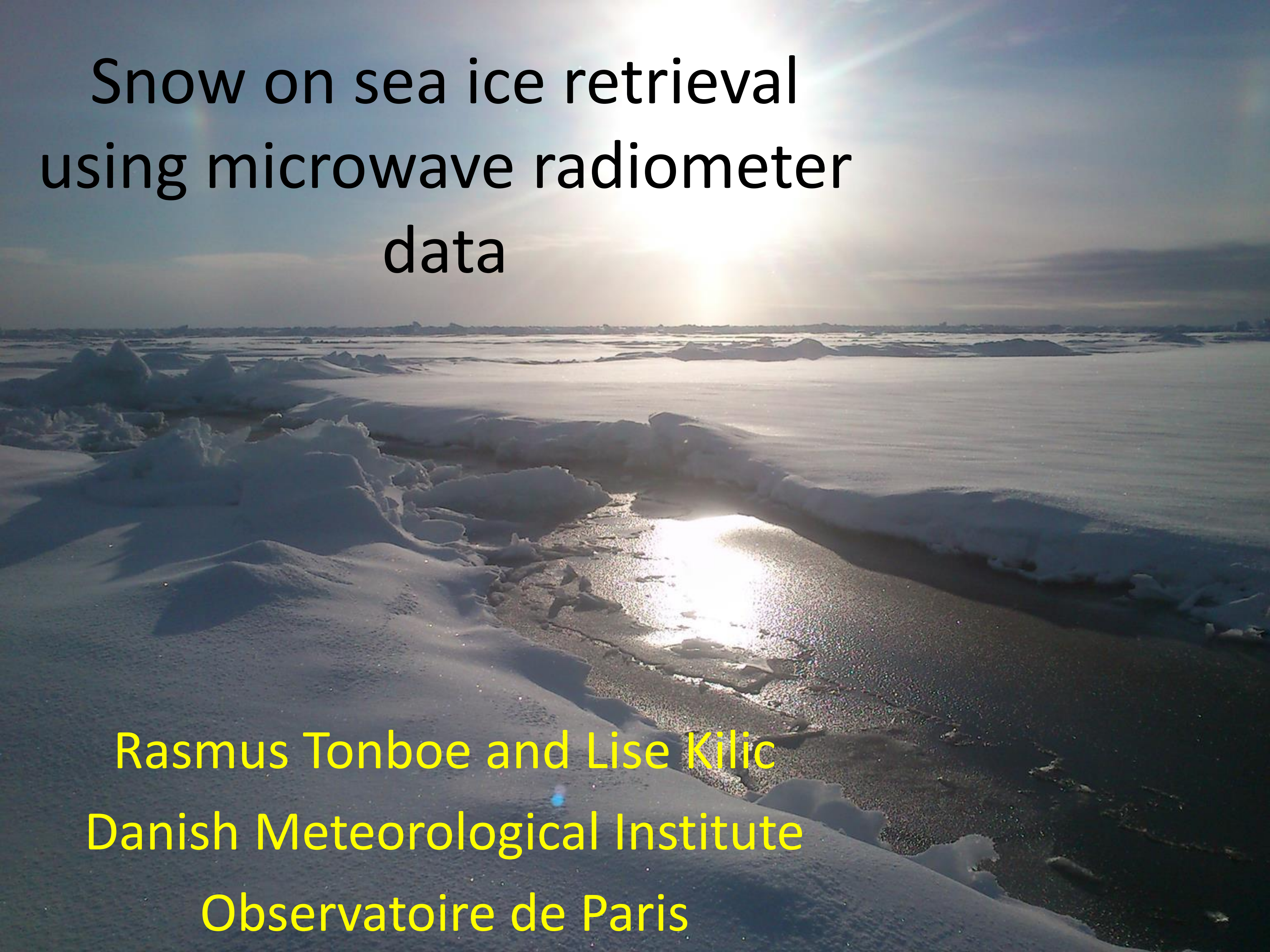
Snow on sea ice retrieval using microwave radiometer data



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Danish Meteorological Institute
Observatoire de Paris

We know something about snow

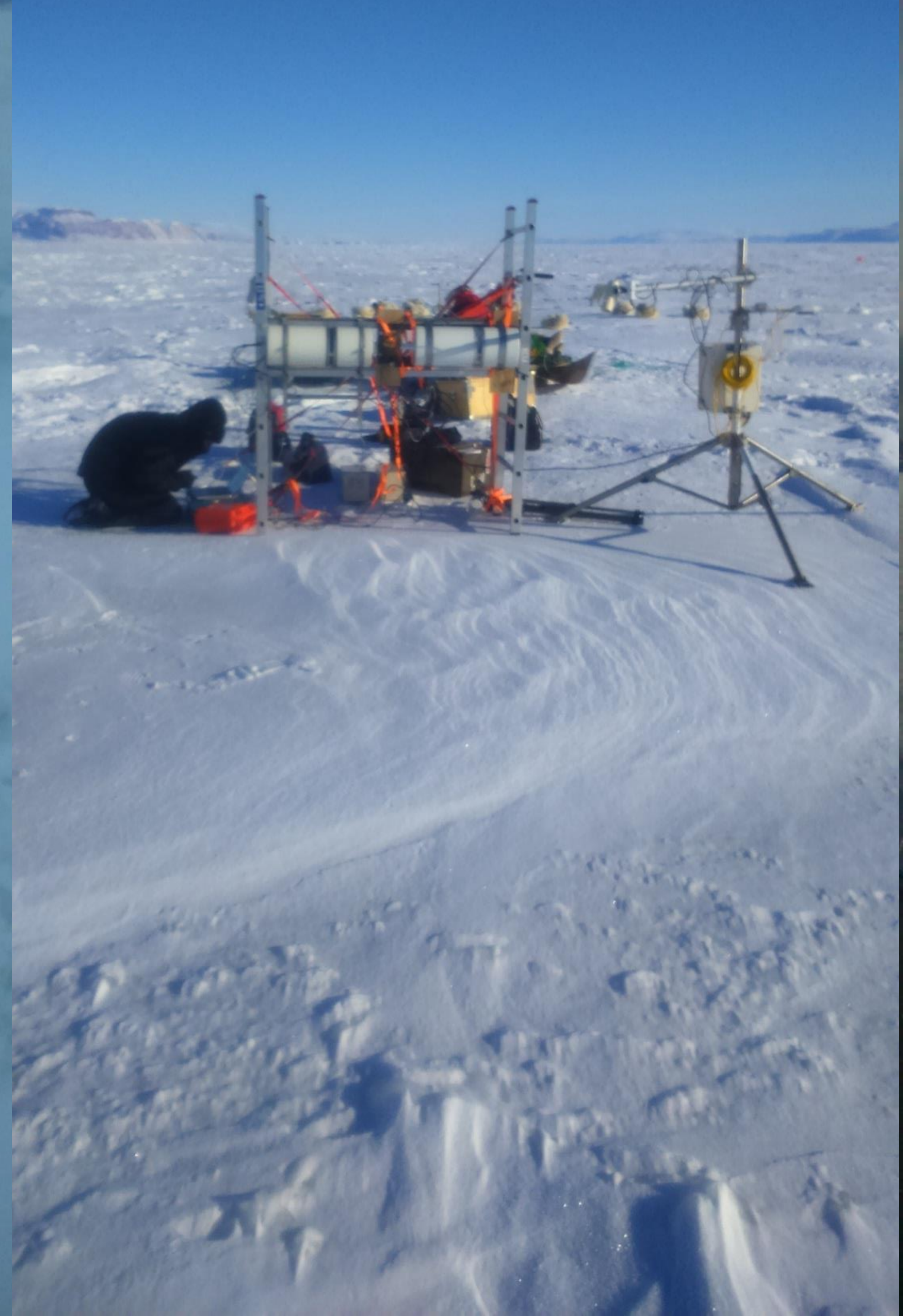
- The temperature gradient within the snow is approximately linear and also in the ice it is linear. The temperature gradient in the snow is much larger than in the ice because the thermal conductivity in the snow (0.3 W/mK) is much lower than for ice (2.1 W/mK) by a factor of about 7. The snowpack metamorphosis is a function of the temperature gradient, the snow density and snow grain-size.
- After snowfall where the new snow deposit density is determined by temperature and wind speed compaction sets in driven by the load of the snowpack itself and recrystallisation processes, temperature and density of the snowpack.
- The thermal conductivity depend on the snow density and snow temperature and in ice on the ice salinity and temperature.
- Snow is a layered medium: In microwave radiometry it is very important to capture the layering in the snow in order to simulate realistic signatures.

