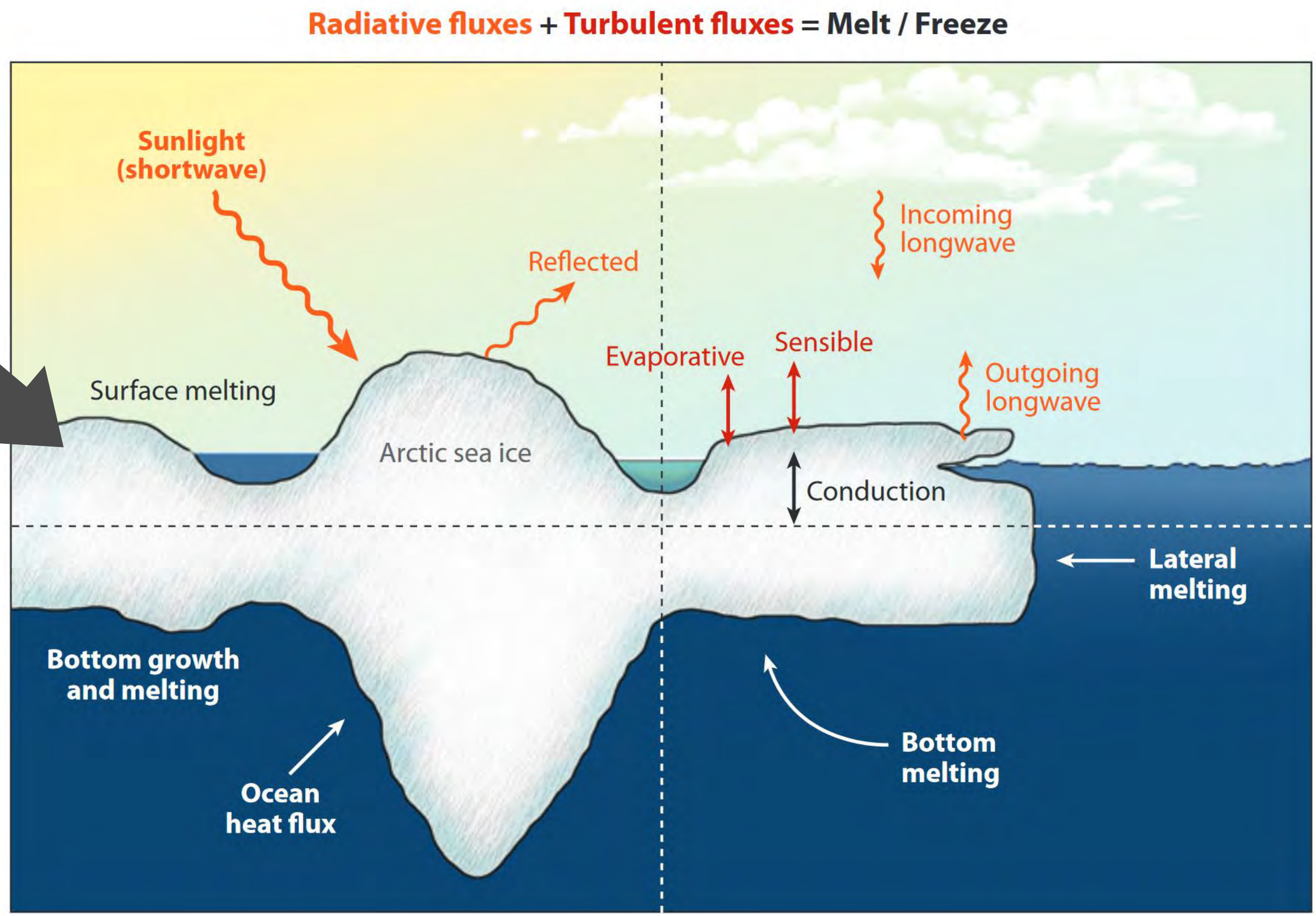
Sea Ice Growth And Decay

A Remote Sensing Perspective

ESA Cryosphere Remote Sensing Training Course 2018

Sea Ice Growth & Decay

Add snow here



[Loss of Sea Ice in the Arctic]
Donald K. Perovich and Jacqueline A. Richter-Menge Annual Review of Marine Science 2009 1:1, 417-441

Sea Ice Remote Sensing

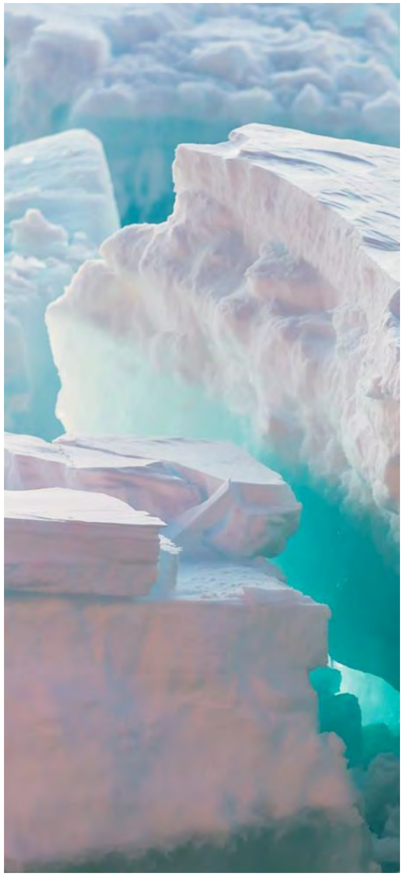
Method	Physical Property	Sensor Type	Geophysical Variable
Passive Microwave	Surface Emissivity ~ 1 – 100 GHz	Radiometer	Sea Ice Concentration Sea Ice Classification Sea Ice Motion Thin Sea Ice Thickness (*Snow Depth*)
Active Microwave	Backscatter	SAR	Sea Ice Classification Sea Ice Motion Very Thin Sea Ice Thickness
		Scatterometer	Sea Ice Type
		Altimeter	Sea Ice Thickness (*Snow Depth*)
Optical	Spectral Albedo	Spectrometer	Floe Sizes Distribution Melt Pond Coverage Melt Pond Depth
Infrared	Surface Emissivity	Radiometer	Sea Ice Surface Temperature Thin Sea Ice Thickness
Laser	Backscatter	Altimeter	Sea Ice Thickness

What are the main processes of sea ice growth & decay?

How do they affect sea ice remote sensing?

How to observe these processes independently?

Formation
& Growth

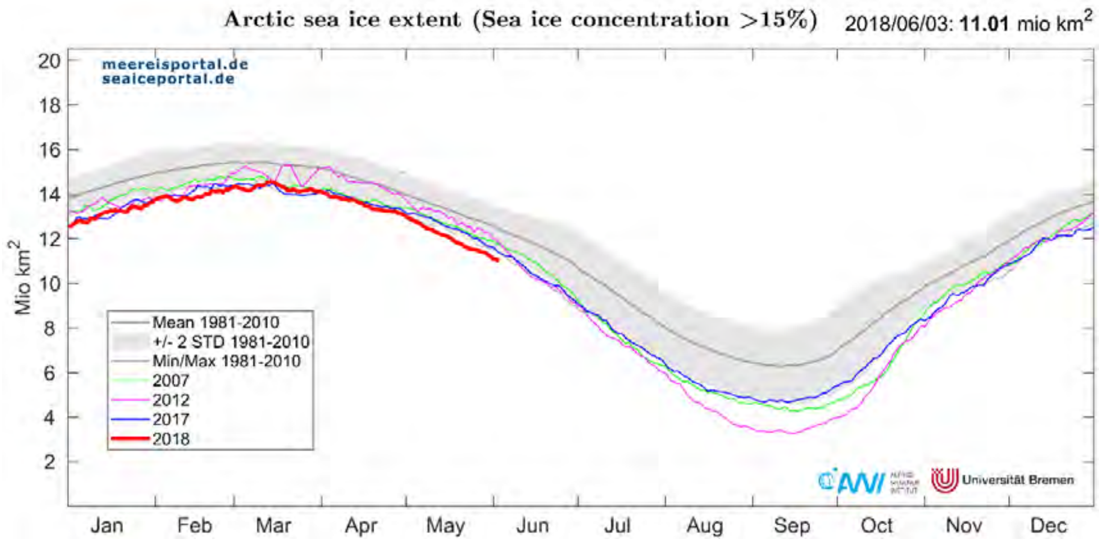


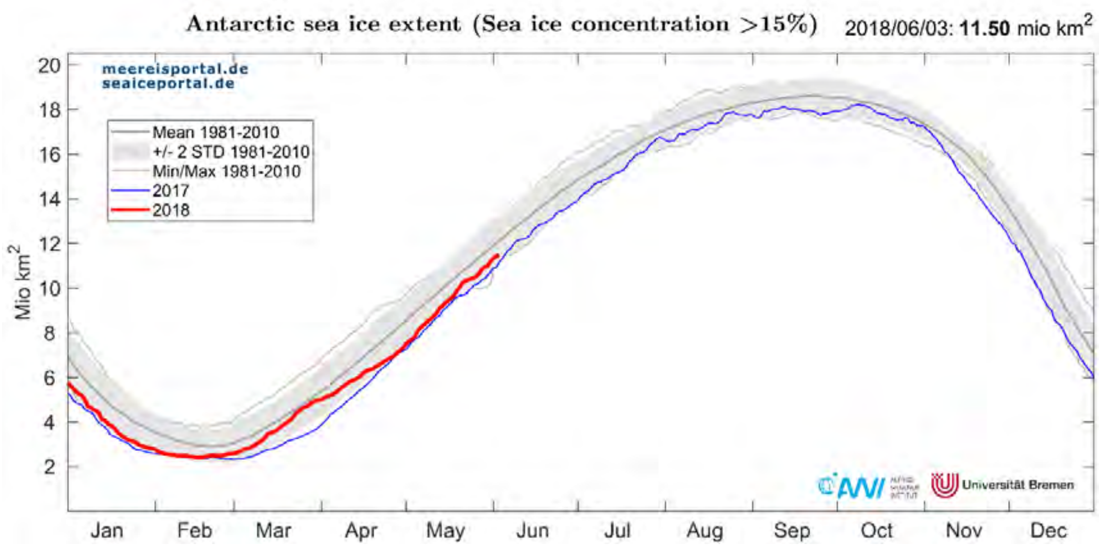
Redistribution

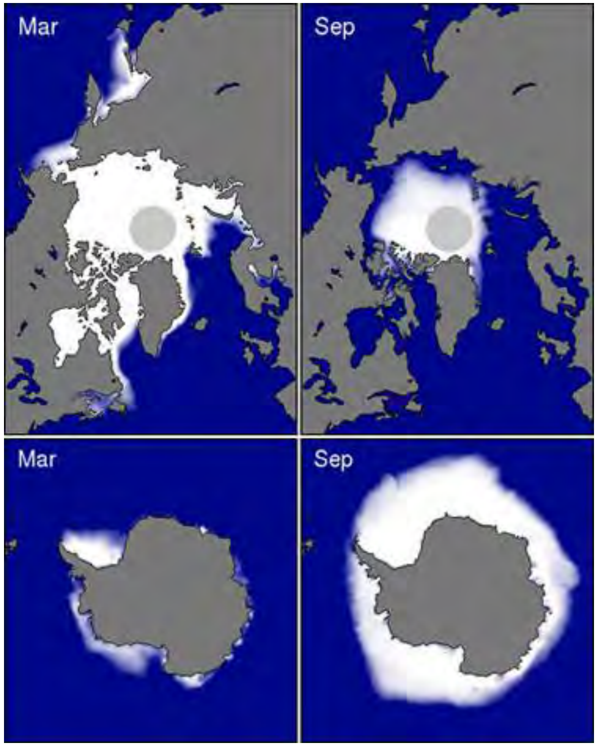
Snow Surface
Processes

Melt

Annual Cycle of Sea Ice







Sea Ice Extent

Area covered at least with 15% sea ice (according to passive microwave data)

