NS-02 5505
AGU FM 2007

Resistivity Tomography and 50 MHz Dielectric Probes: Sea Ice Salinity and Microstructure

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Objectives

Our aim is to exploit contrasts in the electrical properties between the brine and ice components of sea ice to:

1. Examine complex brine inclusion microstructure through its influence on anisotropic electrical properties.
2. Pursue automated sea ice salinity measurements for scientific and operational monitoring. This requires a tight correlation between brine volume fraction v_b and some measurable quantity.

Background & Motivation

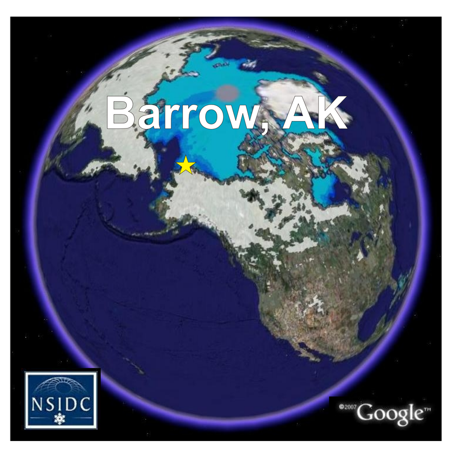
Sea ice is a complex porous medium of mostly ice, with brine and gas inclusions. Relationships are known for the brine volume fraction as a function of salinity and temperature: $v_b(S,T)$.

The complex microstructure includes: oriented ice crystals, intra-crystalline brine inclusions, grain boundaries, secondary drainage networks, and a proposed 'percolation threshold' at $v_b \approx 5\%$.

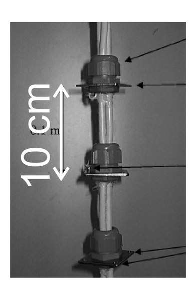
There is electrical anisotropy in single crystals due to aligned brine layers. And at floe scales vertical resistivity $\rho_V < \rho_H$ horizontal resistivity. This has complicated surface-based resistivity soundings.

Monitoring of sea ice conditions is important for on-ice science, travel and logistics. Physical properties depend on temperature and bulk salinity.

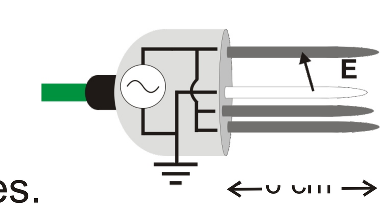
But there are no reliable automated salinity measurements.



Methods and Measurements



Cross-borehole resistivity tomography: two 2m vertical electrode strings frozen into growing first year ice, Barrow Alaska: inversion to find 2-D and 3-D resistivity structures.



50 MHz dielectric probes (Stevens Water Monitoring Hydraprobes): impedance measurements of complex permittivity $\varepsilon = \varepsilon' - j\varepsilon''$ where ε' is 'dielectric constant', ε'' is 'loss factor. Radial *E* field between central and 3 outer tines.

Acknowledgments:

Barrow Arctic Science Consortium. NSF, Royal Society of New Zealand.
Lars Backström for data and useful discussions.

References:

Backstrom, L. G. E. and H. Eicken (2006) Capacitance probe measurements of brine volume and bulk salinity in first-year sea ice. Cold Reg. Sci. Technol., 46, 167-180
Ingham, M., D. J. Pringle, and H. Eicken (2007), Cross-borehole resistivity tomography of sea ice, Cold Reg. Sci. Technol. 10.1016/jcoldregions.2007.05.002
Pringle, D.J., Dubuis, G.J.G, Eicken, H., Impedance measurements of complex dielectric permittivity of sea ice at 50 MHz: single crystals and salinity monitoring, *(to be submitted.)*
Vant, M. R., Ramseier, R. O. and Makios, V. (1978) The complex-dielectric constant of sea-ice at frequencies in the range 0.1-40 Ghz, J. Appl. Phys., 49(3) (Erratum, J.Appl. Phys. 53(2), 1982)

Cross Borehole Resistivity Tomography

Electrode strings frozen into growing, land-fast, first year sea ice, Jan' 2006.

Theoretical treatment of anisotropic medium used to select current, potential electrode configurations to measure horizontal resistivity ρ_H .

Measurements made through melt-season: April, May, June, 2006.

