Sea Ice, Climate Change and Remote Sensing

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Lecture outline

1) Arctic Climate Change and Remote Sensing

2) Geophysics, dielectrics and thermodynamics

3) Scattering and emission modeling

Outline of this talk

- The Electro-thermophysical concept
- The complex dielectric constant
- Scattering and emission models
- A few examples
- Conclusions

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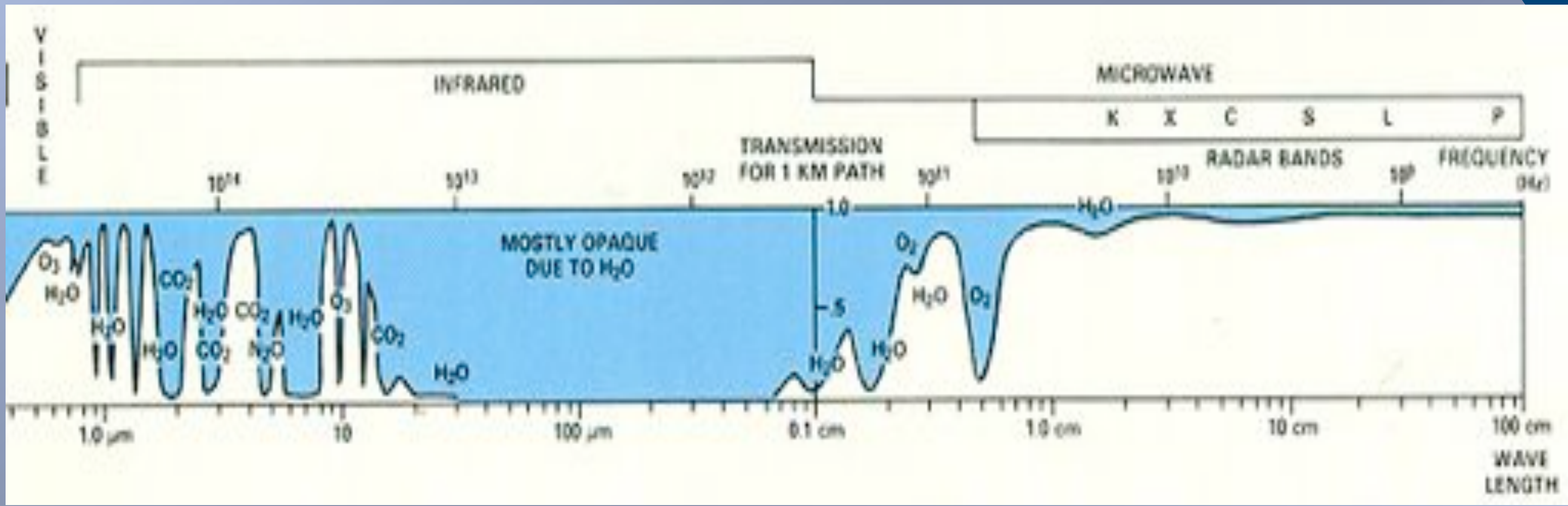
Three key features of the Arctic:

1) it is cold
2) it is dark
3) it is cloudy
4) it is changing

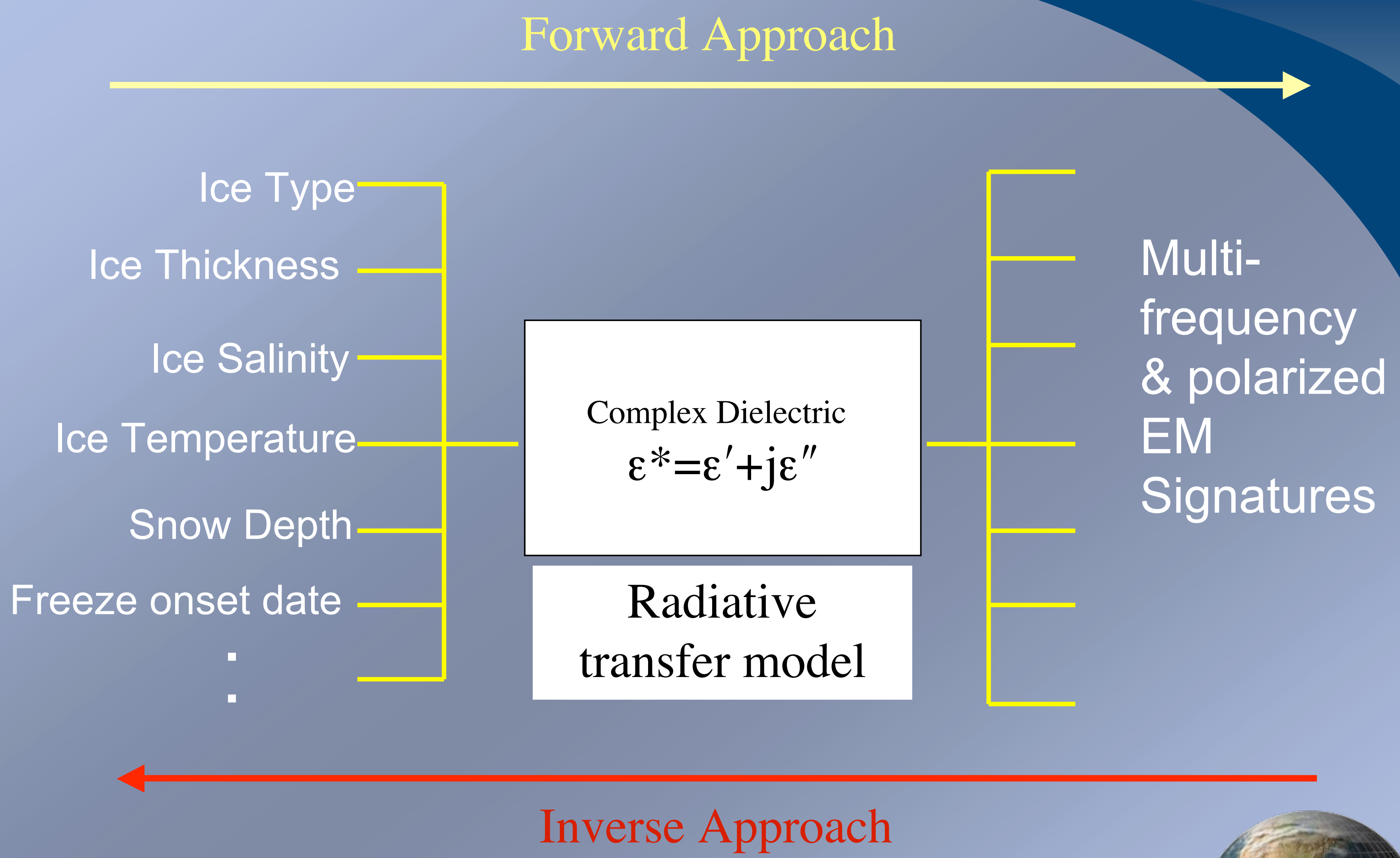
The Electro-thermophysical concept

Atmospheric Transmission and EMI



Review of Sea Ice Microwave Scattering Theory

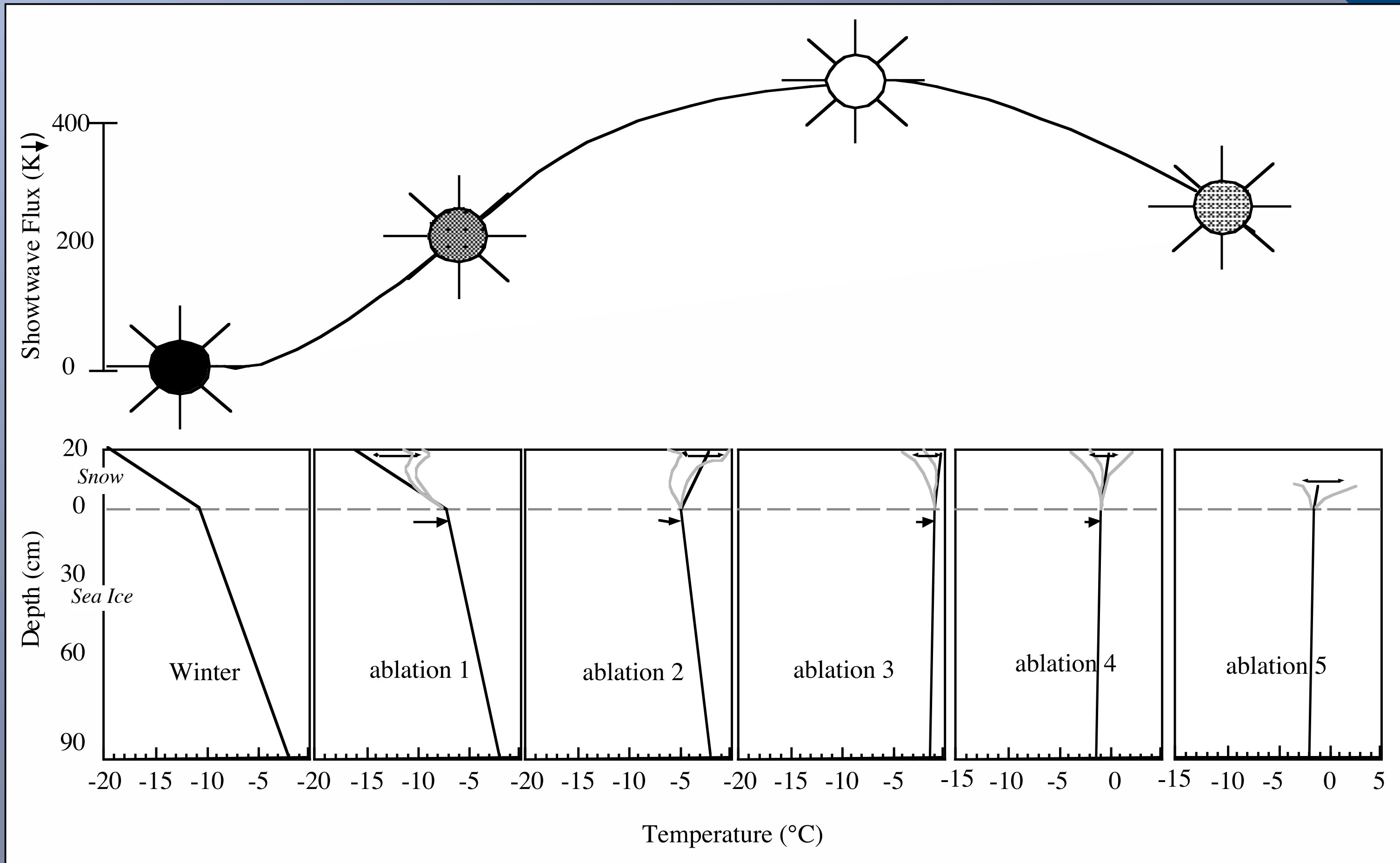
- Microwave scattering from Sea Ice is controlled by three factors:
  - 1) The Complex Dielectric Constant
  - 2) The inhomogeneities of Scattering Inclusions
  - 3) The Frequency, Polarization and Sensor Geometry of the SAR



The electromagnetic properties of sea ice

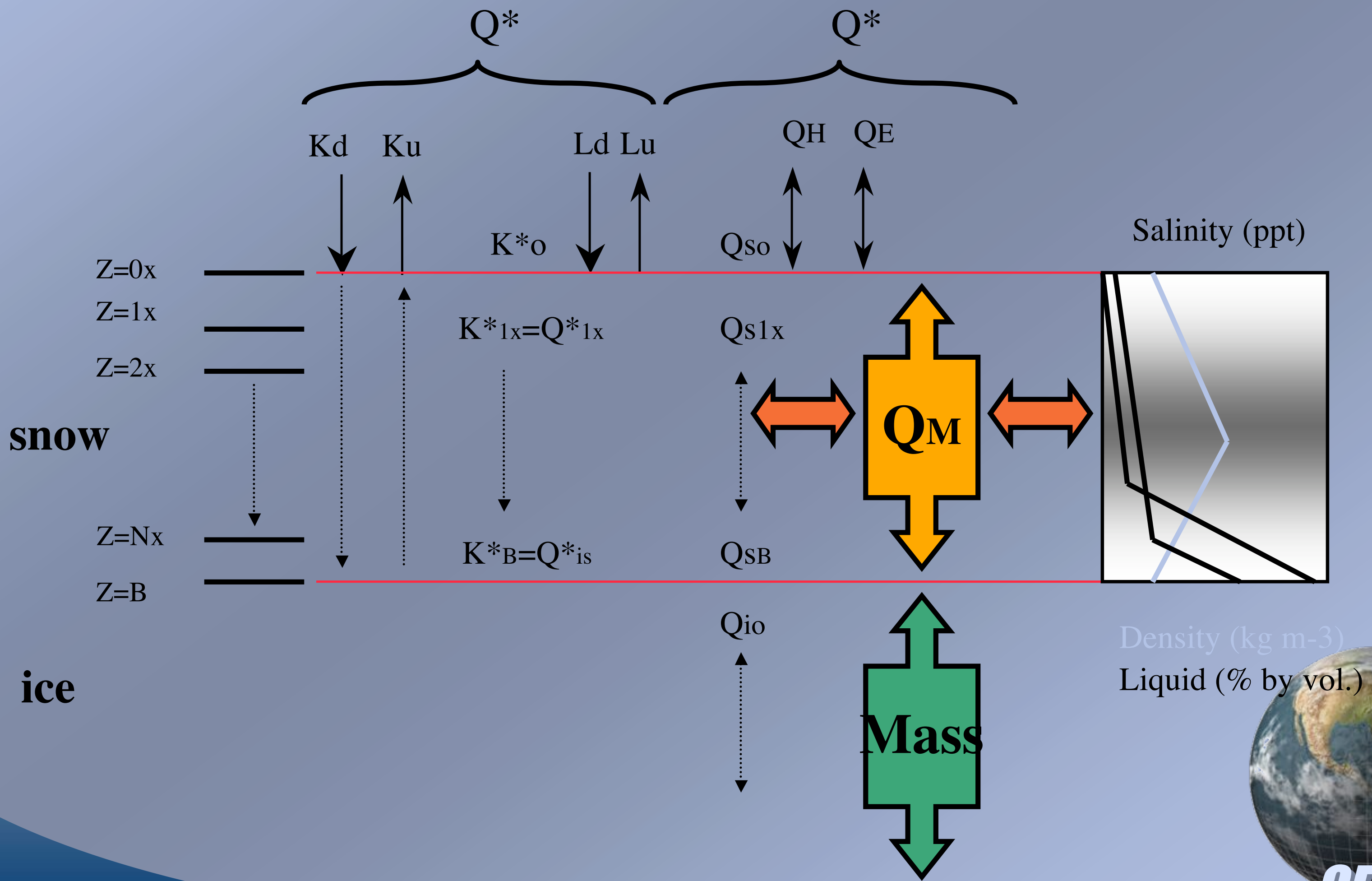
IEEE TGARS, ONR ARI special issue. 36(5): 1750-1763