Long-Term Sea Ice Trends

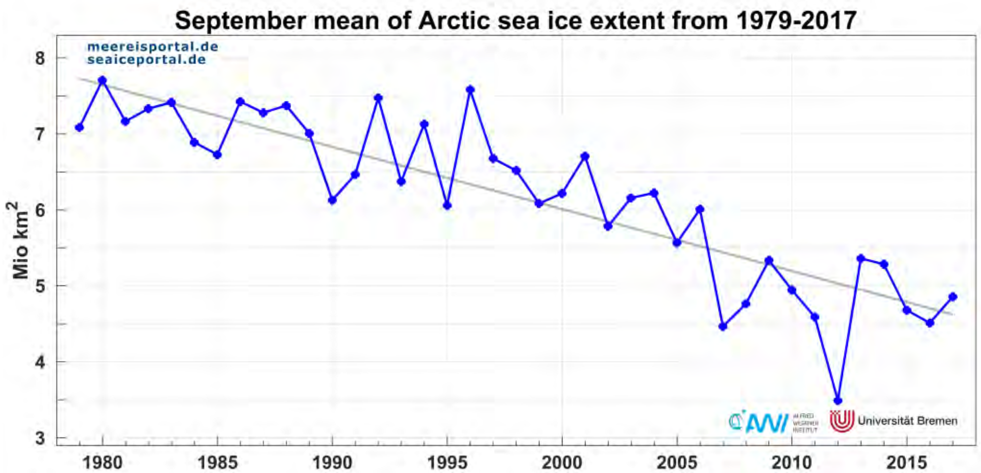
Sea Ice Extent

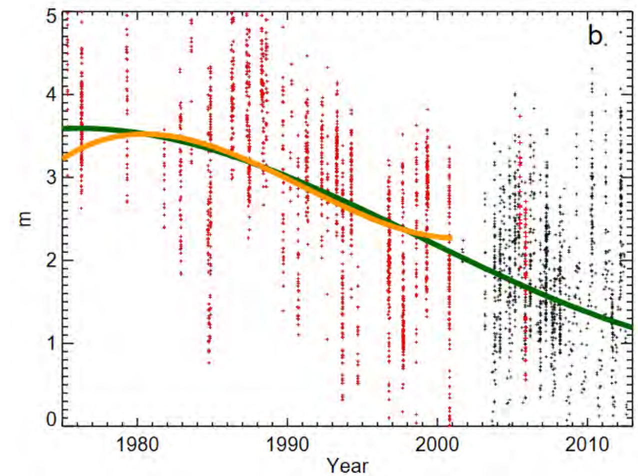
Passive Microwave Time Series

Sea Ice Thickness

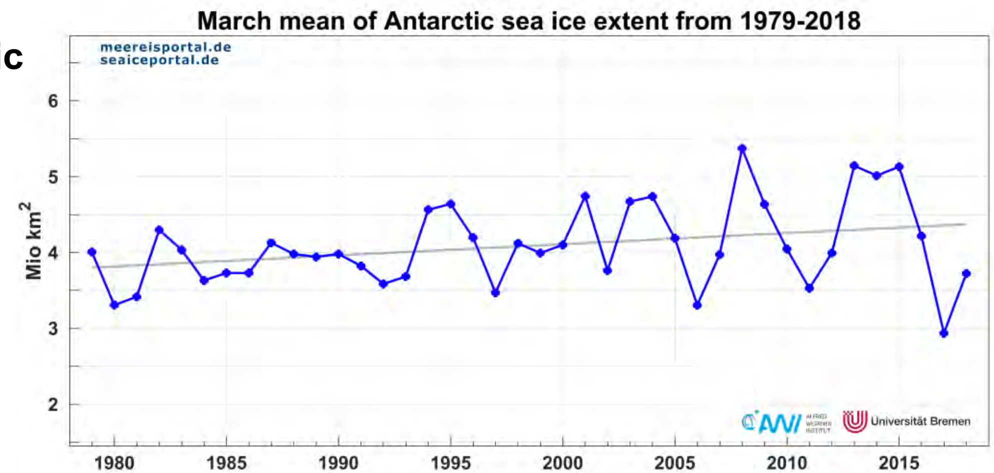
Submarines, Moorings, Airborne Surveys

Arctic



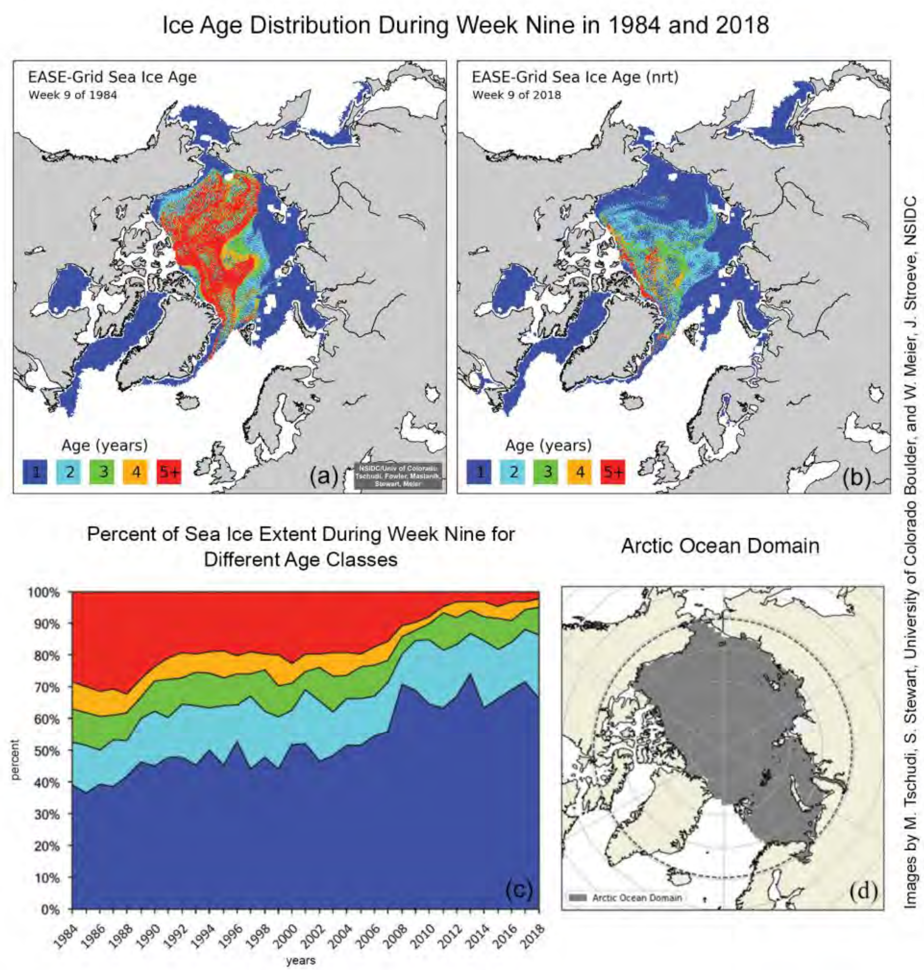


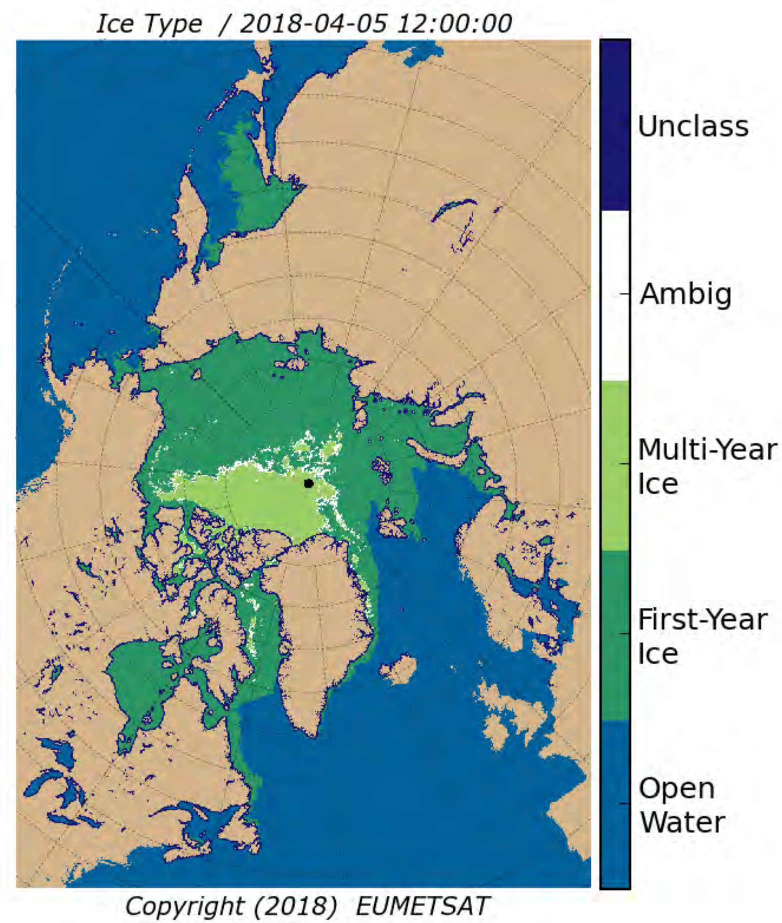
Antarctic



No comparable sea ice thickness data record

Sea Ice Age & Type



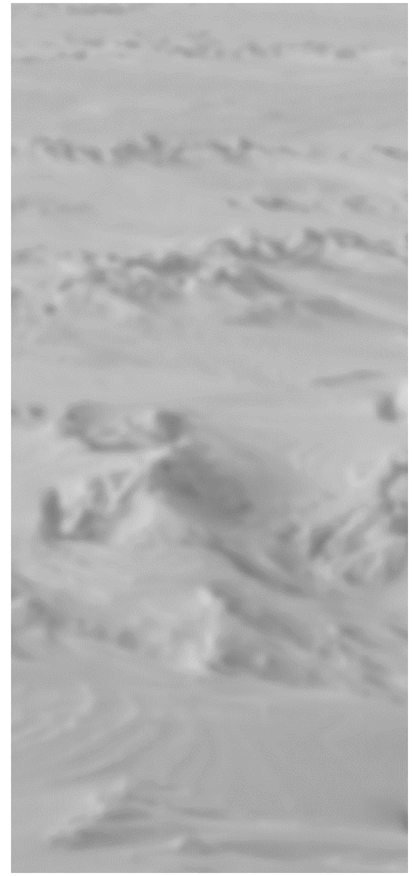


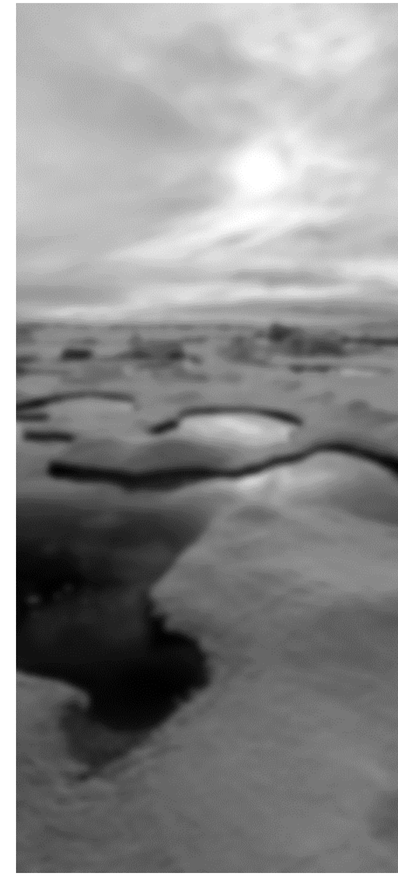
Sea Ice Age

Model with observed ice drift & concentration

Sea Ice Type

Passive & Active Microwave





Formation & Growth

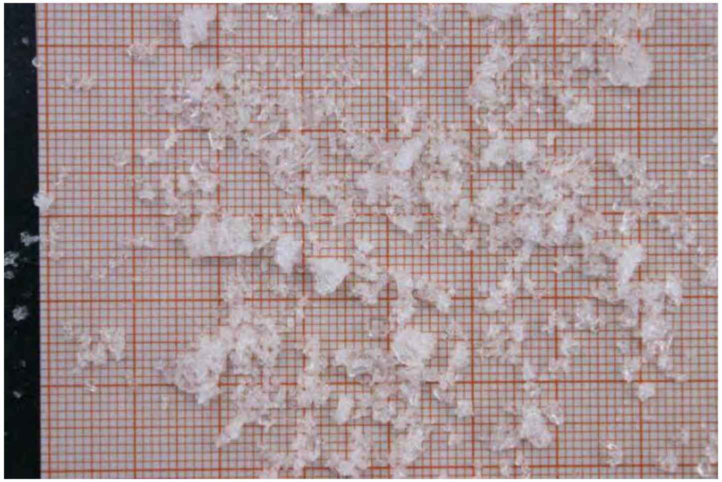
Redistribution

Snow Surface Processes

Melt

Early Sea Ice Formation

- Sea water (salinity 34 PSU) freezes at -1.86C
- Formation of loose ice crystals (Frazil Ice)
- Pure freshwater ice, salt segregation in liquid brine phase



Types of Sea Ice

Thickness

2	**Sea Ice Formation**
2.1	New ice
2.1.1	Frazil
2.1.2	Grease ice
2.1.3	Slush
2.1.4	Shuga
2.2	Nilas
2.2.1	Dark nilas
2.2.2	Light nilas
2.2.3	Ice rind
2.3	Pancake ice
2.4	Young ice
2.4.1	Grey ice
2.4.2	Grey-white ice
2.5	First-year ice
2.5.1	Thin first-year ice / white ice
2.5.1.1	Thin first-year ice / white ice first stage
2.5.1.2	Thin first-year ice / white ice second stage
2.5.2	Medium first-year ice
2.5.3	Thick first-year ice
2.6	Old ice
2.6.1	Residual ice
2.6.2	Second-year ice
2.6.3	Multi-year ice

