Sea Ice, Climate Change and Remote Sensing

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Lecture outline

1) Arctic Climate Change and Remote Sensing

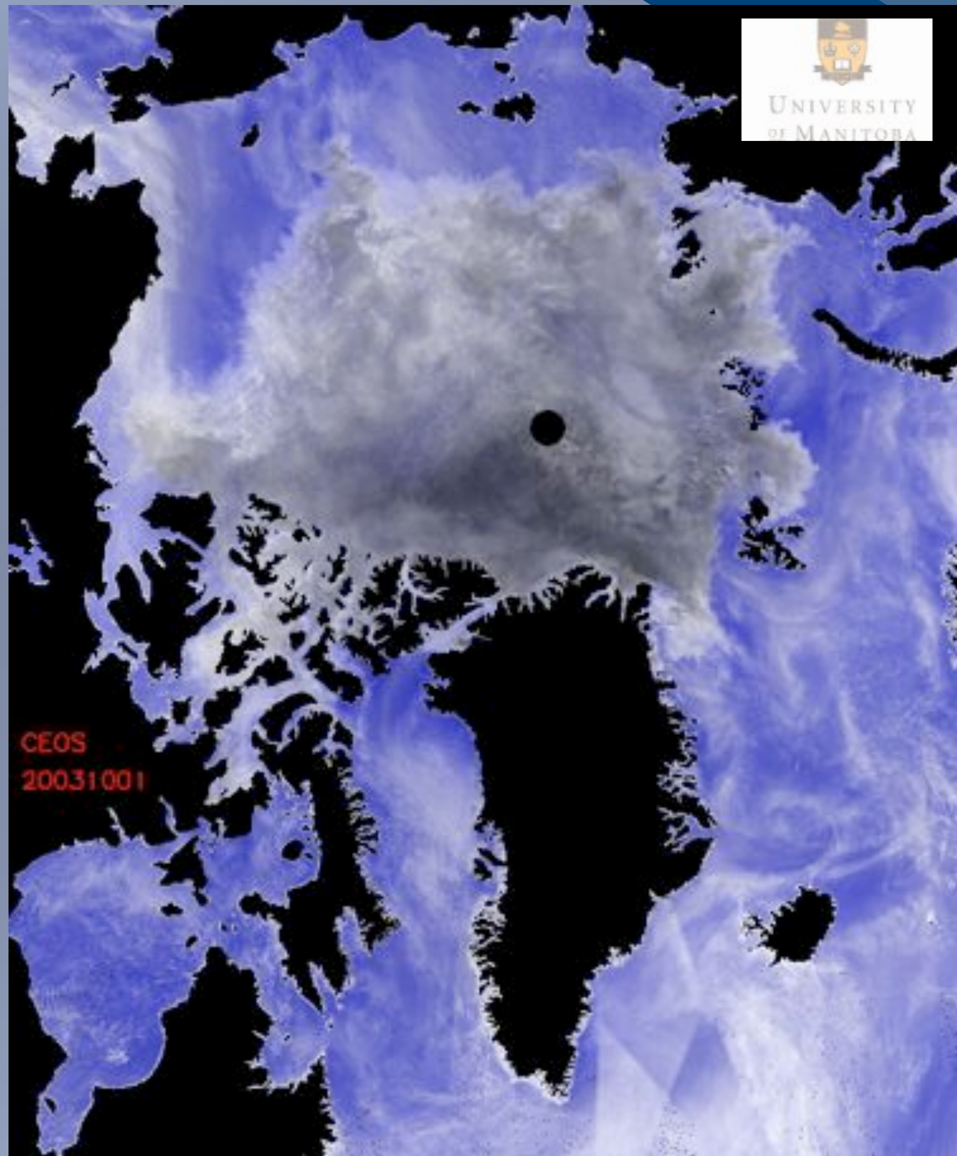
2) Thermodynamics, Geophysics and AOP/IOPs

3) Dielectrics, scattering and emission modeling

Outline of this talk

- A look at thermodynamic processes
- Snow geophysics
- Sea ice geophysics
- A look at complexity
- Conclusions


Yearly Mean
S O N D J F M A M J J A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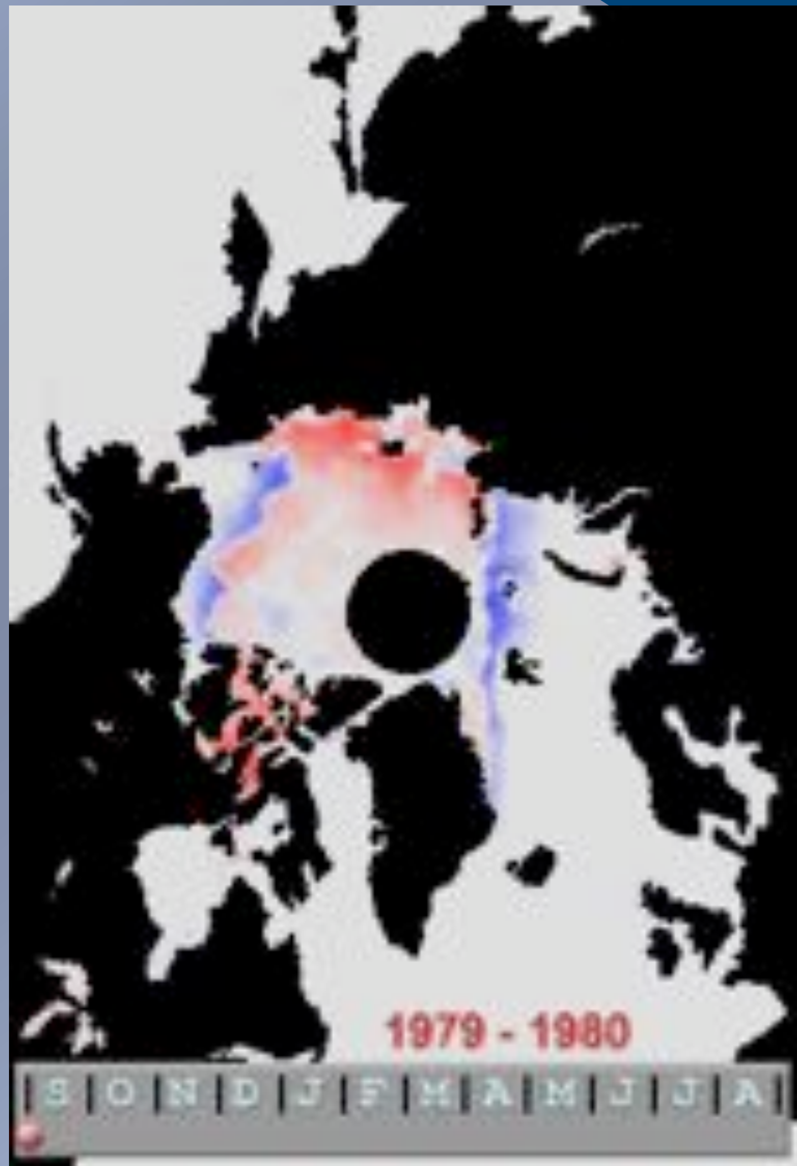
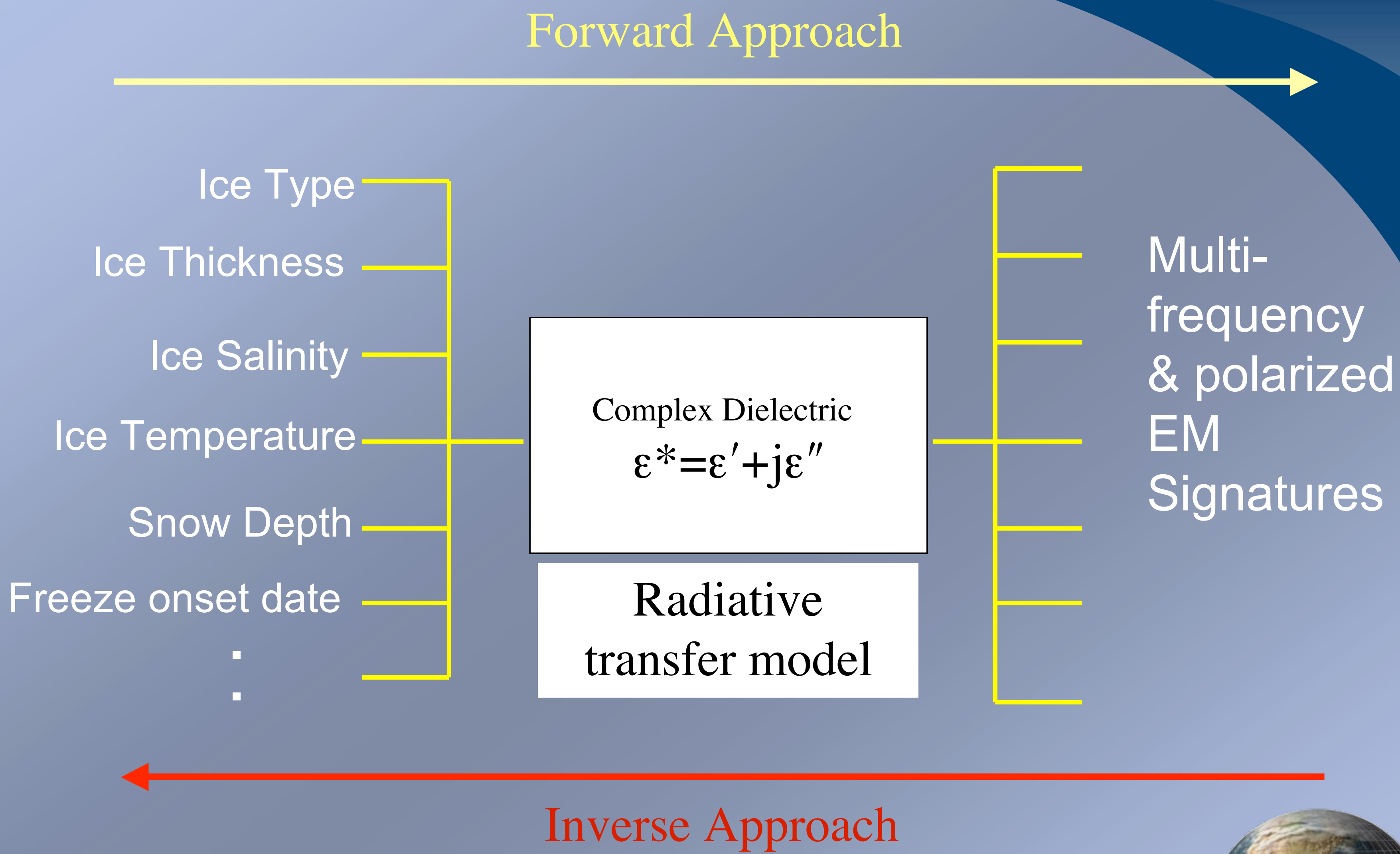
Yearly Mean
S O N D J F M A M J J A

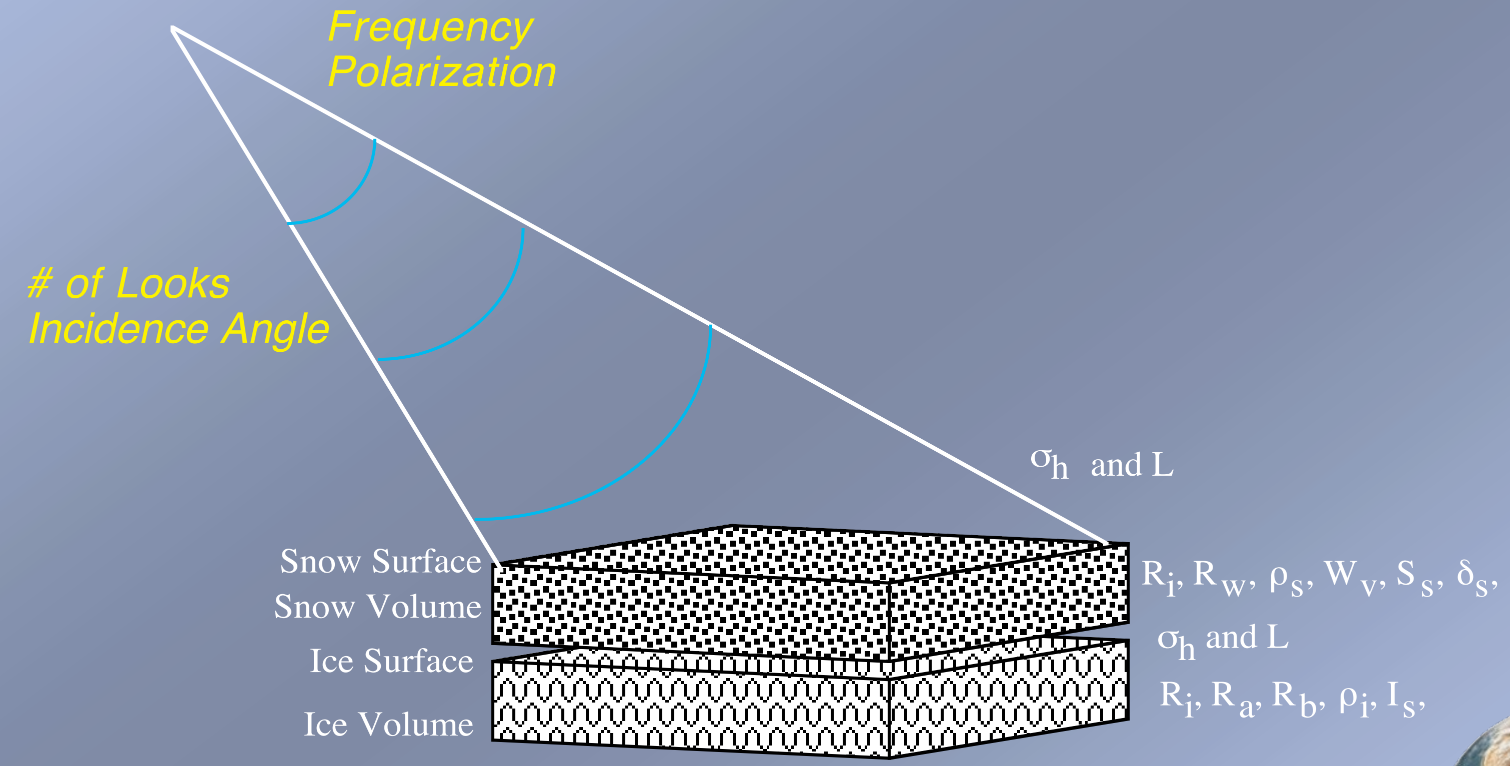

1979 - 1980
S O N D J F M A M J J A



The electromagnetic properties of sea ice

IEEE TGARS, ONR ARI special issue. 36(5): 1750-1763

Frequency/Polarization and Sensor Geometry



$$\sigma^\circ_{total} = \sigma^\circ_{ss} + \Psi_{as}(\theta) * \sigma^\circ_{sv}(\theta') + \Psi_{s}(\theta') * \sigma^\circ_{is} + \Psi_{si}(\theta'') * \sigma^\circ_{iv}(\theta'')$$

Thermodynamic Processes

Multilayer thermodynamic model

$$\rho_s c_s \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z}\left(k_s \frac{\partial T_s}{\partial z} + I_o\right)$$

snow

$$\rho_i c_i \frac{\partial T_i}{\partial t} = \frac{\partial}{\partial z}\left(k_i \frac{\partial \theta_i}{\partial z} + I_o\right)$$

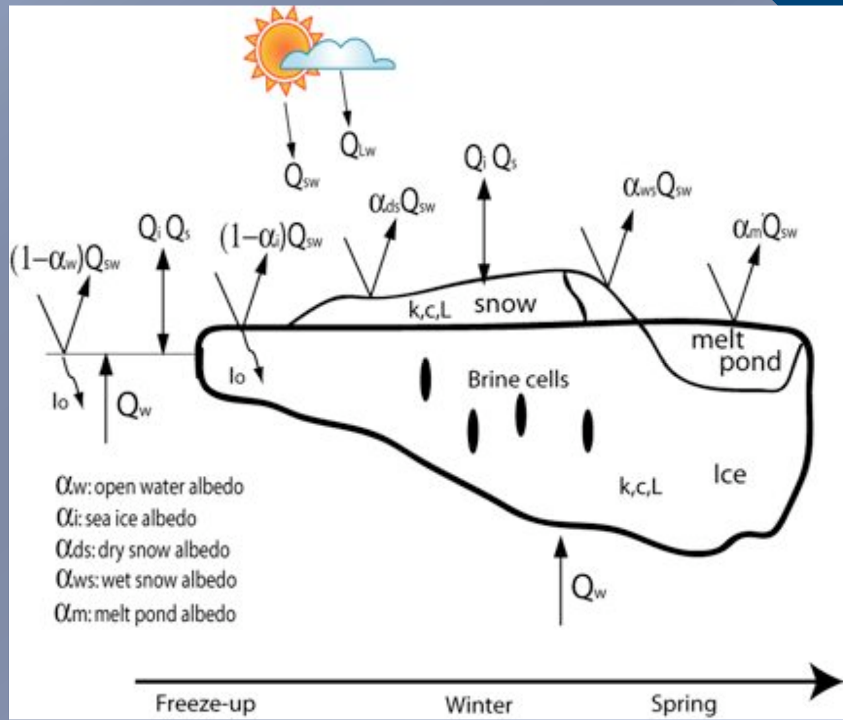
ice

$$k_s \frac{\partial T_s}{\partial z}\bigg|_{SI} = k_i \frac{\partial T_i}{\partial z}\bigg|_{SI}$$

Snow/ice

$$-k_i \frac{\partial Ti}{\partial z}\bigg|_{IO} = Q_w - L_i W_{IO}$$

Ice/ocean

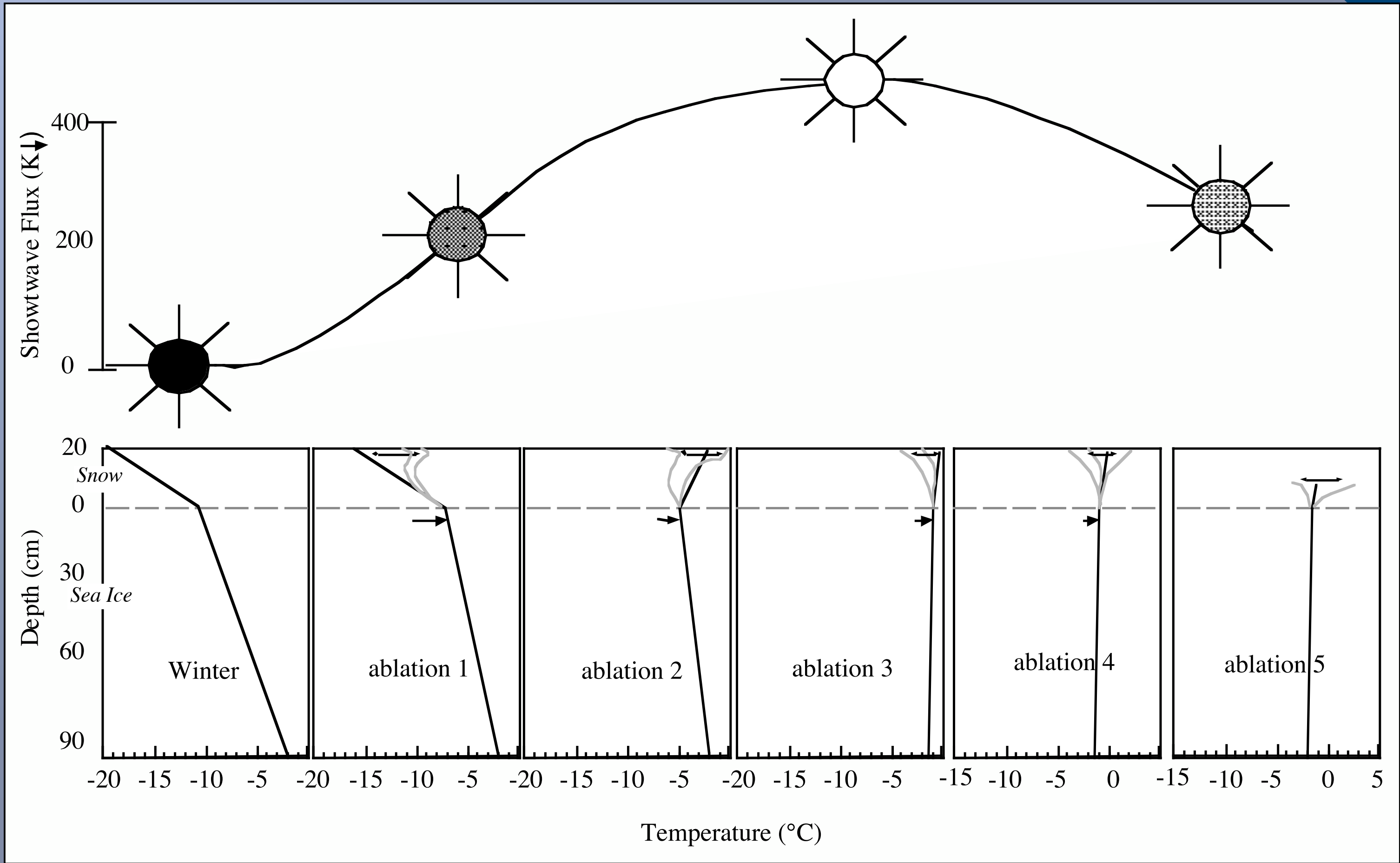


Coupled column model

$$-k_{(i/s)} \frac{\partial T_{(i/s)}}{\partial z} + (1-\alpha_{(i/s)})Q_{SW} + Q_{LW} - \sigma\varepsilon_{(i/s)} T_{AI}^4 - Q_s - Q_l - I_o = L_{(i/s)} W_{AI}$$