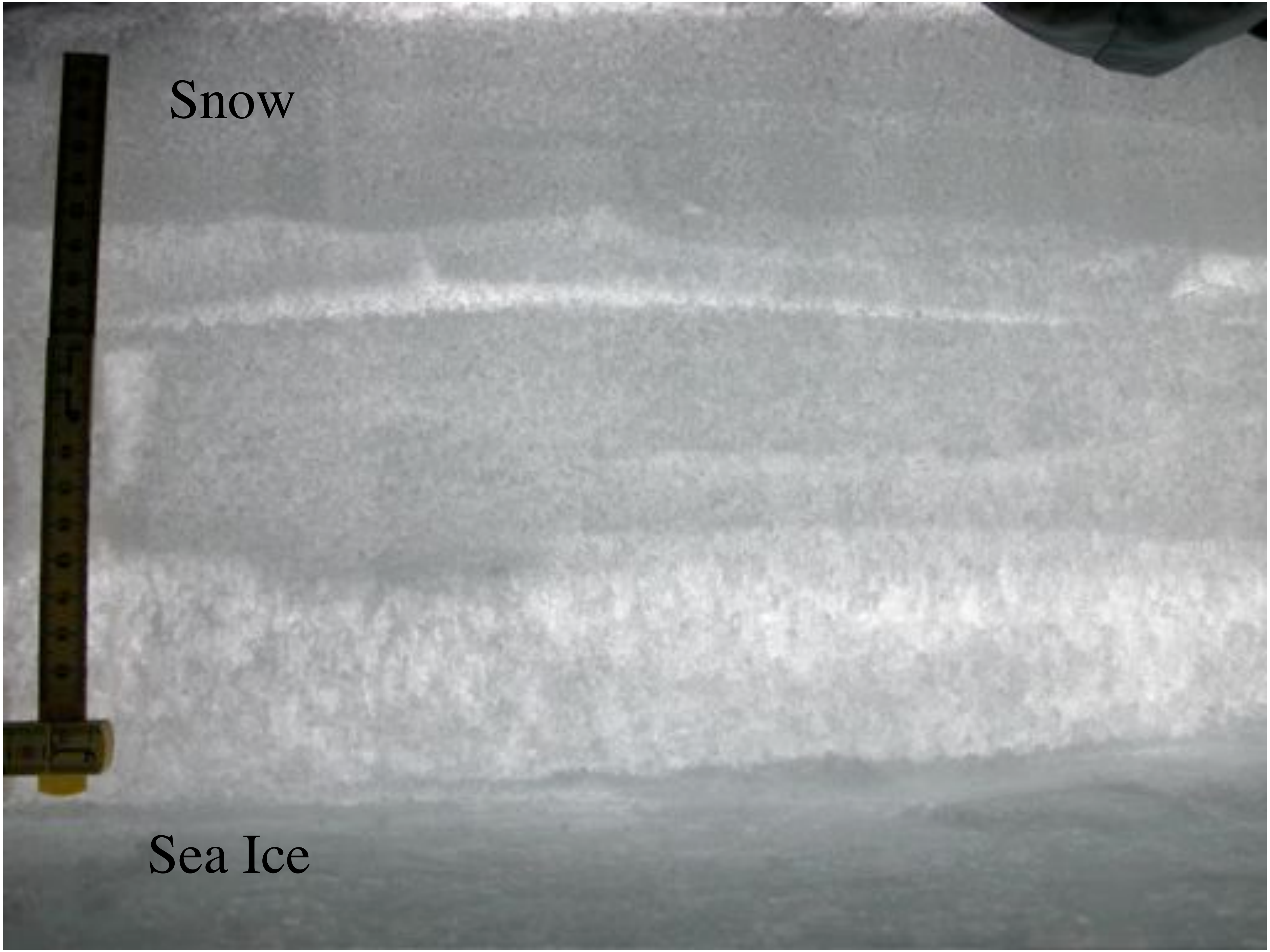
Temperature is the control

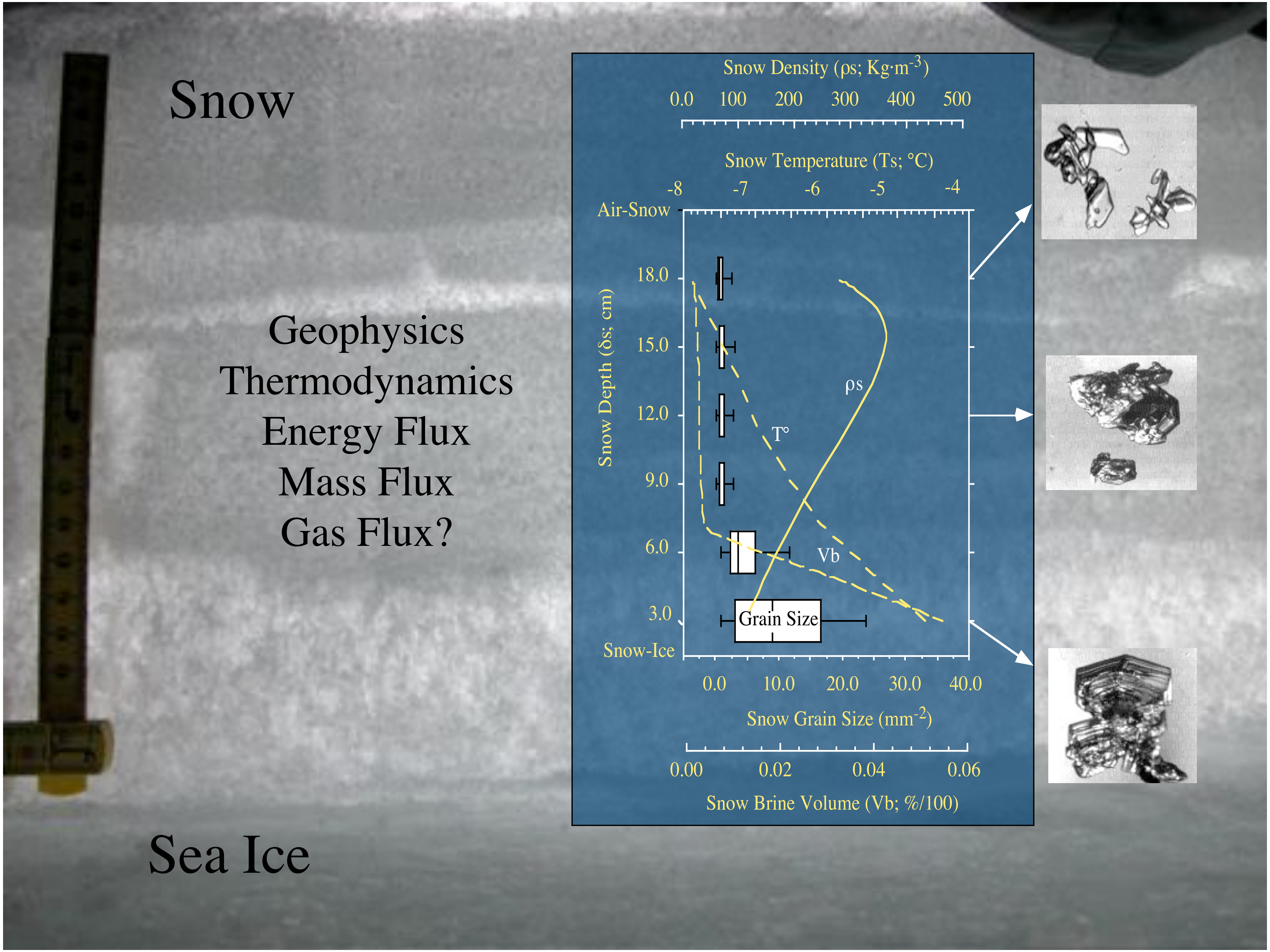


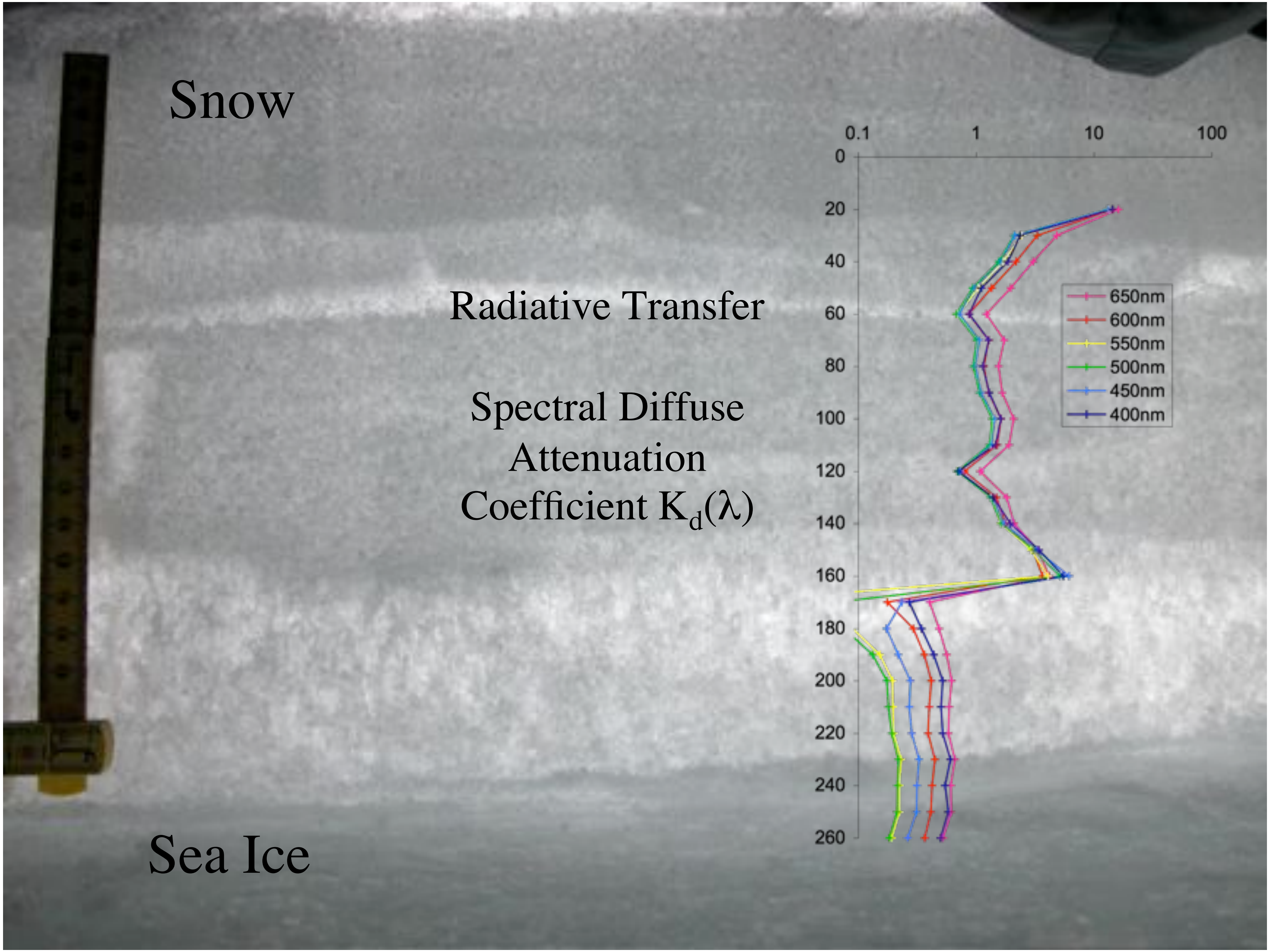
Barber et al. 1998

An electro-thermophysical model of snow covered sea ice

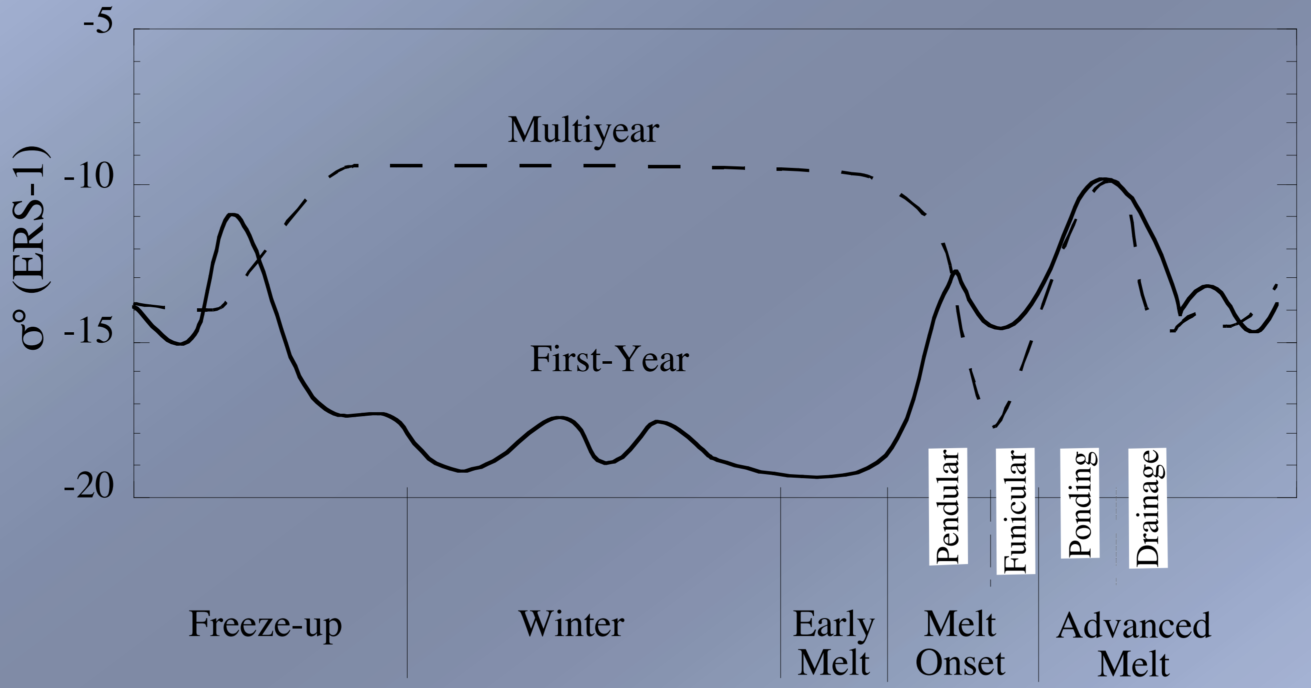



Snow
Sea Ice

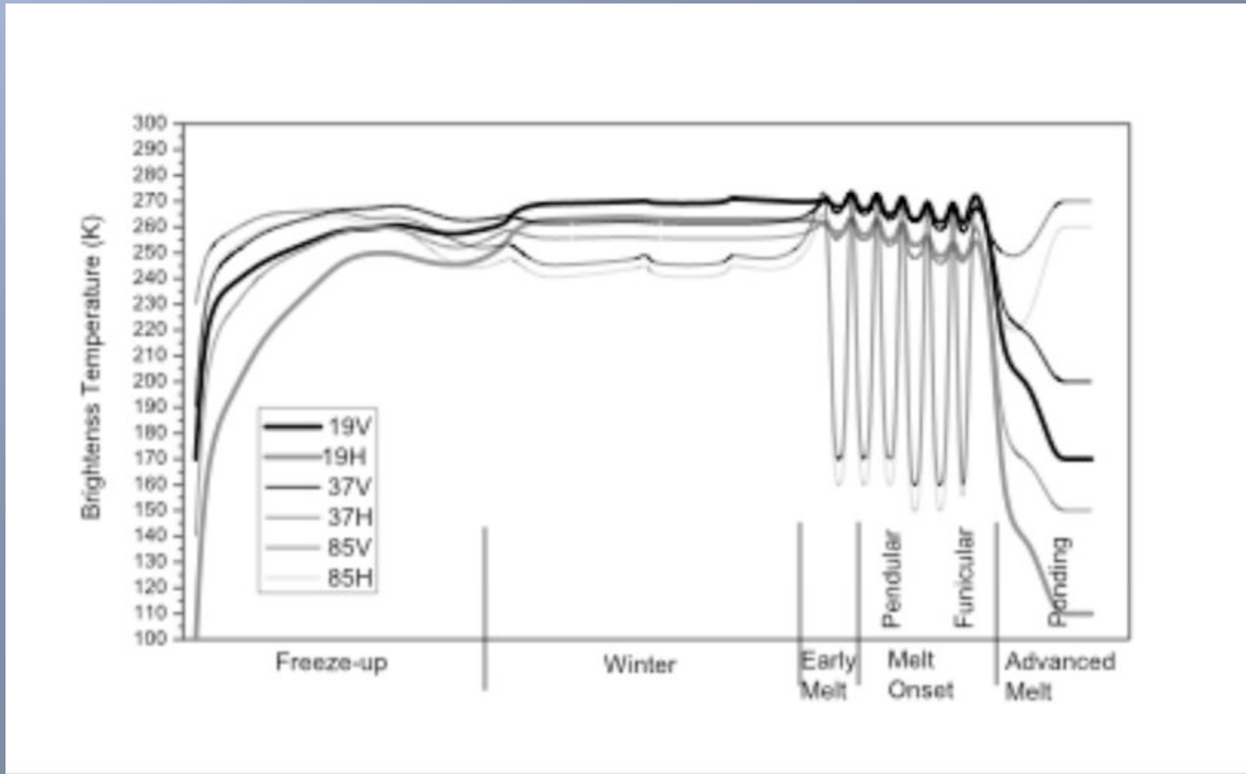

Snow
Geophysics
Thermodynamics
Energy Flux
Mass Flux
Gas Flux?
Sea Ice
Snow Density (ρs; Kg·m-3)
0.0 100 200 300 400 500
Snow Temperature (Ts; °C)
-8 -7 -6 -5 -4
Air-Snow
Snow Depth (δs; cm)
18.0
15.0
12.0
9.0
6.0
3.0
Snow-Ice
ρs
T°
Vb
Grain Size
0.0 10.0 20.0 30.0 40.0
Snow Grain Size (mm-2)
0.00 0.02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