Survived Summer (2.6.1–2.6.3)

WMO Sea-Ice Nomenclature (Link)

Nilas

First stage of sheet ice

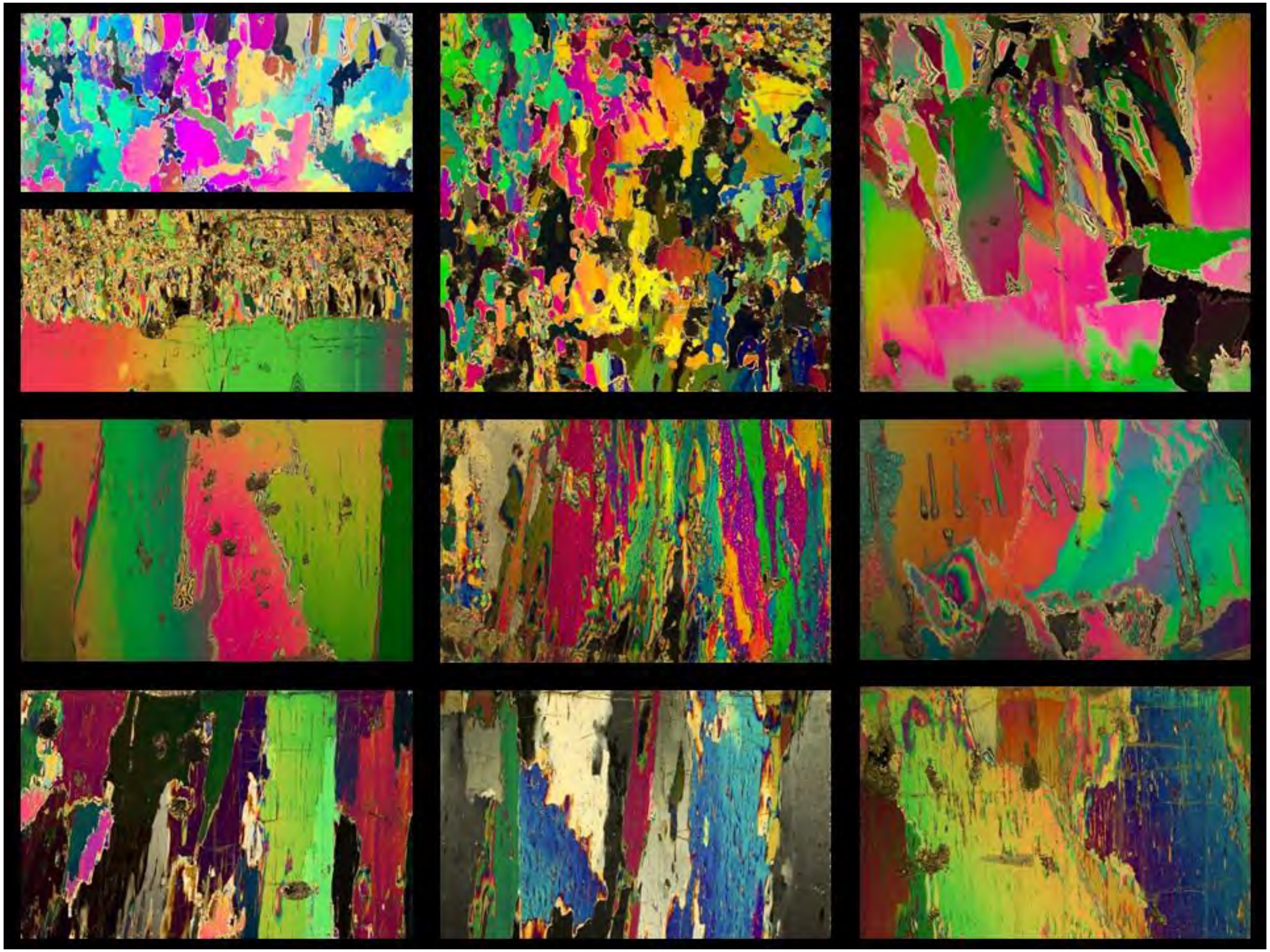
Frost flowers form on warm ice under cold conditions

Ice Growth in Dynamic Environment

Pancake Sea Ice

Consolidated Pancakes

Fingerprint of Ice Growth

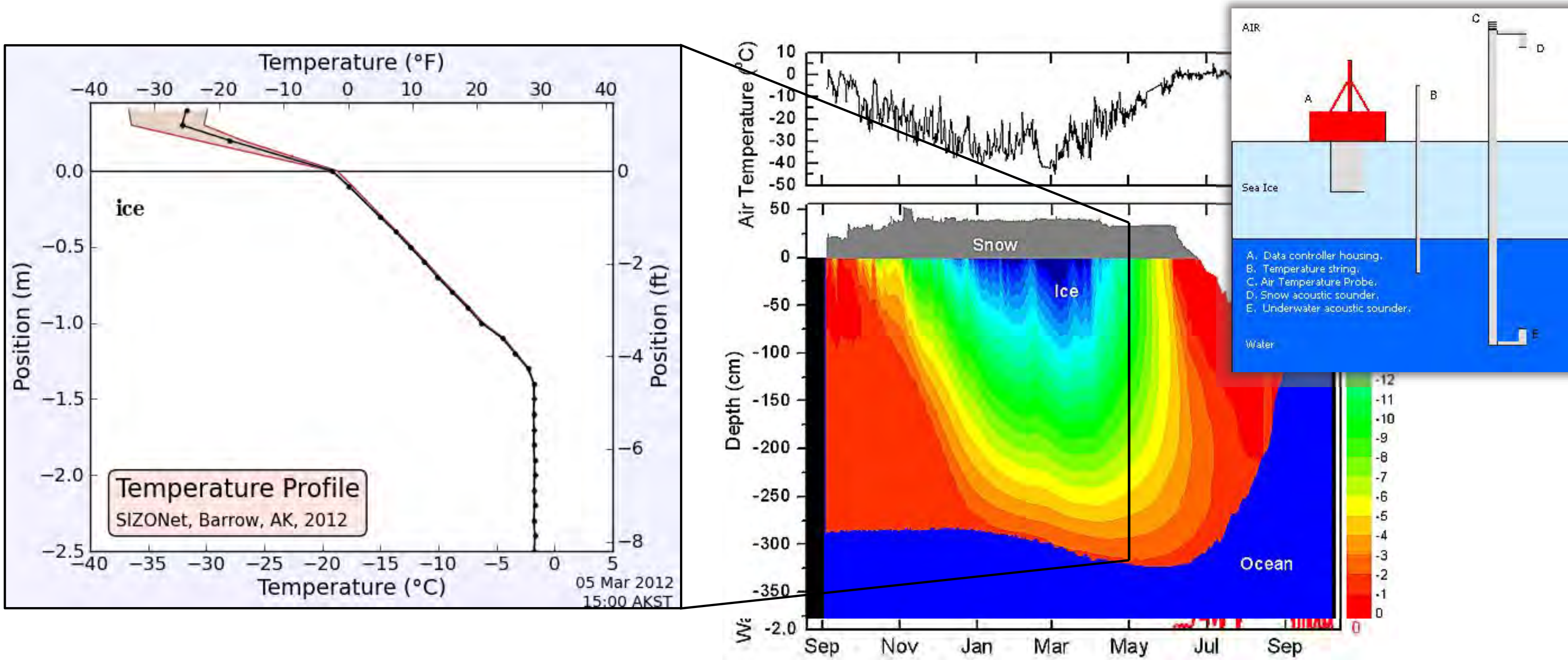


Granular Ice
dynamic environment

Columnar Ice
sheltered environment

Thin Sections with polarized light (*Polona Itkin and Anja Rösel, Norwegian Polar Institute*)

Sea Ice Thermodynamics



Sea Ice Temperature Profiles from Ice Mass Balance Buoys

Ice temperature: product of air temperature and thermal conductivity

Thermal Conductivity: Snow (0.11 – 0.35 W m^{-1} K^{-1}) < Sea Ice ~ 2.3 W m^{-1} K^{-1})

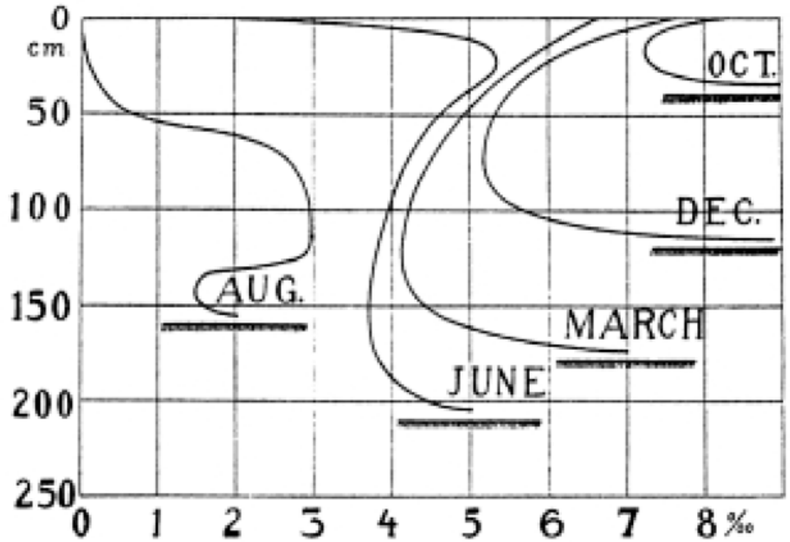
Perovich, D. K., J. A. Richter-Menge, K. F. Jones, and B. Light (2008), Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007, *Geophys. Res. Lett.*, 35

Salinity Evolution of Sea Ice

Surface Melt

▷ Meltwater flush

▷ Lower density of second/multi-year ice



Salt Segregation
+
Cooling from Surface
▷ Desalination processes
+
Warmer Bottom
▷ More saline new ice
=
Typical C-Shape

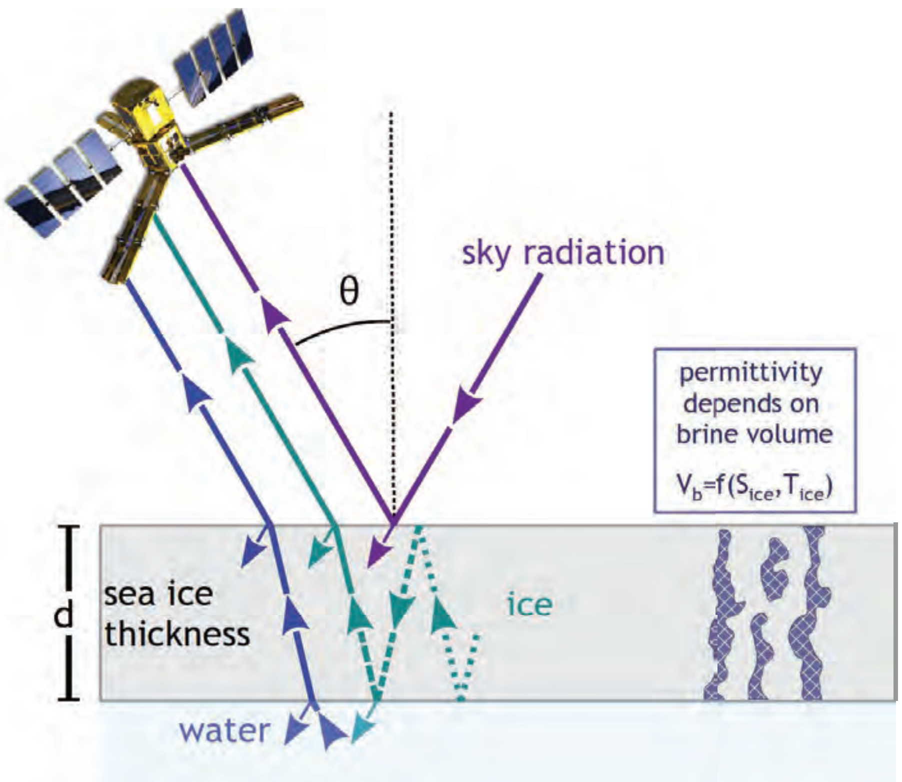
Two types of sea ice desalination

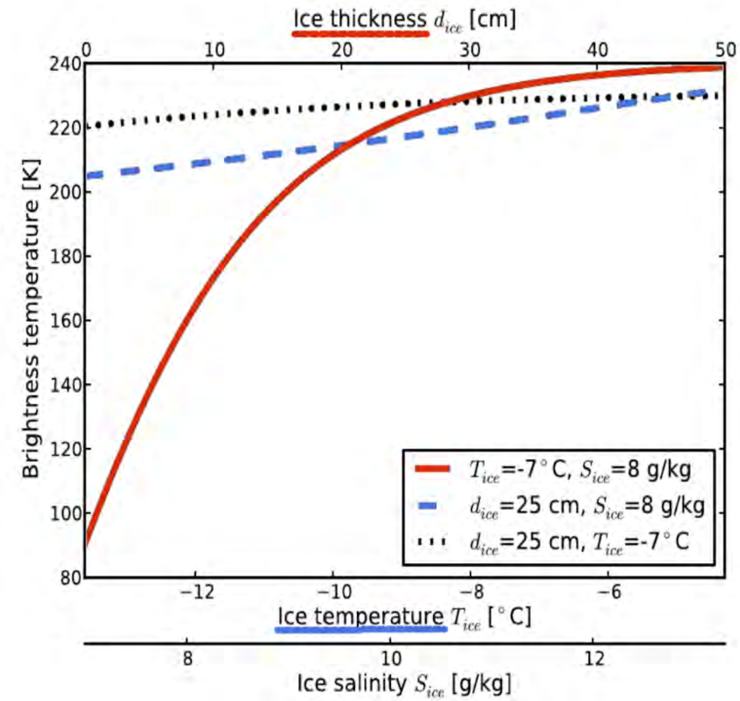
[cold ice] gravity drainage (thermal gradient) & brine expulsion (volume change by cooling)