Snow on sea ice microwave radiometry

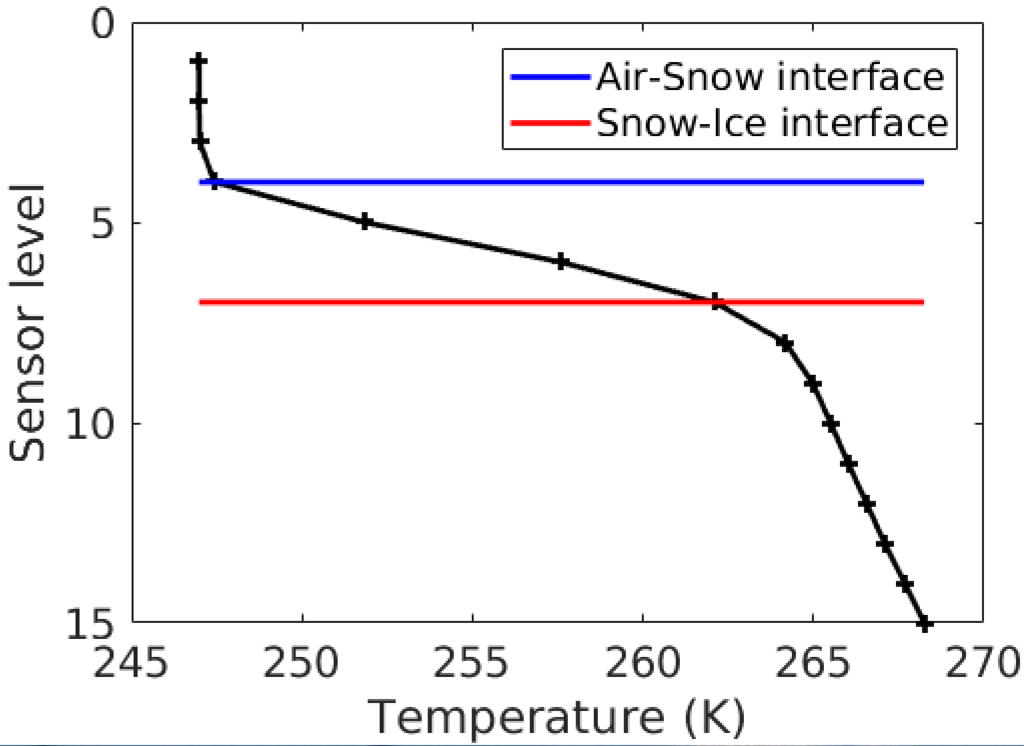

First-year ice
Ridges/ deformed ice


Multiyear ice
Melt-ponds


Refrozen meltponds

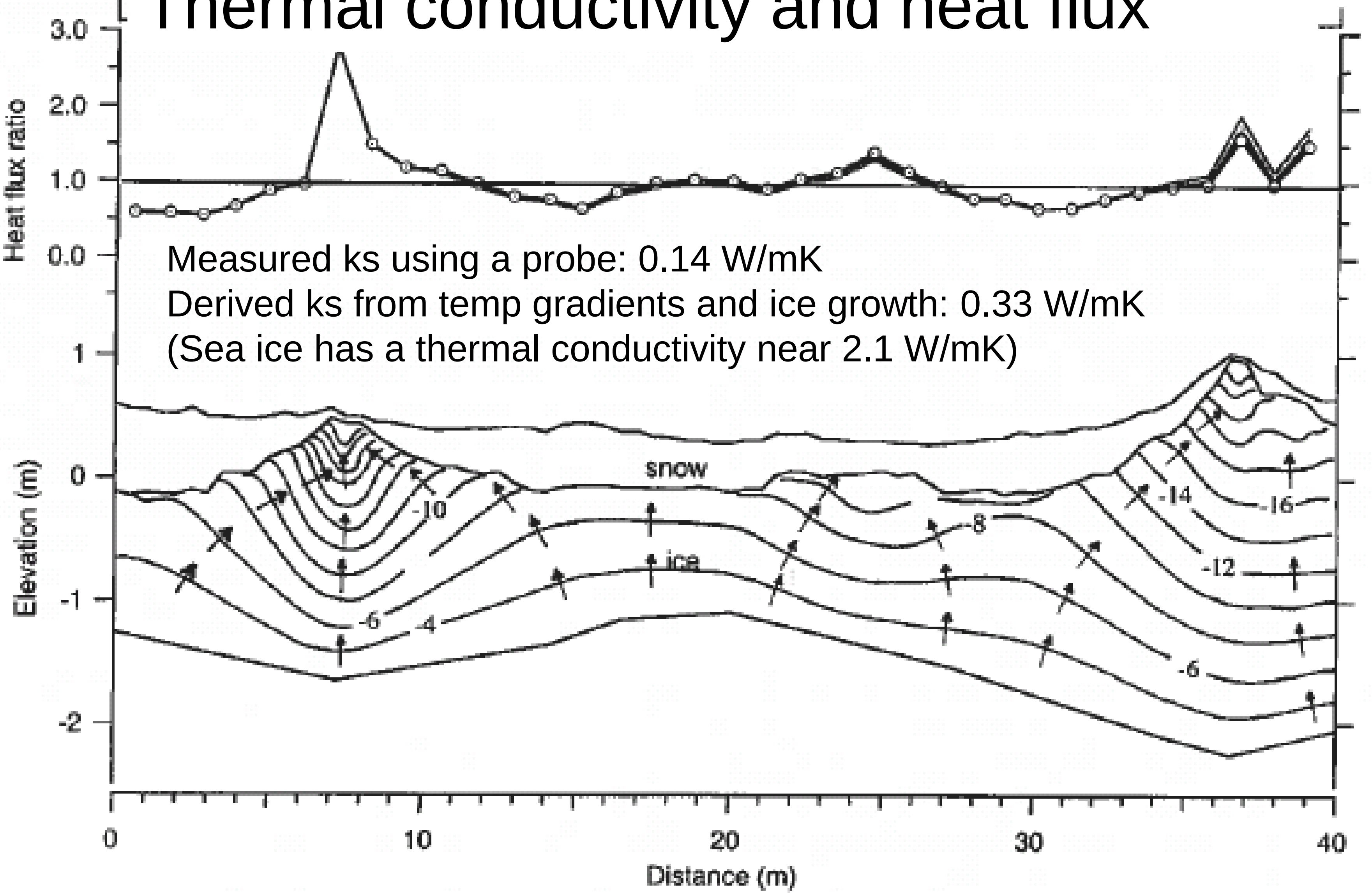
The thermodynamics of sea ice



$$ki\left(\frac{Tw-Tsi}{hi}\right)=ks\left(\frac{Tsi-Ta}{hs}\right)$$

- ***ki***: thermal conductivity of ice f(salinity, temperature, porosity)
- ***ks***: thermal conductivity of snow f(density)
- ***Tw***: water temperature (271.35K)
- ***Tsi***: snow ice tinterface temperature (measured by satellite?)
- ***Ta***: snow surface temperature (measured by satellite)
- ***hi***: ice thickness
- ***hs***: snow depth

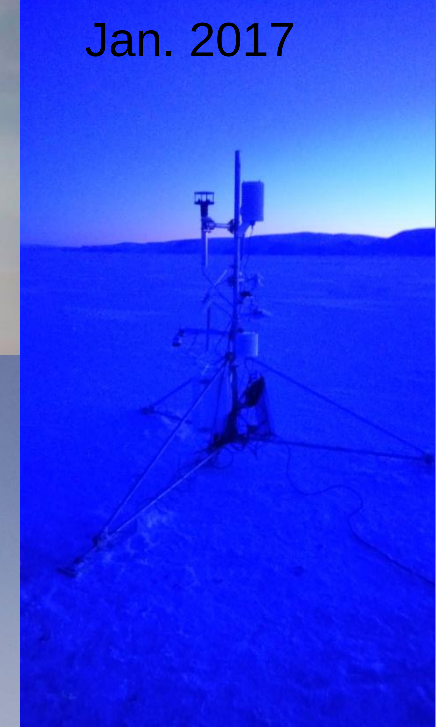
Thermal conductivity and heat flux



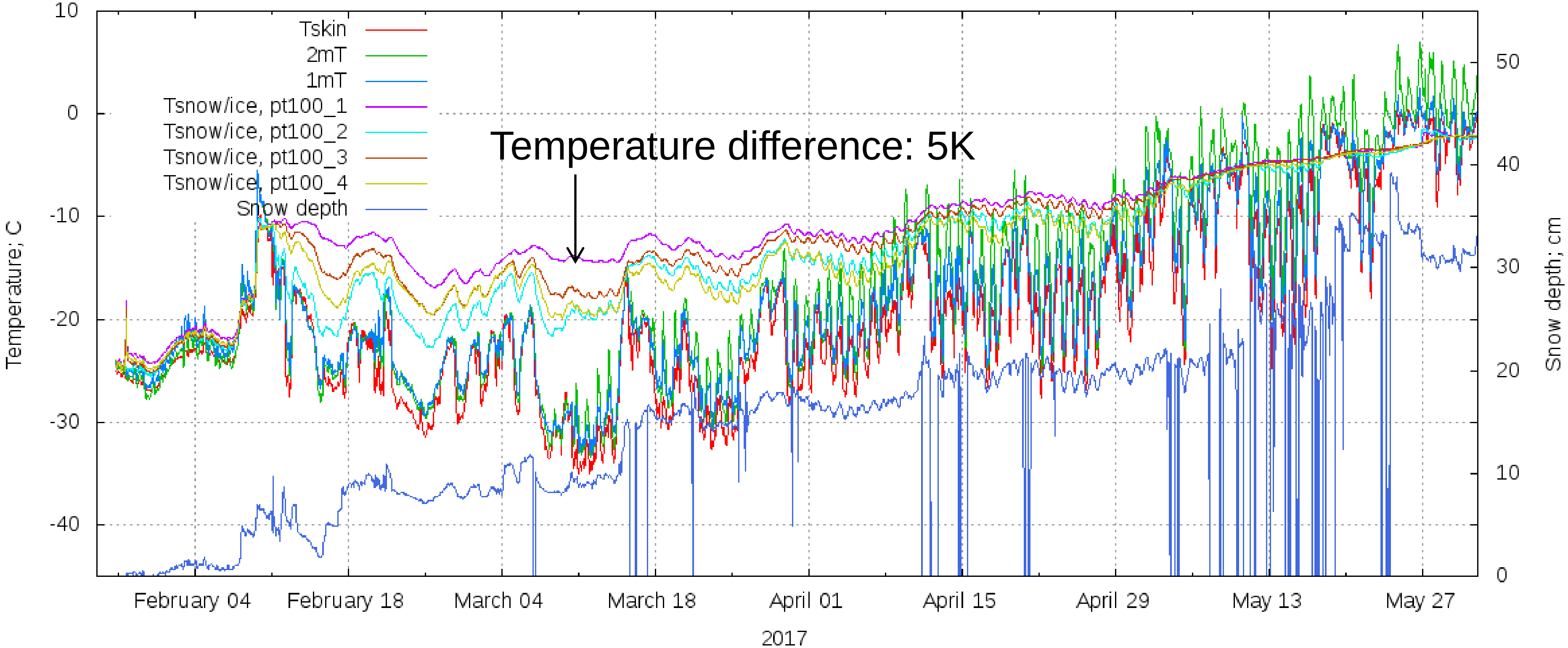
Measured ks using a probe: 0.14 W/mK
Derived ks from temp gradients and ice growth: 0.33 W/mK
(Sea ice has a thermal conductivity near 2.1 W/mK)

Sturm, M. D. K. Perovich, J. Holmgren. 2002. Thermal conductivity and heat transfer through the snow on the ice of the Beaufort Sea. JGR 107(C21), 8043, doi:10.1029/2000JC000409

Weather station in North West Greenland



Temperatures and snow depth from the weather station 2017



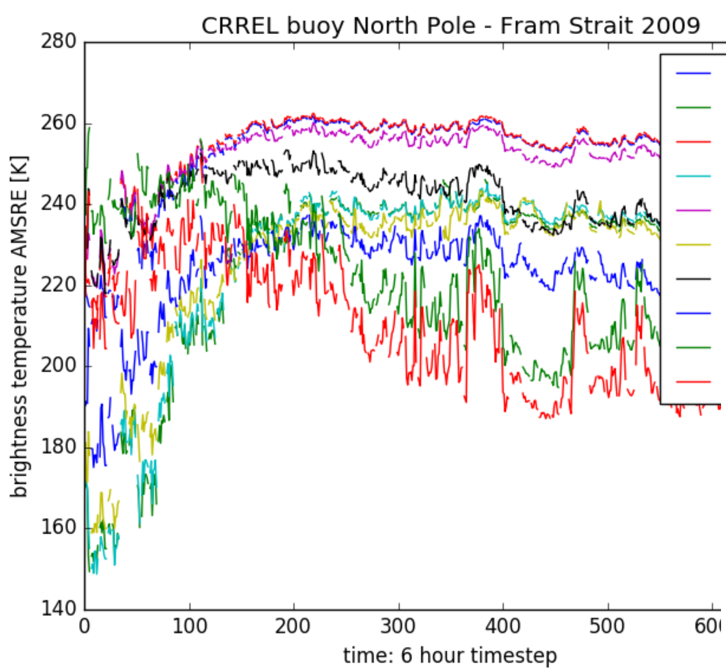
How to measure snow?

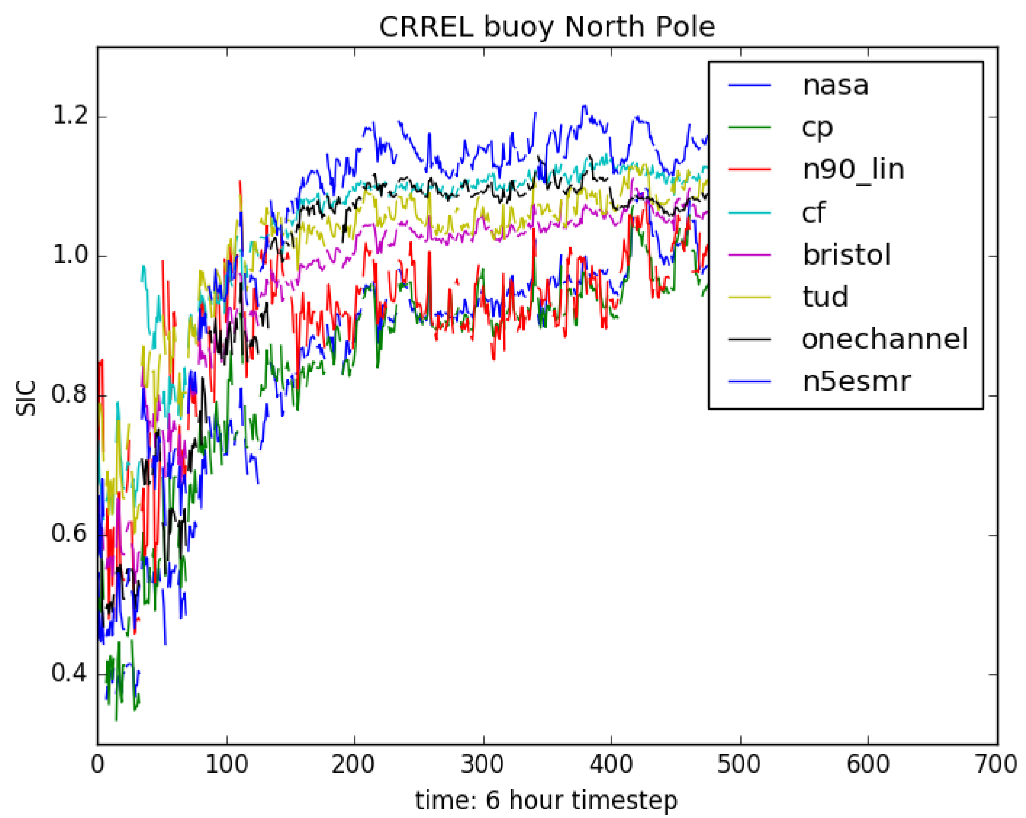
- Ice mass balance buoys: point measurements, interfaces derived from temperature profile.
- Snow radar: NASA Operation Ice Bridge (OIB), long transects covering different ice types, data in the Arctic are primarily from March and April
- Campaigns: measuring along snow lines, can include detailed description of density, grain size, temperature and salinity.

