Remote sensing of sea ice

Ice concentration/extent

Age/type

Drift

Melting

Thickness

Christian Haas

Remote Sensing Methods

- **Passive**: senses shortwave (visible), thermal (infrared) or microwave radiation emitted by Earth
  - SSMI/AMSR: microwave 19-89 GHz, V and H polarization
    - Global ice coverage (25 km resolution)
  - AVHRR: optical & thermal (5 bands)
    - Ice coverage, ice temperature, ice drift (1 km resolution)
  - MODIS: optical & thermal (36 bands)
    - Ice coverage & processes, melt (250 m resolution)
- **Active**: actively transmits microwave (radar) or shortwave
  - Radar (e.g. Radarsat, Quikscat) C- & Ku-band (5-13 GHz)
    - Ice types, surface roughness, ice drift, ice melt (3-75 m resolution)
  - Altimeters (laser and radar; e.g. ICESat, CryoSat)
    - Ice freeboard & thickness (300 m resolution, one-dimensional)

Microwave Remote Sensing

- Can “see” through clouds and snow
- Independent of daytime/solar radiation

- **Passive**: Low spatial resolution, but daily, global coverage
- **Active** (radar): High spatial resolution, narrow swaths

- Exclusive use of polar orbiting satellites

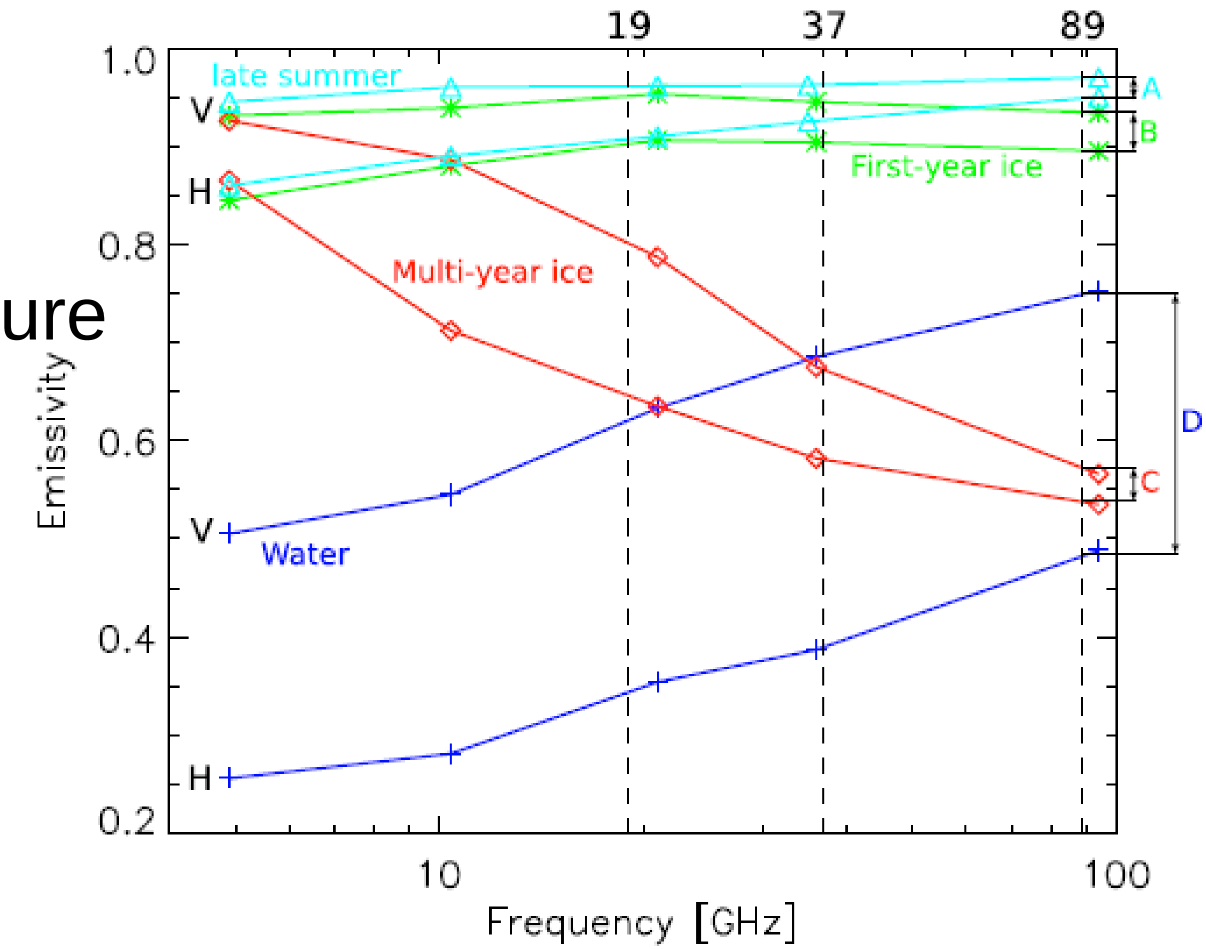
Satellite-measured surface brightness temperature T_b

$$T_b = \varepsilon T_0$$

ε: Emissivity

T_0: Surface temperature

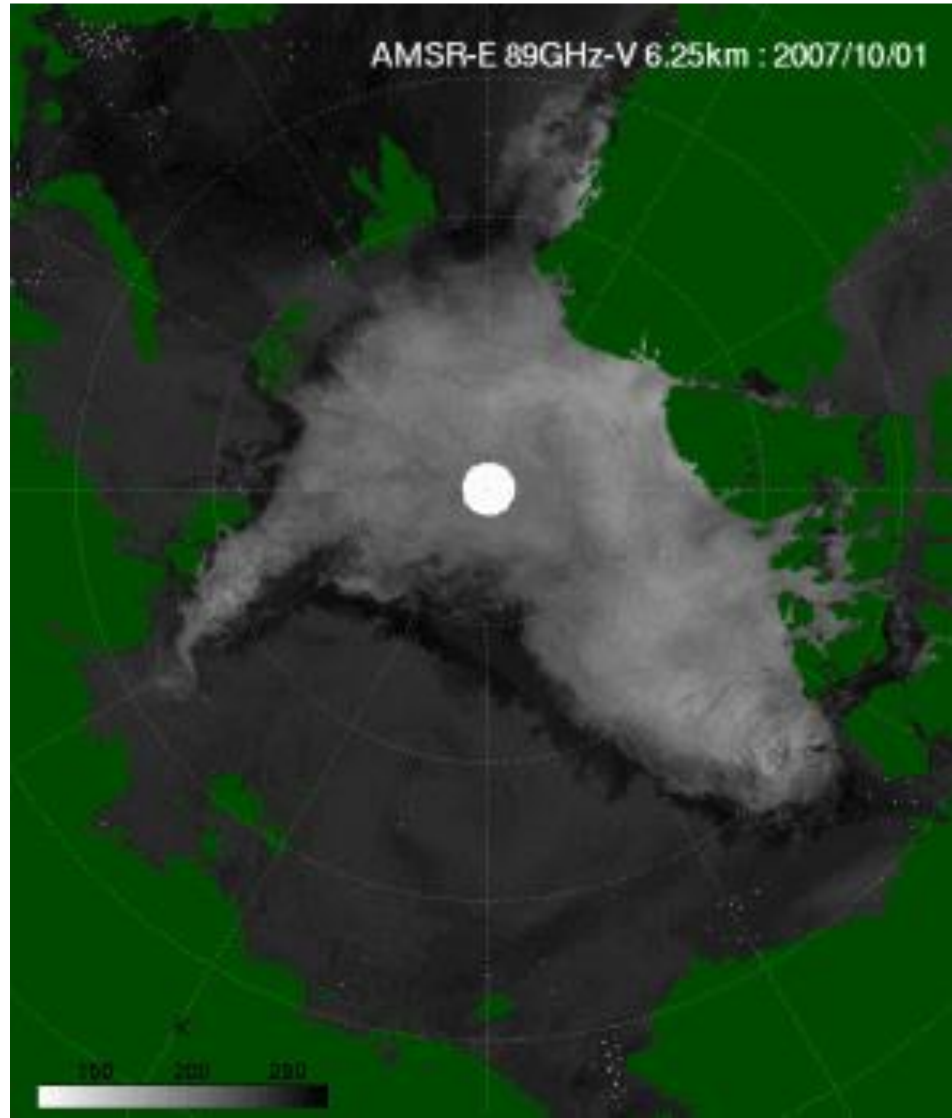
- Water: low emissivity
- Multiyear ice: intermediate emissivity
- First-year ice: high emissivity
- Varies with frequency and polarization



H- and V-pol emissivity at 50° incidence angle (Spreen et al., 2008)

Brightness temperature of the Arctic Ocean

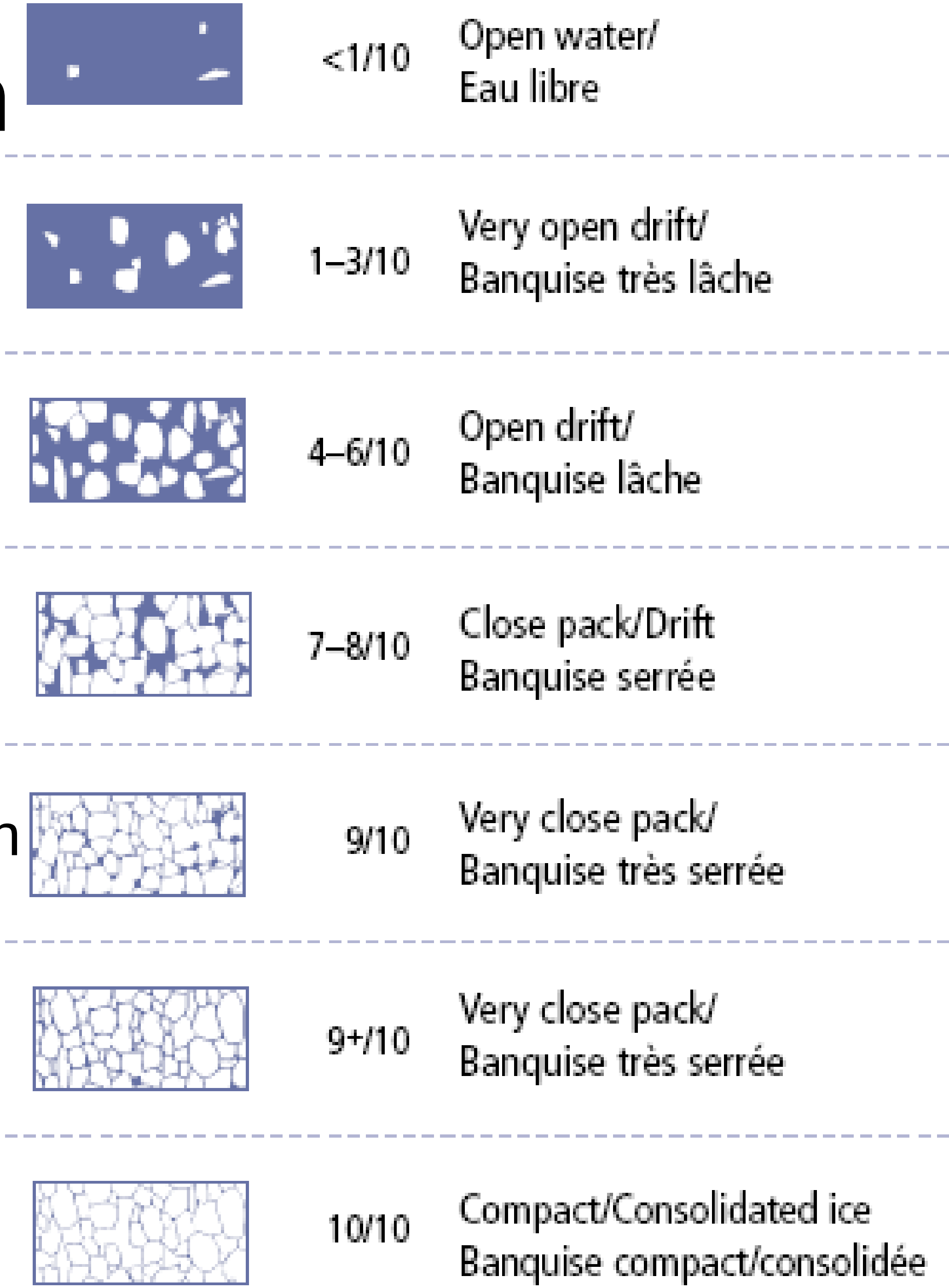
- September 2007 – April 2008
- **A**dvanced **M**icrowave **S**canning **R**adiometer (higher spatial resolution 6.25 km)
- Died on October 4, 2011



Koji Shimada of JAMSTEC (Japan Agency for Marine-Earth Science and Technology)

Ice concentration

- The ice cover is composed of ice floes and is discontinuous, often with a gradual transition to open water
- Ice coverage is normally given as ice concentration, in 1/10s or %



Retrieval of ice concentration: "NASA Team Algorithm"