[warm ice] meltwater flushing (porosity)

Eicken, H. (2008). From the Microscopic, to the Macroscopic, to the Regional Scale: Growth, Microstructure and Properties of Sea Ice. In Sea Ice (eds D. N. Thomas and G. S. Dieckmann). doi:10.1002/9780470757161.ch2

Thin Ice Thickness Remote Sensing





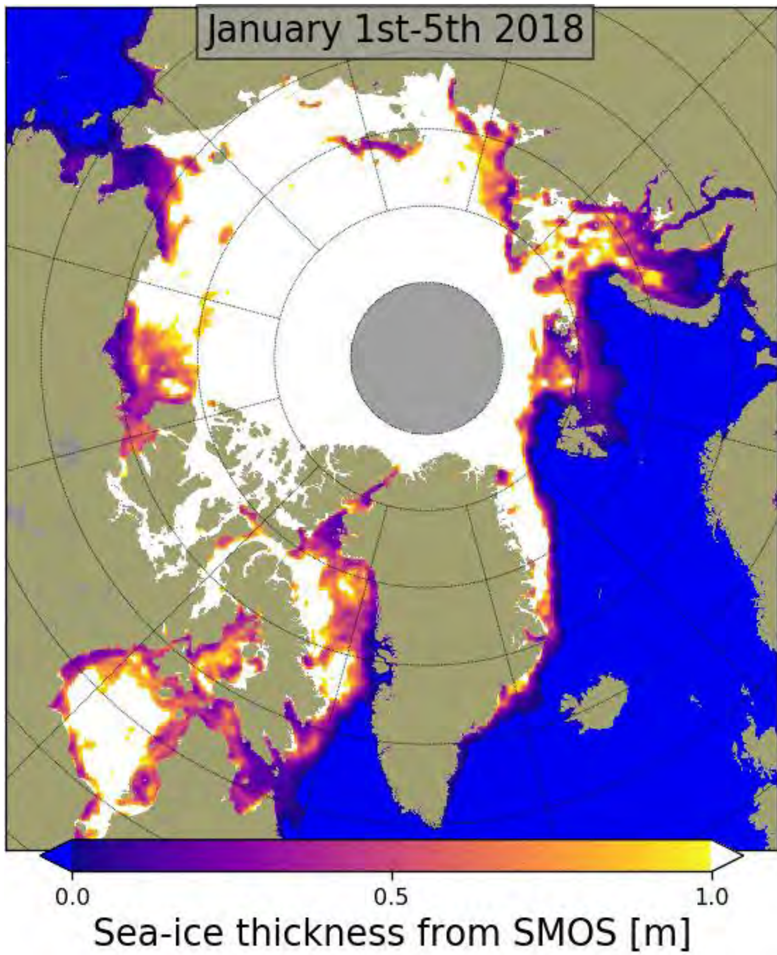
Observation of Surface Emissivity with Passive Microwaves

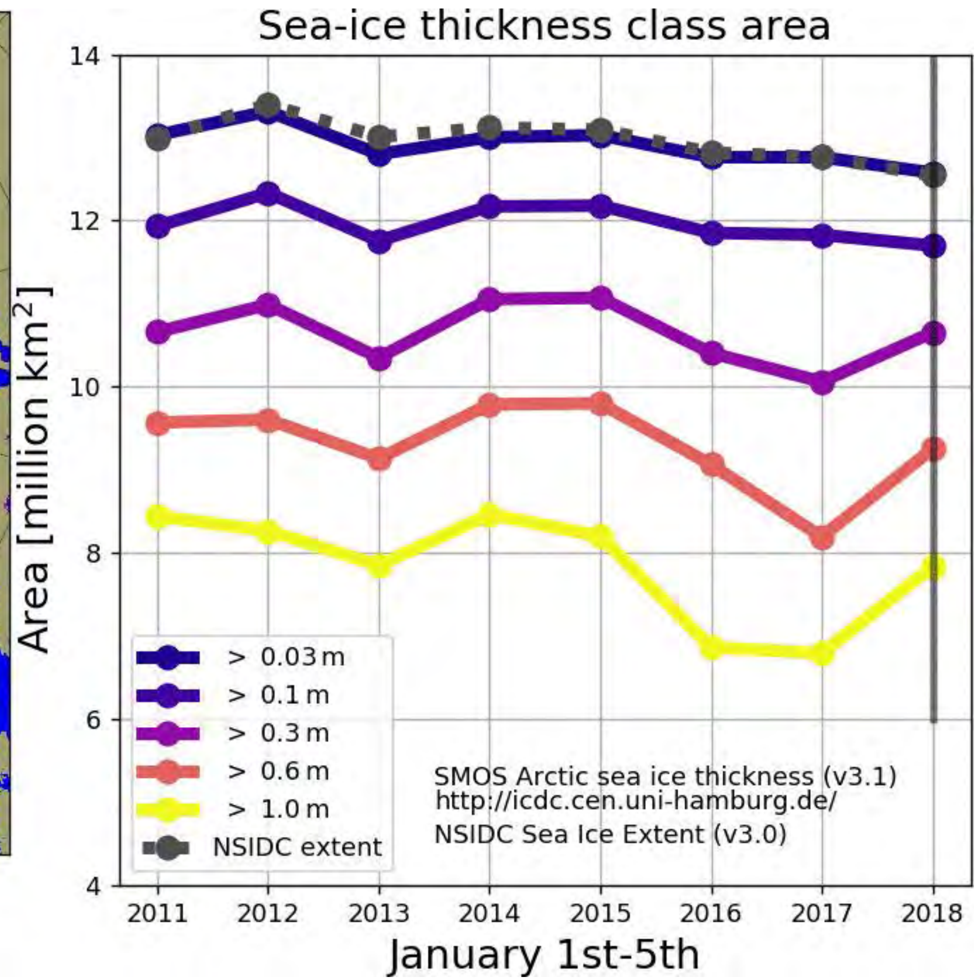
Surface Emissivity in Microwave Frequencies: Function of thickness and ice temp. & salinity

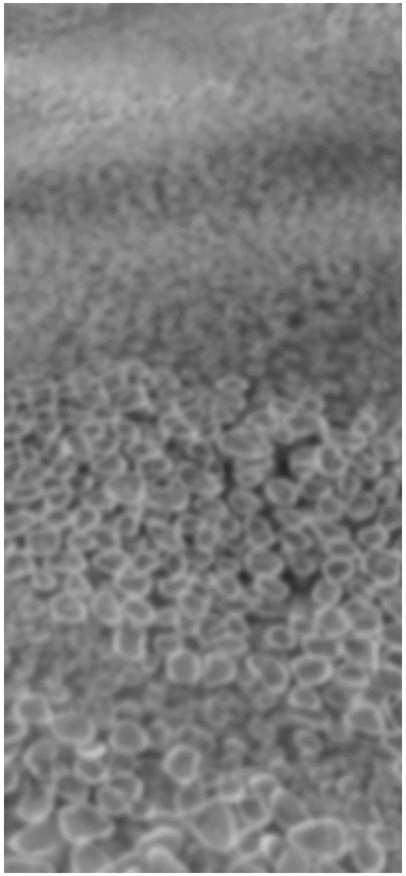
Thickness retrieval with ice properties as priori information

