostatic Equilibrium

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

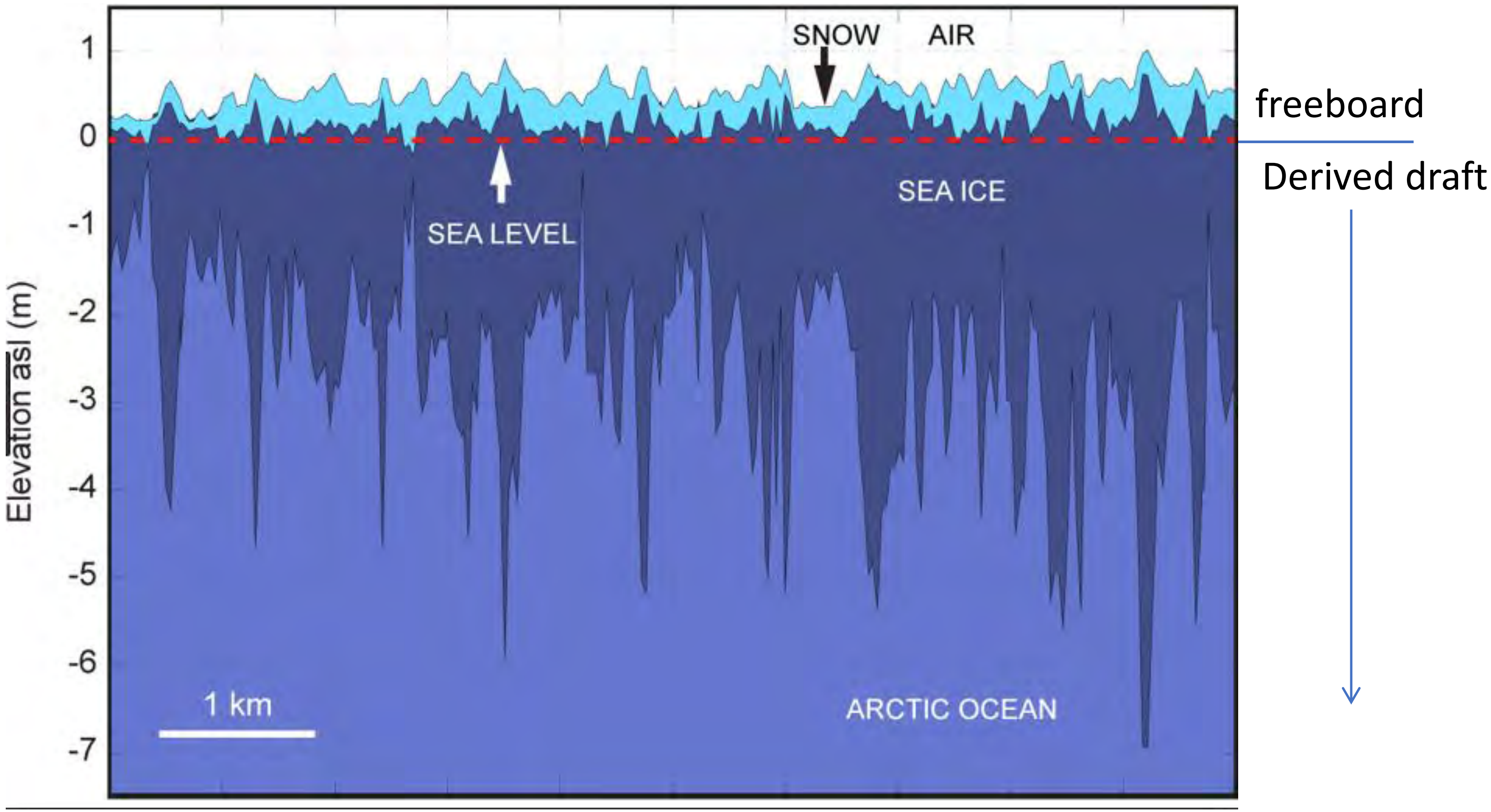
$$h_i = \left(\frac{\rho_w}{\rho_w - \rho_i}\right) h_{fi} + \left(\frac{\rho_s}{\rho_w - \rho_i}\right) h_{fs} \quad \text{(radar)}$$

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

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

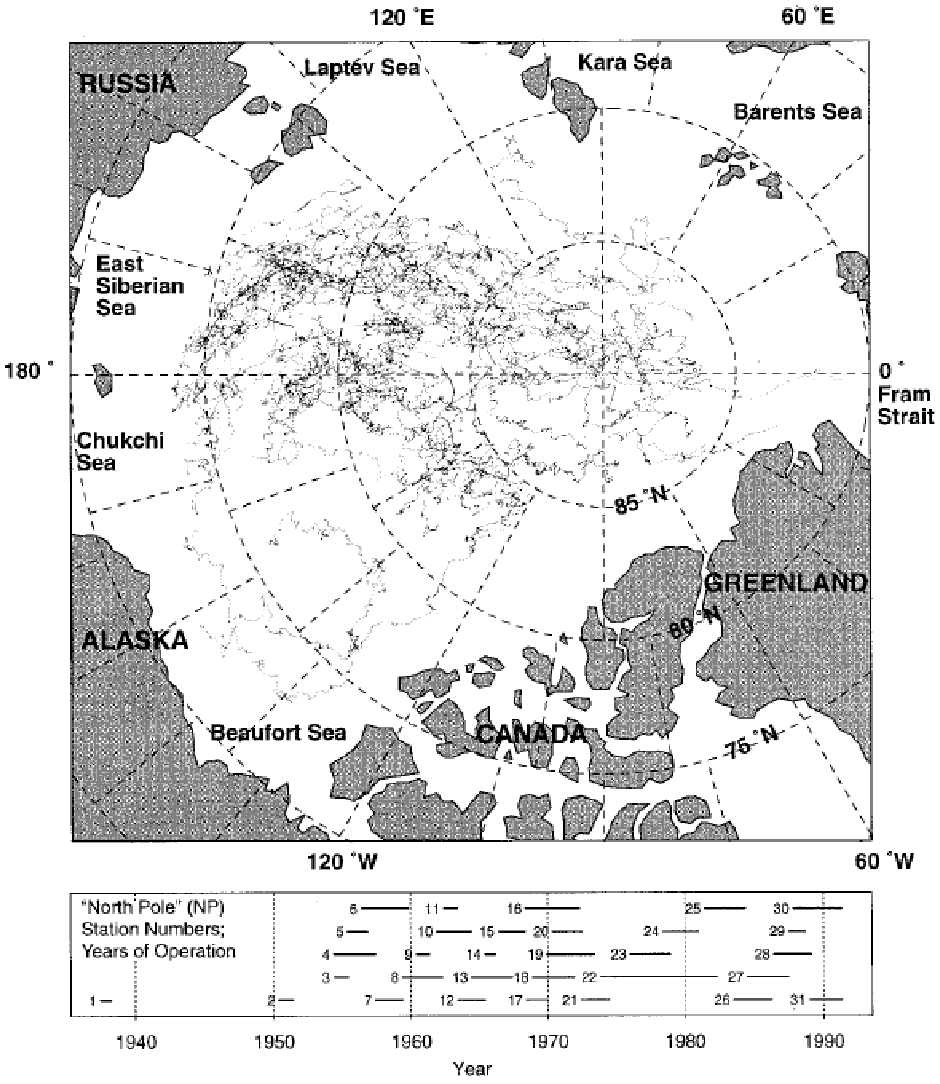
$$\left(\frac{\rho_s}{\rho_w - \rho_i}\right) \sim 3$$

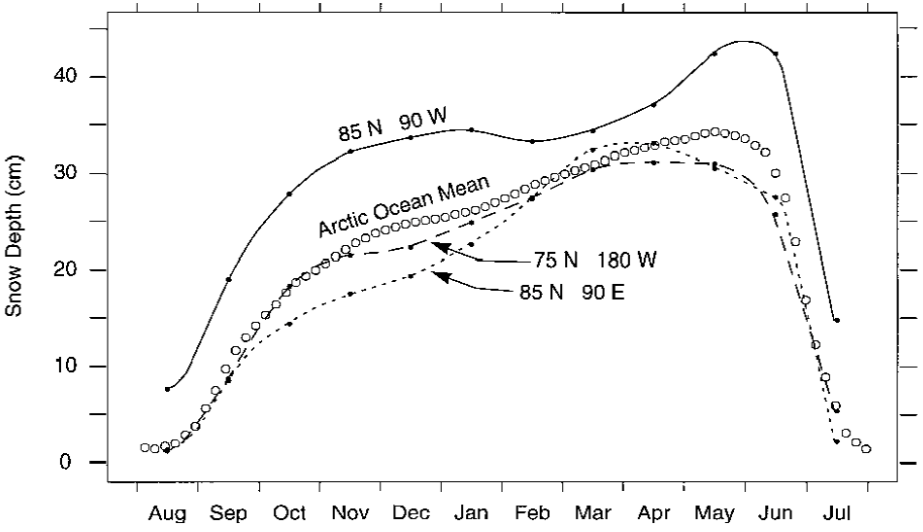
Draft/freeboard/thickness



from Operation IceBridge

What do we know about Arctic snow depth?