Ice/water mixture

$$T_{B,ij} = C_W T_{B,W,ij} + C_{FY} T_{B,FY,ij} + C_{MY} T_{B,MY,ij}$$

$$PR[18] = \frac{T_B[18V] - T_B[18H]}{T_B[18V] + T_B[18H]}$$

Polarization ratio

$$GR[37V/18V] = \frac{T_B[37V] - T_B[18H]}{T_B[37V] + T_B[18H]}$$

Gradient ratio

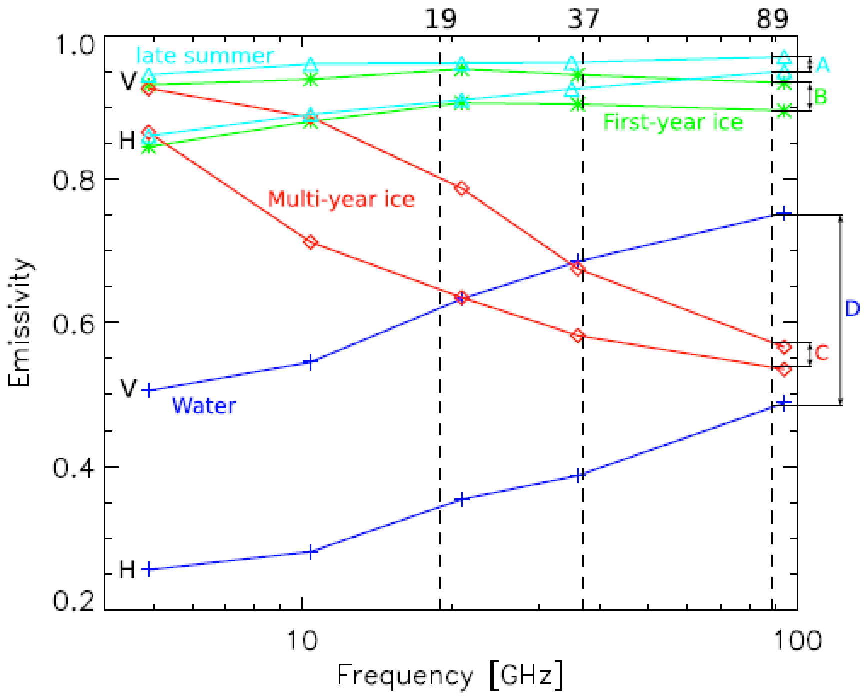
$$C_{FY} = \frac{F_0 + F_1 PR + F_2 GR + F_3 (PR)(GR)}{D}$$

$$C_{MY} = \frac{M_0 + M_1 PR + M_2 GR + M_3 (PR)(GR)}{D}$$

$$D = D_0 + D_1 PR + D_2 GR + D_3 (PR)(GR)$$

D: based on observed T_bs

$$C_T = C_{FY} + C_{MY}$$



NASA Team algorithm

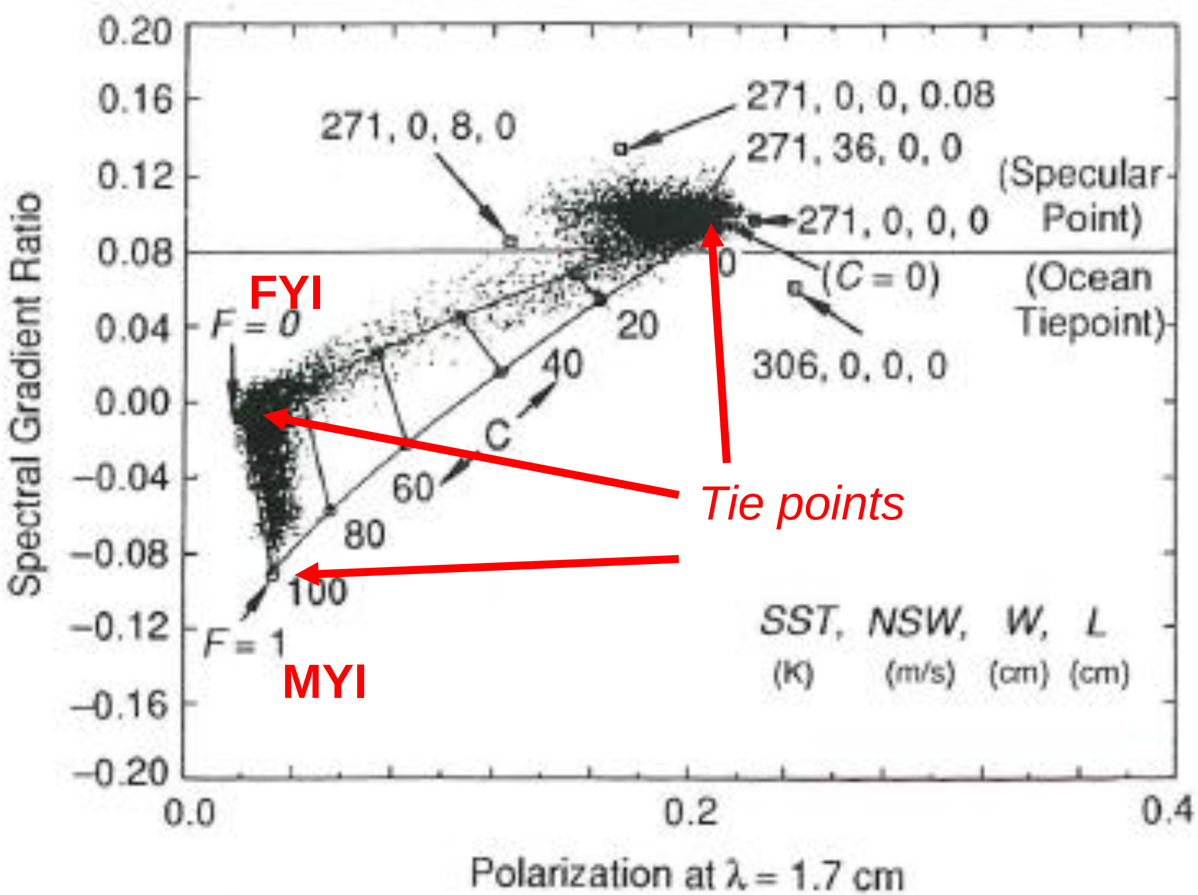
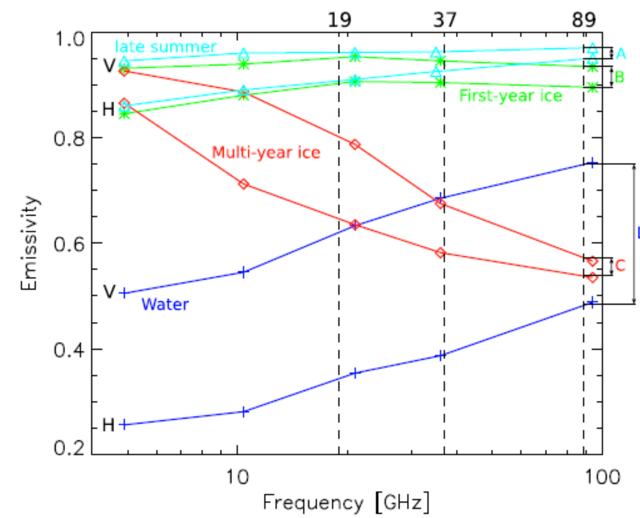
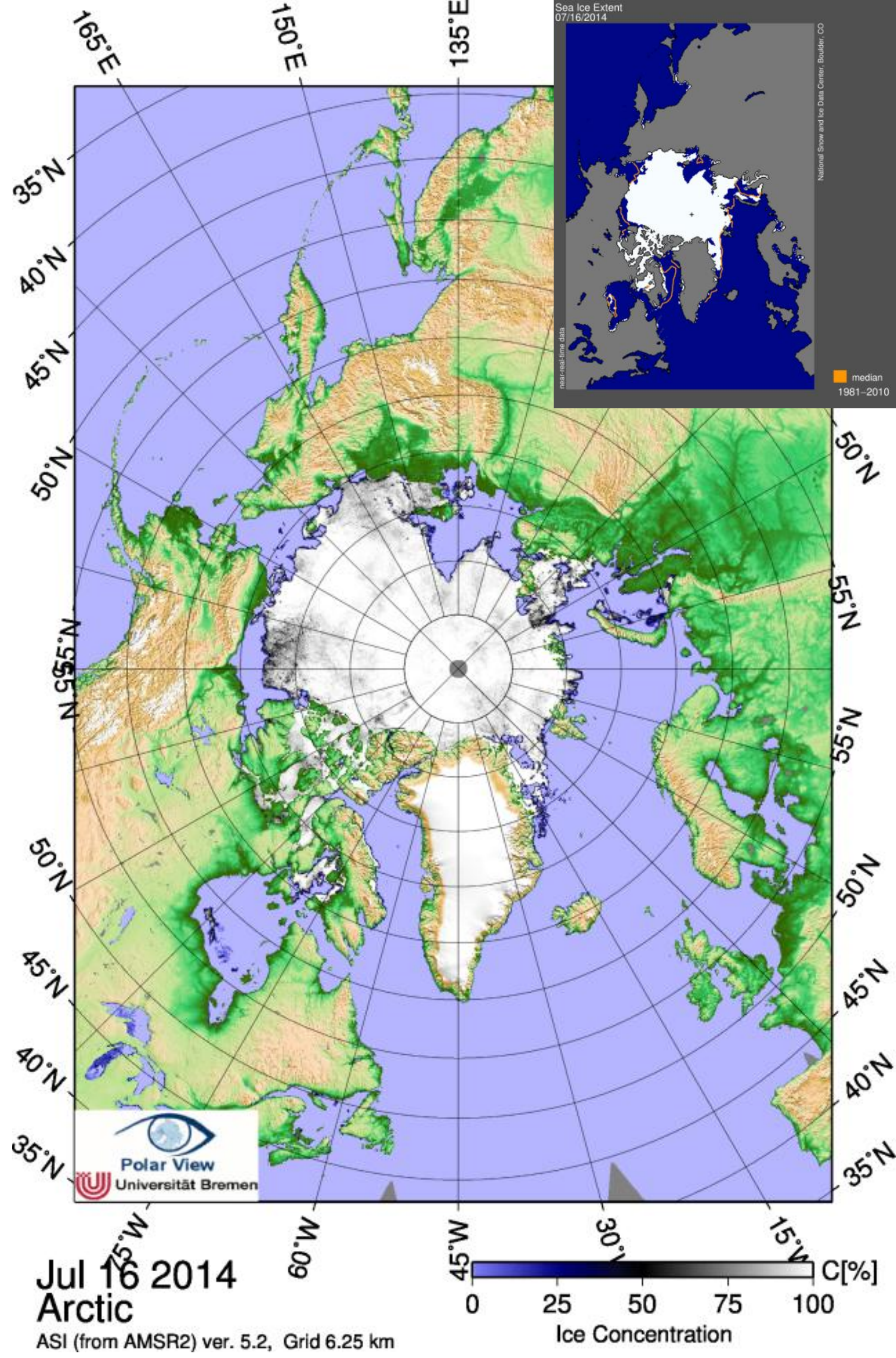


Fig. 10-2. Spectral gradient ratio versus polarization at 1.7 cm for the north polar area, February 3 to 7, 1979. The curved triangle is a representation of the algorithm used to calculate sea-ice concentration and age. Terms are listed as sea-surface temperature (K), near-surface wind (m/s), water vapor (cm), and cloud droplets (cm). The arrows indicate model calculation of *GR* and *PR* deviations from cold, specular, oceanic conditions [Gloersen and Cavalieri, 1986].



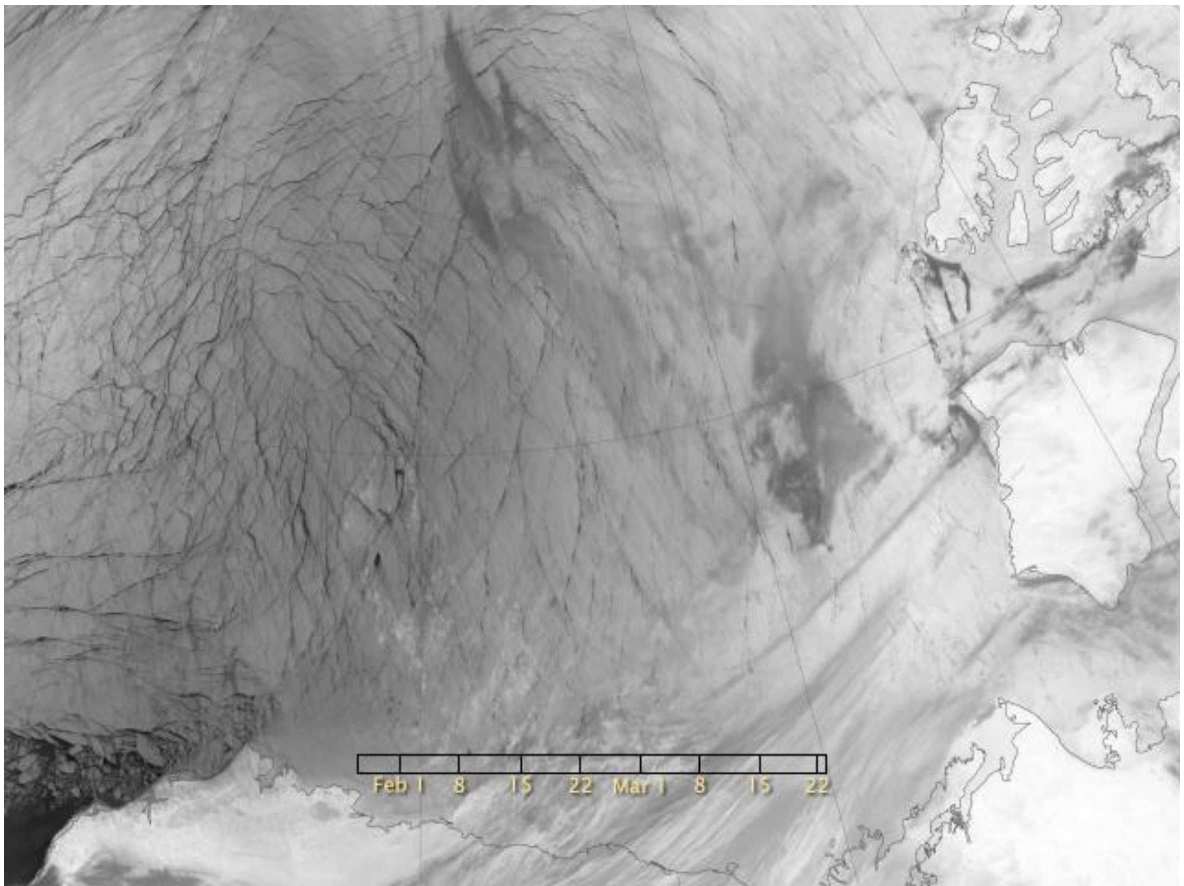
Ice extent vs. area

- Ice Extent: area A_e enclosed by 15% ice concentration isoline
- Ice Area: Actual area covered by ice, accounting for ice concentration < 100%, i.e. A_e * C



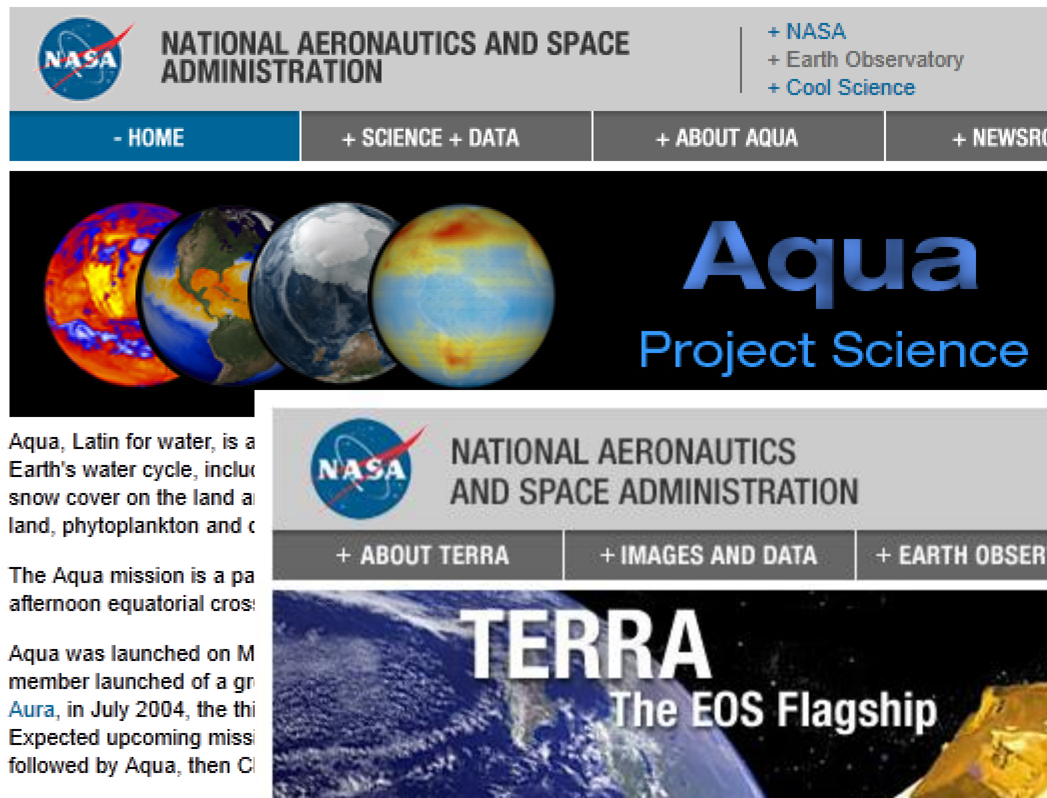
Advanced Very High Resolution Radiometer (AVHRR)