Maximum thickness depends on frequency, e.g. L-Band, 1.4 GHz (SMOS): < 1 m

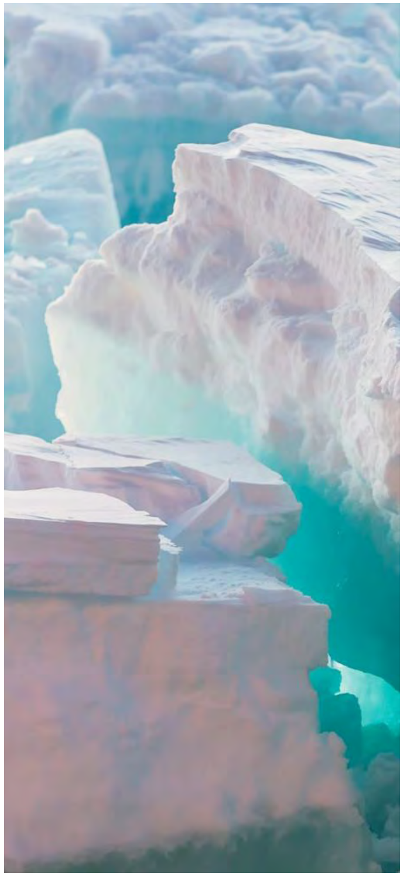
Thin Ice Examples



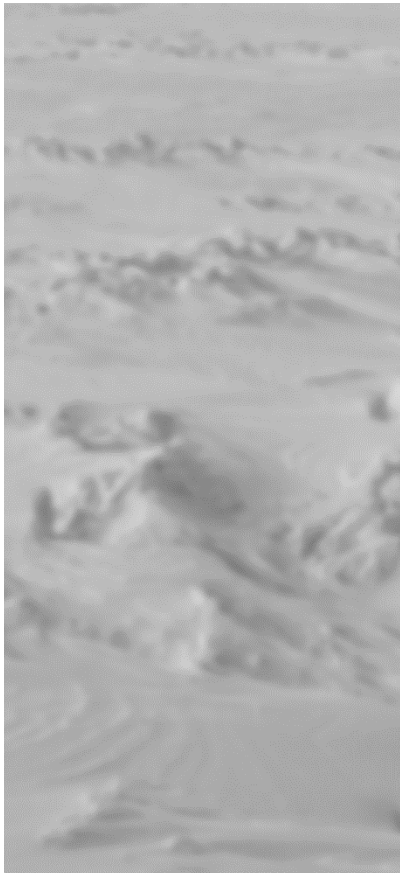




Formation & Growth



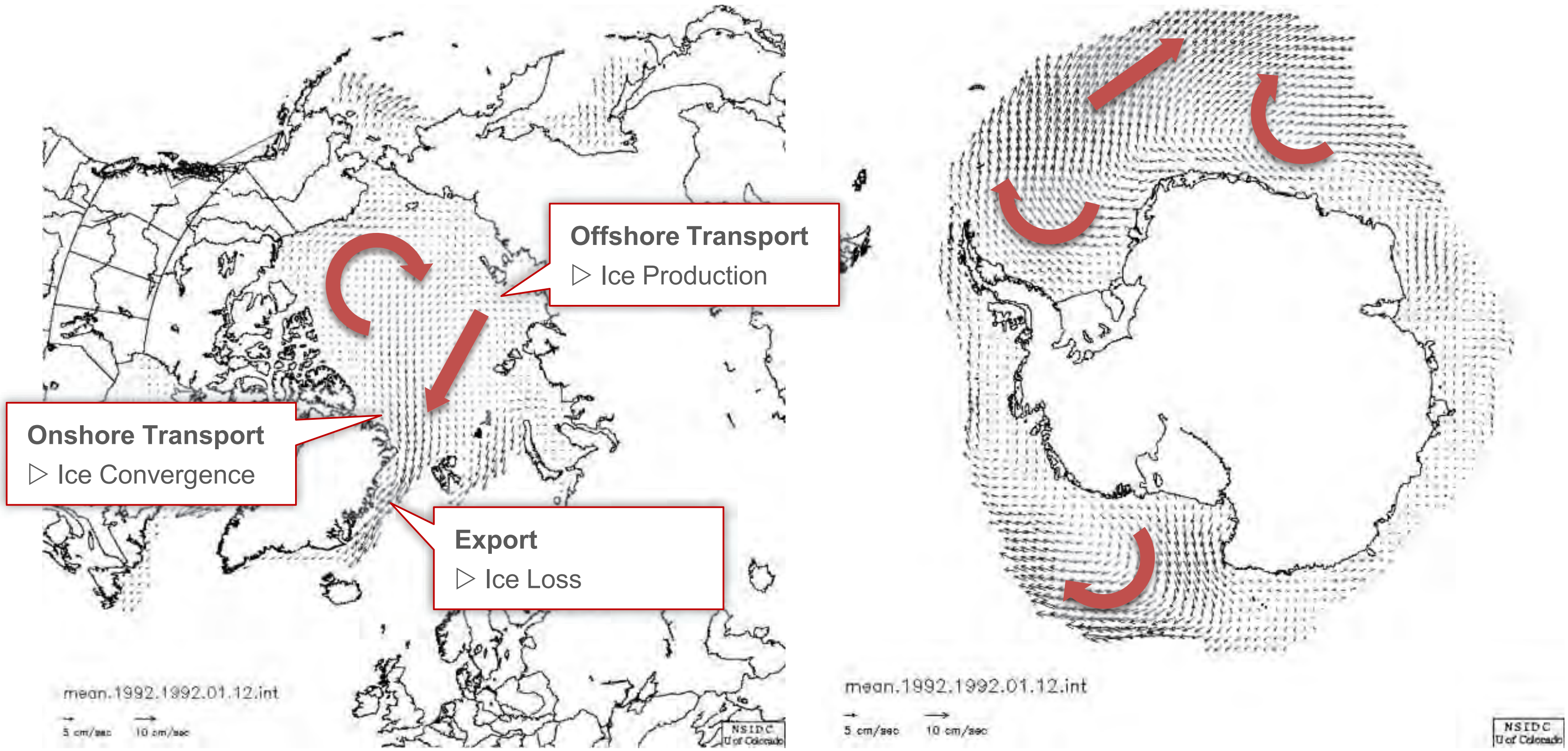
Redistribution



Snow Surface Processes

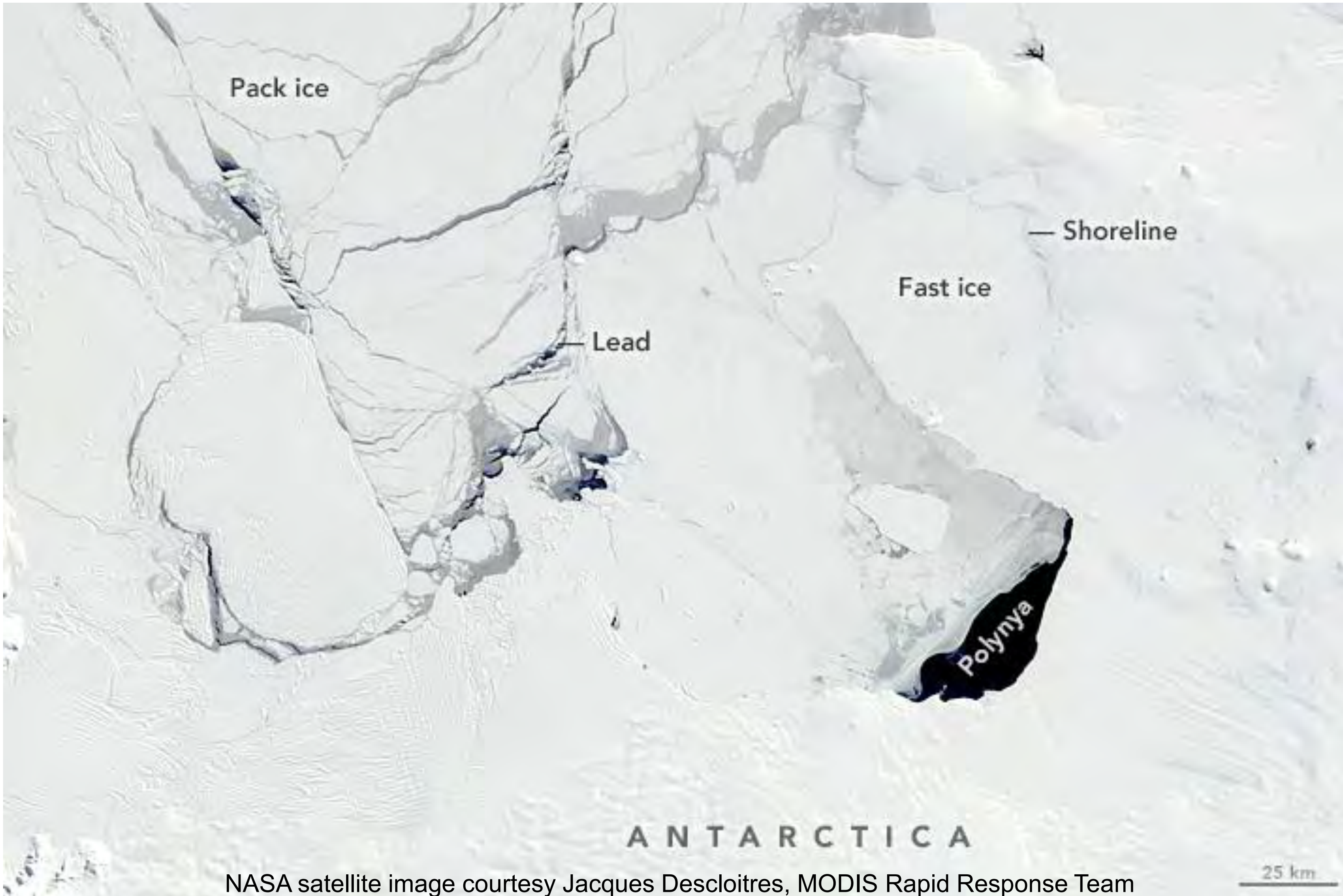
Melt

The Drift of Sea Ice



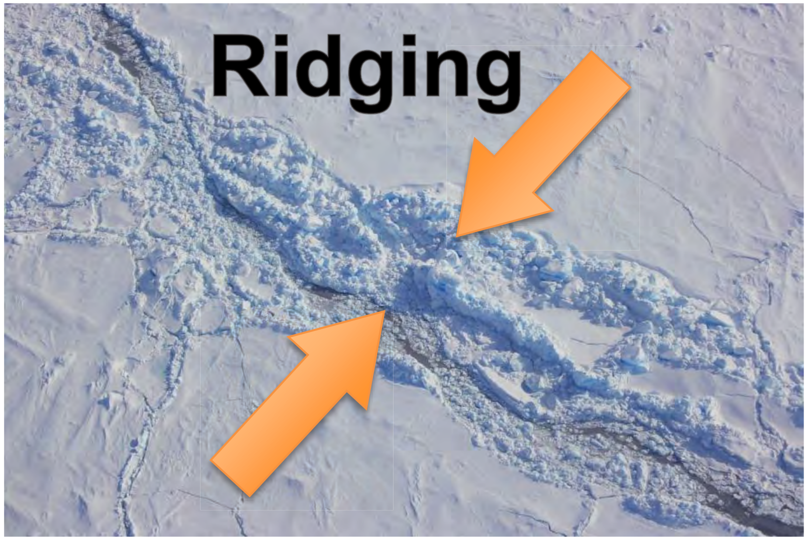
NSIDC ice motion data set

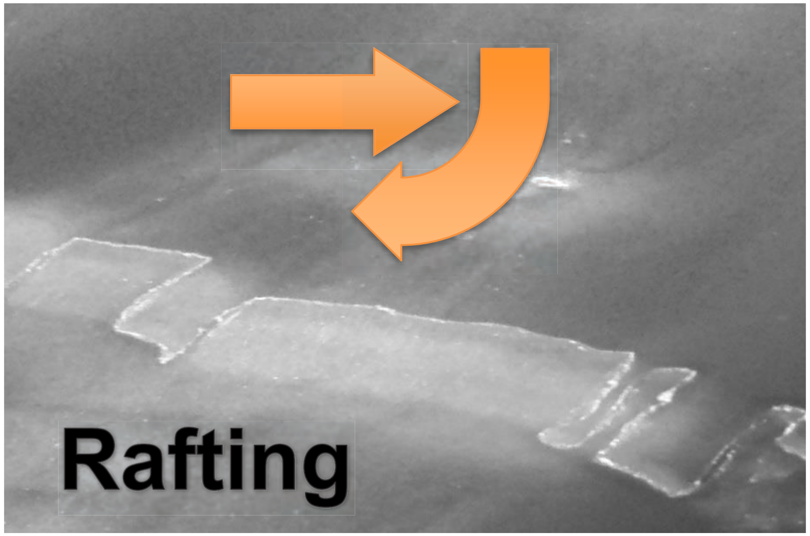
Drift vs. (Land-)Fast Sea Ice

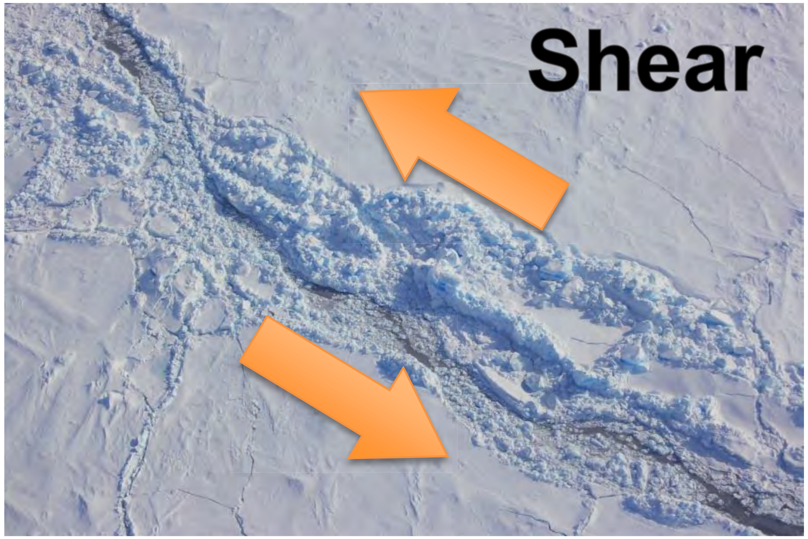


NASA satellite image courtesy Jacques Descloitres, MODIS Rapid Response Team

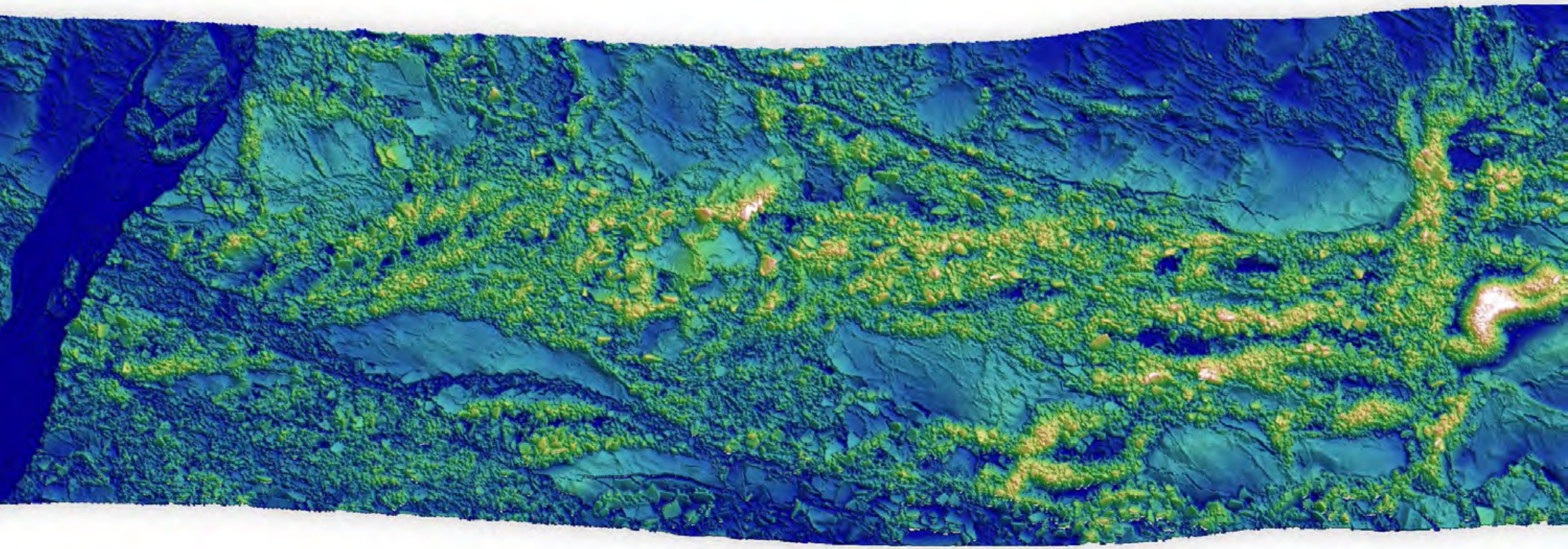
Sea Ice Deformation







Surface Variability



Digital Elevation Model with 25cm Resolution
(Airborne Laserscanner)