Warren et al., 1999

'Warren Climatology': relatively cooler air temps and older ice in the central Arctic

Bulk Density of sea ice

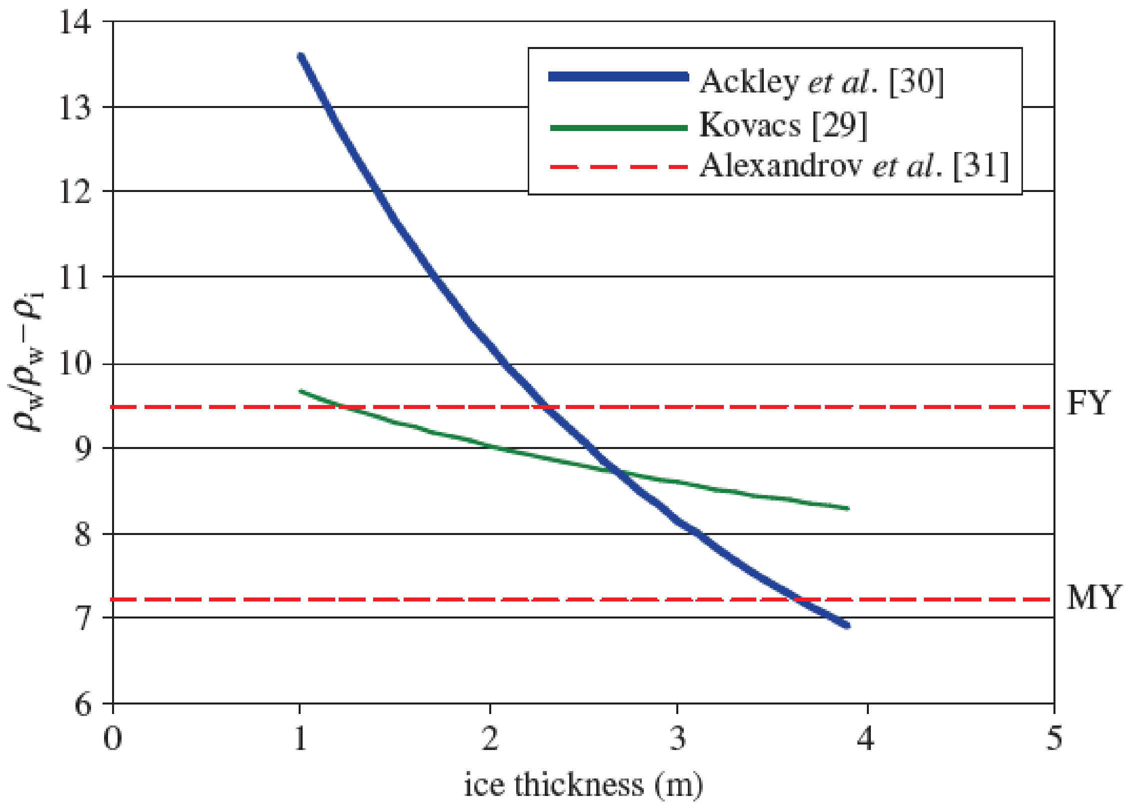


Figure 2. Dependence of $\rho_w/(\rho_w - \rho_i)$ in equation (3.1) on the ice thickness using ice densities from Ackley *et al.* [30], Kovacs [29] and Alexandrov *et al.* [31].

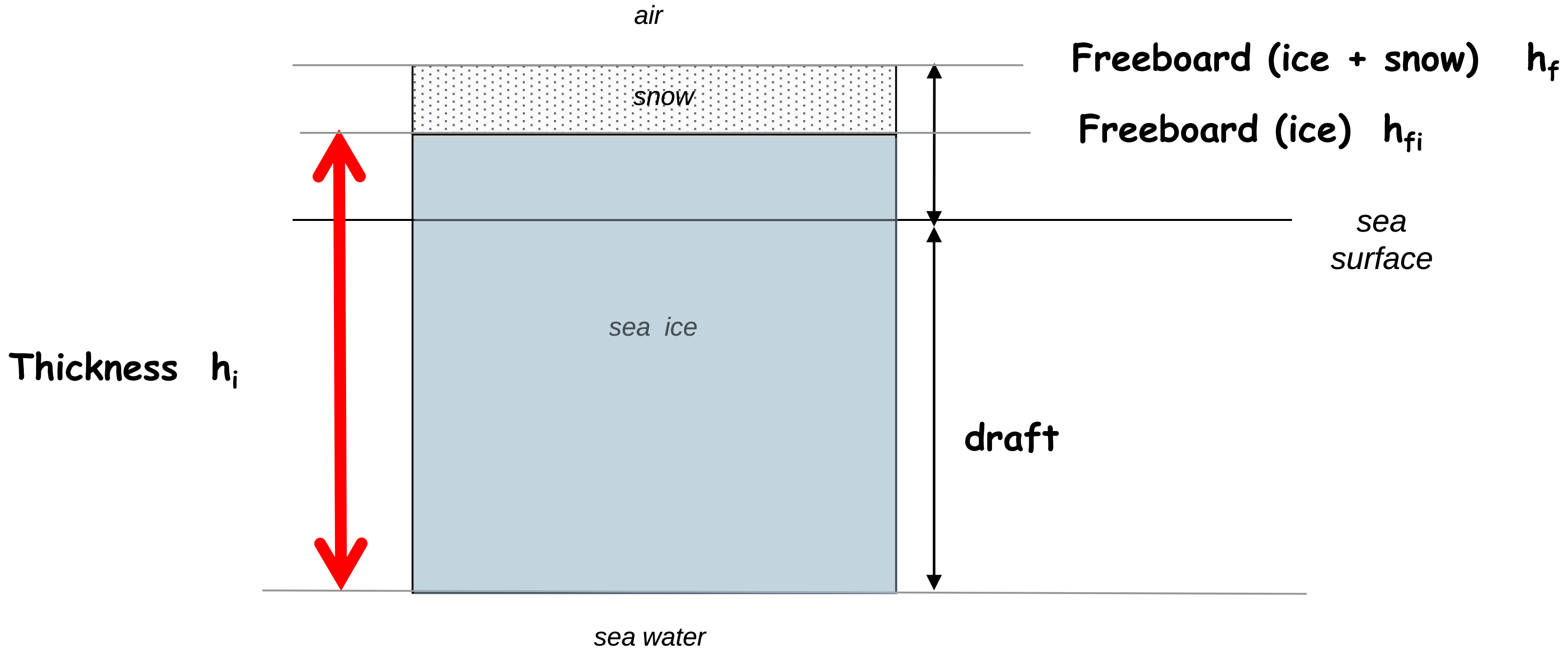
$$\rho_i^{FY} = 917\,\mathrm{kg\,m^{-3}} \text{ and } \rho_i^{MY} = 882\,\mathrm{kg\,m^{-3}}$$

Satellite technology

What are the challenges?

- for thickness calculations, altimetry has to provide:
  - Snow or ice surface relative to local sea surface
- Requirements on lidars/radars
  - High precision altimetry (centimeter level)
  - Resolution: Leads are narrow
  - Ice/water discrimination
- Snow depth
  - Modeling accumulation
  - Climatology
  - Empirical relationships between snow depth and freeboard

Freeboard, Snow depth, Ice Draft and Thickness

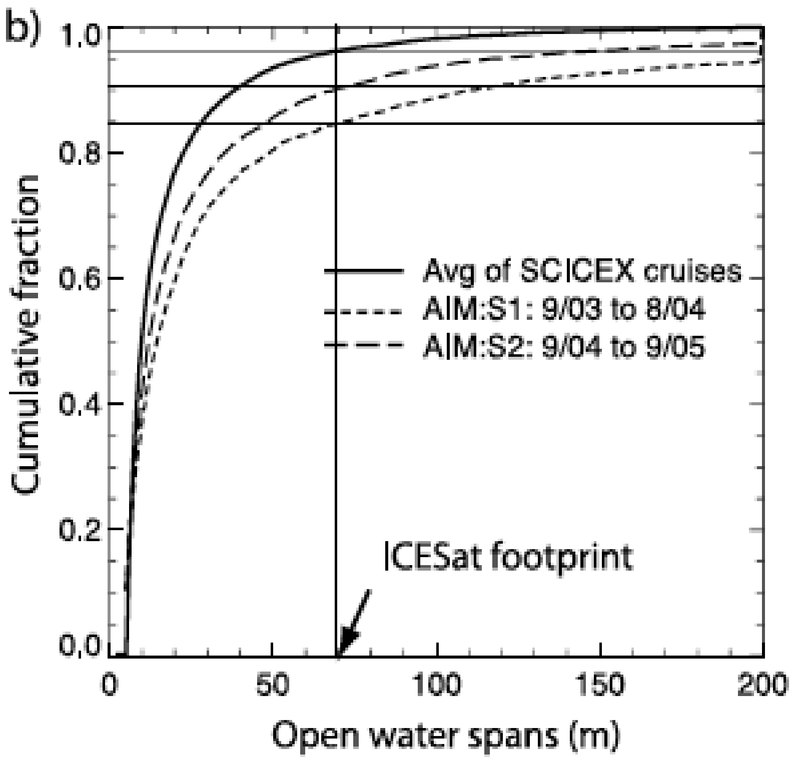


Isostatic Equilibrium

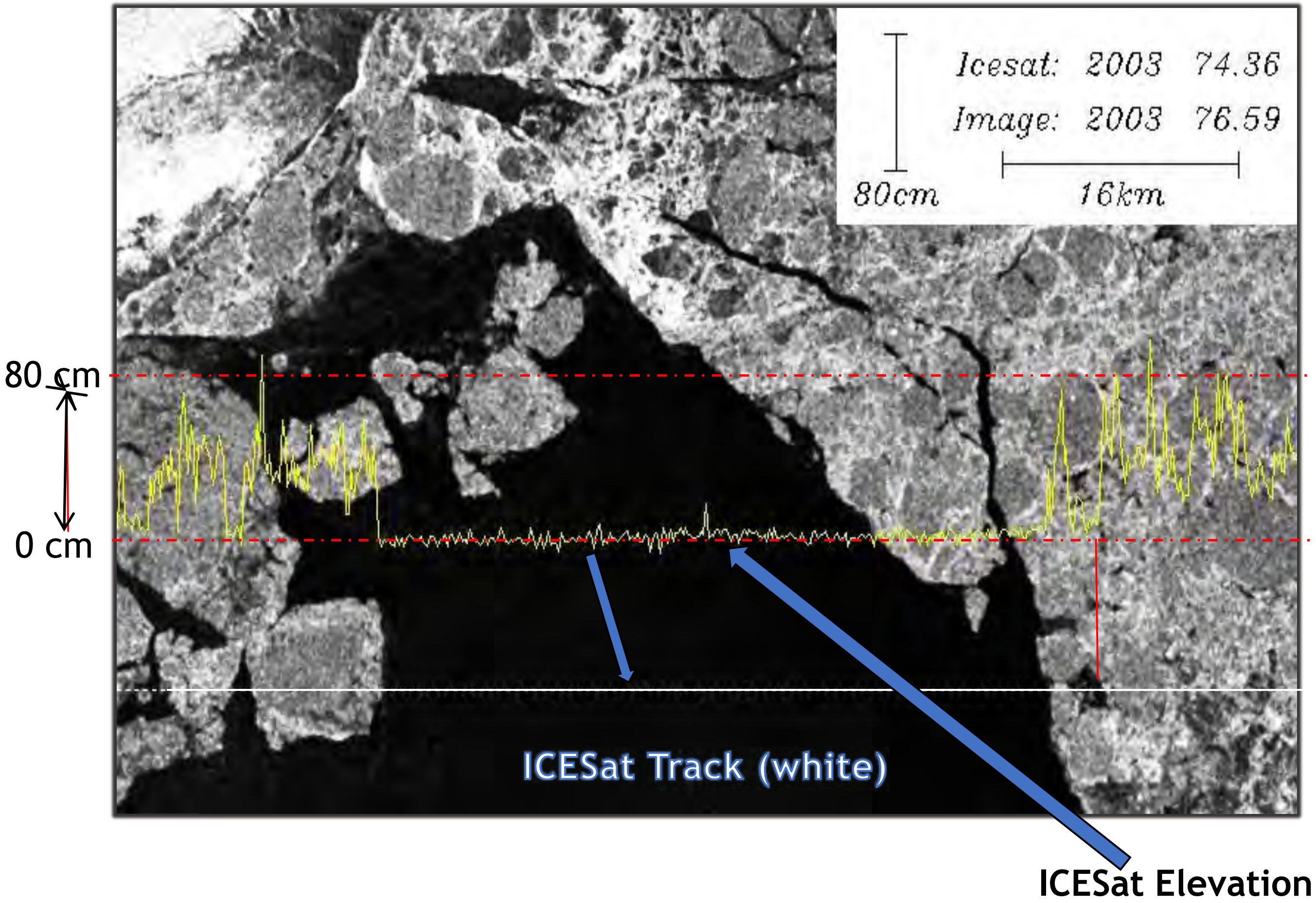
$$h_i = \left(\frac{\rho_w}{\rho_w - \rho_i}\right) h_f - \left(\frac{\rho_w - \rho_s}{\rho_w - \rho_i}\right) h_{fs} \quad \text{(lidar)}$$