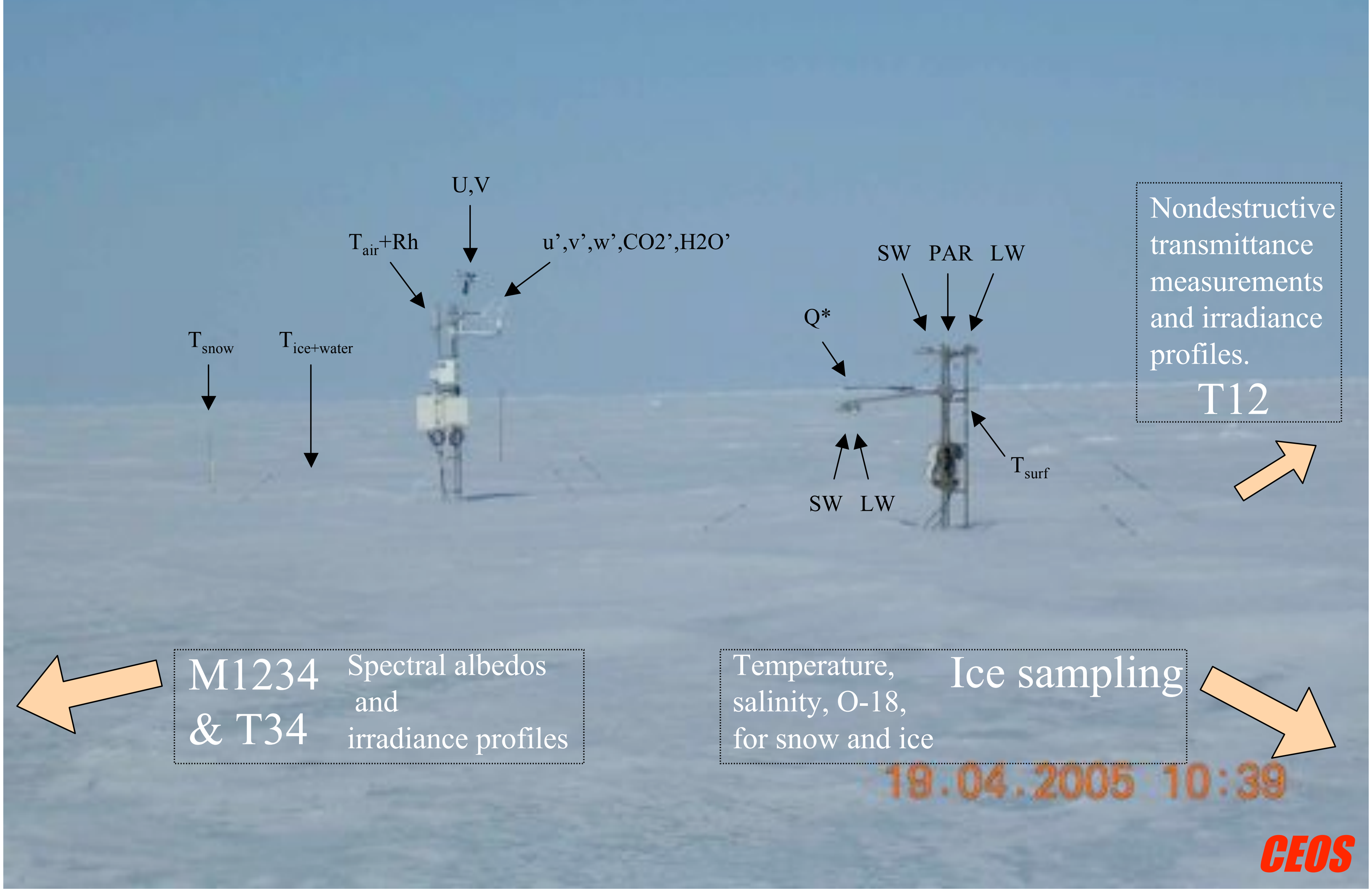
Air/snow

Temperature is the control

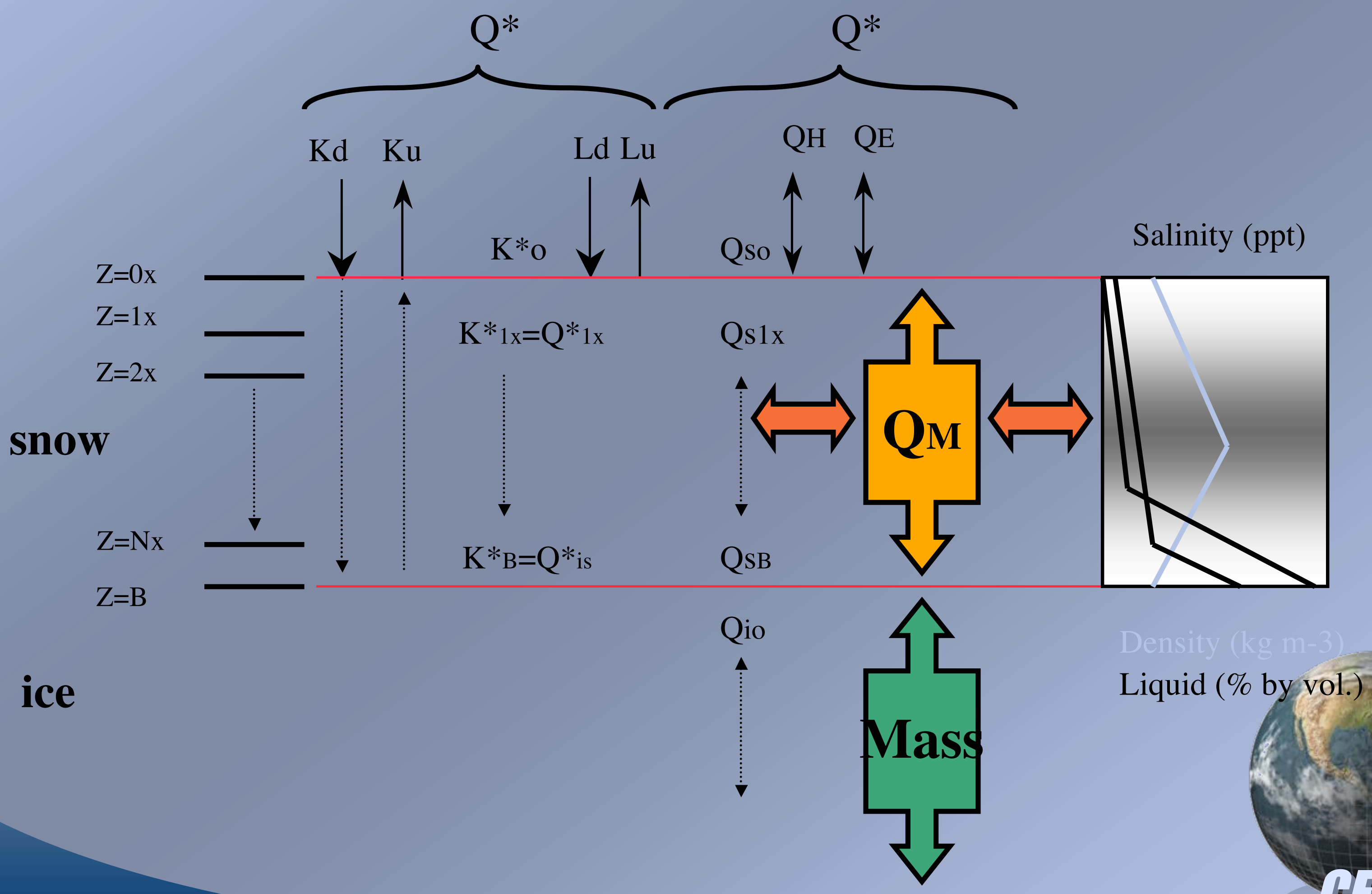


Barber et al. 1998

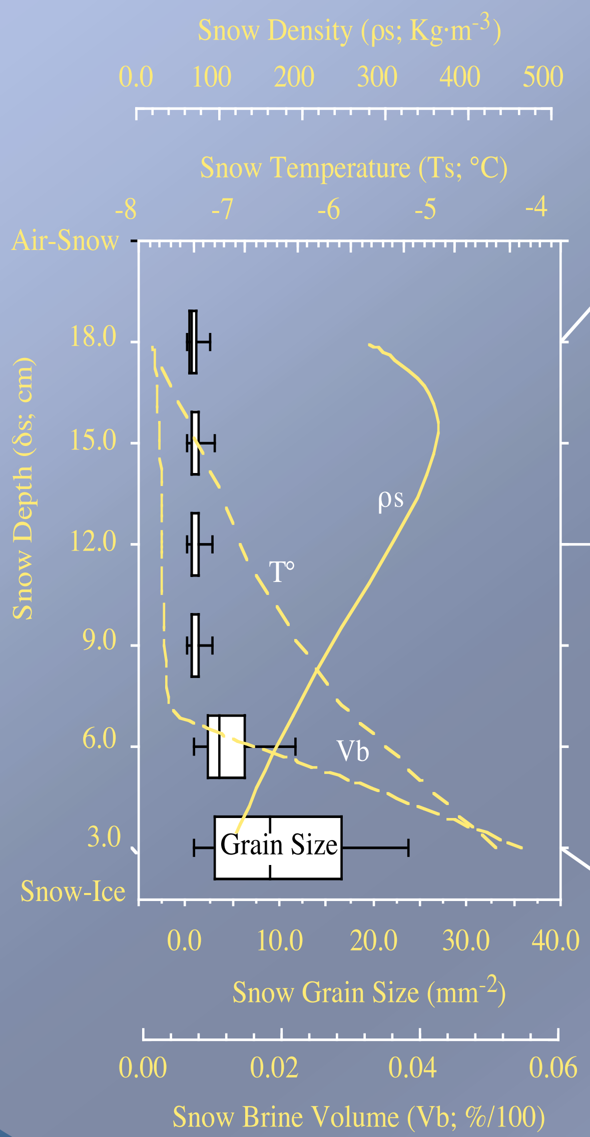
Ice site overview, measurements

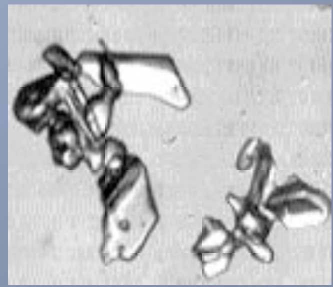


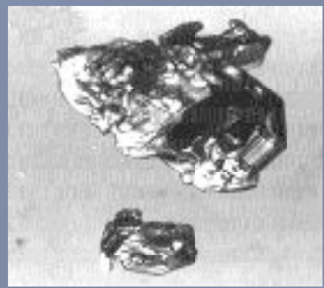
Radiation, Heat and Mass Transfer Processes of Snow over FYI



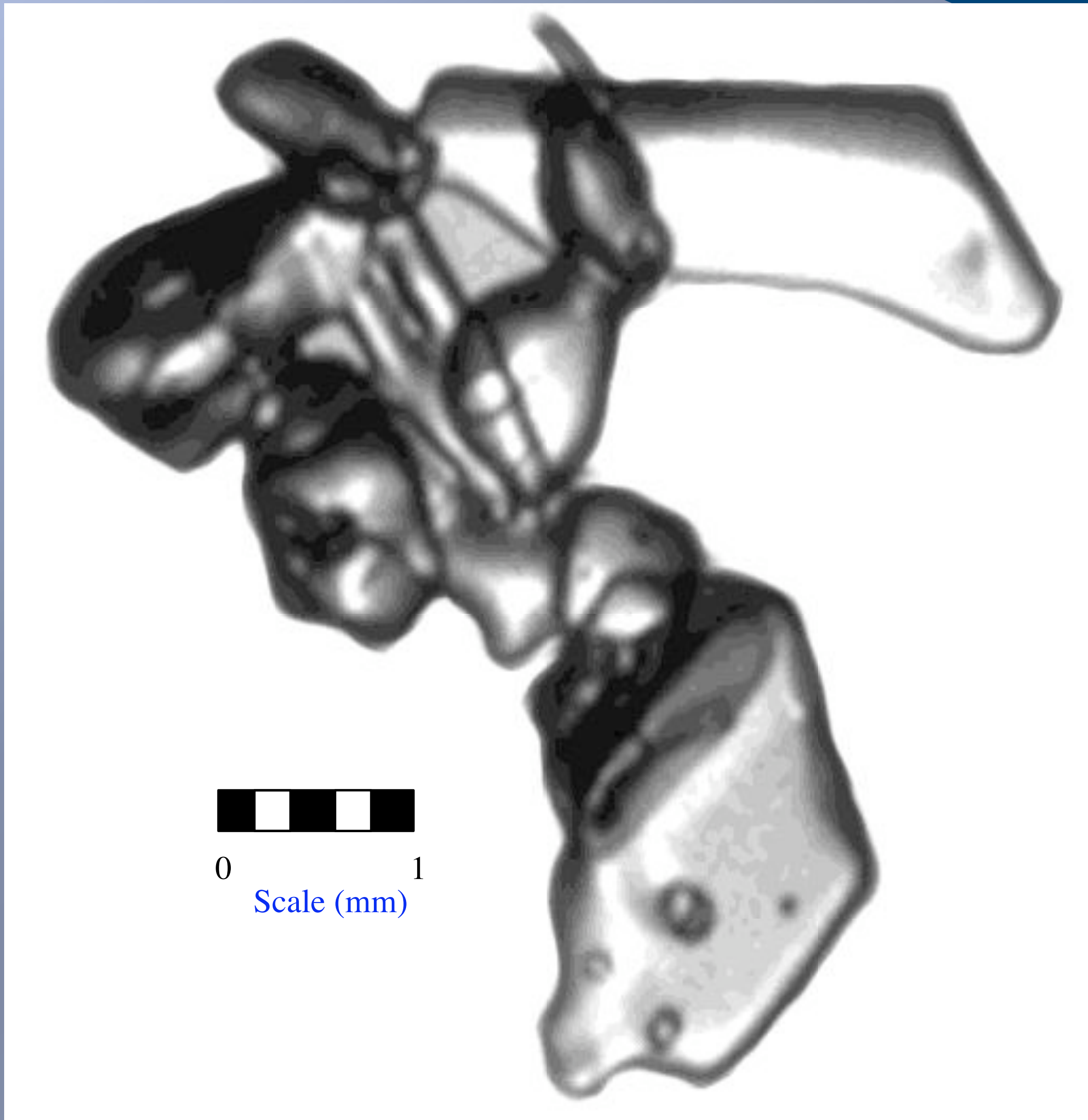
Snow





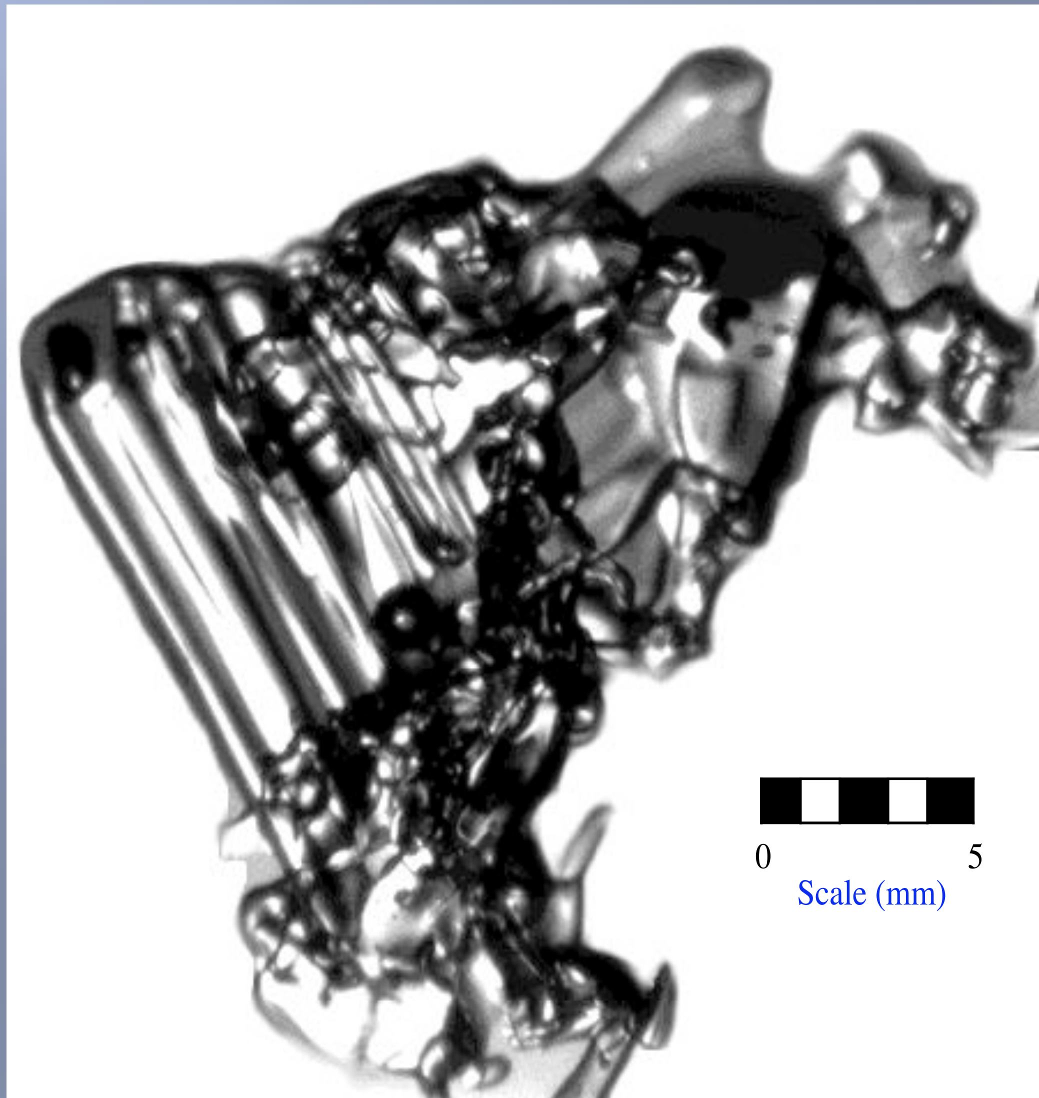


- Variables
- Processes


0
1
Scale (mm)

Dendrites

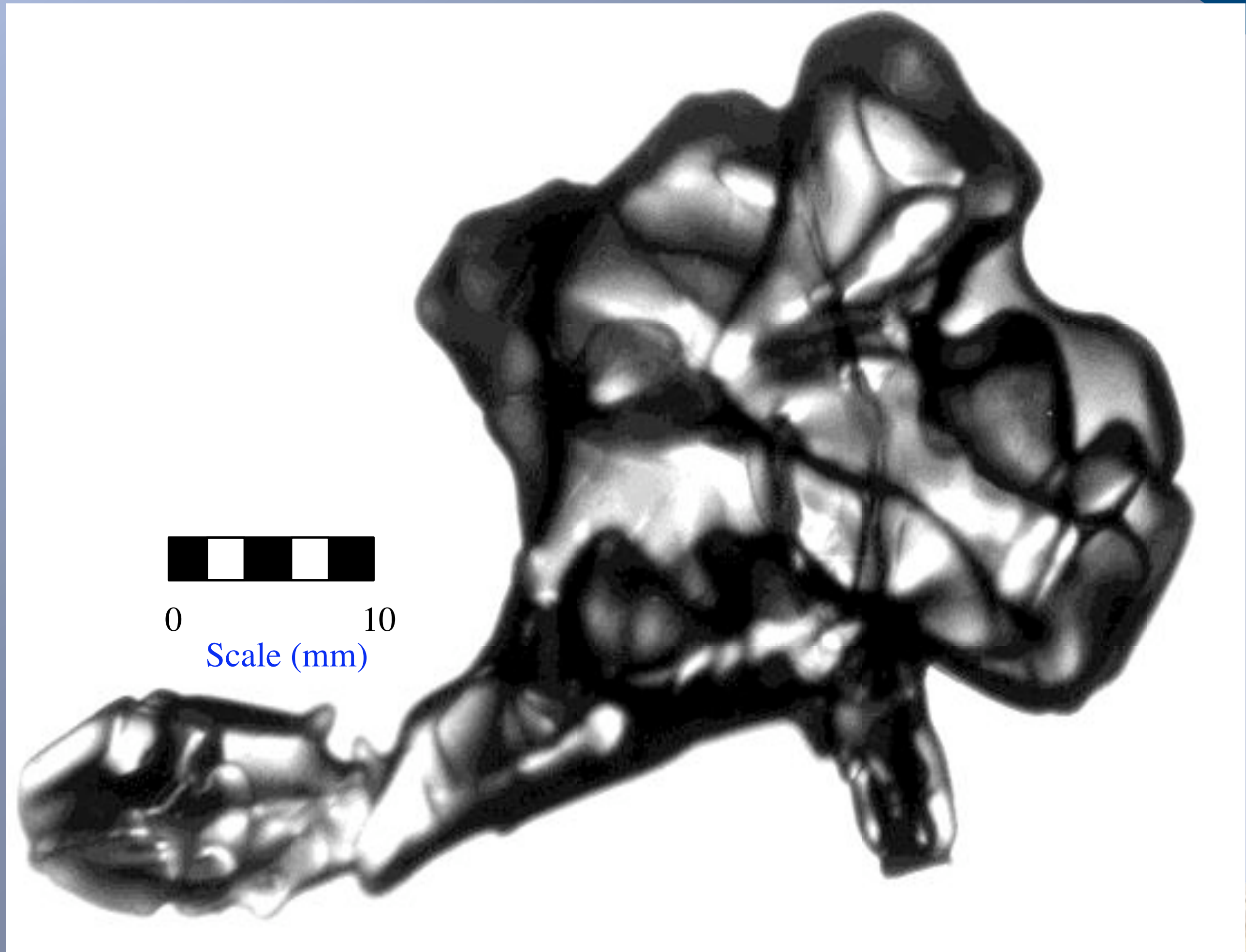
- Snow is a complex crystalline material which forms from the condensation and sublimation of water vapour onto a nucleating material.
- Upon deposition the dendritic structures (small angular crystal pieces which make up the snow flake) break into fragments (a process known as saltation).
- This saltation process quickly increases the density of the snow as it is blown across the Arctic sea ice.
- As the dendrites age a process called sintering occurs (i.e., bonds forming at the points of adjacent dendrites).
- This process results in an equilibrium density for snow of about 375 kg·m-3 for snow on Arctic sea ice.