- Based on SW reflectivity and IR emission; 1 km resolution (@ nadir)
- First-of its kind, valuable mesoscale ice information
- Leads often appear exaggerated

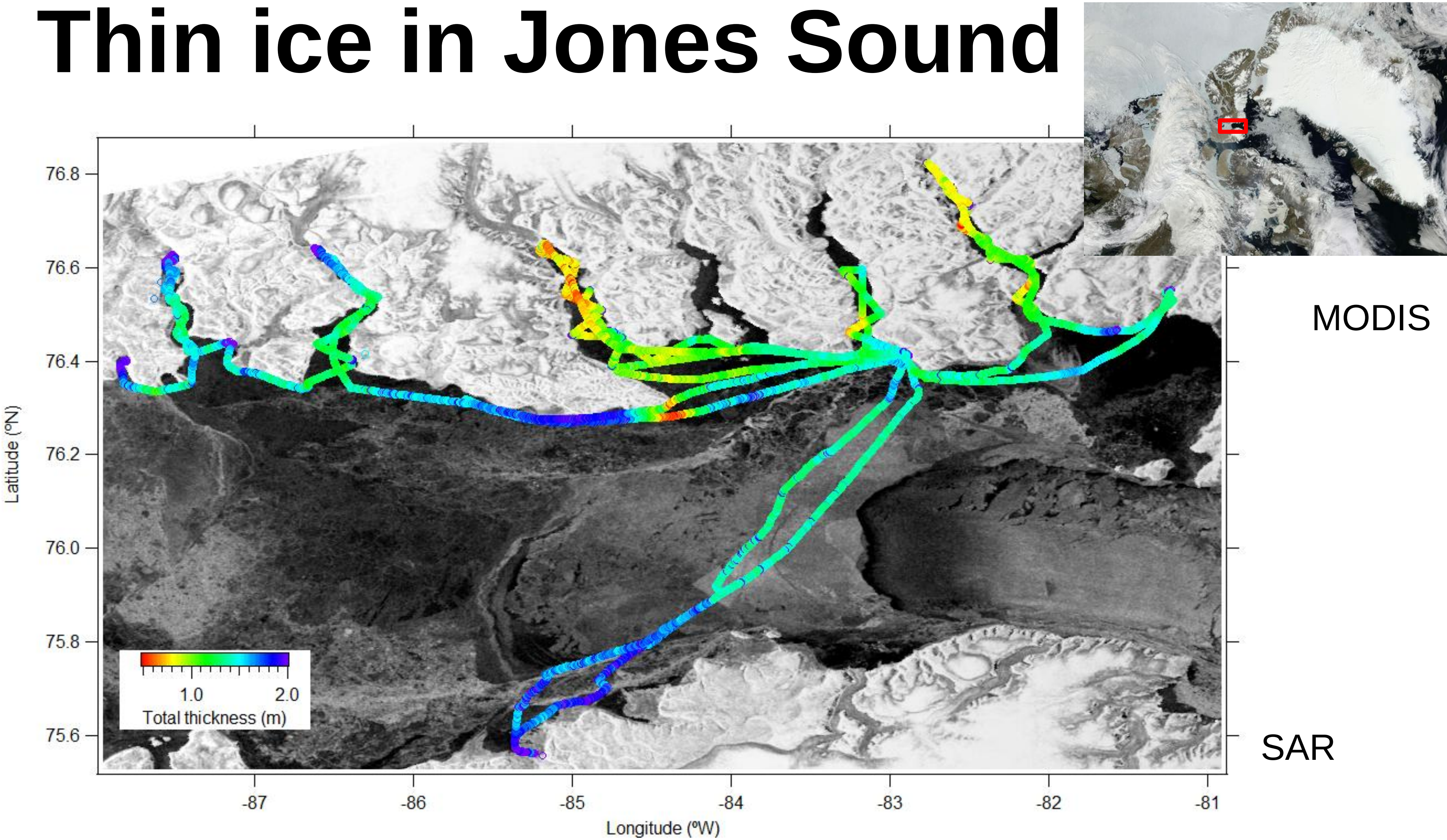


MODIS: Moderate Resolution Imaging Spectroradiometer

- Sensor on NASA's Earth Observing System (EOS) mission program
- Operated on Terra and Aqua satellites
- **GLOBAL** products
- 250 m resolution (@ nadir)

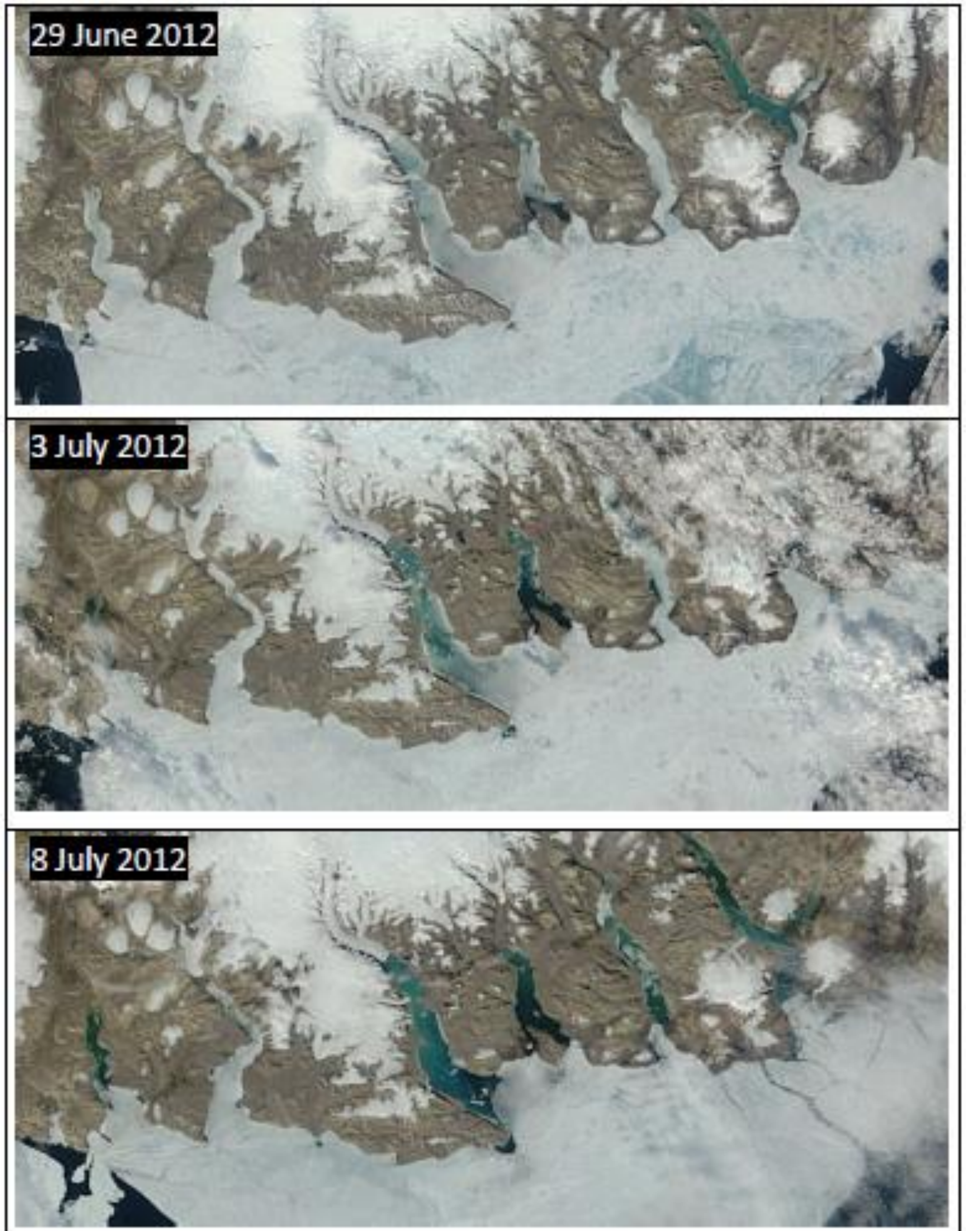


Thin ice in Jones Sound



- Thin ice in fjords due to enhanced ocean heat flux
- Possible future polynyas?

Polynyas and primary productivity



Melling, Haas, Brossier, unpublished

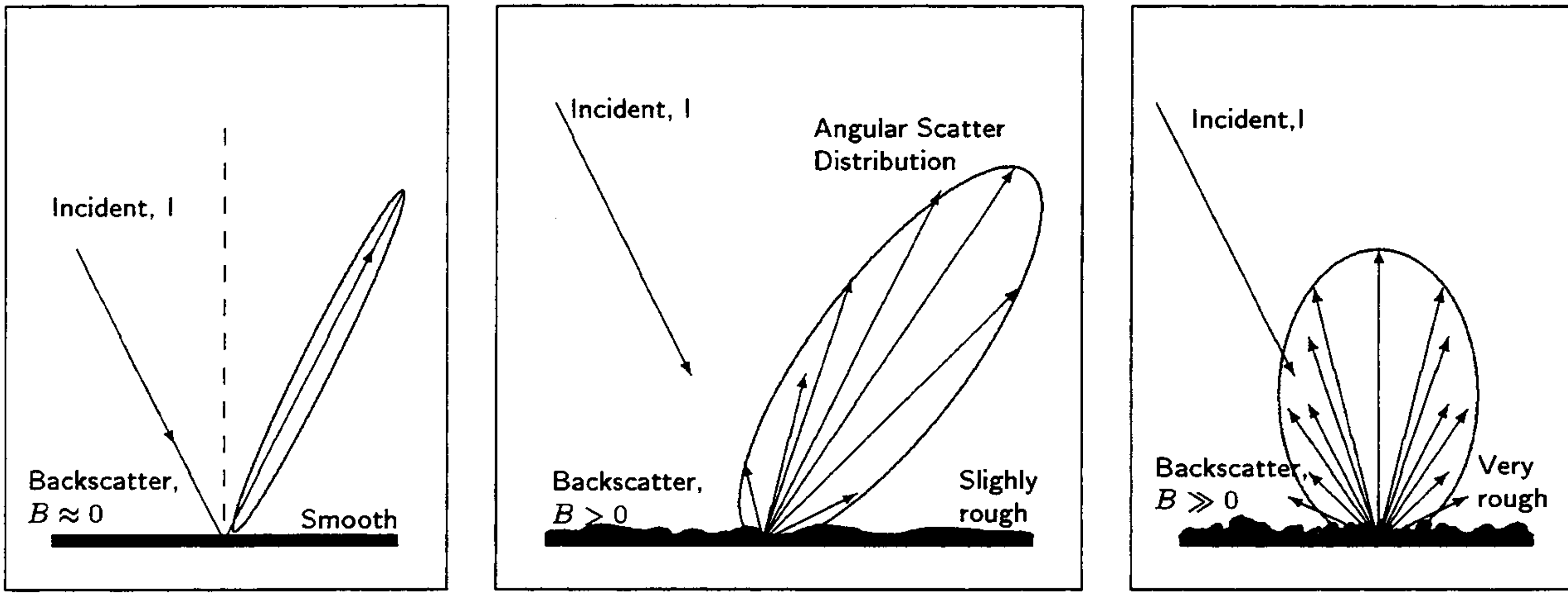
Typical radar frequencies & wavelengths

- Radar waves can penetrate into matter, e.g. into snow, ice, dry sand, through vegetation

Table 9-3. RADAR Wavelengths and Frequencies Used in Active Microwave Remote Sensing Investigations

RADAR Band Designations (common wavelengths shown in parentheses)	Wavelength (λ) in cm	Frequency (υ) in GHz
K_a (0.86 cm)	0.75 – 1.18	40.0 – 26.5
K	1.19 – 1.67	26.5 – 18.0
K_u	1.67 – 2.4	18.0 – 12.5
X (3.0 and 3.2 cm)	2.4 – 3.8	12.5 – 8.0
C (7.5, 6.0 cm)	3.9 – 7.5	8.0 – 4.0
S (8.0, 9.6, 12.6 cm)	7.5 – 15.0	4.0 – 2.0
L (23.5, 24.0, 25.0 cm)	15.0 – 30.0	2.0 – 1.0
P (68.0 cm)	30.0 – 100	1.0 – 0.3

Backscatter as function of surface roughness



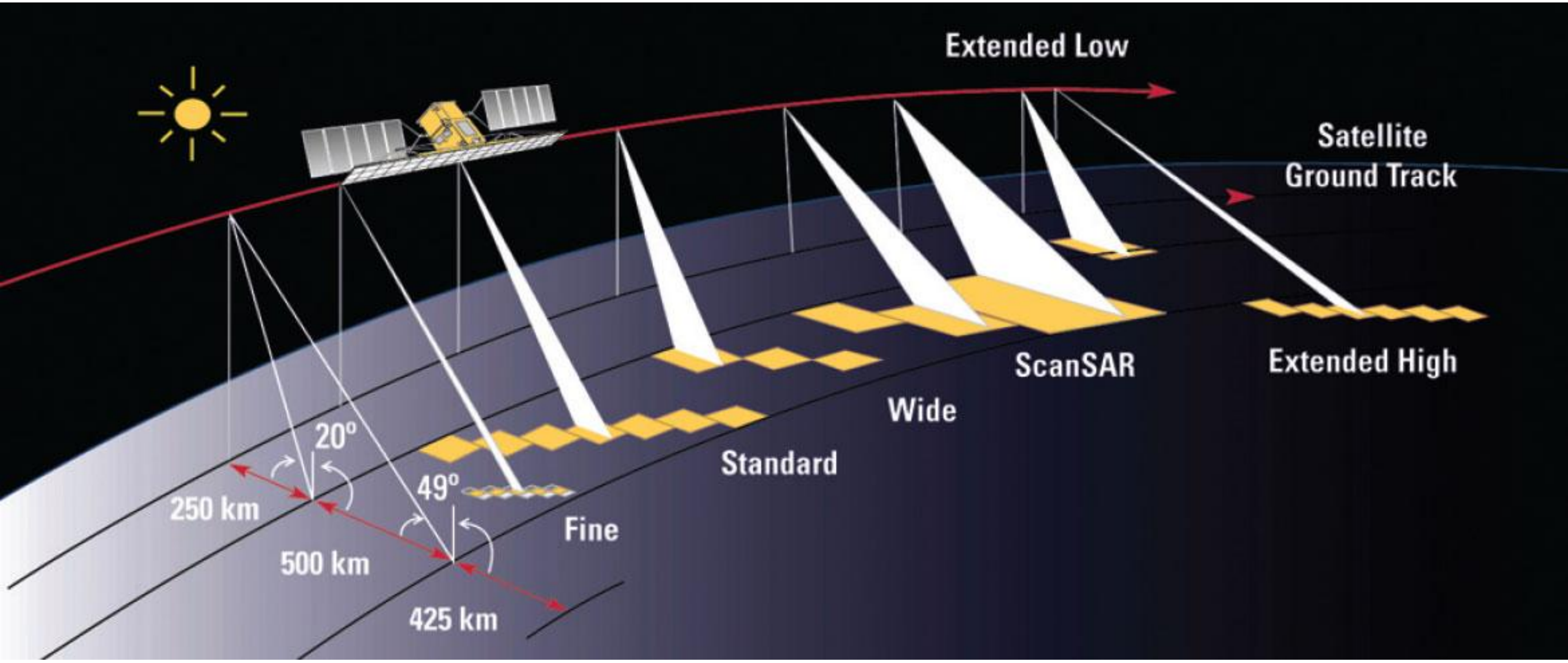
$$\text{Backscatter } \sigma_0 = \frac{backscattered\ \ power}{incident\ \ power}$$