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

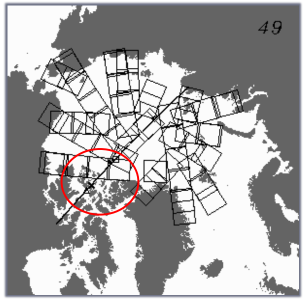
Leads are narrow



Profiling of sea ice freeboard from space

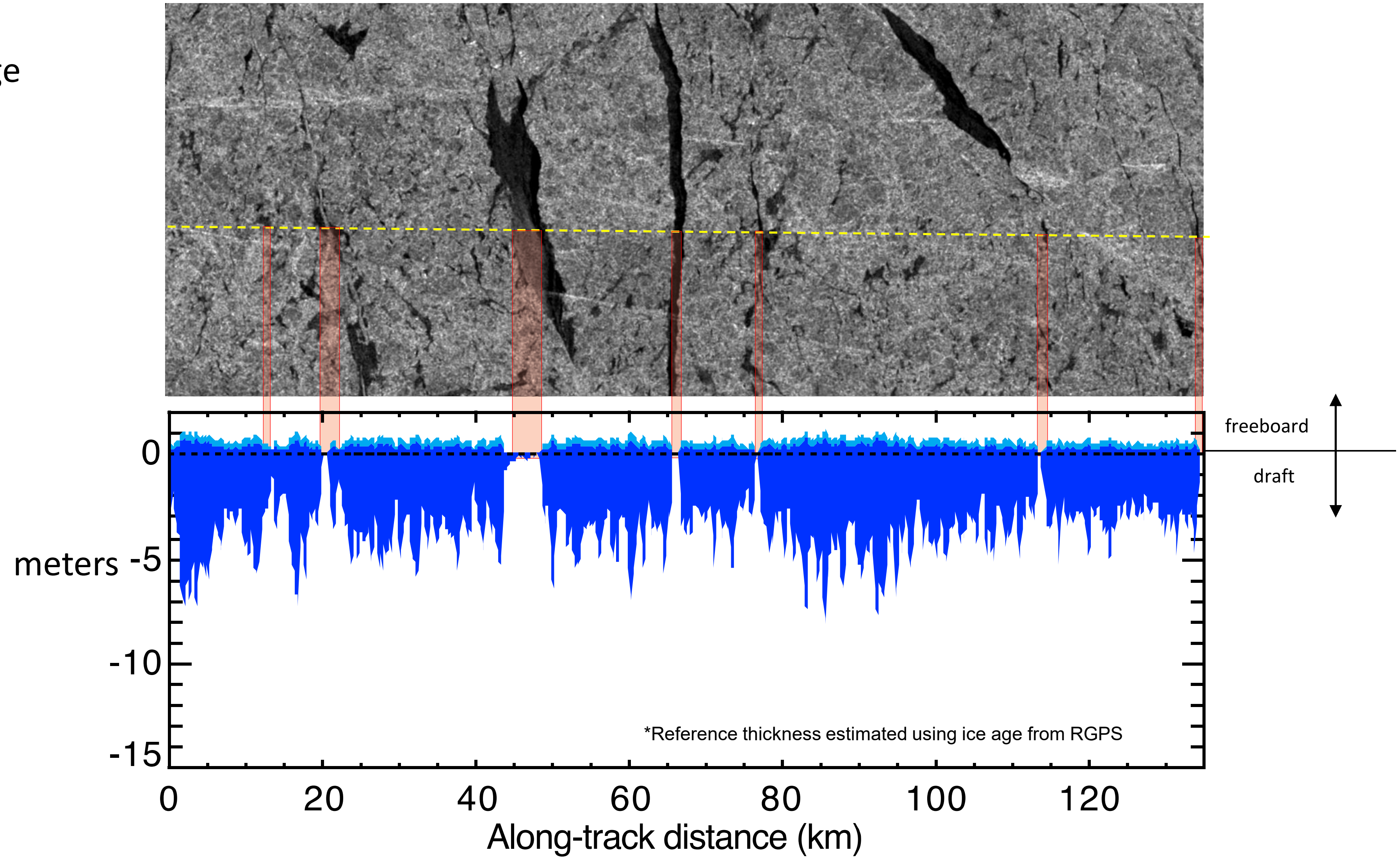


- ~1.5 - 2 cm

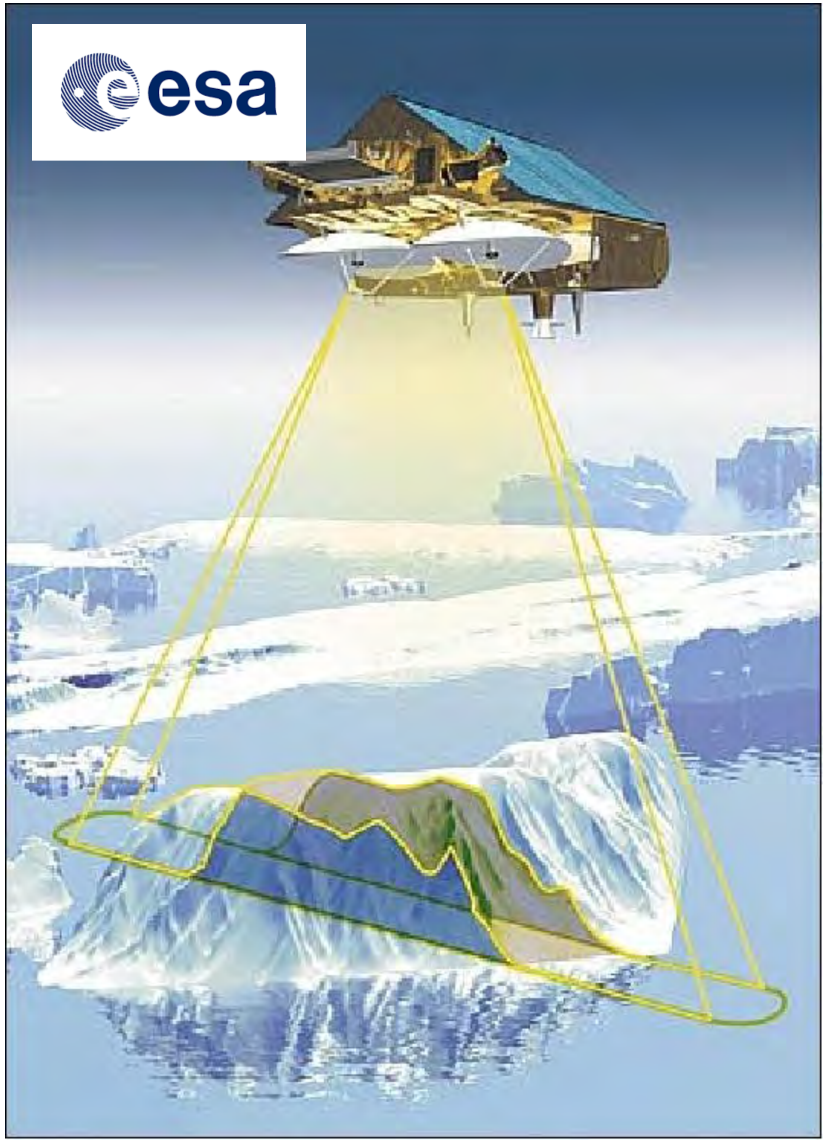


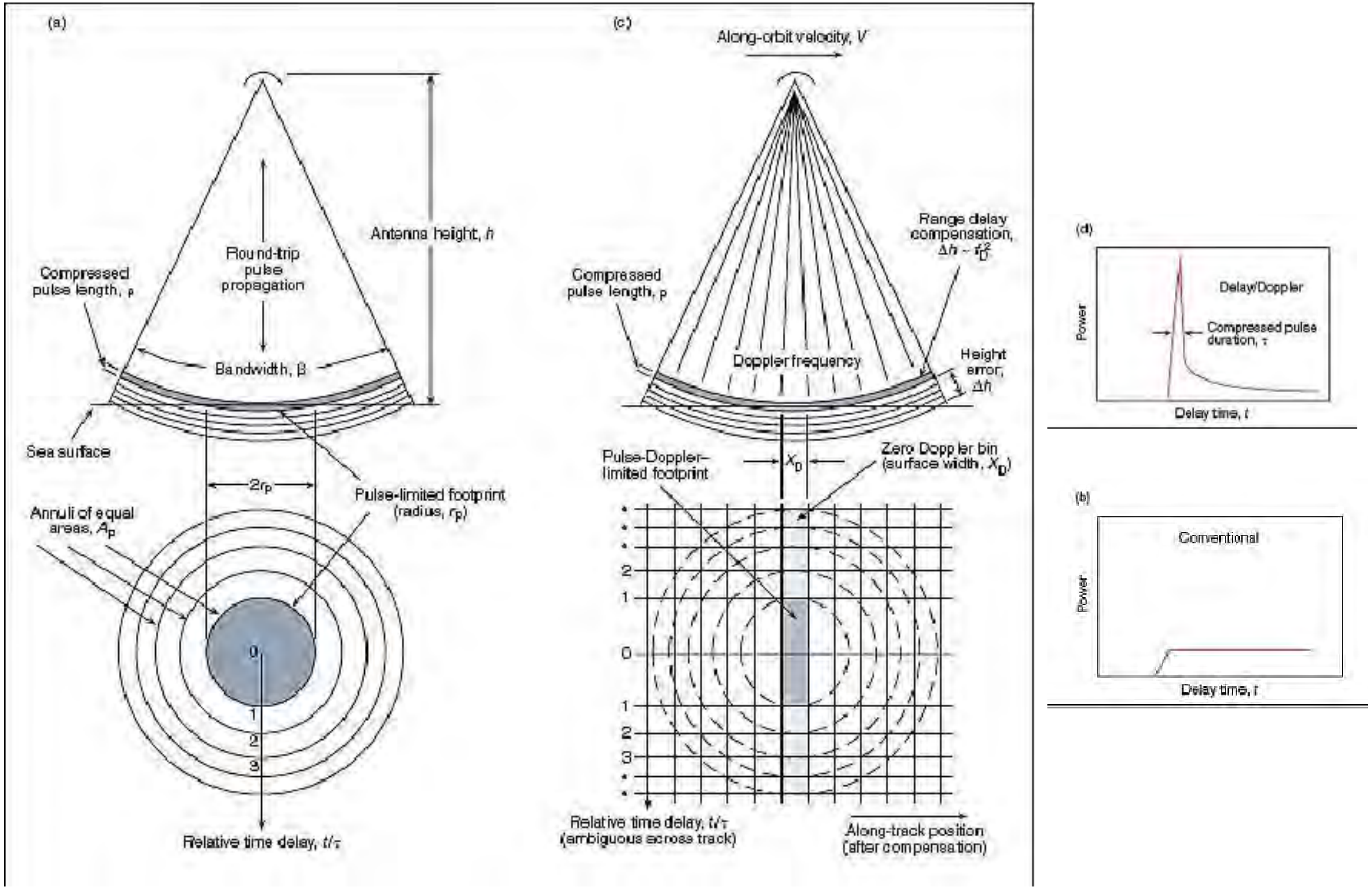
ICESat (profiling lidar) and RADARSAT (image)

ICESat track on RADARSAT image



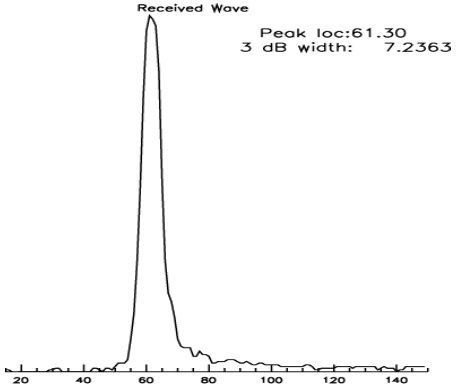
ESA's CryoSat-2
Delayed Doppler Synthetic Aperture





ICESat - GLAS lidar

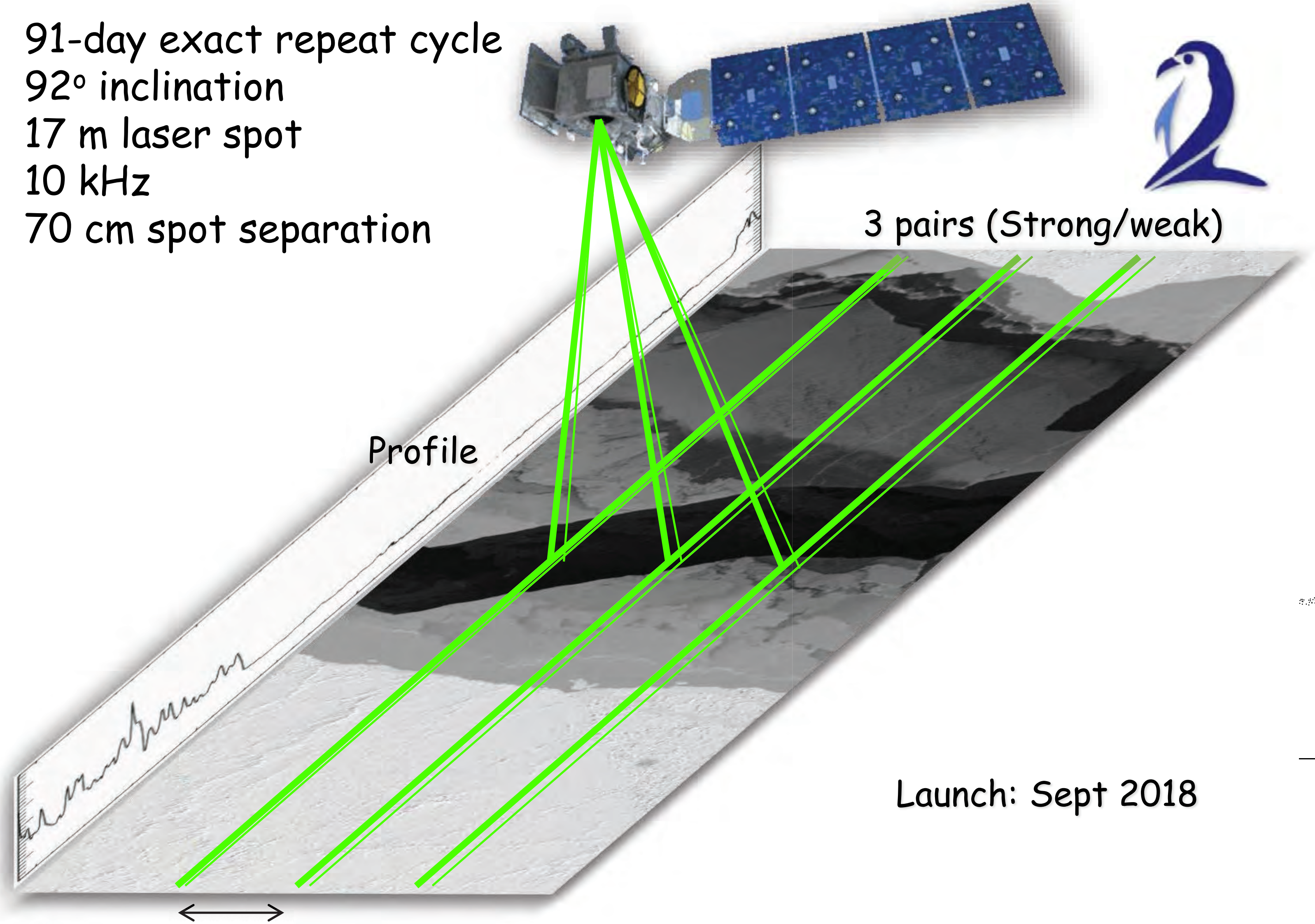
- Number of Lasers: 3 (two channels: 1064 nm and 532 nm)