Snow
Radiative Transfer
Spectral Diffuse
Attenuation
Coefficient $K_d(\lambda)$
0.1
1
10
100
0
20
40
60
80
100
120
140
160
180
200
220
240
260
650nm
600nm
550nm
500nm
450nm
400nm
Sea Ice

The Temporal Evolution of σ°



The Temporal Evolution of T_b



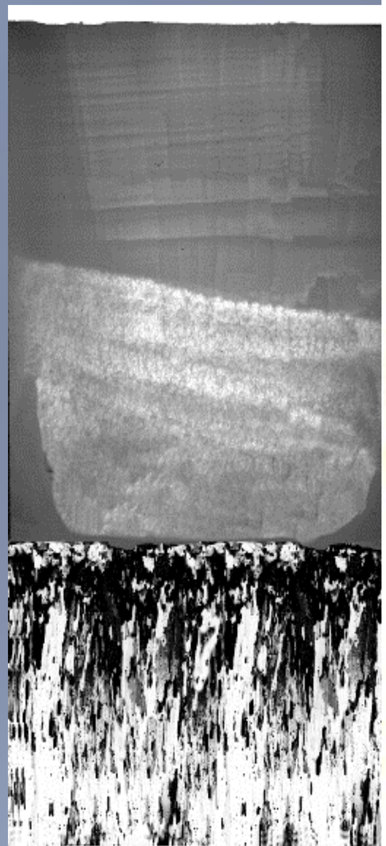
Coupled sea Ice thermophysical and dielectrics model.

- The complex dielectric constant is defined as:

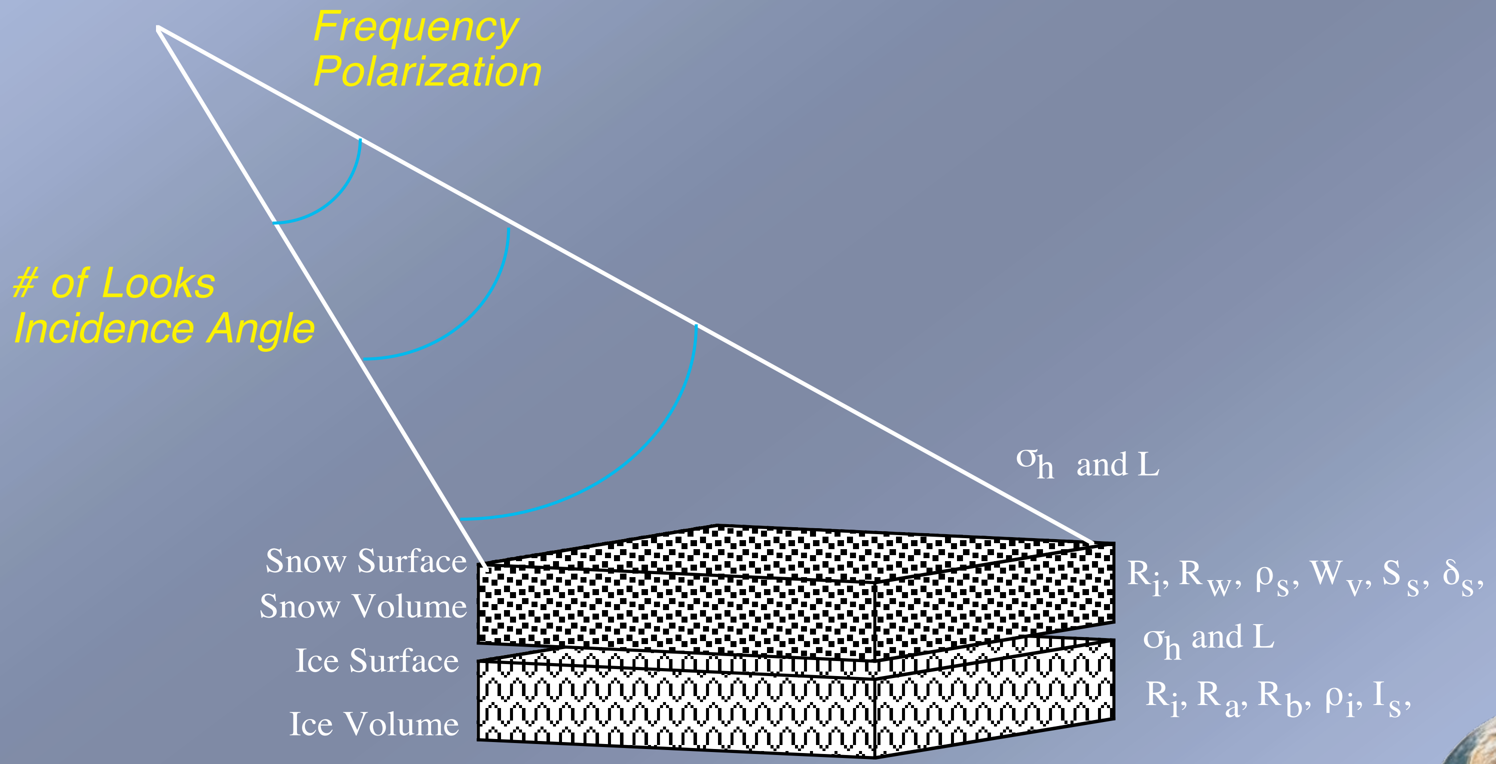
$\varepsilon^* = \varepsilon' + j\varepsilon''$

ε' is the permittivity

ε'' is the loss



Frequency/Polarization and Sensor Geometry



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

The dielectric constant

The Complex Dielectric Constant

- The complex dielectric constant consists of a complex number

$\varepsilon^* = \varepsilon' + j\varepsilon''$

ε' is the permittivity

ε'' is the loss

The Complex Dielectric Constant

$$\varepsilon'_w = \varepsilon_{w\infty} + \frac{\varepsilon_{w0} - \varepsilon_{w\infty}}{1 + (2\pi f \tau_w)^2} \qquad \varepsilon''_w = \frac{2\pi f \tau_w (\varepsilon_{w0} - \varepsilon_{w\infty})}{1 + (2\pi f \tau_w)^2}$$

$$\varepsilon_{w0}(T) = 88.045 - 0.4147T + 6.295\times10^{-4}T^2 + 1.075\times10^{-5}T^3$$

$$2\pi\tau_w(T) = 1.1109\times10^{-10} - 3.824\times10^{-12}T + 6.938\times10^{-14}T^2 - 5.096\times10^{-6}T^3$$

where ε_{w0} is static dielectric constant of pure water, $\varepsilon_{w\infty}$ is high-frequency (or optical) limit of ε_w ($\varepsilon_{w\infty} = 4.9$) , τ_w is relaxation time of pure water (s); f is electromagnetic frequency (Hz).

The Debye Model - Water

The Complex Dielectric Constant

$$\varepsilon_b' = \varepsilon_{w\infty} + \frac{\varepsilon_{b0} - \varepsilon_{w\infty}}{1 + (2\pi f \tau_b)^2} \qquad \varepsilon_b'' = \frac{2\pi f \tau_b (\varepsilon_{b0} - \varepsilon_{w\infty})}{1 + (2\pi f \tau_b)^2} + \frac{\sigma_b}{2\pi \varepsilon_0 f}$$

$$\varepsilon_{b0} = \frac{(939.66 - 19.068T)}{(10.737 - T)} \qquad \varepsilon_\infty = \frac{(82.79 + 8.19T^2)}{(15.68 + T^2)}$$

$$2\pi\tau = 0.10990 + 0.13603 \times 10^{-2} T + 0.20894 \times 10^{-3} T^2 + 0.28167 \times 10^{-5} T^3$$

The Debye Model - Brine

Dielectric Mixture Models

$$\varepsilon_{ds} = 1 + 3\varepsilon_{ds} v_i \left(\frac{\varepsilon_i - 1}{\varepsilon_i + 2\varepsilon_{ds}} \right)$$

Dry snow

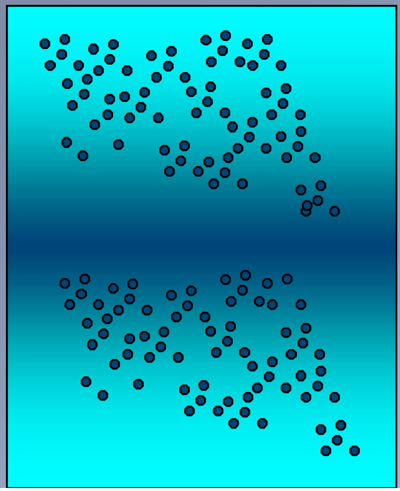
$$\varepsilon_{ws} = \varepsilon_{ds} + \frac{m_v \varepsilon_{ws}}{3} (\varepsilon_w - \varepsilon_{ds}) \sum_{i=1}^{3} [\varepsilon_{ws} + (\varepsilon_w - \varepsilon_{ws}) N_i]^{-1}$$

Wet snow

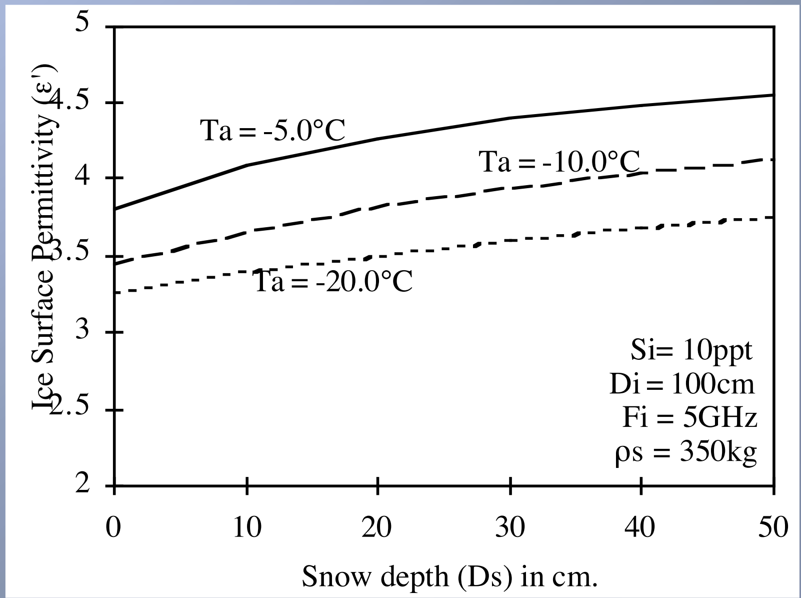
$$\varepsilon_{si} = \varepsilon_i + \frac{3\varepsilon_{si} f_a (1 - \varepsilon_i)}{2\varepsilon_{si} + 1} + \frac{\varepsilon_{si} f_b (\varepsilon_b - \varepsilon_i)}{3} \left[\frac{1}{\varepsilon_{si}(1 - N_i) + N_i \varepsilon_b} + \frac{1}{\varepsilon_{si}(1 + N_1) + \varepsilon_b (1 - N_1)} \right]$$