One of the most comprehensive and also publicly available datasets where microwave data is combined with snow data is the ESA CCI Round Robin Data Package: http://www.seaice.dk/sicci2/

The round robin data package for snow and sea ice (concentration)

www.seaice.dk/sicci2/

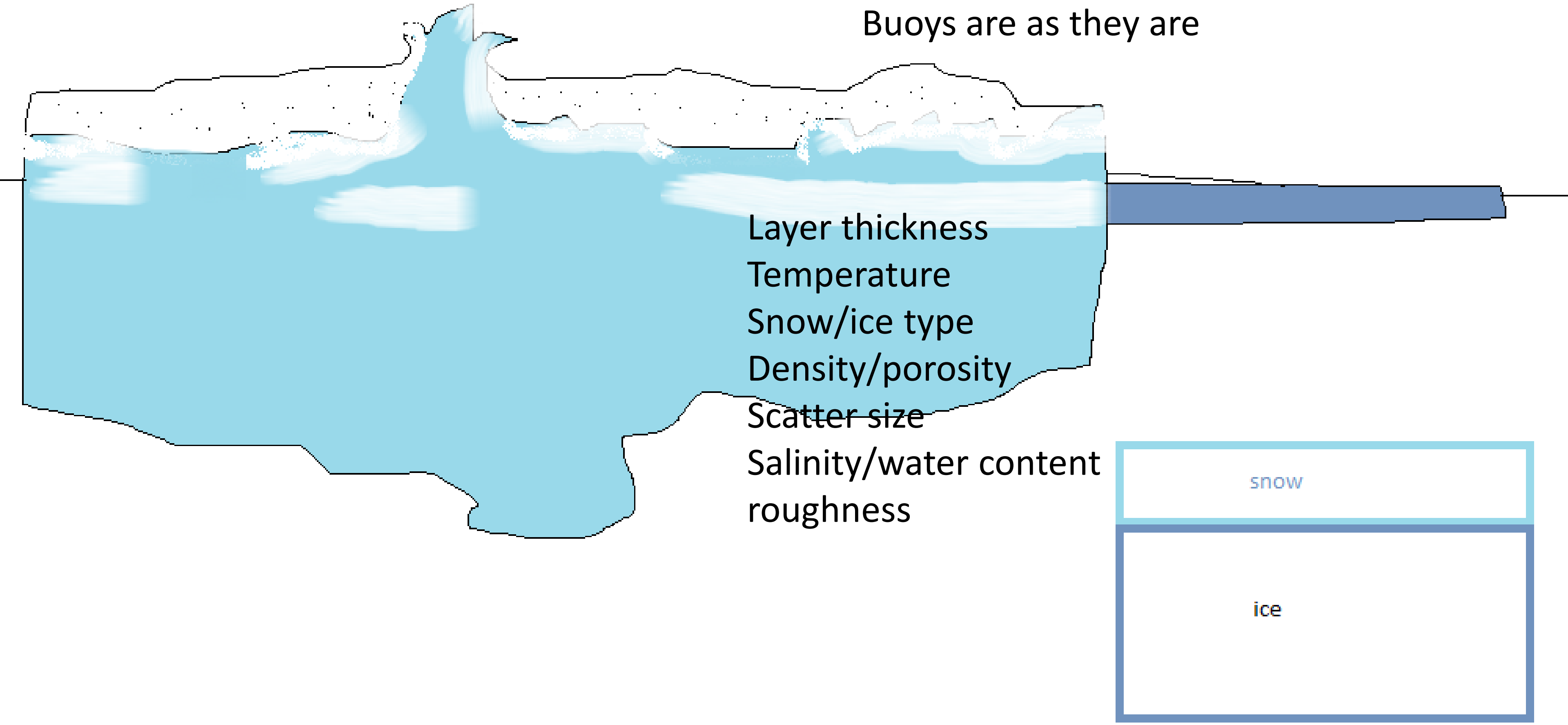




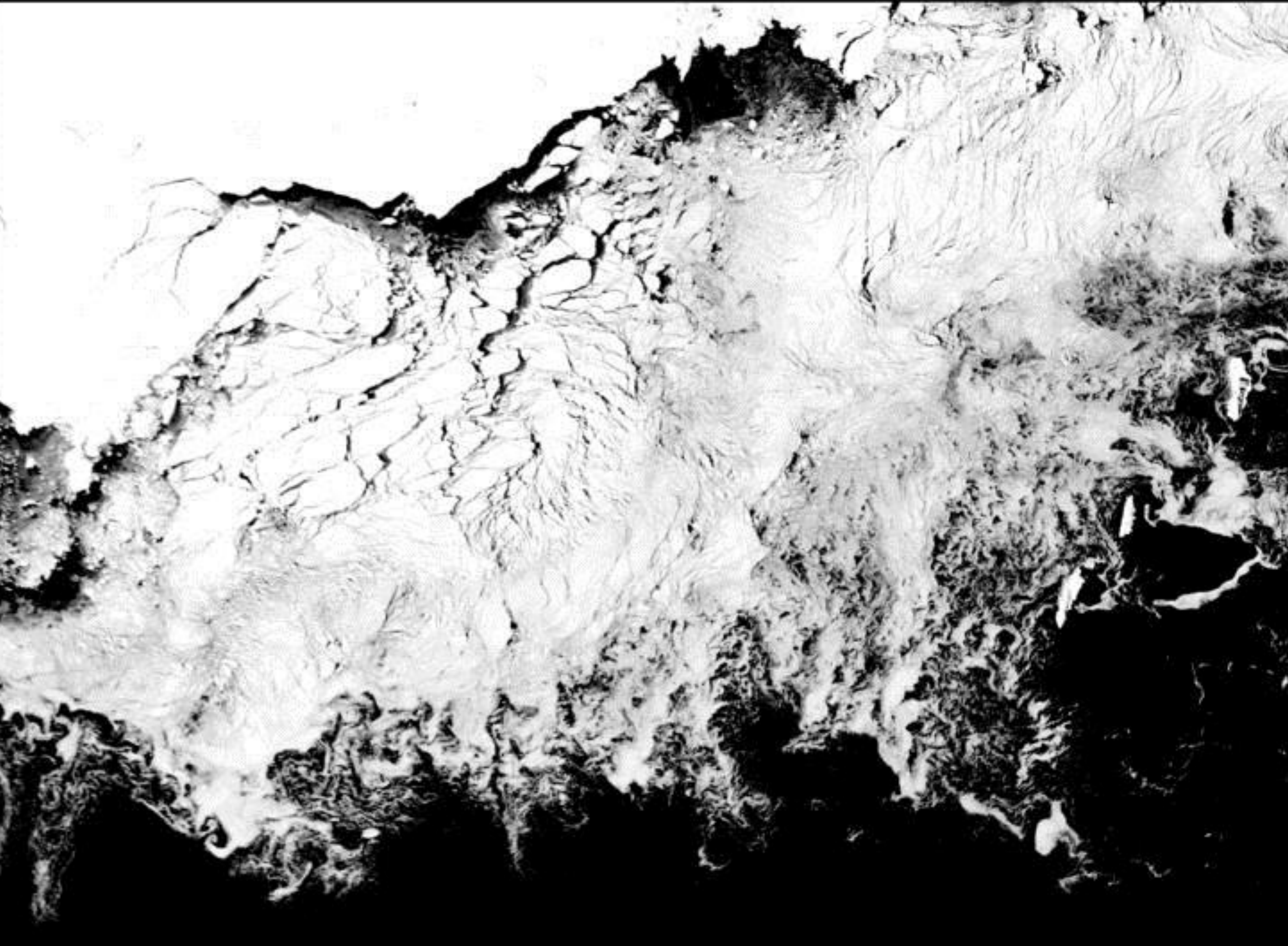
Point vs spatially averaged footprints

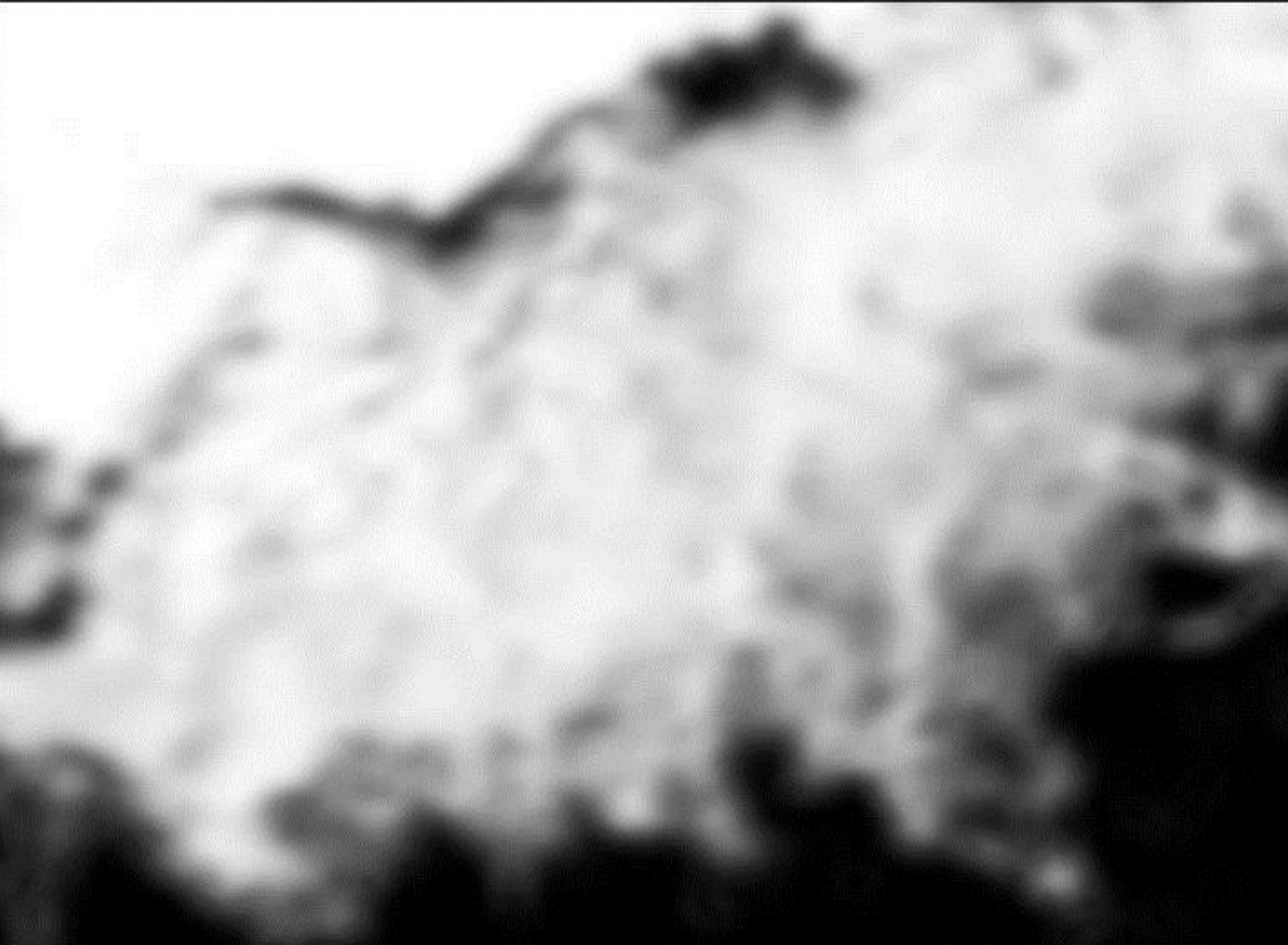
Sea ice concentration
Spatial distribution of snow

RRDP
Satellite data are on a 50 km grid
OIB are averaged on 50km sections
Buoys are as they are