- Laser divergence angle (beam width: 70-110 urad)
- Firing rate: 40 Hz (70 m on the ground; separation of ~170 m)
- Predicted accuracy of surface elevation: 15 cm
- Elevations from waveform tracking - not leading edge detection
- Pulse width: 6 ns
- Telescope: 100 cm
- Digitizer rate: 1 ns



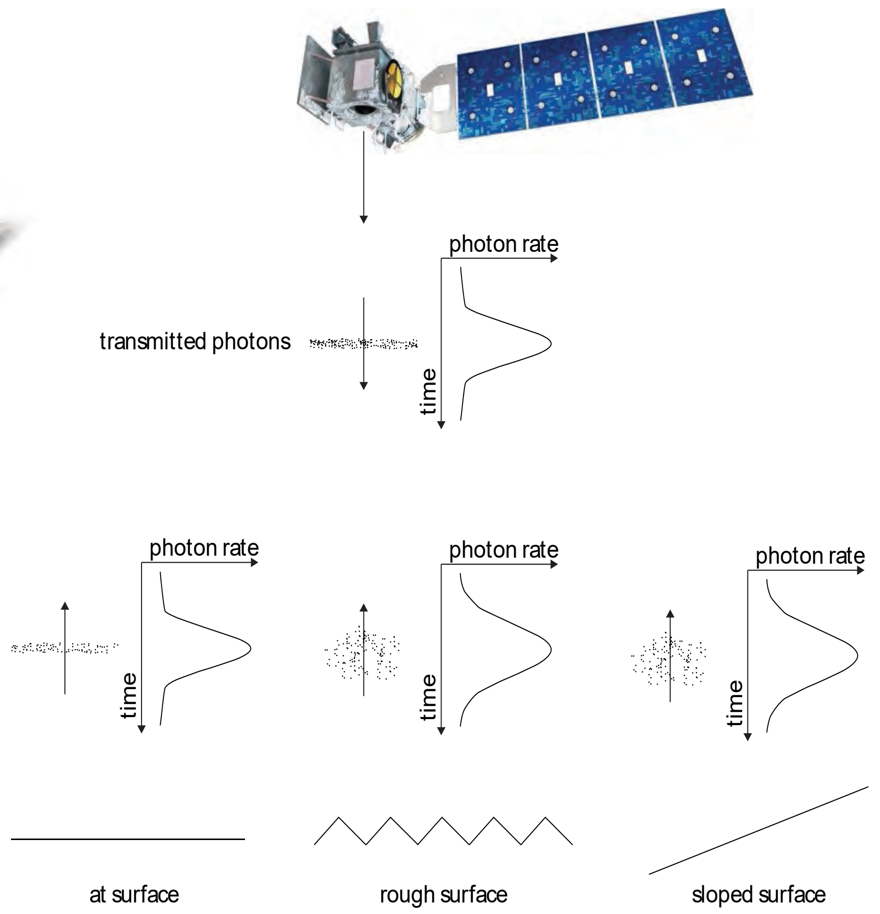
- ICESat
  - Inclination: 94 deg
  - Altitude: 600 km
  - Launched: Jan 2003
  - Status:
    - Laser 1 operation (activated 2/20; 3/29 failed)
    - Laser 2 operation
      - 3 campaigns
        - ~33-day each
        - 3 per year (Feb-Mar, May-Jun, Oct-Nov)
    - Laser 3
      - > 9 campaigns