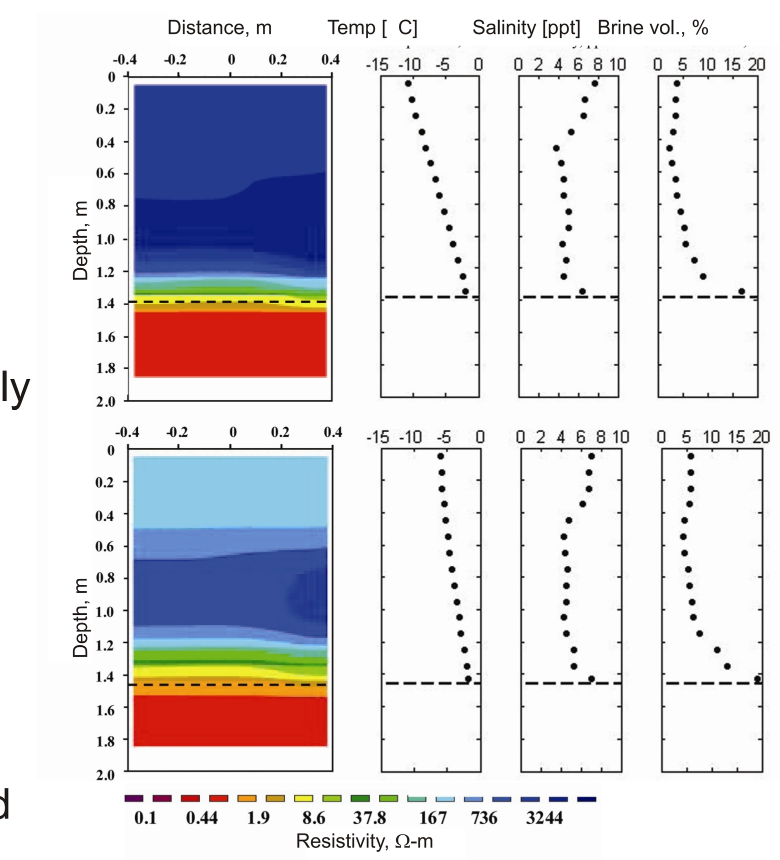


Fig 1. Resistivity slices from 3D inversions. Slice cuts plane between electrode strings. (a) high-ρ in cold ice in April, and (b) decreasing ρ in warming, May ice.

Resistivity Inversion

3-D inversions show:
- ρ_H decreases with v_b - significantly when $v_b >$ 5 - 7 %,
- ice base clearly resolved,
- halo regions of lower ρ_H around strings, (not shown)

Archie's Law Analysis

Conductivity of two-phase saturated porous media:

$$\rho = v_b^{-m}\rho_b$$

v_b = brine volume fraction
ρ_b = brine resistivity.
'Formation factor' FF $= \rho_H/\rho_b$

Archie's-Law-like response when T < -5 °C (low v_b) but faster decrease for v_b > 8-10%