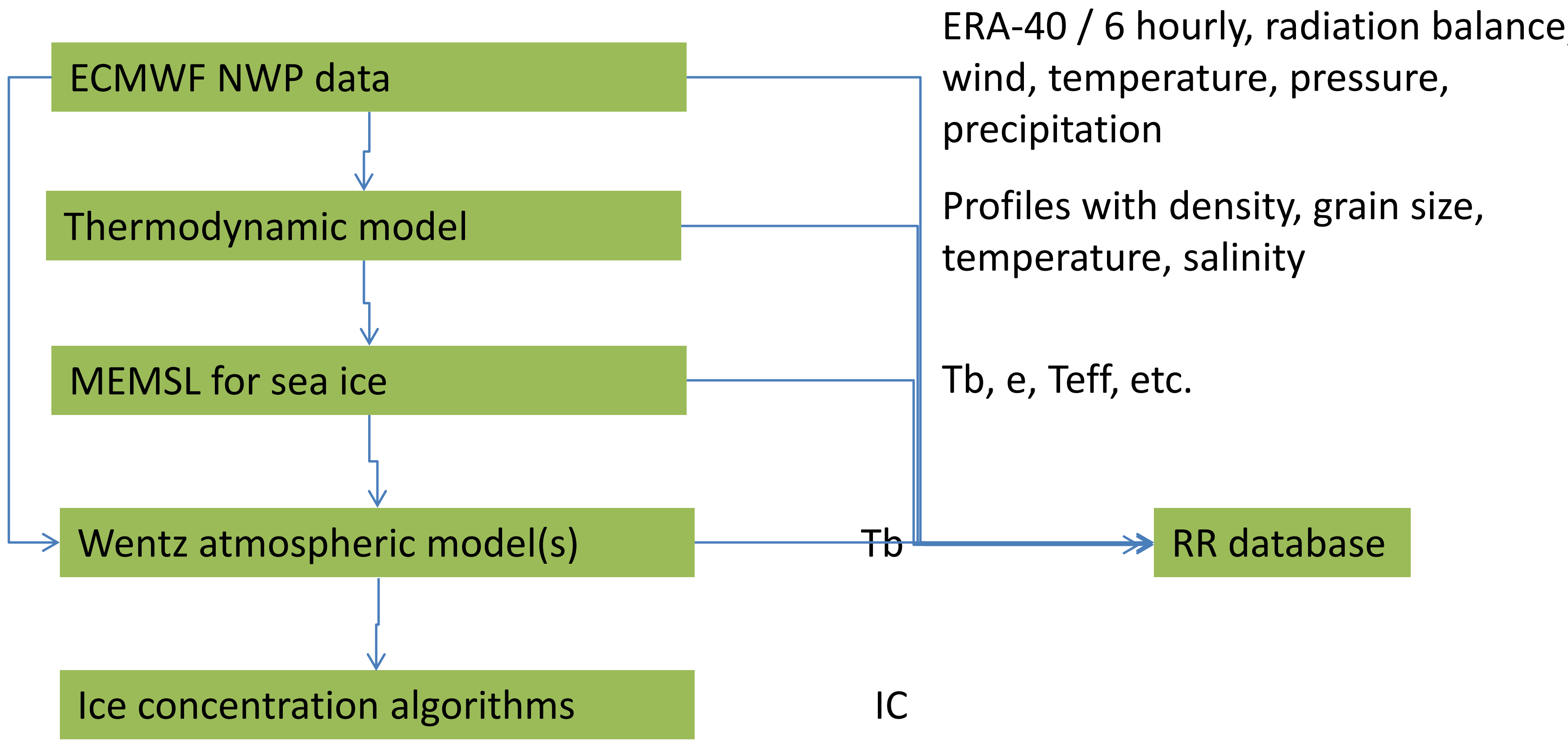
Layer thickness
Temperature
Snow/ice type
Density/porosity
Scatter size
Salinity/water content
roughness





Microwave radiometry

The simulated data

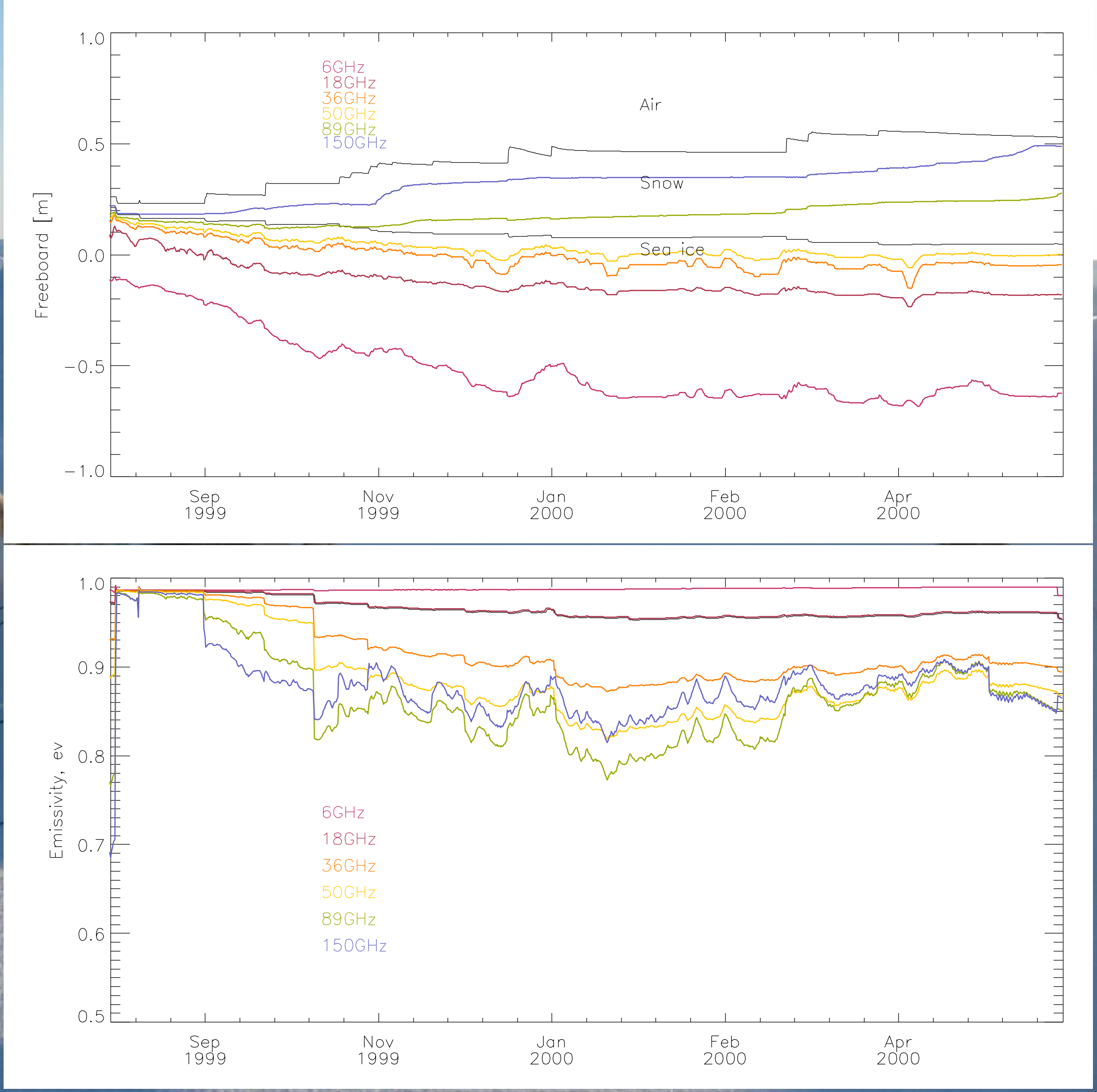


The system is described in:
Tonboe, R. T. The simulated sea ice thermal microwave emission at window and sounding frequencies. Tellus 62A, 333-344, 2010.
Tonboe, R. T., G. Dybkjær, J. L. Høyer. Simulations of the snow covered sea ice surface temperature and microwave effective temperature. Tellus 63A, 1028-1037, 2011.

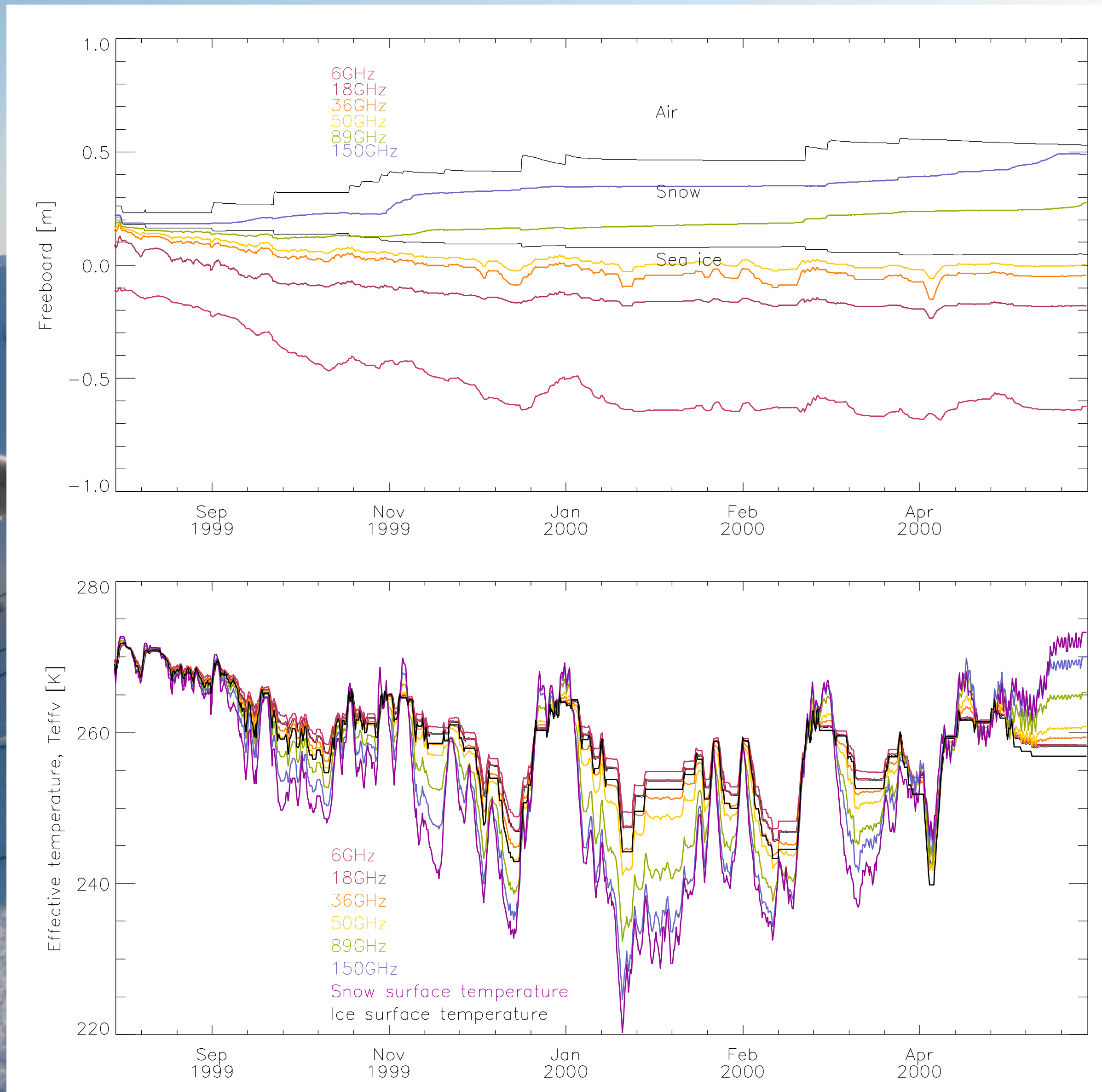
Energy and mass balance

- Air temperature
- Wind speed
- Radiation balance
- Snow accumulation
- Ice growth