Multibeam Photon Counting Altimetry -ATLAS

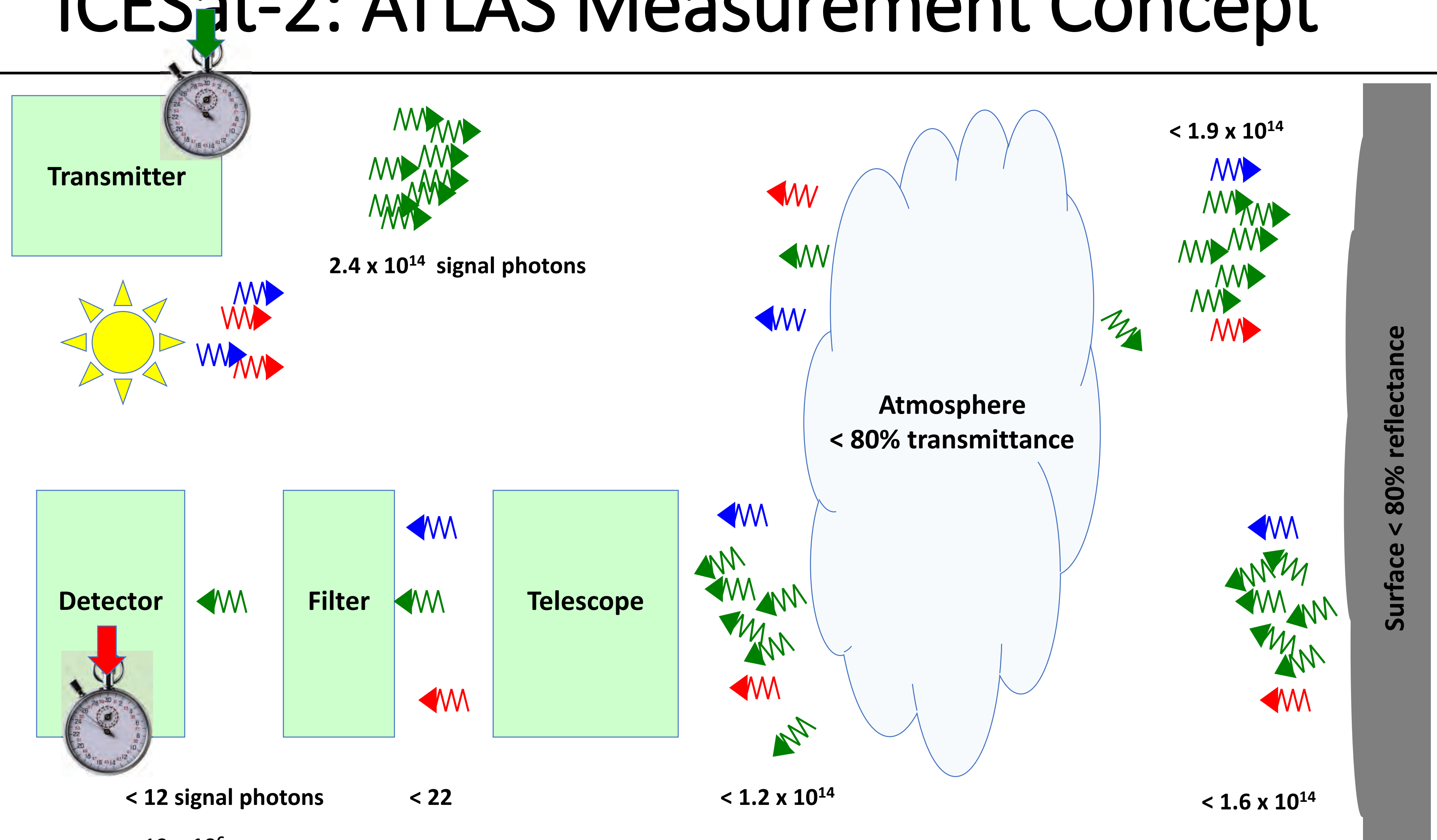
91-day exact repeat cycle
92° inclination
17 m laser spot
10 kHz
70 cm spot separation



Launch: Sept 2018

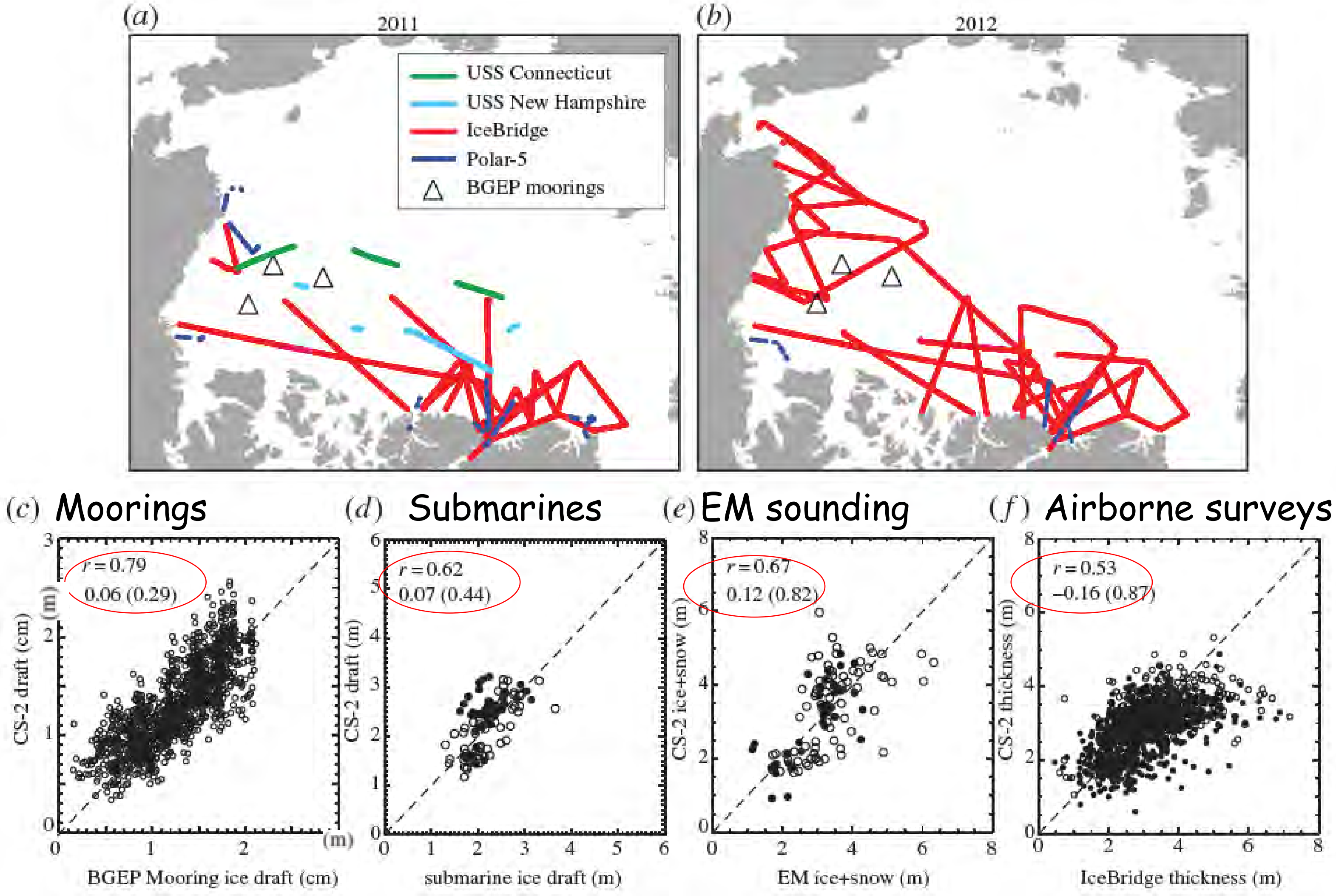


ICESat-2: ATLAS Measurement Concept



ATLAS reports times of laser firings and photon detections to the ground. Range and surface elevation are computed by data processing on the ground.