$\Rightarrow$ enhanced connectivity of brine inclusions

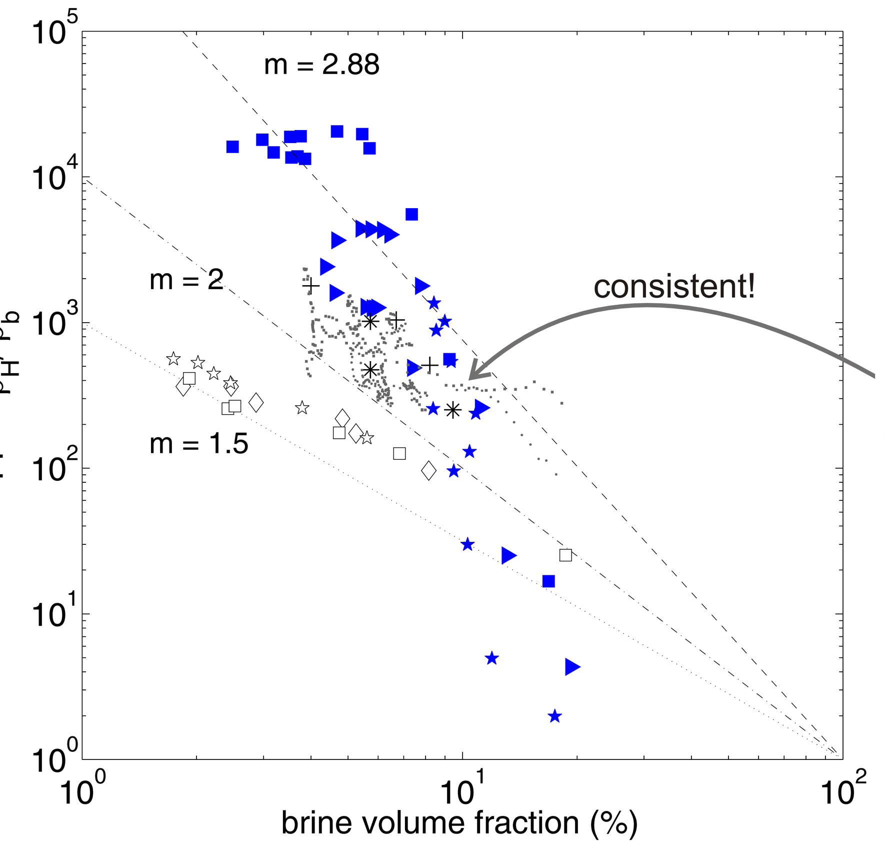


Fig 2. Log-log plot of formation factor FF = ρ_H/ρ_b. Squares 22-25 April; triangles 11 May; stars 8 June 2006. Open symbols, Morey et al. (1984); crosses Timco (1979); asterisks Buckley et al (1984). Small dots from hydraprobe measurements, see right.

Ongoing Work

We are fully-automating data collection, analyzing 4-string measurements in 2007, and incorporating Wenner Array soundings to isolate ρ_V and ρ_H.

Conclusions: Resistivity Tomography

Treating theory for anisotropic resistivitiy, electrode configurations can be found to measure the horizontal resistivity, ρ_H .

2-D and 3-D inversions show Archie's Law behavior for T < -5 °C (low v_b) with m= 2.88, but a faster decrease in ρ_H for v_b > 8 -10% due to enhanced connectivity of brine inclusions.

Scatter too high for accurate inversion of v_b (and S) from these particular measurements.

There is ongoing work to improve measurements and to refine analysis on anisotropy in resistivity and brine inclusion connectivity.

50 MHz Hydraprobes

In-situ measurements during growth of land-fast, first year sea ice, Barrow, January - June 2007.

Deriving S from ε'

Prior measurements showed linear $v_b(\varepsilon')$, allowing calculation of $S(\varepsilon')$. (Backström and Eicken, 2006).

But combined measurements show scatter attributed to:
- uncertainty in derived values of v_b ,
- natural variability, small sample size,
- microstructural dependence via interface contributions to ε.