100 m

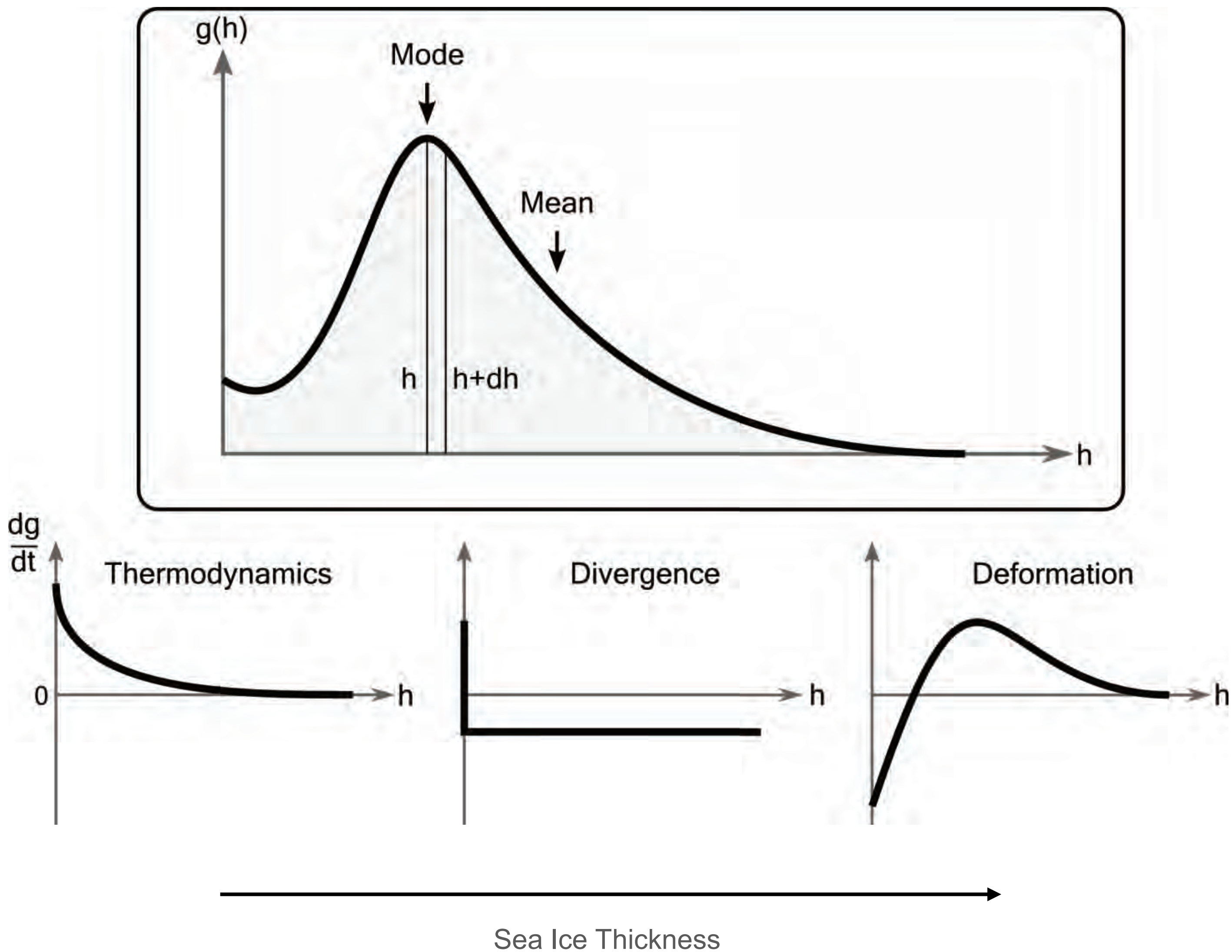
Beaufort Sea, April 2017

Surface Roughness

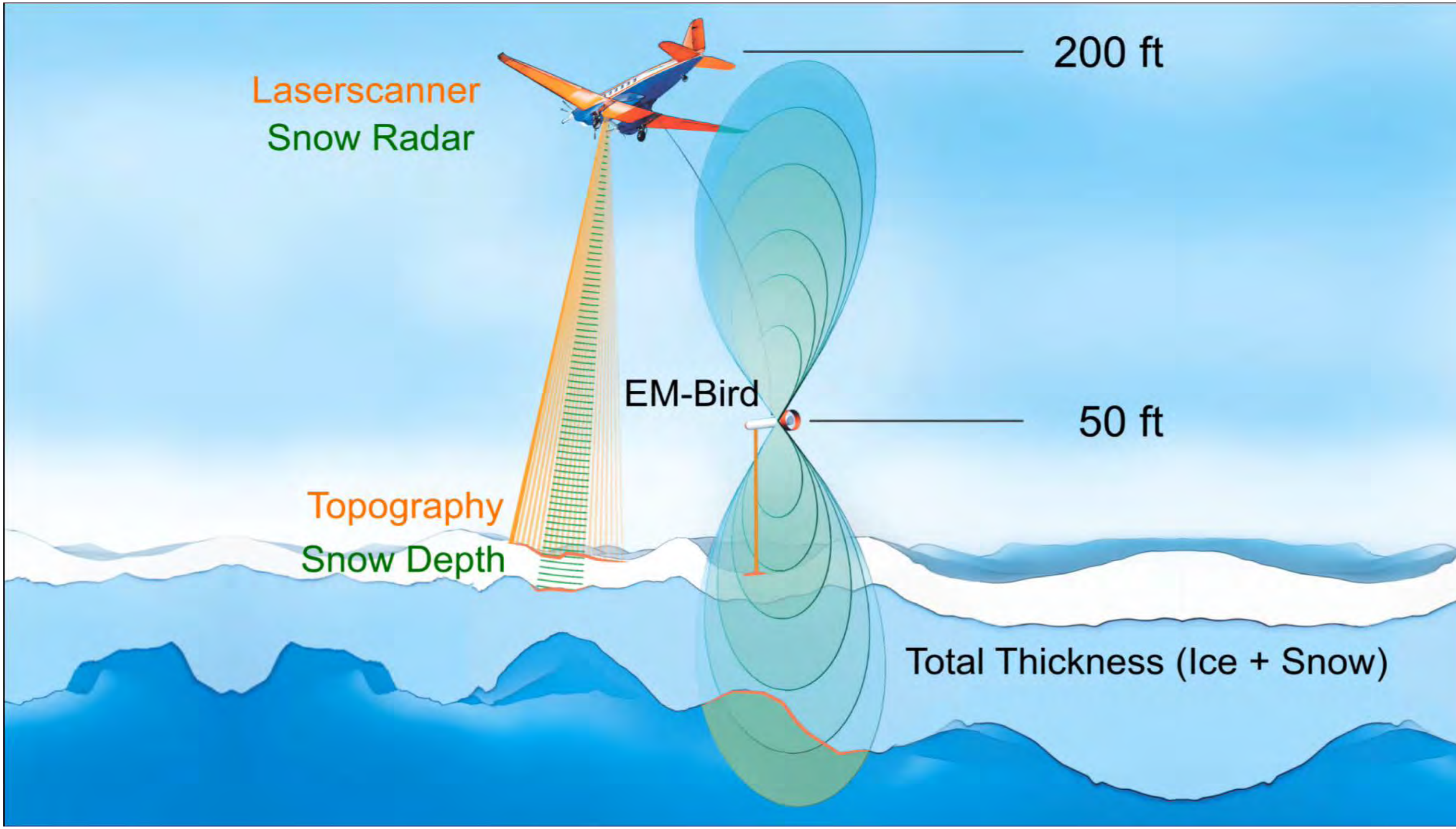
Major factor in sea ice backscatter properties