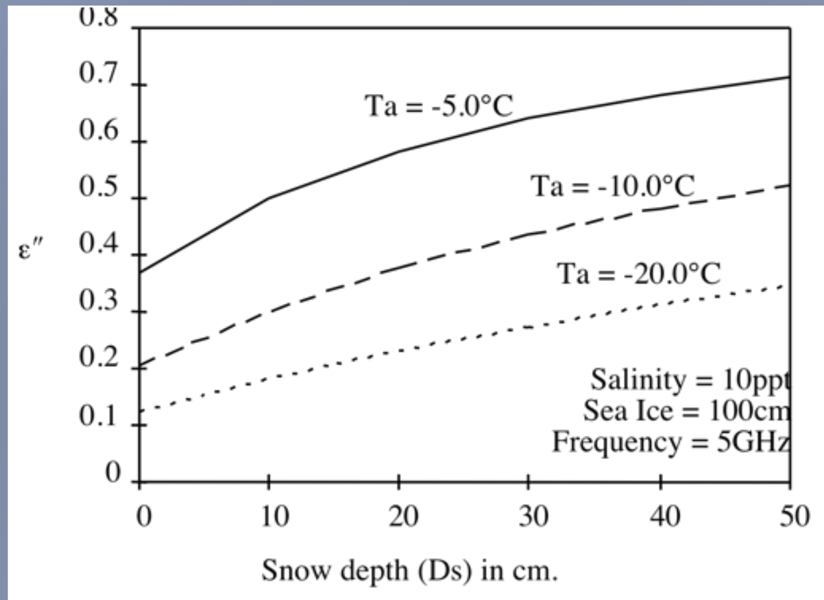
Sea Ice

Inclusion dielectric
in an air
background



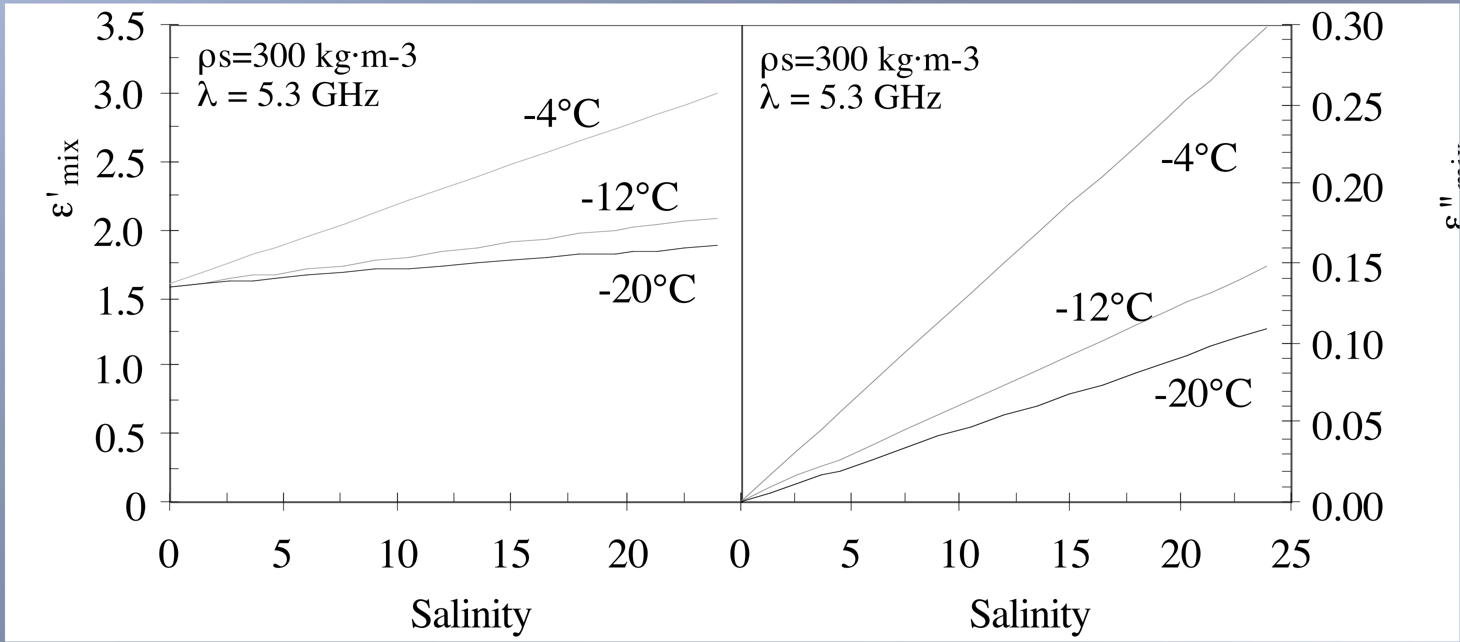
Dielectric Mixture Models





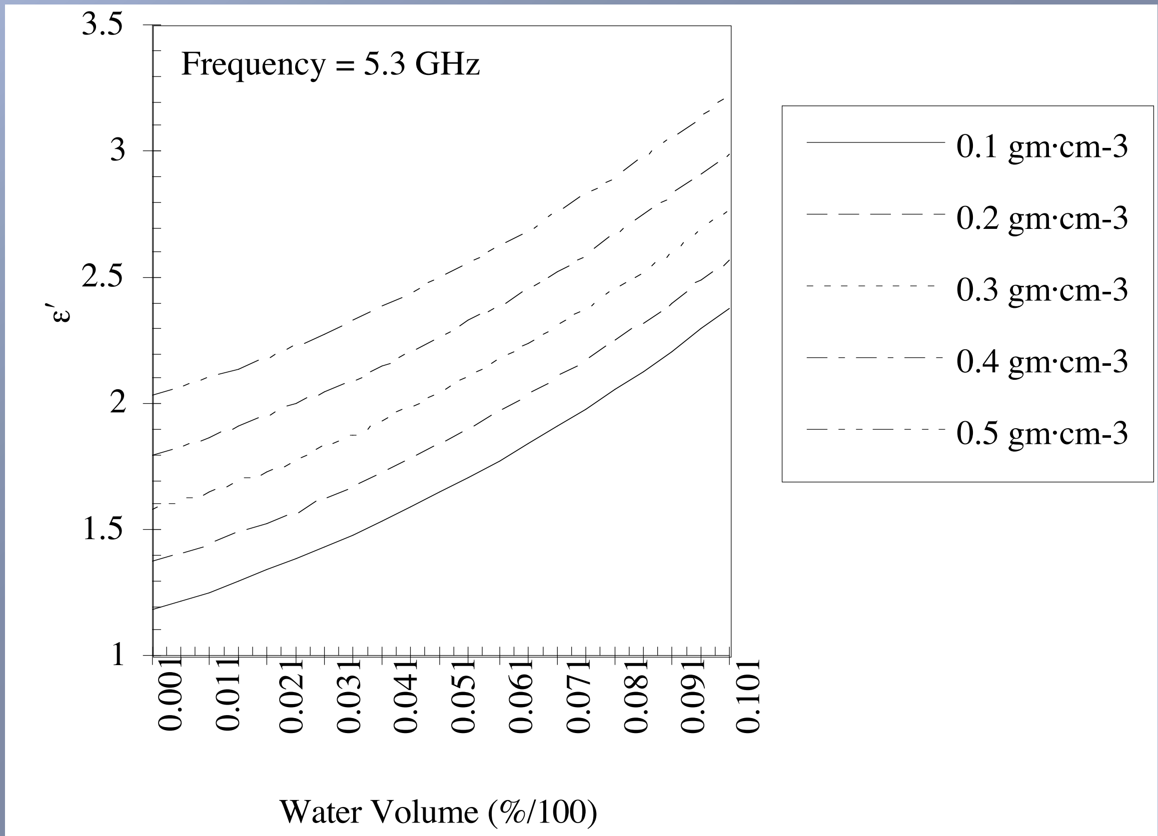
Change in ε′ *and* ε′′ at the sea ice surface as a function of air temperature and snow thickness.

Dielectric Mixture Models



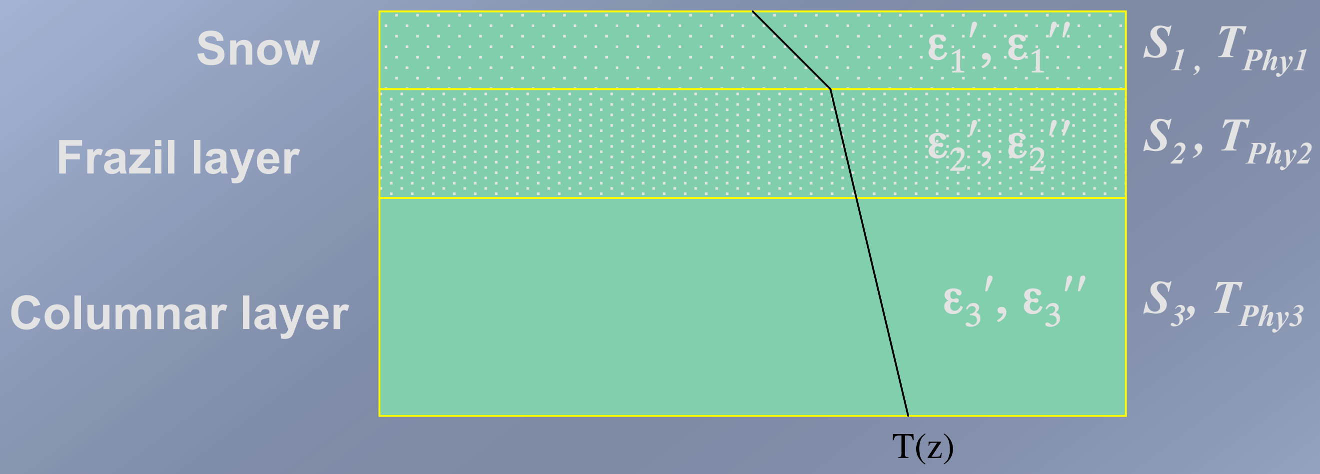
Modeled permittivity () and loss () as a function of snow salinity and snow temperatures.

Dielectric Mixture Models



Bulk dielectric permittivity (ε′) of snow as a function of water volume and snow density

Link between dielectrics and scattering/emission



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

Layer properties defined by the Fresnel reflection (Γ) coefficient

Scattering & Emission Models

Classes of Models

Multi-layer reflection

Multilayer Fresnel formula

- No scattering effects
- Applicable only to Young saline ice

Reflection-volume signature

Many layer SFT

- Scattering effects to some extent
- Applicable to Young saline ice, frozen melt ponds (up to 40 GHz)
- bubbly ice (up to 20 GHz)

Volume scattering

Rayleigh scattering
DMRT
DMT

- No reflection effects
- Poor agreements (at H-pol) over young ice, frozen melt ponds
- Bubbly ice up to 19 GHz

Numerical method
Empirical method

- Good potential
- Backscattering problem
- Snow application

Integrated surface-volume signature model

DMT-integration model

- No significant improvement from DMT
- This indicated no significant rough surface scattering effects

Rough surface scattering

PS
GO
SP
Integration

DMRT; Dense Medium Radiative Transfer; DMT: Dense Medium Theory, PS: physical optics under the scalar approximation, GO: geometric optics approximation, SP: small perturbation method

(Winebrenner et al., 1992; Nassar et al., 2000; Wiesmann and Matzler, 1999)

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Emission/Scattering Theory

$$R_s = \frac{1}{4\pi}\int[\varphi_{ah}(k_o,k)+\varphi_{av}(k_o,k)]\sin\theta d\theta d\phi$$

Backscattering

$$\sigma^\circ(k_o) = \sigma^\circ_{ss} + T^2(k_o)\sigma^\circ_{sv} + T^2(k_o)\sigma^\circ_s$$

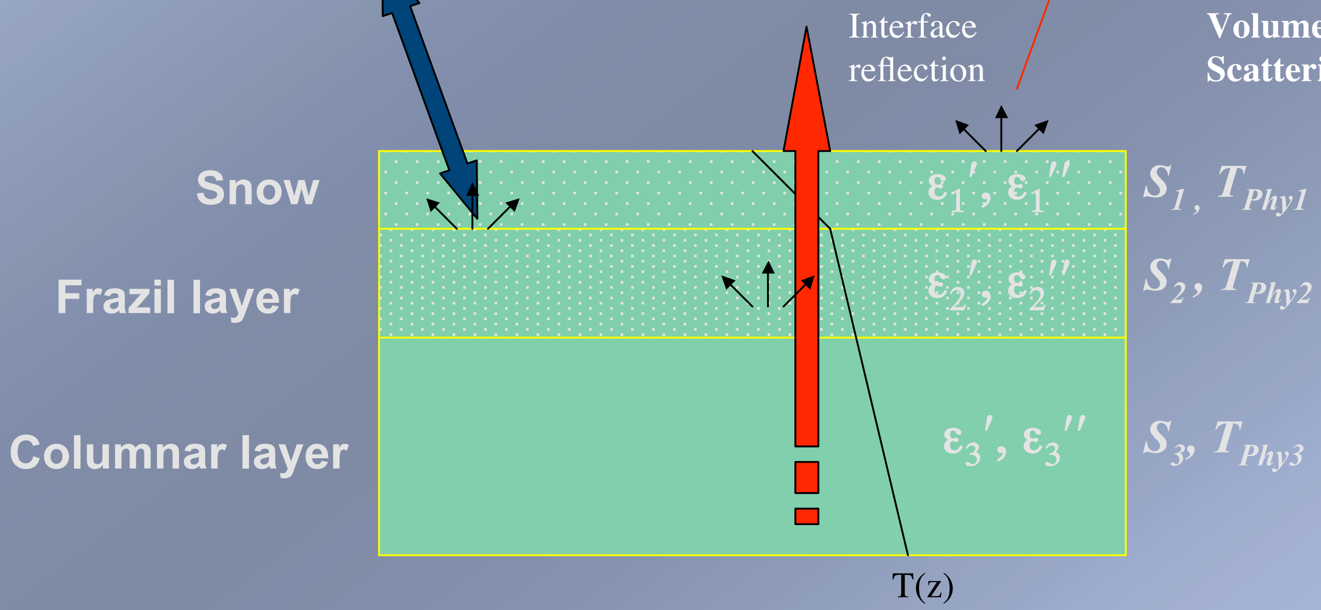
snow surface | snow volume | **Snow/sea ice interface**

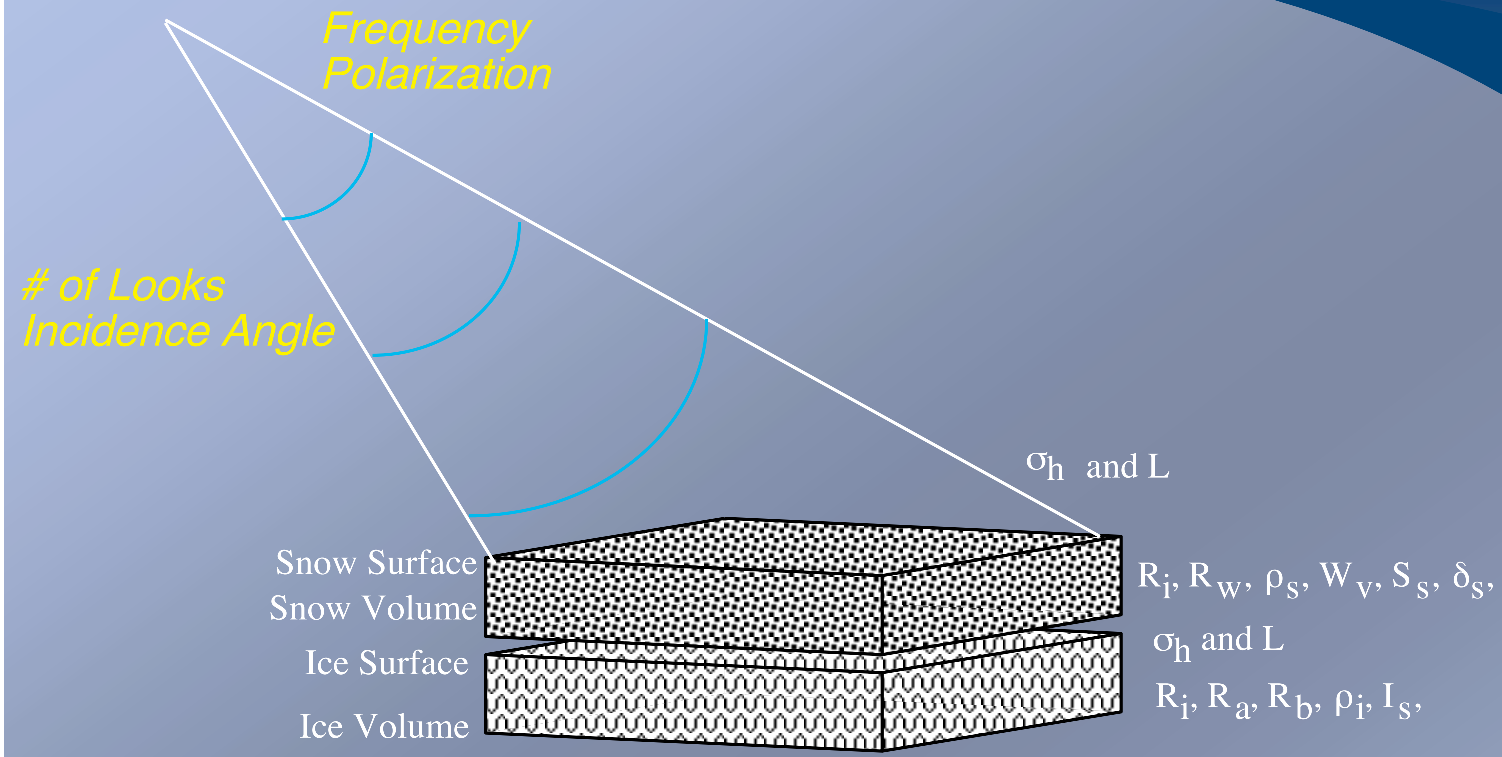
Emission

$$T_a(k_0,0) = \varepsilon_a(k_0)T_{si}$$

$$\varepsilon_a(k_0) = 1 - |R|^2 - \frac{1}{4\pi}\int[\gamma_{ah}(k_0,k)+\gamma_{av}(k_0,k)]\sin\theta d\theta d\phi$$