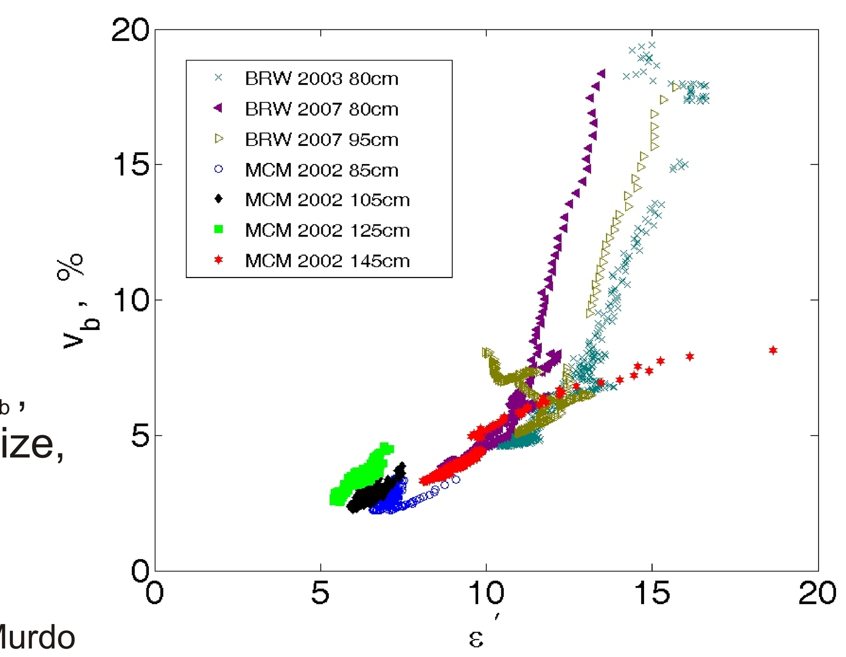
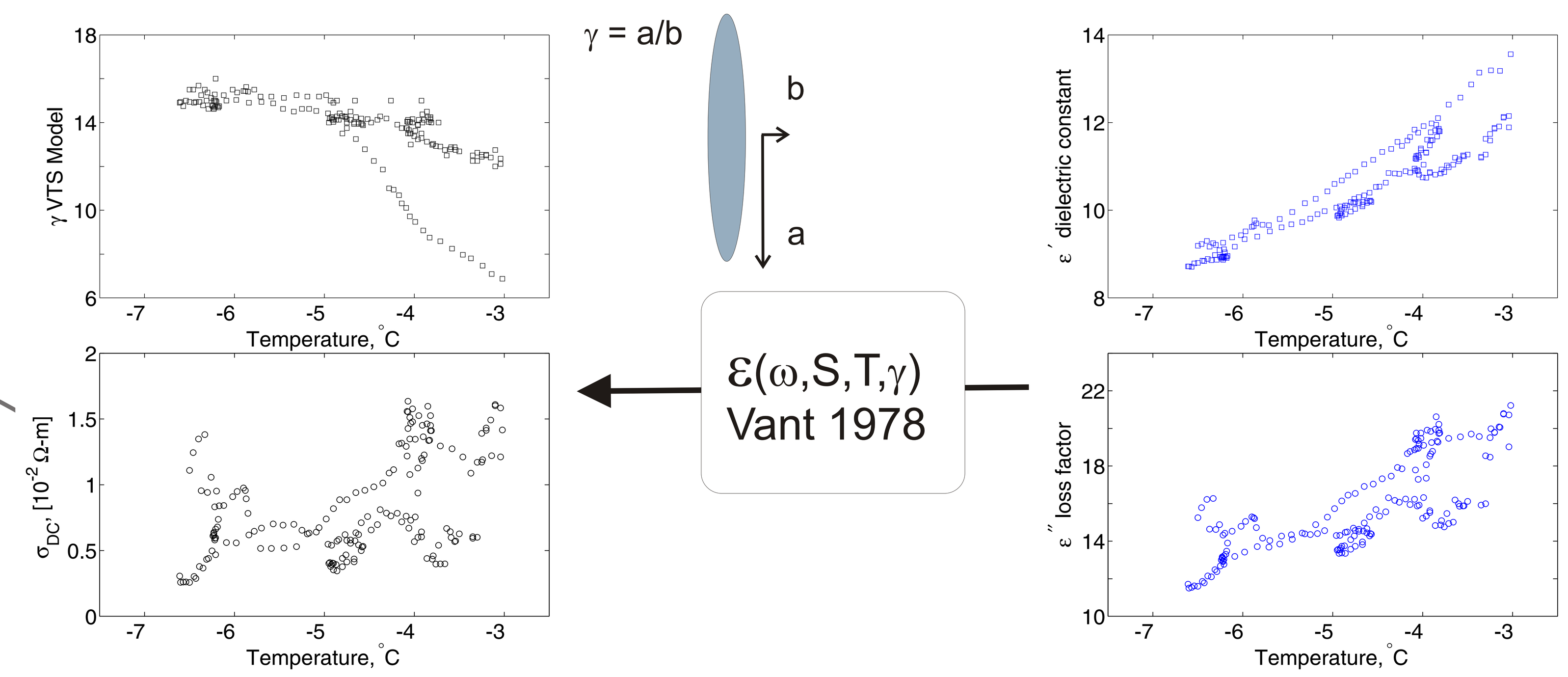


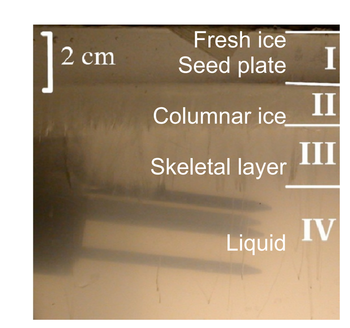
Fig 3. v_b vs. ε' From Barrow (BRW) and McMurdo Sound, Antarctica (MCM). v_b from salinity coring.

Microstructure and Conductivity

Invert Vant/Tinga/Stogryn (Vant, 1978) ellipsoidal inclusion model: σ_{DC} and measure of inclusions geometry (γ – ellipsoid aspect ratio). σ_{DC} consistent with tomography. γ similar to smaller-scale optical measurements.



Single Crystal Lab Measurements



Tines parallel or perpendicular to brine layers. Weak anisotropy in ε' but 20-40% higher ε'' due to enhanced σ_{DC} along brine layers. γ factors similar and σ_{DC} higher than field measurements.

Conclusions: Hydraprobes

Measurement volume too small for automated S measurements without additional microstructural information and investigation.

Effective brine inclusion aspect ratio γ derived over large volume - and therefore large number of inclusions - compared with other microstructural studies.

Field measurements: γ values similar to other observation, and signatures of brine overturning events when v_b exceeds 5.5 % (not shown).

Derived DC conductivity consistent with cross-borehole resistivity tomography

Single crystal measurements show hysteresis in γ - to be examined further.
NB: Caution with salinity, temperature and recommended operation conditions.