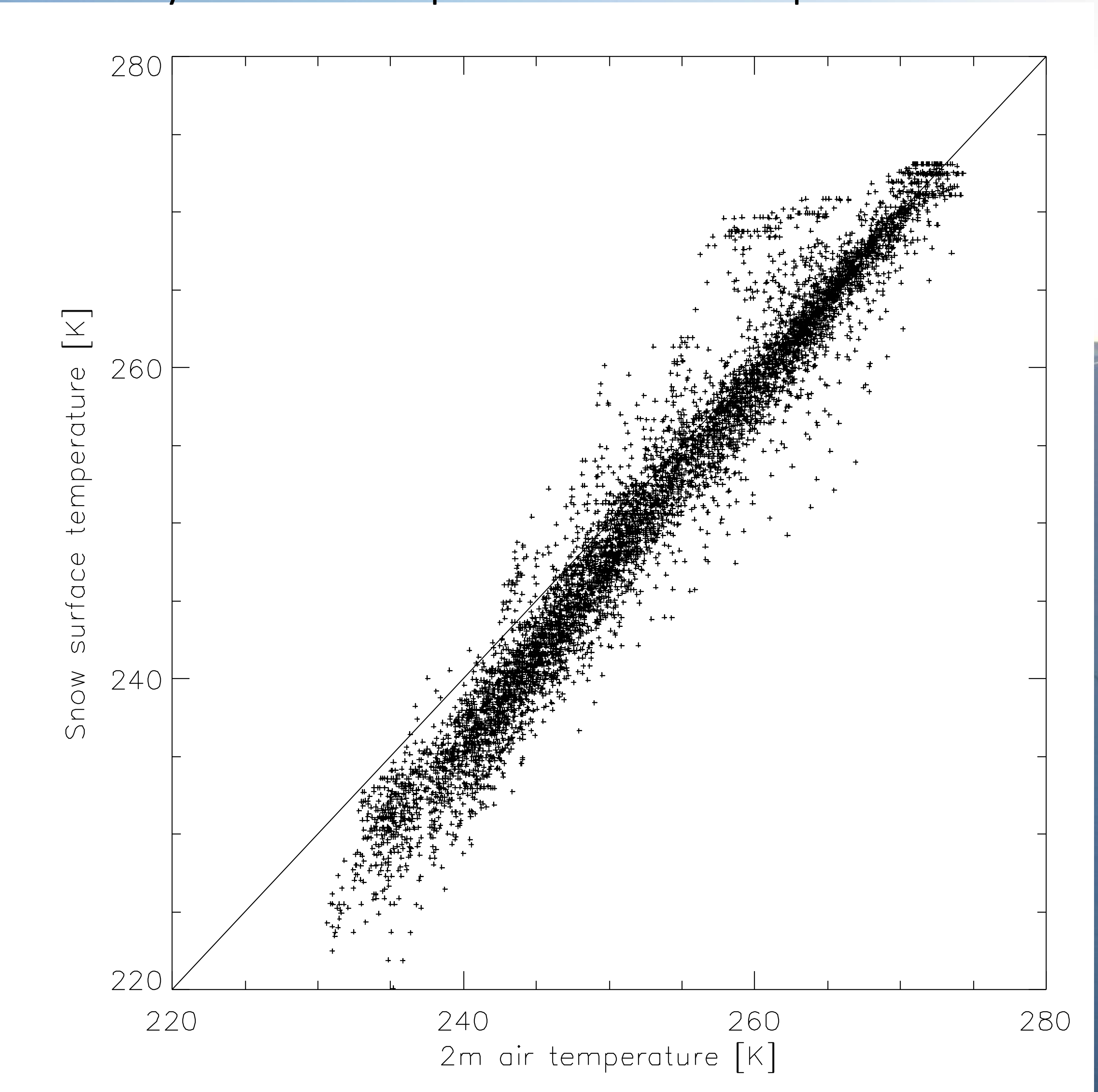
The microwave emissivity (6-150GHz)



The effective temperature (6-150GHz)

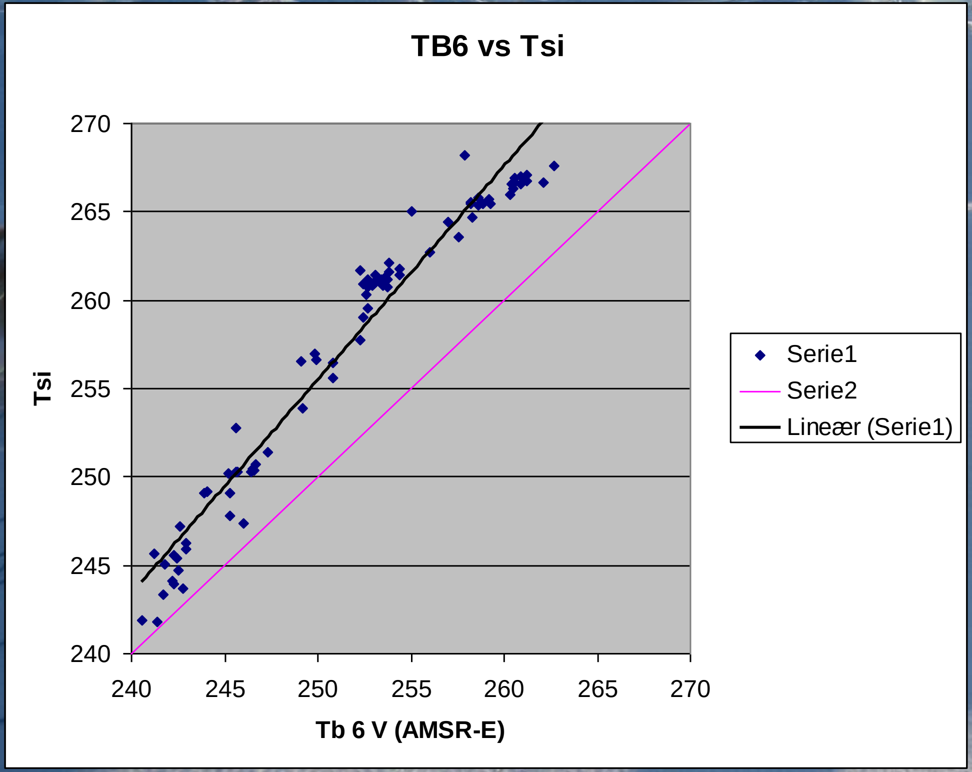


Multiyear ice air temperature surface temperature

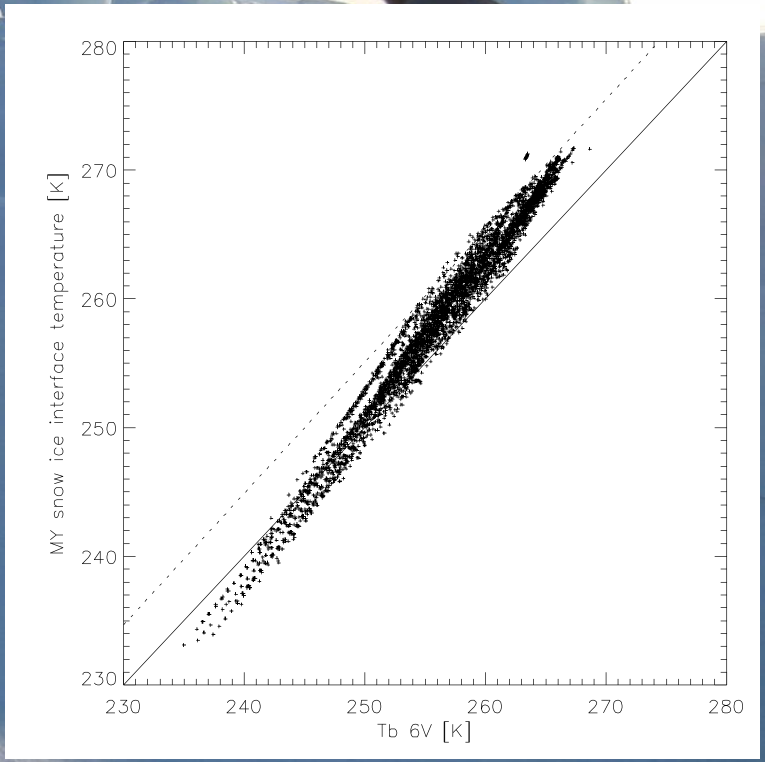


Penetration depth is a function of (ice) temperature and *vice versa*

Measurements collocated with satellite observations (from Phil Hwang)



6 simulated multiyear ice profiles



Physical temperature vs. effective temperature?

Snow depth algorithms using microwave radiometer data

Proxy for scattering, hs = a1 + a2 GRV(ice)

Markus, T. and D. J. Cavalieri. 1998. Snow depth distribution over sea ice in the Southern Ocean from satellite passive microwave data. In Antarctic Sea Ice: Physical Processes, Interactions and Variability, 19-39. Washington, DC: American Geophysical Union.

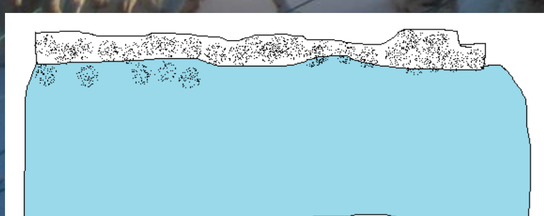
Thermodynamical effect of the snow cover

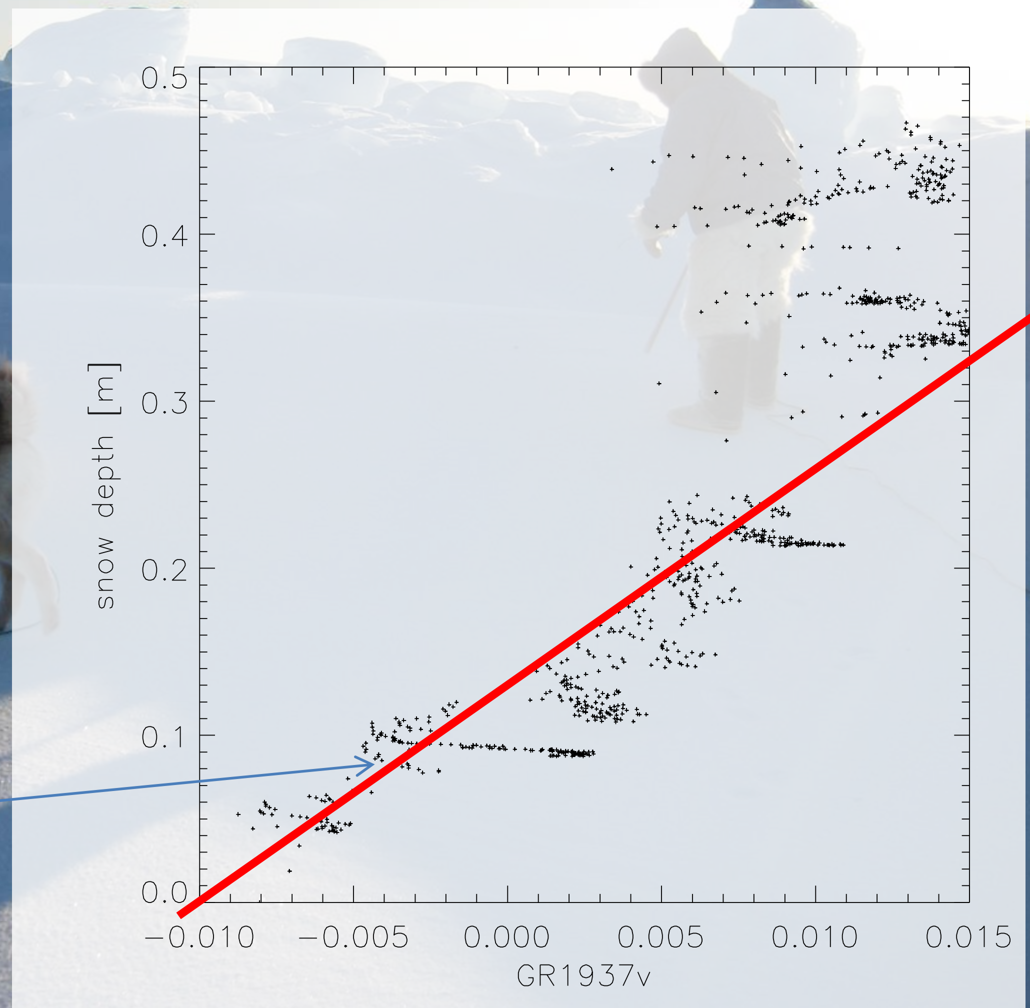
Maass et al. Snow thickness retrieval over thick Arctic sea ice using SMOS satellite data. The Cryosphere 7, 1971-1989, 2013.

Retrieval of snow depth is either retrieved directly (SD=f(GR…)) or by inversion (Tb=f(SD…)). Sometimes a translation between the detailed input to the model and the bulk parameters to retrieve.