Interface reflection | **Volume Scattering loss**



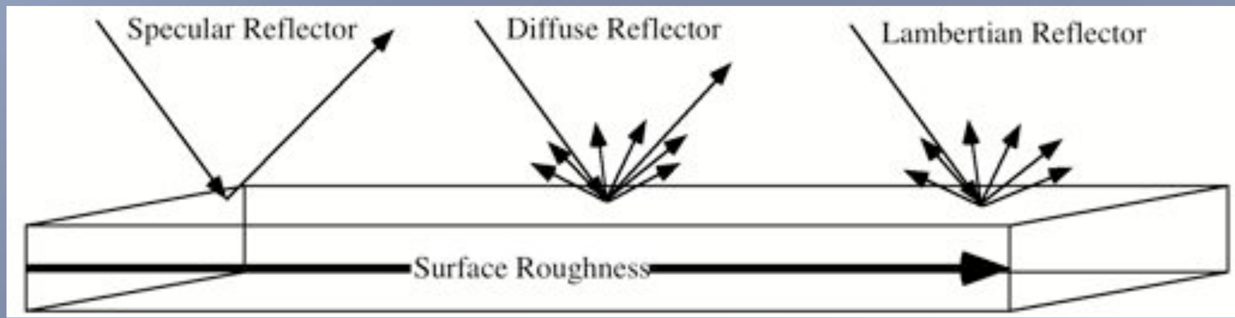


$$\sigma^{\circ}_{total} = \sigma^{\circ}_{ss} + \Psi_{as}(\theta) * \sigma^{\circ}_{sv}(\theta') + \Psi_{s}(\theta') * \sigma^{\circ}_{is} + \Psi_{si}(\theta'') * \sigma^{\circ}_{iv}(\theta'')$$

Forward scattering model defined for Microwave Scattering

physical optics/geometric optics

- Surface Scattering

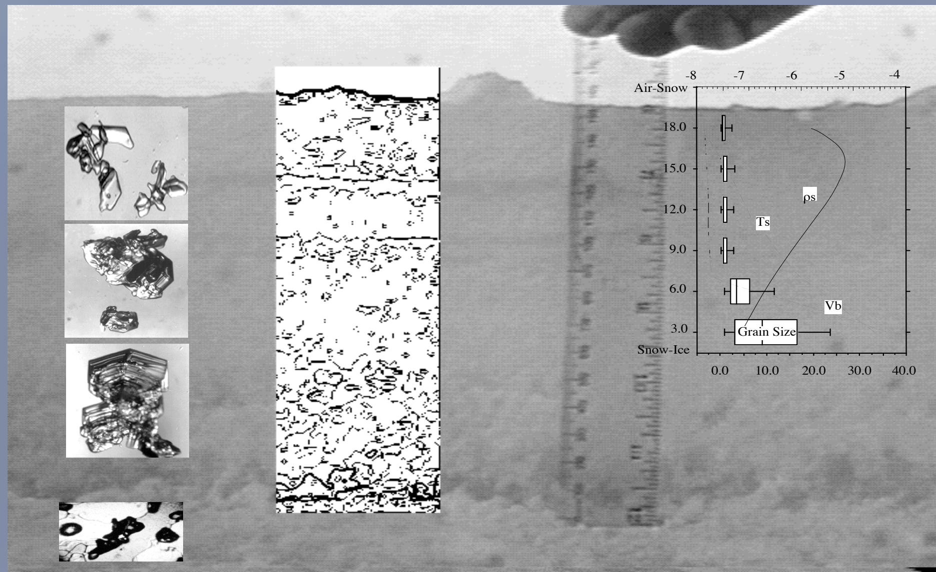


$$\sigma < \frac{\lambda}{32\cos\theta}$$

RMS height
Correlation length

Volume scattering

Number density
Volume fraction
Scattering physics



Surface Scattering

$$\sigma^o_s(\theta) = 2\,|\Gamma_{HH}|^2 \cos^2\theta \, \exp(-4\,K_o^2\,\sigma^2\cos^2\theta)$$

$$\cdot \sum_{n=1}^{\infty} \frac{(4K_o^2\,\sigma^2\cos^2\theta)^n}{n!} \cdot \frac{(K_o^2\, n / l)}{(4K_o^2\sin^2\theta + n^2/l^2)^{3/2}}$$

Where:

$$\Gamma_{HH} = \frac{\xi_2 \text{ x } \cos\theta - \xi_1 \text{ x } \cos\theta'}{\xi_2 \text{ x } \cos\theta + \xi_1 \text{ x } \cos\theta'}$$

$$\xi_1 = \frac{1}{\sqrt[2]{\varepsilon' + \varepsilon''}},$$ for material #1 (air)

Forward scattering model defined for Microwave Scattering

Volume Scattering

$$\sigma^{o}_{sv}(\theta) = \frac{\sigma_v \cos\theta'}{2K_e}\left(1 - \frac{1}{(\exp(K_e d \sec(\theta')))^2}\right)$$

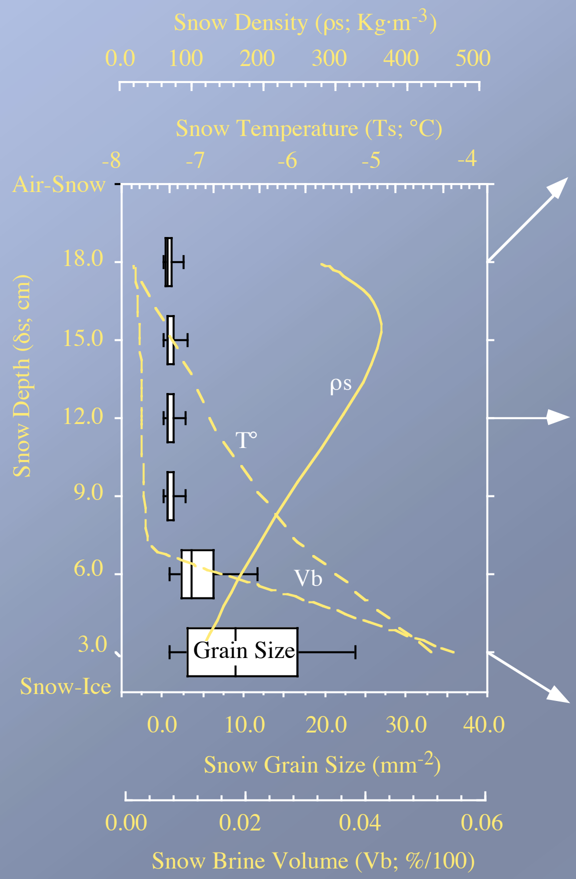
Where:

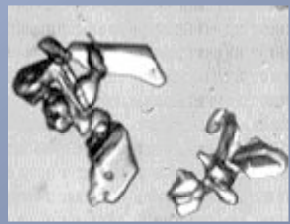
$$\sigma_v = N_i\,\sigma_{b_i} + N_w\,\sigma_{b_w}$$

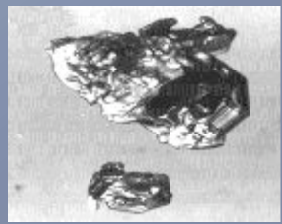
$$\sigma_b = \frac{64\,\pi^5\,r^6}{\lambda_o^4}\,|K|^2$$

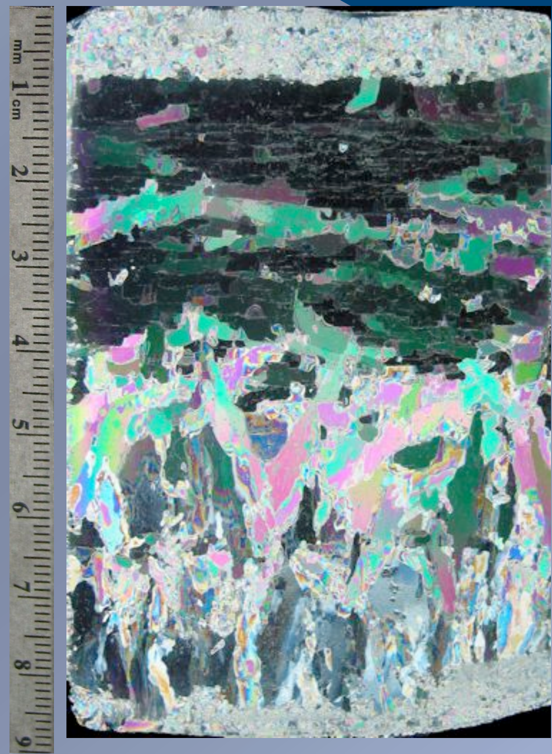
Forward scattering model defined for Microwave Scattering

Features in the mm range affect scattering

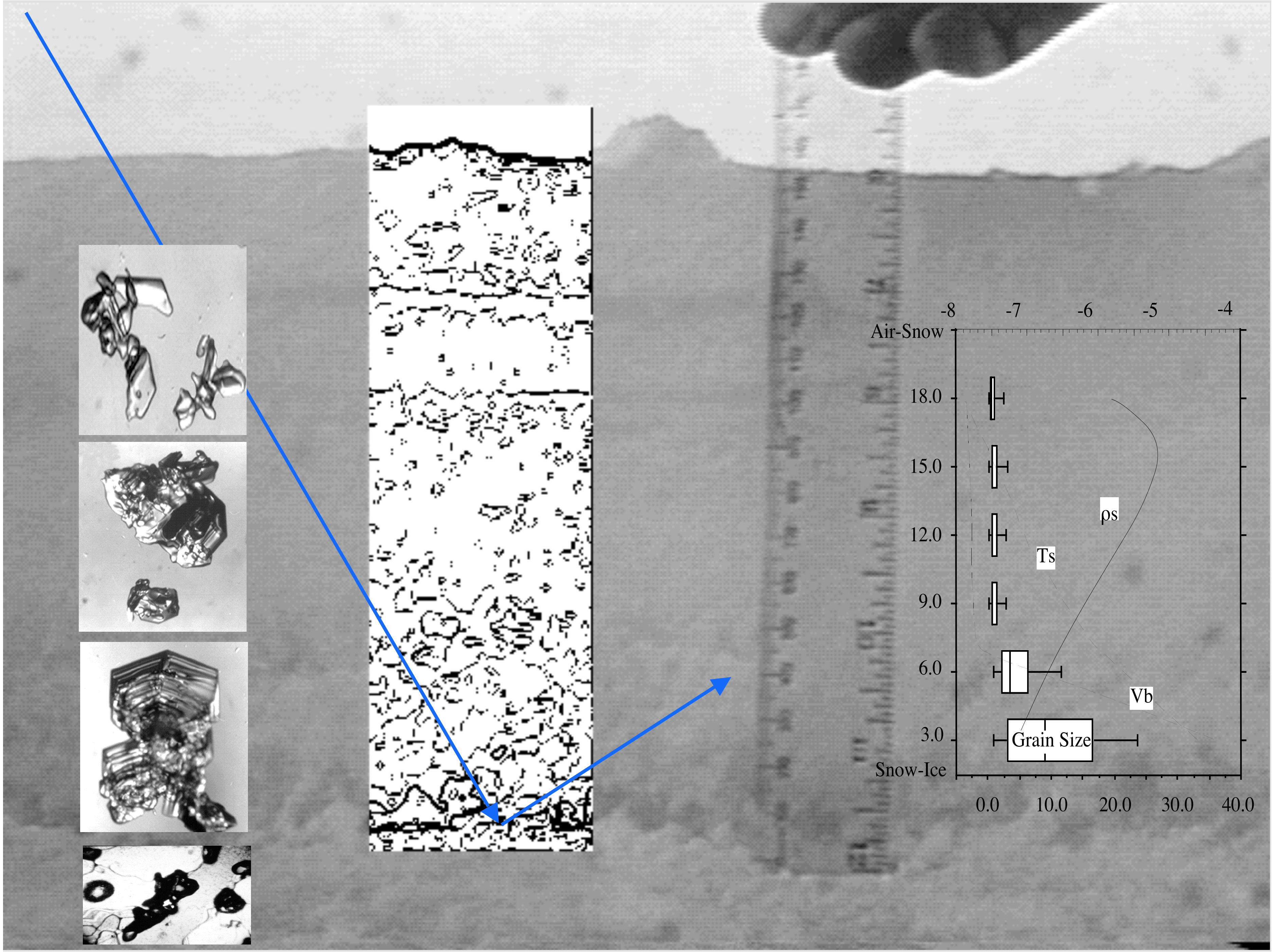








Ehn et al.



-8
-7
-6
-5
-4
Air-Snow
18.0
15.0
12.0
9.0
6.0
3.0
Snow-Ice
ρs
Ts
Vb
Grain Size
0.0
10.0
20.0
30.0
40.0

Many layer SFT model (scattering and emission)

Description

-assumes the snow/sea ice is a piecewise-continuous random medium and accounts for the interference between waves reflected and transmitted coherently by the various planar layers

- accounts for the mean propagation and first-order multiple scattering effects by using bilocal and distorted born approximations

(Winebrenner et al., 1992)

Many layer SFT model (scattering and emission)

Input parameters
General: frequency (GHz), angles
For ice: temperature, salinity, density, ice grain size (mm), air bubble size, brine aspect ratio and tilted angle.

For snow: temperature, density, snow wetness (fractional volume)*, snow grain size (mm).
*liquid water distributed between grains as well as around grains (Stogryn, 1985).

Output parameters
Microwave brightness temperature (emissivity) and backscattering (sigma) for V and H polarizations.

