Remote Sensing of Sea Ice

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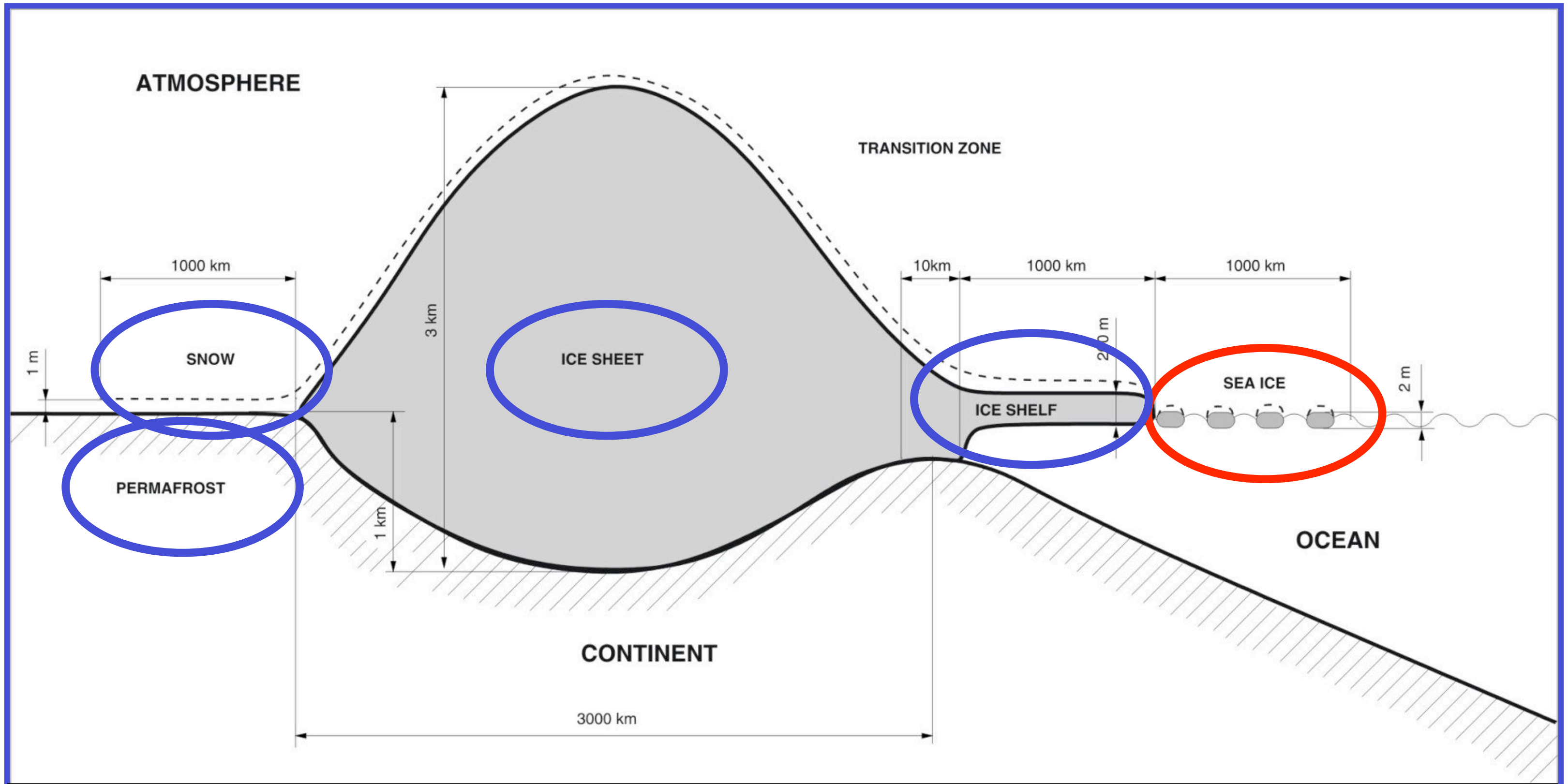
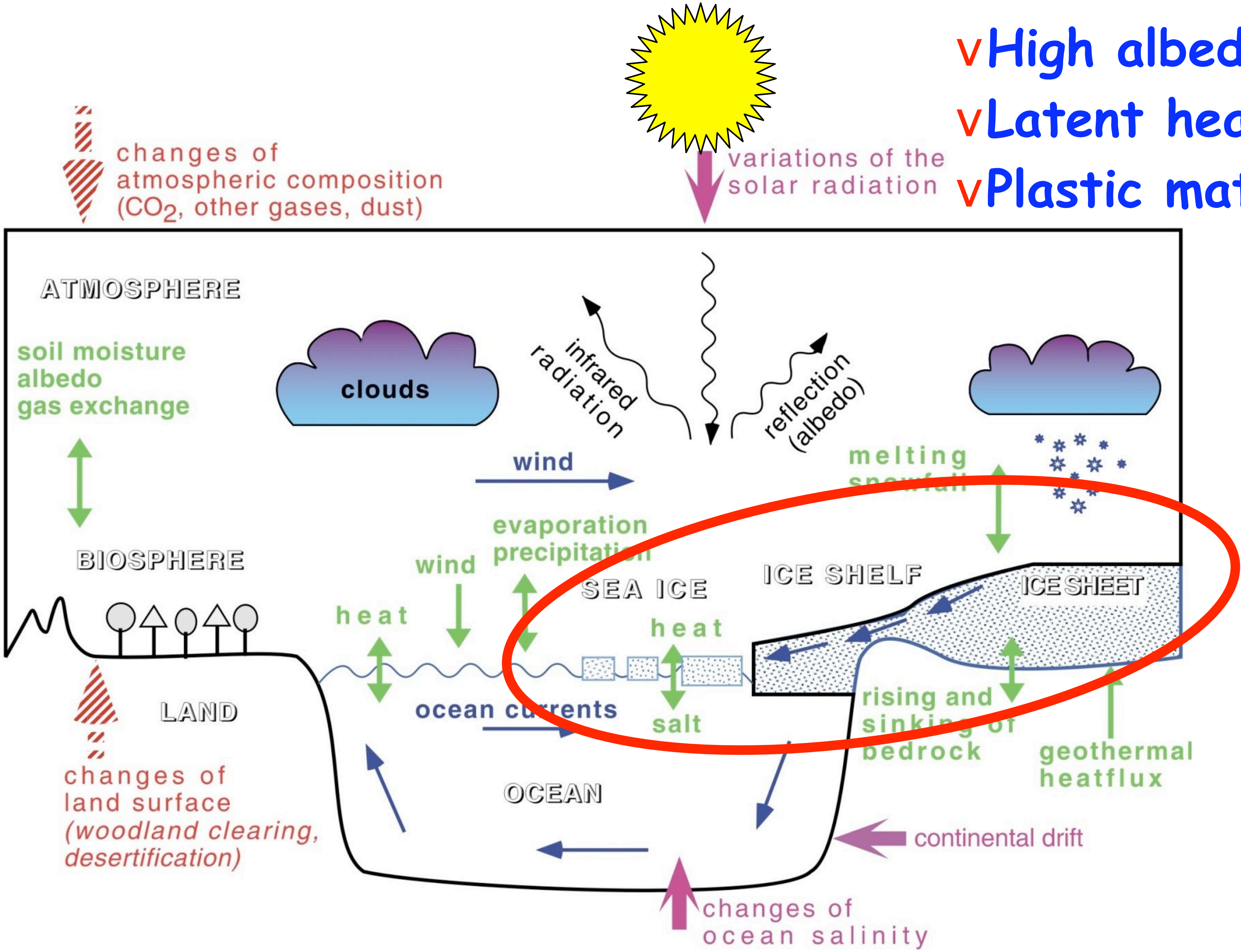
The Cryosphere



	Area [10^6 km^2]	Volume [10^6 km^3]	Volume [relativ]
Ice Sheets	**14.8**	**28.8**	**600**
Ice Shelves	**1.4**	**0.5**	**10**
Sea Ice	**23.0**	**0.05**	**1**
Snow	**45.0**	**0.0025**	**0.05**

Climate System

- High albedo
- Latent heat
- Plastic material



Role of Ice in Climate

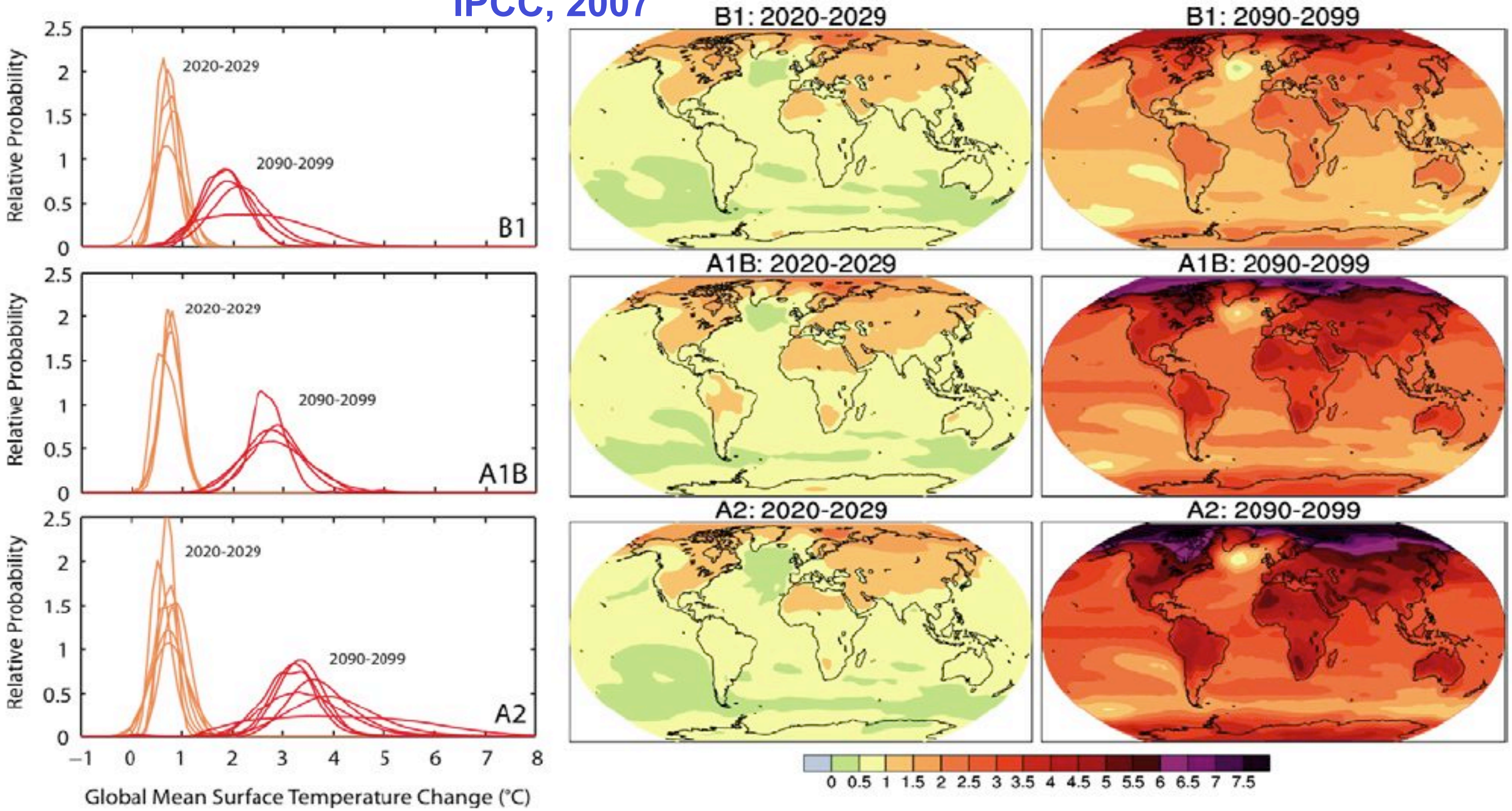
- Impact on surface energy balance (**global sink**)
  - ◊ Atmospheric circulation
  - ◊ Oceanic circulation
  - ◊ Polar amplification
- Impact on gas exchange between the atmosphere and Earth's surface
- Impact on water cycle, water supply
- Impact on sea level (**ice mass imbalance**)
- Defines boundary conditions for ecosystems

Role of Ice in Climate

- **Polar amplification in CO_2 warming scenarios**

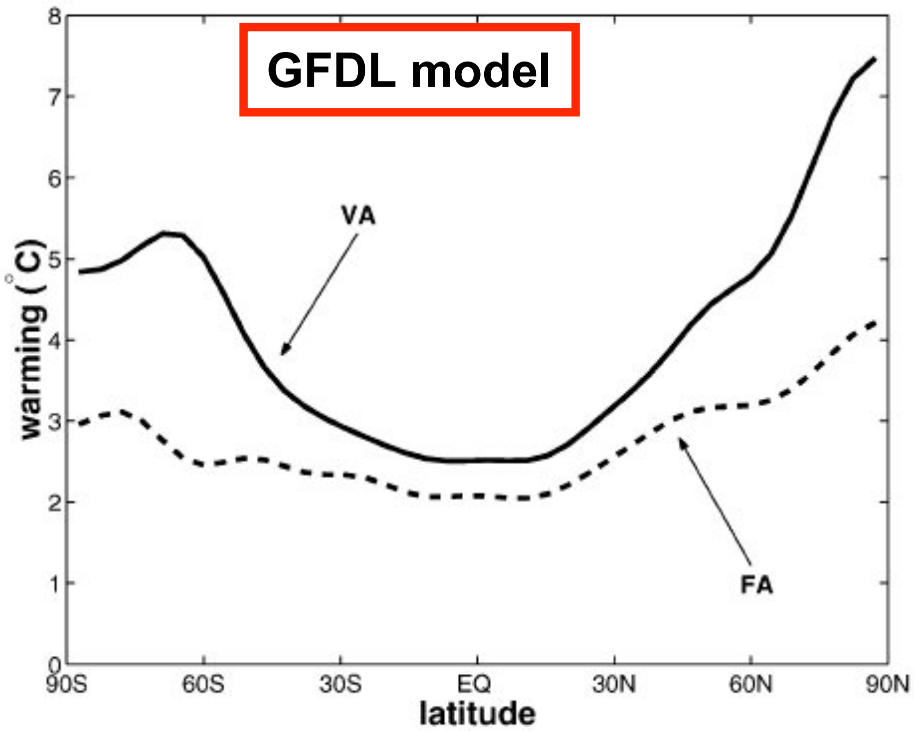
(surface energy balance; temperature – ice albedo feedback)

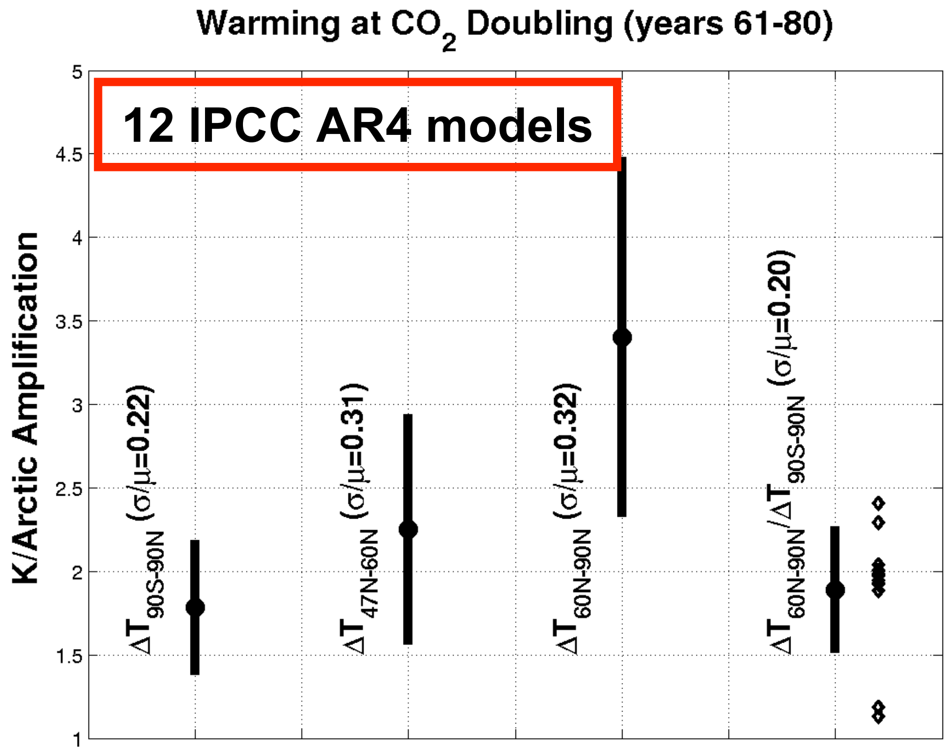
IPCC, 2007



Role of Ice in Climate

Polar amplification





Warming from CO_2 doubling with fixed albedo (FA) and with surface albedo feedback included (VA) (Hall, 2004)

Warming at CO_2 doubling (years 61-80) (Winton, 2006)

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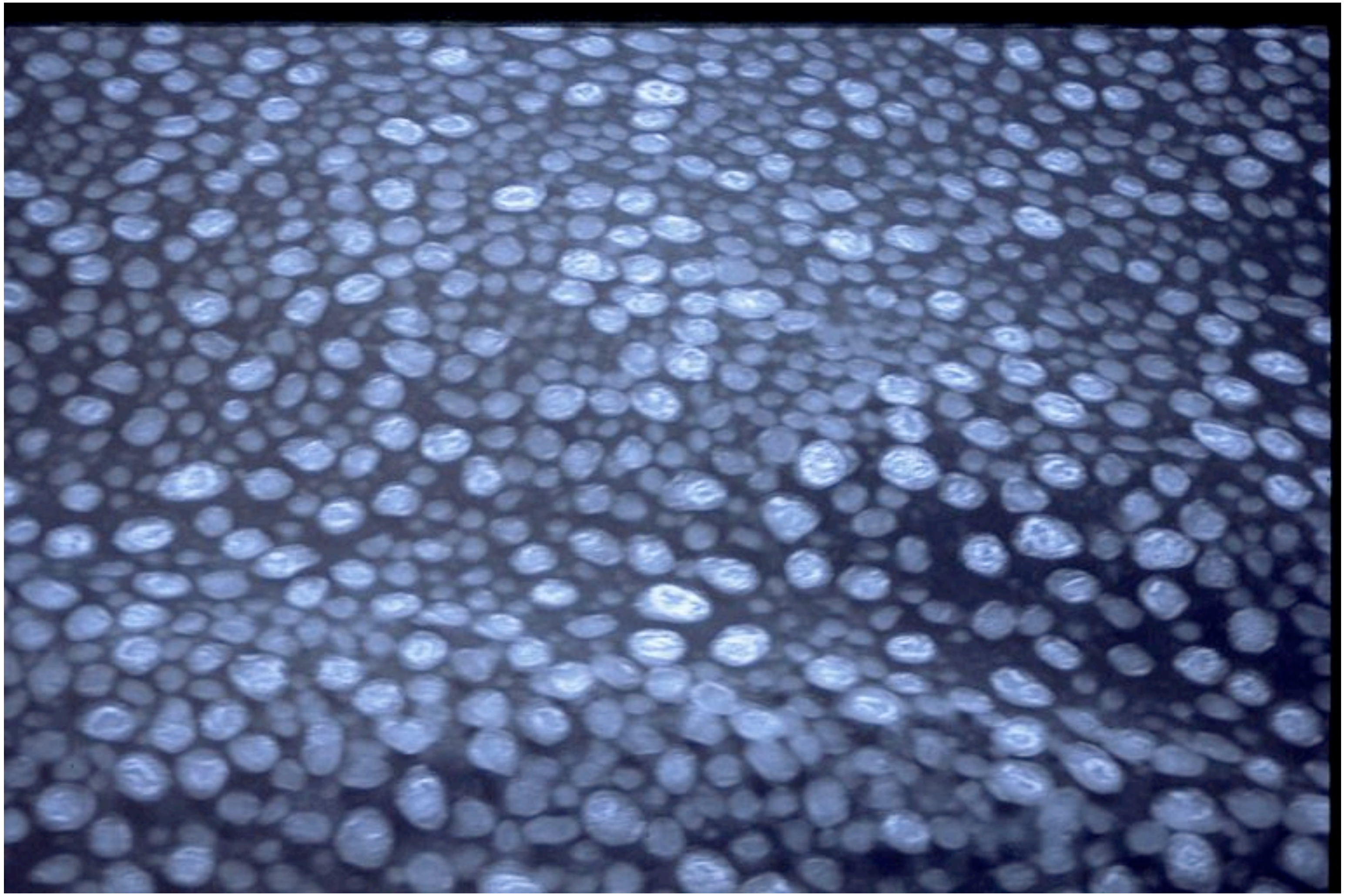
1. Ice and climate
2. Sea Ice Properties
3. Remote Sensing Techniques