"radar reflectivity";
"scattering albedo"

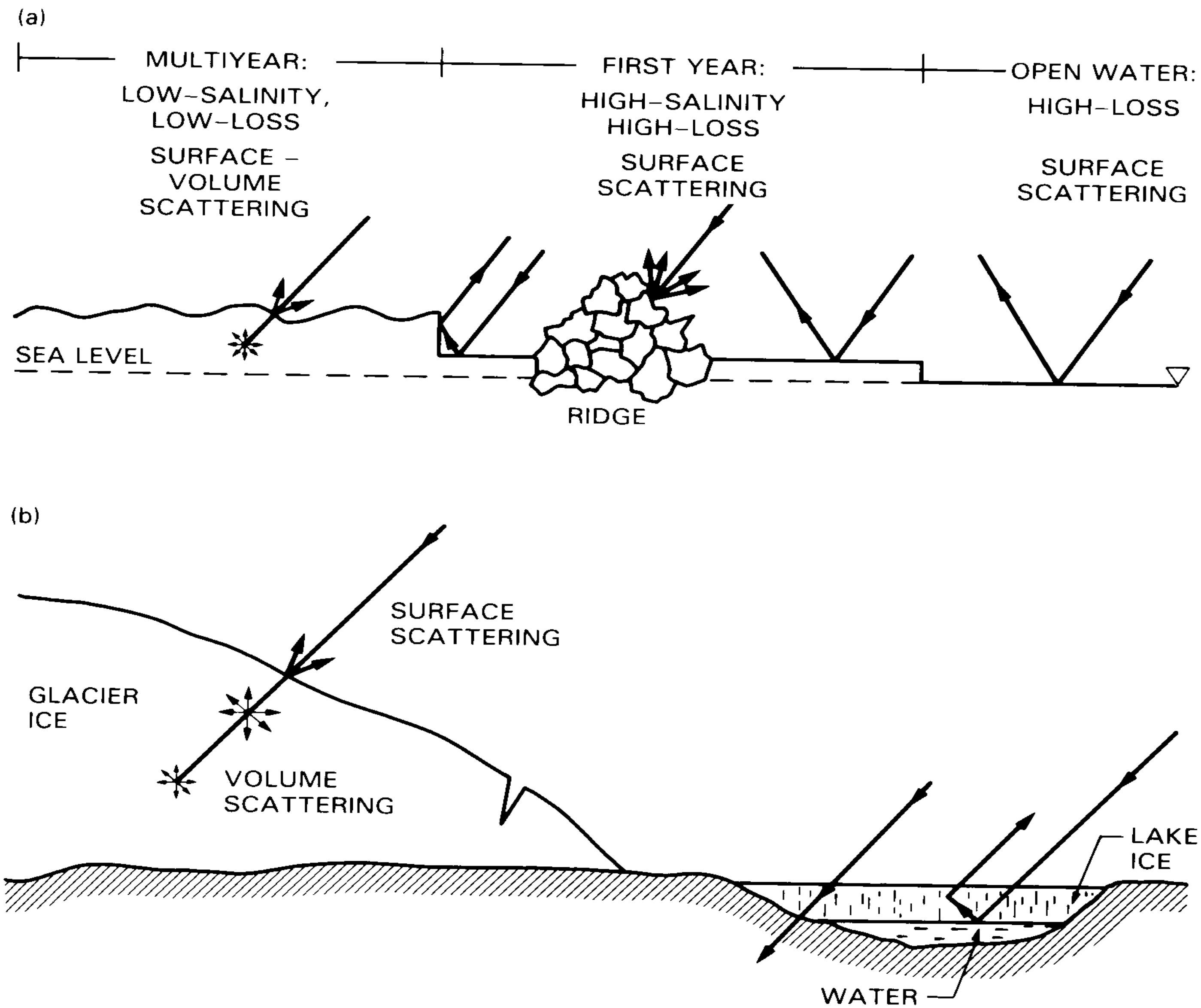
"Lambertian scattering"

Synthetic-Aperture Radar (SAR)

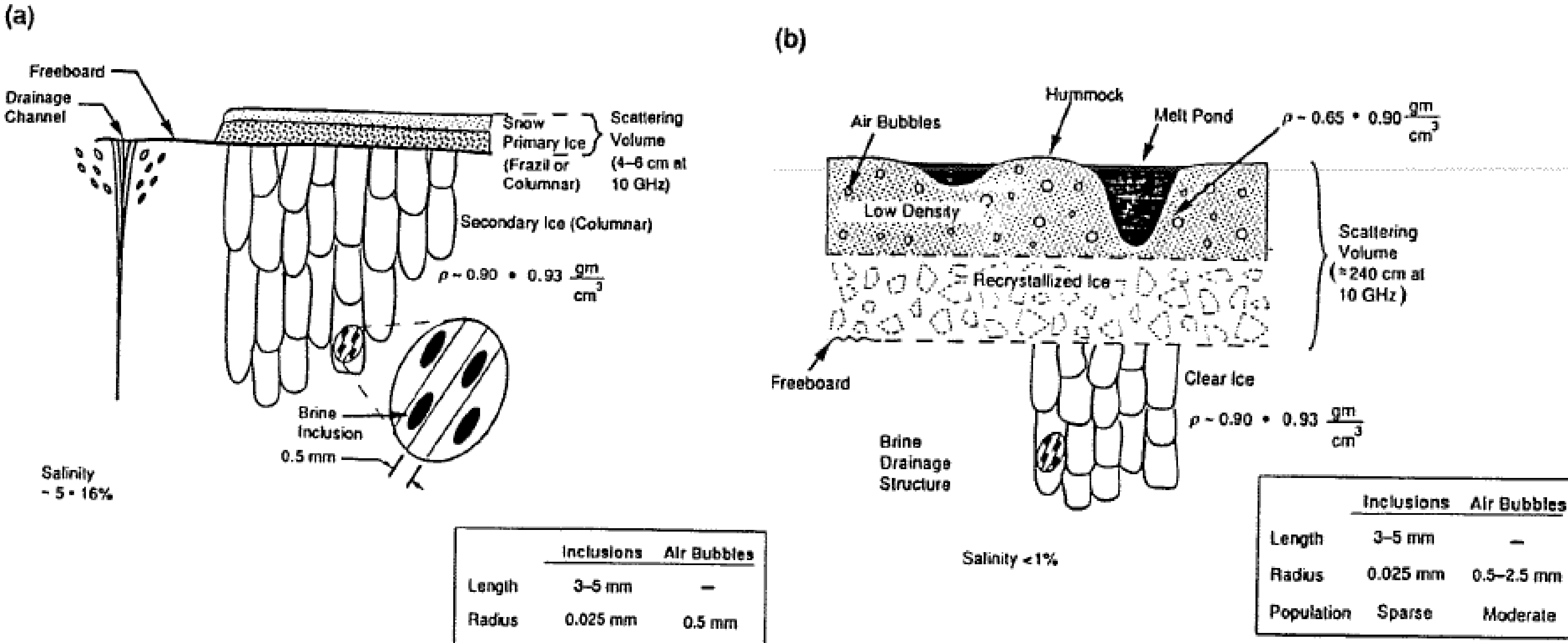
- e.g. ERS, Envisat, Radarsat
- C-Band SAR
- Very high spatial resolution achieved by along-track (azimuth) synthetic-aperture (Doppler) radar processing



Radar microwave interaction with ice



FYI vs MYI microstructure & properties



(a)

	Inclusions	Air Bubbles
Length	3–5 mm	–
Radius	0.025 mm	0.5 mm
Population	Dense	Sparse

(b)

	Inclusions	Air Bubbles
Length	3–5 mm	–
Radius	0.025 mm	0.5–2.5 mm
Population	Sparse	Moderate

Fig. 5-4. Cross sections of (a) first-year and (b) multiyear sea ice.

- FYI: saline, low porosity → low backscatter
- MYI: desalinated by melt, porous, low density → high (volume) backscatter

Backscatter of different ice types

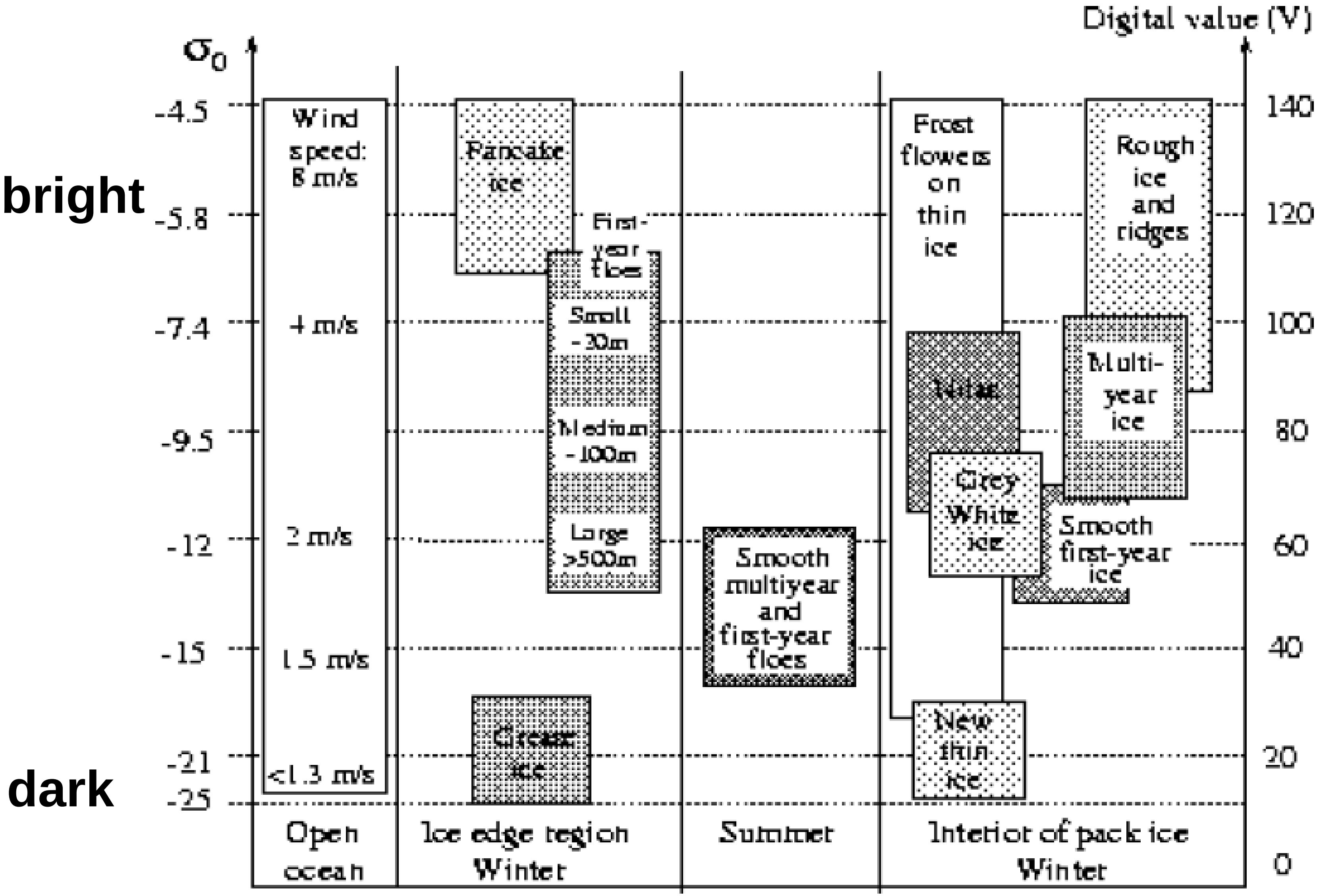
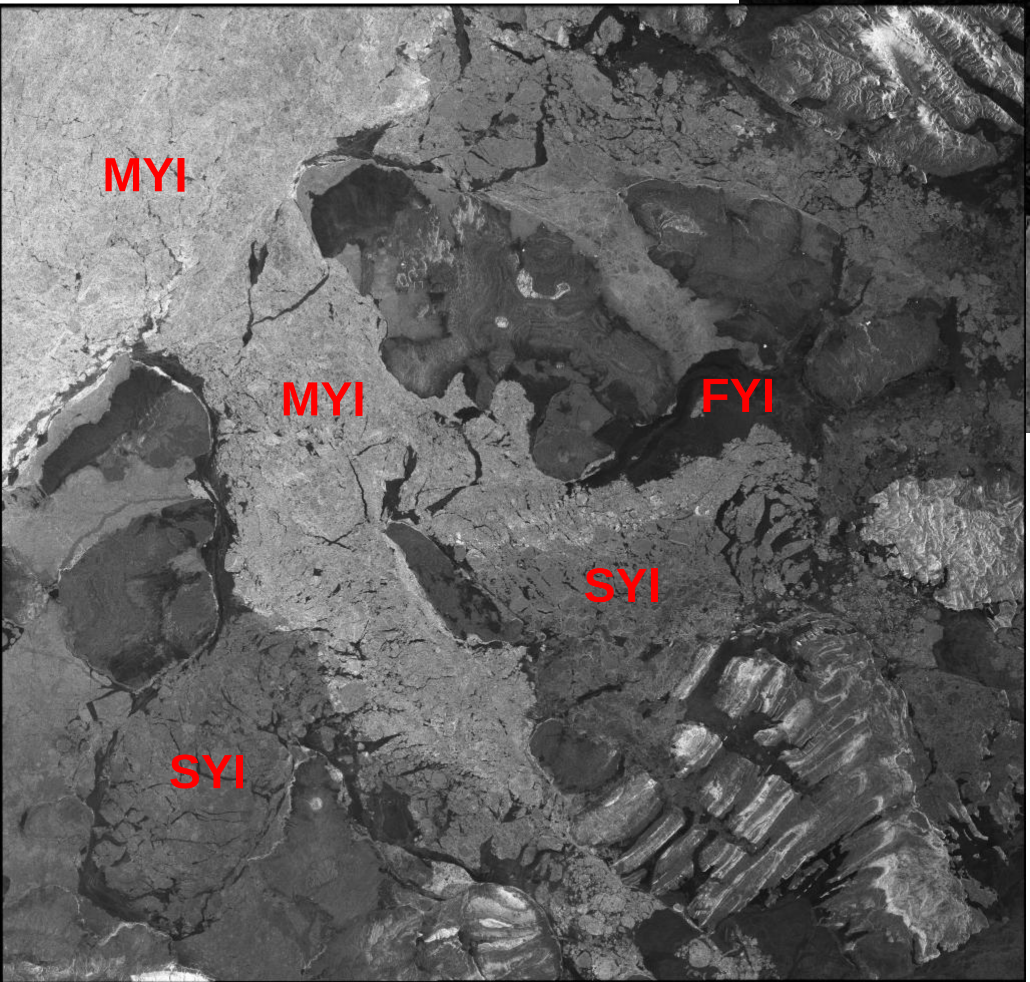