(Winebrenner et al., 1992)

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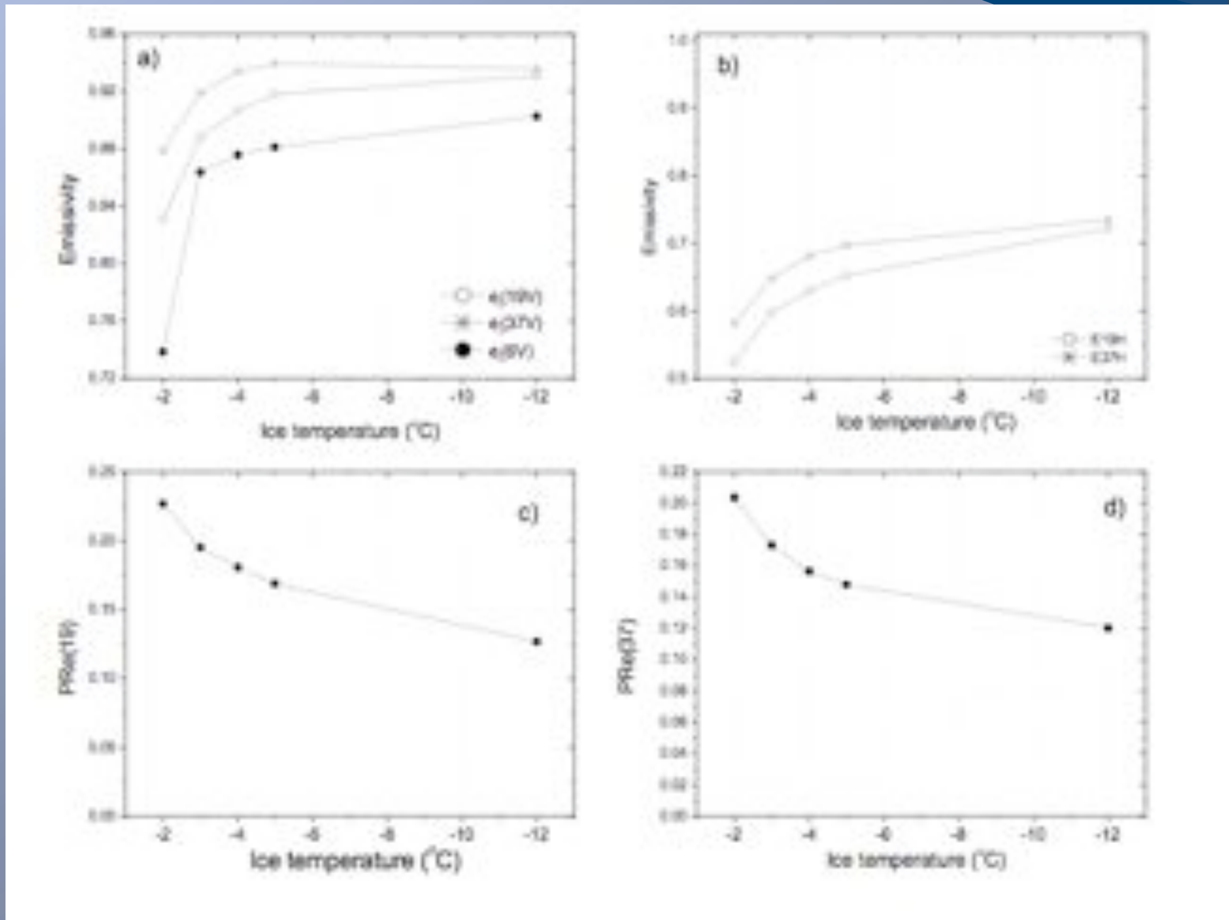

Extending signatures temporally - Ice emissivity simulated by the many layer strong fluctuation theory model. The brine skim/wet slush was set to be 5 mm, and ice salinity based on field data

Hwang and Barber, JGR, in press

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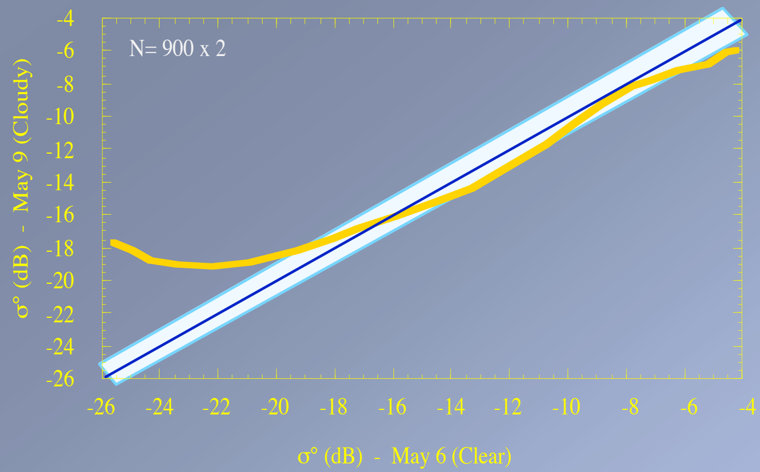
Some examples

Snow Thickness

- Scattering Response

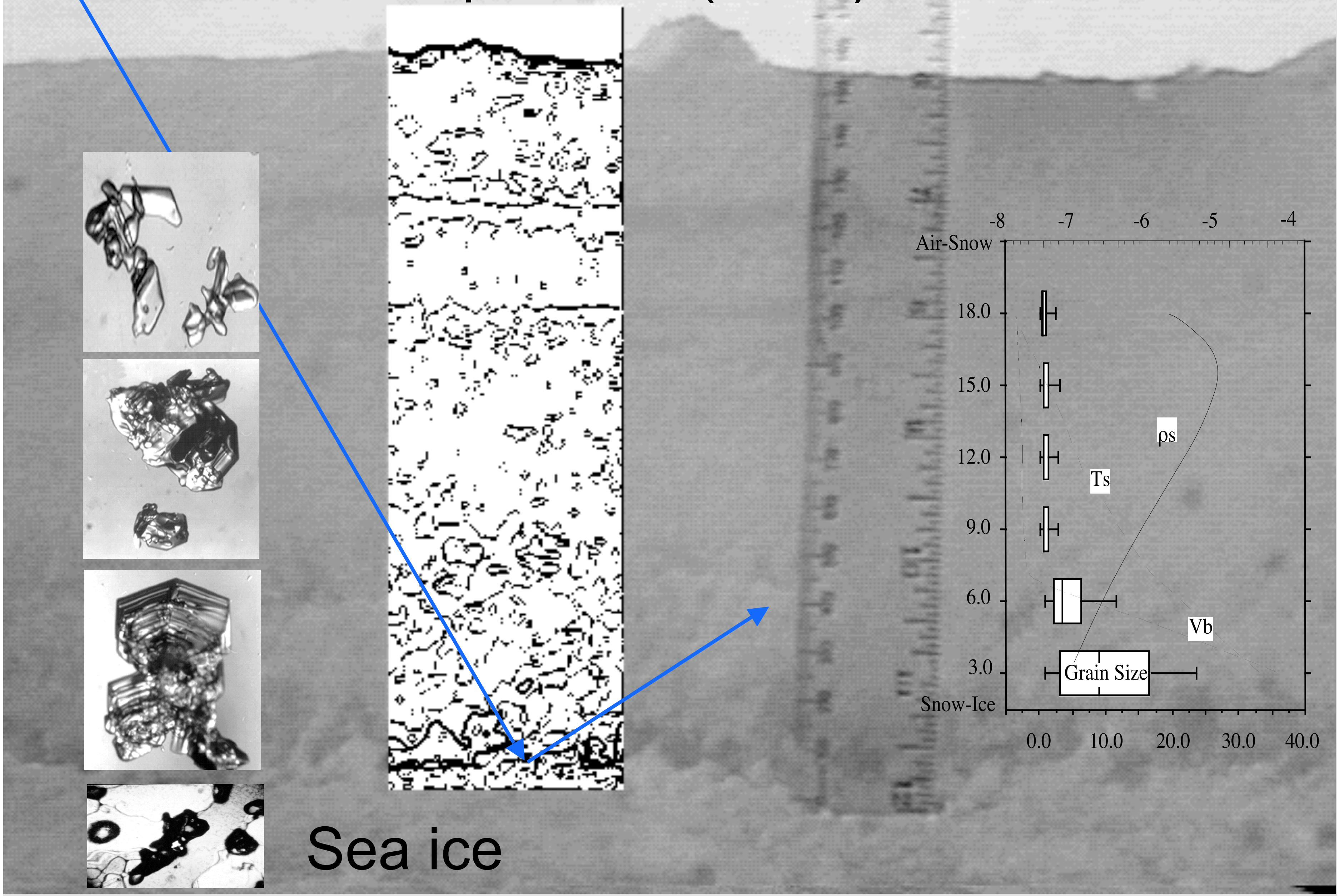
May 6 (Clear)

May 9 (Cloudy)



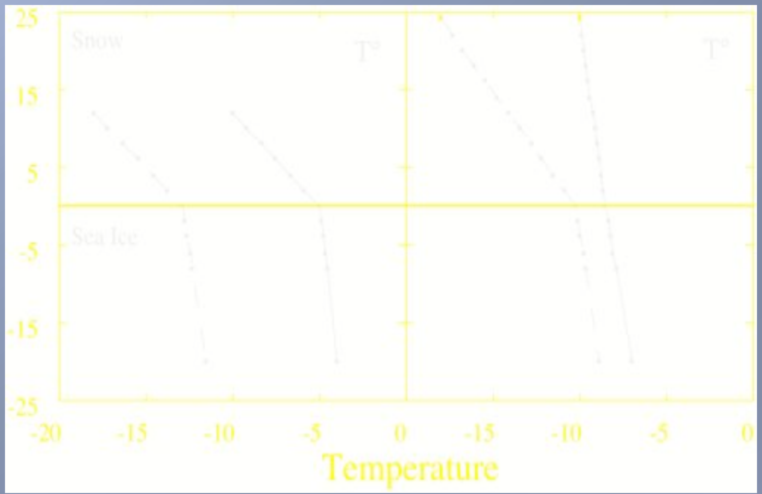
Barber and Thomas, 1998

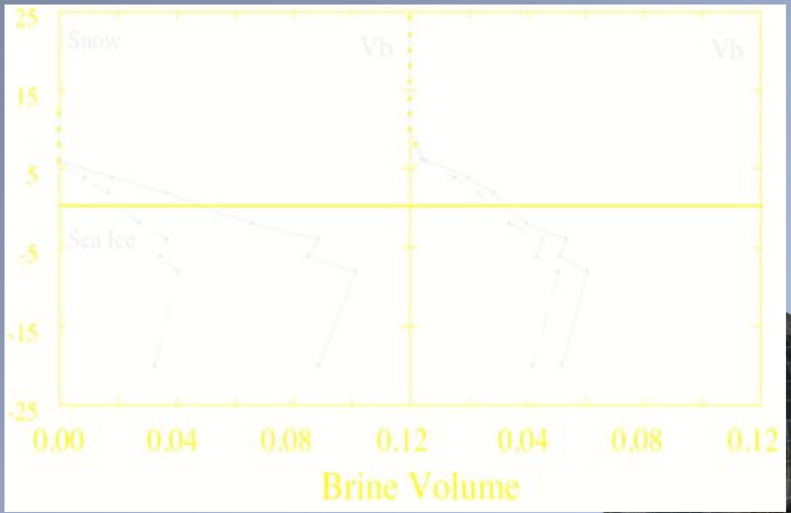
Snow water equivalent (SWE)



SWE and Scattering

- Observed Response to Snow Thickness





Barber et al. 1998

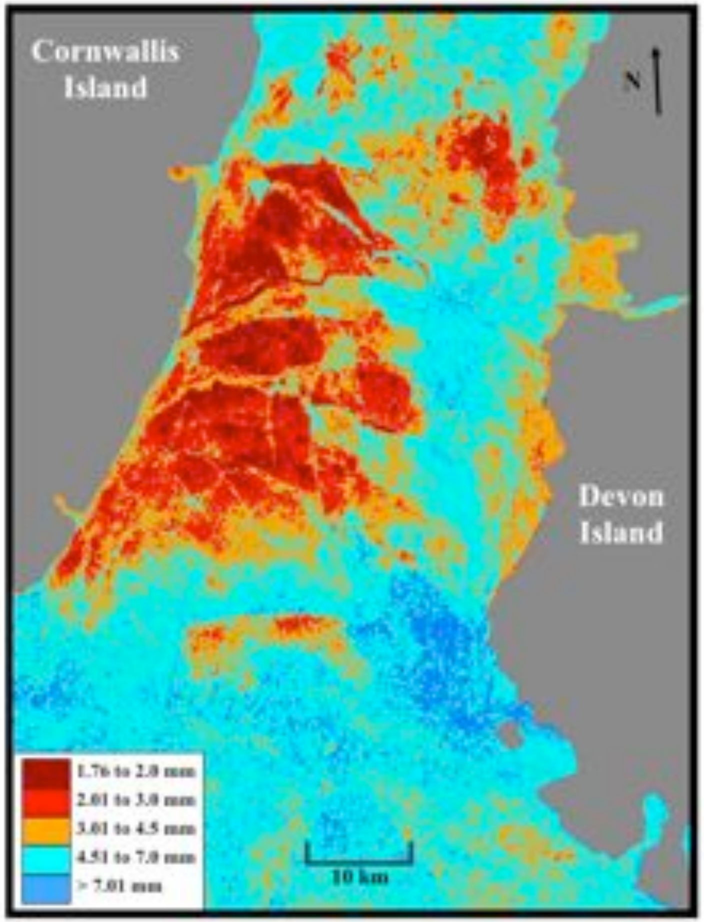
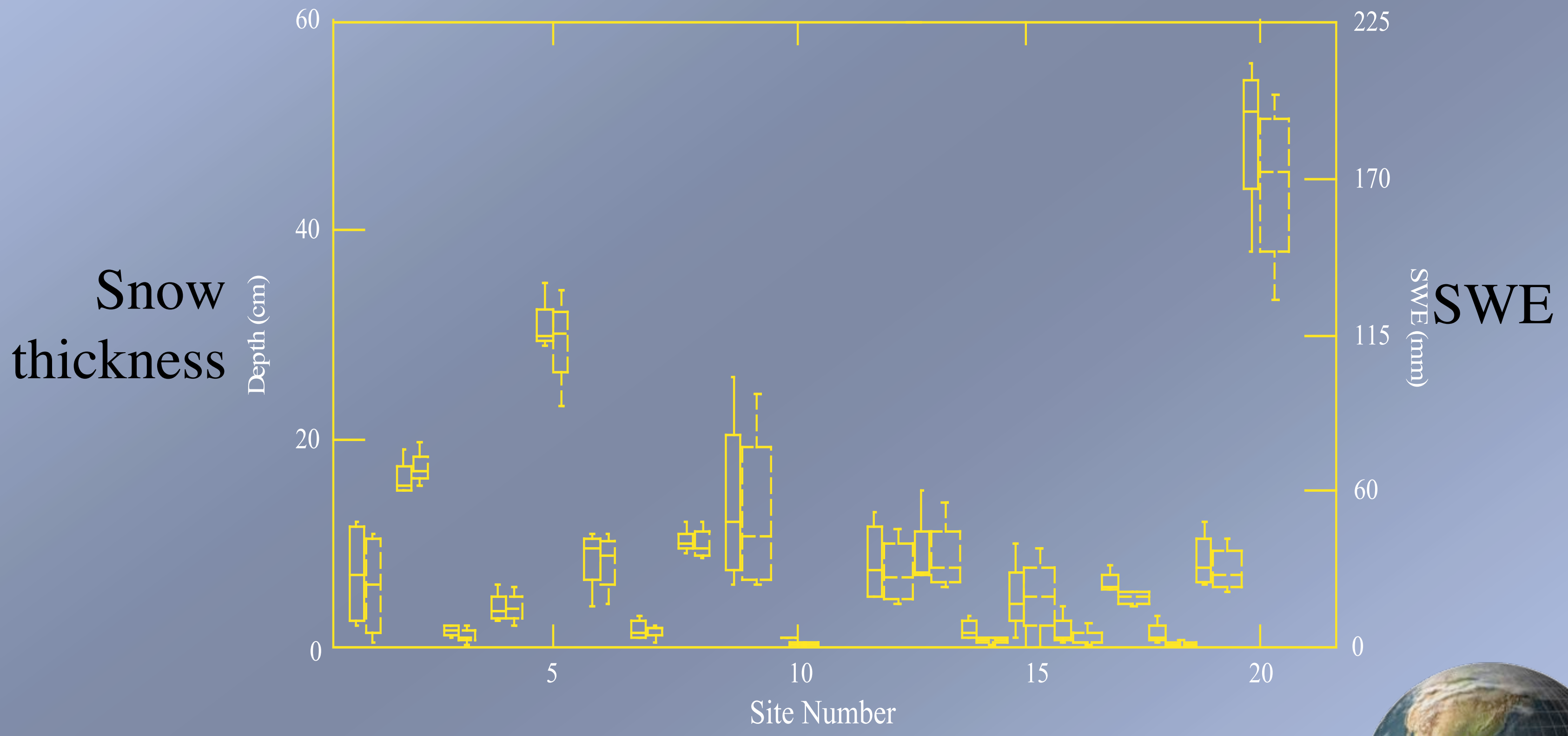


Figure 7: Map of change in SWE (all change is positive amounts) from March 26 to May 7, 1999 over smooth first-year sea ice in Wellington Channel, Nunavut, Canada.