Significant sub-footprint variability

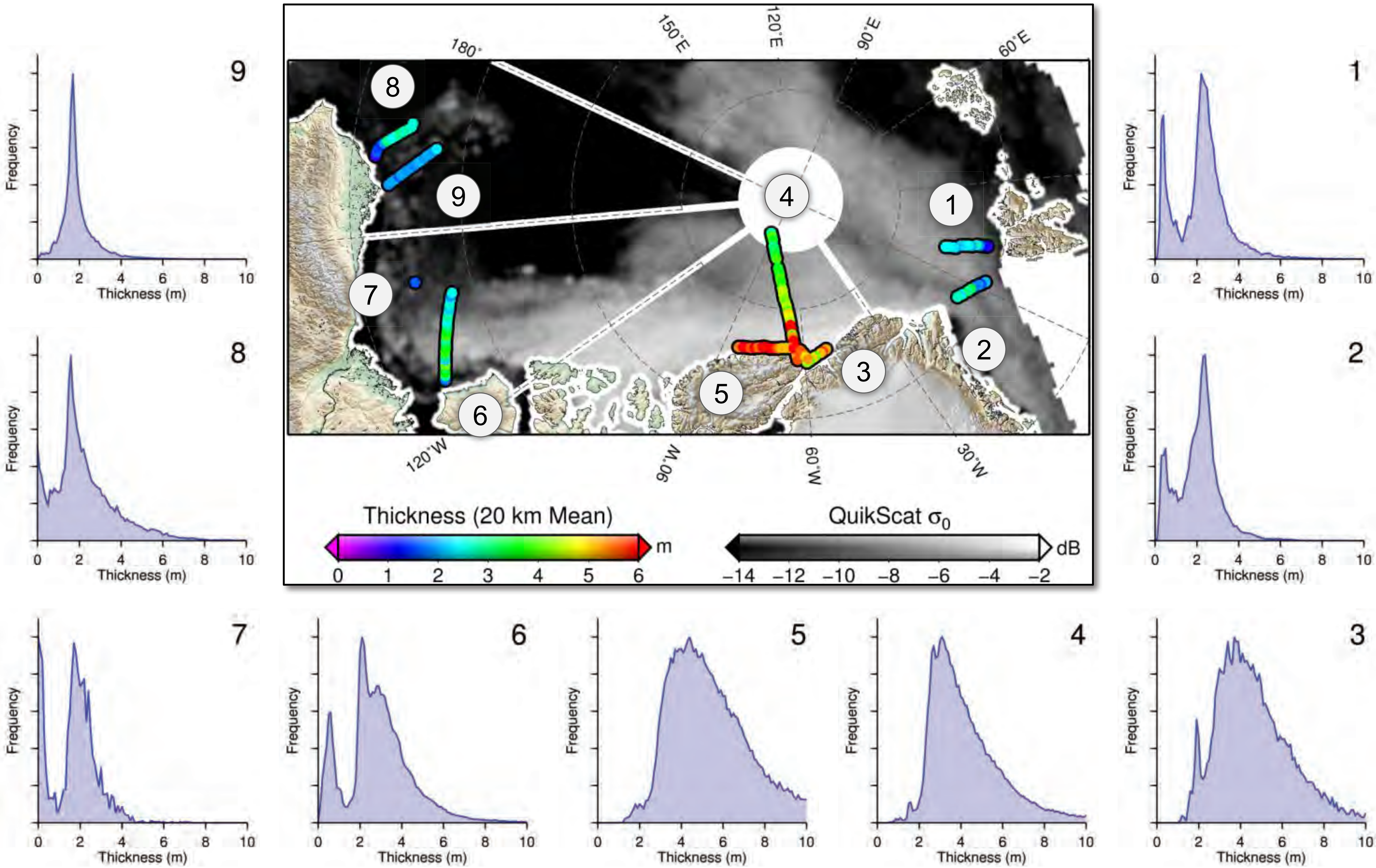
Sea Ice Thickness DistributionS



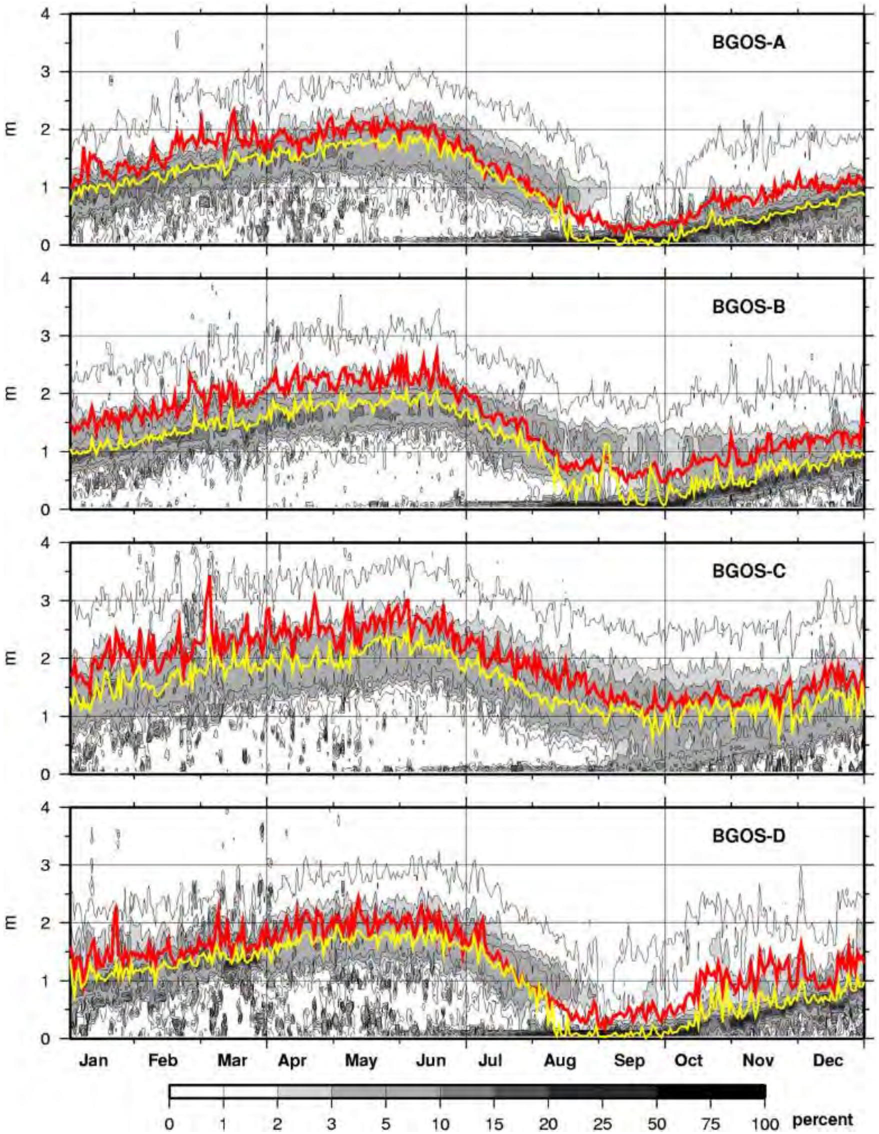
Airborne Measurements

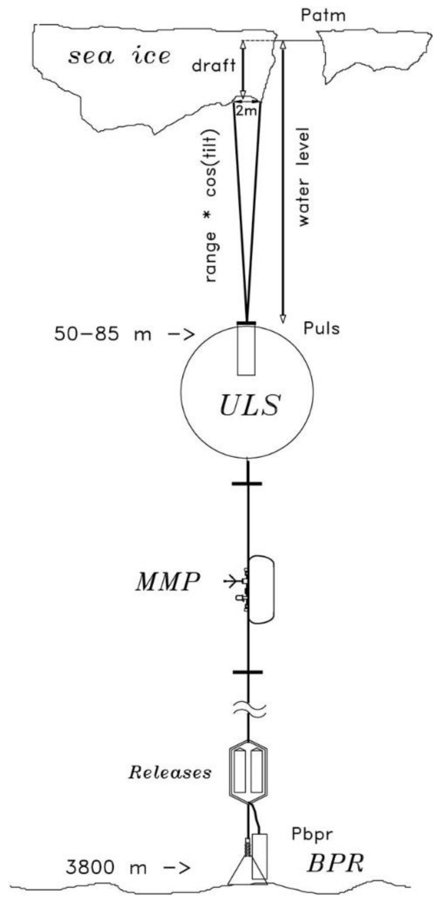


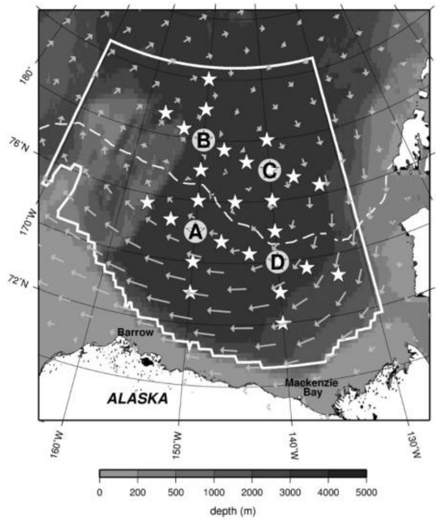
Sea Ice Thickness Distribution



Upward Looking Sonar



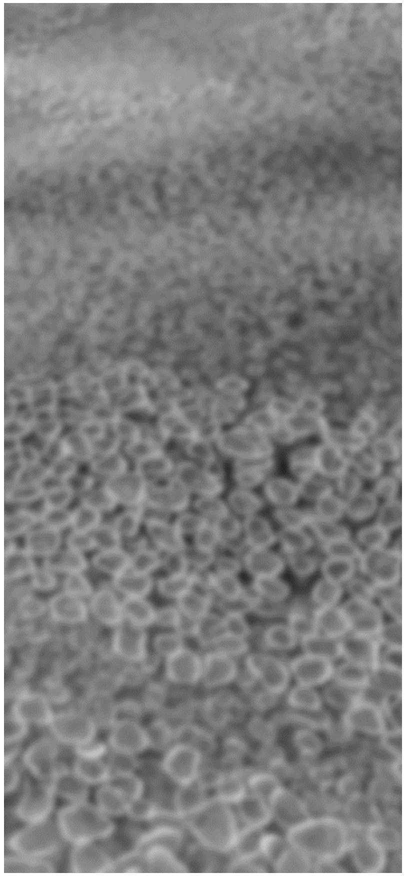




Moored or

Submarine / AUV

Krishfield, R. A., A. Proshutinsky, K. Tateyama, W. J. Williams, E. C. Carmack, F. A. McLaughlin, and M.-L. Timmermans (2014), Deterioration of perennial sea ice in the Beaufort Gyre from 2003 to 2012 and its impact on the oceanic freshwater cycle, *J. Geophys. Res. Oceans*, 119, 1271–1305



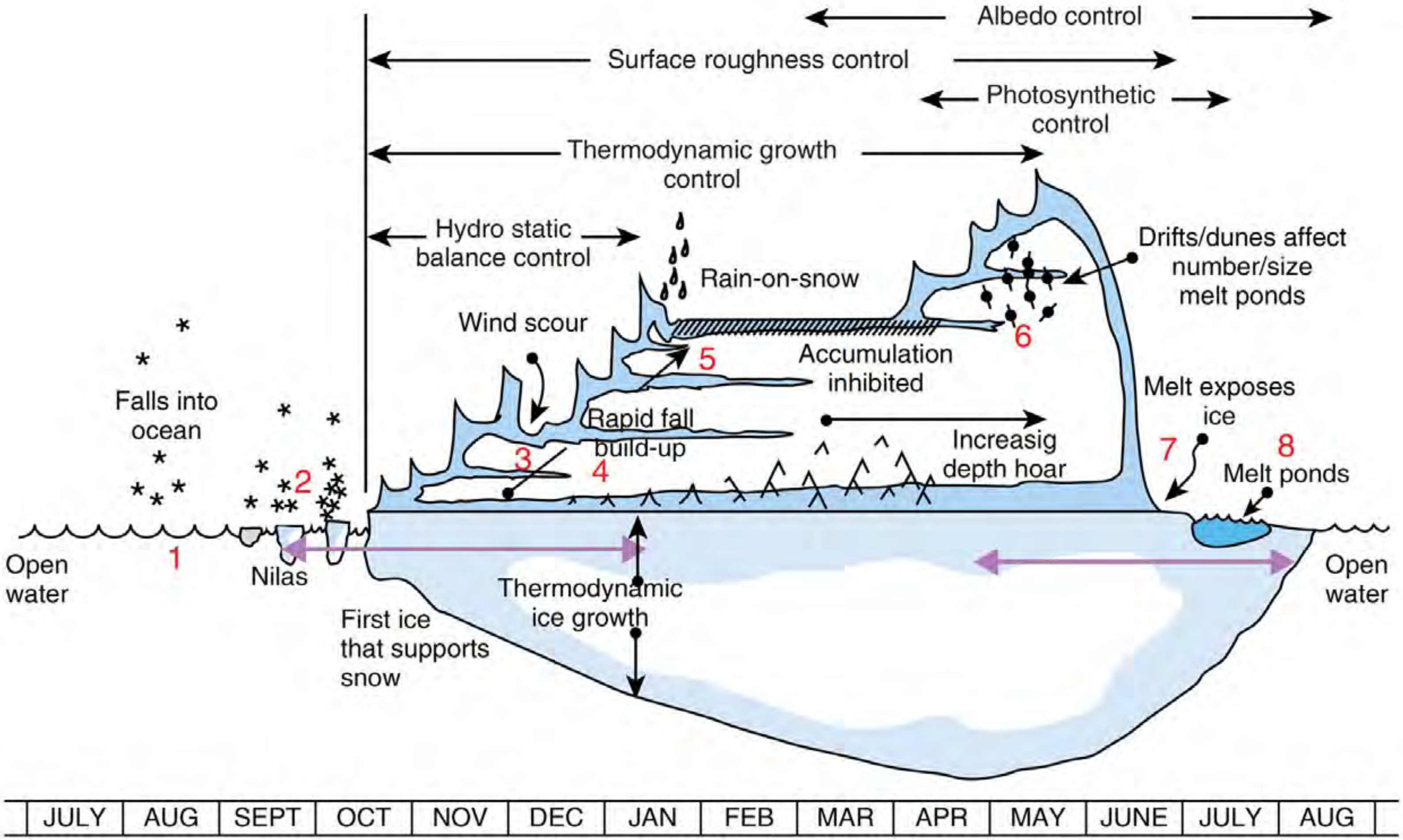
Formation
& Growth

Redistribution

Snow Surface
Processes

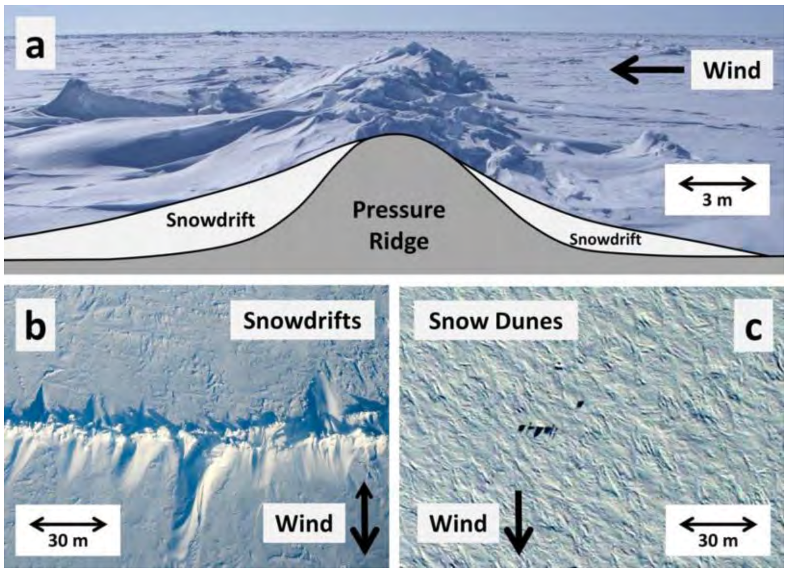
Melt

Snow Processes

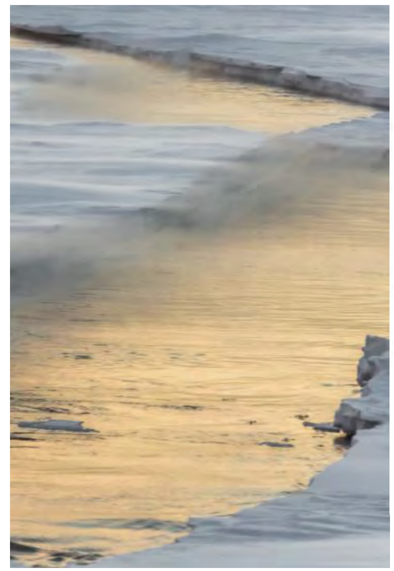


Evolution of Snow Depth

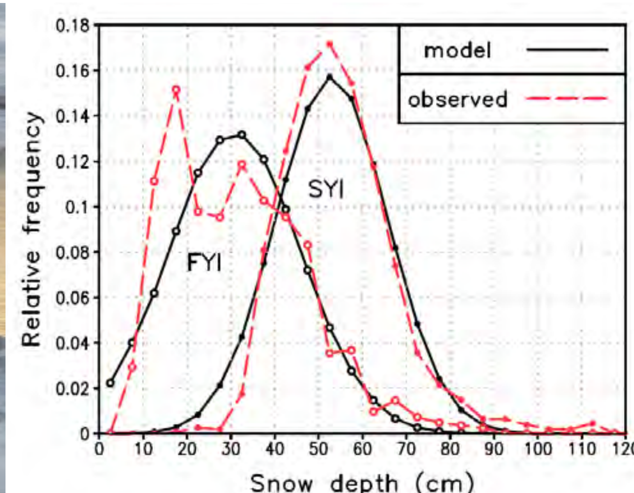
Snow Accumulation



Snow Loss in Leads



Snow Model vs Obs.