The snow thickness algorithm -an empirical regression model

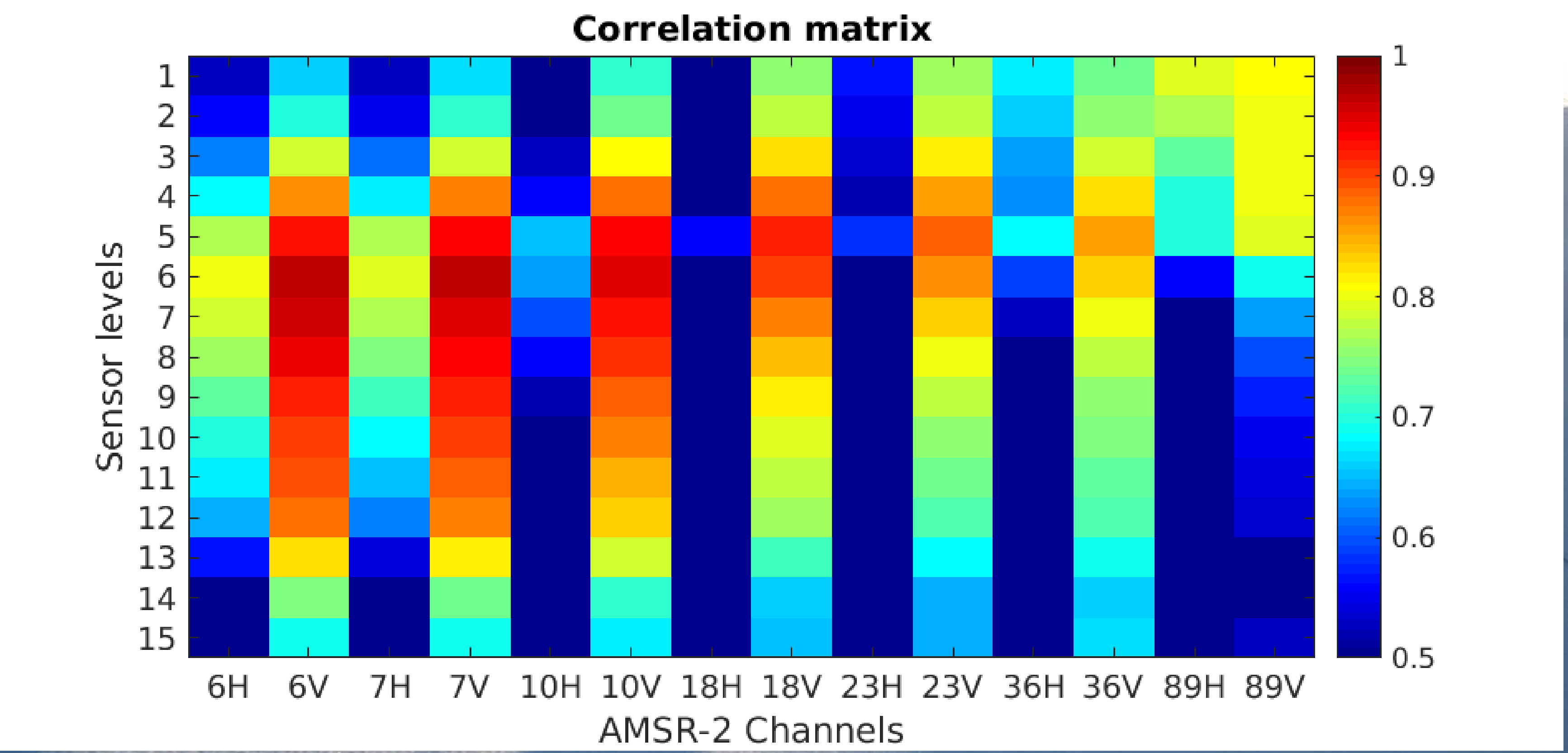
Depth hoar above ice surface
Lincoln Sea 2006





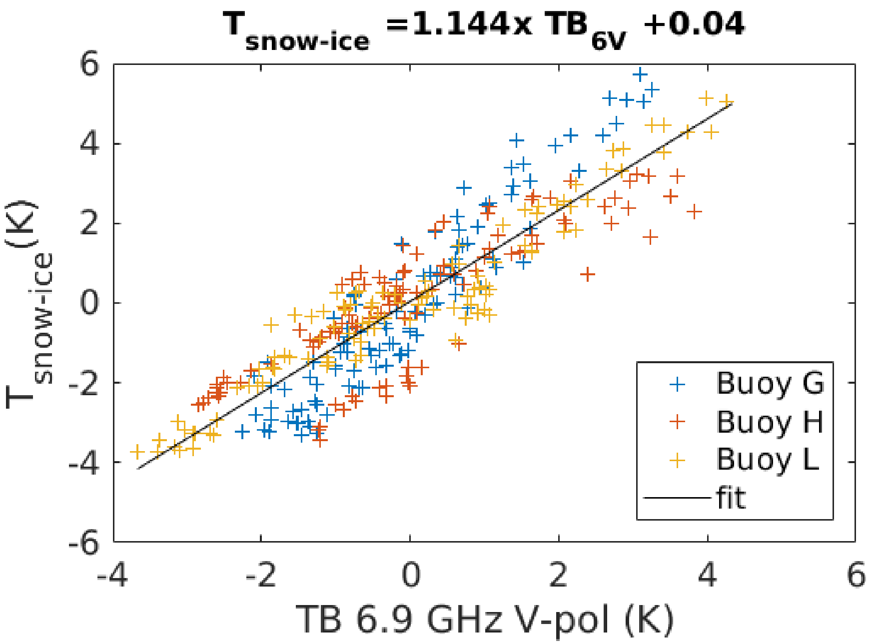
The line slope and offset are based on a particular dataset

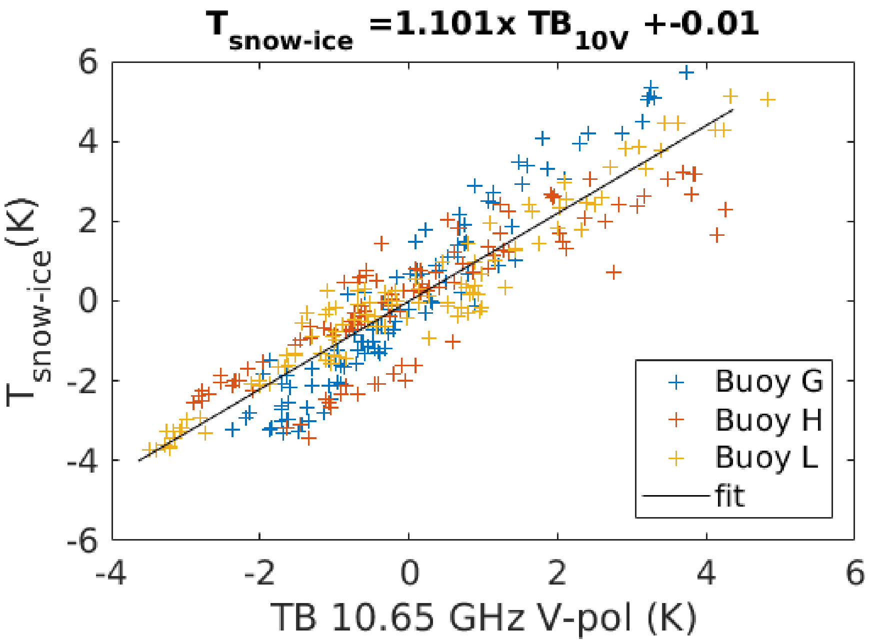
CRREL buoy 2012J



Top story on http://www.osi-saf.org/

The snow ice interface temperature

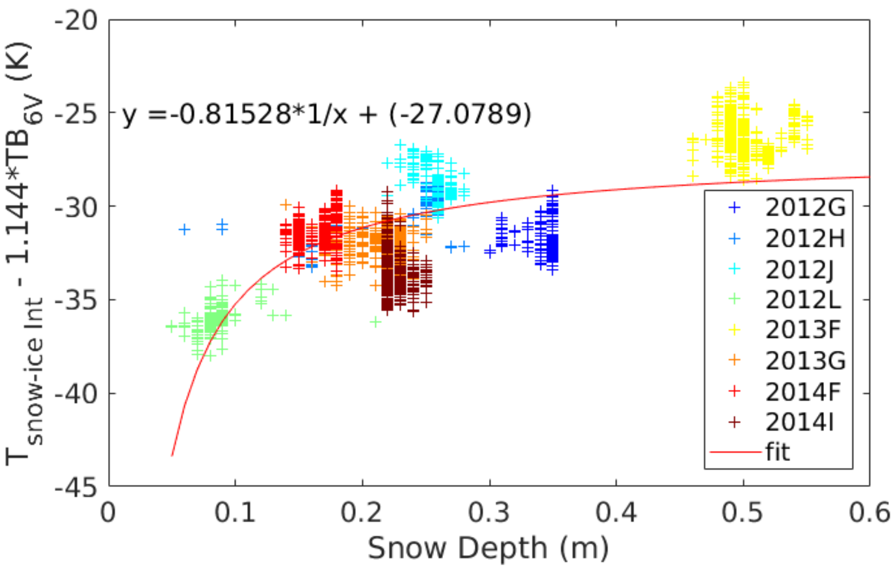


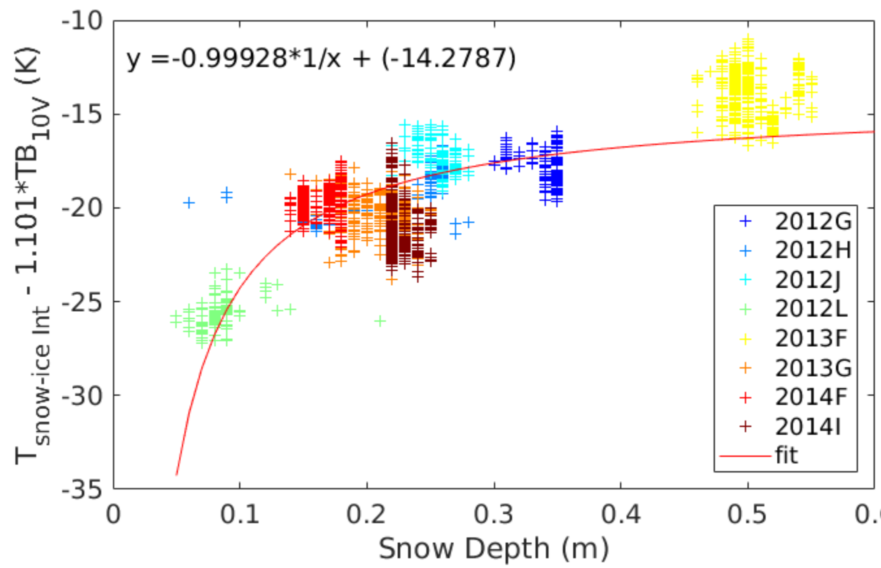


$$\frac{dT}{dz} = \frac{Ta - Tsi}{hs}$$

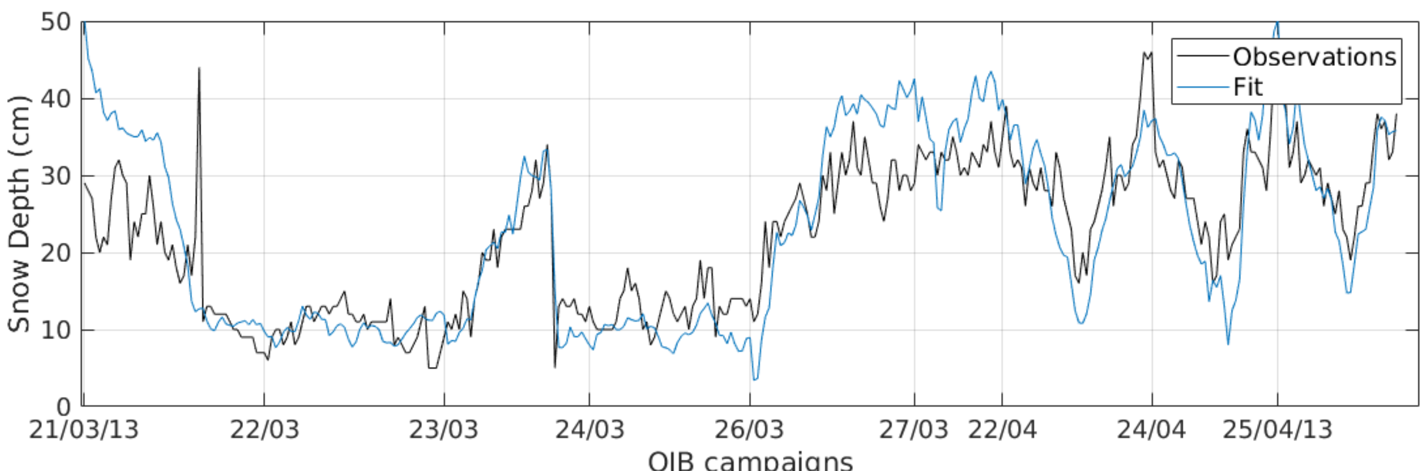
$$Tsi = Ta/2 + C/hs$$

The snow depth dependence





$$hs = 1.7701 + 0.017462 \times T6v - 0.02801 \times T18v + 0.0040926 \times T37v$$



Different ways to retrieve snow depth

Simple regression models

Snow_depth = f(GR1836v), e.g. Markus and Cavalieri, 1998

Snow_depth = f(GR0610v, GR0618v, …..) using linear regression and the RRDP data.