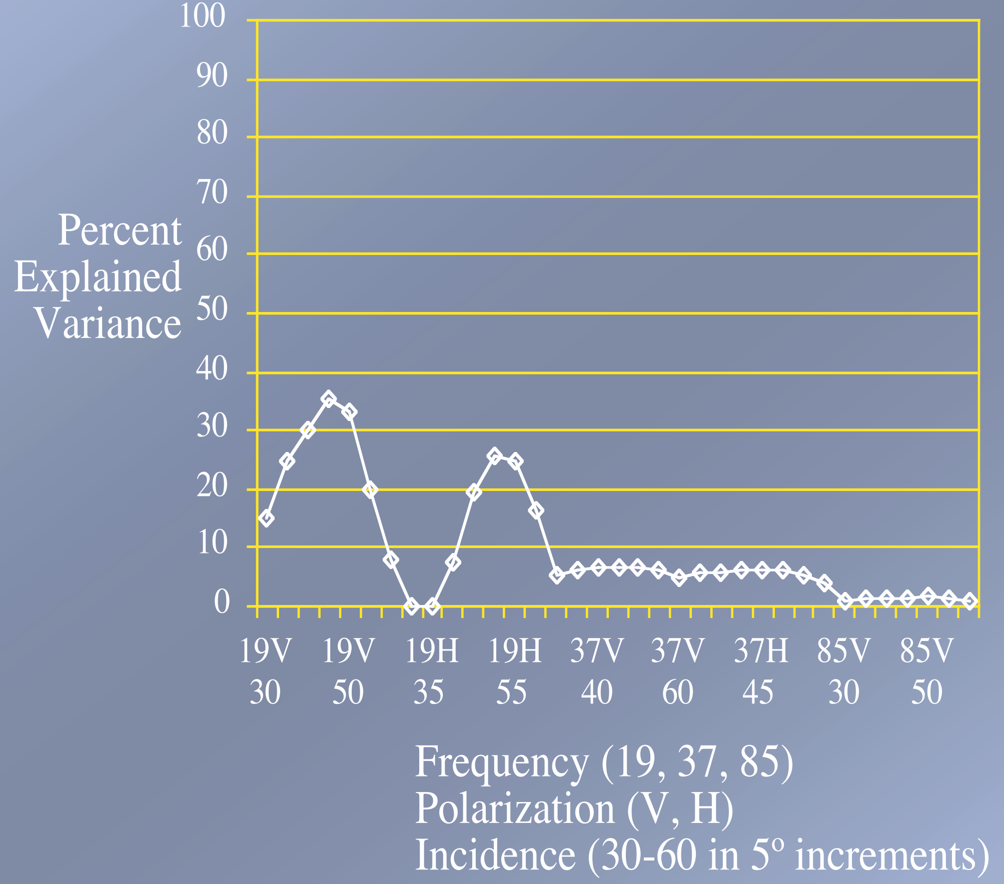
Yackel and Barber, 2000

SWE and Radiometry (20 sites)



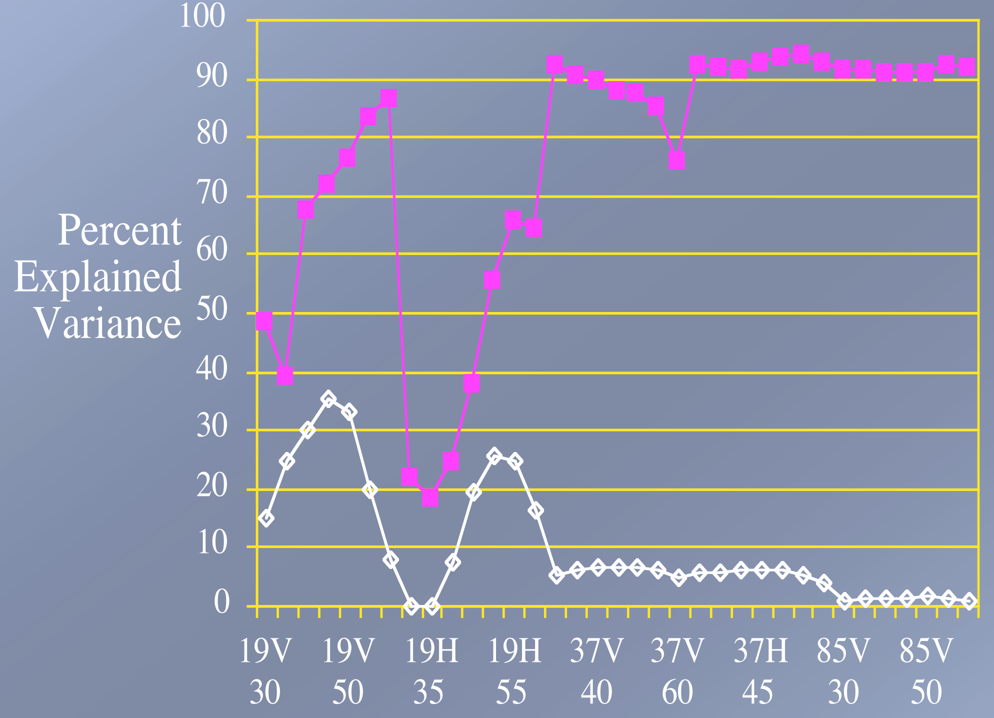
Barber et al. 2000.

Explained variance versus f,P, and θ



Barber et al. 2000.

Explained variance versus *ƒ*,P, and θ



Tb and Ts

Frequency (19, 37, 85)
Polarization (V, H)
Incidence (30-60 in 5° increments)

Barber et al. 2000.

Late season sea ice

$$\varepsilon^* = \varepsilon' + j\varepsilon''$$

Melt Pond Dielectrics

$\varepsilon^* = 65.80 + j36.51$

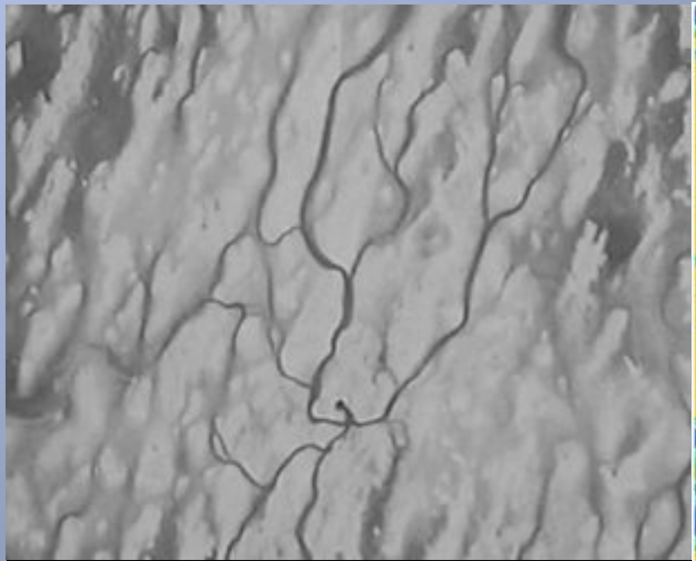
for pure water at
0°C, 5.3 GHz

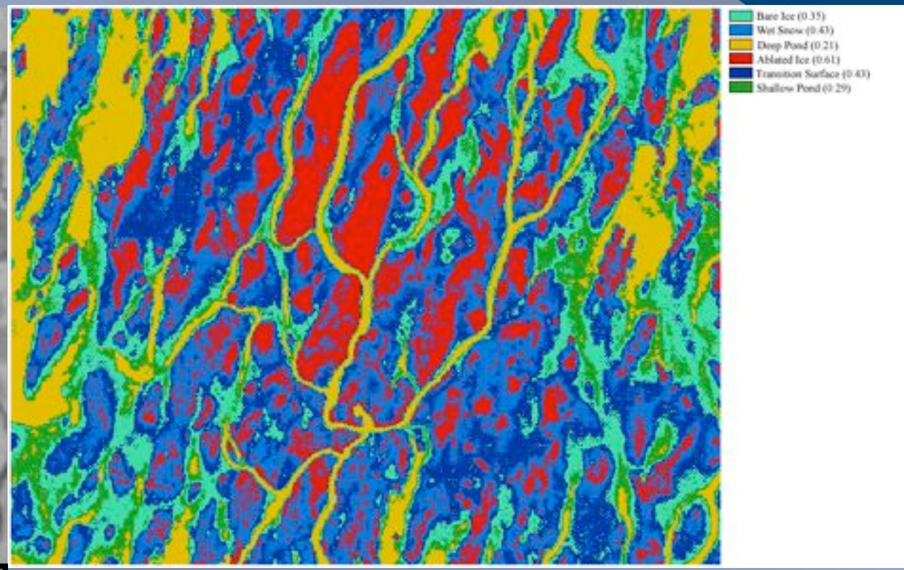
Snow Patch Dielectrics

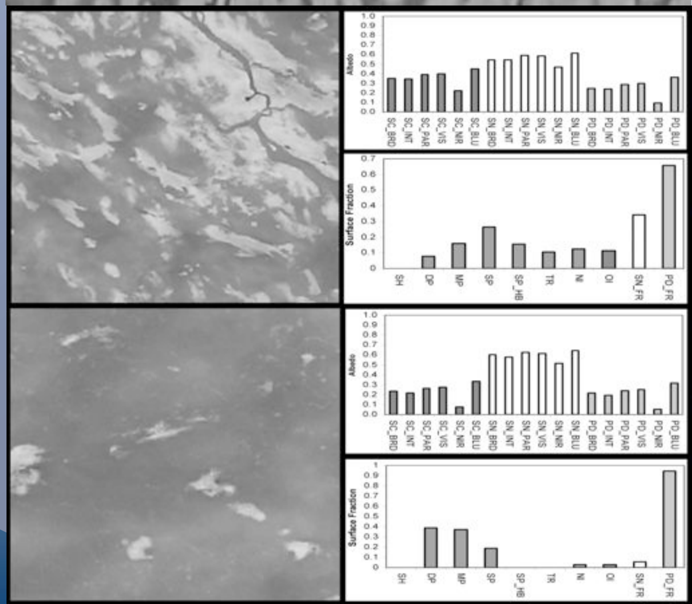
$\varepsilon^* = 1.91 + j0.11$

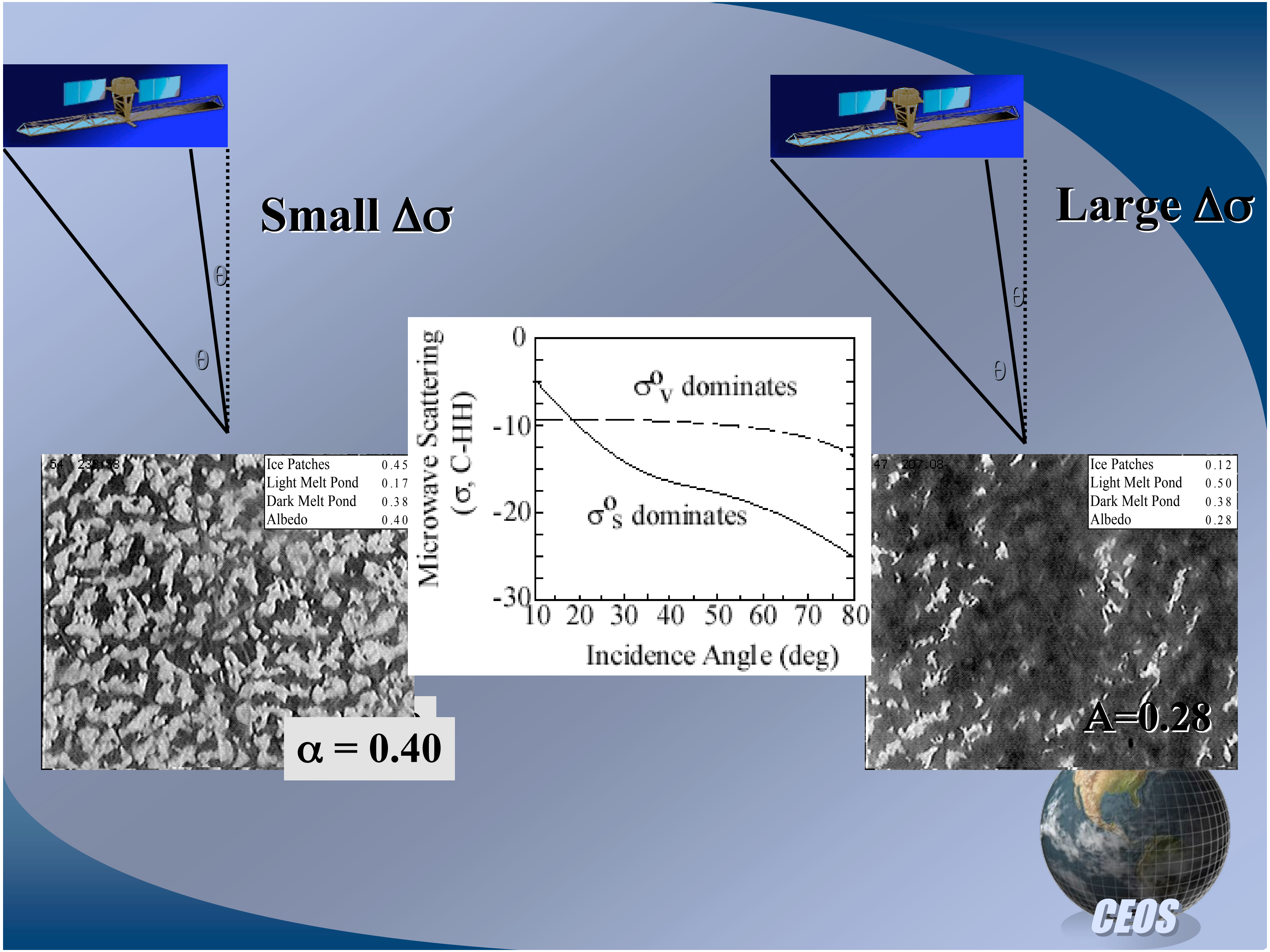
for wet snow at
-1°C, 0.3 $gm.m^{-3}$, 0.1 Wv

Melt Ponds on Landfast First Year Sea Ice.