Pancake Ice



Pancake Ice

Old Pancake Ice

First Year Ice

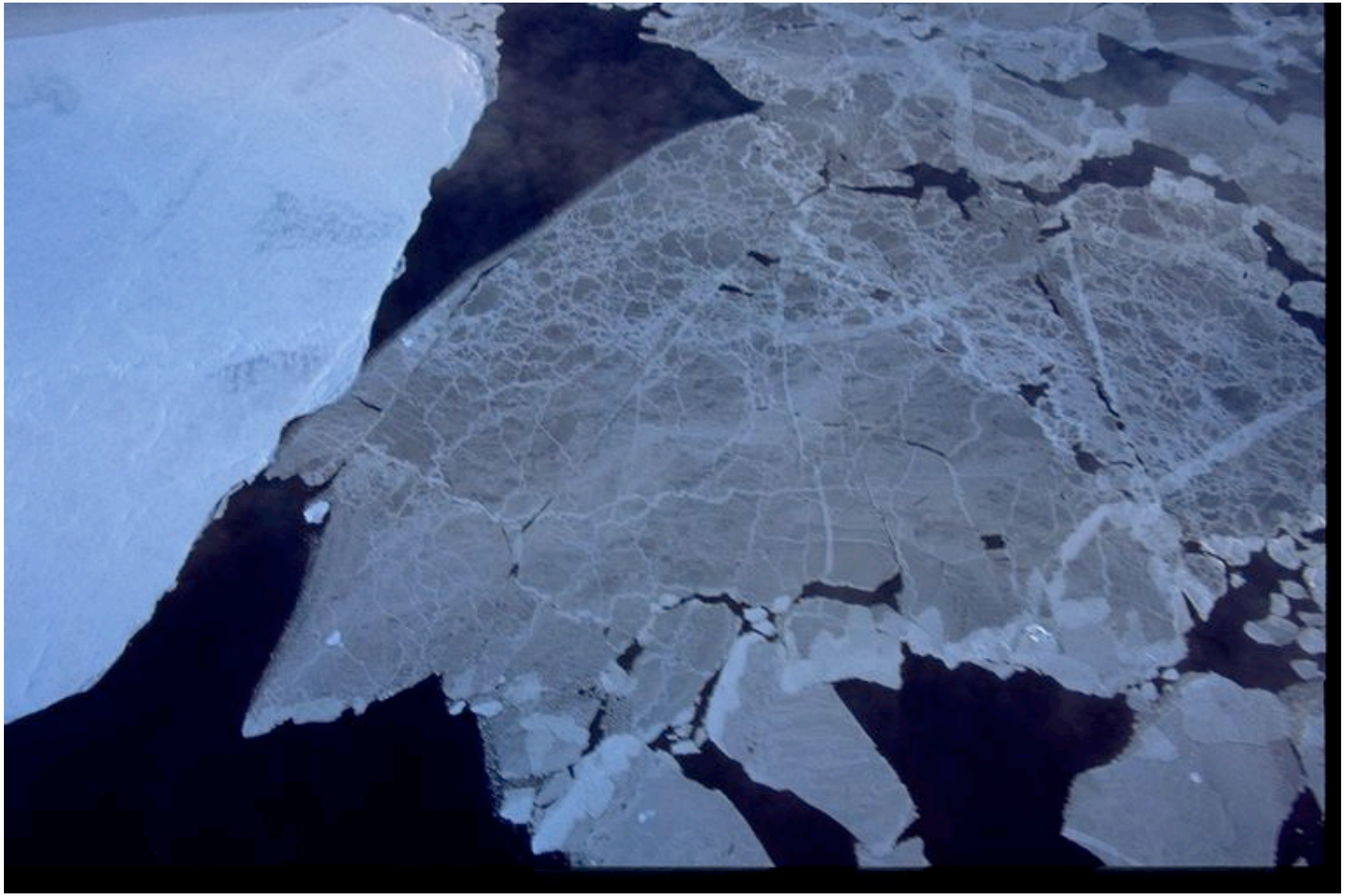
Pressure Ridges

Pressure Ridges

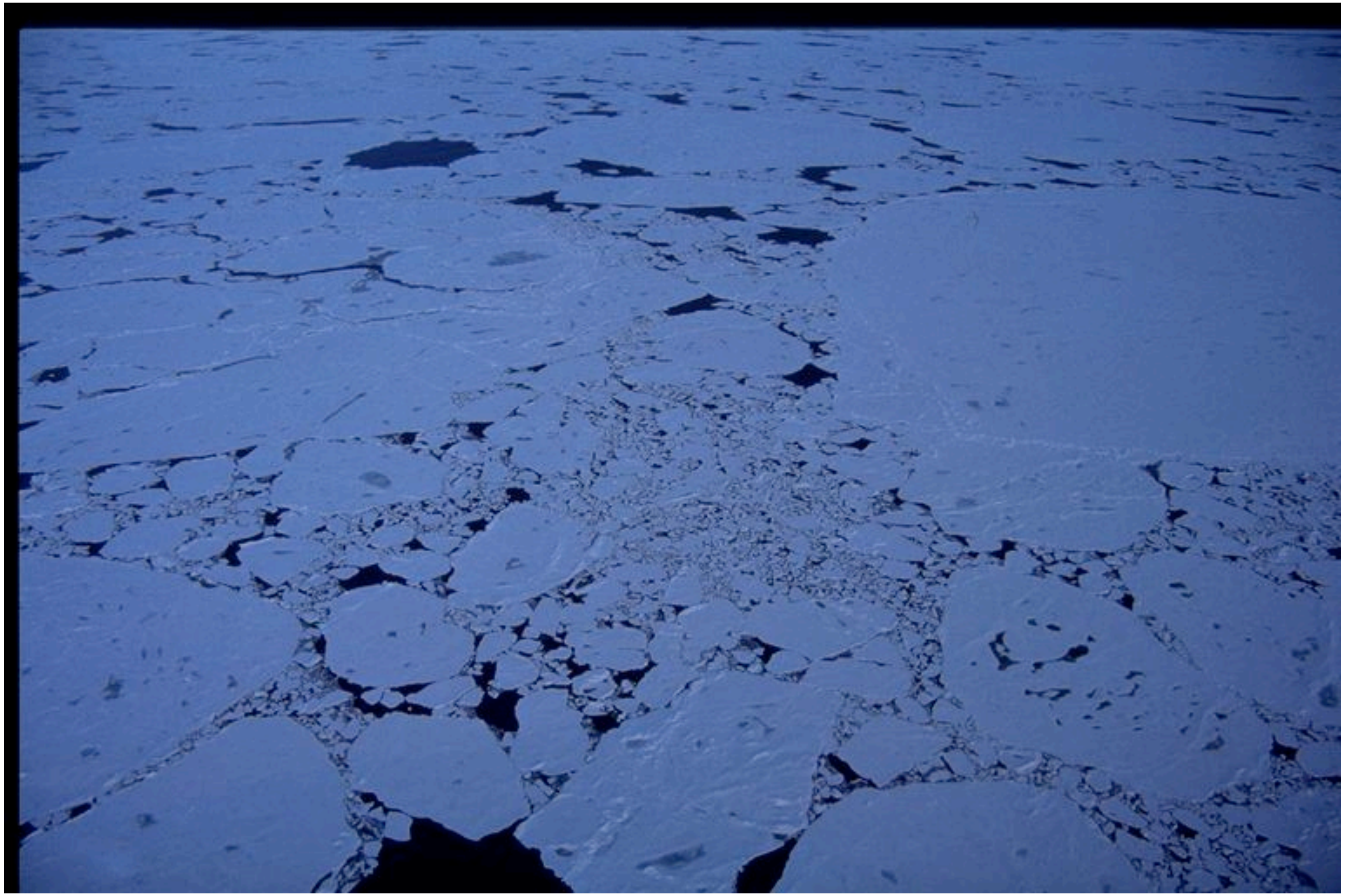
New Ice Formation in Leads

New Ice Formation in Leads

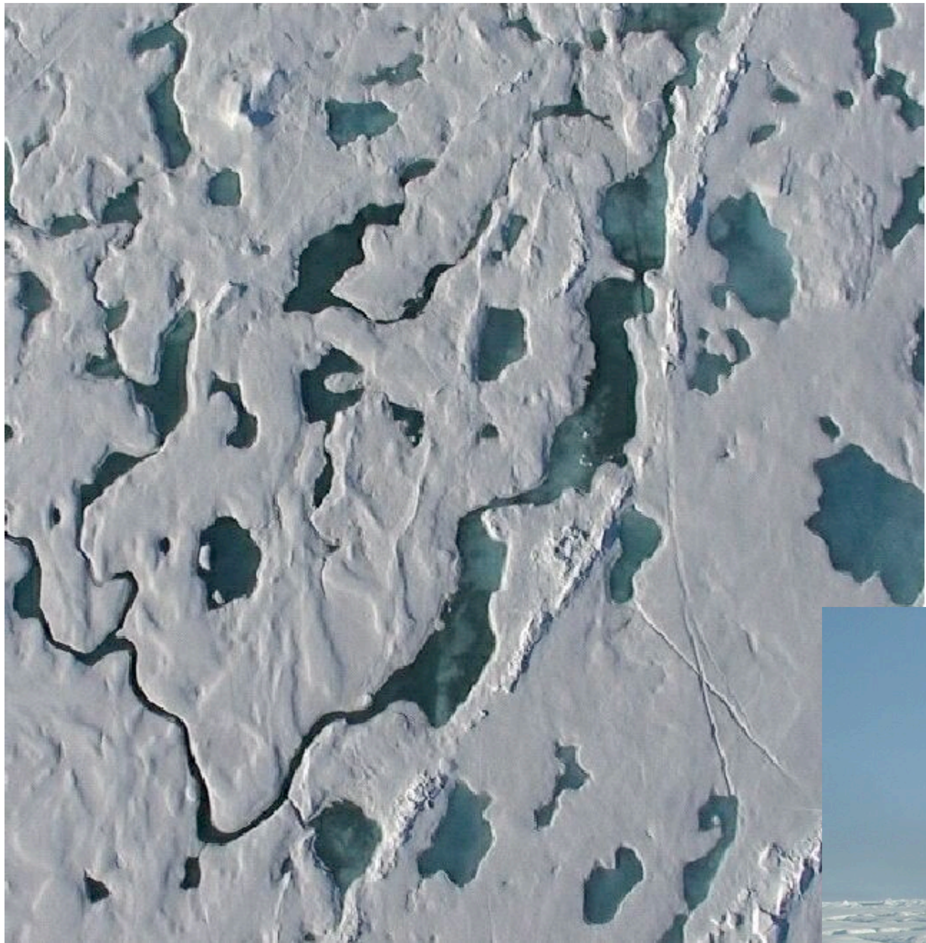
New Ice Formation in Leads



Melt Ponds on Arctic Sea Ice

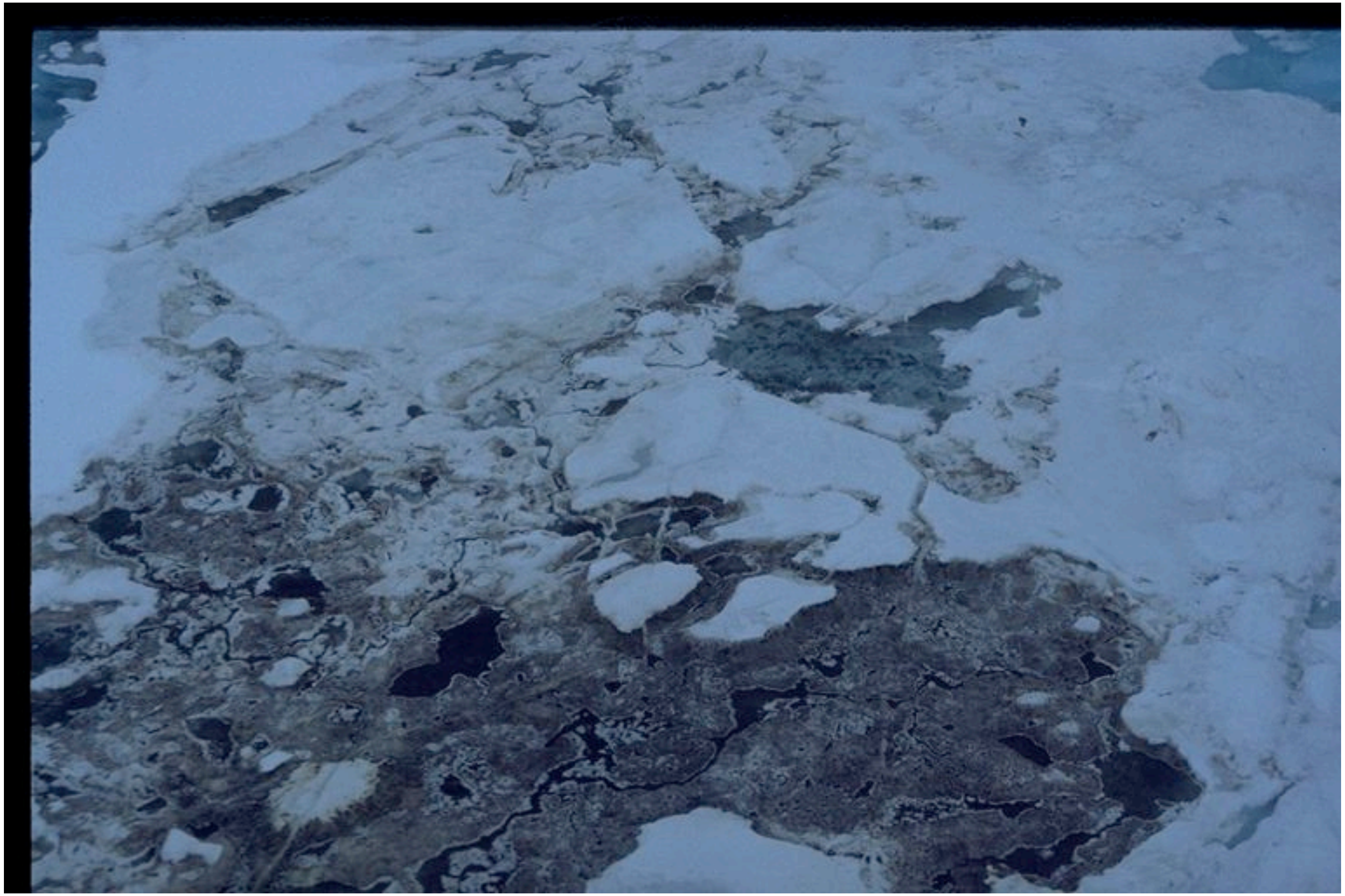


Melt ponds in the Arctic

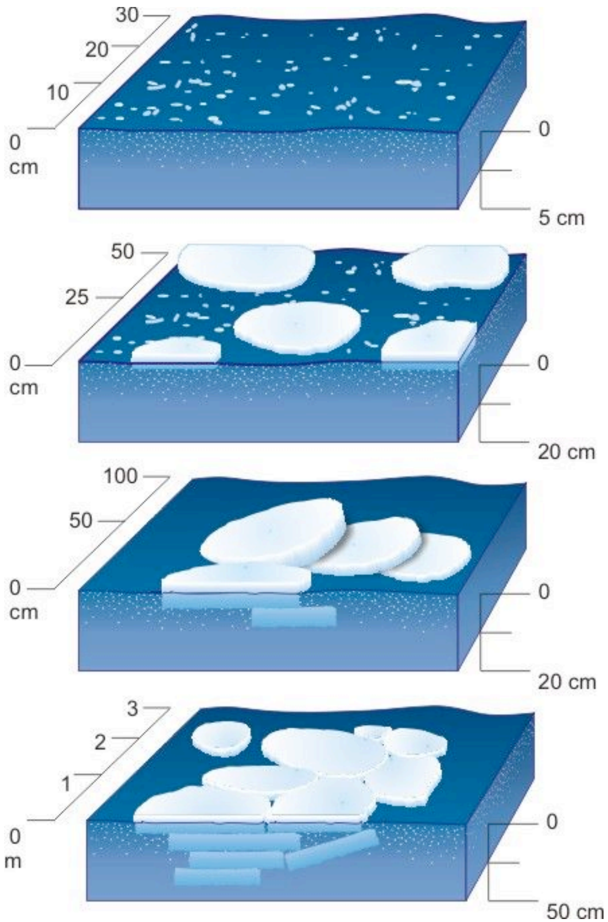


150 m

Sediment Patch on Arctic Sea Ice



Sea Ice Formation



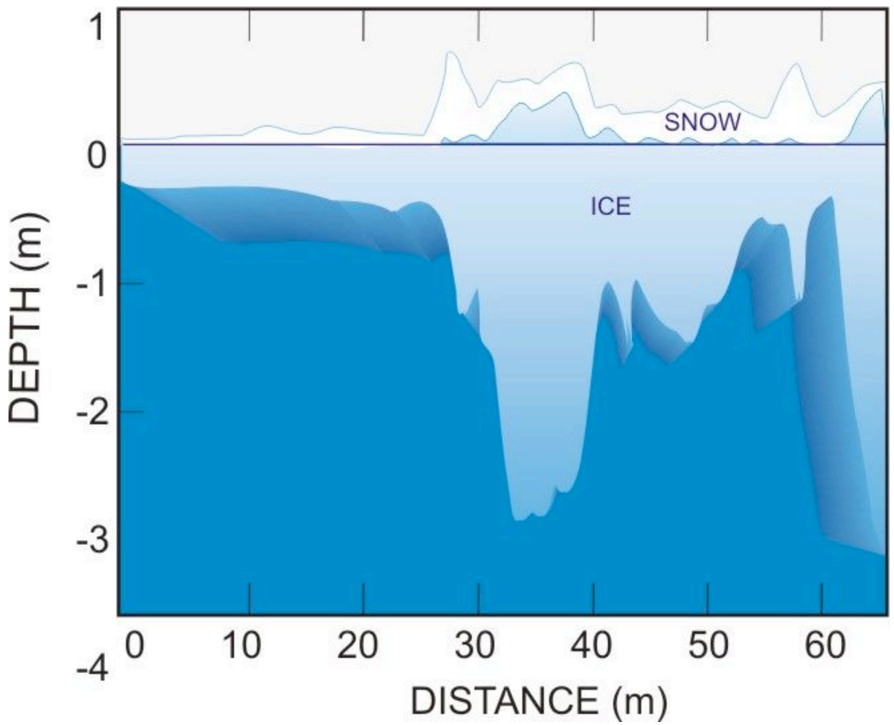
Frazil ice,
Grease Ice

Pancake Ice

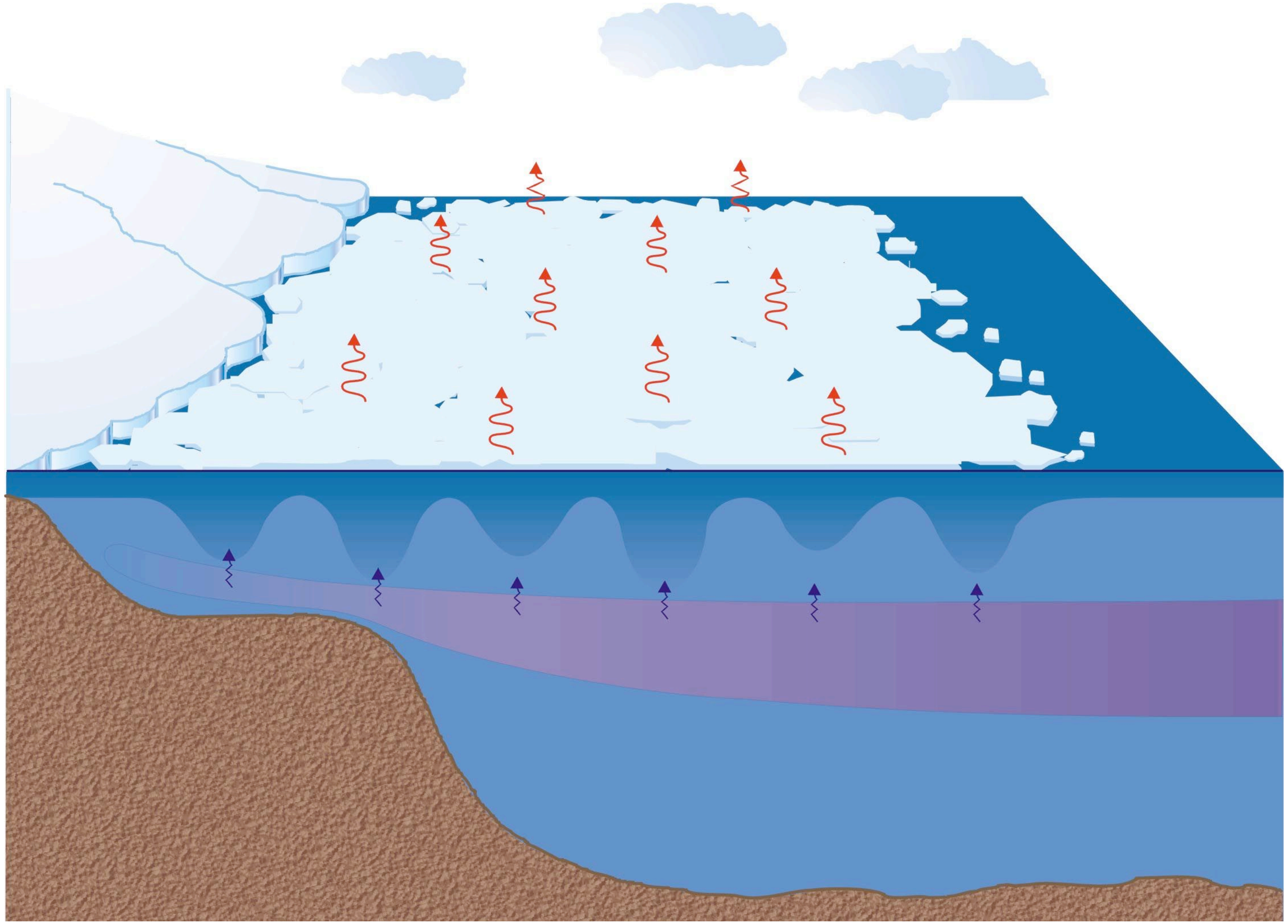
Larger Floes

One-year Ice,