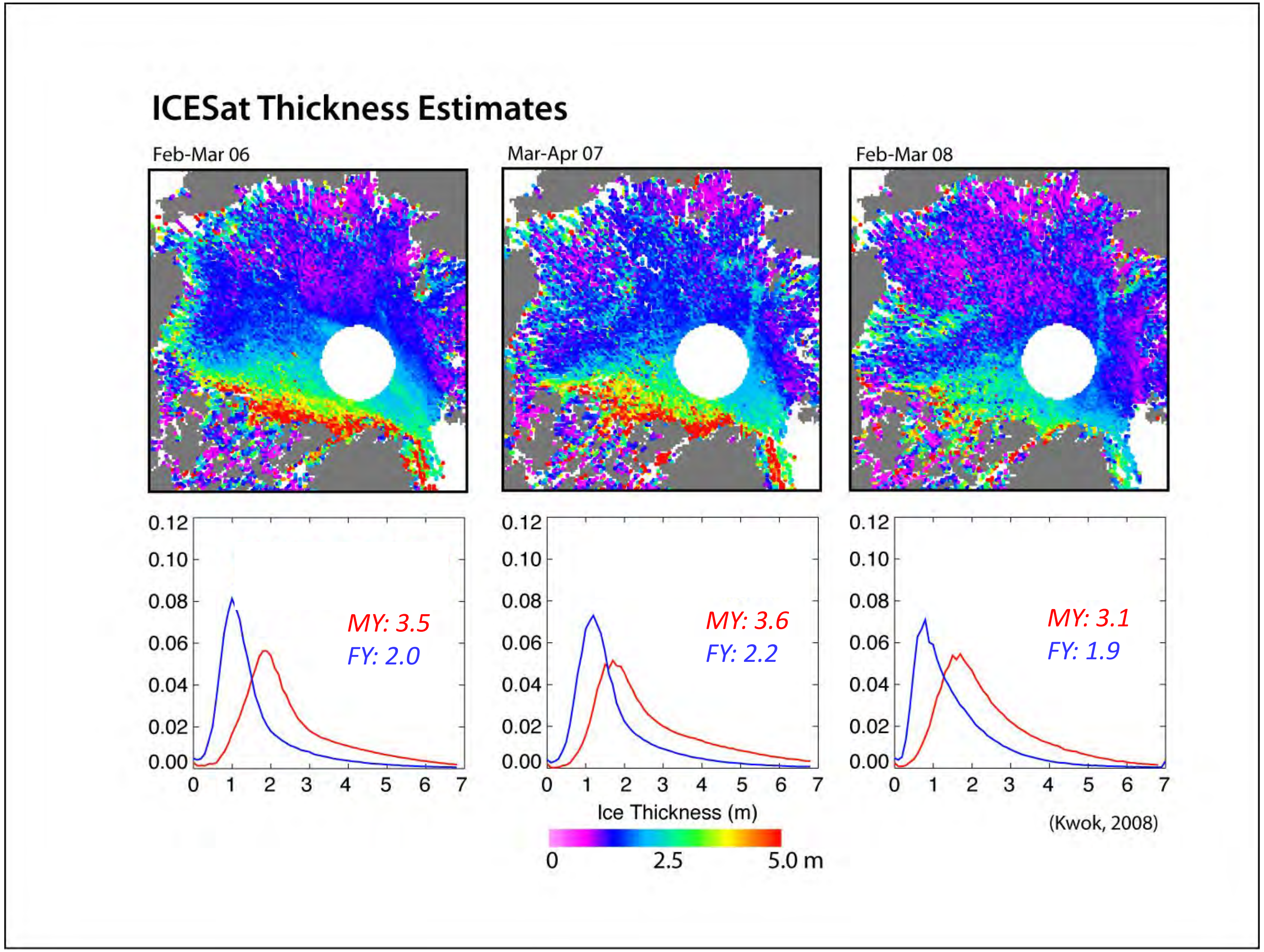
Assessment of CS-2 ice thickness retrievals



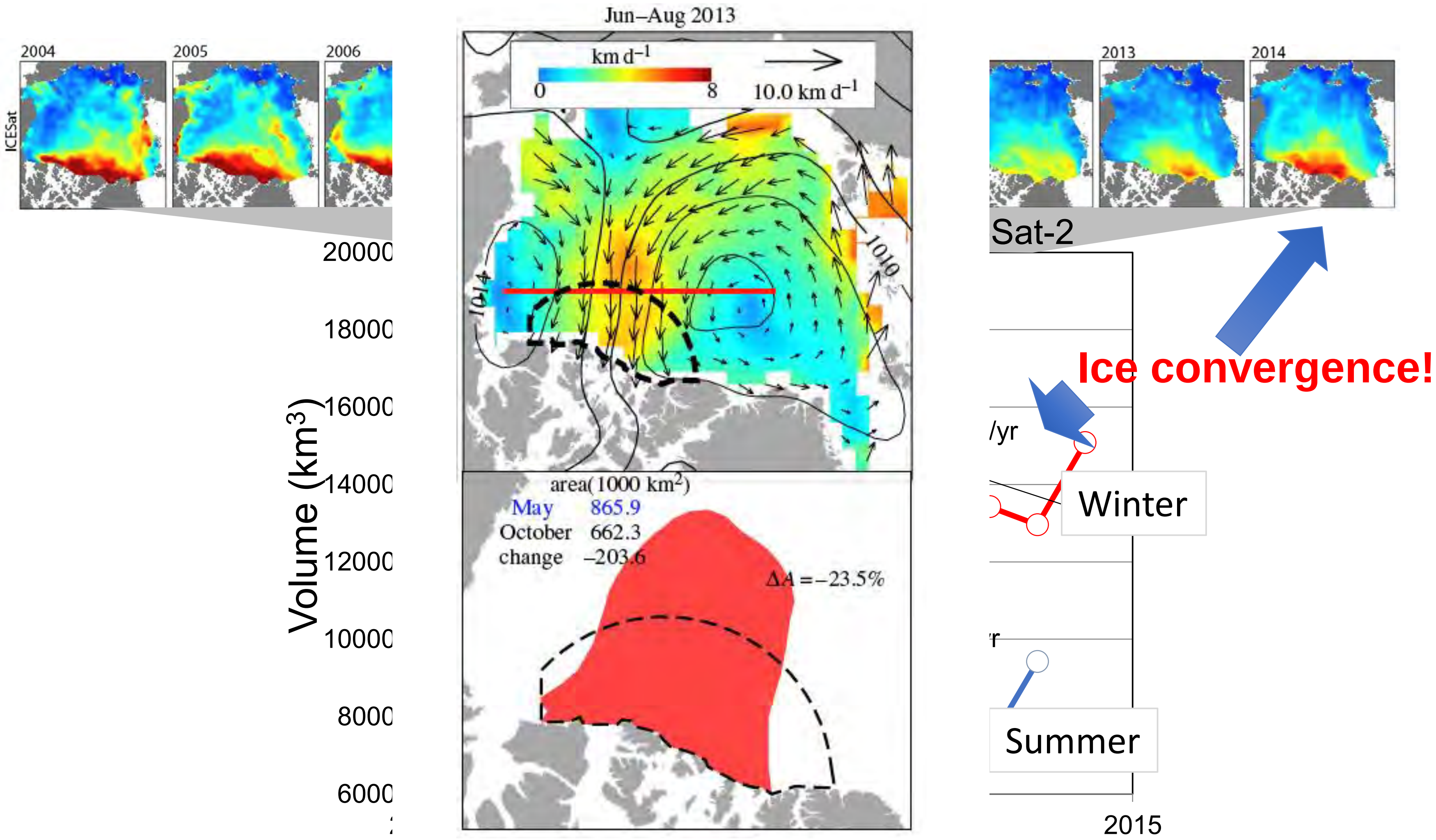
Kwok and Cunningham, 2013

Recent Results

Ice thickness from ICESat

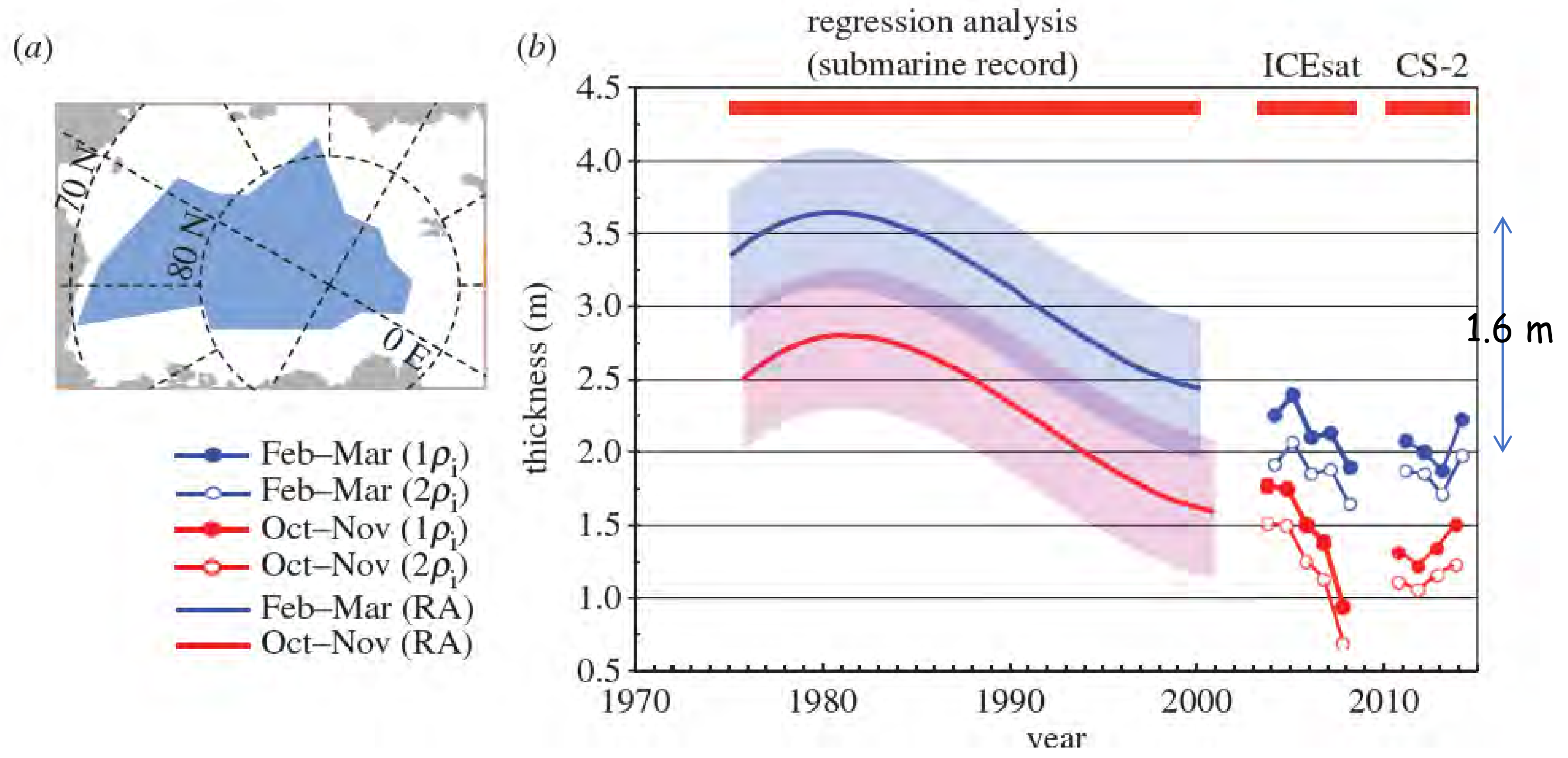


Trends in Arctic Sea Ice Volume 2003-2015



Kwok, R. and G. F. Cunningham (2015), Variability of Arctic sea ice thickness and volume from CryoSat-2, *Phil. Trans. R. Soc. A*, 373:20140157, doi:10.1098/rsta.2014.0157.