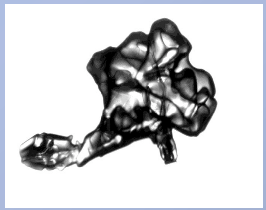


0
5
Scale (mm)

Kinetic structures

- Under temperature gradient metamorphism there is a transfer of mass along the temperature gradient.
- This process is typified by the sublimation at the warm end of the snow grain, transfer along the vapour pressure gradient, and a corresponding phase change from vapour back to a solid at the colder end of the snow grain.
- This process results in a predominantly elongated crystal structure with the long axis parallel to the direction of the vapour gradient.
- The metamorphic state which results from this process is often called kinetic growth snow grain.


0
10
Scale (mm)



Aggregate Structures

- When water in liquid phase is low (or absent) equi-temperature metamorphosis will create larger grains at the expense of smaller grains due to the vapour pressures associated with the snow grain shapes.
- This is the principal process associated with early spring grain growth or snow ripening.
- When water in liquid phase increases large grains will combine into polycrystalline aggregates.
- When adjacent equitemperature grains aggregate large single grain entities result .
- This usually coincides with draining within the snow pack.

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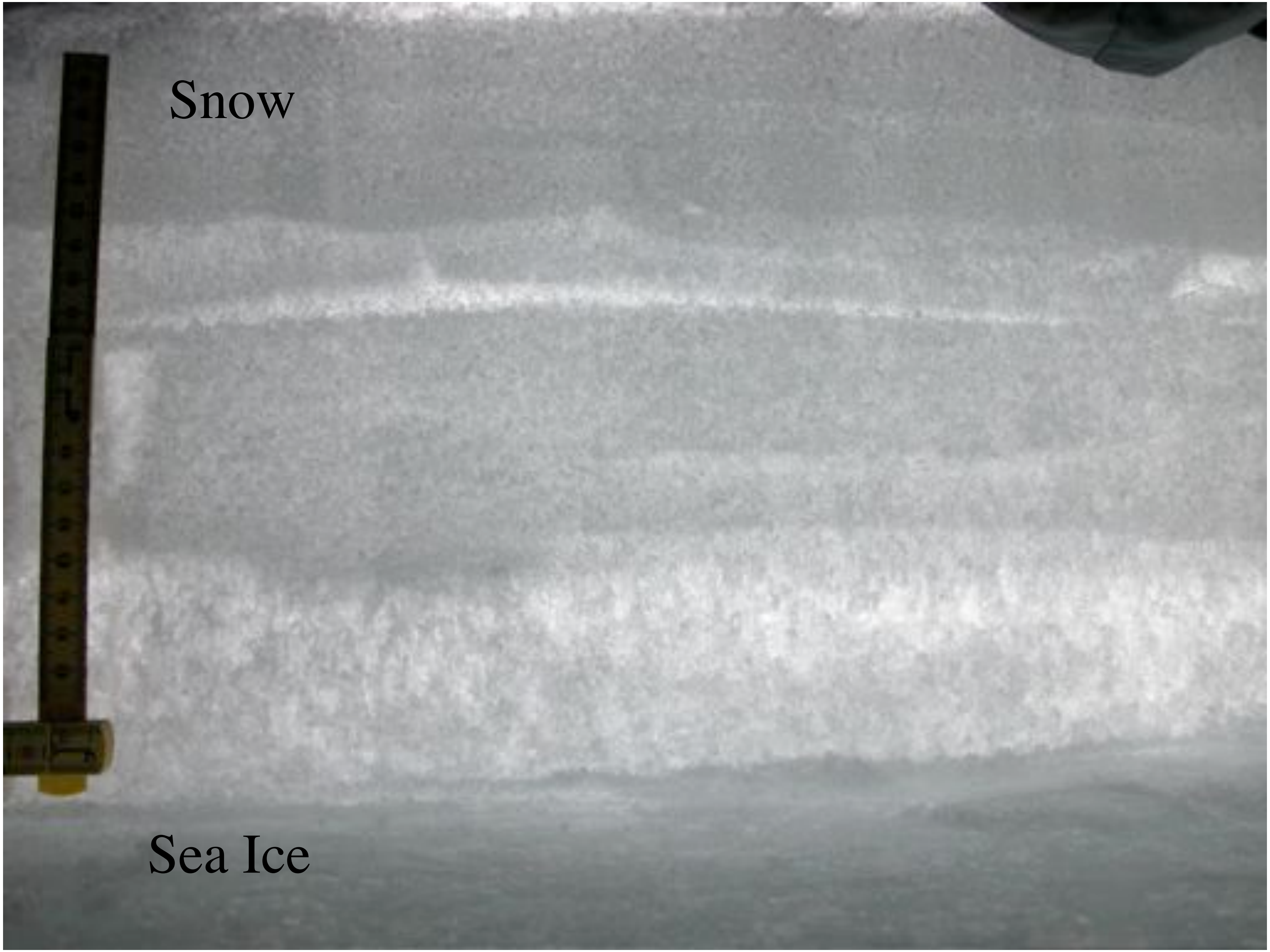
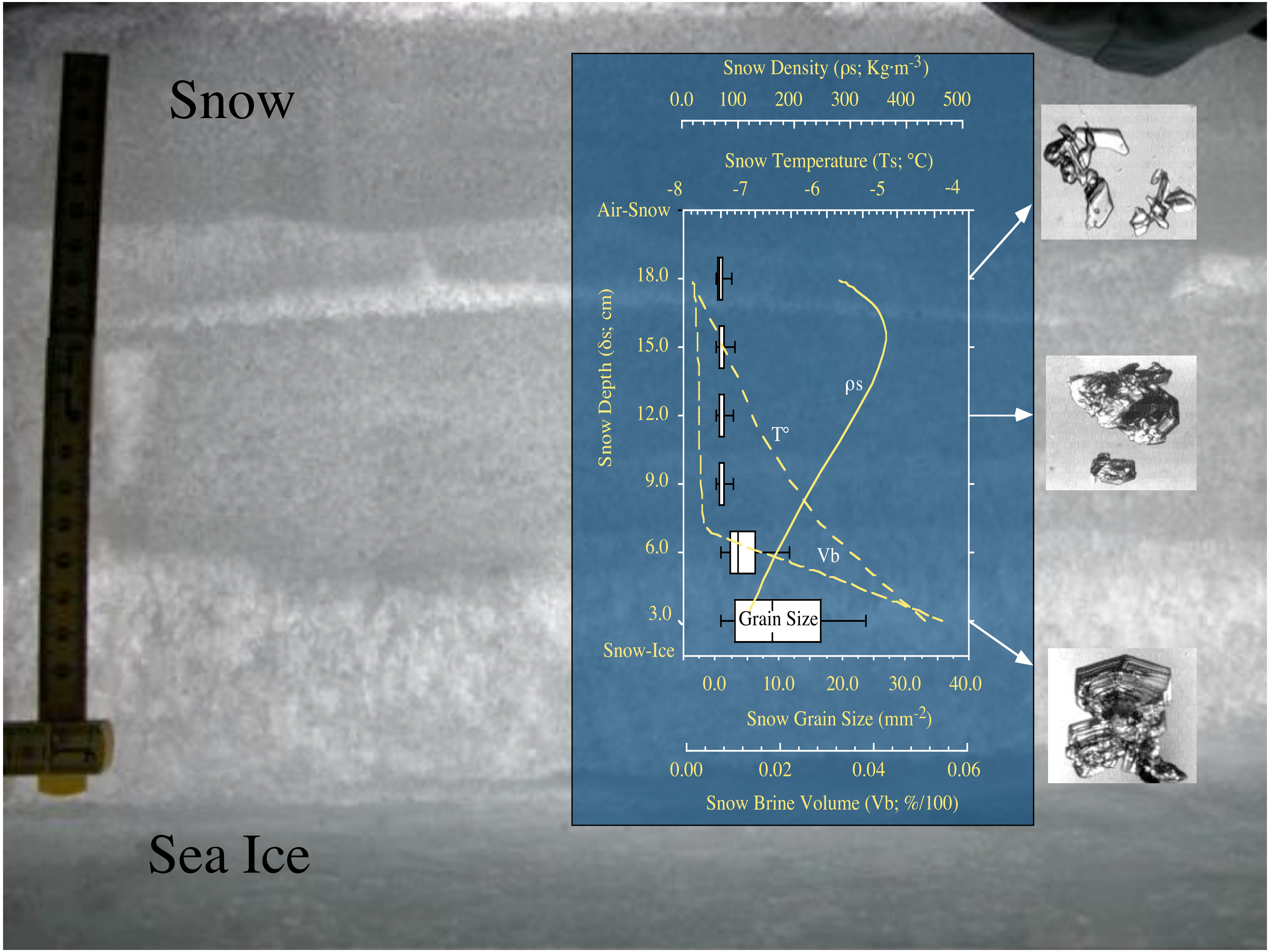
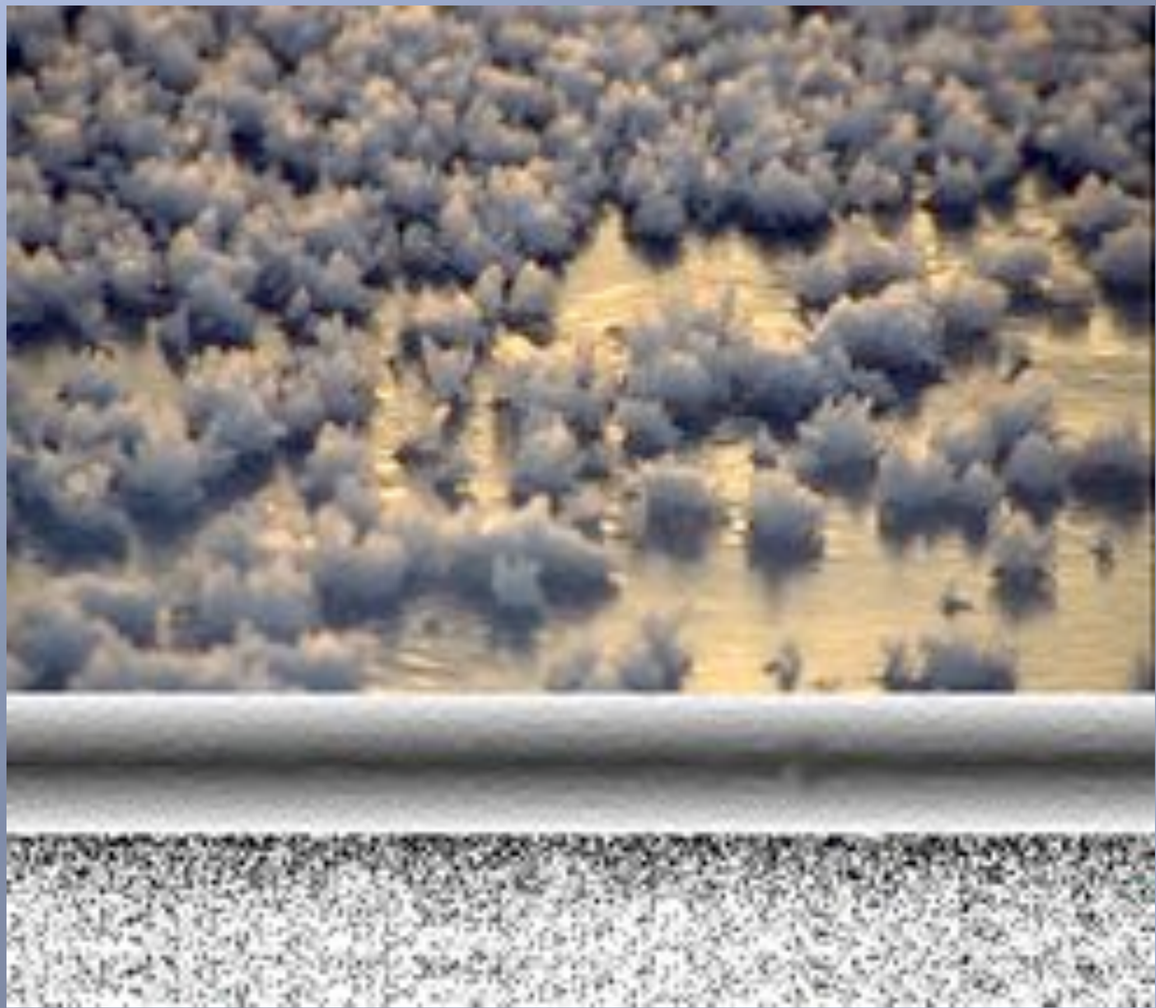

Snow
Sea Ice


Snow
Sea Ice
Snow Density (ρs; Kg·m-3)
0.0 100 200 300 400 500
Snow Temperature (Ts; °C)
-8 -7 -6 -5 -4
Air-Snow
Snow-Ice
Snow Depth (δs; cm)
18.0
15.0
12.0
9.0
6.0
3.0
ρs
T°
Vb
Grain Size
0.0 10.0 20.0 30.0 40.0
Snow Grain Size (mm-2)
0.00 0.02 0.04 0.06
Snow Brine Volume (Vb; %/100)

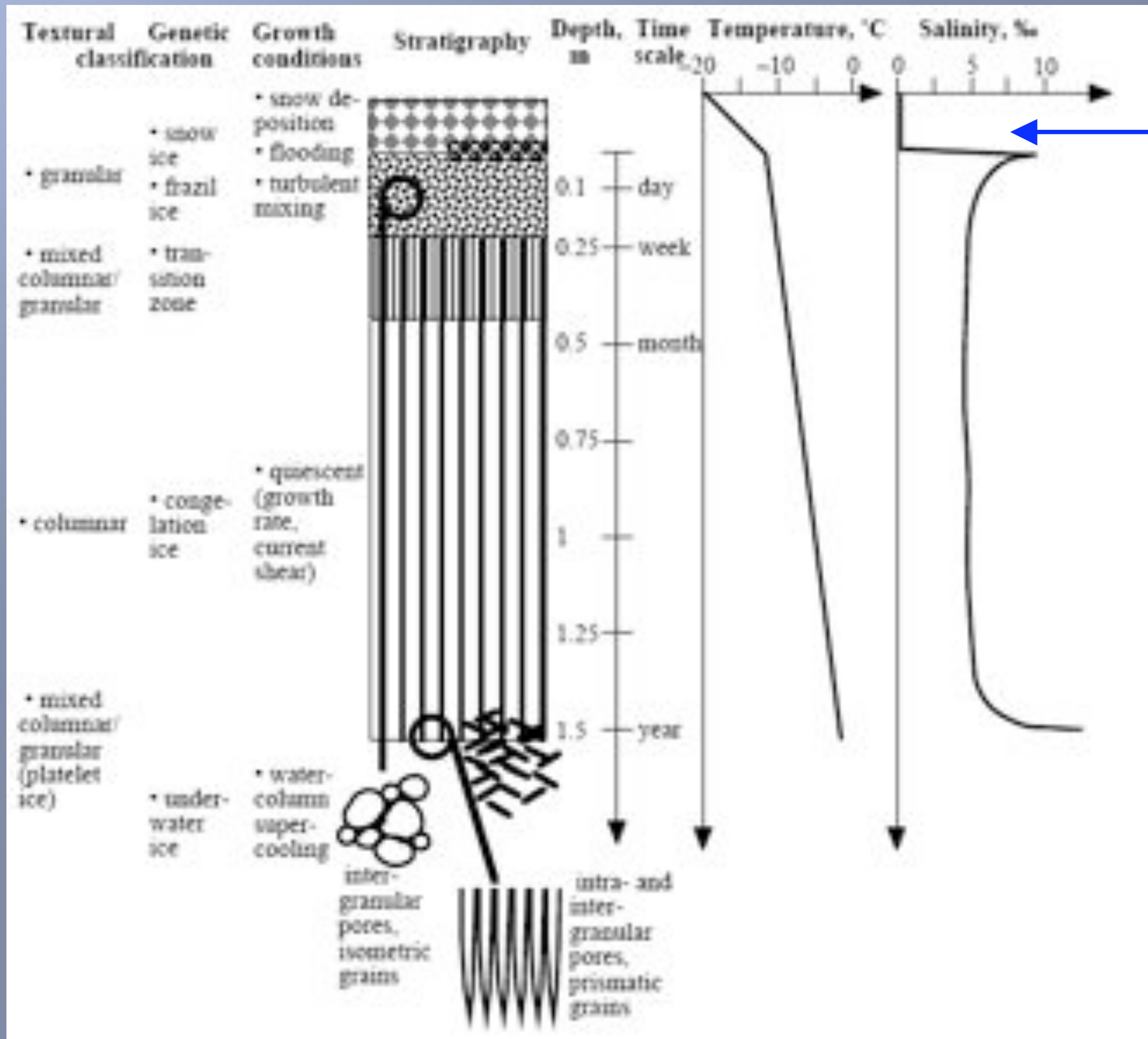
Sea Ice



Brine flux

New Sea Ice

First year sea ice microstructure



Snow is saline

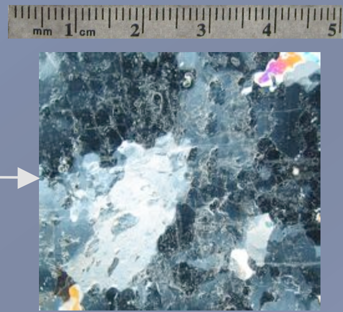
(Eicken's chapter in Thomas and Dieckmann (ed) 2004)

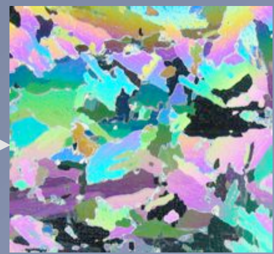
Ice microstructure, light nilas, Cape Bathurst polynya