Snow depth = f(Tb6v, Tb18v...)

Brightness temperature models based on regression combined with OE

```
function [T6vsim,T6hsim,T10vsim,T10hsim,T18vsim,T18hsim,T36vsim,T36hsim,T89vsim,T89hsim]=reg_mod13(IST,SD,IT)

%the mar+april 2013 model

T6vsim= 151.981535394 + 0.39827296166 .* IST+ 23.3600203008 .* SD -3.03183834111 .* IT;

T6hsim= 55.2623240539 + 0.687577210357 .* IST+ 12.9621301692 .* SD -1.66486943272 .* IT;

T10vsim= 145.878105173 + 0.435432823207 .* IST+ 0.743658800361 .* SD -4.20200228328 .* IT;

T10hsim= 45

T18vsim= 13
```

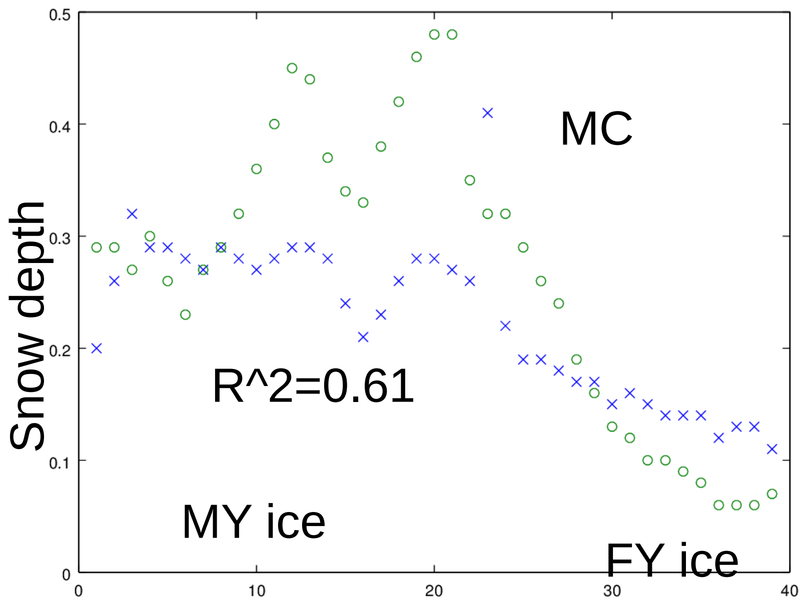
Brightness temperature model based on physics combined with OE

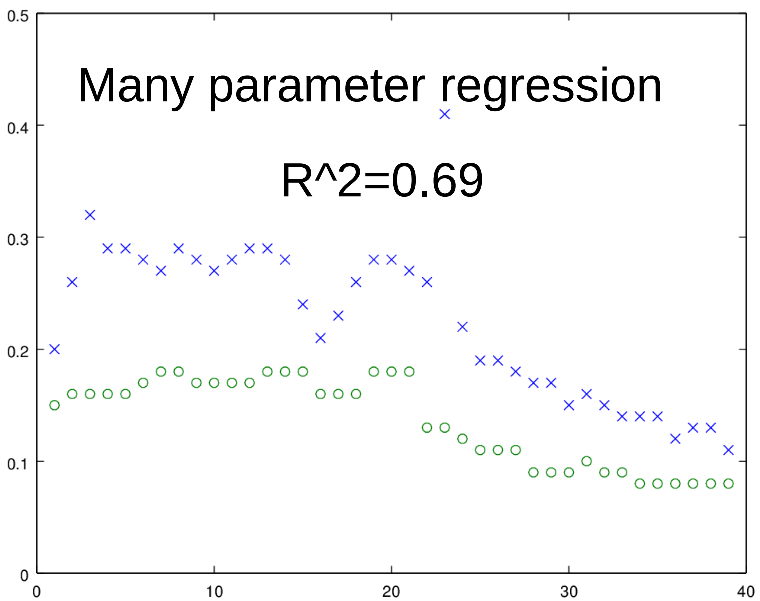
High resolution 1-D emission model - a sea ice version of MEMLS in combination with optimal estimation.

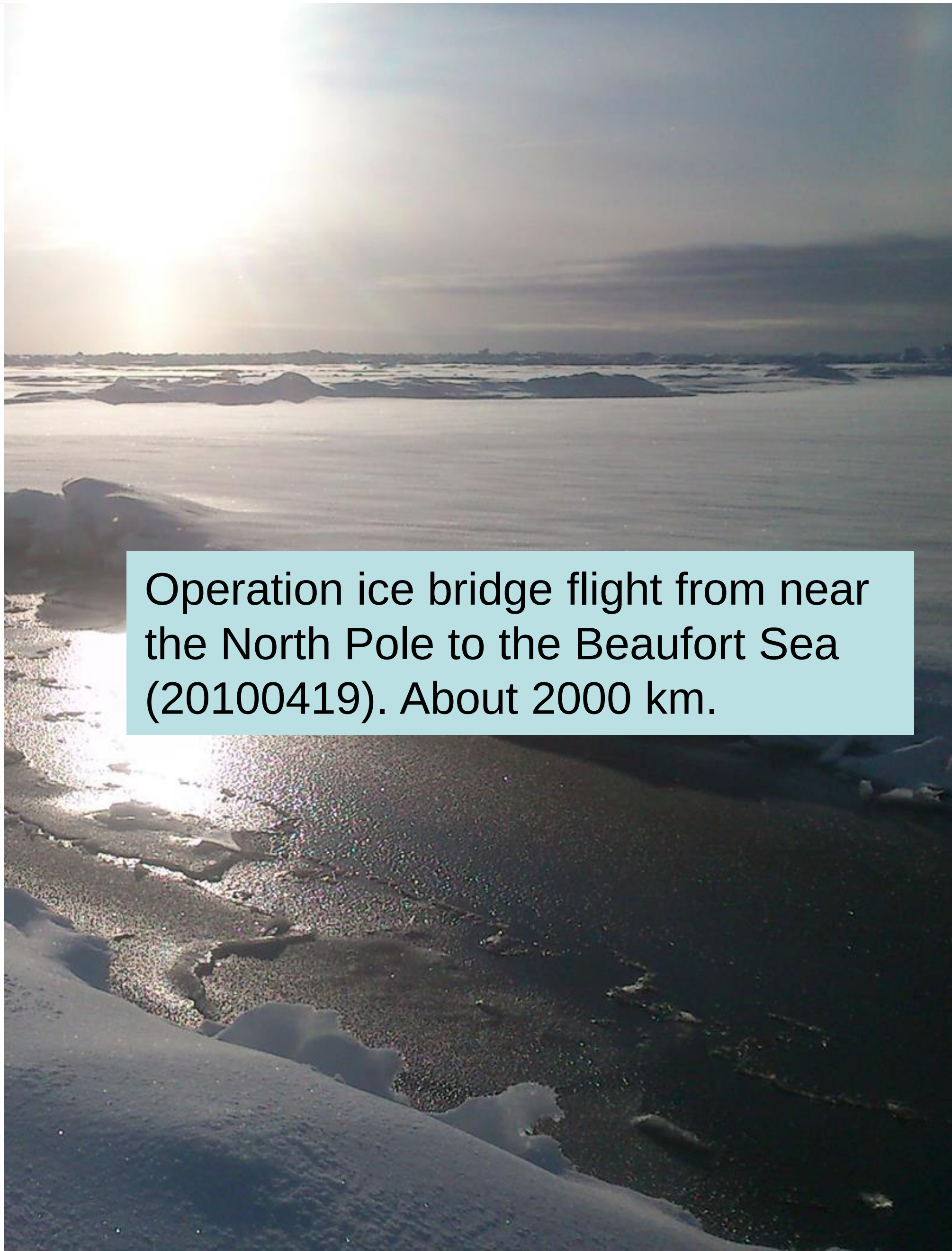
```
T36hsim= 131.862853412 + 0.429489868157 .* IST -214.352191714 .* SD -3.03524993537 .* IT;

T89vsim= 2.52567864217 + 0.902202528995 .* IST -180.427137566 .* SD+ 1.90480465092 .* IT;

T89hsim= 31.1206976877 + 0.743826485118 .* IST -184.806381816 .* SD+ 3.19723383624 .* IT;
```

Optimal estimation aka statistical estimation theory needs first guess and covariance matrices