Decline in multiyear/thick sea ice coverage from scatterometers (1999-2014)



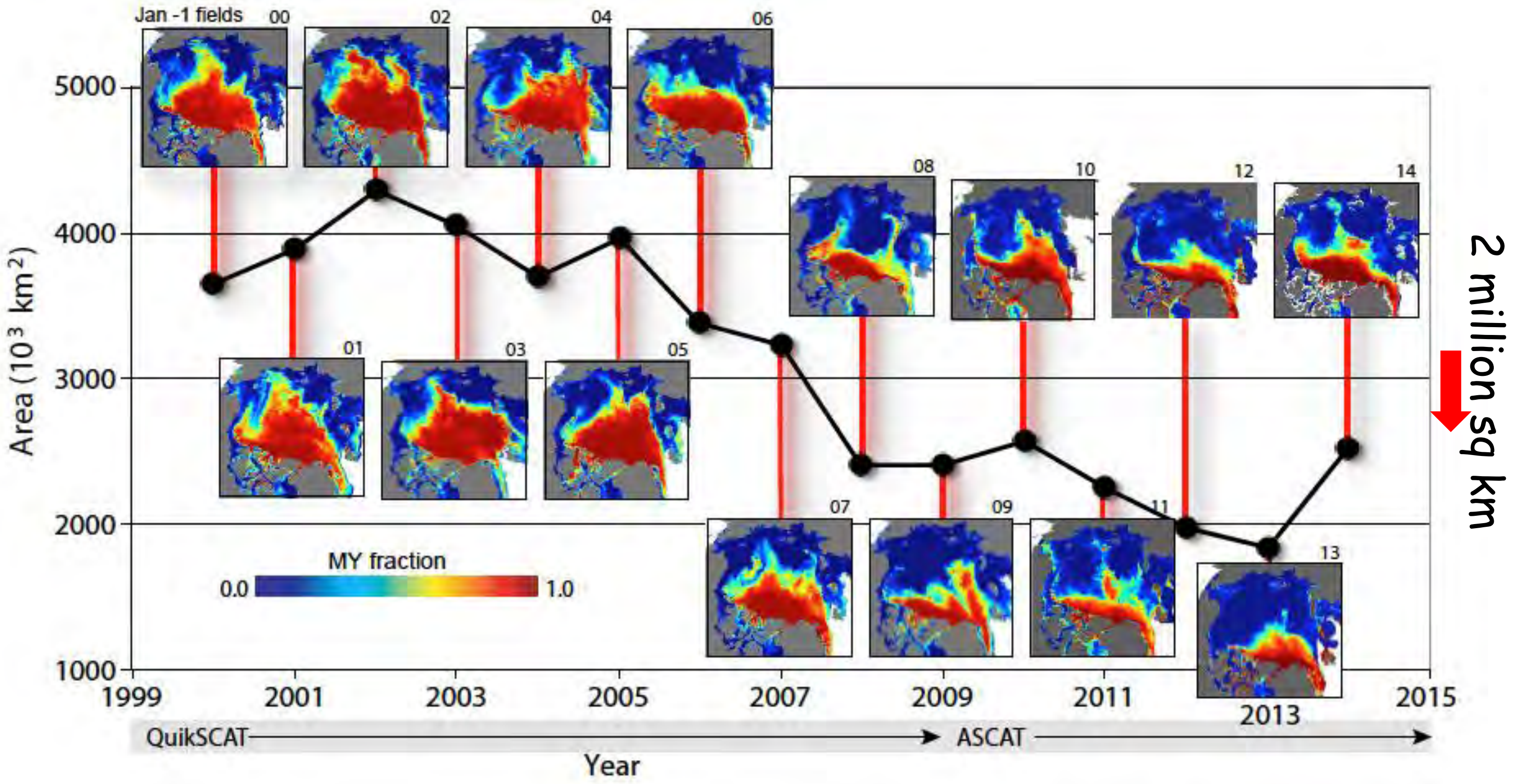
Summary Remarks

- Altimetry and sea ice science

- On-orbit and upcoming missions:
  – CryoSat-2, AltiKa, Sentinel-3, and ICESat-2

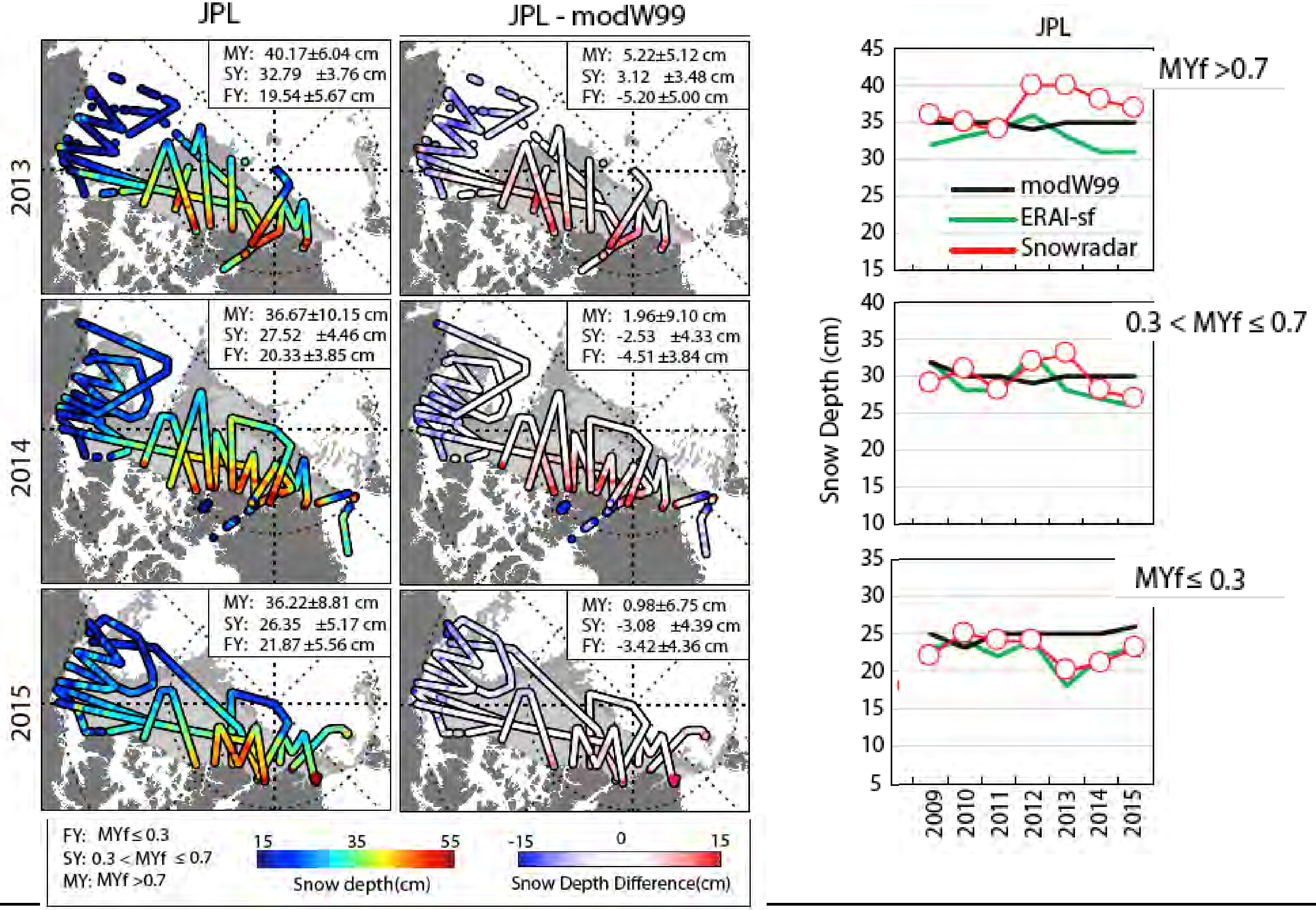

Thank you

Decline in multiyear/thick sea ice coverage from scatterometers (1999-2014)



$$\rho_i(f_{FY}) = \rho_i^{MY}(1 - f_{FY}) + \rho_i^{FY} f_{FY}.$$

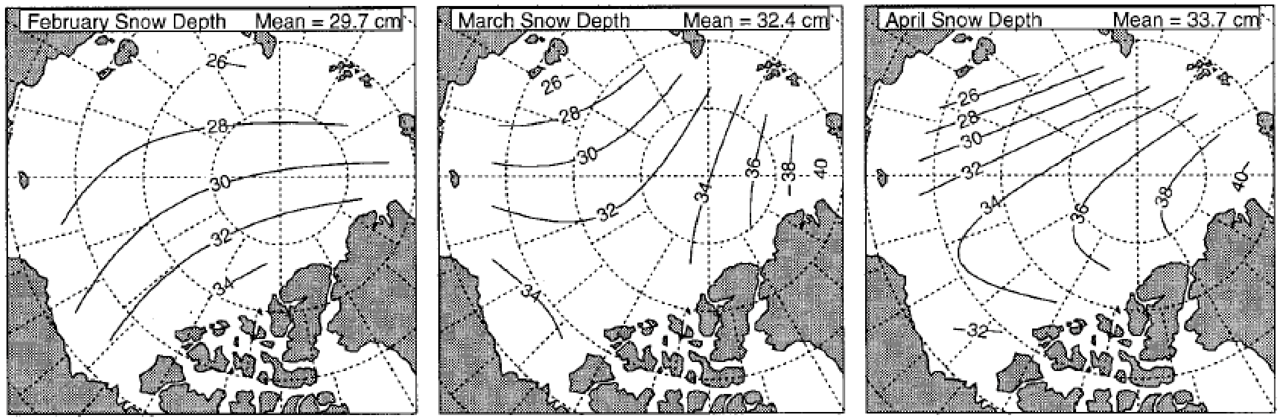
Comparison with airborne snow radar /ERA-interim



What about thickness of the Southern Ocean ice cover?