Multi-year Ice

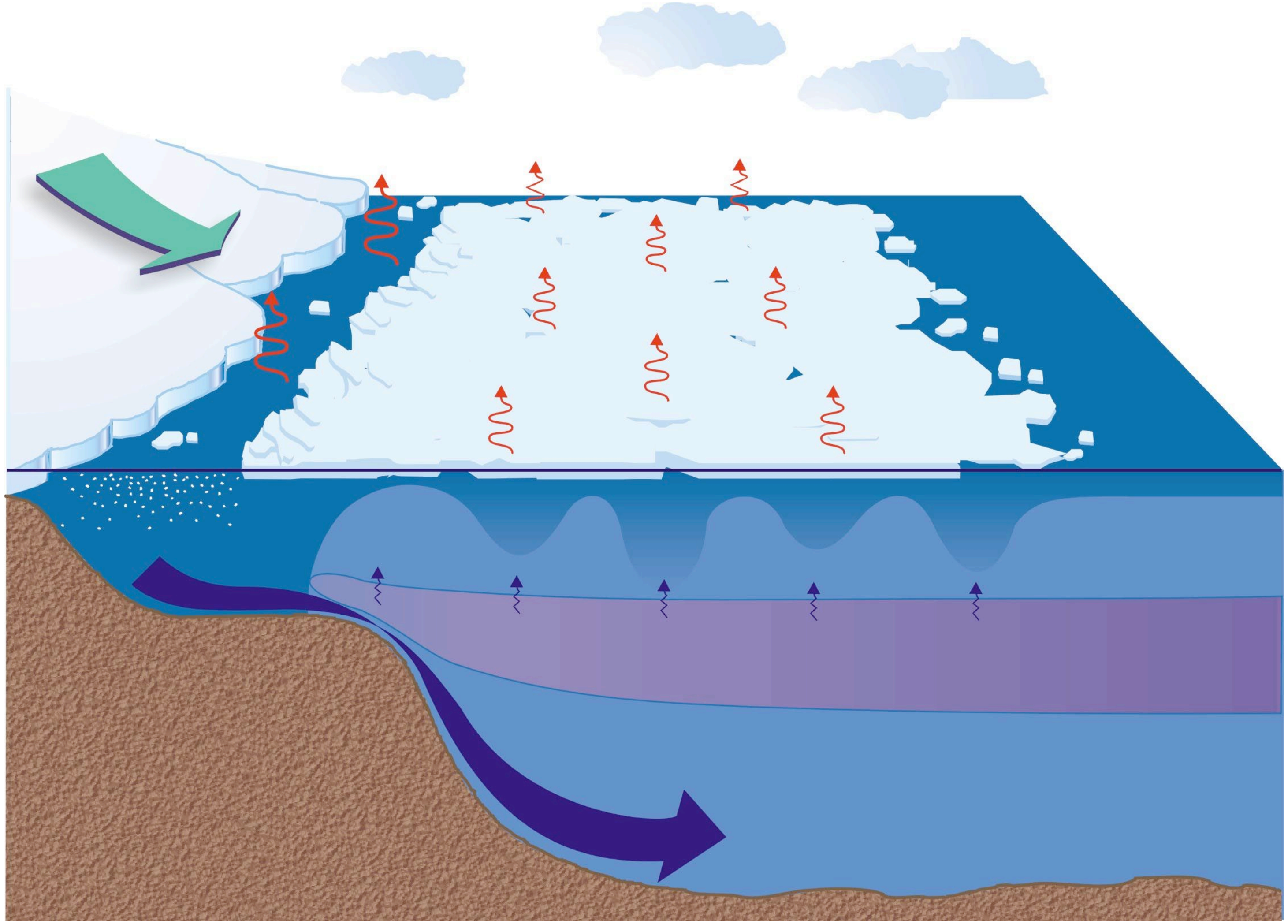
Deformation: Pressure Ridges



Sea Ice Reduces Heat Exchange

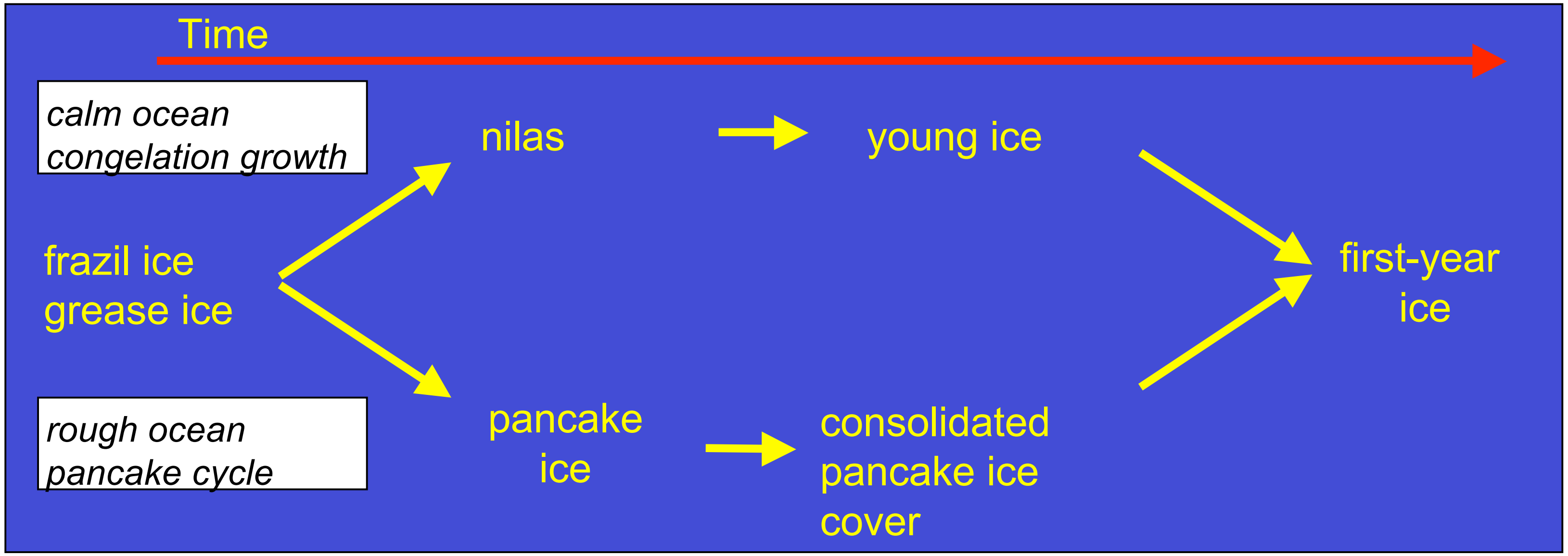


Deep and Bottom Water Formation

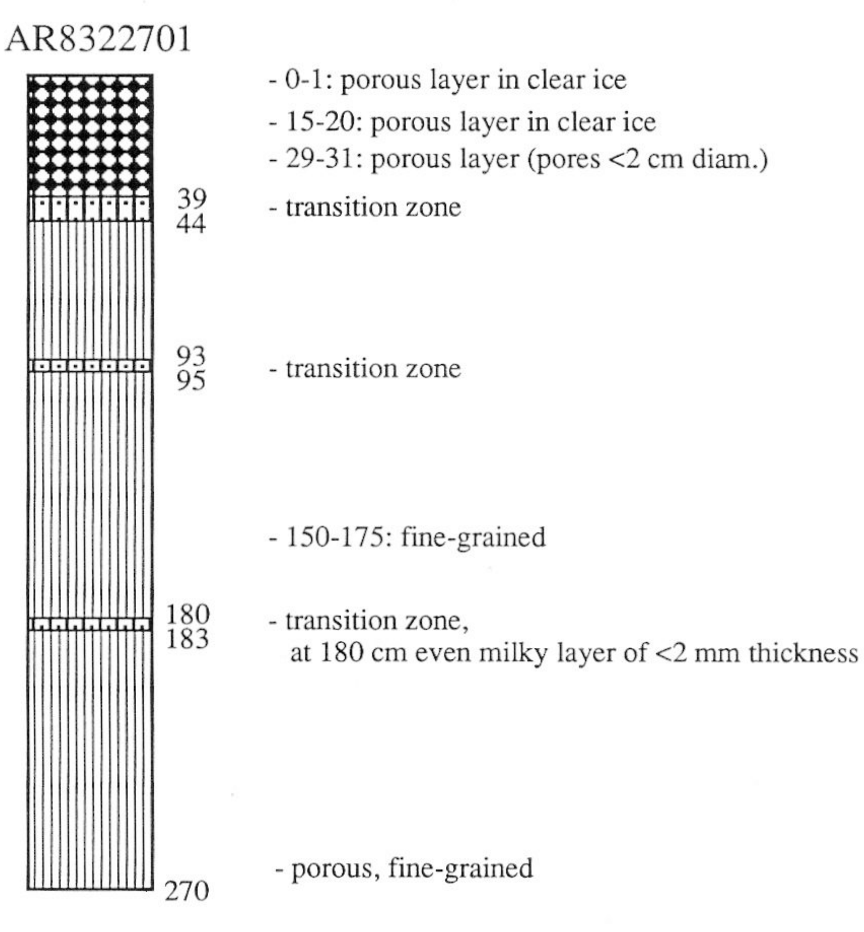


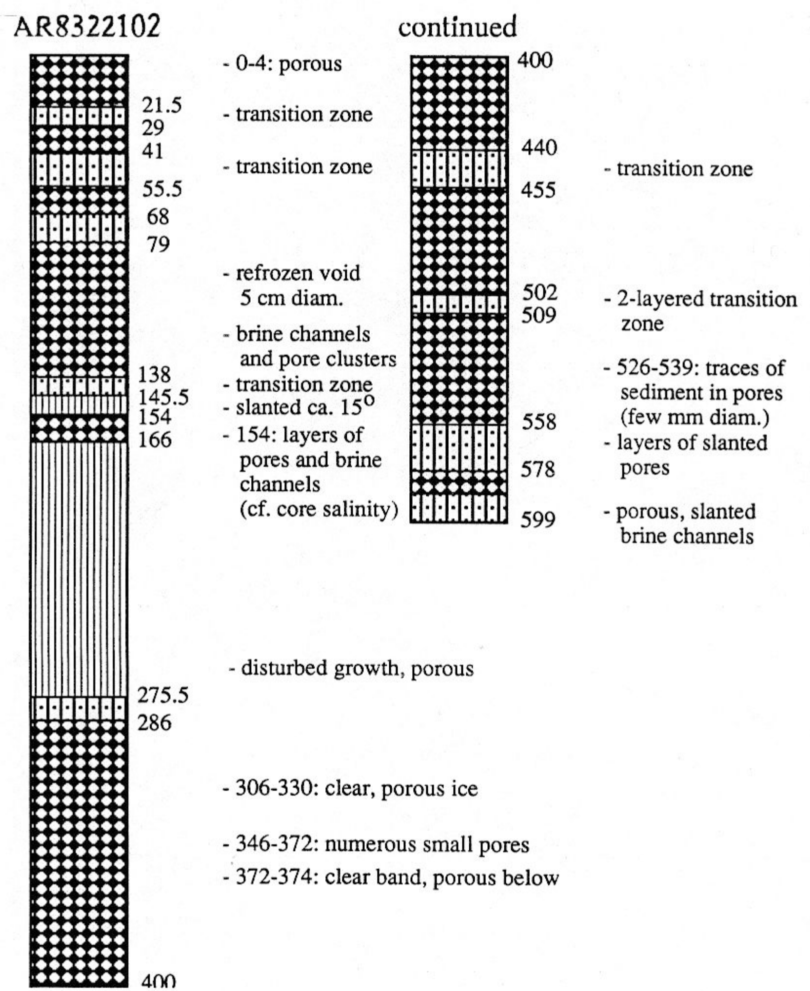
Sea Ice Types

Class	Description	Thickness
New ice	ice which began to grow a few hours or days ago	0 – 10 cm
Young ice	transition between new and first-year ice	10 - 30 cm
First-year ice	ice of no more than one winter's growth	30 – 200 cm
Old ice	ice that has survived at least one summer's melt; most topographic features are smoother than on first-year ice	> 200 cm