Figure 3.4. *SAR backscatter signatures as a function of ice types observed during ERS SAR ice validation experiments.*


Grease ice

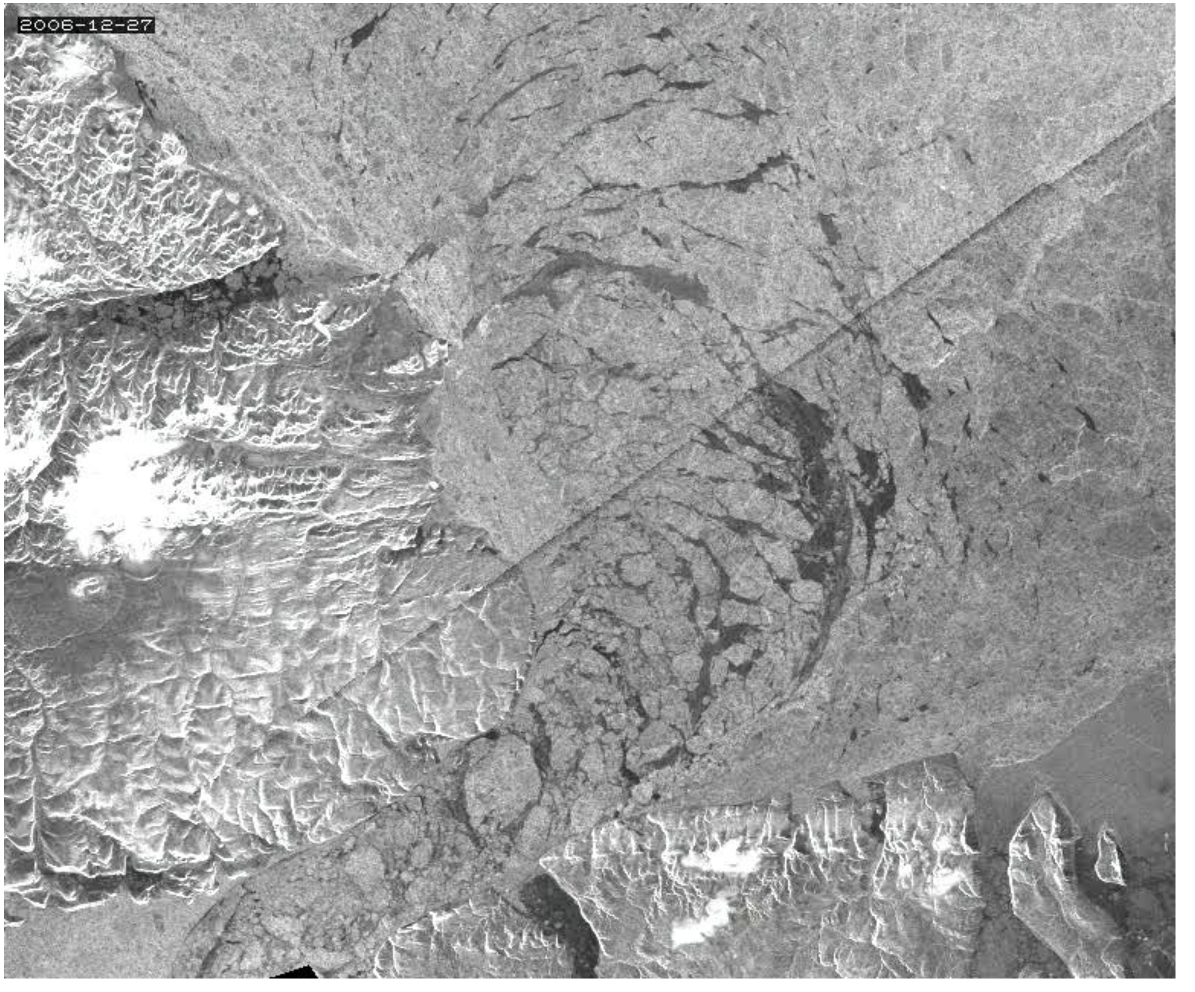

MYI
MYI
FYI
SYI
SYI

Envisat SAR image Jan 26, 2009

- High backscatter: MYI regions

Ice information from satellite Synthetic Aperture Radar data

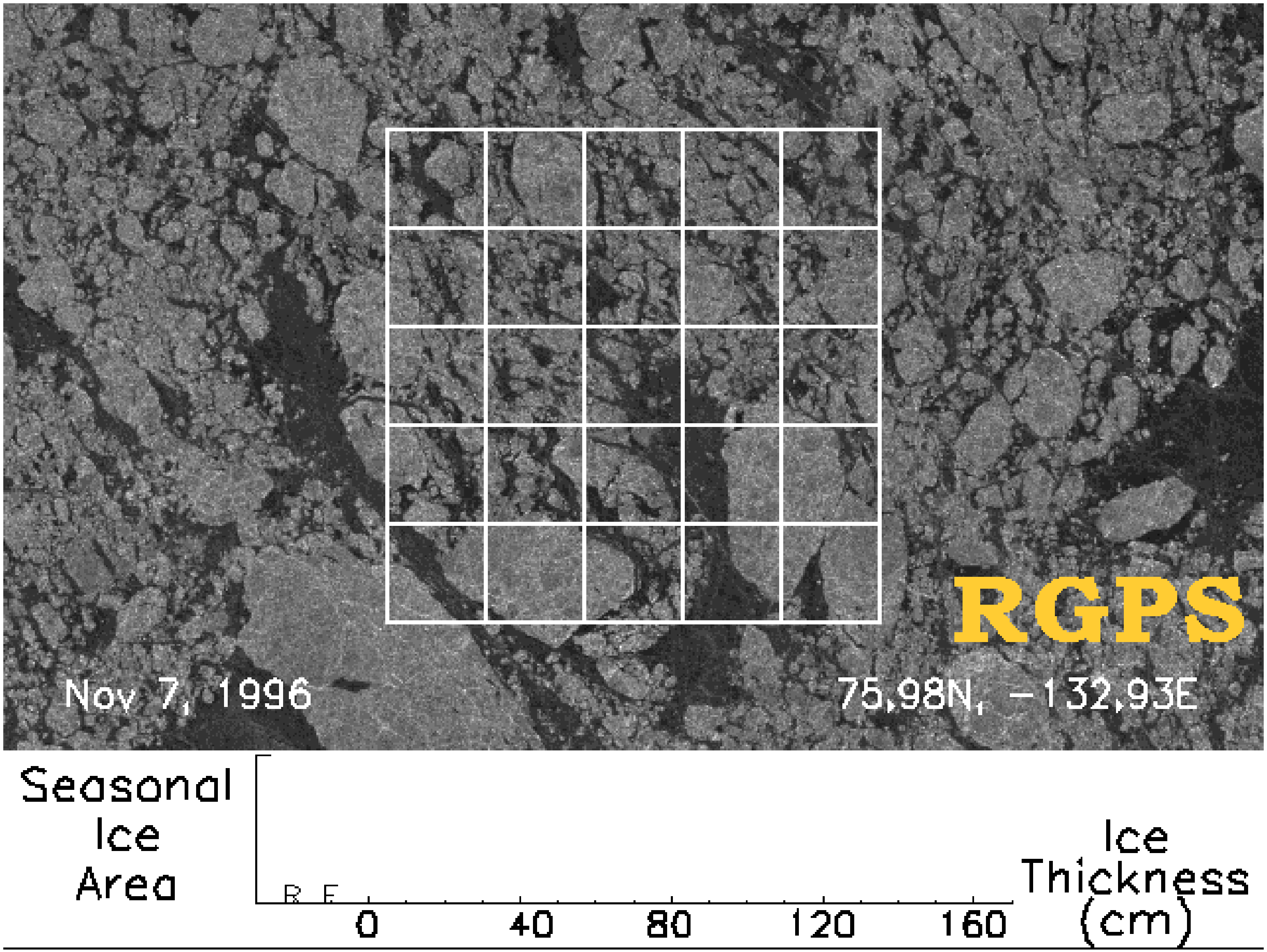
- Shows ice dynamics and deformation
- Retrieval of geophysical ice properties has yet to be improved



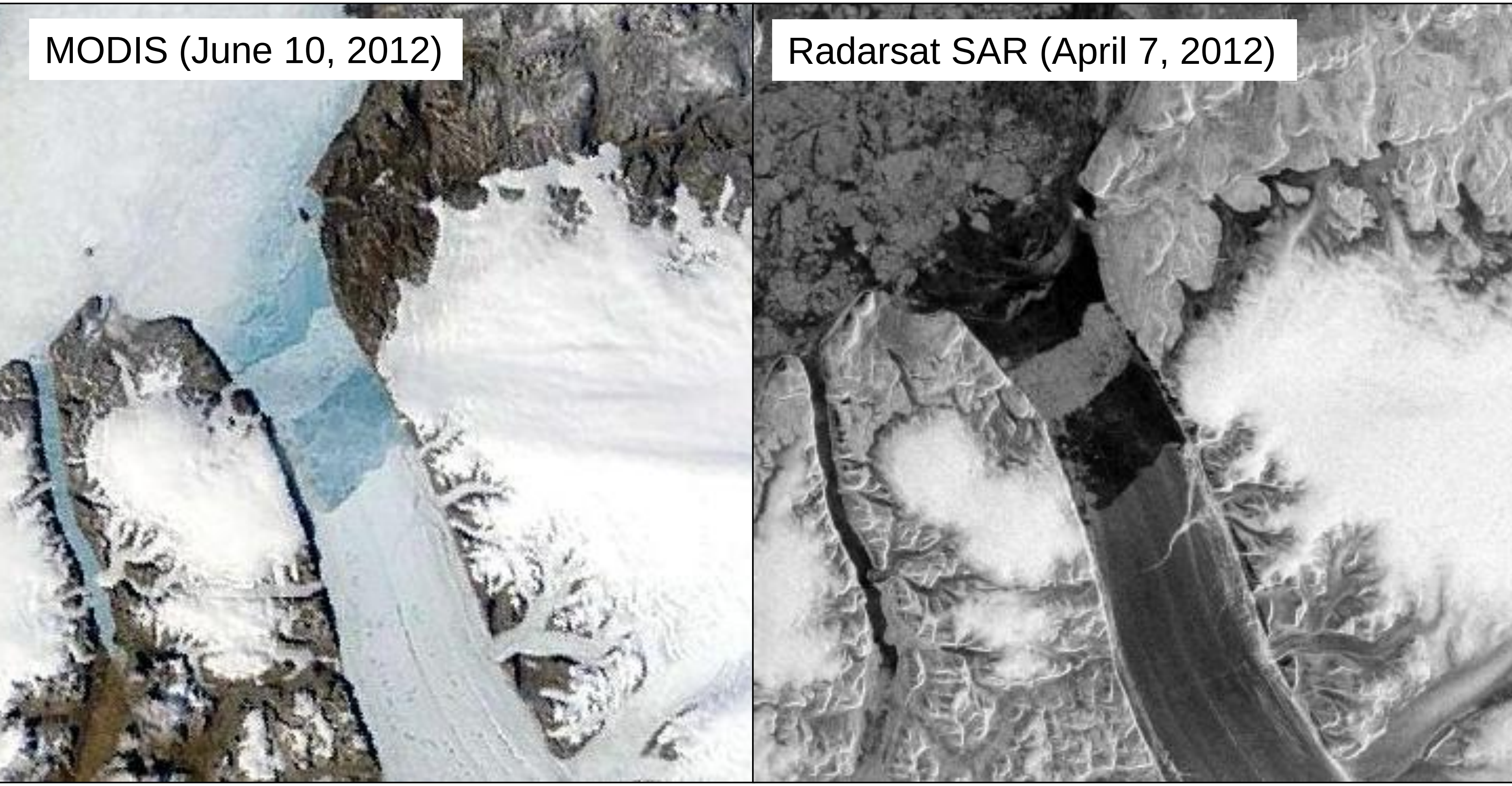
Jan-May 2007

Envisat (C-Band)