Small Δσ
Large Δσ
θ
θ
θ
θ
Ice Patches 0.45
Light Melt Pond 0.17
Dark Melt Pond 0.38
Albedo 0.40
α = 0.40
Microwave Scattering (σ, C-HH)
0
-10
-20
-30
10 20 30 40 50 60 70 80
Incidence Angle (deg)
σ°V dominates
σ°S dominates
Ice Patches 0.12
Light Melt Pond 0.50
Dark Melt Pond 0.38
Albedo 0.28
A=0.28
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The Temporal Evolution of Sigma Naught

- Several variables must be taken into consideration:
  - The effect of incidence angle
  - The effect of wind
  - The contribution to backscatter (σ^{o}) by volume and surface scattering as dictated by the dielectrics of the system

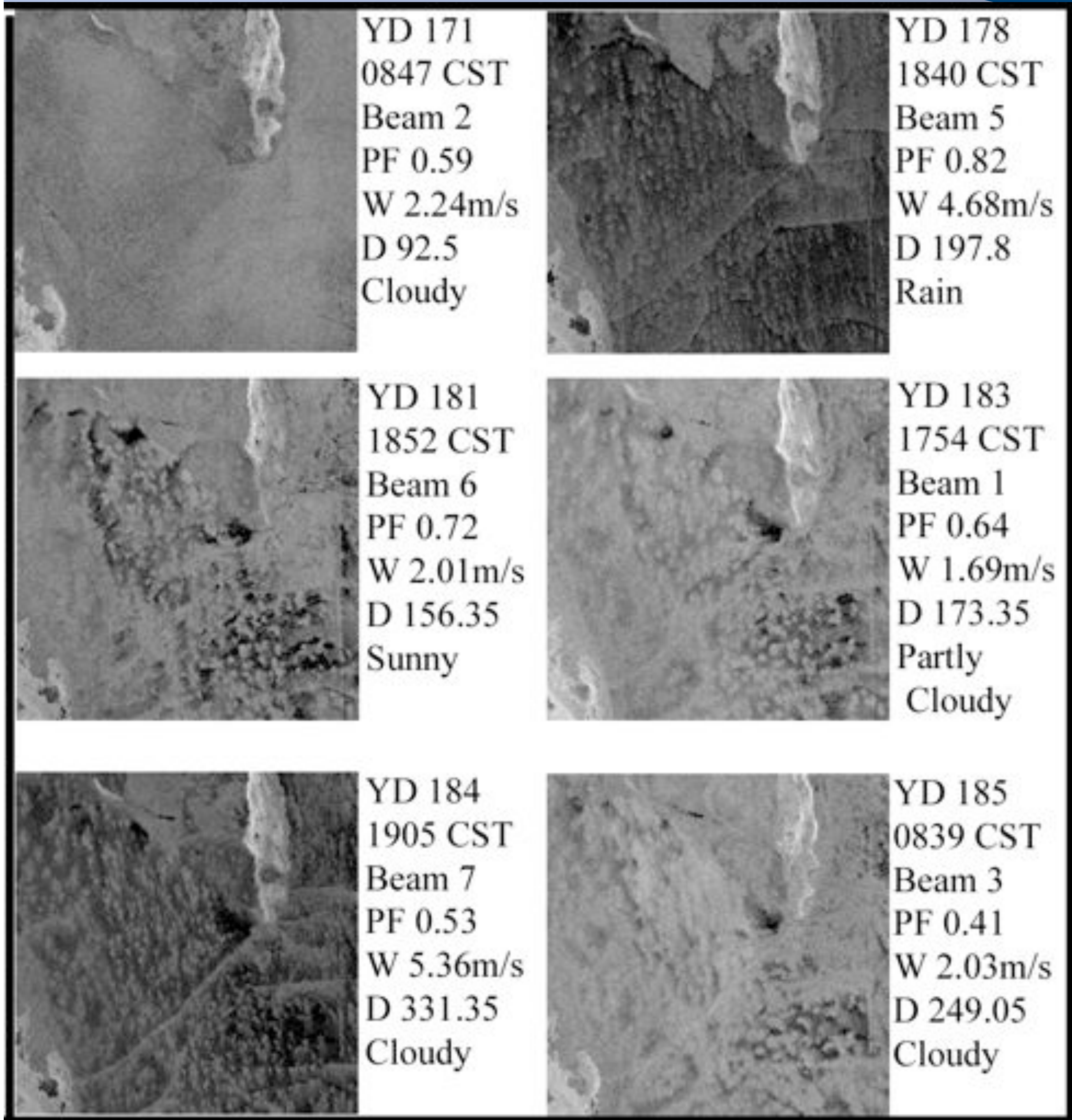
CEOS

The Effect of Incidence Angle

- During periods of cold temperatures the dielectrics of the system are considered static and changes to backscatter are a function of incidence angle and surface roughness
- The Incident Angle Calibration Model (IACM) standardized σ^{o} to the near range of the RADARSAT-1 swath (δ^{o})
  - The IACM explained in excess of 99% of the variability in backscatter which resulted from changes in incidence angle

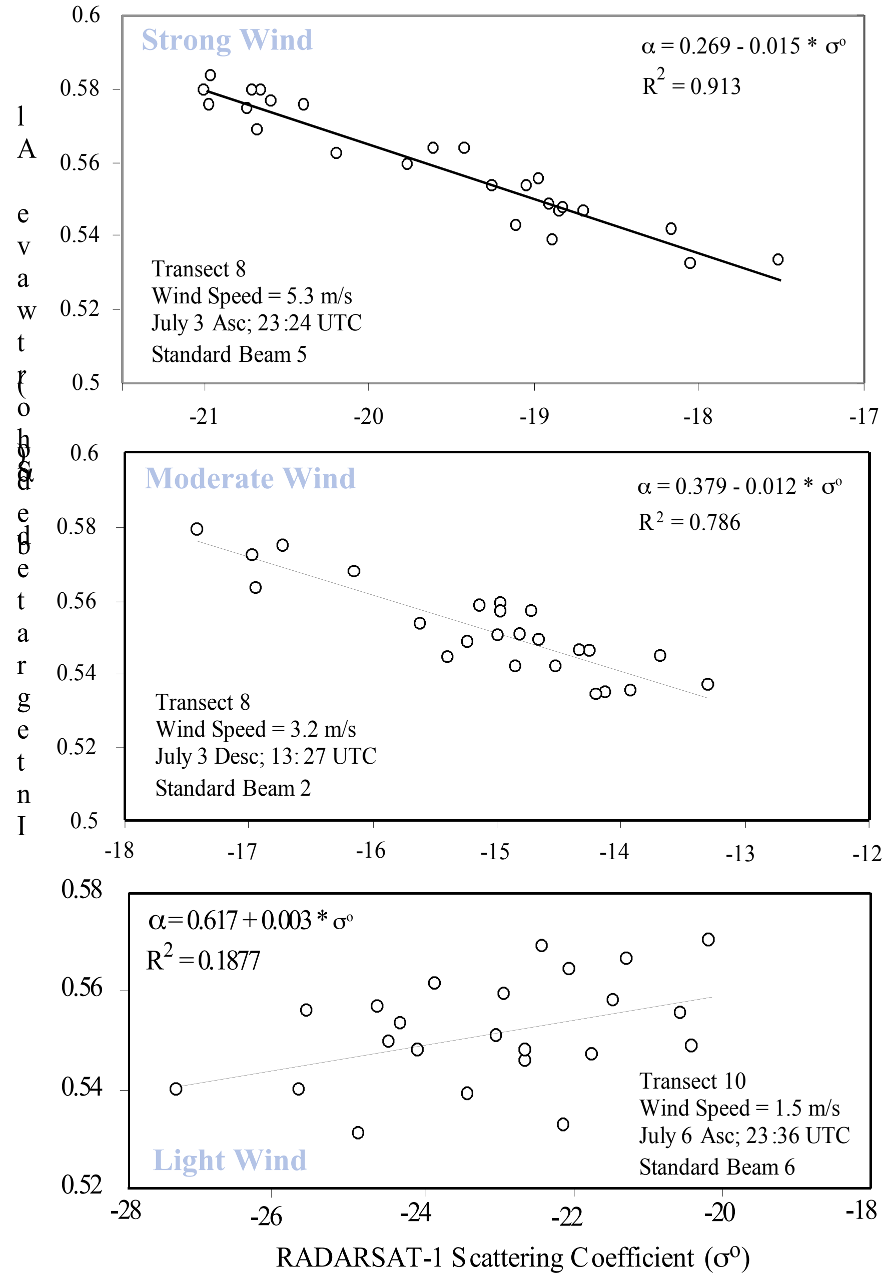
The Effect of Wind

- Under calm conditions, volume scattering within bare ice (σ_i) results in backscatter which is greater than backscatter caused by surface scattering from melt ponds (σ_m) or $\sigma_i > \sigma_m$.
  - This allows for an estimation of melt ponds from SAR
- Over melt ponds, there is an amplification of σ^o as a function of wind speed provided wind direction is orthogonal to the SAR pulse
  - Between 1.5ms^{-1} - 2.5ms^{-1} $\sigma_i = \sigma_m$.
  - Above 2.5ms^{-1} $\sigma_i < \sigma_m$.

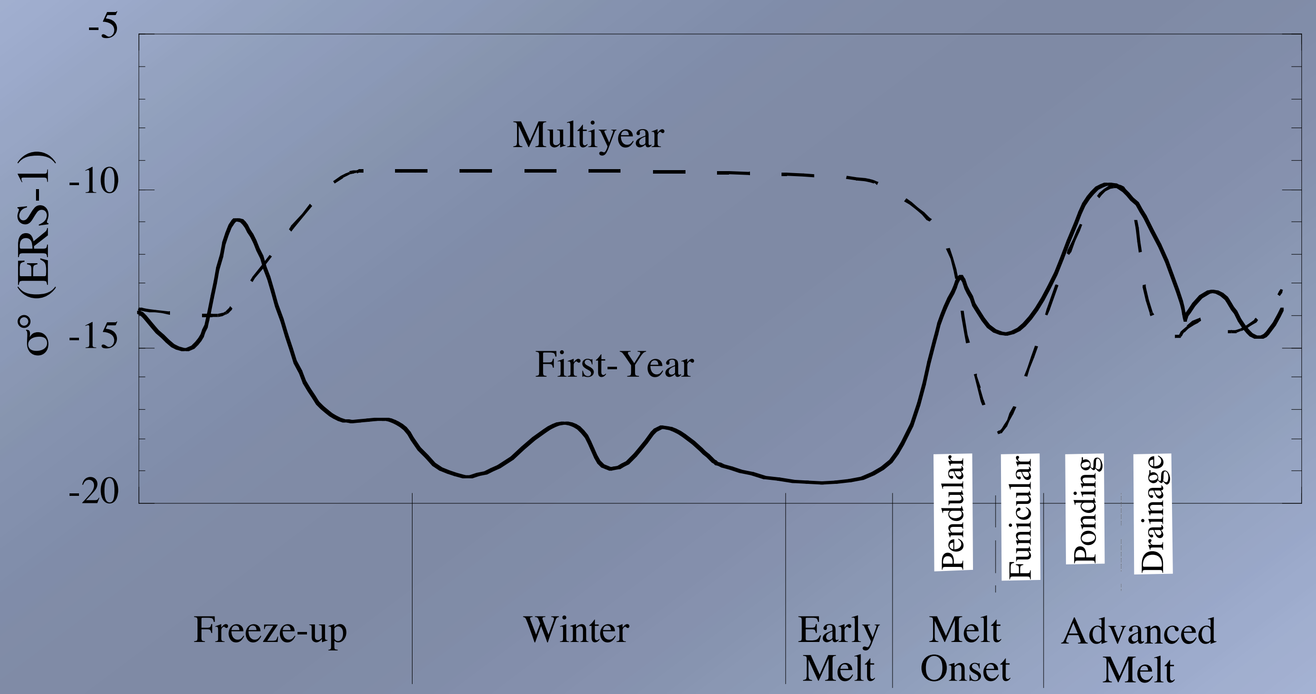


Pond fraction (PF), wind speed (W), wind direction in degrees (D) and weather are all indicated for each image. The images have been calibrated to ASF gamma values and areas of low backscatter appear dark. All images are courtesy of the Canadian Space Agency (© CSA, 2002)

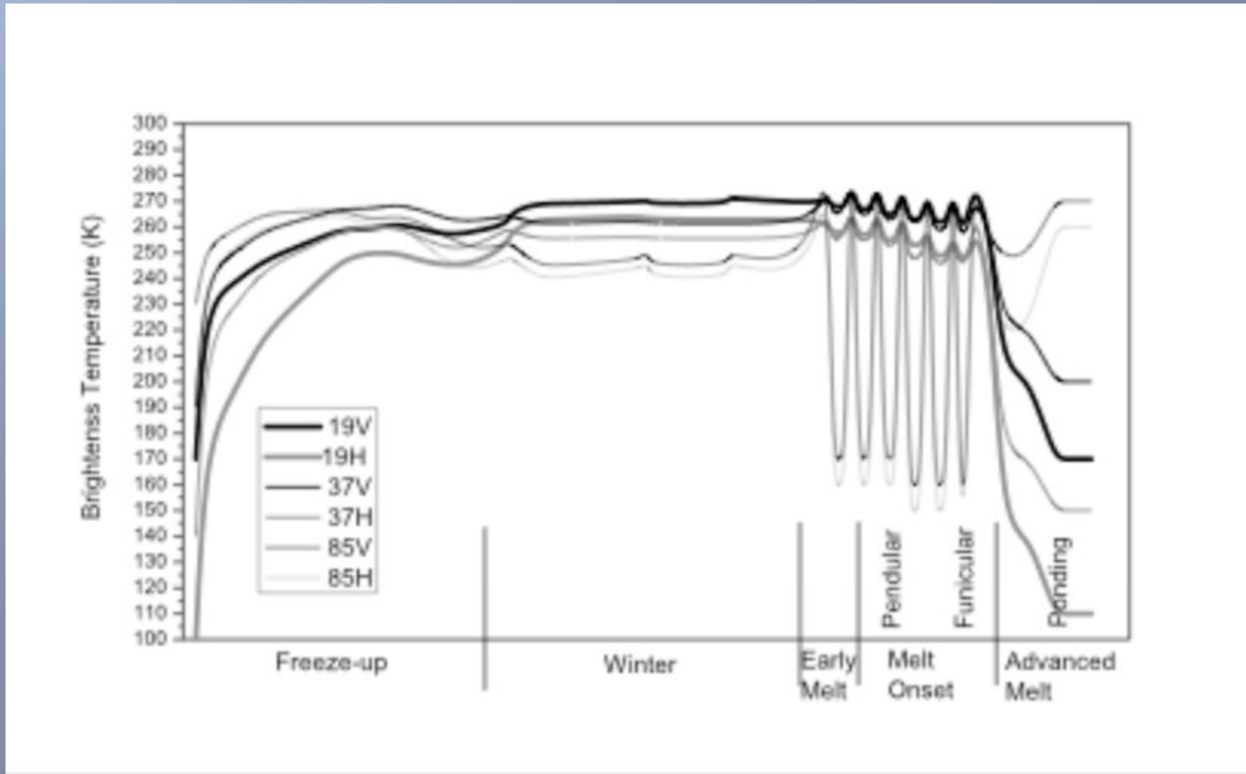
Surface Albedo



The Temporal Evolution of σ°



The Temporal Evolution of T_b



Conclusions

- Electro-thermophysical model (heuristic to physical)
- Emission/scattering models
- Geophysical vs Thermodynamic state (processes)
- Initialization and steering of models, data assimilation
- Scale related science (micro to hemispheric)
- Merger of environmental science and technologies

A metaphor for science and technology

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The real forces behind this work

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Addendum