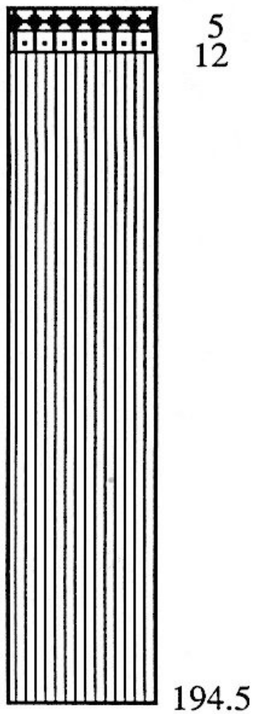
Vertikal Structure





Vertikal Structure

AR8324301

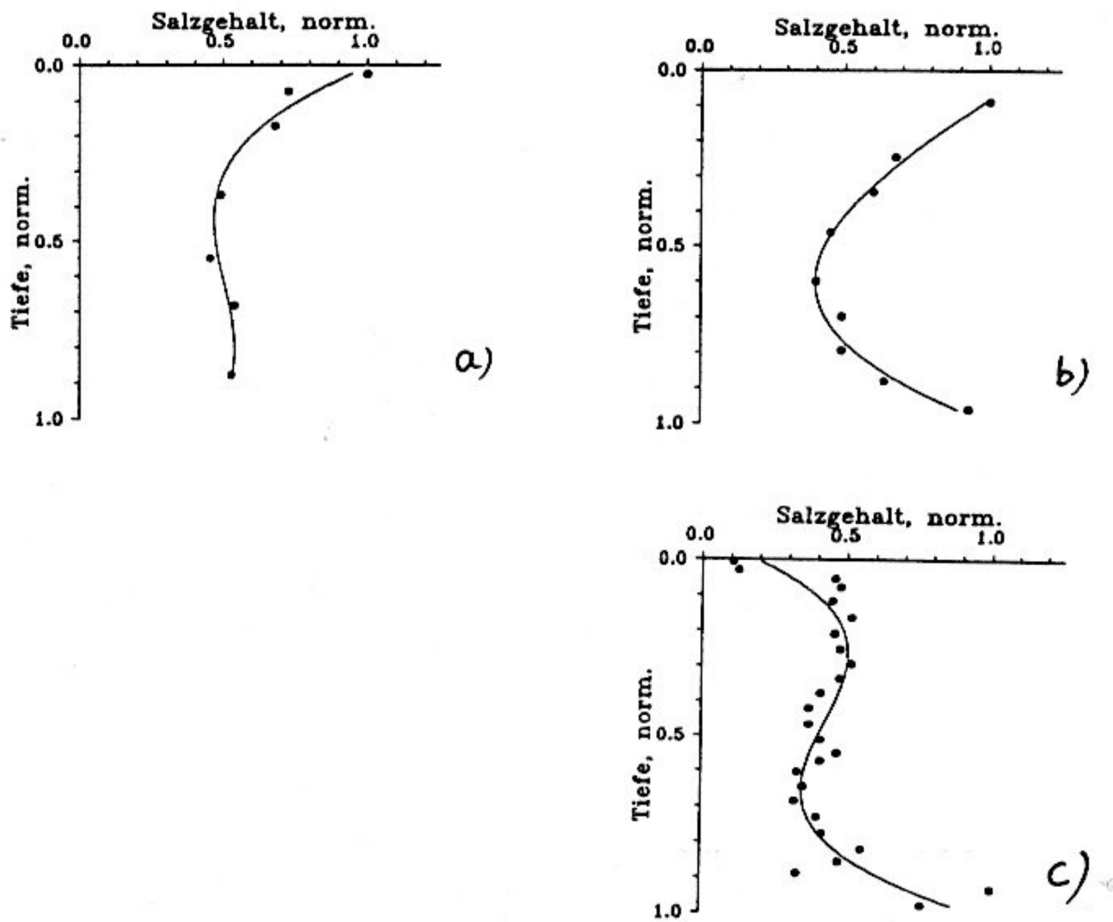


- porous
- clear, no pores, retextured columnar ice enclosing granular grains

retextured

- 83-87.5: clear ice, at 87.5 internal boundary with numerous elongated pores below (not interfering with grain growth)

Salinity Profiles



Vertical Salinity Profiles (Eicken, 1991)

Salinity vs. Thickness (Age)

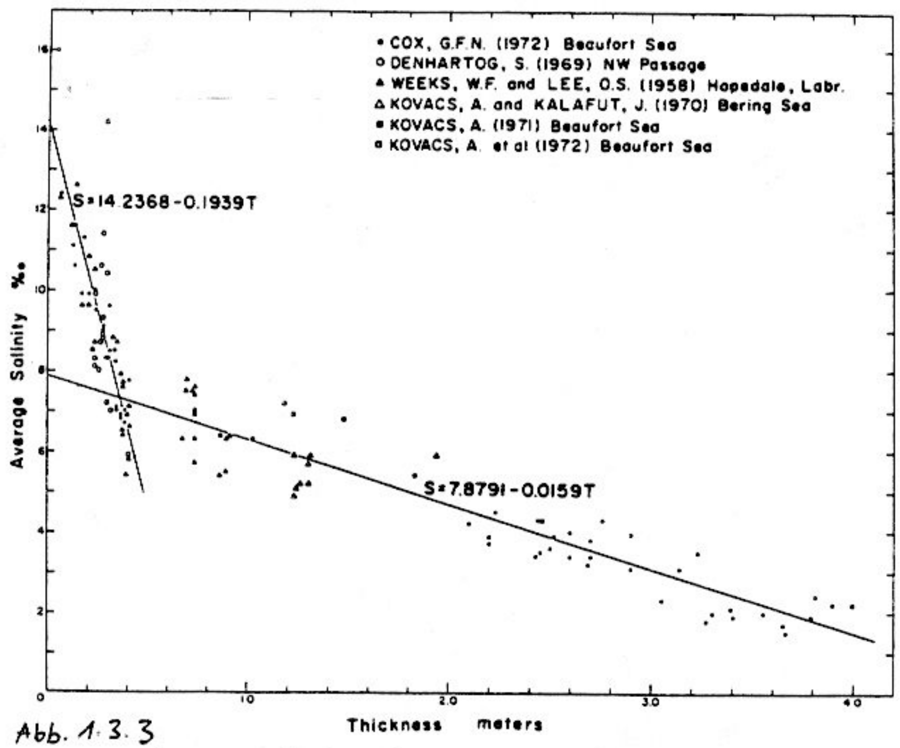


Abb. 1.3.3

Average salinity of sea ice as a function of ice thickness for cold sea ice sampled during the growth season (Cox and Weeks, 1974).

Salinity determines thermal conductivity:

$$\lambda_{si} = \lambda_i + \frac{\beta S_i}{T} \qquad \text{with} \qquad \lambda_i = 9.82 e^{-0.0057T}$$

salinity determines electromagnetic properties:

i.e. dielectric constant

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Sea Ice: Measurement of Properties

Sea Ice Parameters

Fundamental

- albedo
- extent
- concentration
- drift
- type distribution

Measurements

satellite imaging (radar, passive μ-wave, optical and IR) local: aircraft measurements+reconnaissance, ship reports

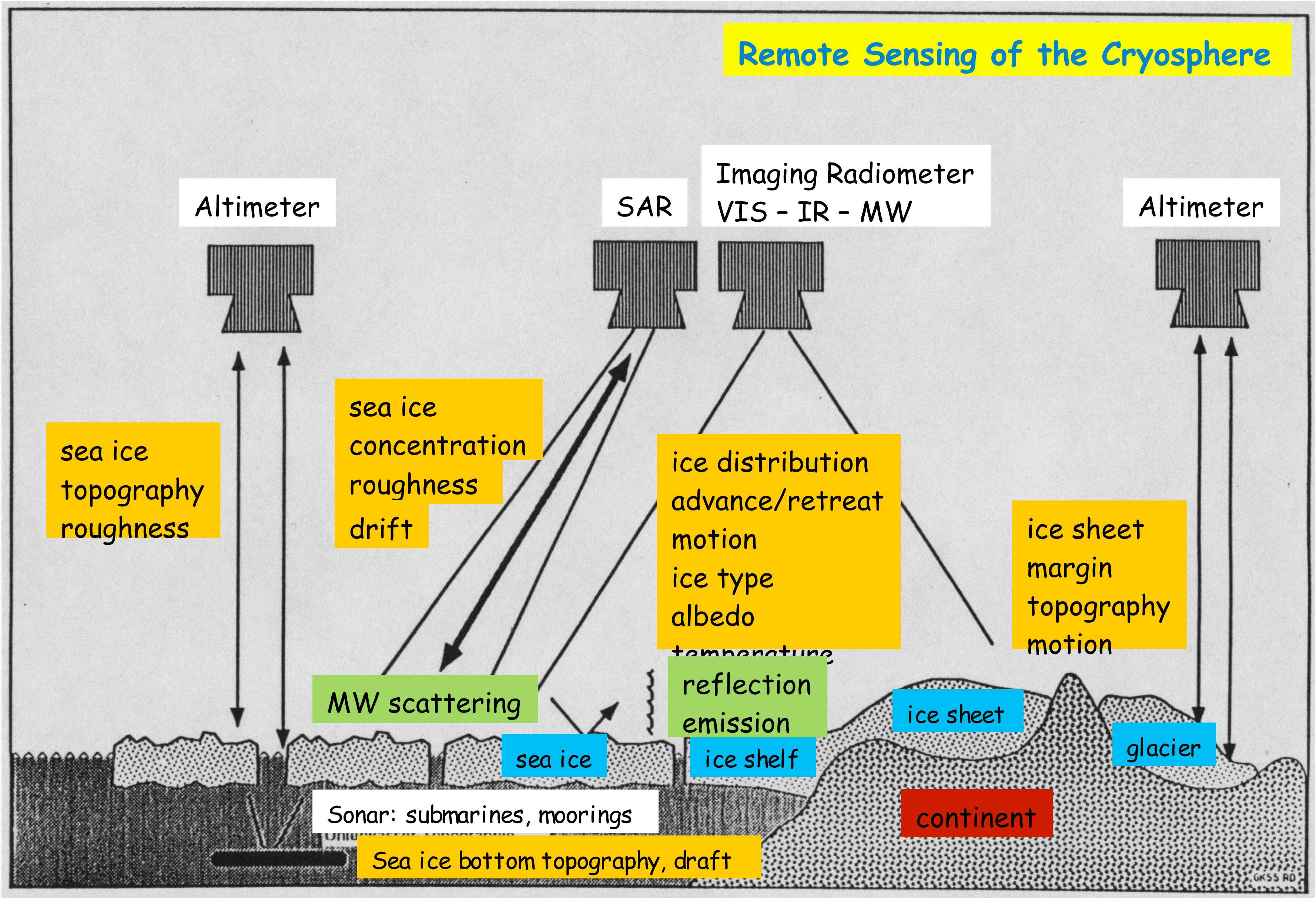
- thickness

radar and laser altimetry, sonar, EM induction sounding, drilling

Specific

- characteristics of leads and polynyas
- ice deformation and roughness
- melt onset and freeze-up
- ice floe size distribution
- thin ice type separation, frost flower detection
- snow properties (thickness, grain size…)

Remote Sensing of the Cryosphere



What Is Directly Measured ?

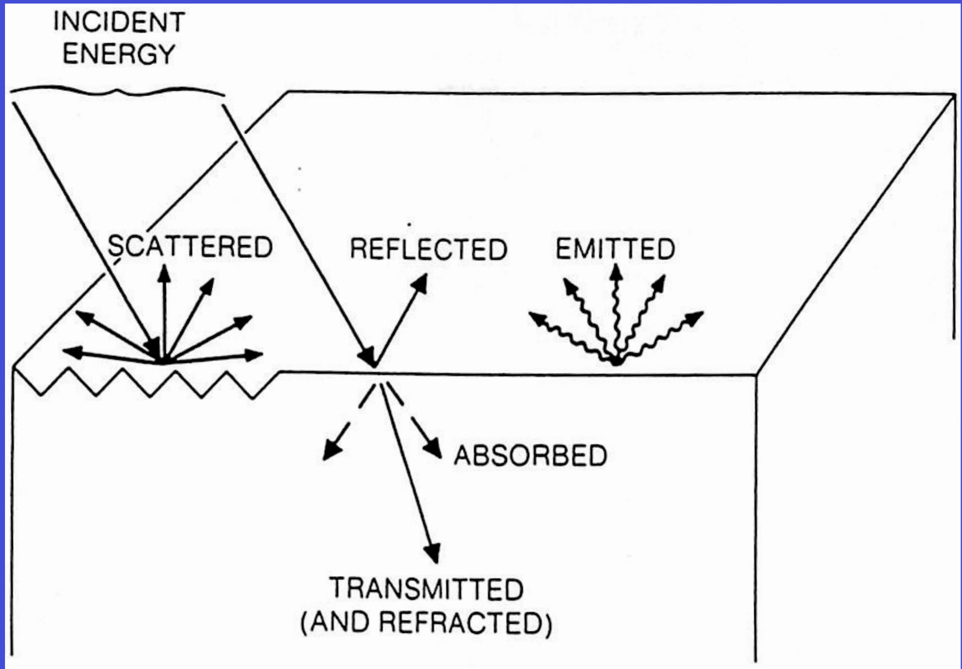


Figure 1-1 Interaction processes between electromagnetic energy and matter.

Surface Reflectivity (VIS and NIR)

Brightness Temperature (IR, μ-wave)
μ-wave: $T_b = \varepsilon T$

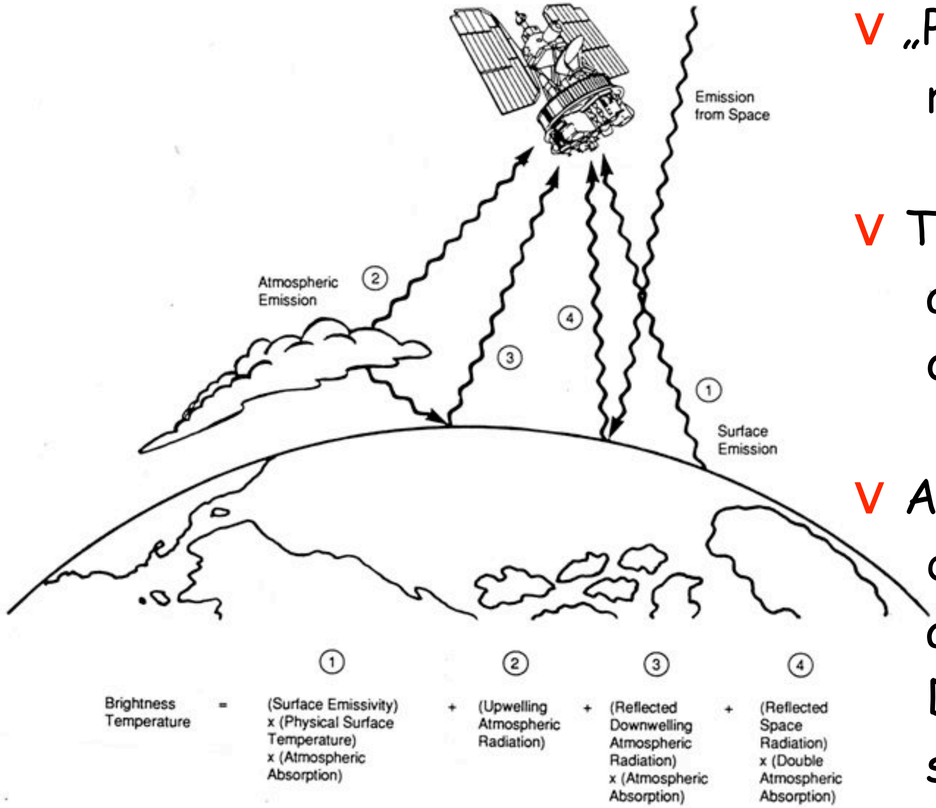
Radar Backscattering Coefficient

+ spatial variations of these parameters

Remote Sensing of Sea Ice Parameters

ice variable	VIS-NIR	IR	MR	SAR	ALT	SCAT	LASER	SONAR
extent	++	++	++	+	++	+	++	++
coverage	++	++	+	++	(+)		++	++
floe size distribution	++	+		++	(+)			(+)
ice type			+	(+)	(+)			
ice thickness					(+)		+	++
ice roughness				(+)	++	(+)	++	++
albedo	++							
drift	++	++	++	++		+		(+)
horiz. resolution	>10m	1 km	30 km	30 m	1 km	50 km	1m	5 m

Sea Ice Passive MW Radiometry

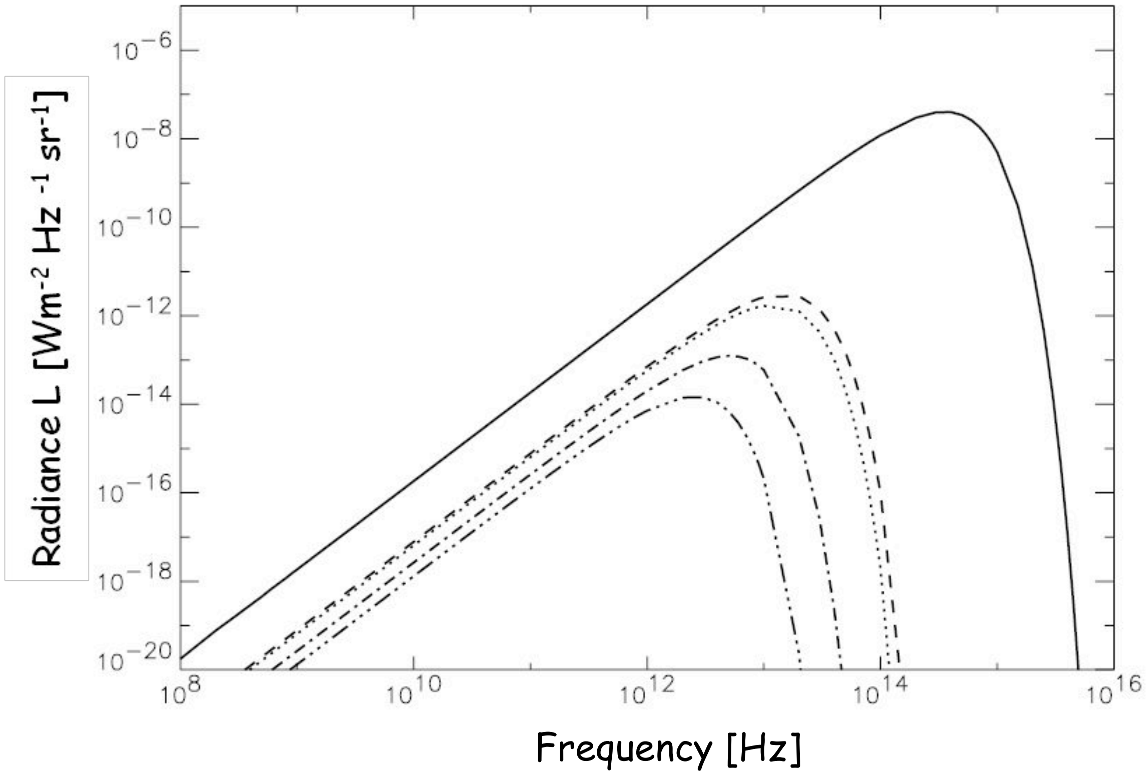


- „Passive": The sensor consists of a receiver and detects the natural radiation.
- The sensor measures the thermal radiation of the Earth's surface in the range of 1-100GHz (microwave region).
- Advantages: measurements do not depend on light conditions and are almost independent of weather conditions. Data are obtained with good spatial and temporal sampling (global coverage of sea ice covered area every day), stable instrument calibration.
- Disadvantage: Spatial resolution is only poor (5-80 km, dependent on frequency and sensor), mixed pixel problem, coastal contamination effects, large variability