Simple regression model case

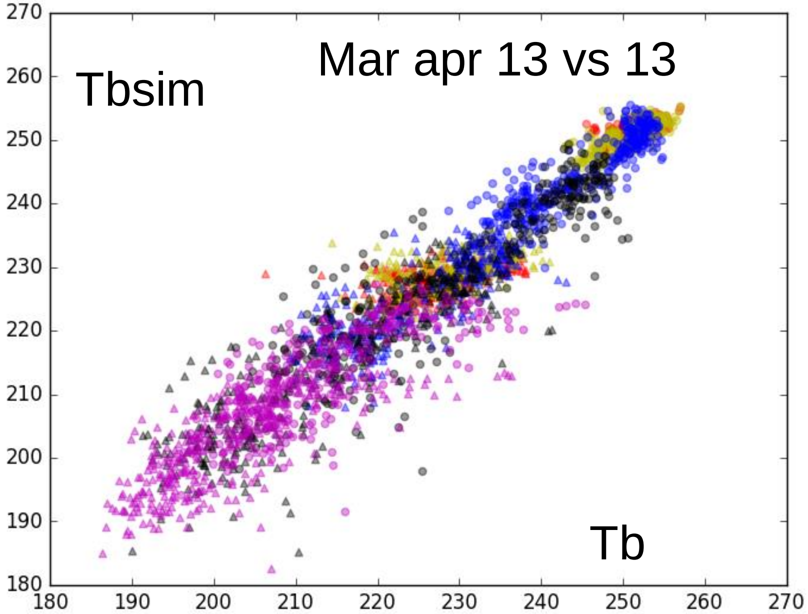


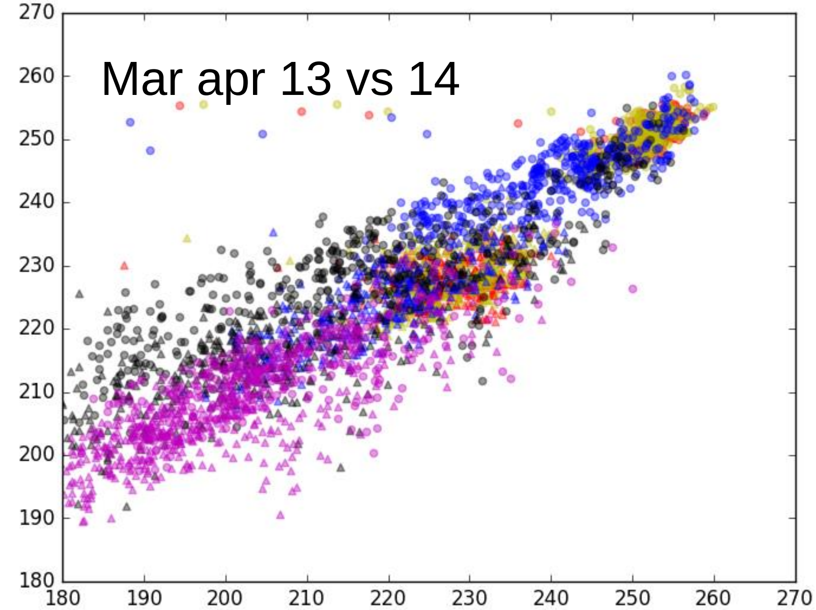


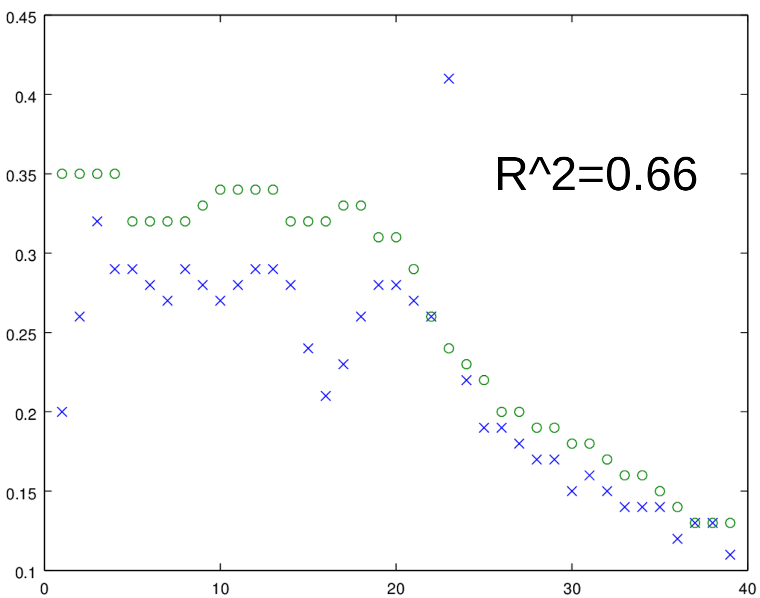


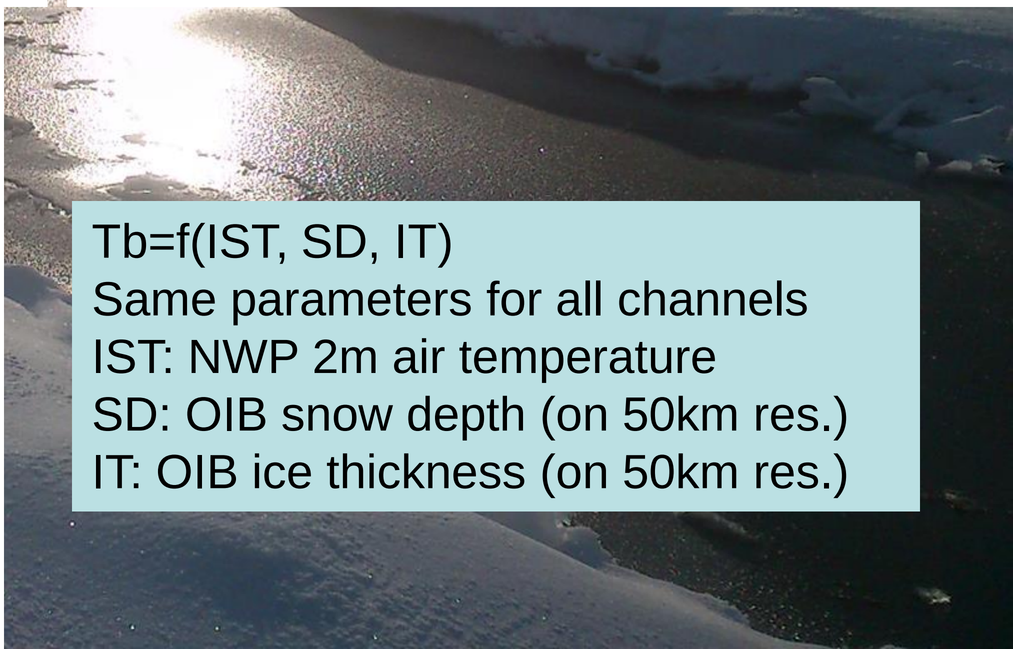
Operation ice bridge flight from near the North Pole to the Beaufort Sea (20100419). About 2000 km.

Brightness temperature model based on regression + OE









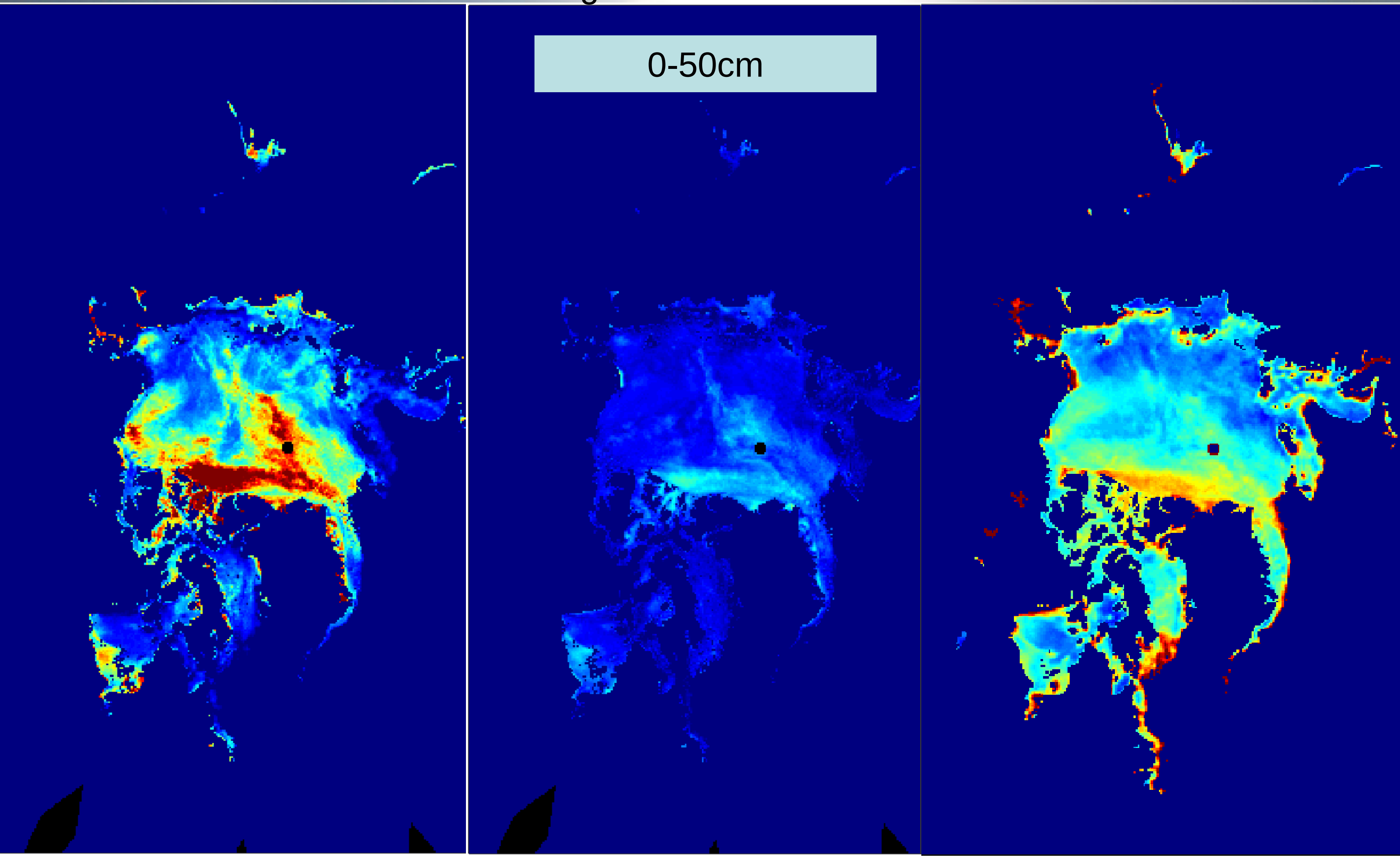
Tb=f(IST, SD, IT)
Same parameters for all channels
IST: NWP 2m air temperature
SD: OIB snow depth (on 50km res.)
IT: OIB ice thickness (on 50km res.)

The NRT AMSR2 daily L3 25km Tb and sea ice concentration polar grids

MC

Multi parameter regression

Tb reg. Model + OE



Optimal estimation with multilayer sea ice emission model

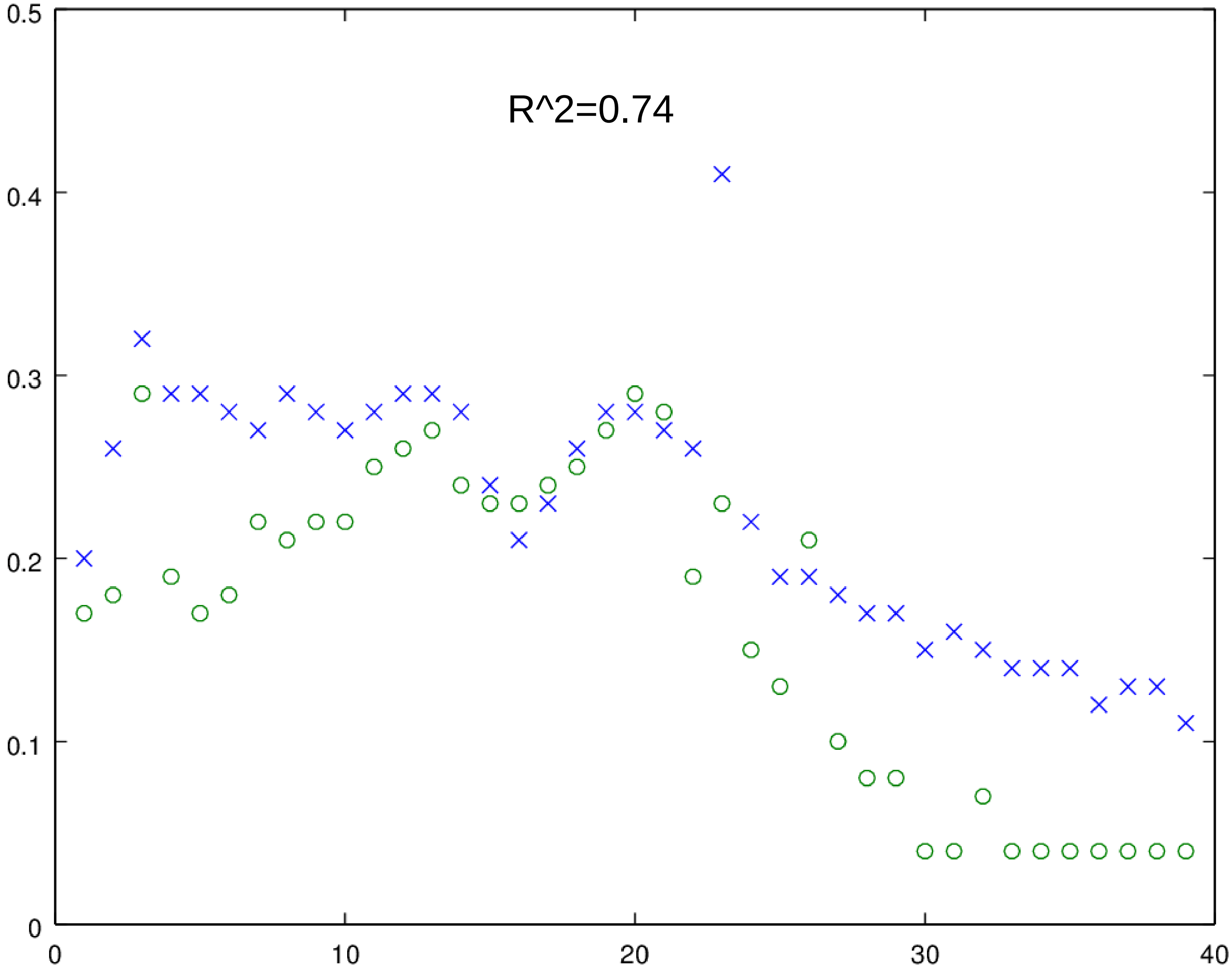
First guess

snow depth = 1.77+0.017*T6v-0.028*T18v+0.0041*T37v (Lise’s equation)
Ts=1.53*T6v-136.6 [220-272 K]
Salinity=8.5+100GR [0-7ppt]
Snow density=320kg/m3
Ice thickness=1-25GR [max 3.5 m]

Vertical distribution

Temperature distribution: linear profile
Snow grain size distribution: linear profile [0.07-0.3 mm] in ice 1.5 mm
Salinity distribution: linear distribution in ice, variable at top and fixed at 3 ppt at the bottom.

Multilayer physical model and OE



Conclusions

It is very important to have a good snow and Tb dataset

A perfect match is not expected but the OIB RRDP files seems to give information on the scale of the foot-print.

Even simple models seem to describe the snow depth variability and there is potential for improving the current situation

More simple physical models will be tested suitable for OE

Snow is very important for many applications and for the microwave signatures.