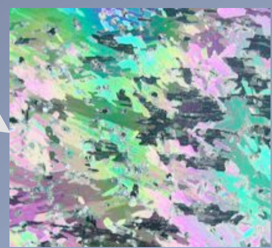
Station 124A on Oct 26, 2003

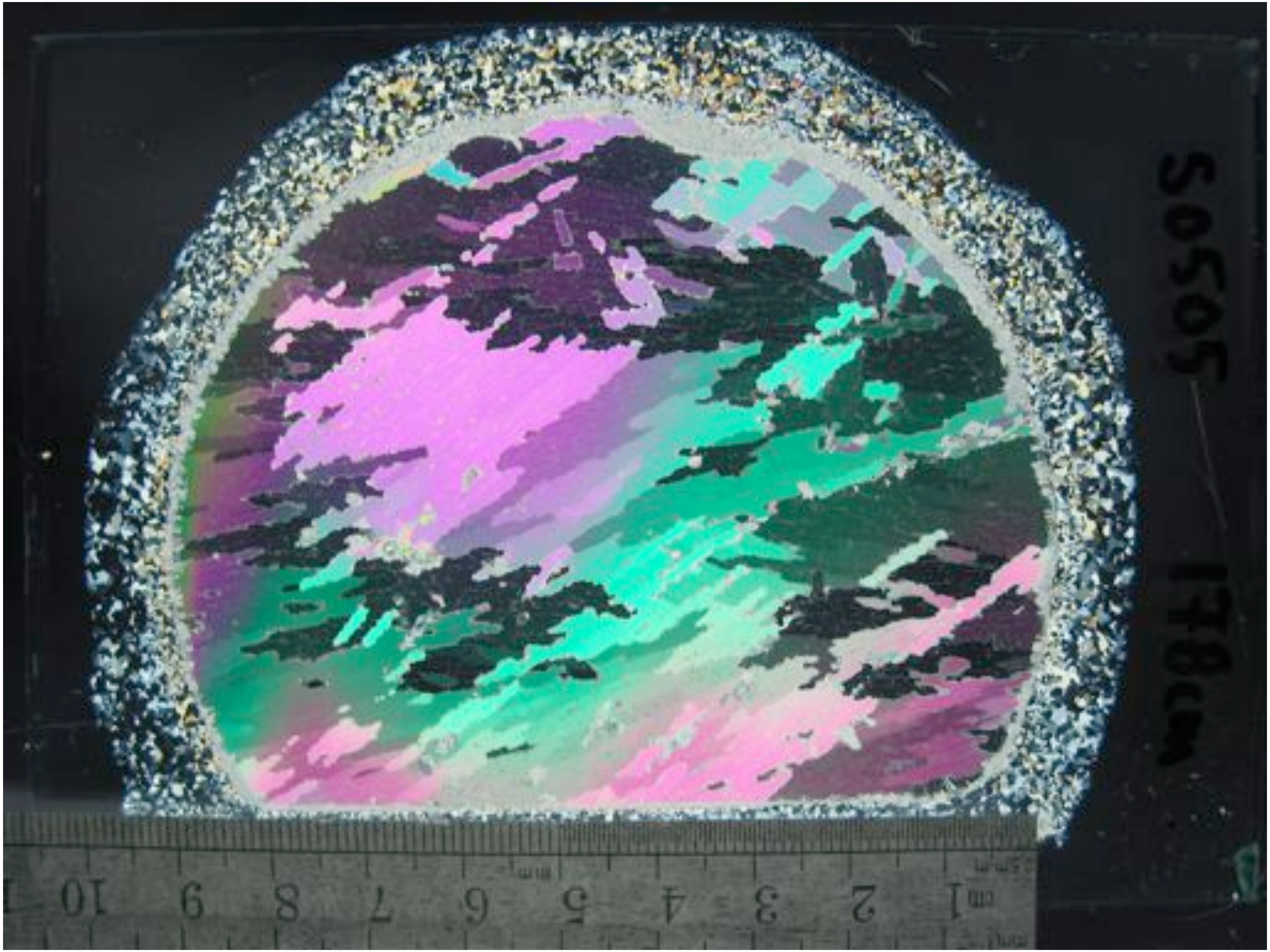
5mm thick section through transmitted light

1mm thin section between polarizing sheets

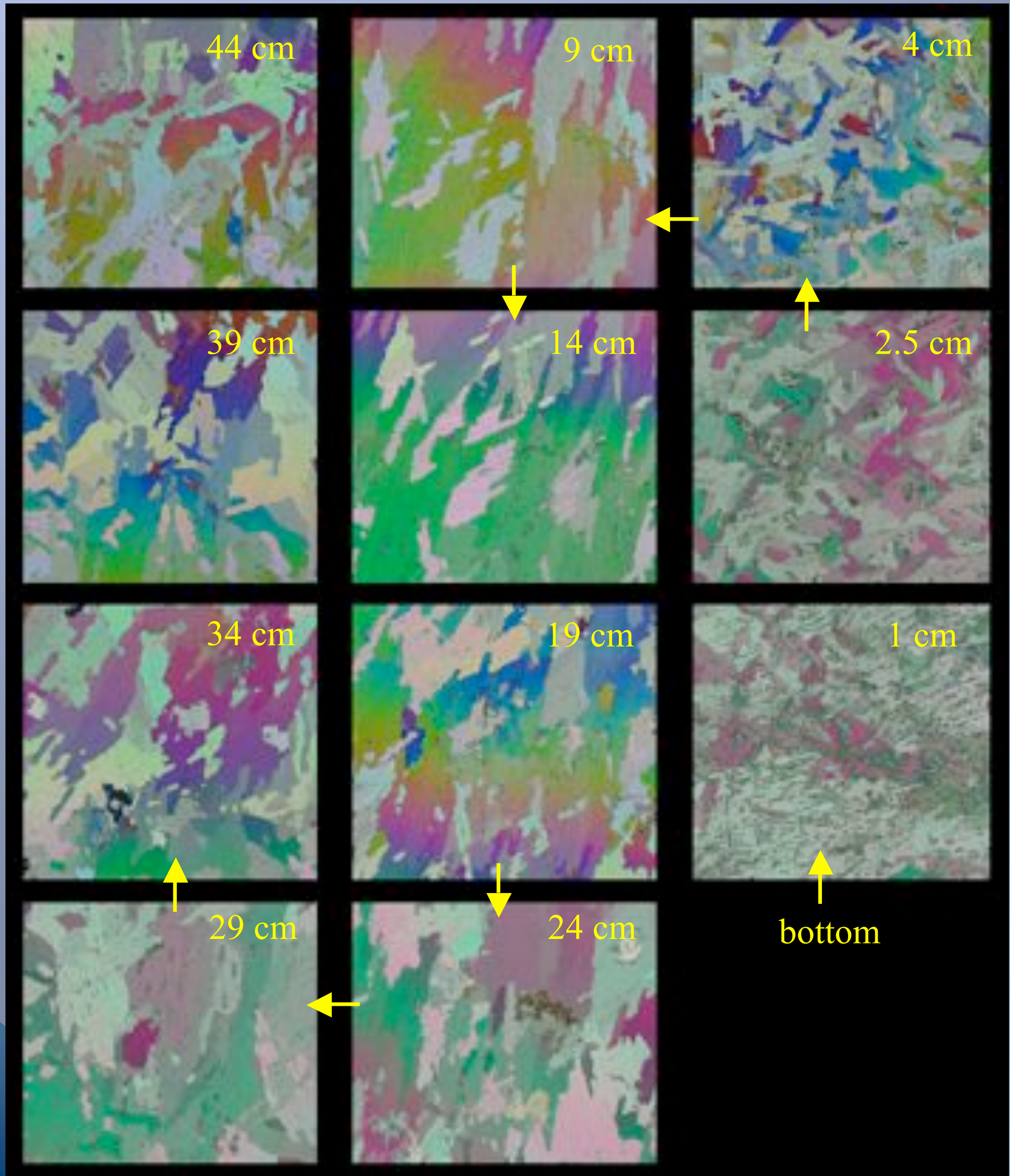






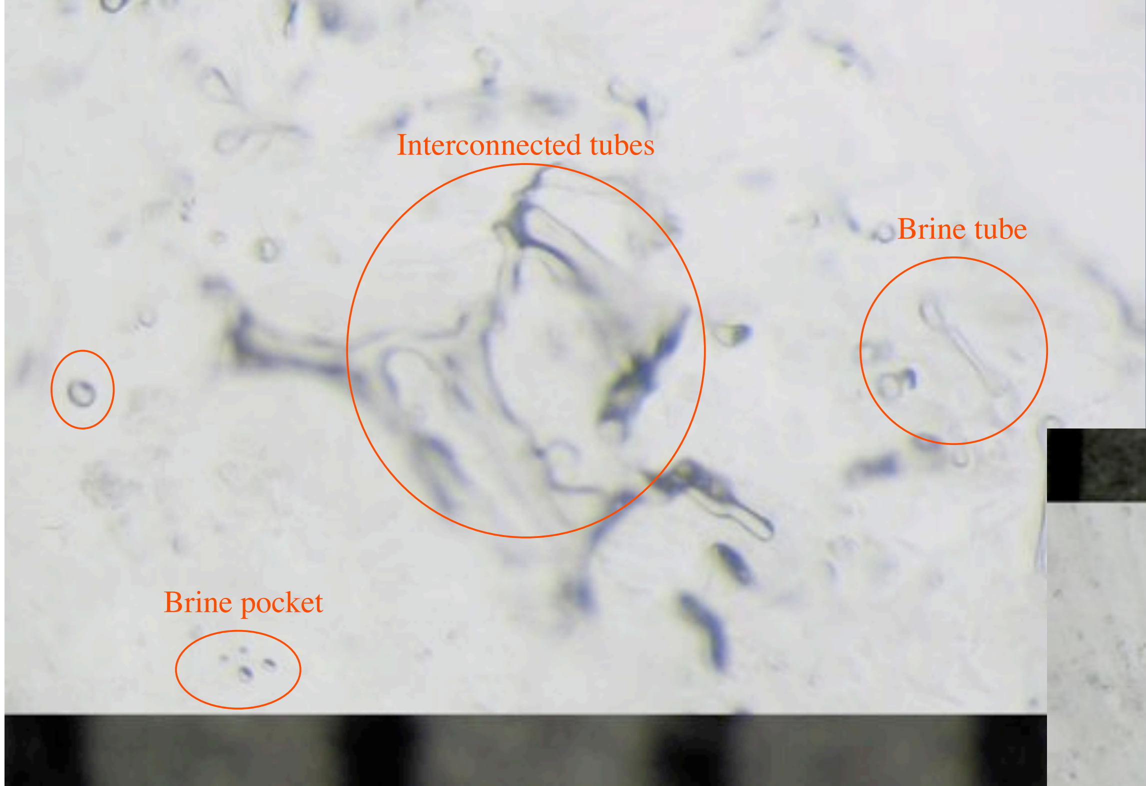


Crystal structure (FYI, Franklin Bay, May 9, 2004)

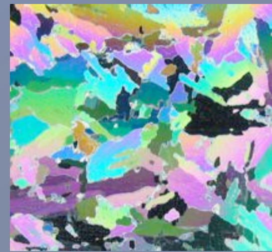


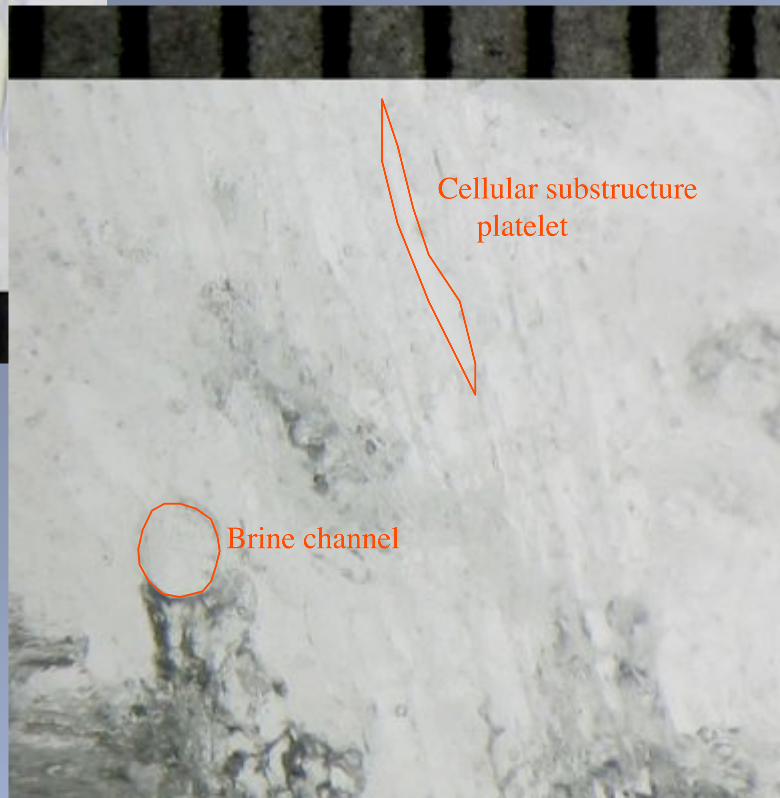
- Sea ice has irregular crystal boundaries
- Growth parallel to (0001) plane is favored
  - ⇒ Geometric selection to vertical c-axis orientation with depth.
- Sizes increase with depth (related to growth rate)
- C-axis alignment with currents
- Close to bottom of thick FYI irregular c-axis orientations observed (no explanation)

Close-ups with microscope viewed from above



6cm





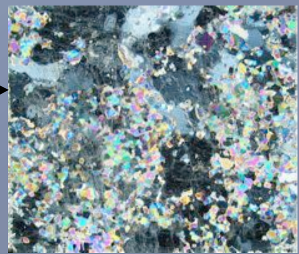
8cm

Very thin ice examples

124F

1.5cm

4cm

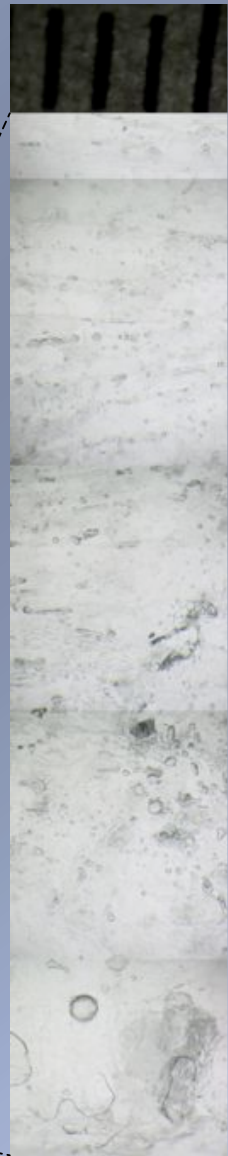


Agitated conditions

200E

2.5cm

Calm conditions



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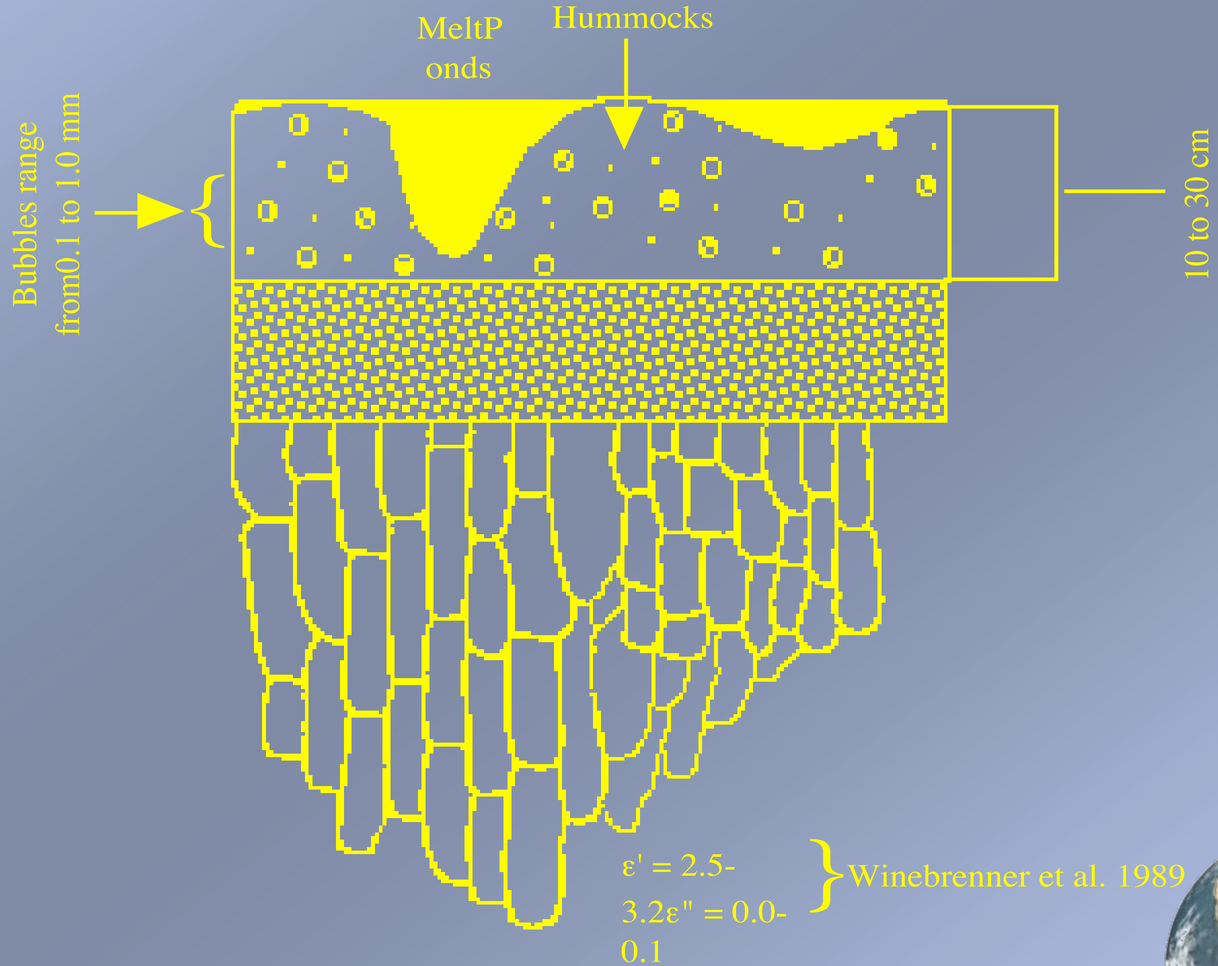
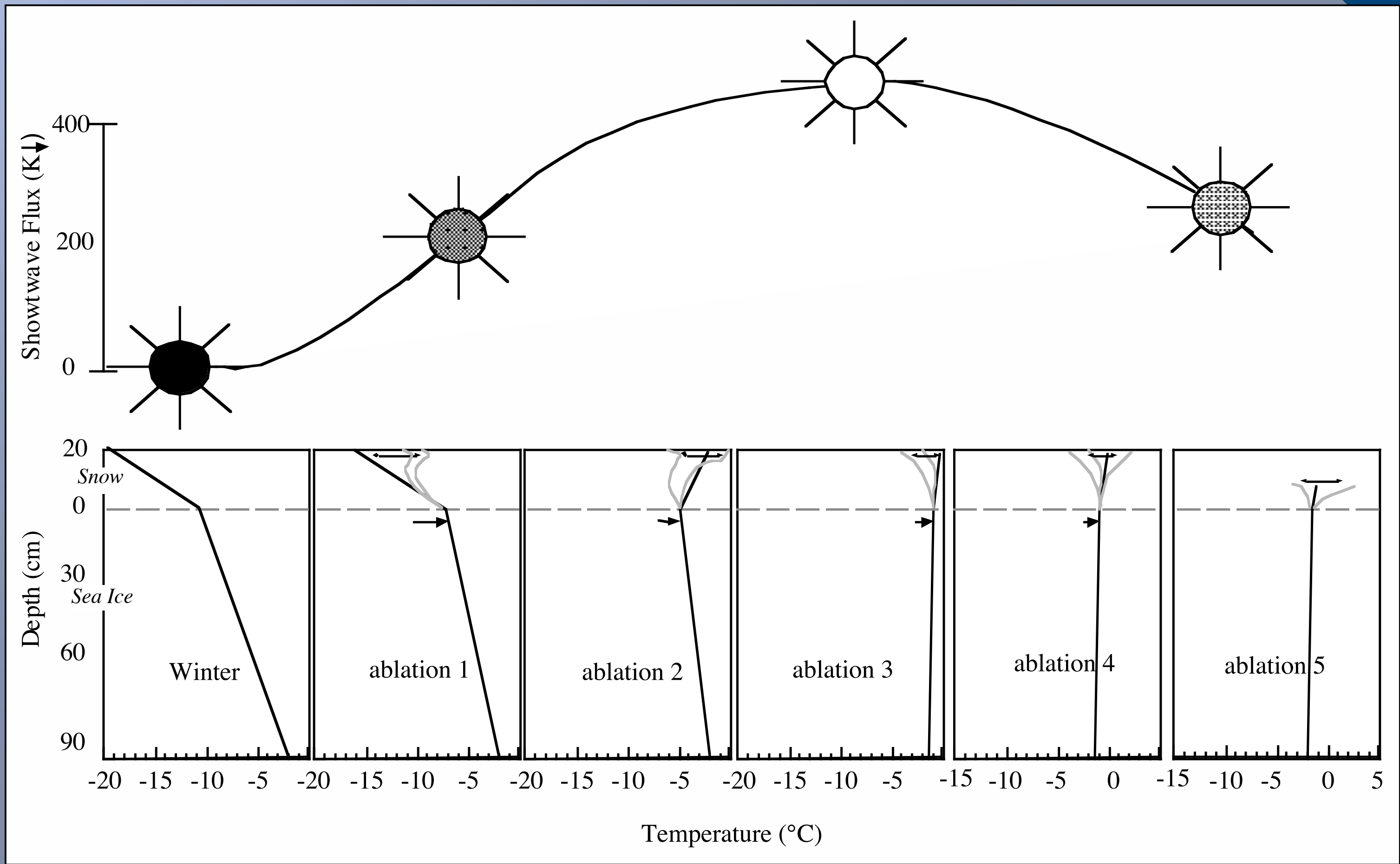
Multiyear sea ice microstructure