Planck Spectrum

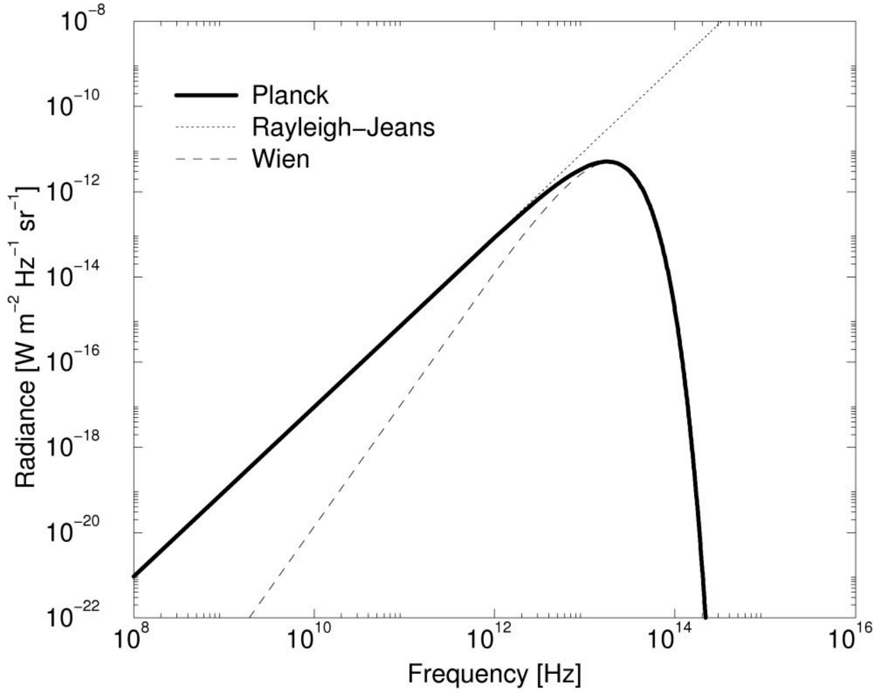
All substances emit electromagnetic radiation. This thermal radiation is a function of temperature. For perfect emitters, i.e. *blackbodies*, the spectral radiance L_ν is related to the absolute temperature through Planck's[II] Law (Fig. 6.5). $L^\star_\nu$ is the energy flux density per solid angle (sr) and frequency interval with the unit $[Wm^{-2}Hz^{-1}sr^{-1}]$.

$$\boxed{L^\star_\nu = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}}$$



Pluto (47K), Jupiter (87K), Mars (211), Earth (255K), Sun (6000K)

Thermal emission in MW Domain



In the microwave domain, where $h\nu \ll kT$, the Rayleigh-Jeans Law applies, which represents an approximation of the Planck Law (6.9). With $\exp[h\nu/(kT)] \simeq 1 + h\nu/(kT)$ one finds

$$L_\nu \simeq \frac{2\nu^2 k}{c^2} T$$

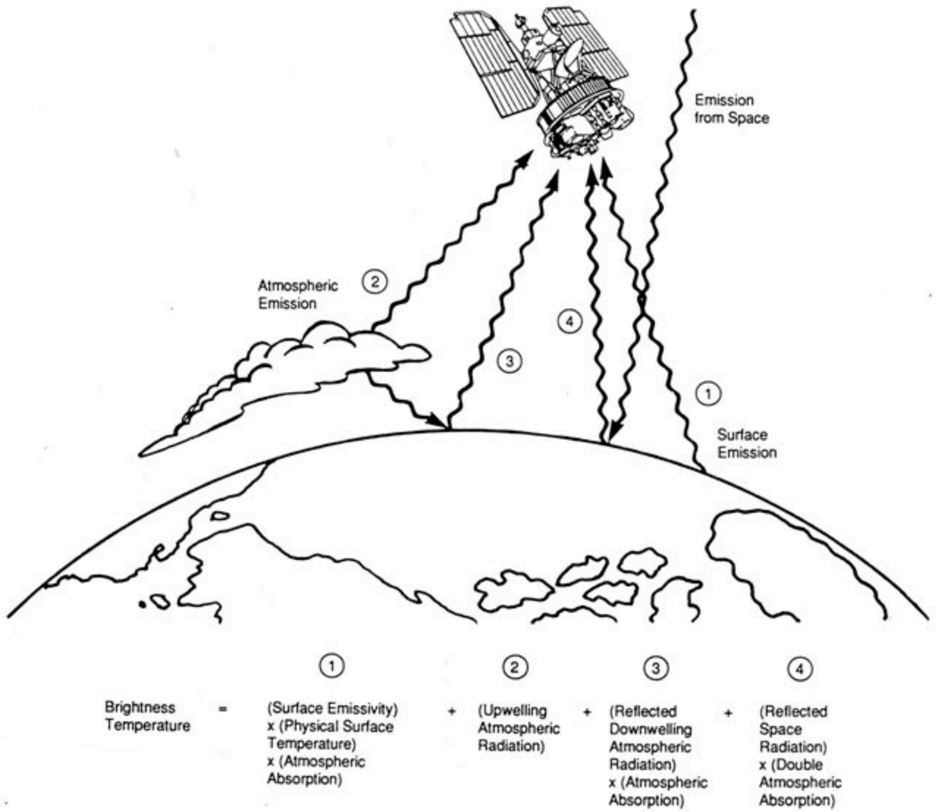
Therefore, the spectral radiance in the microwave domain is directly proportional to the absolute temperature, and a definition of the so-called *radiative temperature* T_B in terms of the observed radiance L_ν is possible.

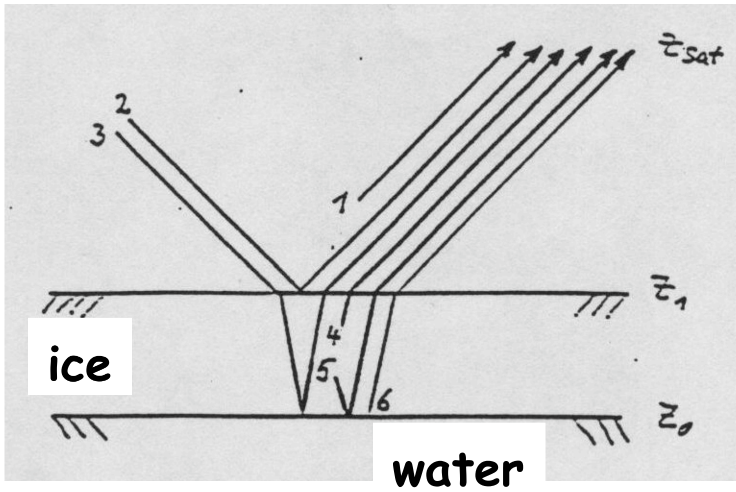
brightness temperature for a black body

$$T_B = \frac{c^2}{2\nu^2 k} L_\nu$$

for natural bodies

Sea Ice Passive MW Radiometry



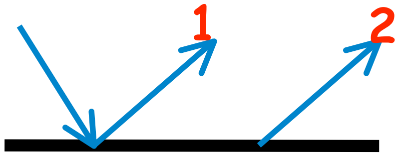


$$\boxed{T_B^{ij} = \overset{1}{e_{ij} T_s e^{-\tau_i}} + \overset{2}{T_{B,up}^{ij}} + \overset{3}{(1-e_{ij}) T_{B,down}^{ij} e^{-\tau_i}} + \overset{4}{(1-e_{ij}) T_{B,sp}^{ij} e^{-2\tau_i}}}$$

surface signal

atmospheric correction

Sea Ice Passive MW Radiometry



$$T_i(\theta) = \underbrace{\rho_i(\theta) T_s}_{1} + \underbrace{e_i(\theta) T_g}_{2}$$

emissivity

$$e_i = 1 - \rho_i$$

reflectivity

$$T_i(\theta) = T_g + \rho_i(\theta)(T_s - T_g)$$

$$T_i(\theta) = T_s + e_i(\theta)(T_g - T_s)$$

water-ice difference:

$$\Delta T = T_o - T_m = (\rho_o - \rho_m)(T_s - T_g) = \Delta\rho(T_s - T_g)$$

$$\rho = \left(\frac{\sqrt{\epsilon} - 1}{\sqrt{\epsilon} + 1}\right)^2 = \left(\frac{n - 1}{n + 1}\right)^2$$

$$\begin{aligned} \rho_m &= 0.07 \\ \rho_o &= 0.64 \\ \Delta\rho &= 0.57 \end{aligned}$$

strong contrast: easily detectable

$$\boxed{\Delta T = -127K}$$

Sea Ice Passive MW Radiometry

temporal evolution of sea ice:

- aging processes
- salinity reduction
- reflectivity change

$$\boxed{\Delta\rho = \rho\frac{2\Delta\epsilon}{\sqrt{\epsilon}\,(\epsilon-1)}}$$

$\boxed{\epsilon=3 \quad \text{and} \quad \Delta\epsilon=0.6 \quad \text{(20\% change)}}$

$$\frac{\Delta\rho}{\rho} = 0.34 \qquad \text{and} \qquad \Delta\rho = 0.34\times 0.07 = 0.024$$

$\boxed{\Delta T = 5.4\ K}$ i.e. ice type also easily detectable

Sea Ice Concentration Algorithm

Mixed pixel: sea ice and water (C = ice concentration)

$$T_B = (1 - C)e_w T_w + C e_i T_i$$

$$\boxed{C = \frac{T_B - e_w T_w}{e_i T_i - e_w T_w}}$$

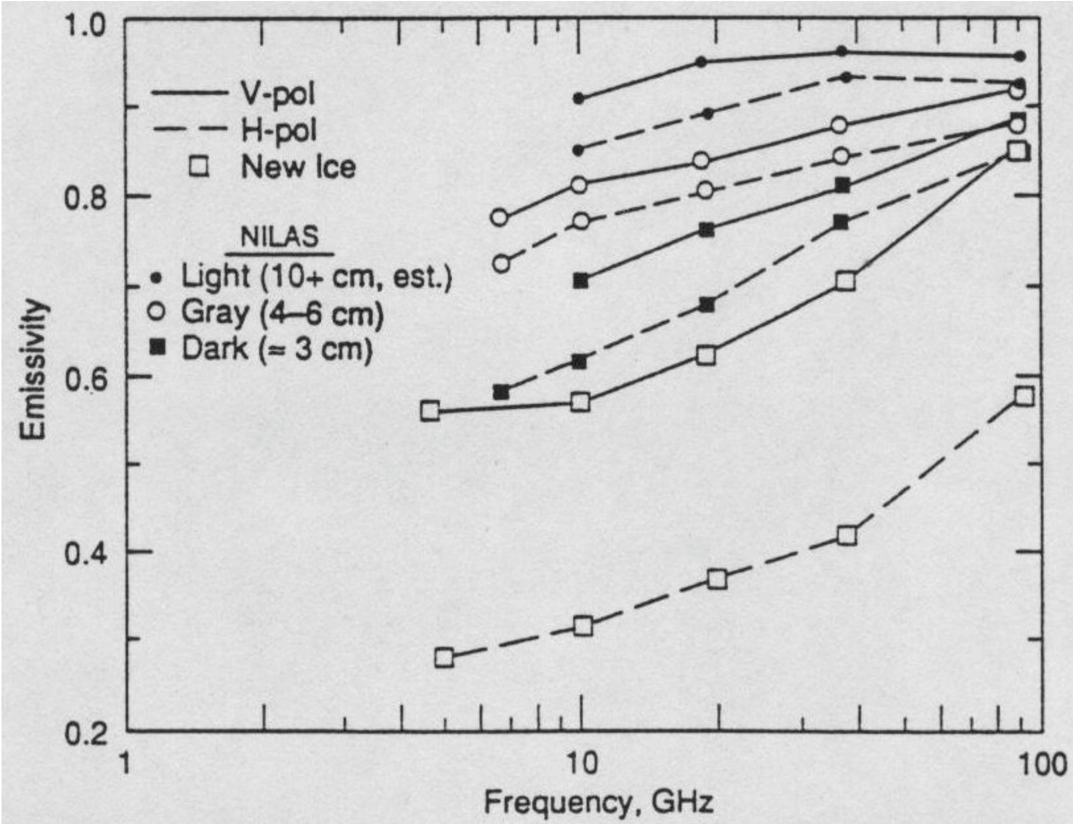
Mixed pixel: three surface types:

First-year sea ice, multi-year sea ice, and water

$$T_B = (1 - C_f - C_m)e_w T_w + C_f e_f T_f + C_m e_m T_m$$

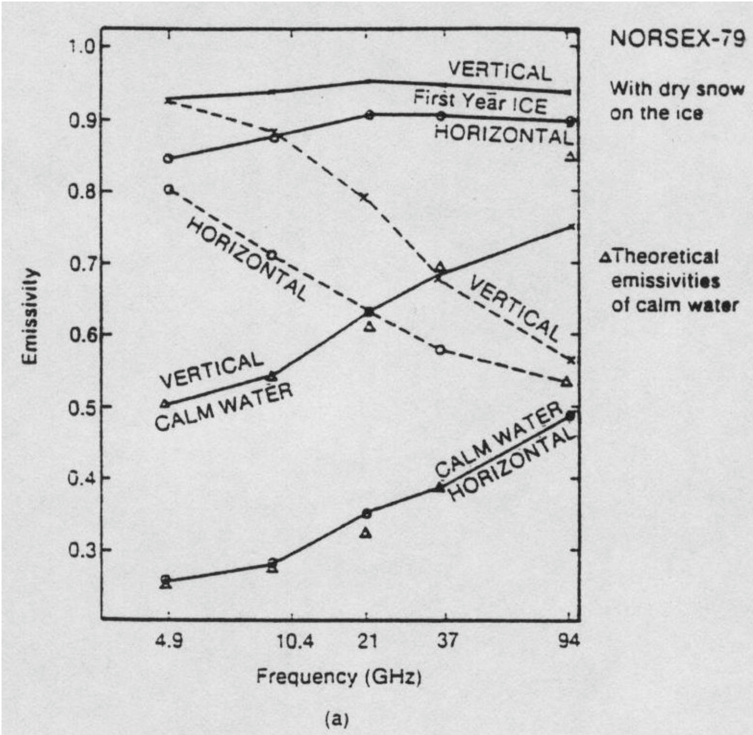
Measurements at more than one frequency or polarization required

Sea Ice Passive MW Radiometry

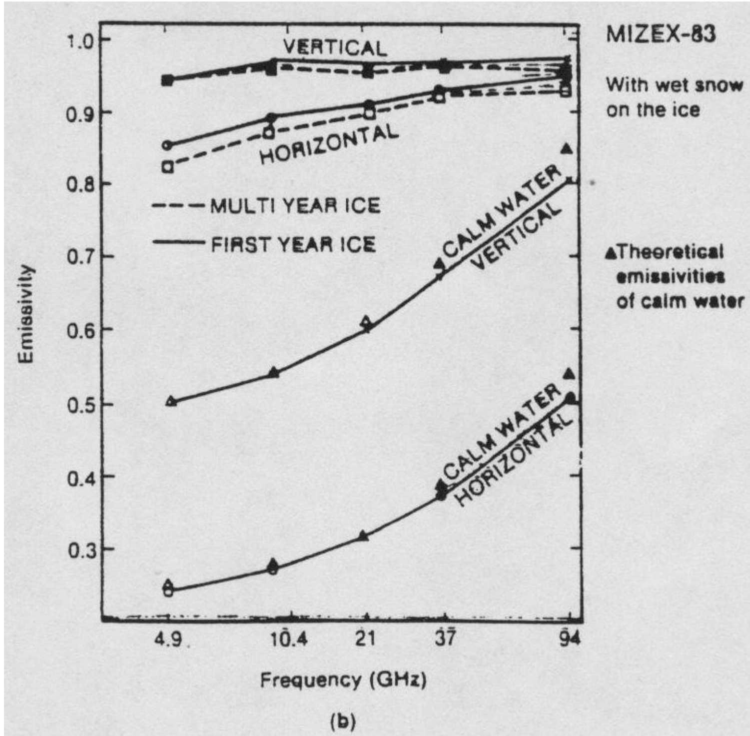


Sea Ice Passive MW Radiometry

sea ice with dry snow cover



sea ice with wet snow cover



Microwave Signatures as a Function of Frequency and Polarizations

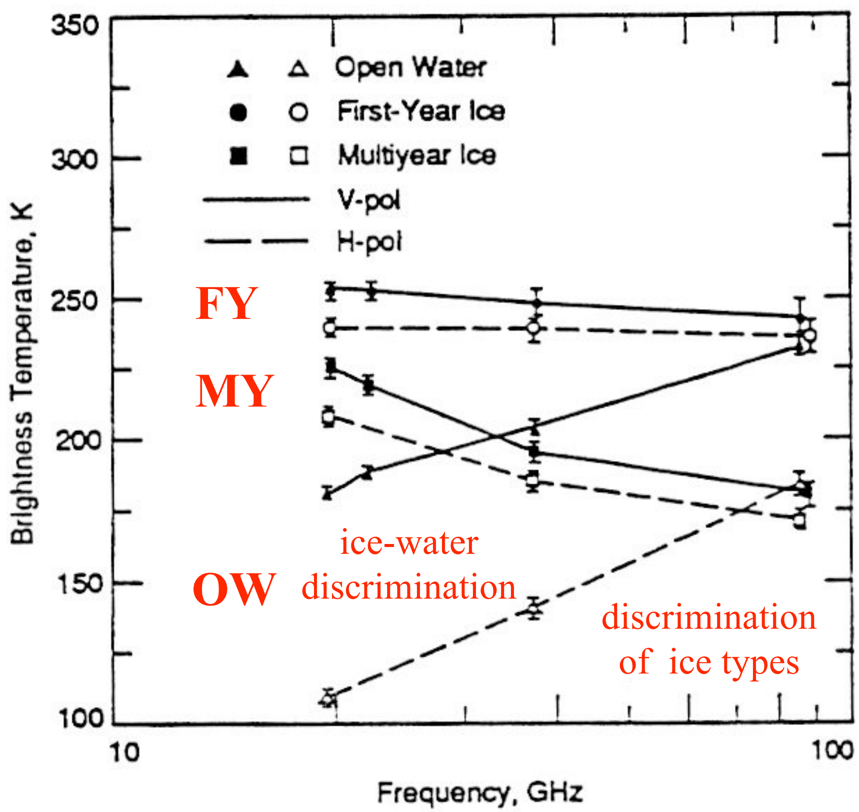


Fig. 4-18. Polarization and spectral characteristics of open water, first-year and multiyear sea ice as observed with the DMSP SSM/I on January 17, 1988.

Separation of ice and water at lower frequencies, using different polarizations

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

(Polarization Ratio)

Separation of FY and MY ice by combination of lower and higher frequencies

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

(Gradient Ratio)

$\Rightarrow$Why are ratios used?

In order to minimize effects of physical temperature.