„Radarsat geophysical processor system“ RGPS: Drift and Deformation

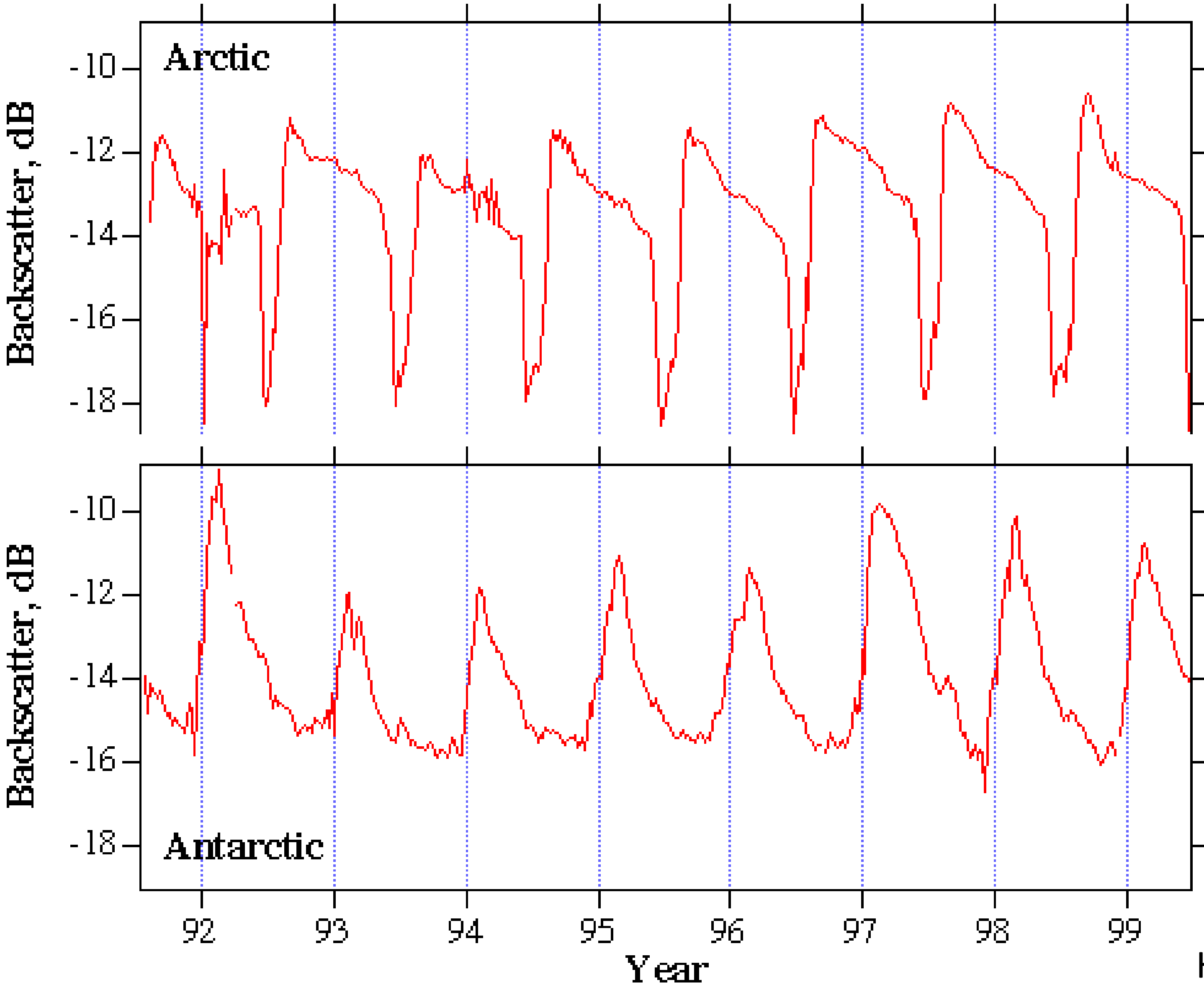


Surface roughness and melt



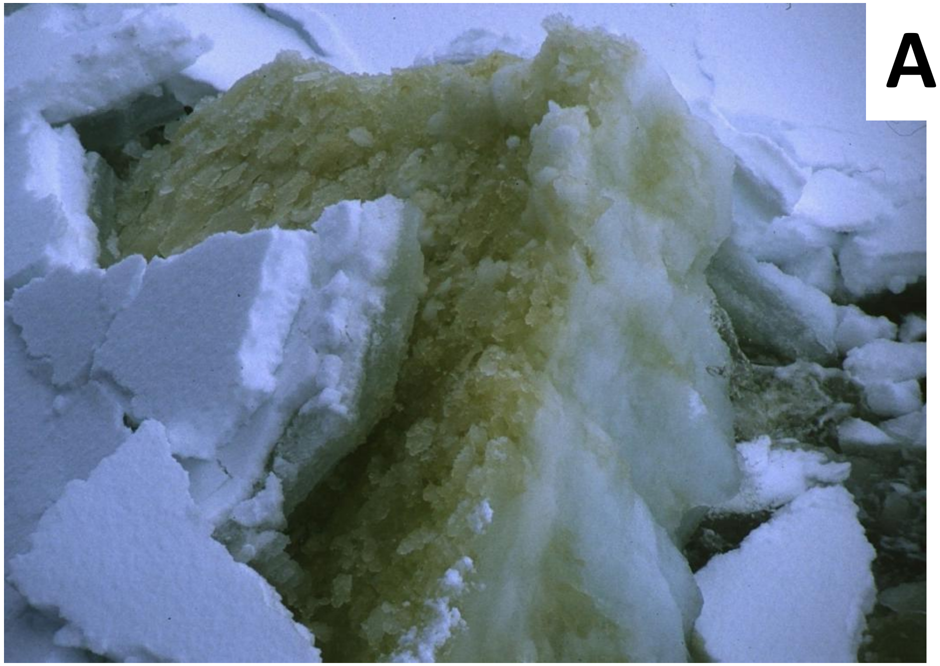
- Rougher ice: High backscatter; less melt ponding due to better drainage/runoff

Arctic/Antarctic contrasts: Seasonal cycle of radar backscatter



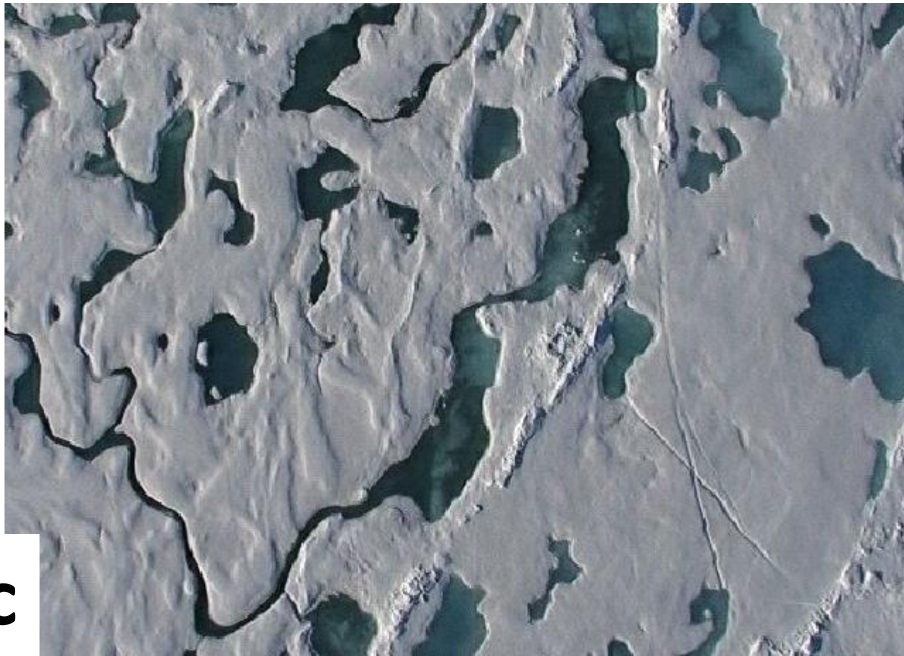
Haas, 2001

Antarctic/Arctic contrasts:
Superimposed ice versus melt ponding



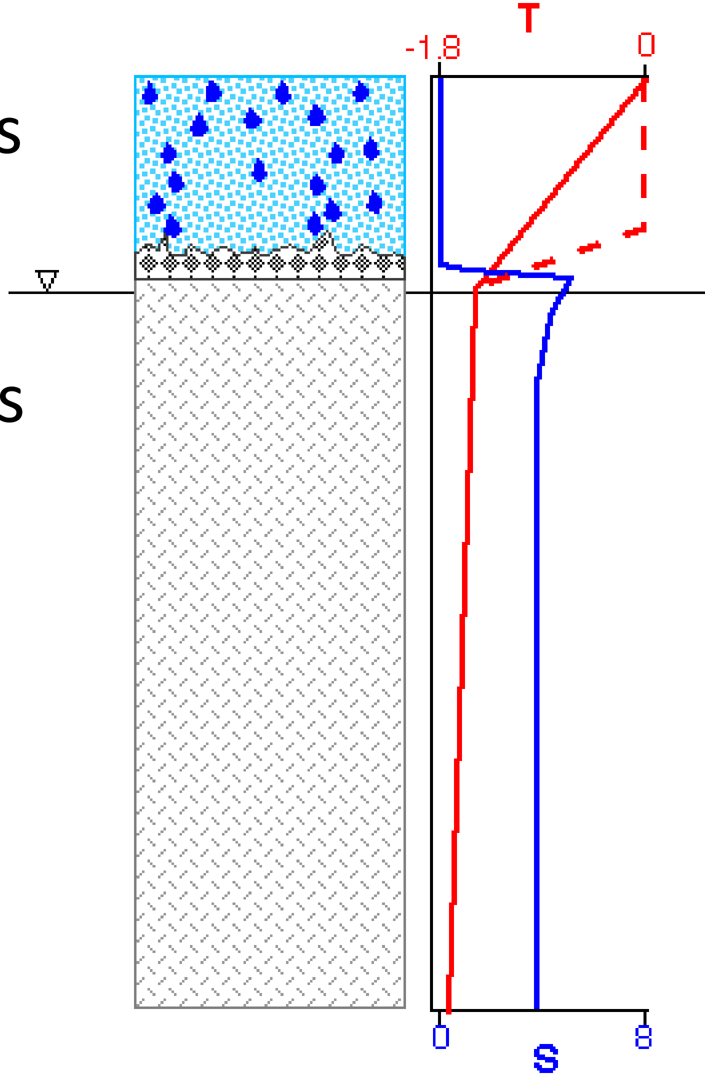
Antarctic

Arctic

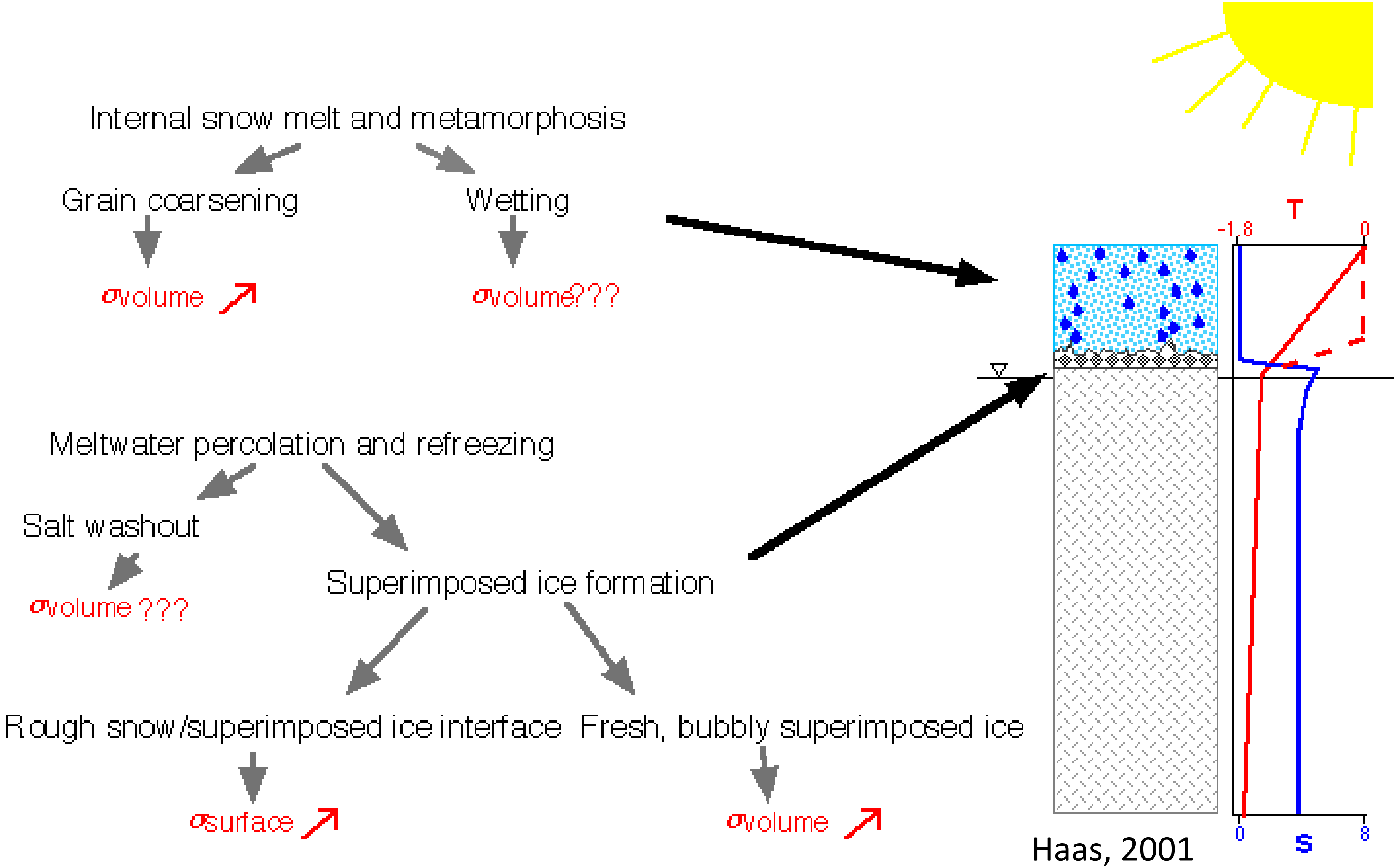


Superimposed ice and ice layer formation / melt freeze cycles

- Warming and reversal of T-gradients
- Snow melting
- Meltwater percolation
- Refreezing within colder snow layers or at the colder snow/ice interface; or:
- Refreezing above slush layer by double diffusion

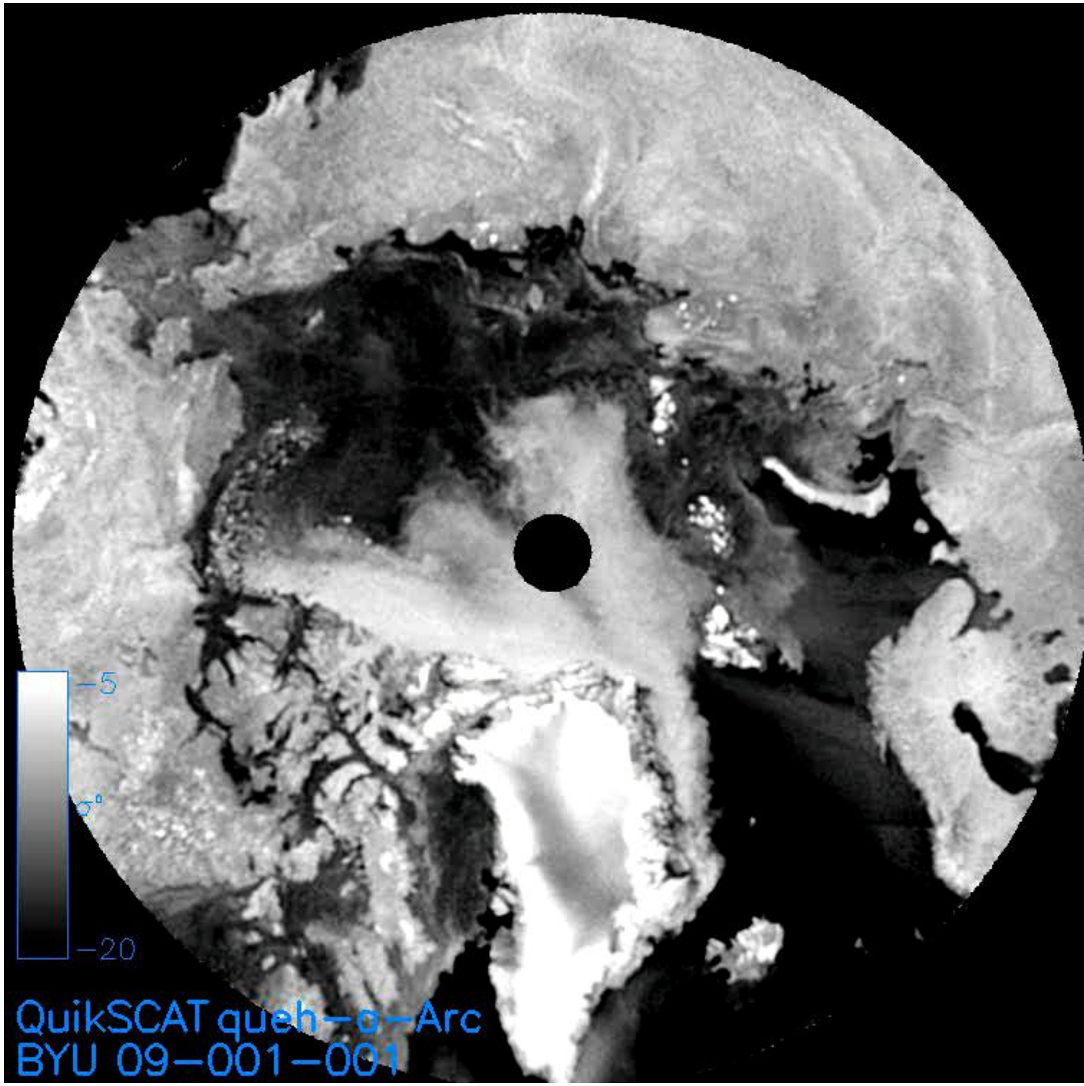


Effect on backscatter increase (and decreasing emissivity)