Temperature is the control



Barber et al. 1998

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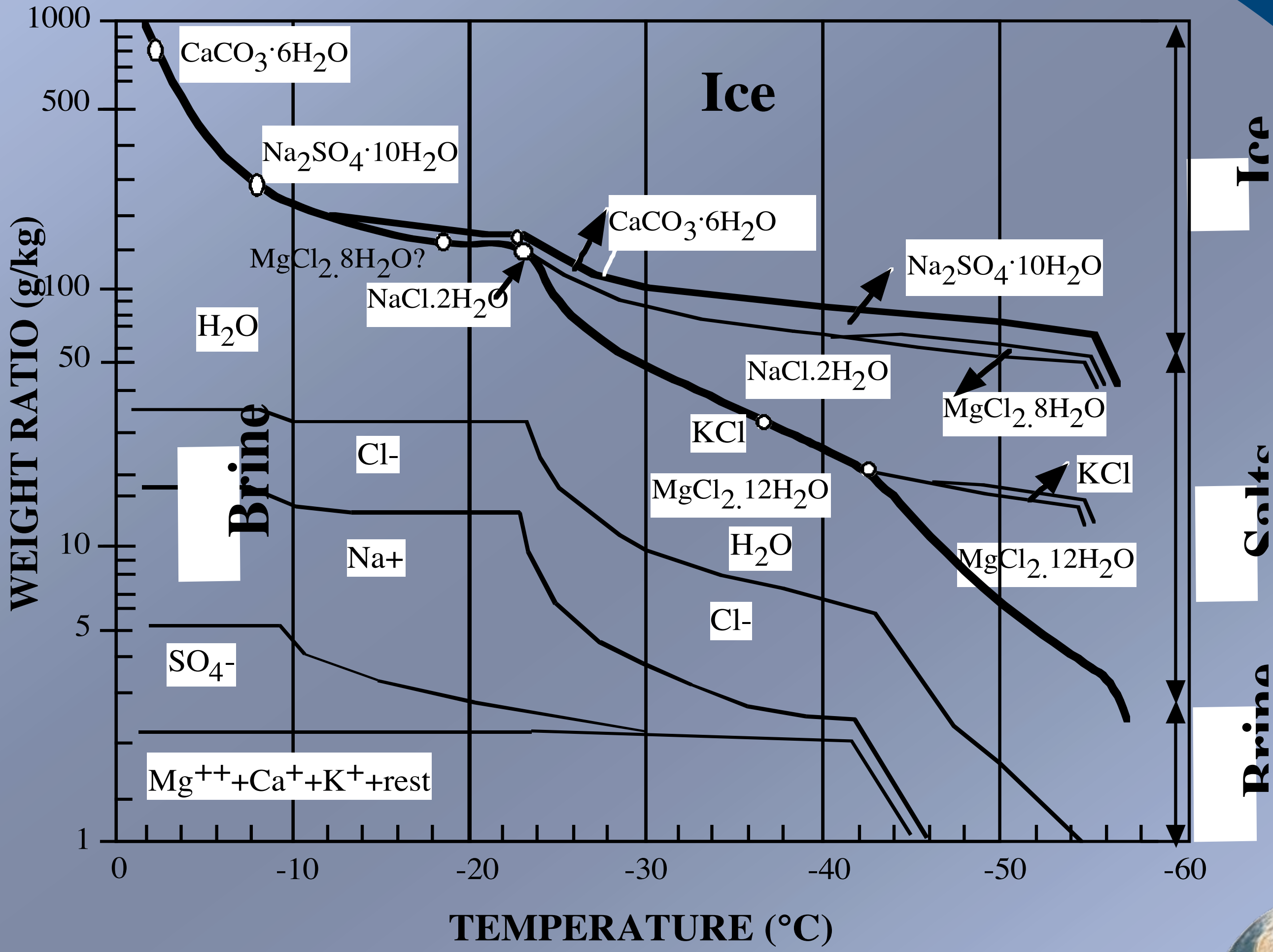
Temp effect on the partial fractions of brine/ice and air



Phase diagram of sea ice showing the relationships between ice in solid phase, brine and solid salts. After Assur, 1958.

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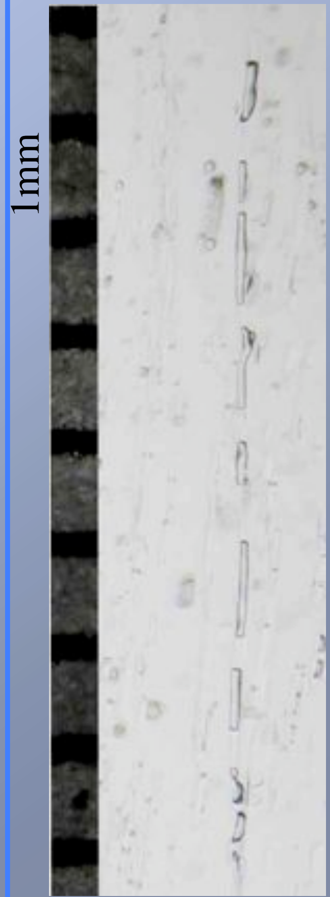
Some effects of temperature

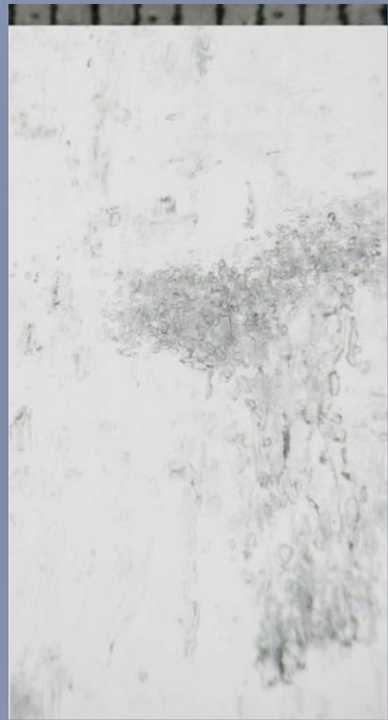
Freezing



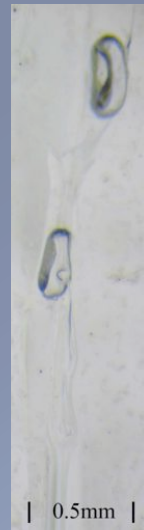
Solid salts precipitate in brine pockets (Light et al., 2002)

Brine tubes become fragmented when cooled (CASES, 10 Apr, 2004)

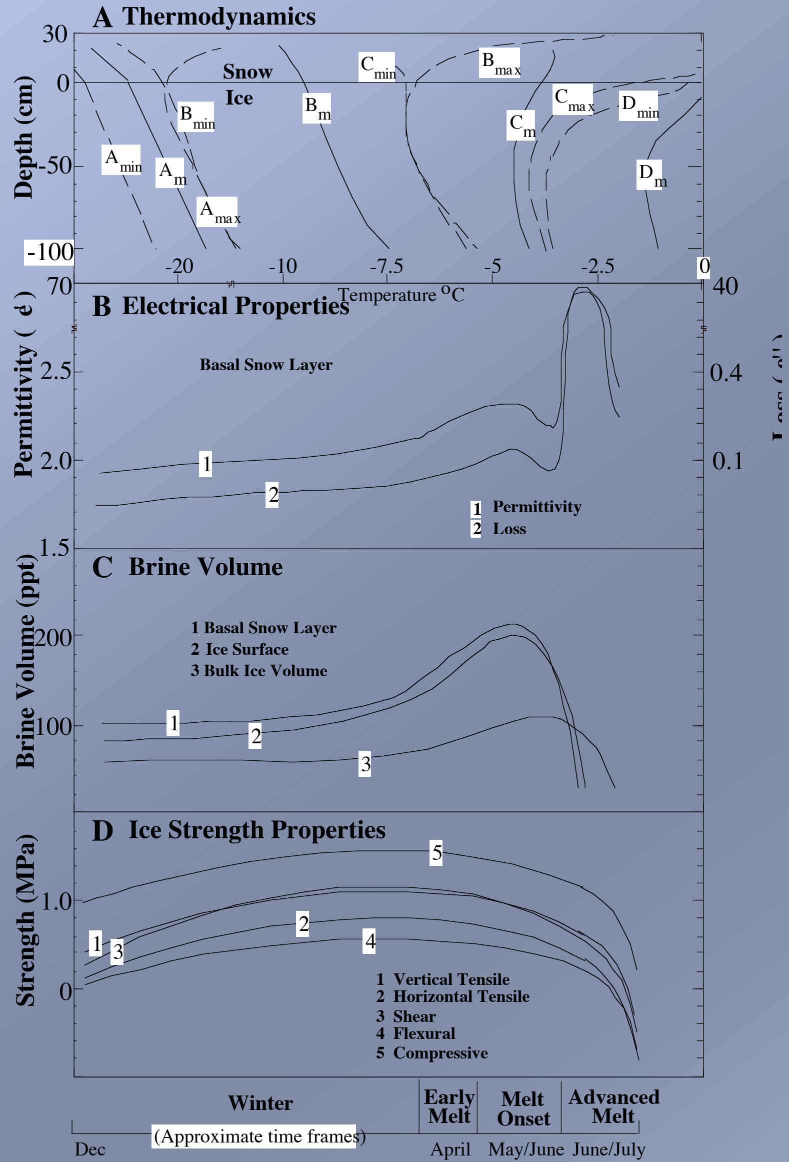
Warming



Brine clusters merge (CASES, May 16, 2004)



Gas bubbles form within tubes. (CASES, May 16)



Barber et al. 1996

The Rule of 5's

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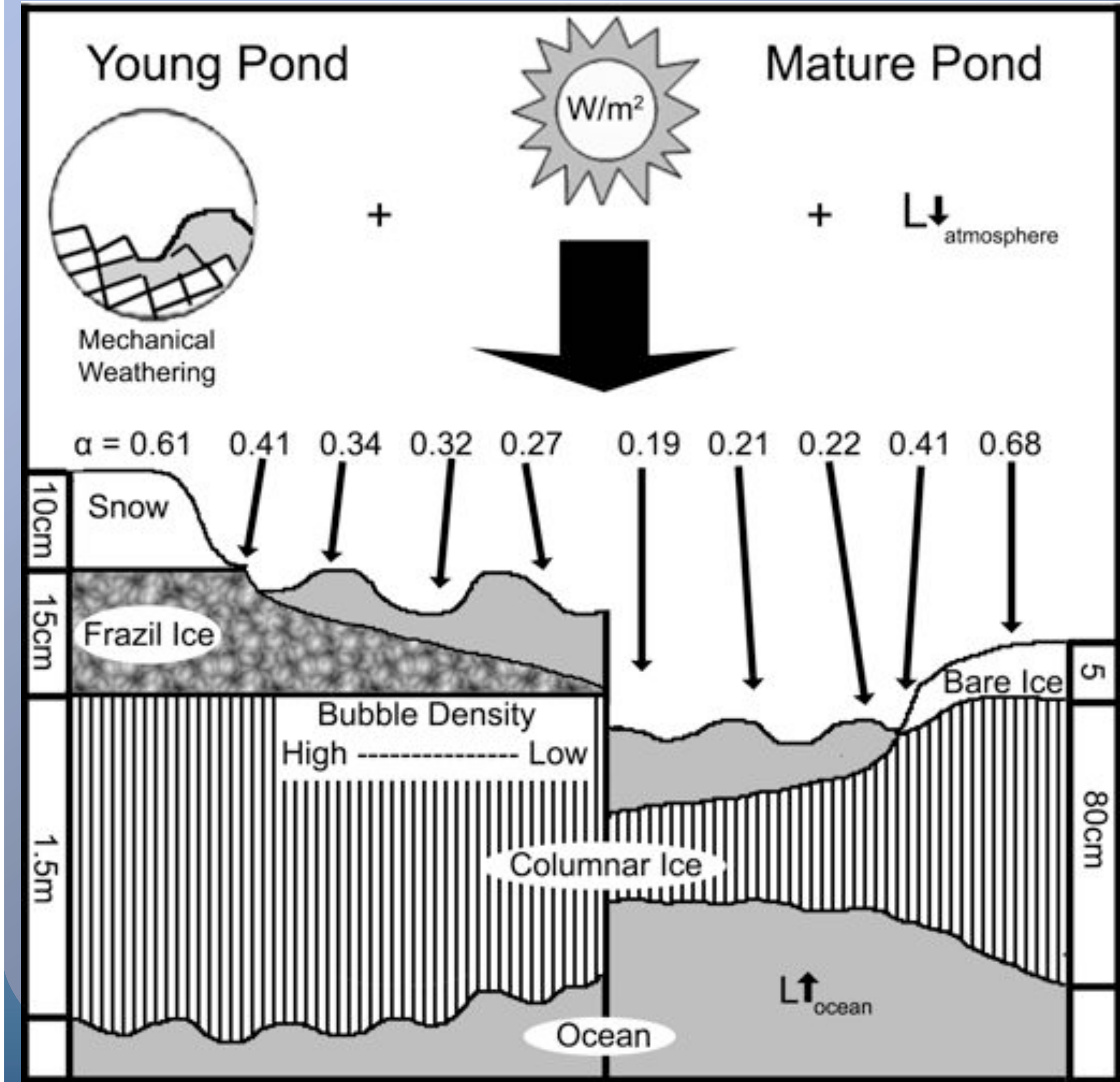
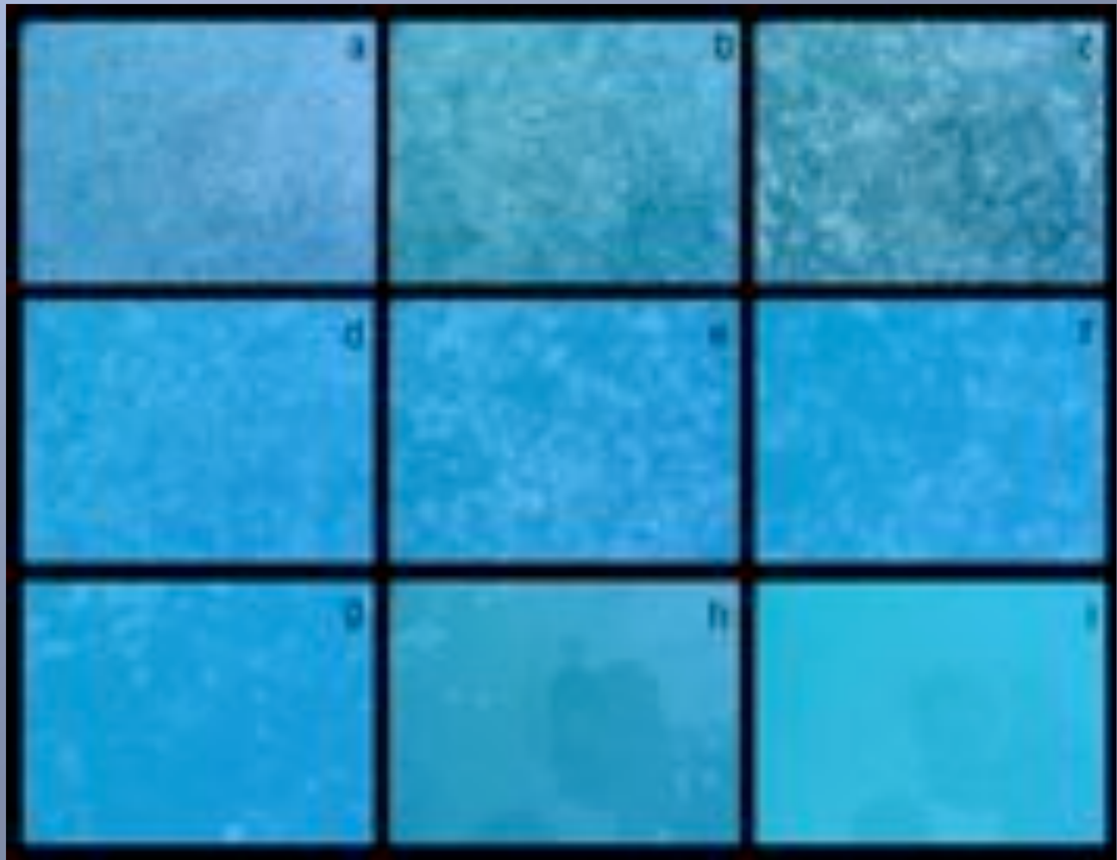
23. 6. 2002



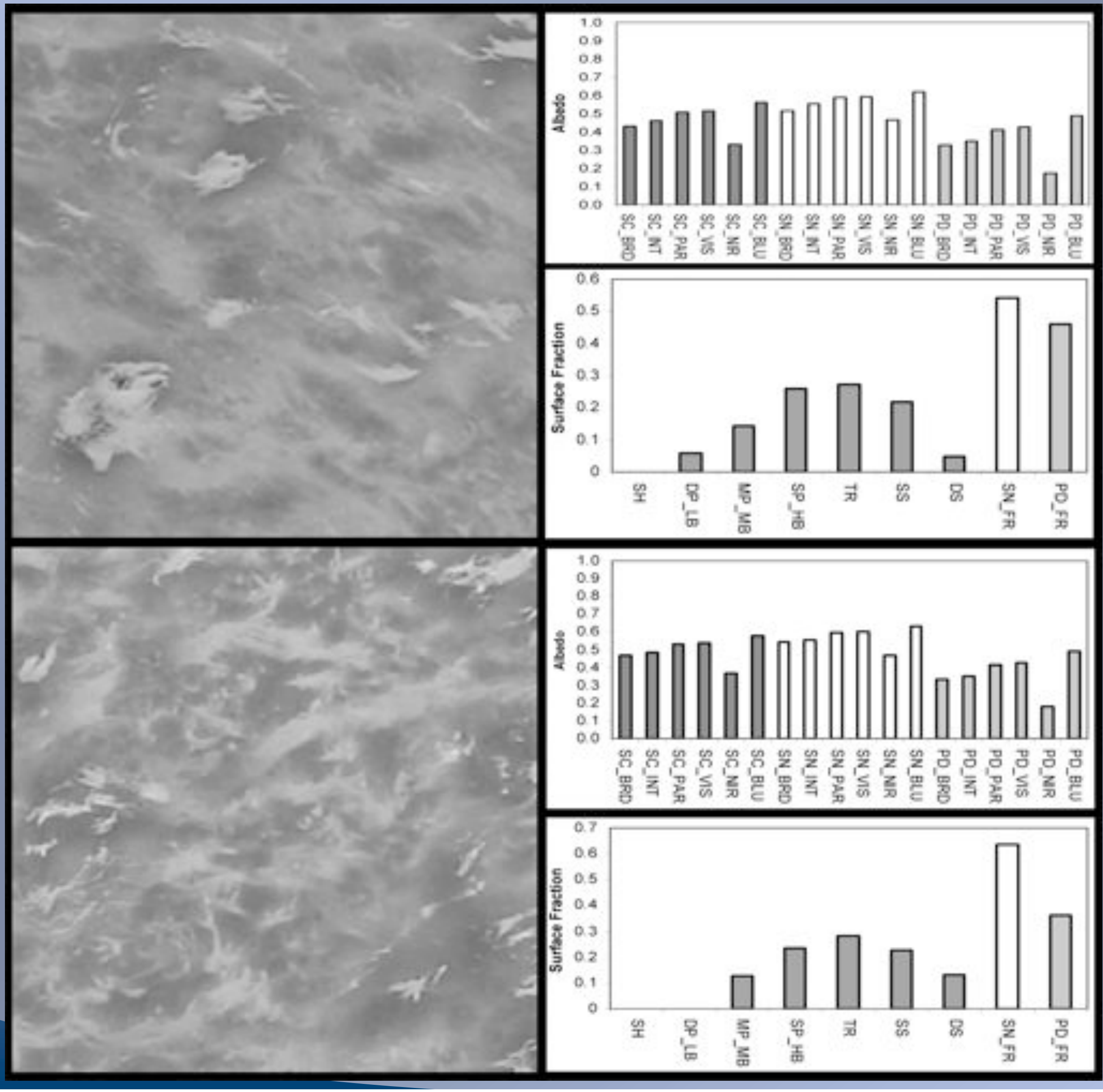
Processes leading to melt pond maturity over FYI. The melt pond – albedo feedback is initiated by an increase in the atmospheric heat flux (L), stimulating snow ablation and the development of melt ponds. During initial pond formation the albedo of young ponds is dictated by pond depth and the scattering properties of the frazil ice layer. Ablation of the frazil layer is a function of the wind induced mechanical weathering, and solar insolation (Wm^{-2}). As the melt ponds matured, the albedo is dictated by pond depth and the optical properties of the columnar ice volume