NASA Team Algorithm

Fractions of first- and multi-year ice:

$$C_f = \frac{a_0 + a_1 PR + a_2 GR + a_3 PR \cdot GR}{D}$$

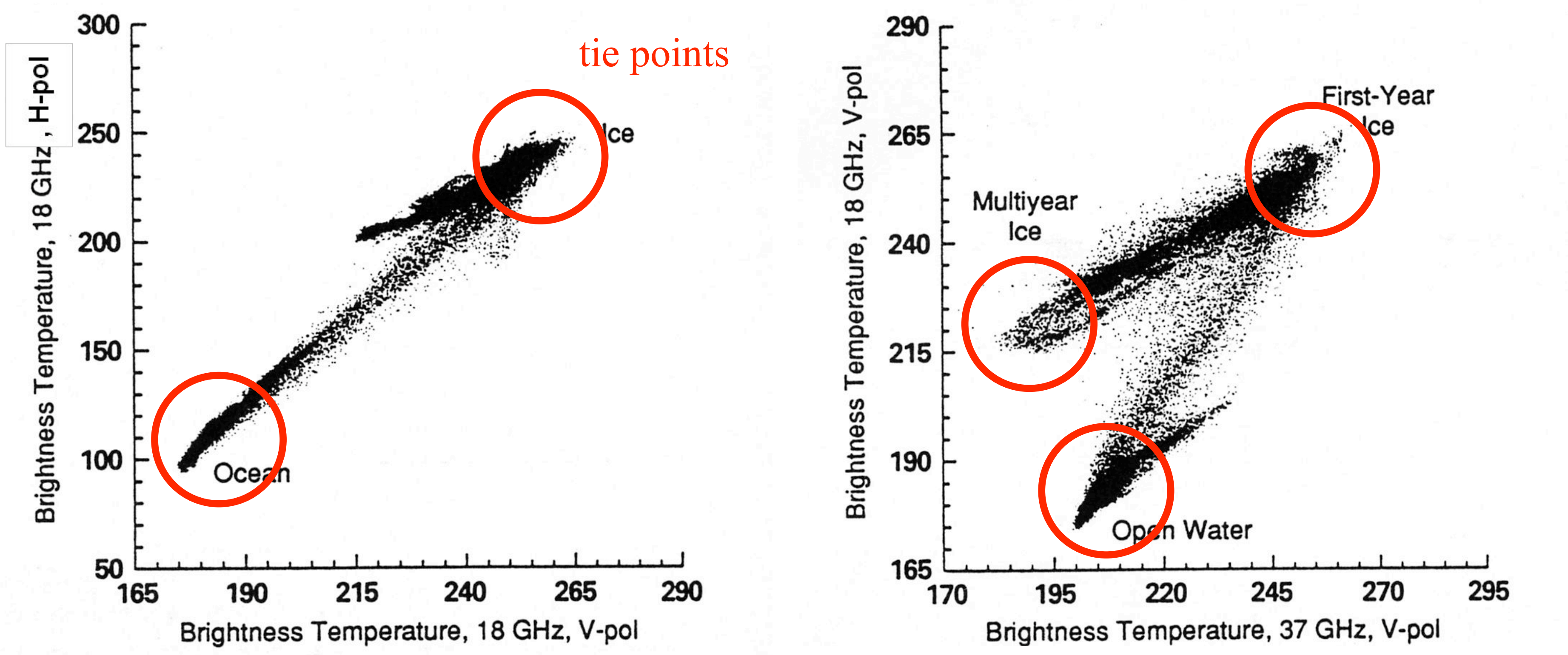
$$C_m = \frac{b_0 + b_1 PR + b_2 GR + b_3 PR \cdot GR}{D}$$

$$D = c_0 + c_1 PR + c_2 GR + c_3 PR \cdot GR$$

Open water fraction ? $C_w = 1 - C_f - C_m$

The coefficients a_i, b_i, c_i are derived from “tie points“, i.e. measurments over 100% FY ice, MY ice, and OW. For the NASA Team Algorithm, this is carried out at 18GHz V+H, and 37GHz V.

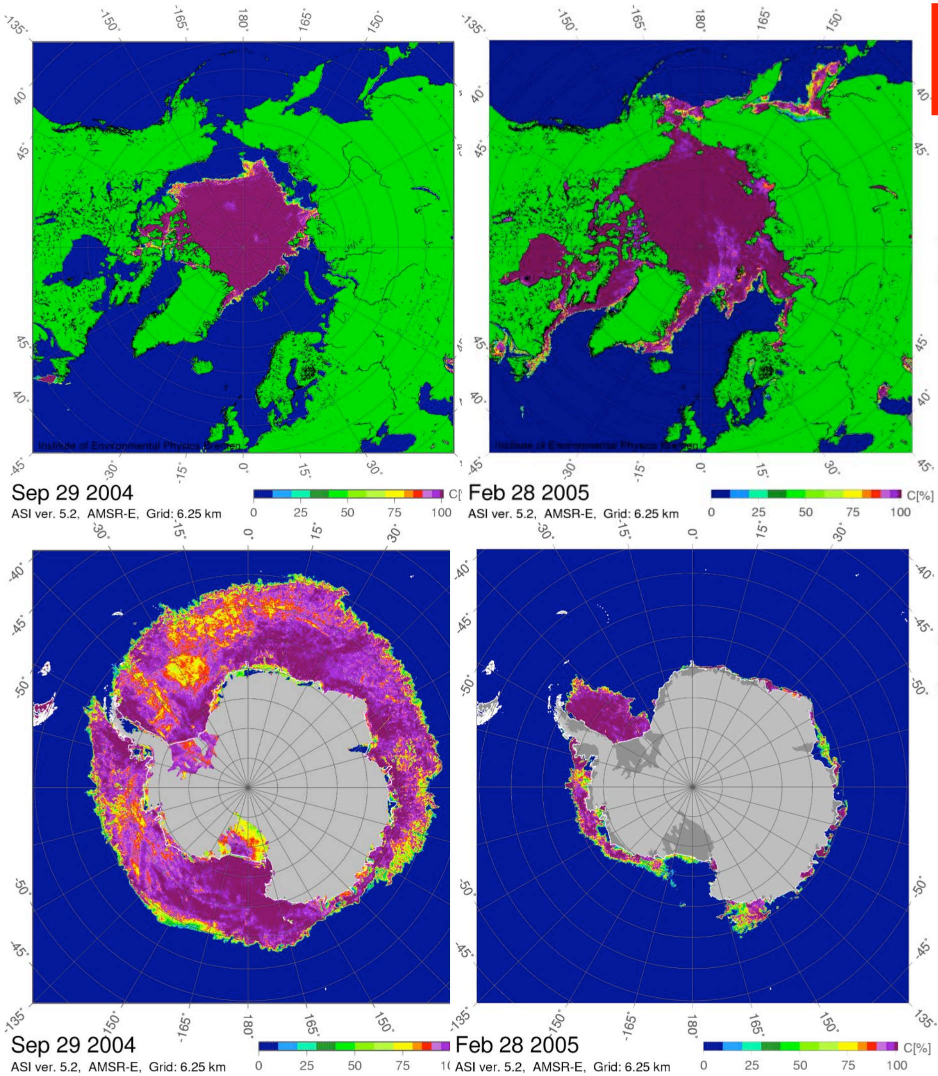
Scatterplots of Brightness Temperatures



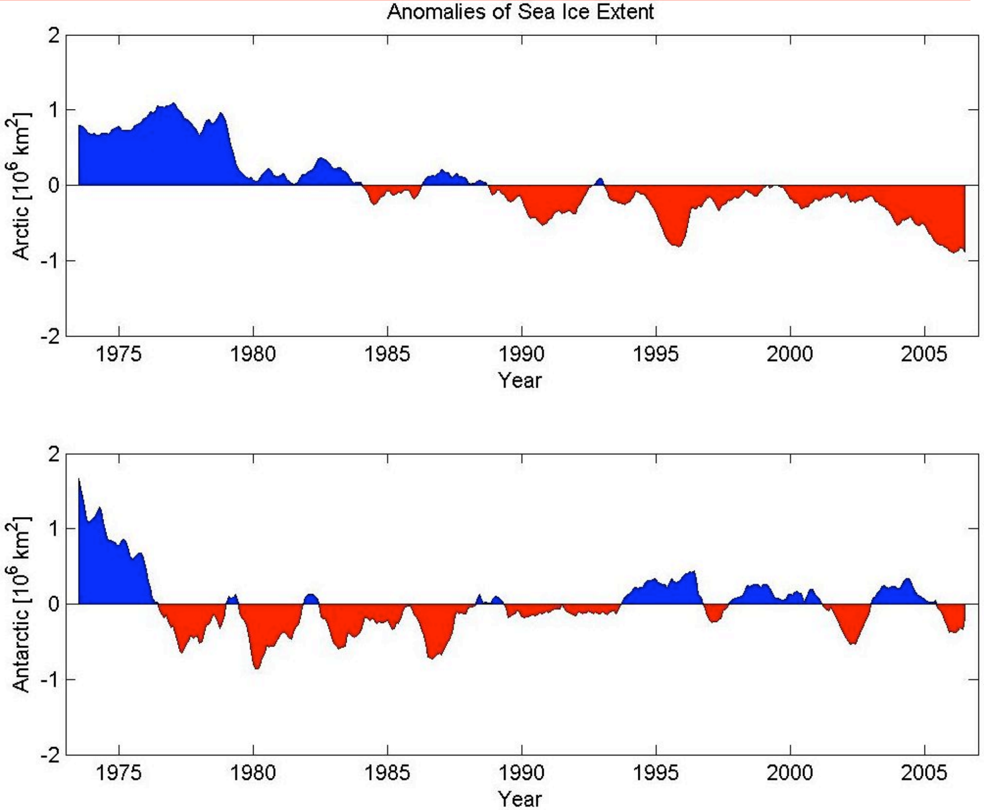
Separation of ice and water at lower frequencies, using different polarizations

Separation of FY and MY ice by combination of lower and higher frequencies

Sea ice extent

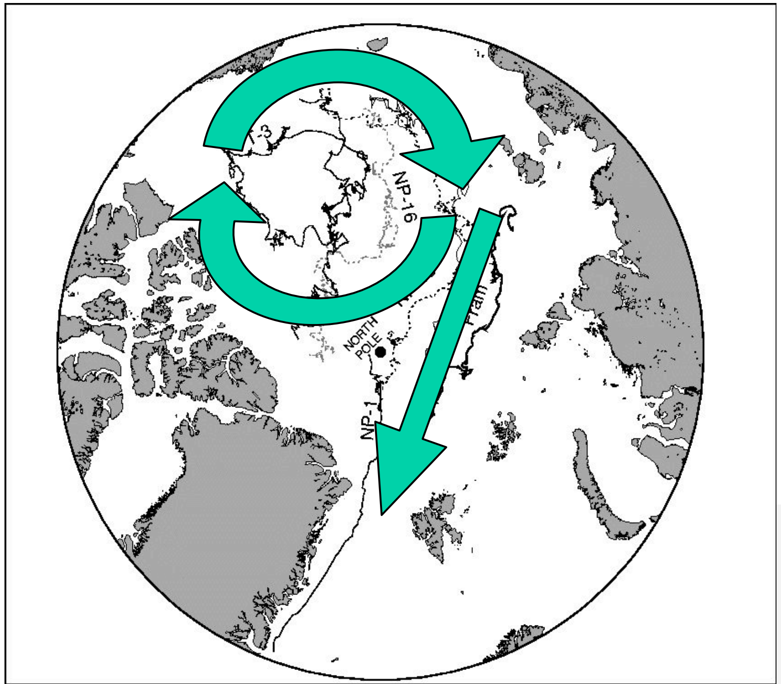


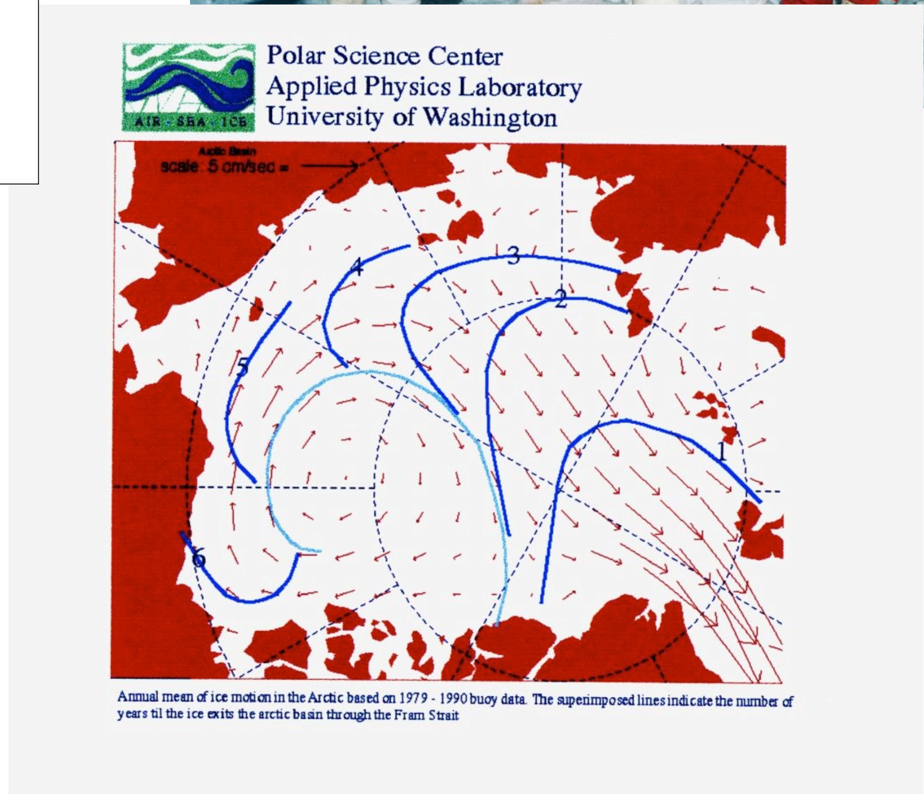
NH trend: -2.7% per decade



SH trend: not significant

Sea ice drift



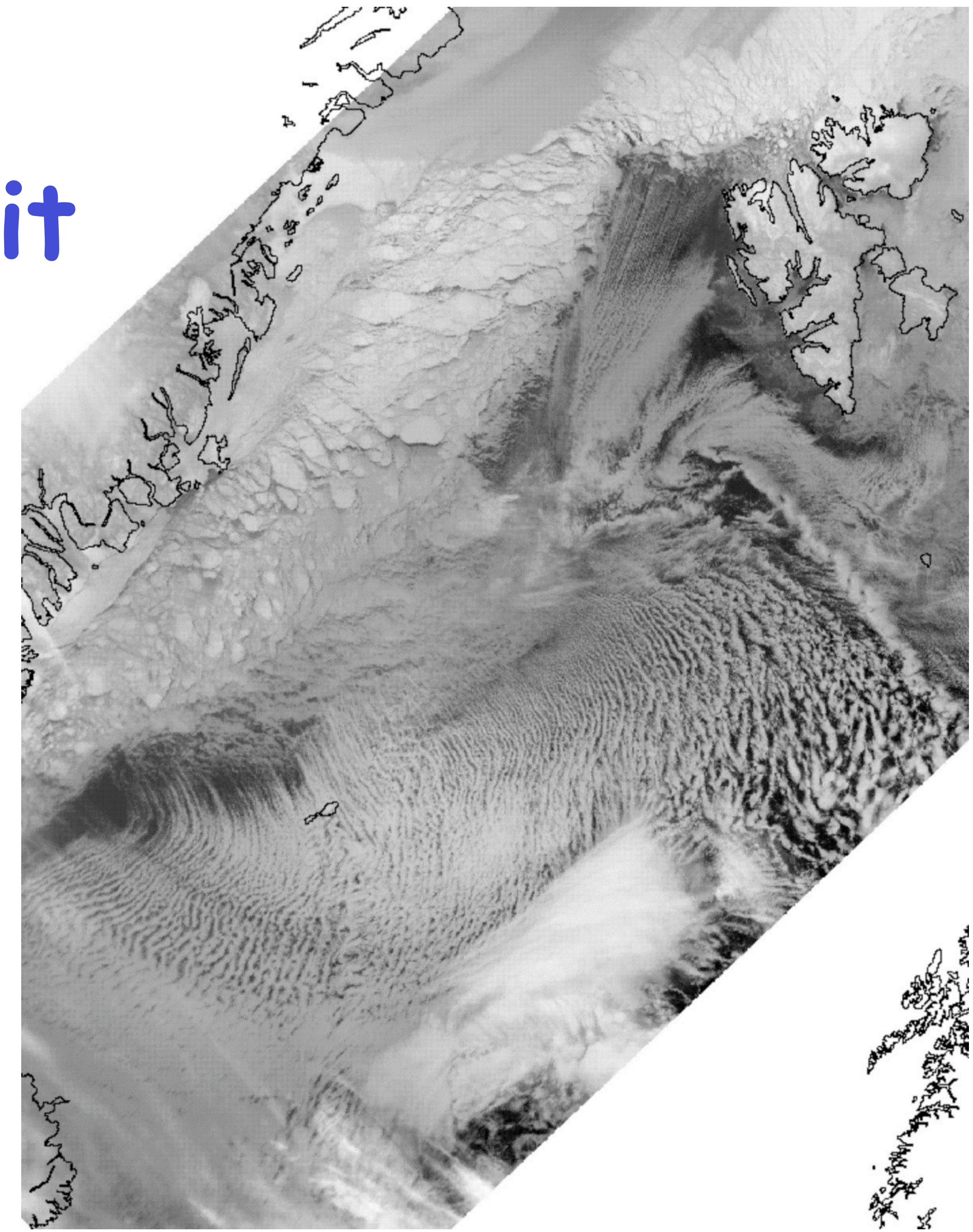


Sea Ice
in Fram Strait

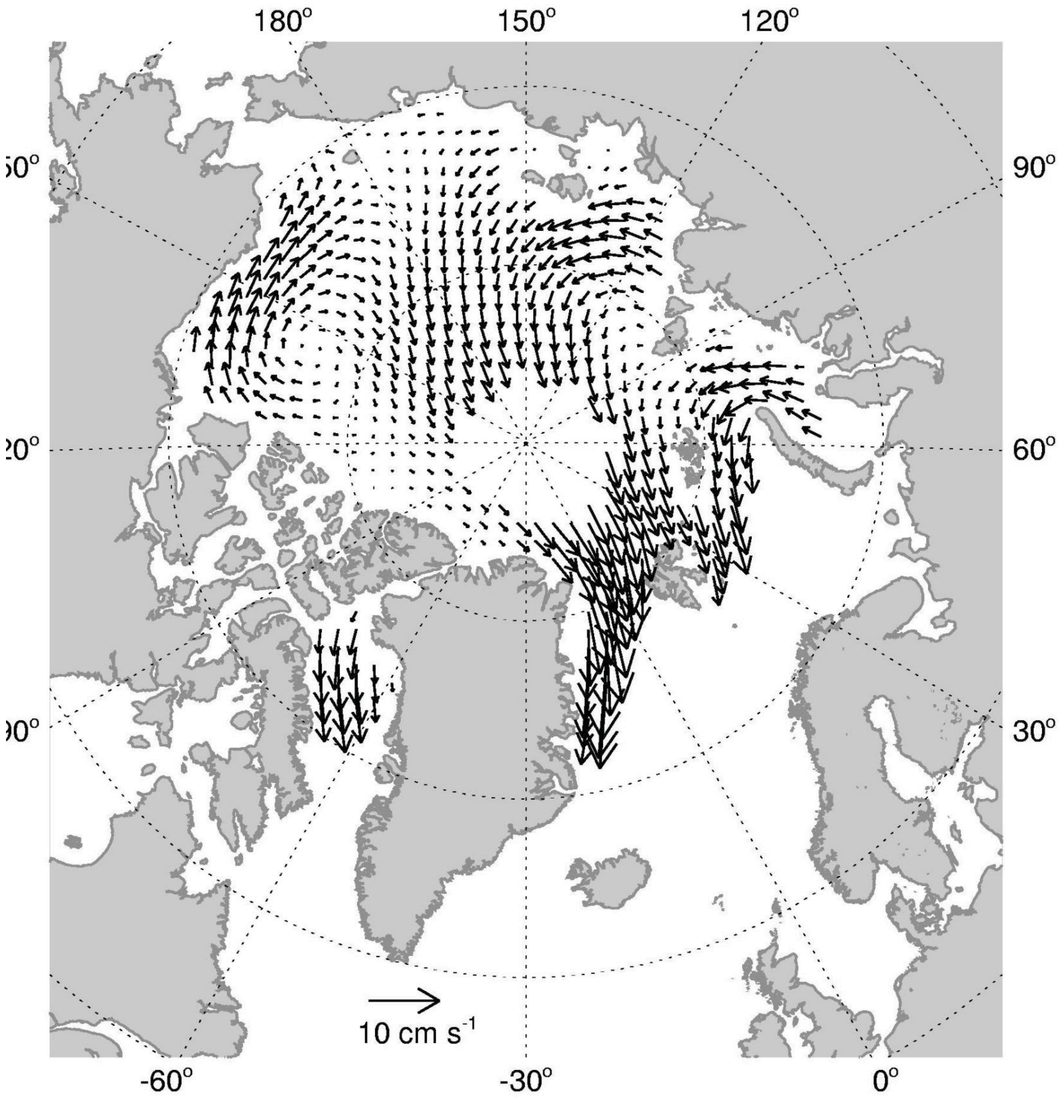
AVHRR - VIS:

Drift

Floe size distributiuon



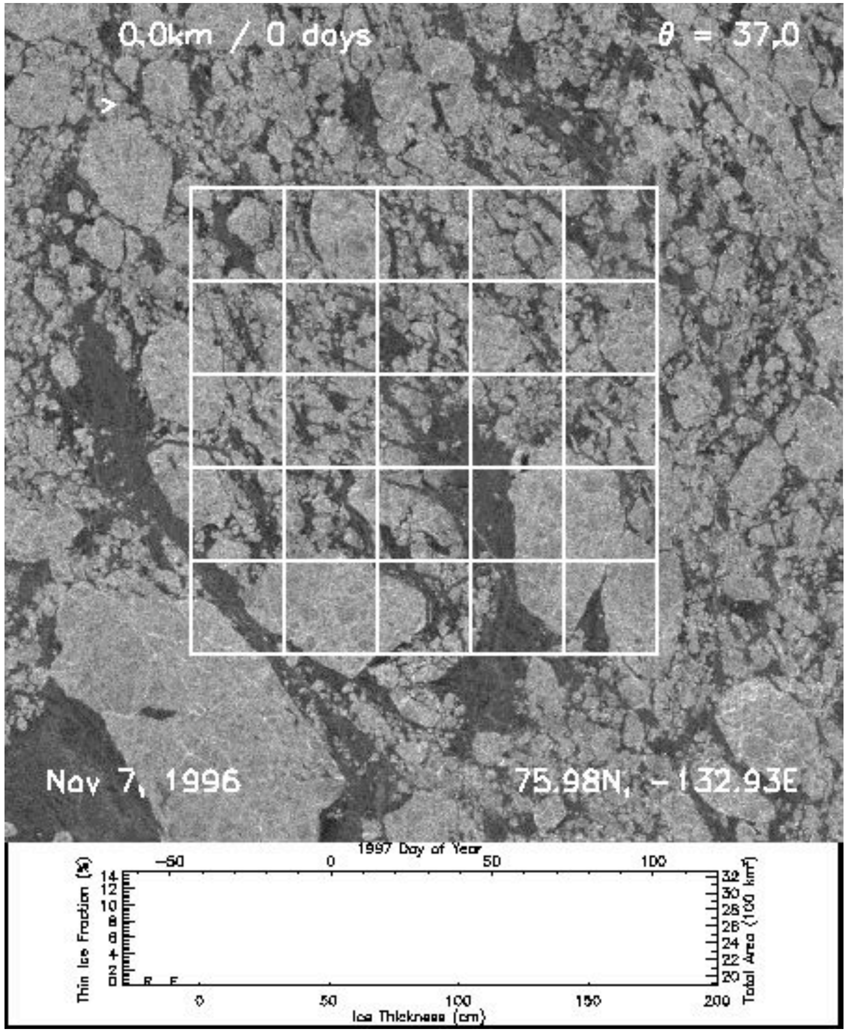
Sea ice drift



Sea Ice Drift from SSM/I Images

Winter 94/95

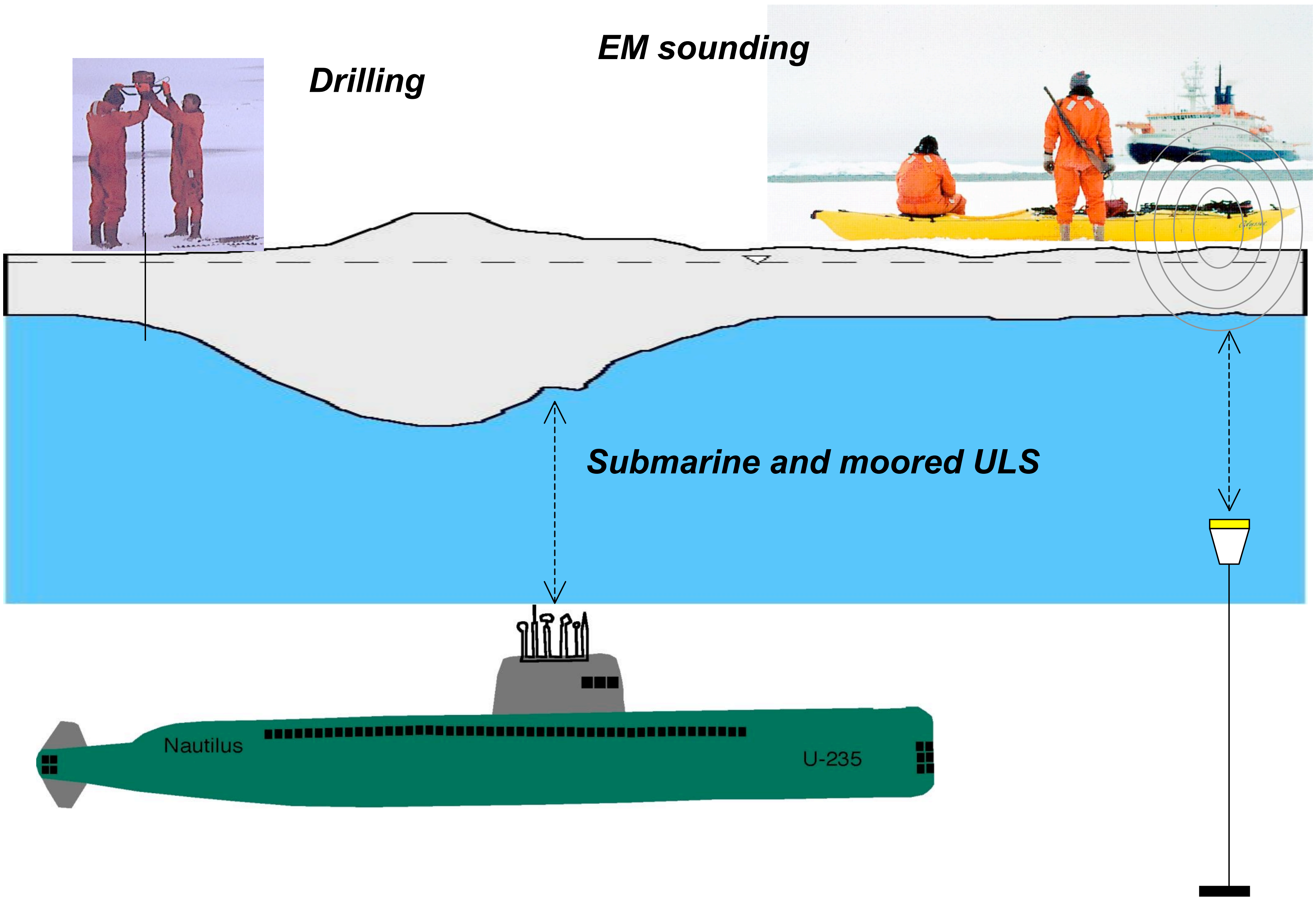
Sea ice drift and -deformation from SAR-imagery



RADARSAT Geophysical Processor System.
Due to a large swath width (~400 km) in ScanSAR mode, an image is obtained at least every 7. day
(by courtesy of Ron Kwok).

Sea Ice Thickness

Ice thickness measuring techniques



EMI on the ice surface

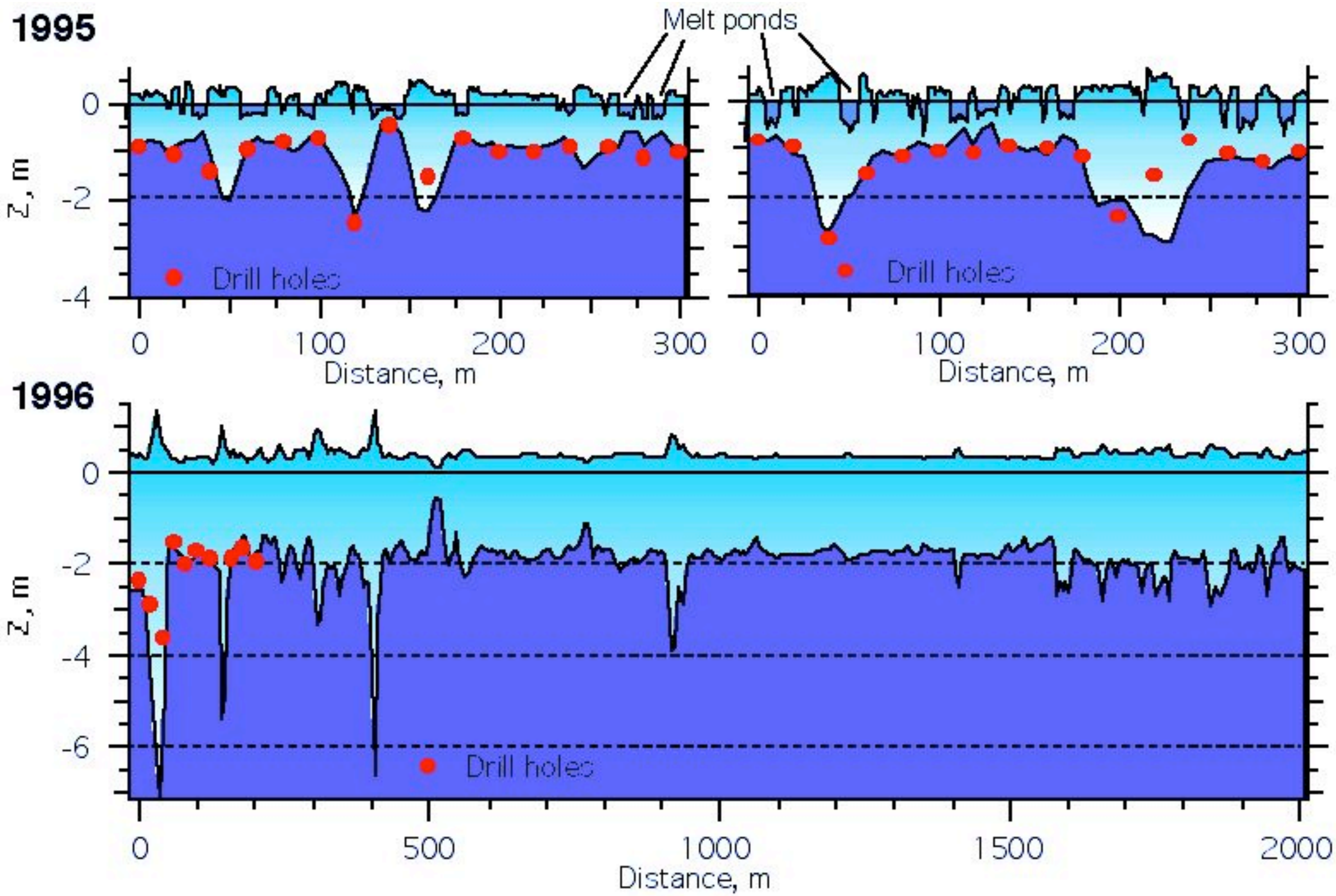
- EM31 (Geonics)
  - Coil seperation 3.66m
  - Frequency 9.8 kHz
  - coils coplanar
  - measures conductivity and inphase ppms

EMI on the ice surface

Germany's smallest research vessel... (the yellow one)

A normal 12h station

EM Thickness Profiles



EMI ship-borne

The SIMS

(Sea Ice Monitoring System)