- Current understanding of changes based only on ice coverage
- Geophysical issues are more complex
  - no snow climatology to speak of
    - much higher precipitation (to ~1 m)
  - very few thickness measurements for validation
  - flooding and snow-ice formation

Snow loading (Spatial distribution + density)



snow loading

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

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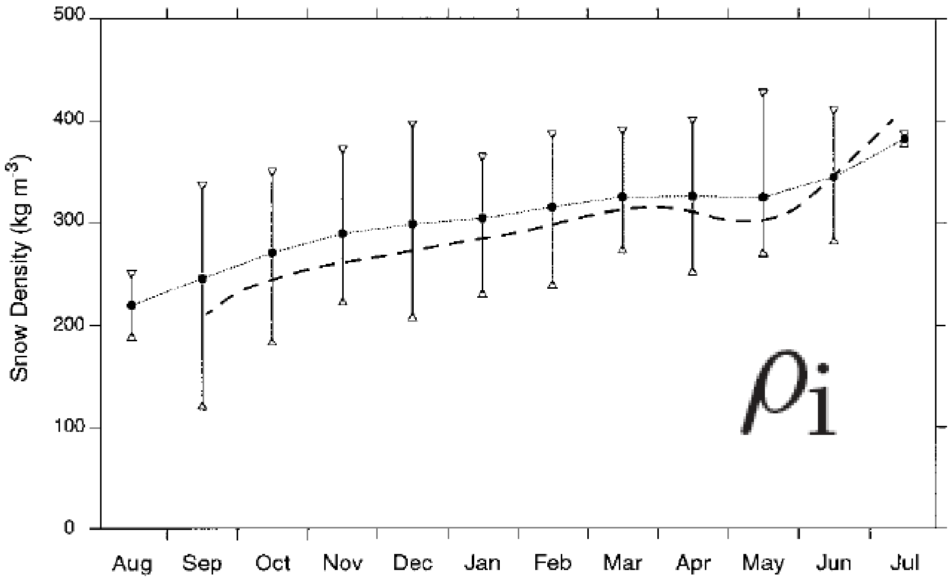
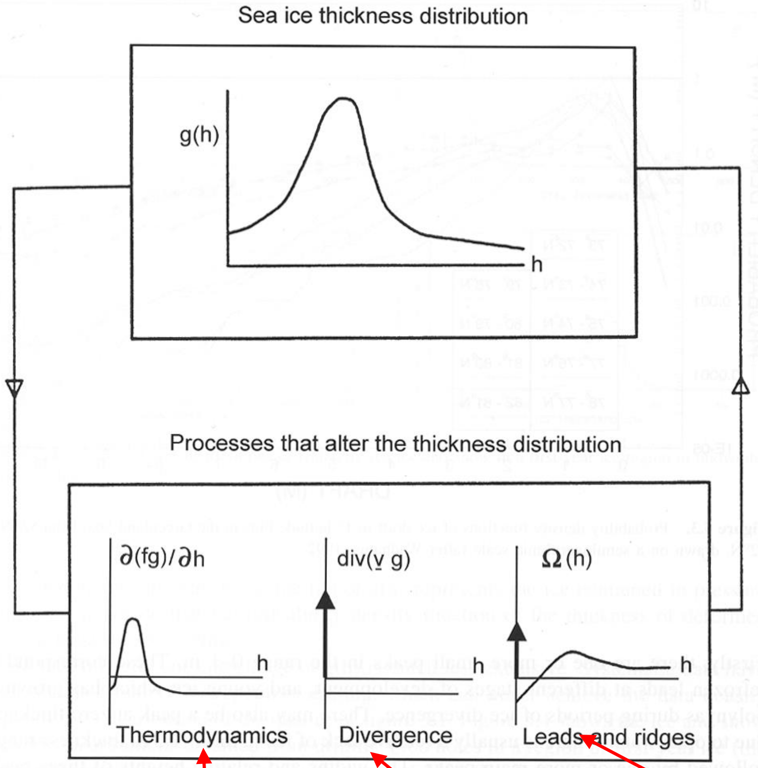


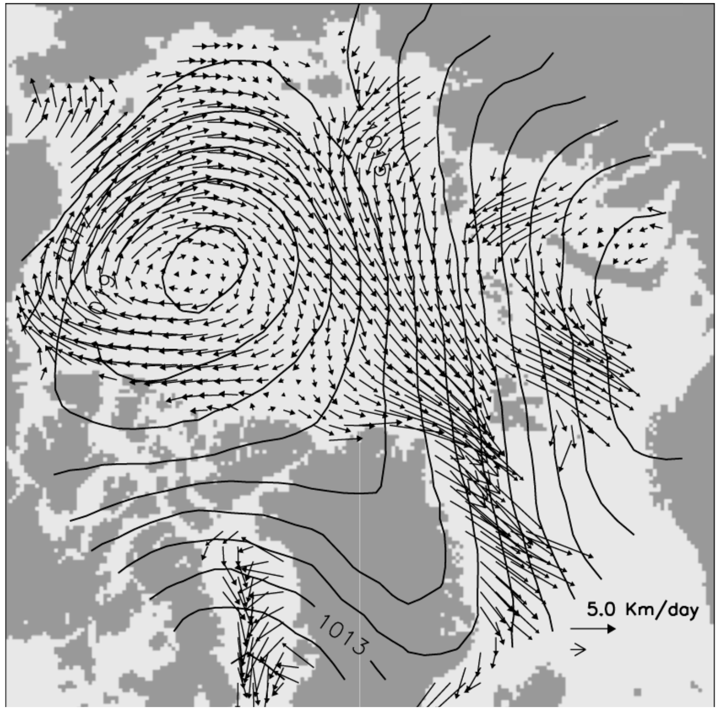
A Framework for understanding the ice thickness distribution g(h)



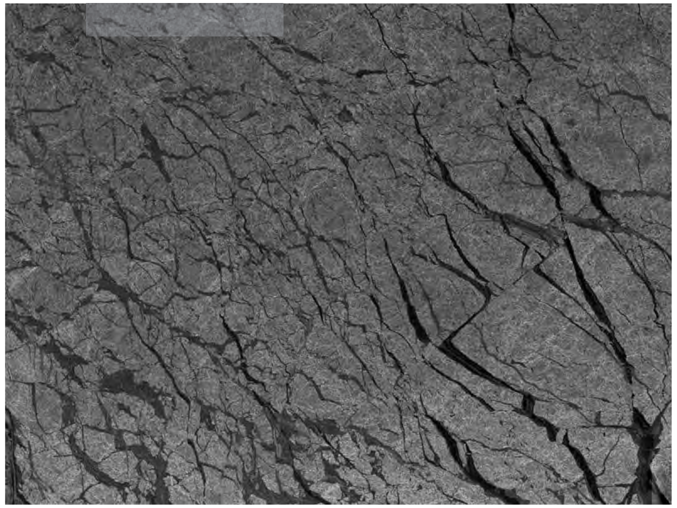
$$\frac{\partial g}{\partial t} = -\frac{\partial (fg)}{\partial h} - \nabla \times (ug) + \Psi$$

Ice Drift (Different length scales)

2000 km



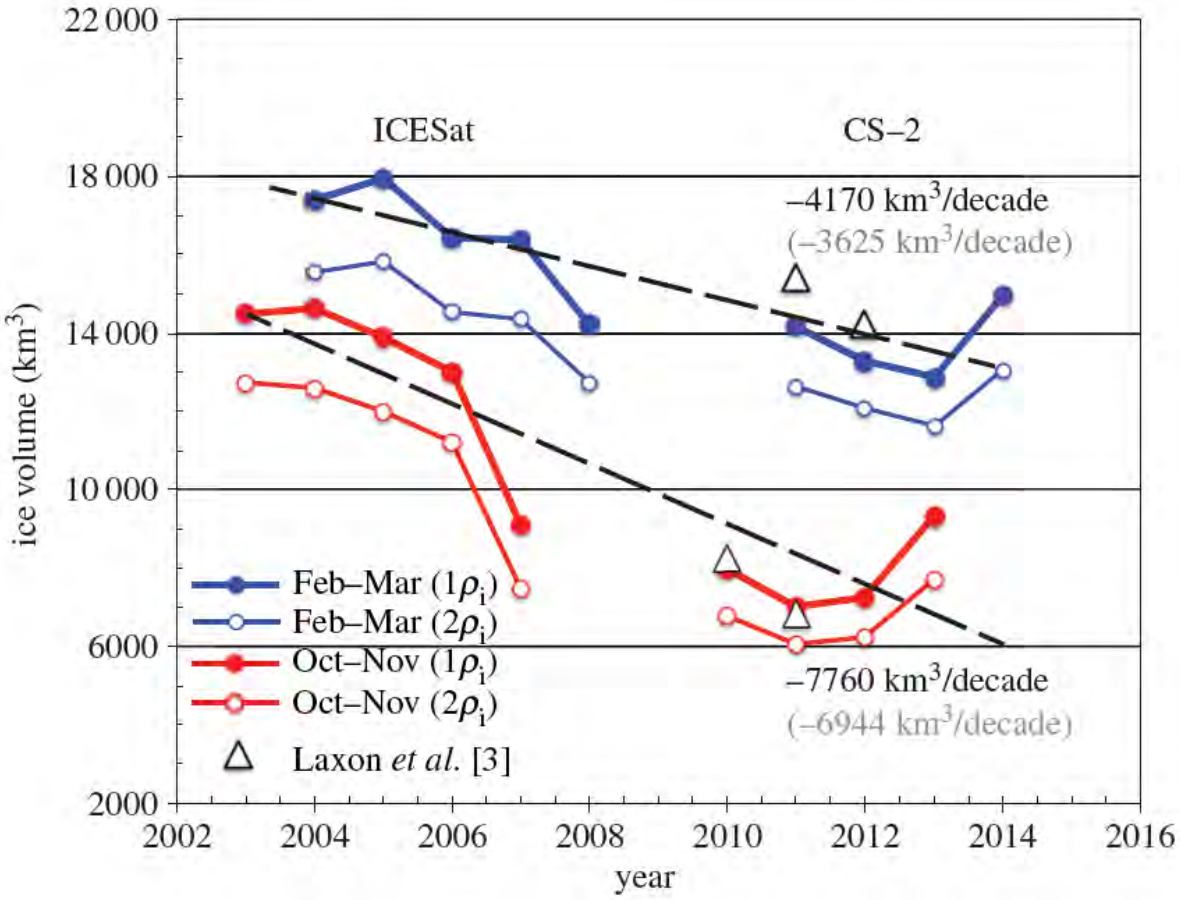
100 km



ICE is a SOLID!

All large scale ‘gradients’ are concentrated in cracks and fractures

Arctic Ocean ice volume with density adjustments



Decline in multiyear/thick sea ice coverage from scatterometers (1999-2014)