The Effect of Frazil Ice On Albedo

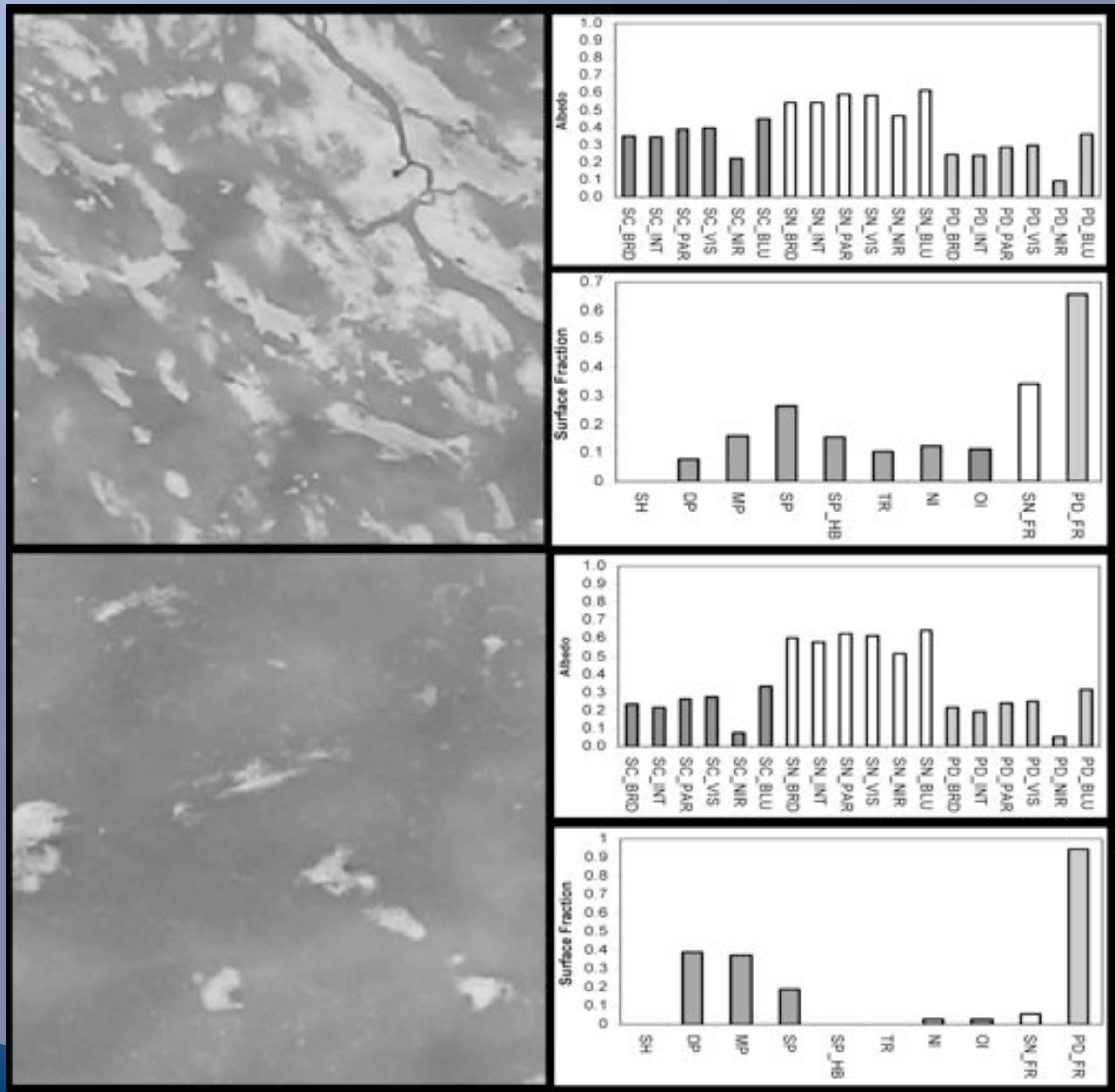


- The evolution of melt ponds through the melt season. Bubble densities quickly reduced after initial ponding however a ring of high bubble density is found along pond fringes during times of advance.

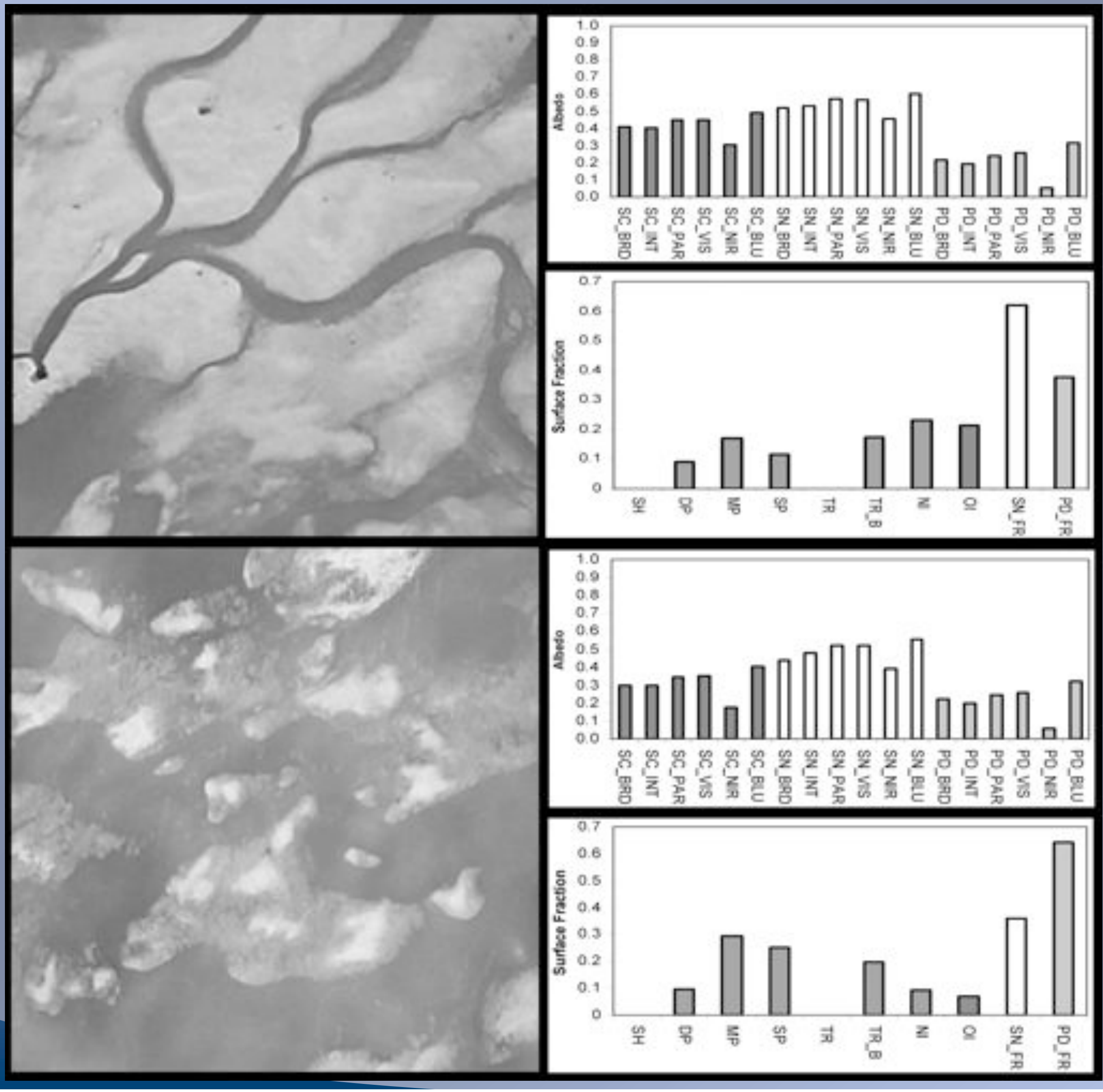
Pond Onset


Albedo
SC_BRD SC_INT SC_PAR SC_VIS SC_NIR SC_BLU SN_BRD SN_INT SN_PAR SN_VIS SN_NIR SN_BLU PD_BRD PD_INT PD_PAR PD_VIS PD_NIR PD_BLU
Surface Fraction
SH DP_LB MP_MB SP_HB TR SS DS SN_FR PD_FR
Albedo
SC_BRD SC_INT SC_PAR SC_VIS SC_NIR SC_BLU SN_BRD SN_INT SN_PAR SN_VIS SN_NIR SN_BLU PD_BRD PD_INT PD_PAR PD_VIS PD_NIR PD_BLU
Surface Fraction
SH DP_LB MP_MB SP_HB TR SS DS SN_FR PD_FR

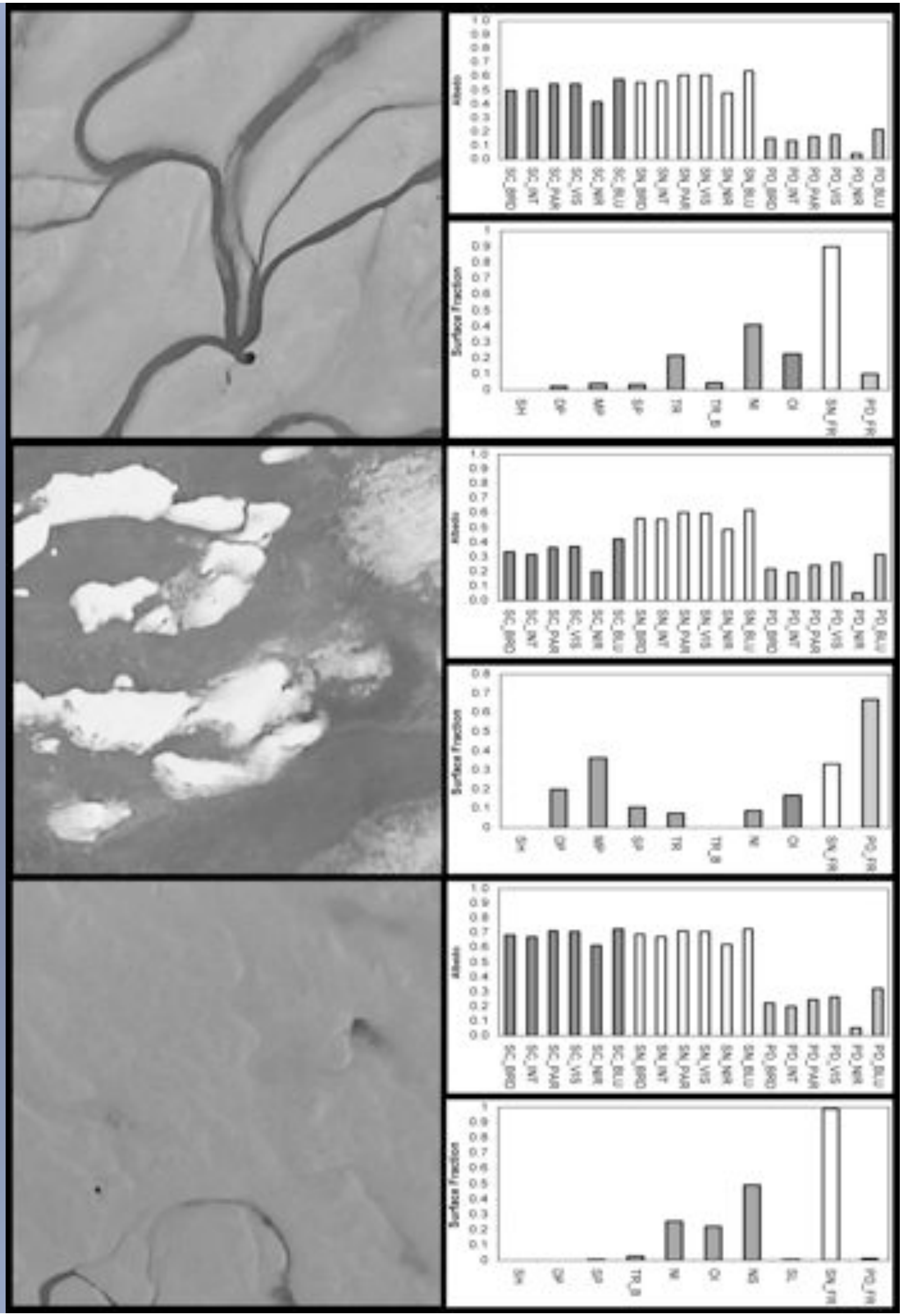
Pond Development



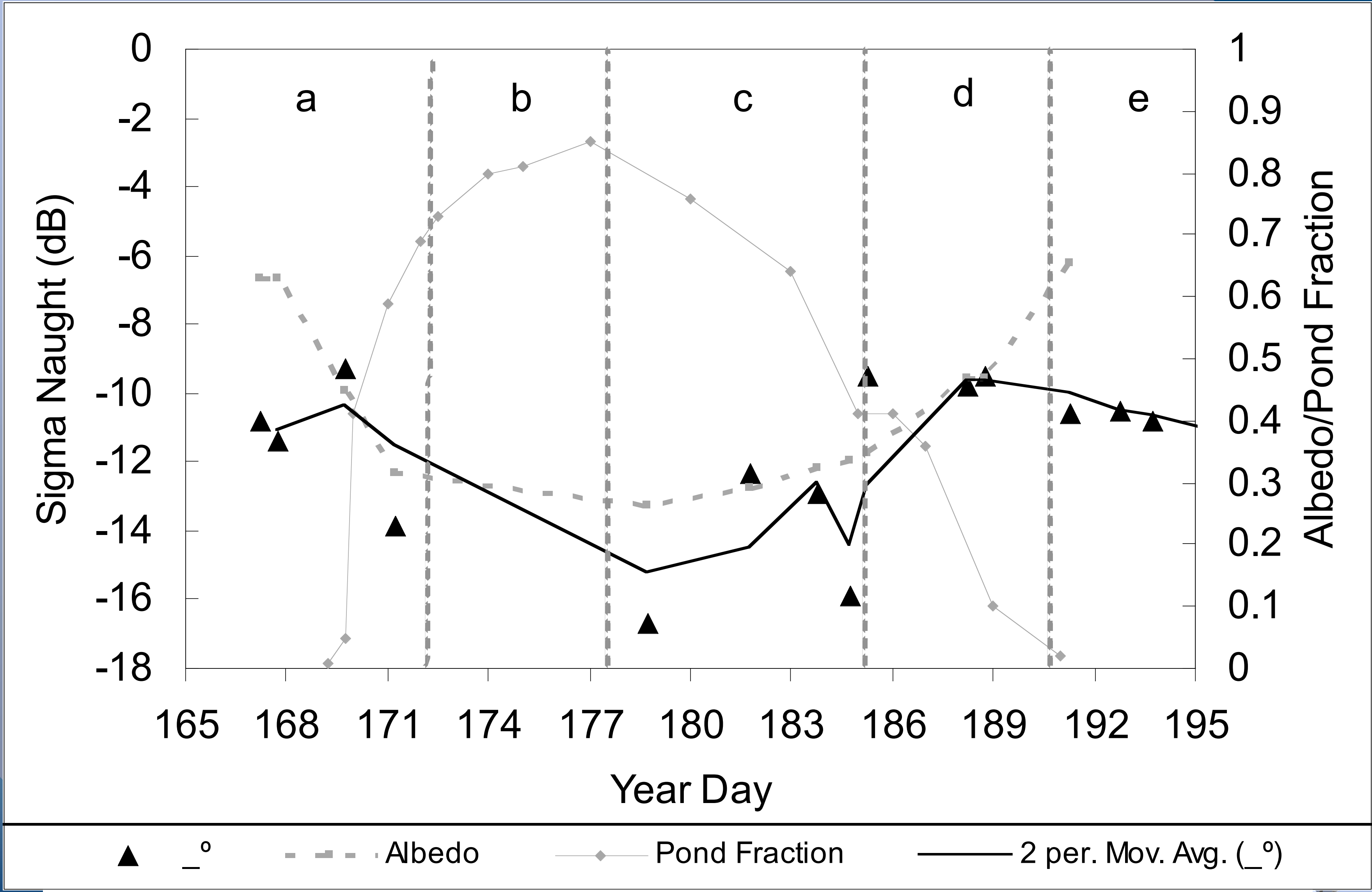
Mature Ponds



Pond Drainage

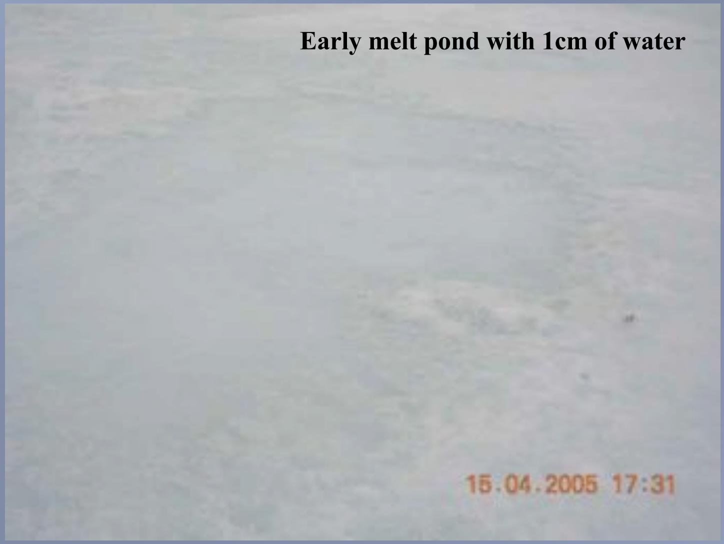


Time Series α, σº and Pond Fraction



IOP and AOP of the seasonal ice cover

Measurements - Spectral albedo site M3



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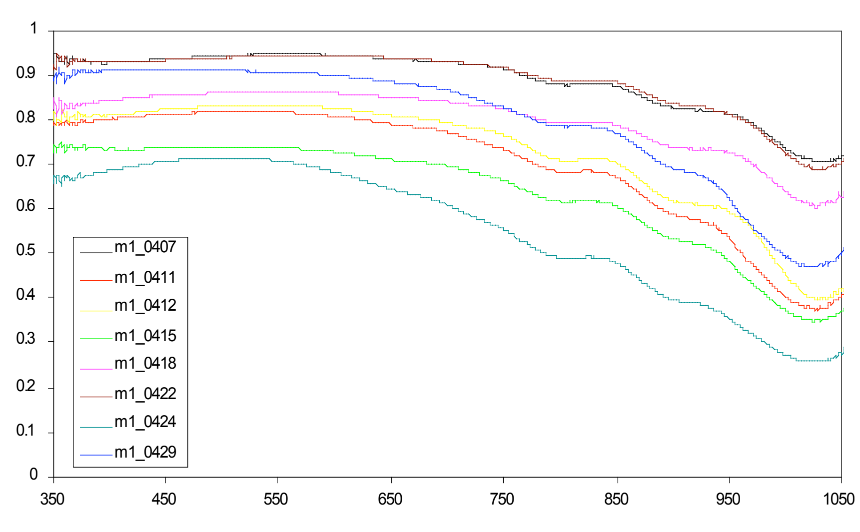
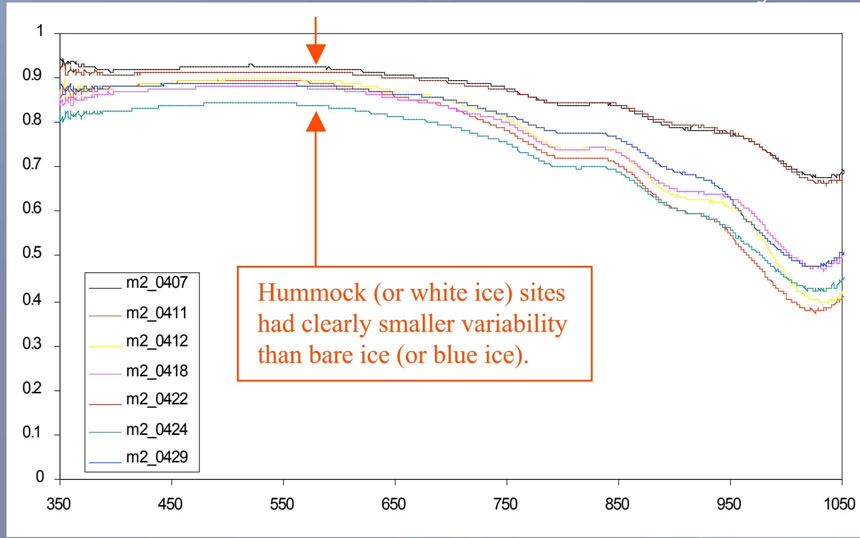
Spectral albedos from Button Bay, HB2005, April 7 to April 29, M-sites