EMI airborne

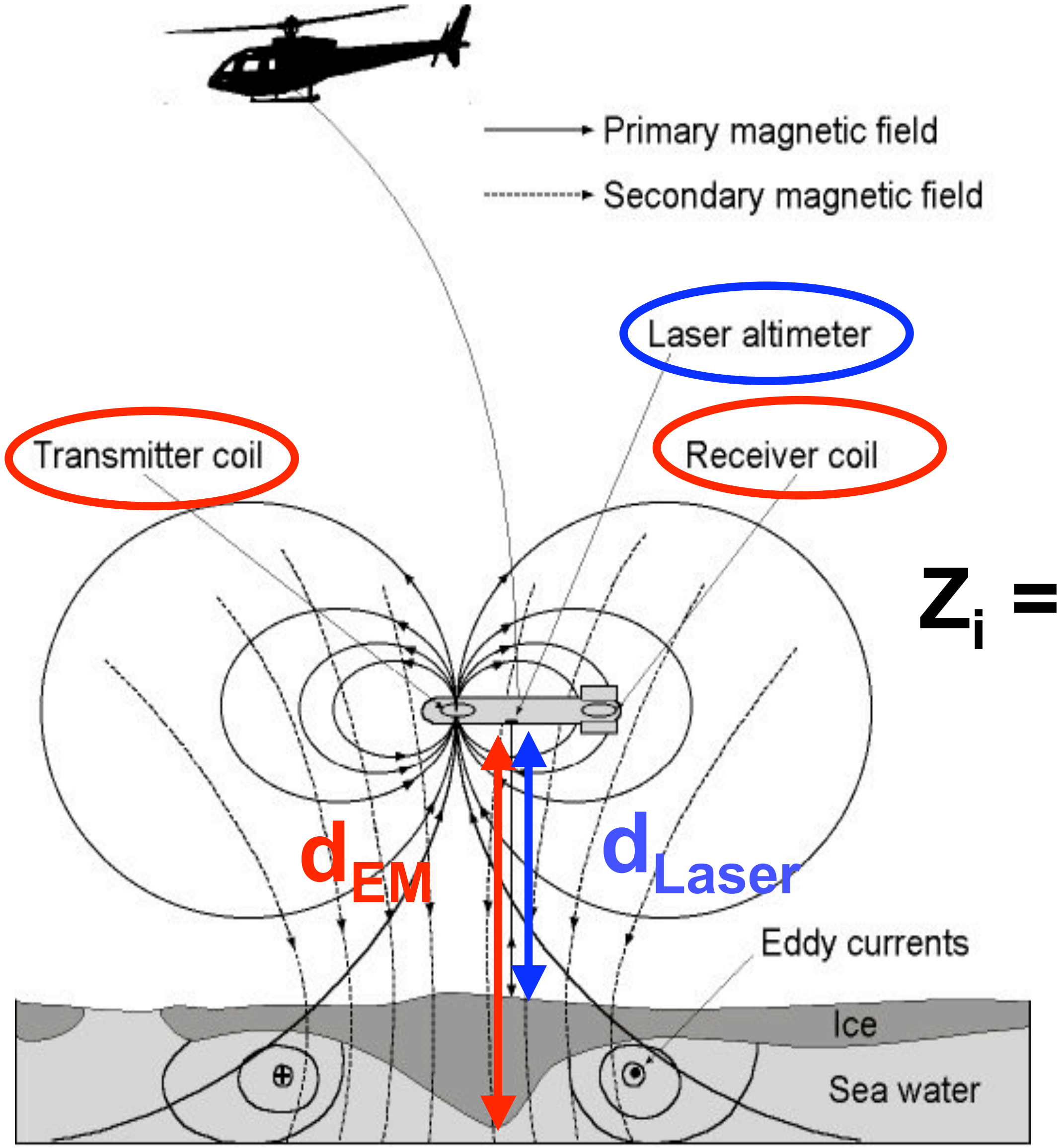
AWI's Helicopter EM system

2 Frequencies
- -3.68 kHz
- -112 kHz

3.4 m length
100 kg weight

Airborne EM ice thickness sounding

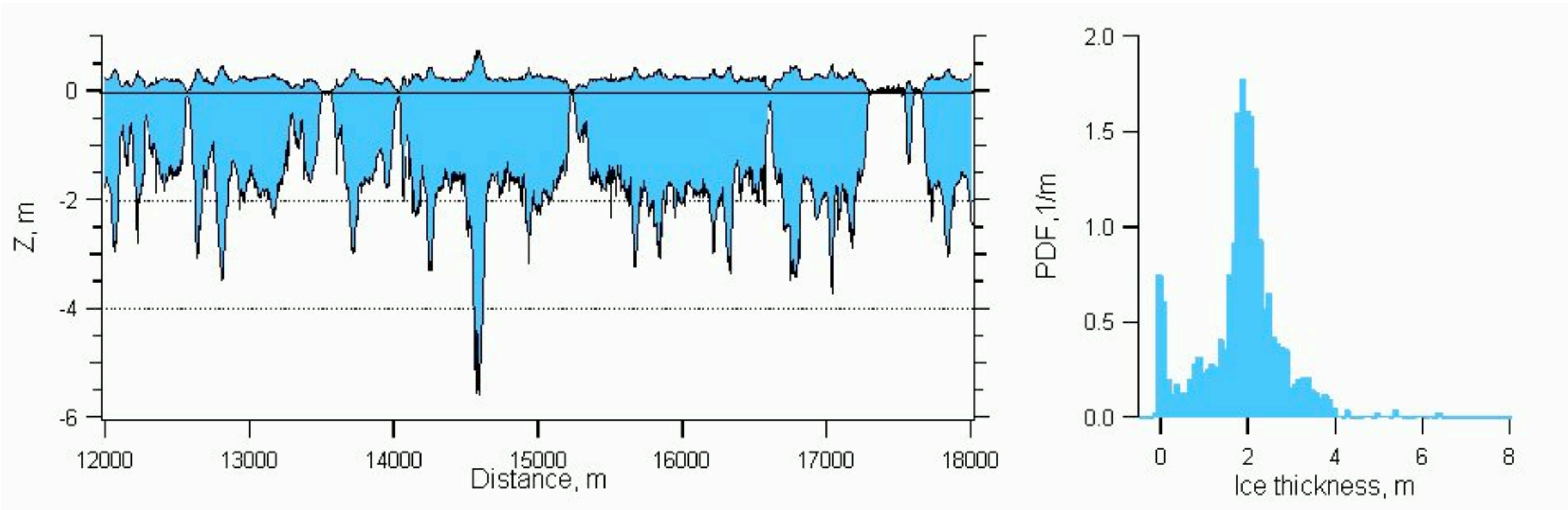
EM induction sea ice thickness sounding



$$Z_i = d_{EM} - d_{Laser}$$

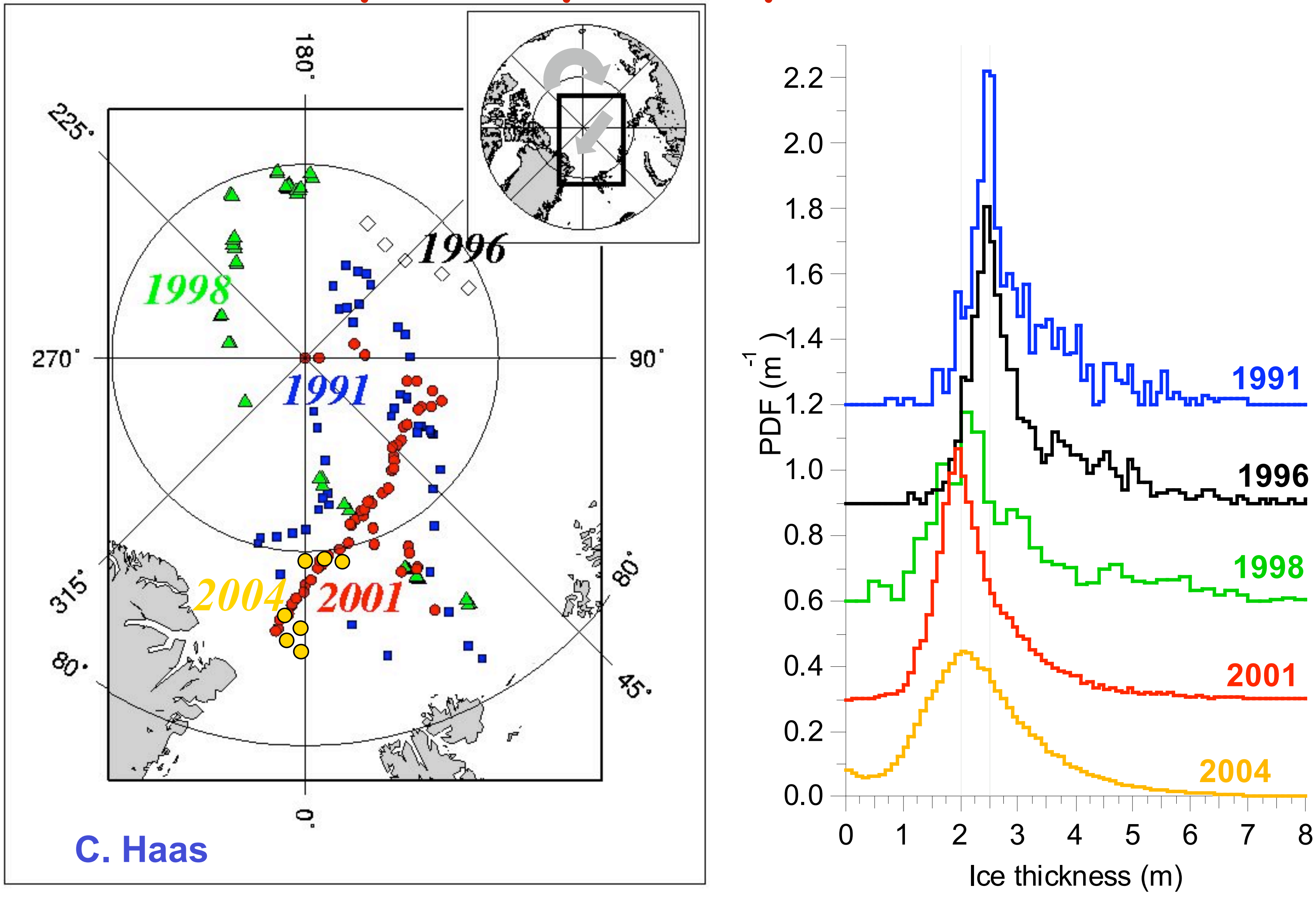
(snow + ice)

$$\sigma_{Ice} \ll \sigma_{Sea\ water}$$

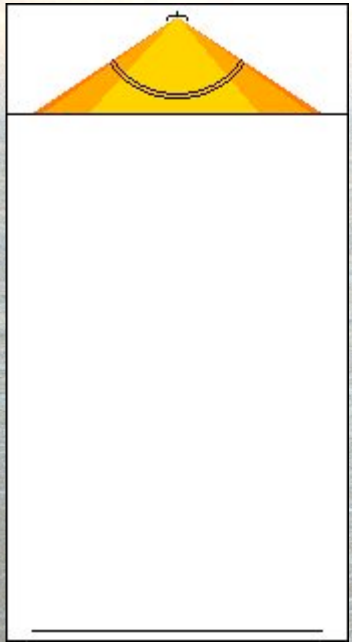


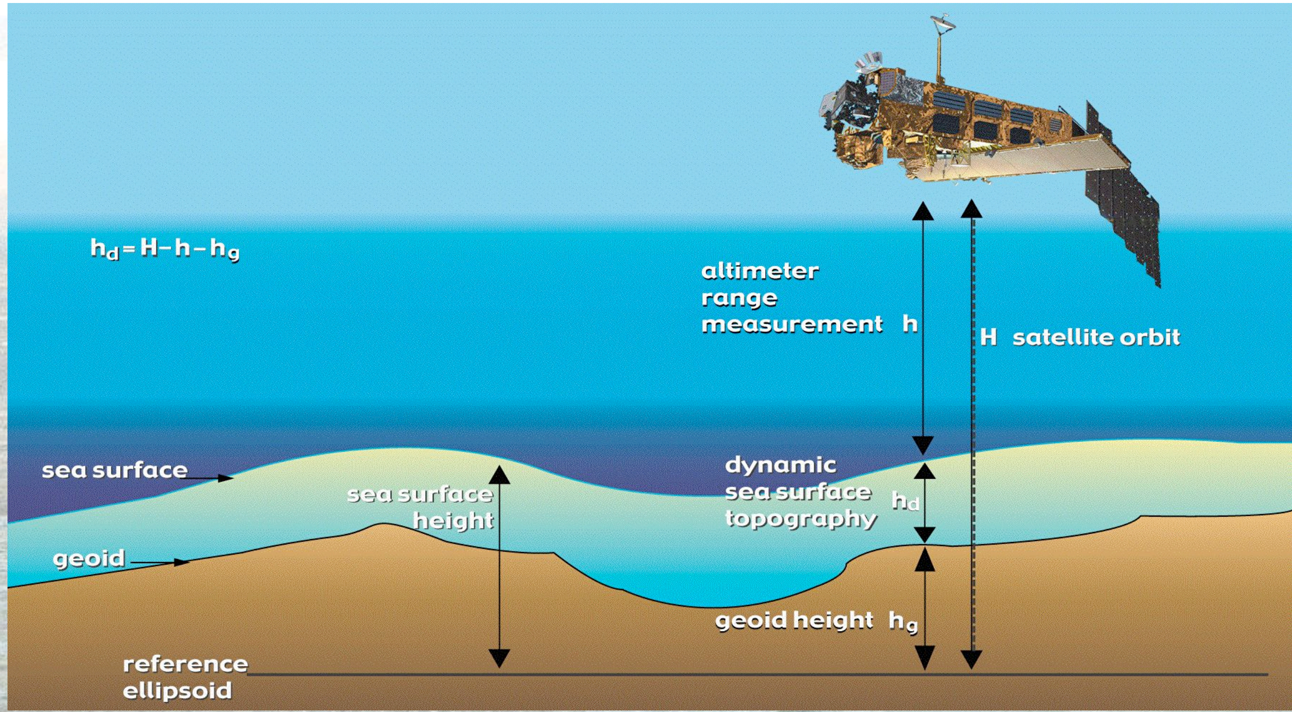
Z, m
0
-2
-4
-6
12000
13000
14000
15000
16000
17000
18000
Distance, m
PDF, 1/m
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
Ice thickness, m

Ice thickness variability in the Transpolar Drift: 1991, 1996, 1998, 2001 & 2004



Travel time



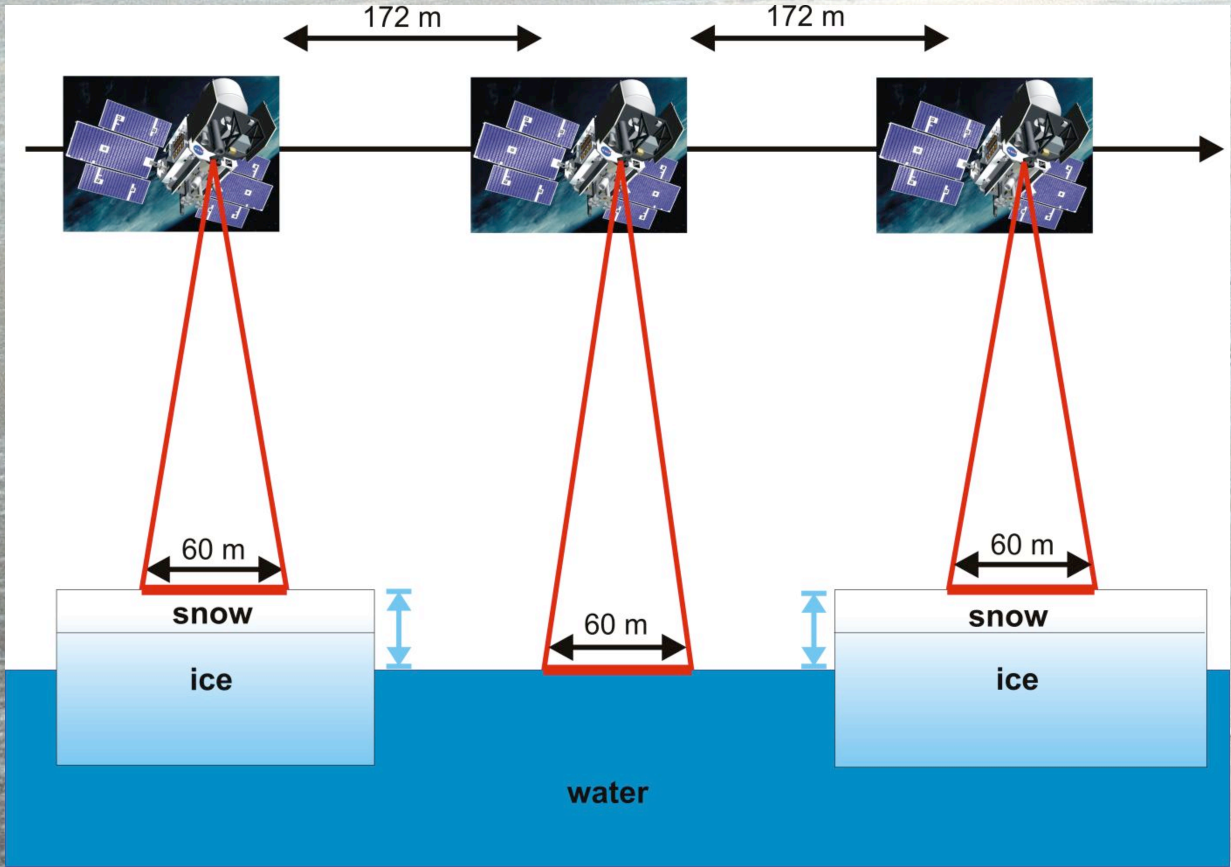


- The travel time of a pulse between the sensor's position and the ice surface is measured (accuracy of a few centimeters, atmospheric corrections are required).

- The orbit of the satellite is also determined with centimeters accuracy.

Freeboard and Ice Thickness

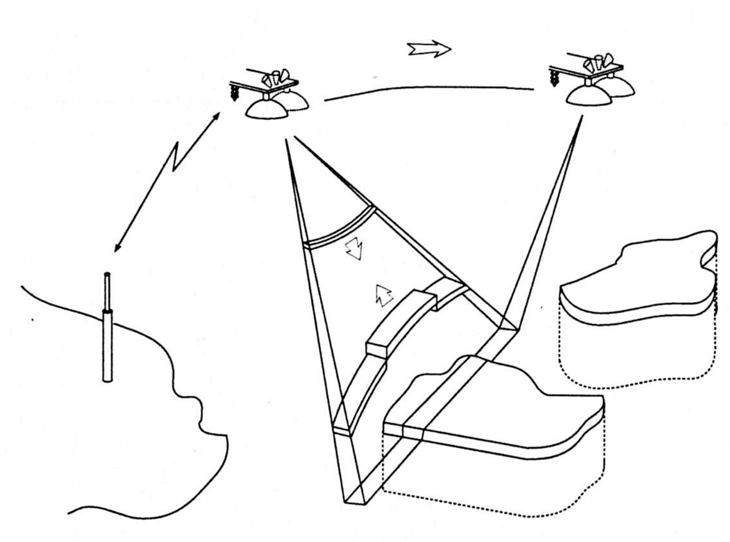
Lidar (e. g. ICESAT)
1-3 cm precision in the vertical



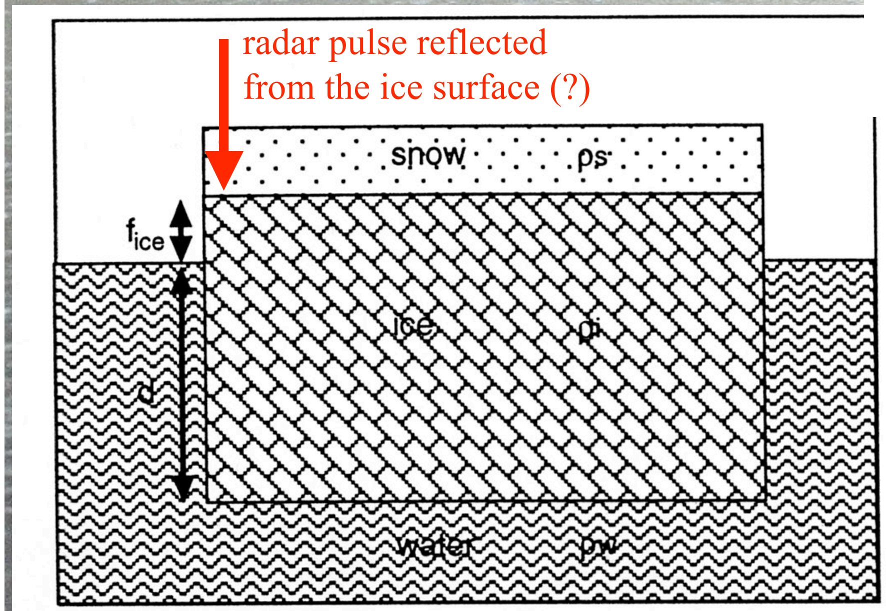
By courtesy of Sibylle Goebell, AWI

Radar:
Spatial resolution
ERS-1, 2 and
ENVISAT:
1.7 km
CRYOSAT:
250 m along-track,
1.5 km across-track

Retrieval of Sea Ice Thickness



- Individual echos are separated into groups “FY- and MY-ice“ and “Open water and thin ice“
- Freeboard is obtained by subtracting travel times over water from travel times over ice.
- Conversion of freeboard into thickness: assumption of hydrostatic equilibrium, using average ice and water densities, and snow „climatologies“



Ice thickness t_E at hydrostatic equilibrium and a snow load of mass m_S per unit area:

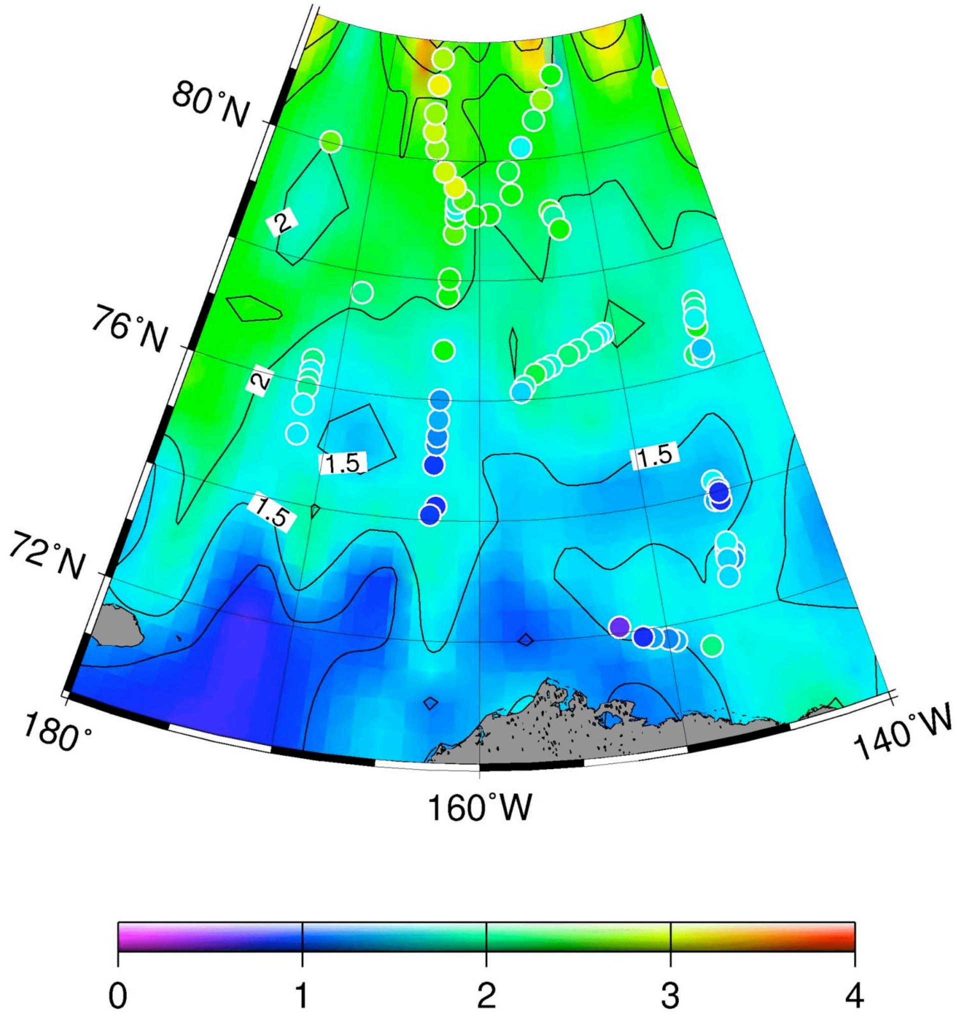
$$t_E = \frac{\rho_W}{\rho_W - \rho_E} f_E + \frac{1}{\rho_W - \rho_E} m_S$$

Altimeter

Freeboard measurements by satellite is the only technique which can provide sea ice thickness data at the time and Length scales required by climate research.

Radar altimeter (ERS):

Accuracy of thickness estimates: ~0.2m



Thanks for your attention