Scatterometry

- QuikSCAT radar scatterometer
- Independent of clouds or daylight
- Low spatial resolution
- Cannot easily be used for ice concentration due to variable backscatter of water



Loss and replenishment of MYI

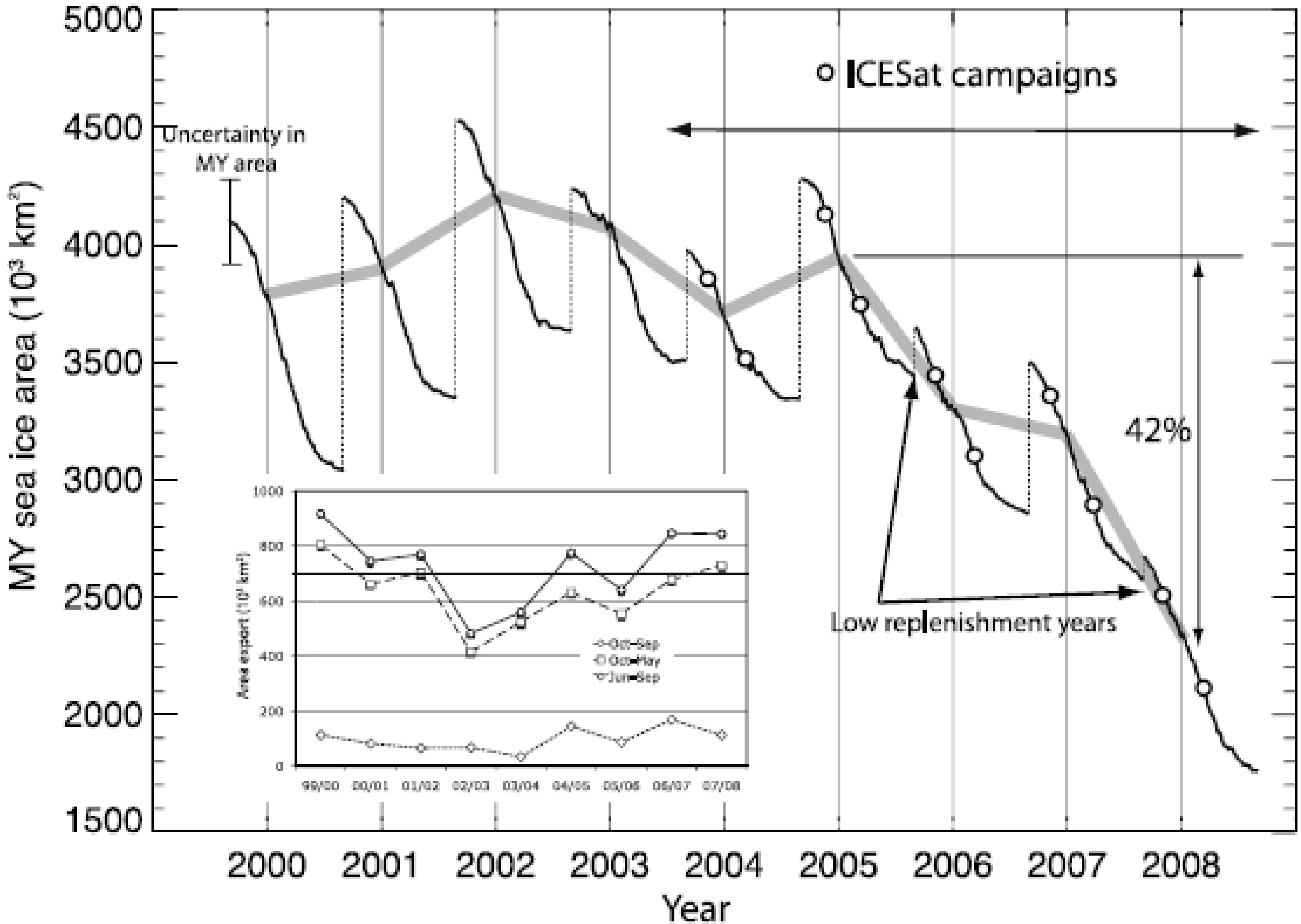
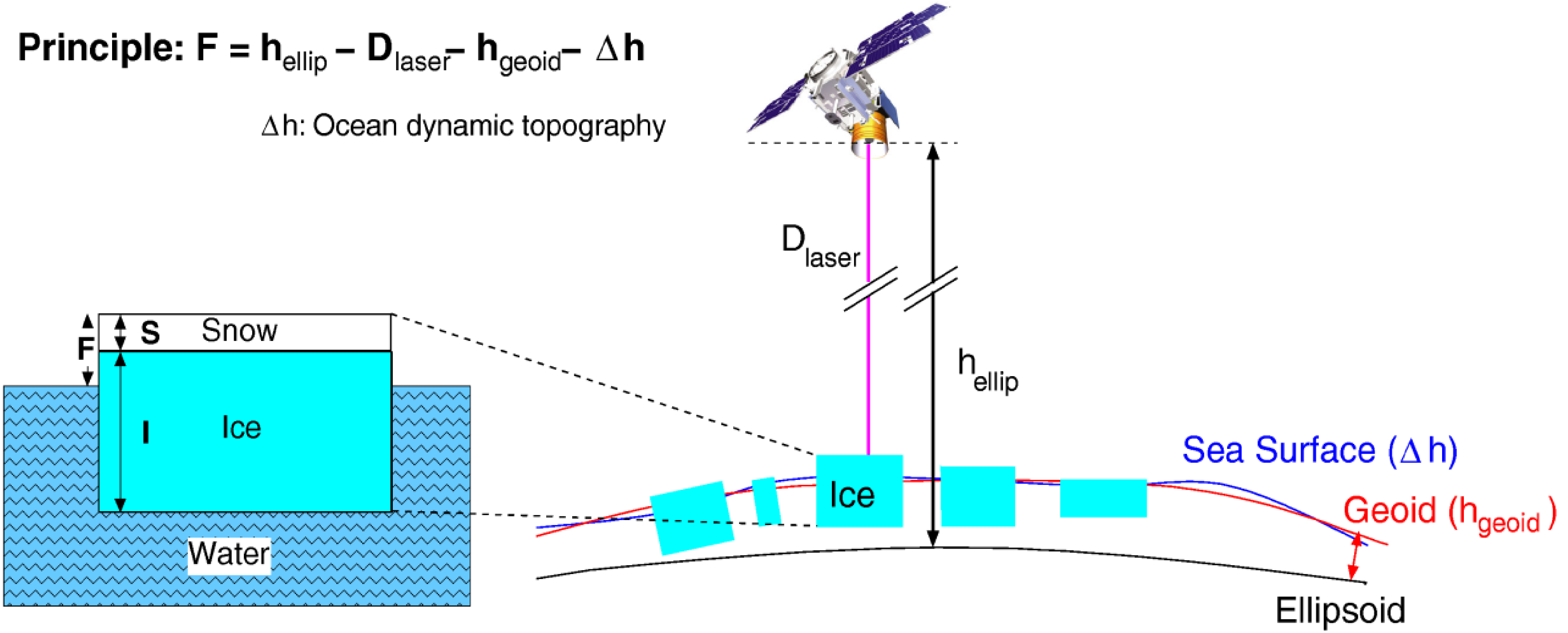


Figure 9. Nine annual cycles of replenishment/export of Arctic Ocean multiyear ice area constructed using QuikSCAT data and Fram Strait ice export. Open circles show the approximate times of the 10 ICESat campaigns used here. The dashed vertical lines show the replenishment of the MY ice reservoir by first-year ice at the end of each summer. The two near-zero replenishment years of 2005 and 2007 are indicated. Inset shows the annual and seasonal Fram Strait ice export over the same period.

Kwok et al., 2009

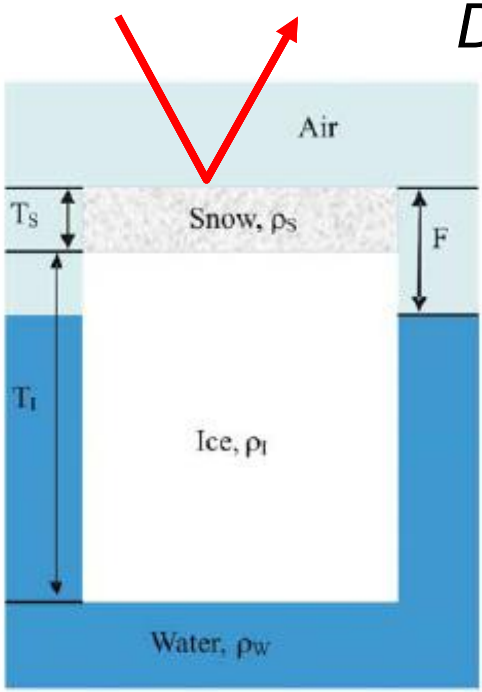
Laser & radar altimetry

- ICESat (Laser, small footprint, NASA)
- CryoSat (Radar, large footprint, ESA)
- Large uncertainties due to unknown sea surface, and snow cover



Sea ice thickness vs. freeboard

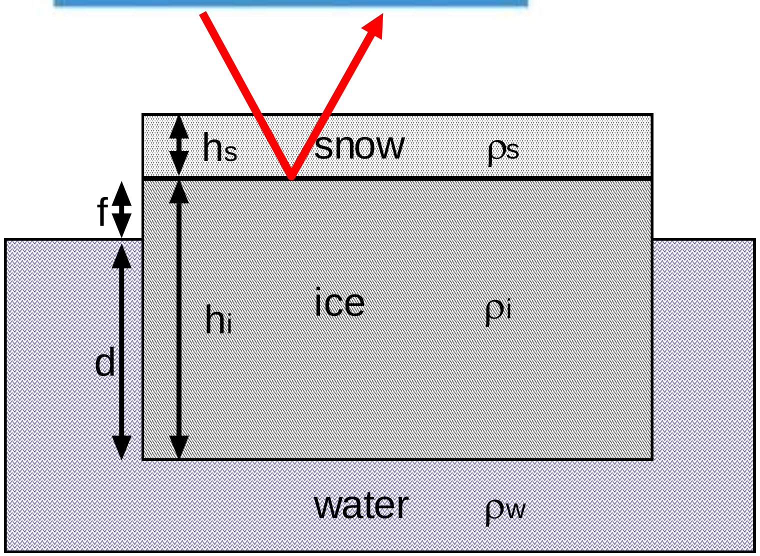
Different definitions of freeboard!



ICESat Laser altimetry:
Freeboard ≡ Elevation of snow surface

$$T_i = F \frac{\rho_w}{\rho_w - \rho_i} - T_s \frac{\rho_w - \rho_s}{\rho_w - \rho_i}$$

≈ 7



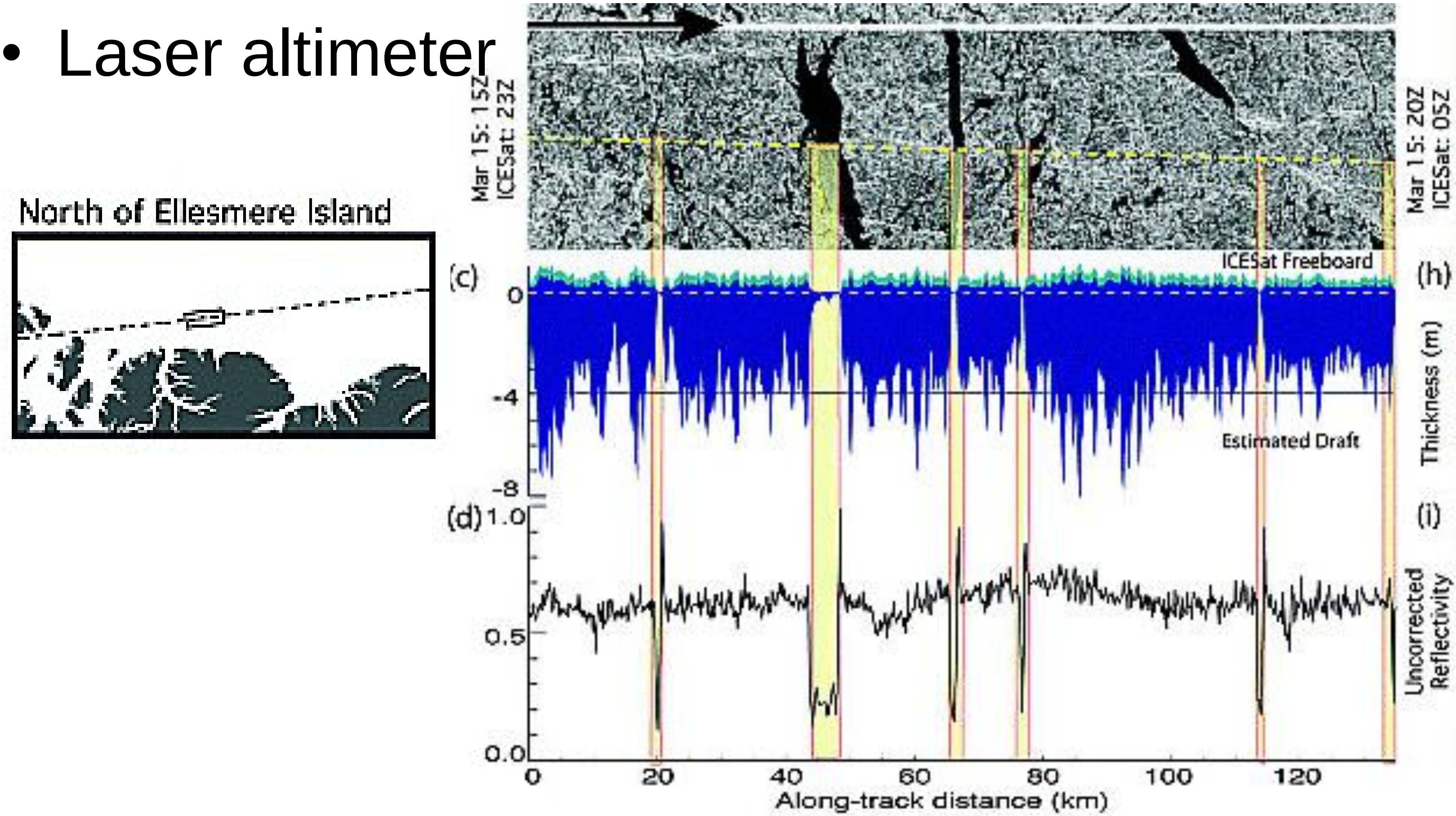
CryoSat Radar altimetry:
Freeboard ≡ Elevation of ice surface