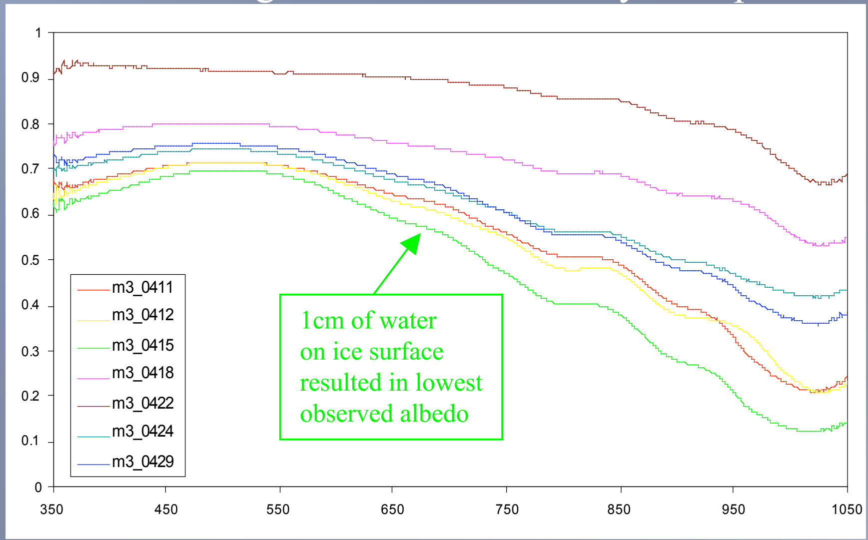
M1 – small bare ice area



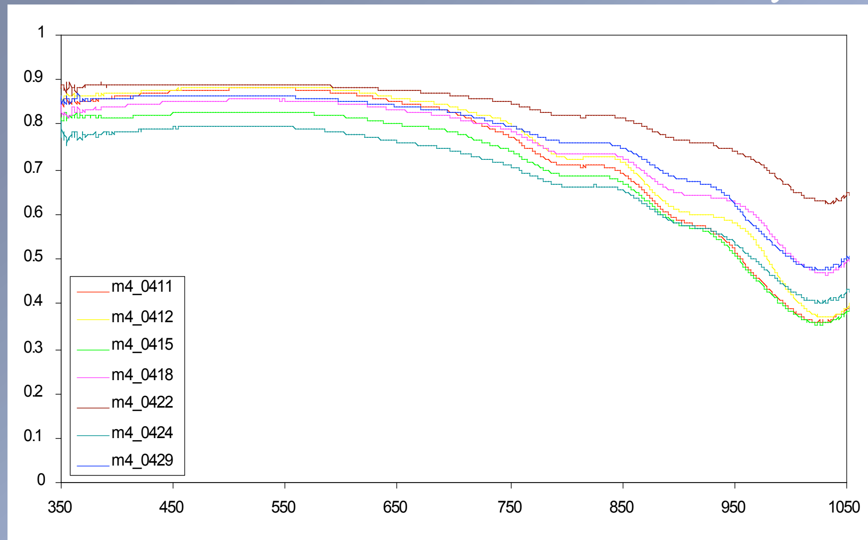
M2 – hummock with ~15cm soft surface layer



M3 – large bare ice area – early melt pond

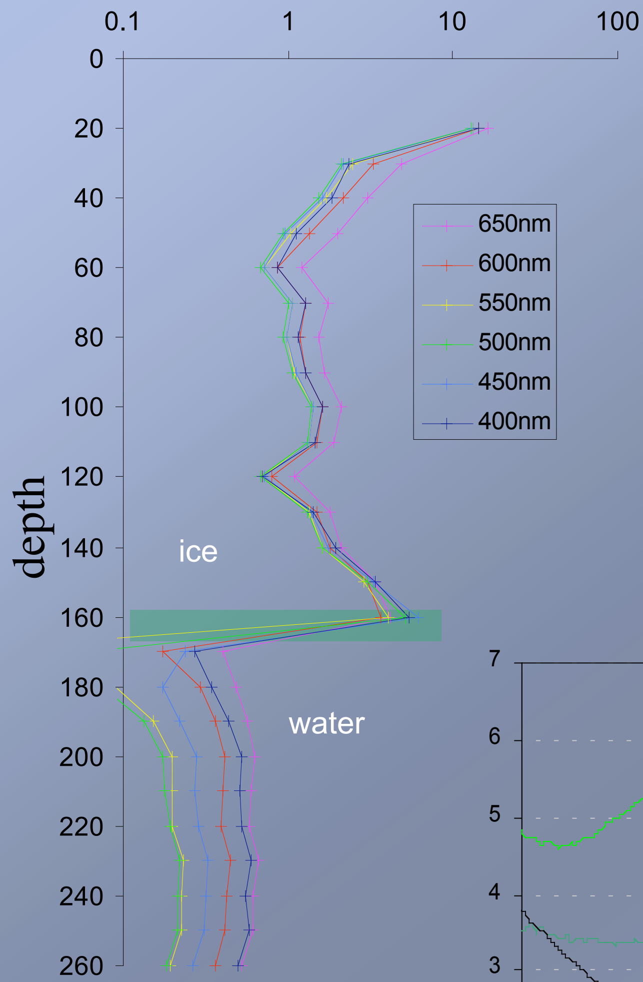


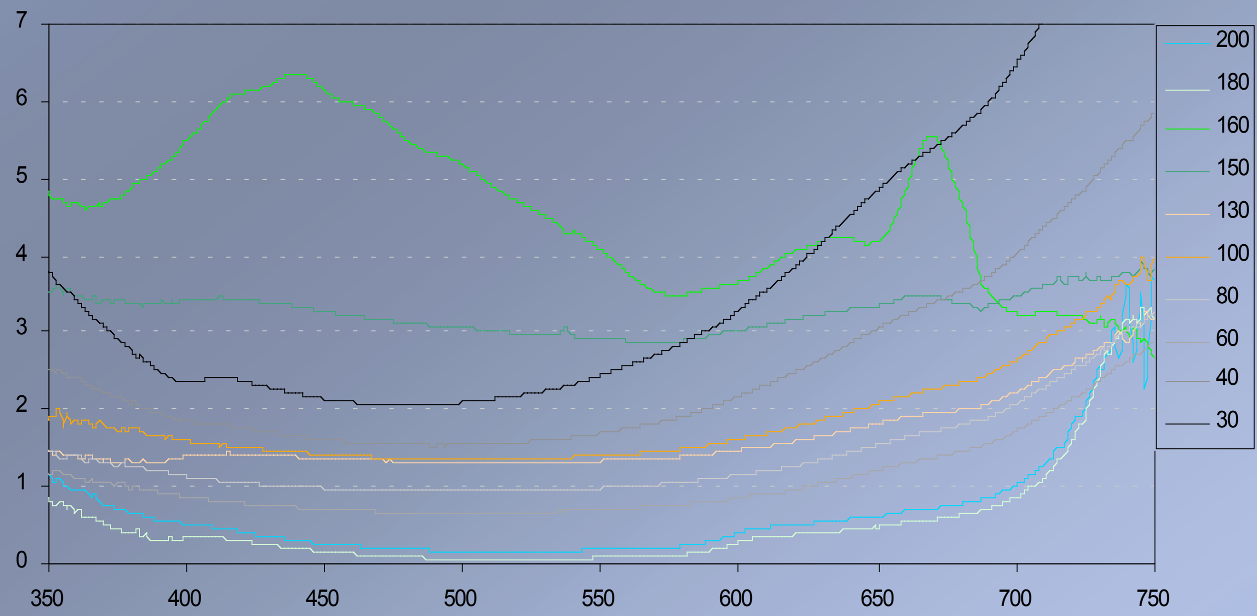
M4 – hummock with ~5cm soft surface layer



Spectral irradiance profiles and transmittance

Diffuse attenuation coefficient $K_d(\lambda)$ calculated from irradiance profile T1_0421 (hummock)





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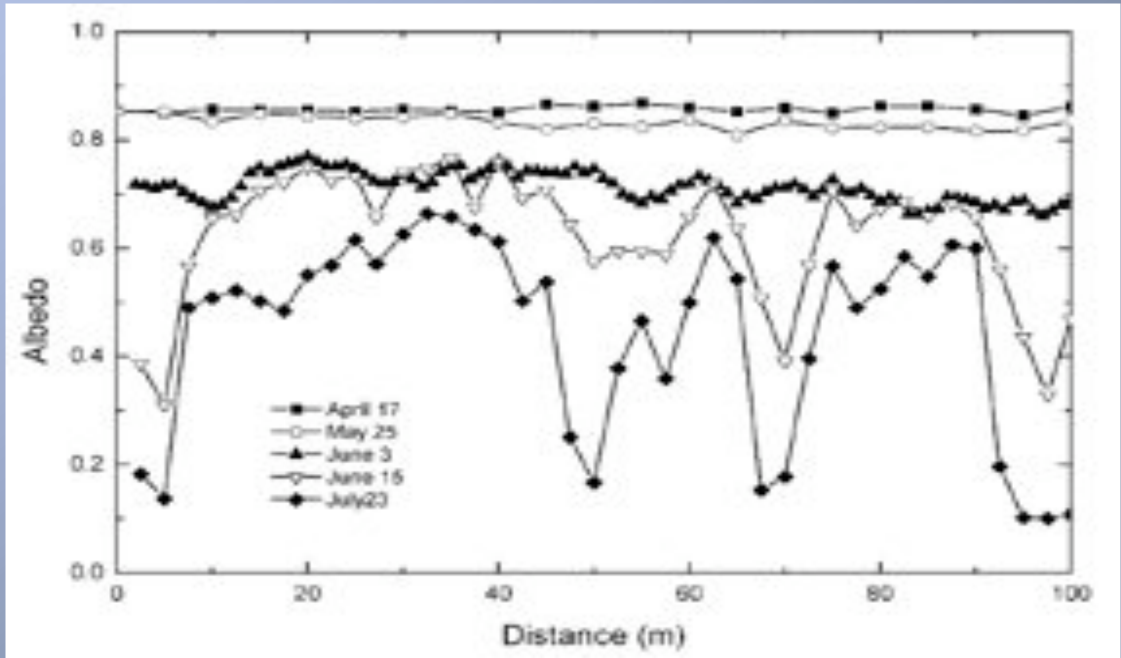
What about spatial variability?



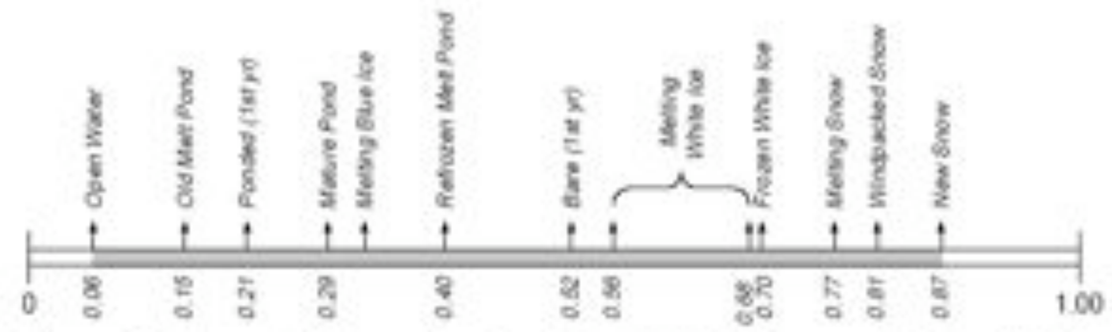
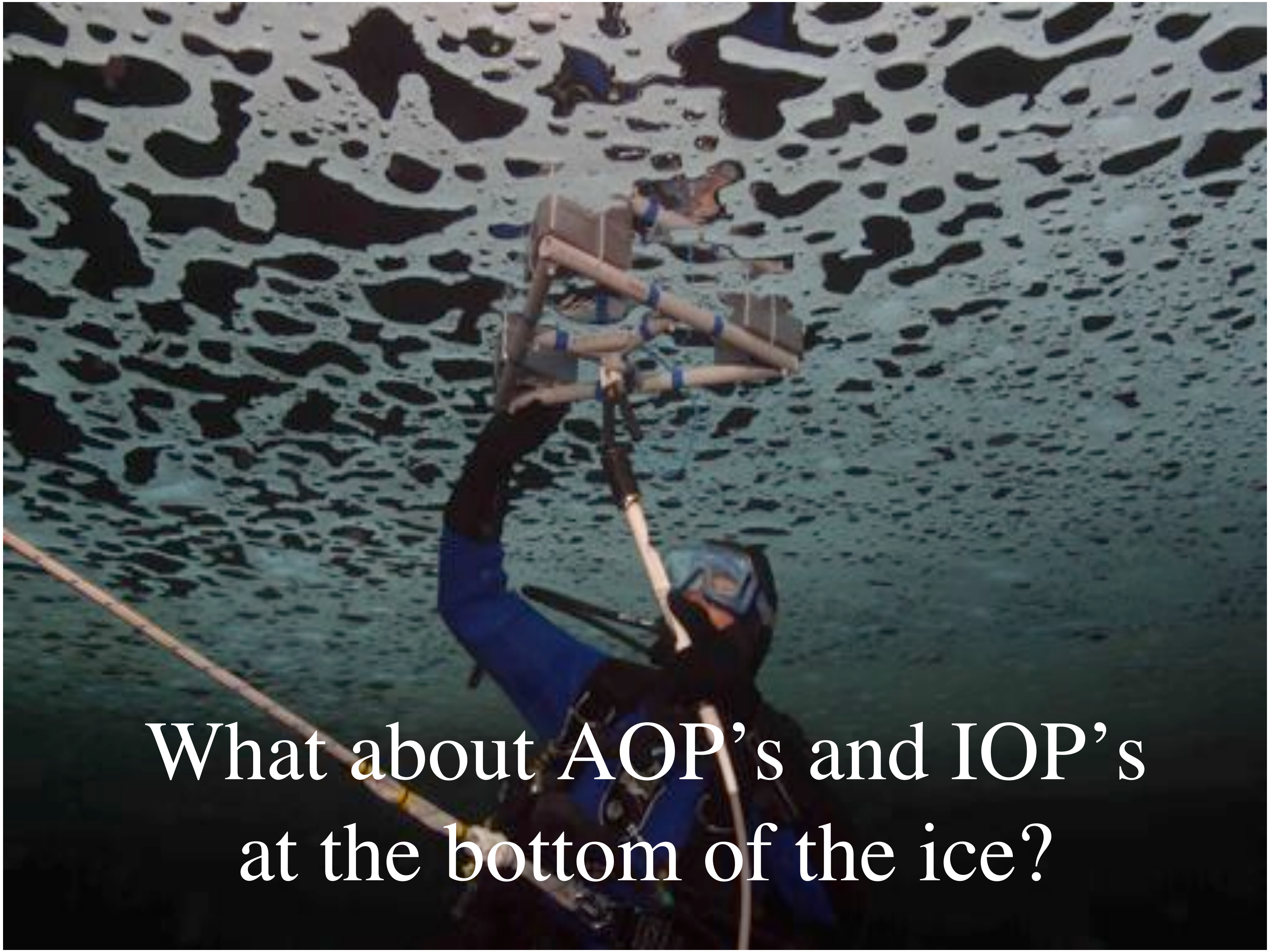
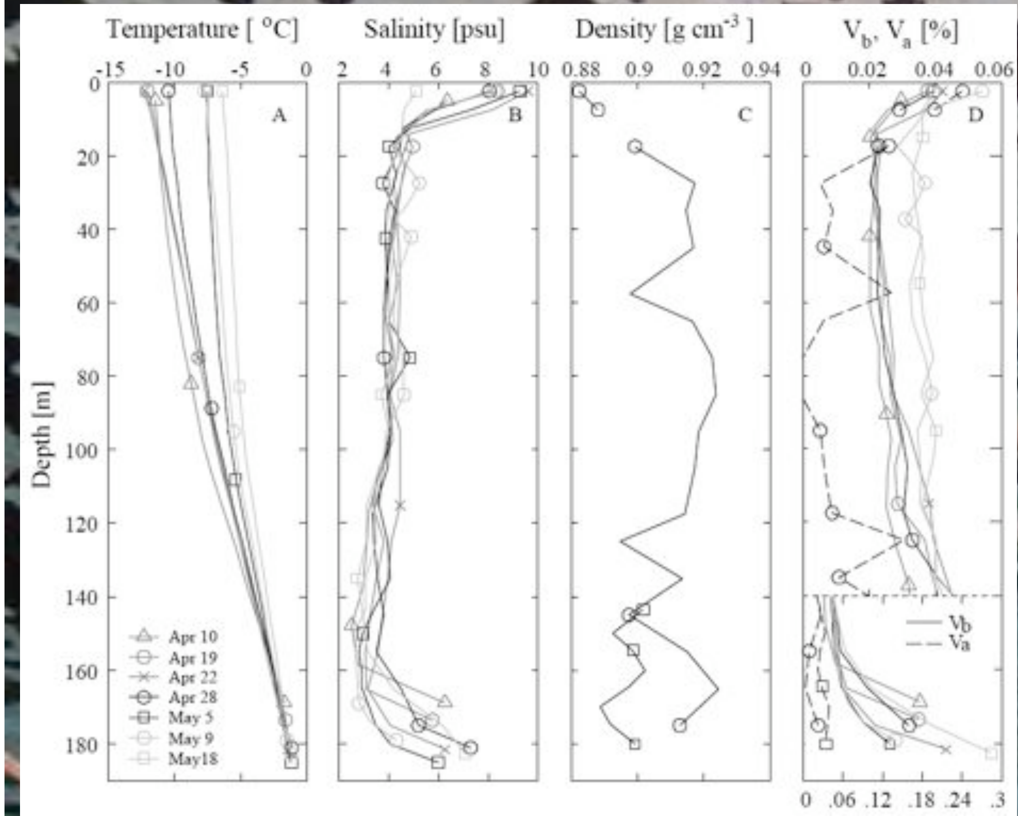
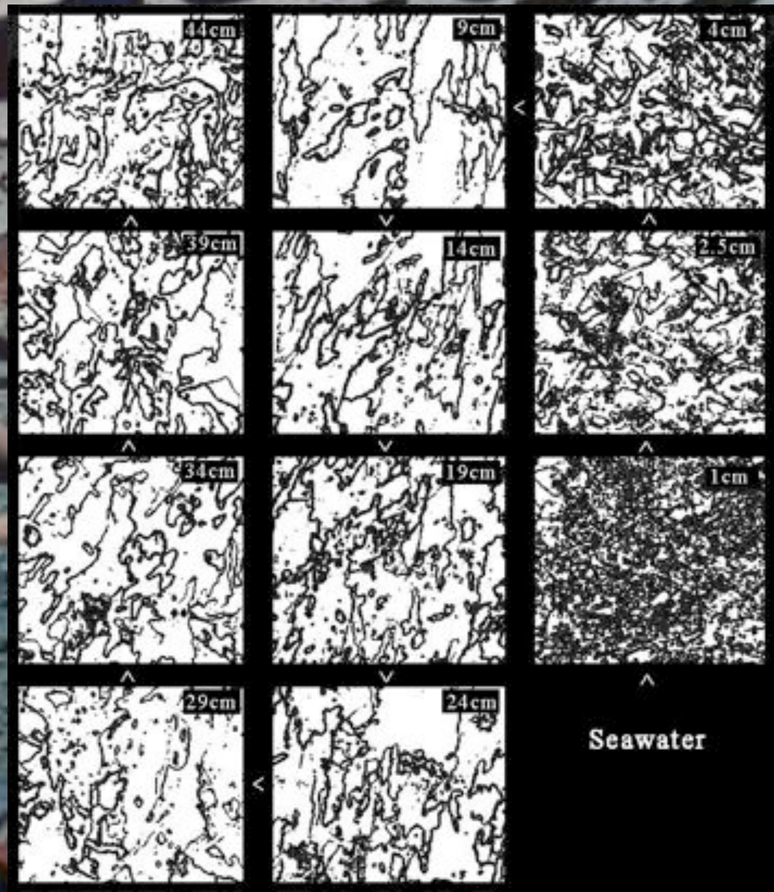


Figure 3. Range of observed values of total albedo for sea ice. The albedos are from Burt (1954), Chernigovskiy (1963), Langleben (1971), Grenfell and Maykut (1977), and Grenfell and Perovich (1984).


What about AOP's and IOP's
at the bottom of the ice?



Vertical profiles in sea ice for (a) temperature (daily mean), (b) salinity and (c) density, with (d) corresponding calculations of brine and air inclusion volume fractions. Note the cut in scale on the latter. The emphasis is on the bottom part where high temperature and salinities resulted in an off the scale increase in volume fractions.