$$h_i = f \frac{\rho_w}{\rho_w - \rho_i} + h_s \frac{\rho_s}{\rho_w - \rho_i}$$

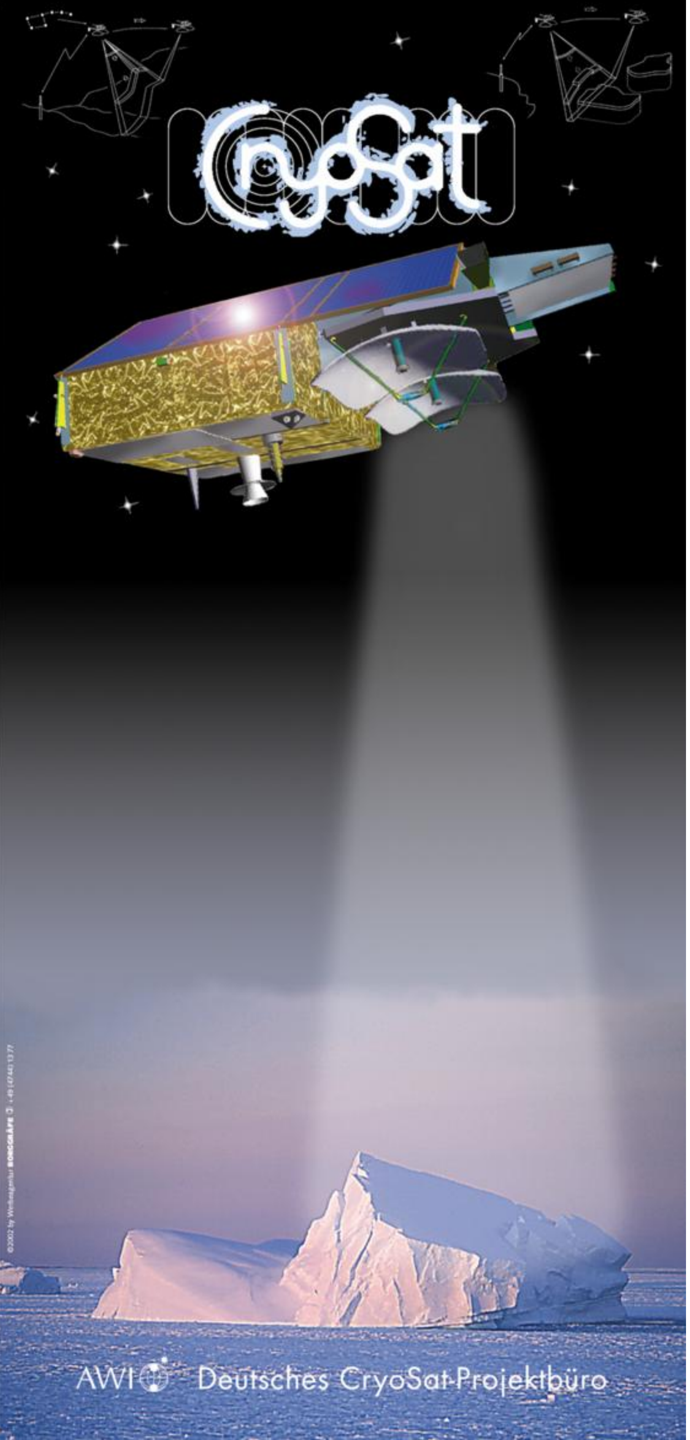
≈ 3

ICESat sea ice thickness results

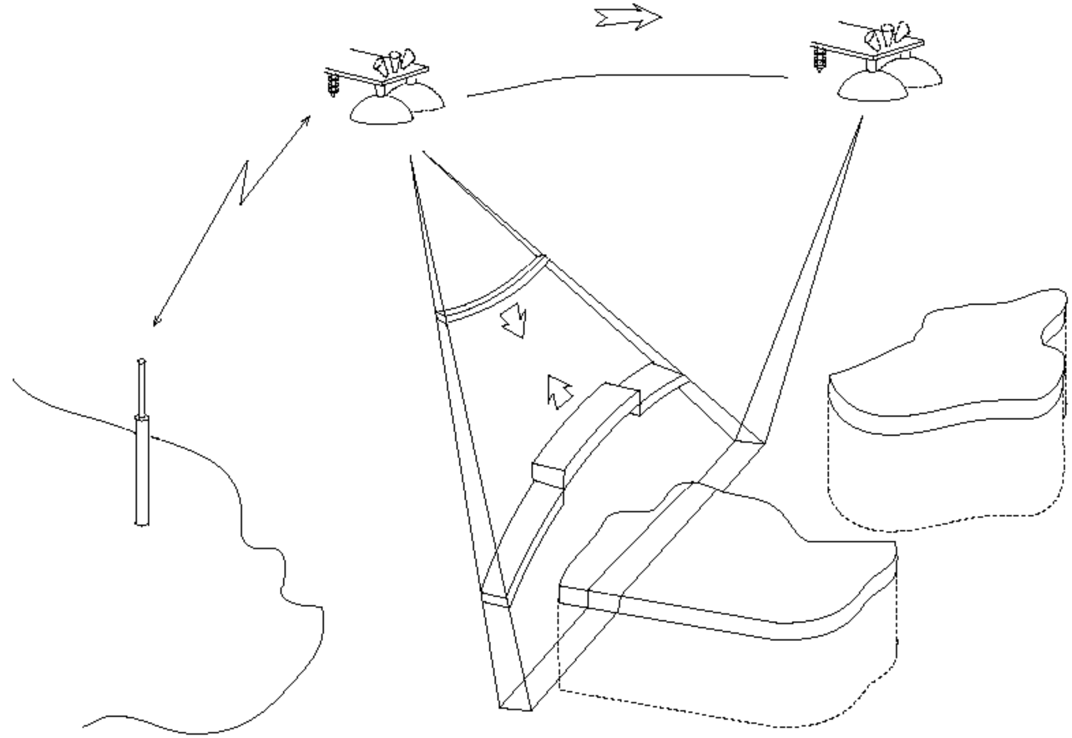
- Laser altimeter

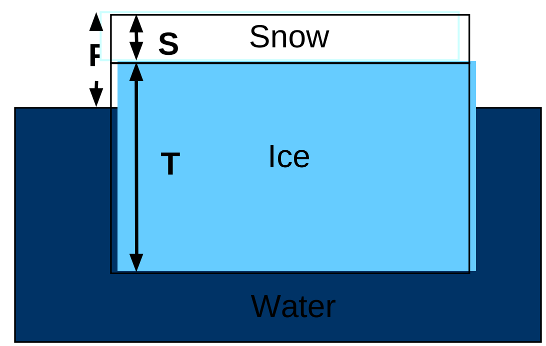


Kwok et al., 2004



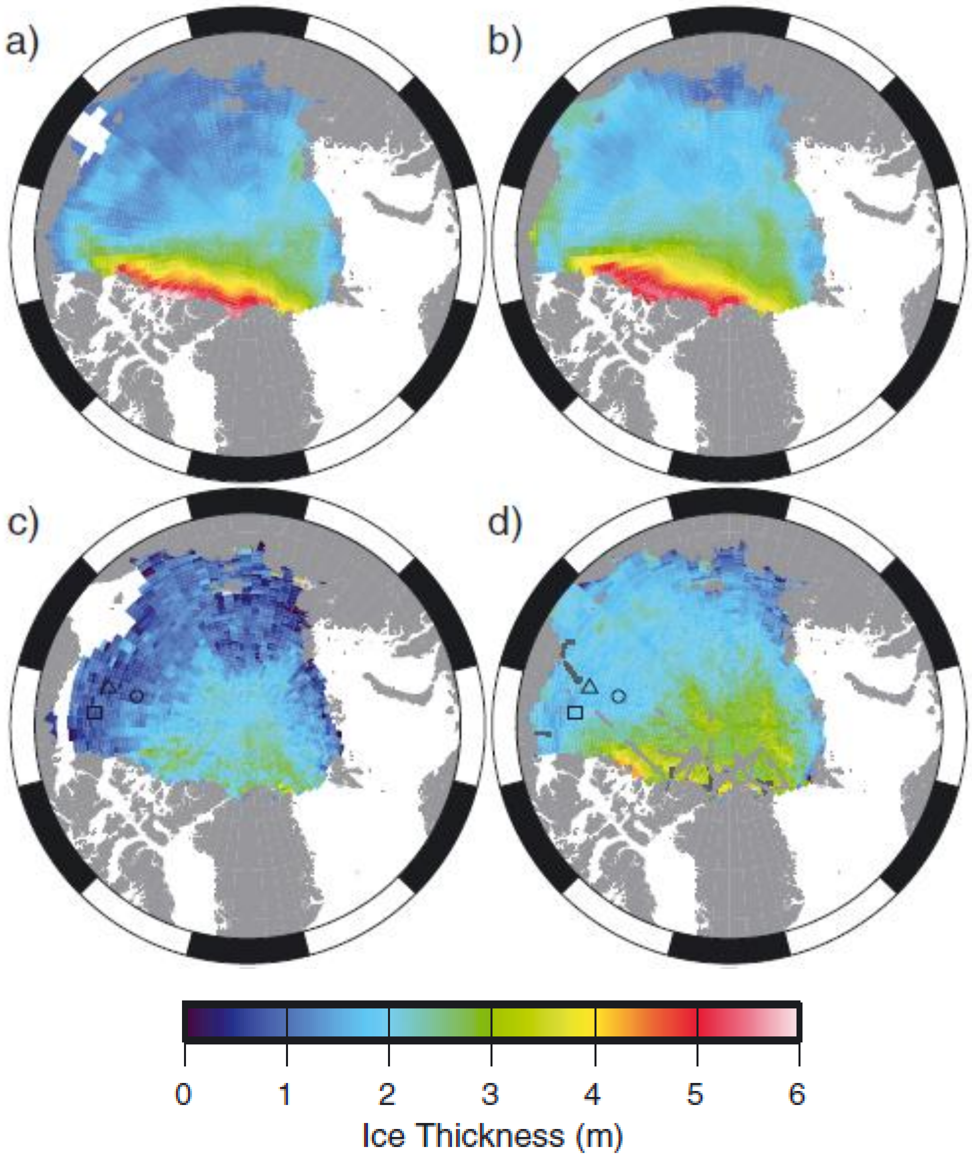
Sea ice freeboard measurement with SAR radar altimeter





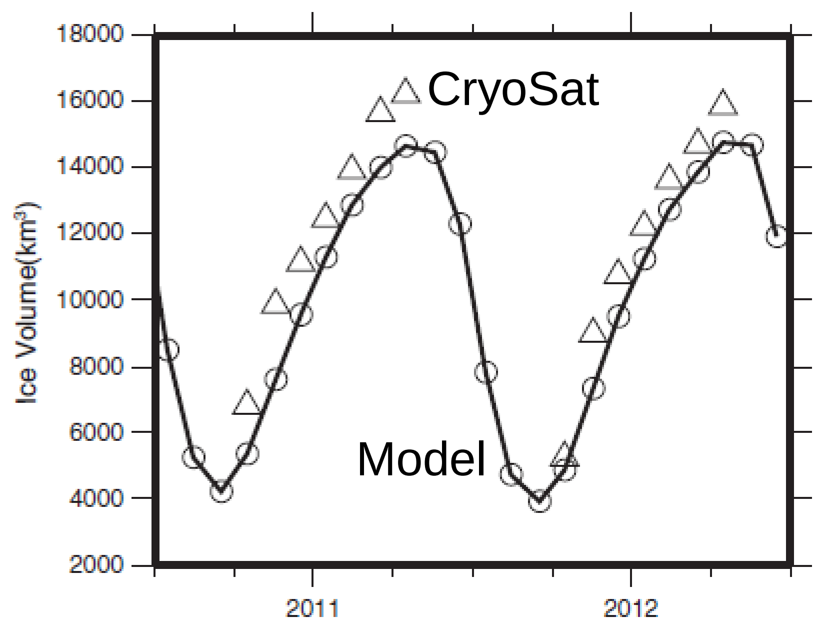
$$h_i = f\frac{\rho_w}{(\rho_w - \rho_i)} + \frac{h_s \rho_s}{(\rho_w - \rho_i)}$$

Fall   Spring



ICESat (2003-08)

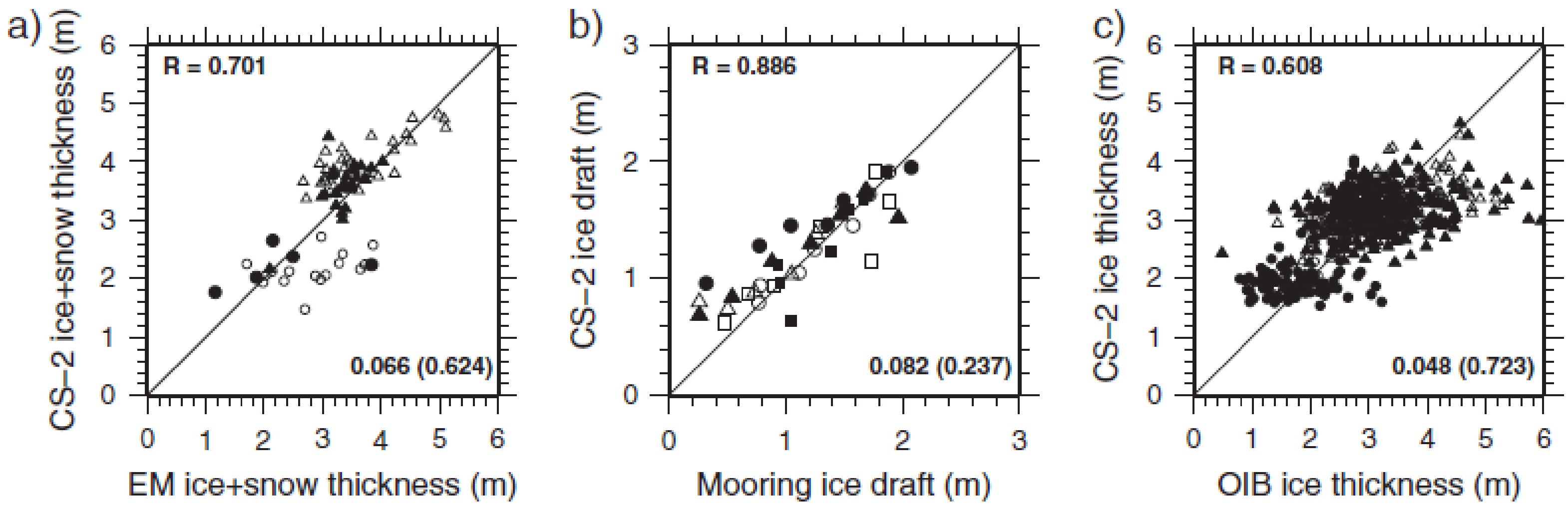
CryoSat (2010-11)



Laxon et al., 2013

- No data during melt season

Validation



- Agreement with validation measurements within 5-8 cm (5 km mean thicknesses)


Snow –
the last frontier!