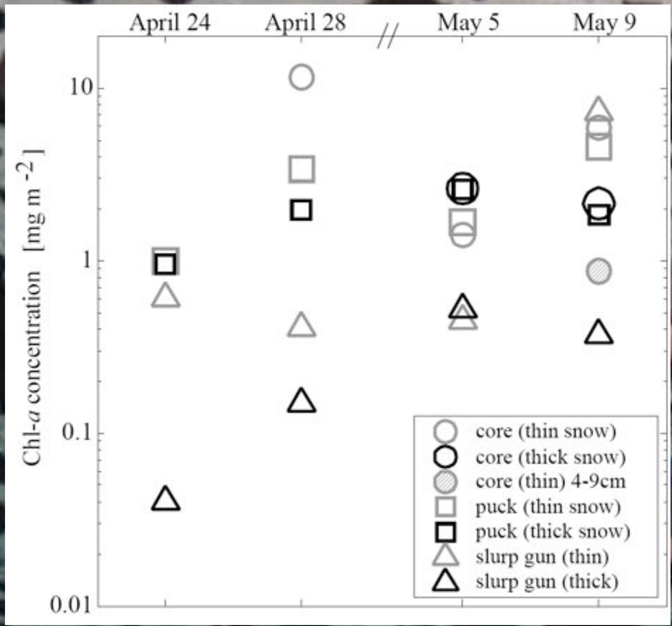


Horizontal microstructure sections of a sea ice sample taken on 9 May. The numbers on the right-hand corner of each image indicate the height above the ice-water interface from which the section was extracted.

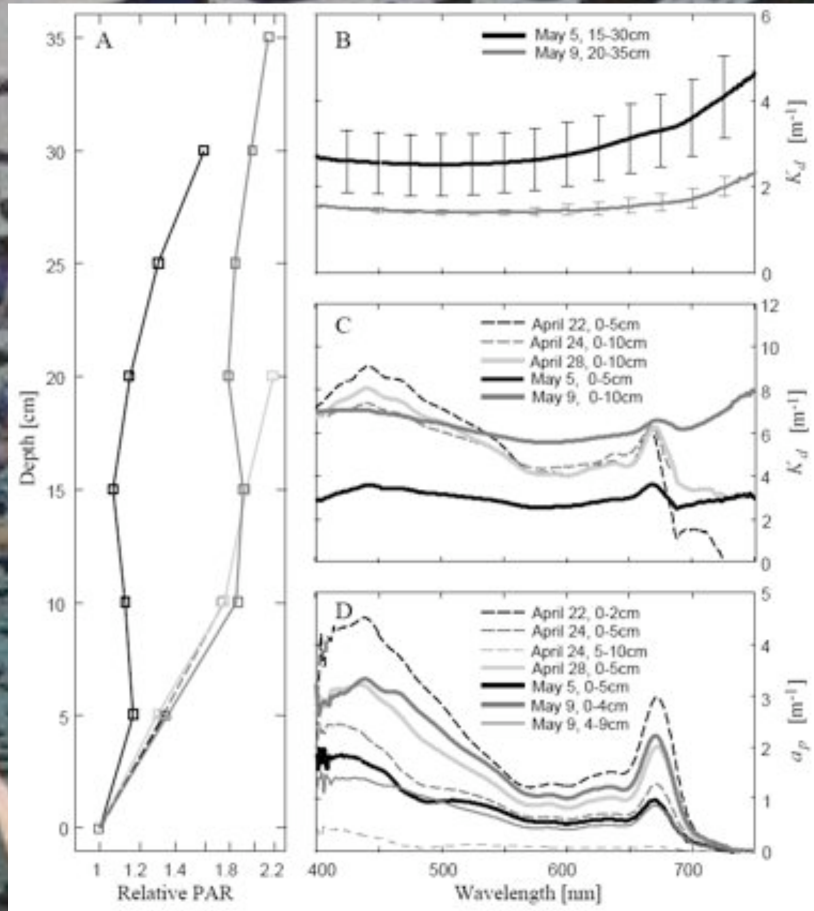
Processing by:

1. Edge detect
2. Torn edges

CEOS



Average chlorophyll-*a* concentrations measured on four occasions using three different methods to extract samples; ice core drilled from surface (core), 4-cm thick ice puck taken by diver from below (puck), and bottommost algae layer sampled by diver using syringe "slurp gun"



(a) The vertical downwelling irradiance profiles integrated over PAR wavelengths and normalized to bottom irradiance values. The corresponding diffuse downwelling irradiance attenuation spectra for the (b) interior ice and (c) bottom 10-cm bottom layer, with comparisons to (d) particulate absorption coefficient.

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A brief look at Complexity?

Snow

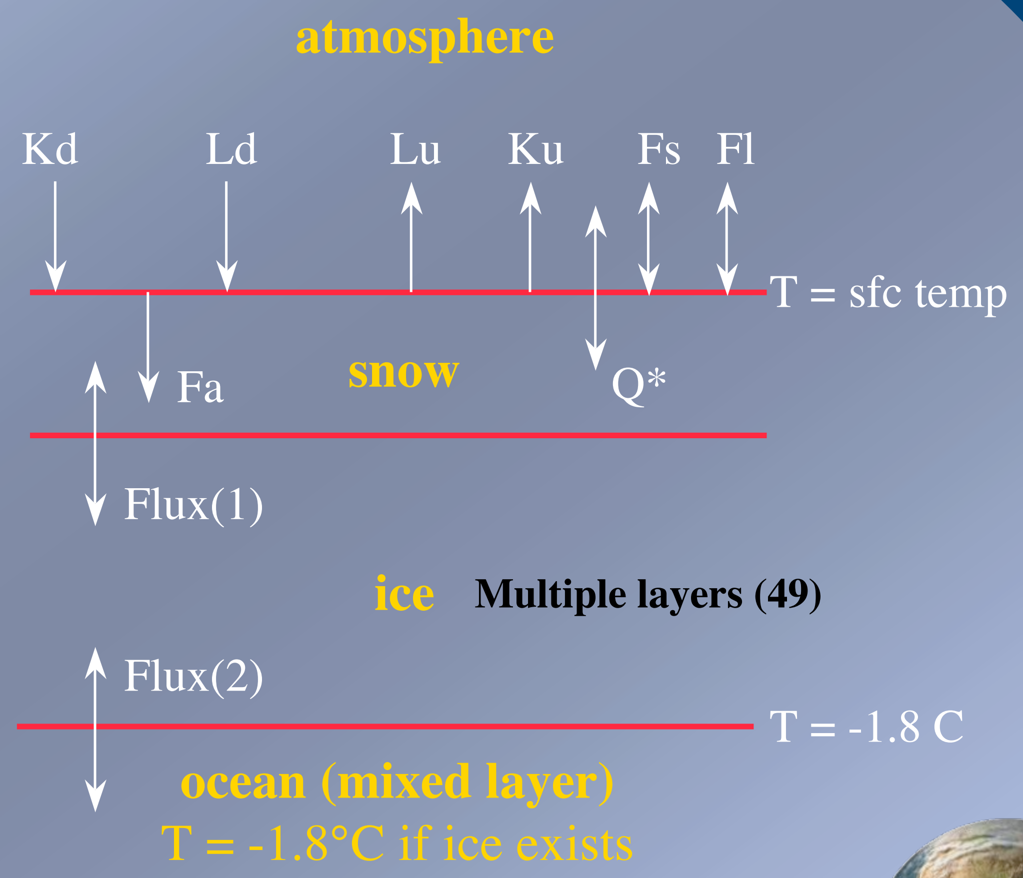
Sea Ice Modeled Processes

Sfc nrg balance

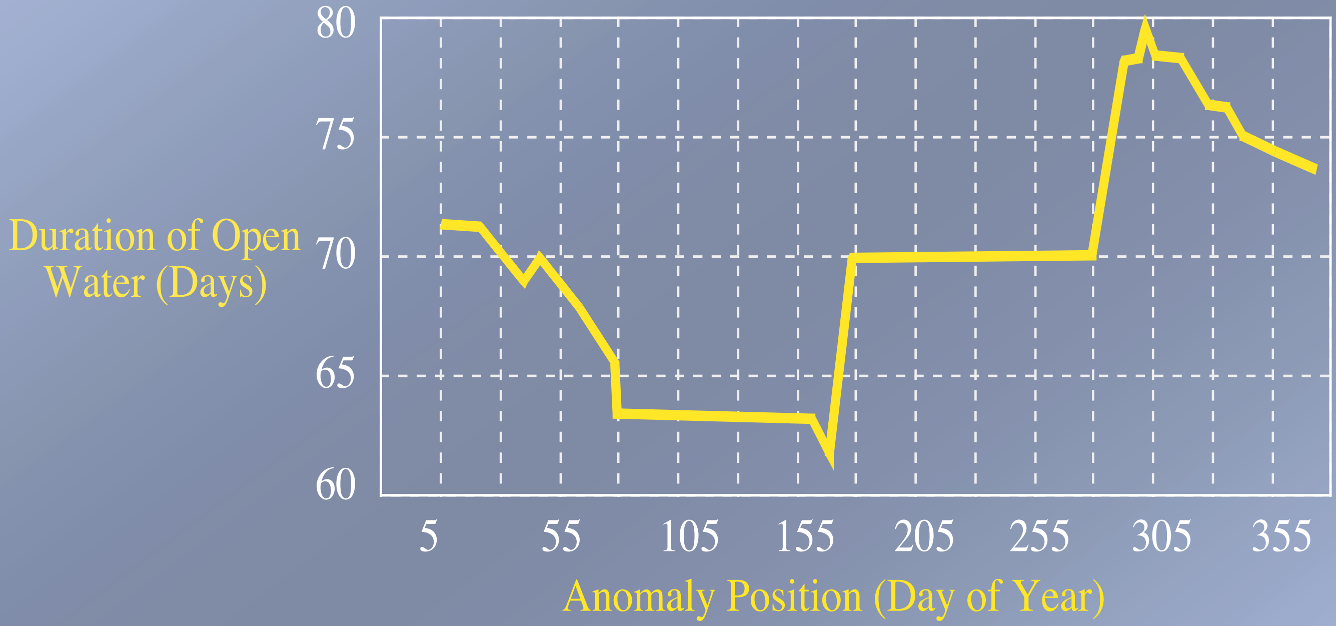
Kd = downwelling SW flux
Ku = upwelling SW flux
Fa = absorbed SW flux
Ld = downwelling LW flux
Lu = upwelling LW flux
Fs = sensible heat flux
Fl = latent heat flux
Q* = net sfc flux

Conductive fluxes

Flux(1)=snow-ice conductive flux
Flux(2)=ice-ocean conductive flux

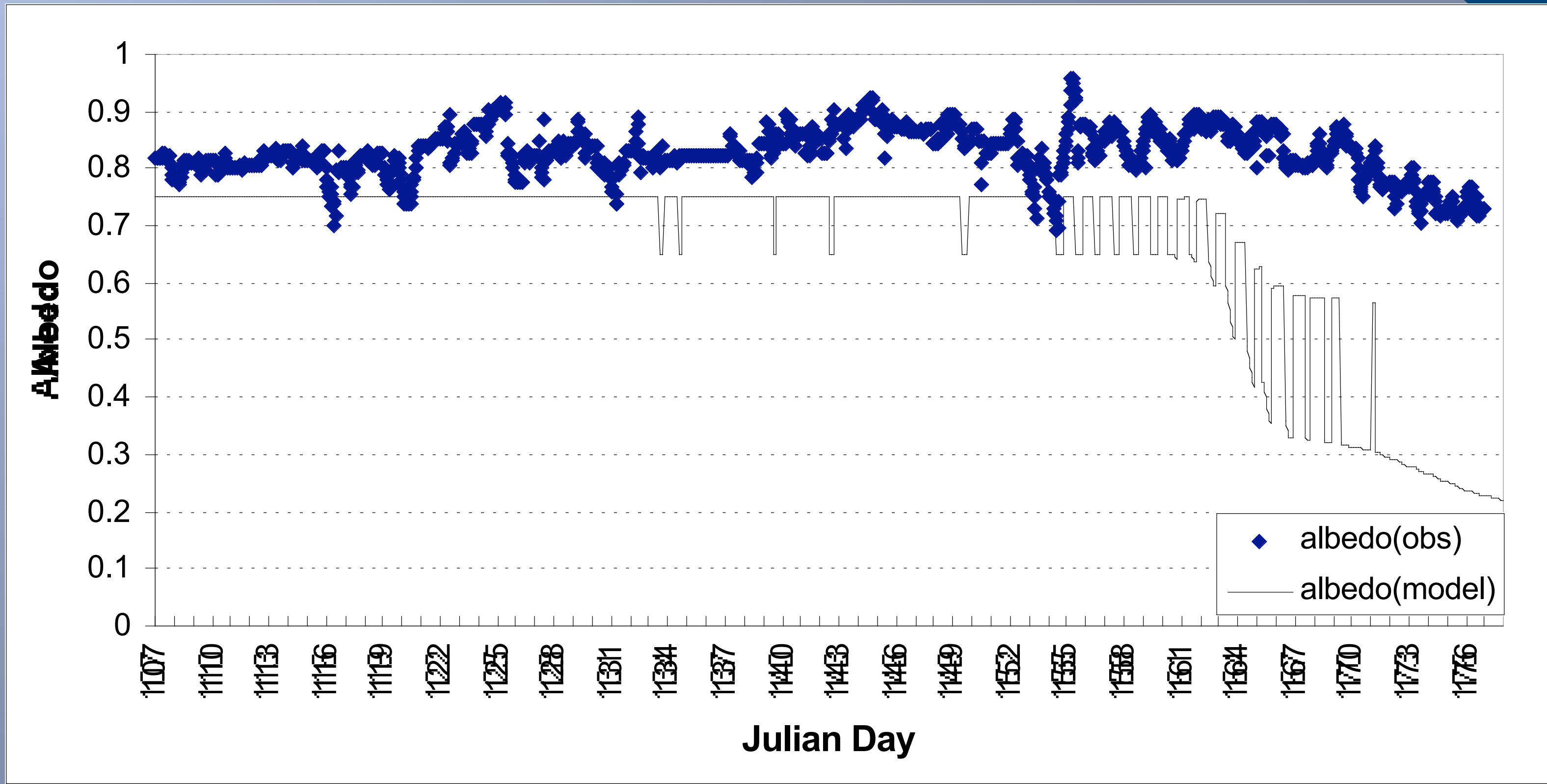


Role of snow in complexity

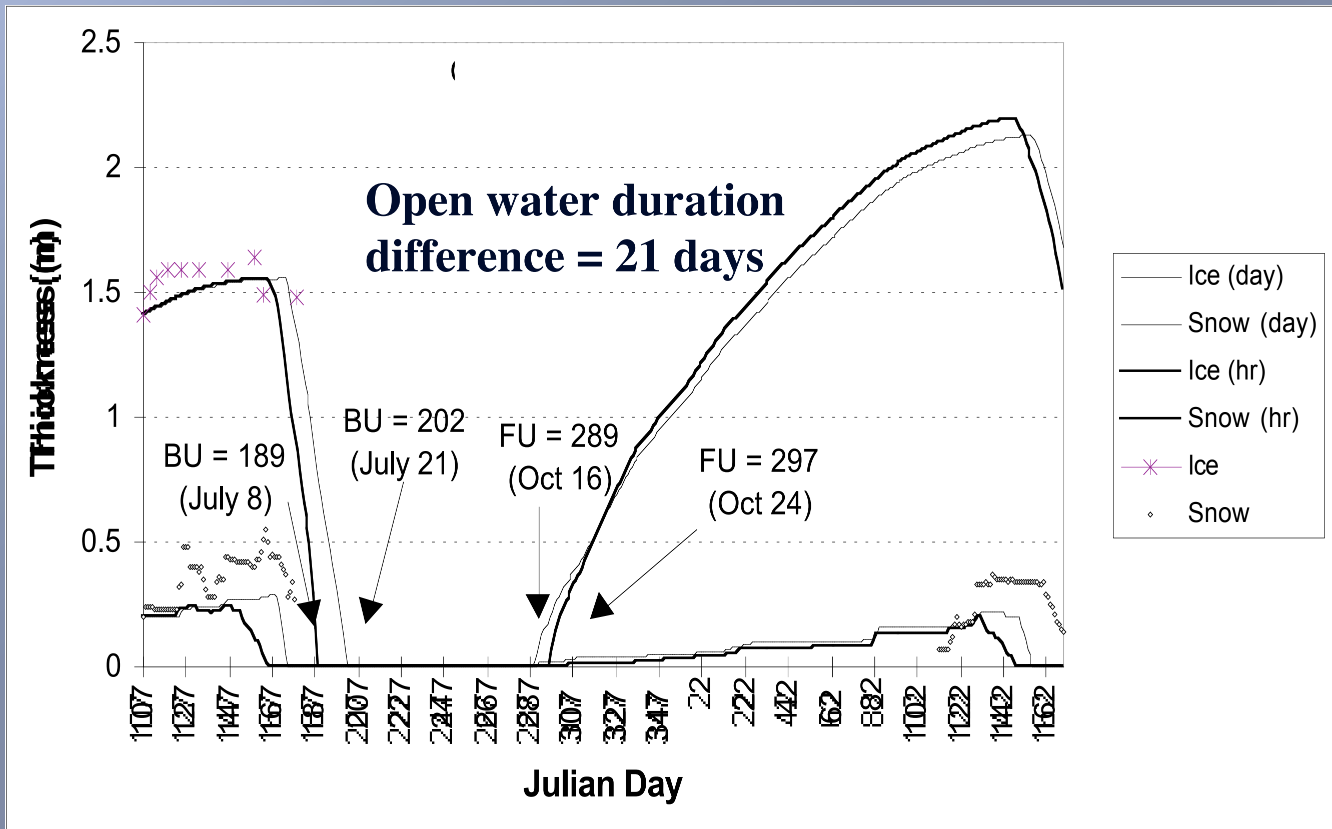


Effect of Moving a 5 day (20cm) Snowfall Anomaly on Open Water Duration (model run 1961-1990).

Modeled vs. Observed Albedo

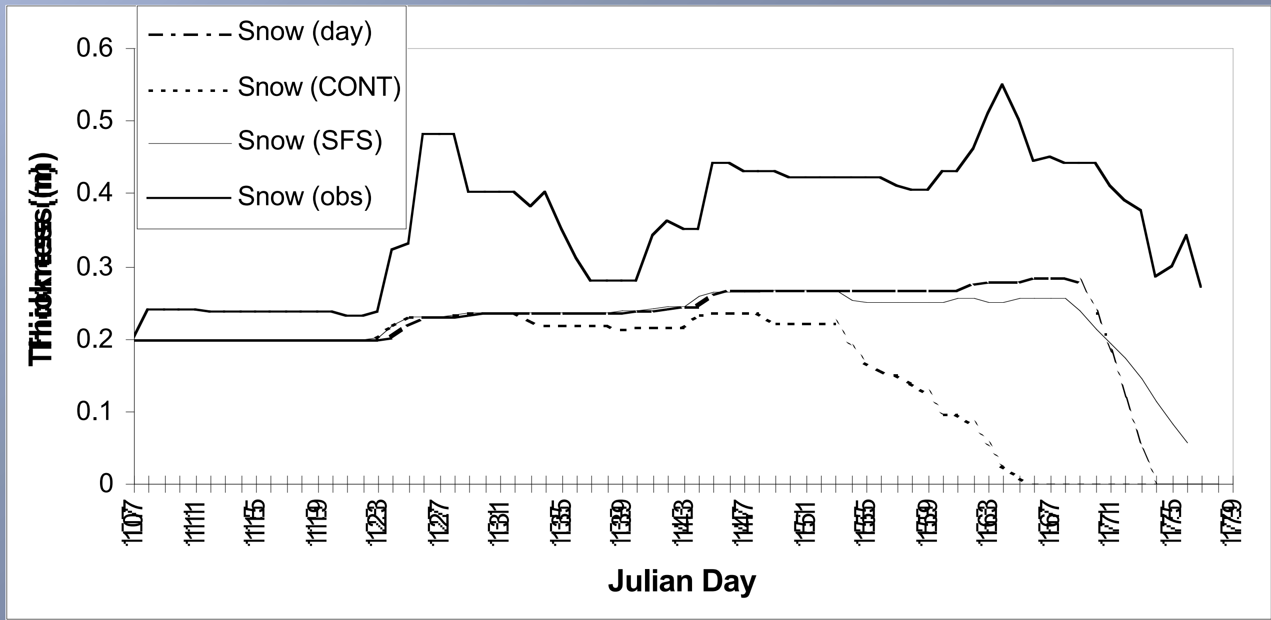


Hourly vs. Daily Forcing



Simulation: April 17, 1992 - June 19, 1993

Bias of ‘land based’ versus ‘on ice’ forcing



	Q*	Q*	Tsfc	Tsfc
	CONT/obs	SFS/obs	CONT/obs	SFS/obs
R-Square	0.44	0.56	0.91	0.98
Mean Error	-2.5	-2	2.5	-0.08
St. Dev.	30	25	3.1	1.7

Hanesiak et al.

SFS more realistic snow & ice ablation

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Conclusions

Conclusions

1. Need to know geophysics and thermodynamics to determine scattering and response to forcing
2. Dynamic vs Thermodynamic processes are NB
3. Many feedbacks exist and processes are not yet well understood (and thus not modelled).
4. System is very sensitive to changes in snow thickness, distribution and deposition (timing of sea ice formation is critical)
5. Assumptions of current processes applicable to the future