Rough Surfaces ▷ Snow Drifts

Level Surfaces ▷ Snow Dunes

Liston, G. E., Polashenski, C., Rösel, A., Itkin, P., King, J., Merkouriadi, I., & Haapala, J. (2018). A distributed snow-evolution model for sea-ice applications (SnowModel). Journal of Geophysical Research: Oceans, 123. https://doi.org/10.1002/2017JC013706

Impact of Snow on Remote Sensing

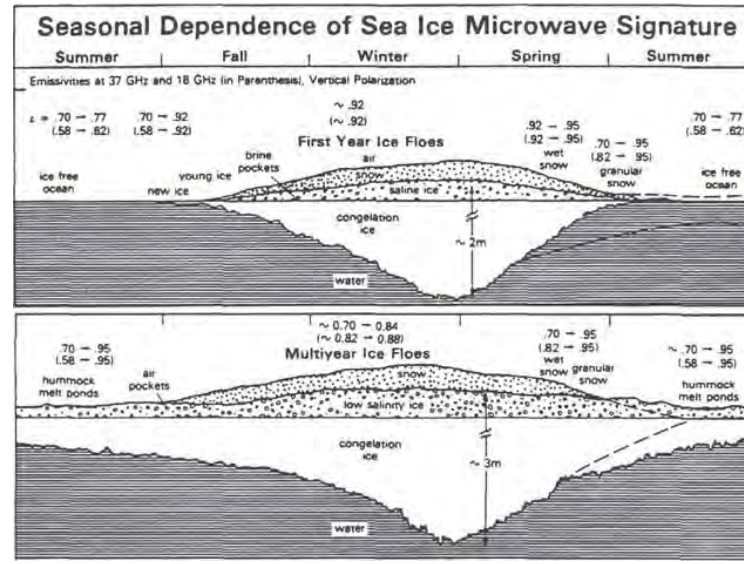
Passive Microwave

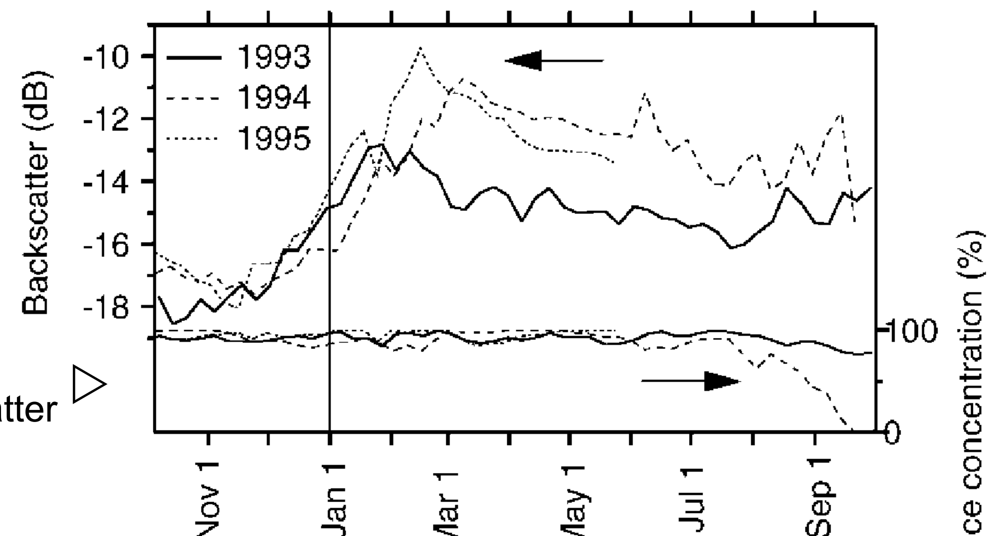
- Surface emissivity changed due to scattering for frequencies > 35 GHz

Active Microwave

- Interface Scattering
- Volume Scattering dependent on
  - Grain Size
  - Salinity
  - Temperature (Wetness)
  - Density
- Absorption

Albedo





Melt onset in surface backscatter ▷

Impact of Snow on Radar Altimeter

866 *S. G. Beaven* et al.

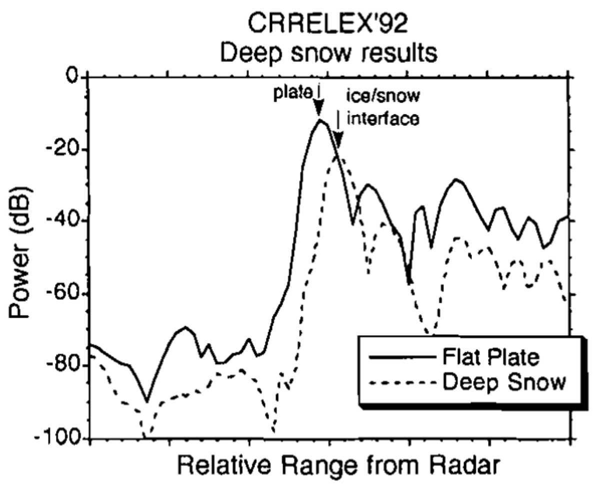
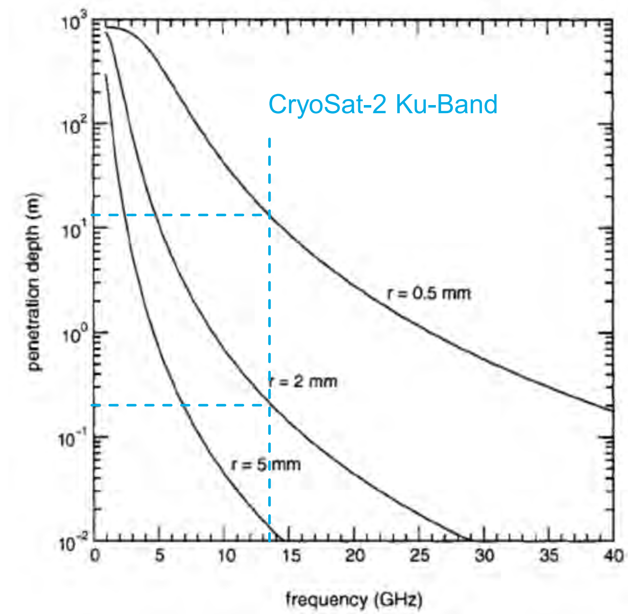


Figure 13. Comparison of K_u-band radar returns at 0° incidence angle from a 21-cm snow pile and a metal plate on top of the snow pile. The ice thickness was 12 cm. This demonstrates that the return from snow-covered saline ice is dominated by scattering from the snow-ice interface.



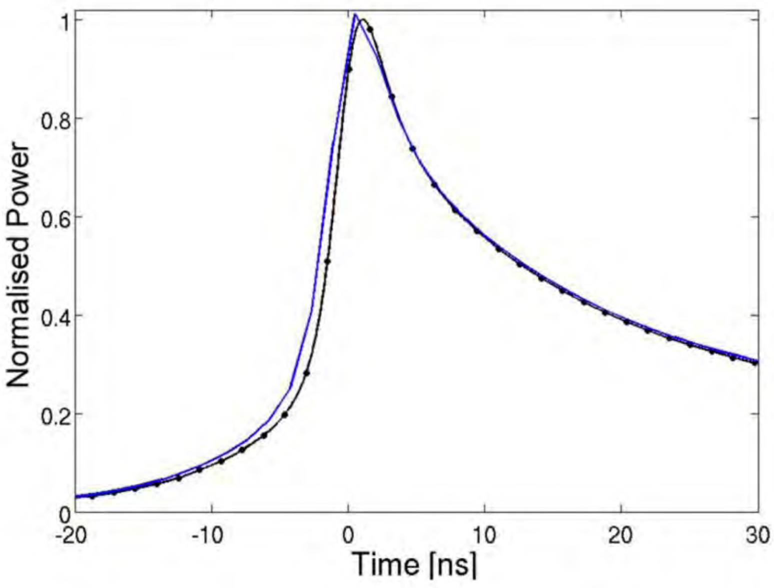
Sea ice thickness from radar altimetry depends on vertical location of radar return

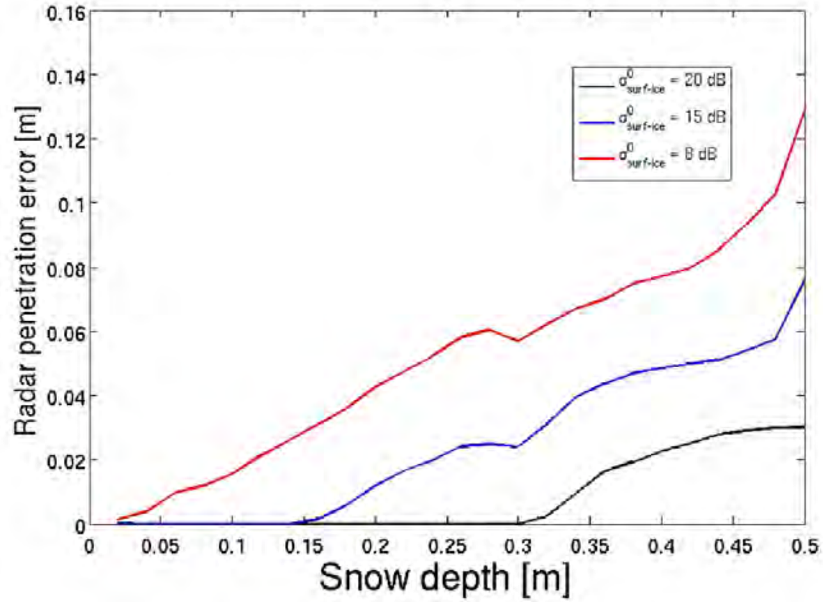
- Ranging biases over snow impact sea ice thickness by approx. factor 10
- Penetration depth for Ku-Band usually > snow depth, but snow backscatter may still be important

S. G. BEAVEN, et al. (2007) Laboratory measurements of radar backscatter from bare and snow-covered saline ice sheets, International Journal of Remote Sensing

A. W. Bingham and M. R. Drinkwater, "Recent changes in the microwave scattering properties of the Antarctic ice sheet," in *IEEE Transactions on Geoscience and Remote Sensing*

Impact of Snow on Ranging – cont



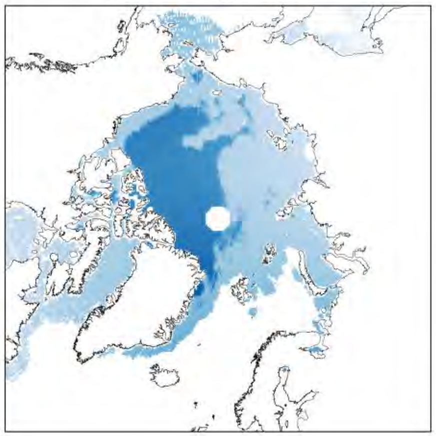


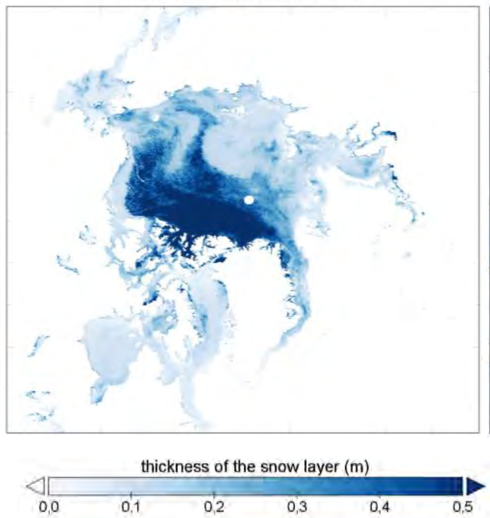
snow interface & volume scattering may still impact Ku-Band radar

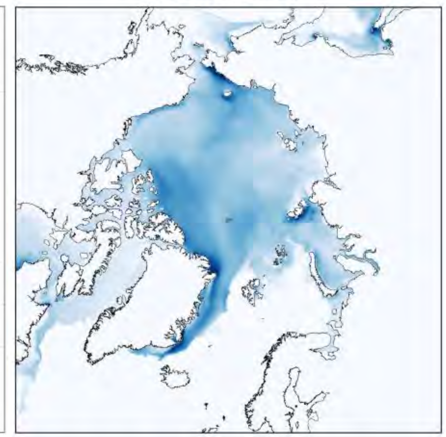
EM waves travel slower in snow (correction: ~ 22% of snow depth)

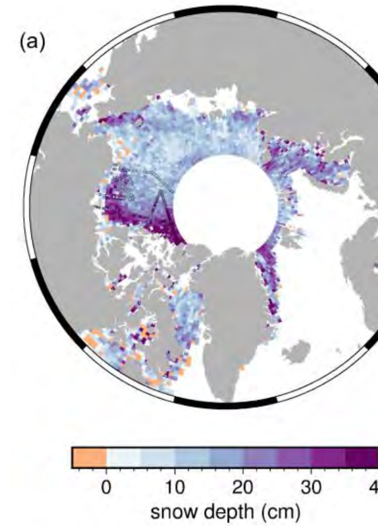
Kurtz, N. T., Galin, N., and Studinger, M.: An improved CryoSat-2 sea ice freeboard retrieval algorithm through the use of waveform fitting, The Cryosphere, 8, 1217-1237, https://doi.org/10.5194/tc-8-1217-2014, 2014.

Snow Depth Sources









Climatology

- Monthly
- Static
- Often modified by ice type (50% over first-year ice)

Passive Microwave

- Daily
- Ambiguity of snow and ice type retrieval?

Reanalysis

- Daily
- Model-based

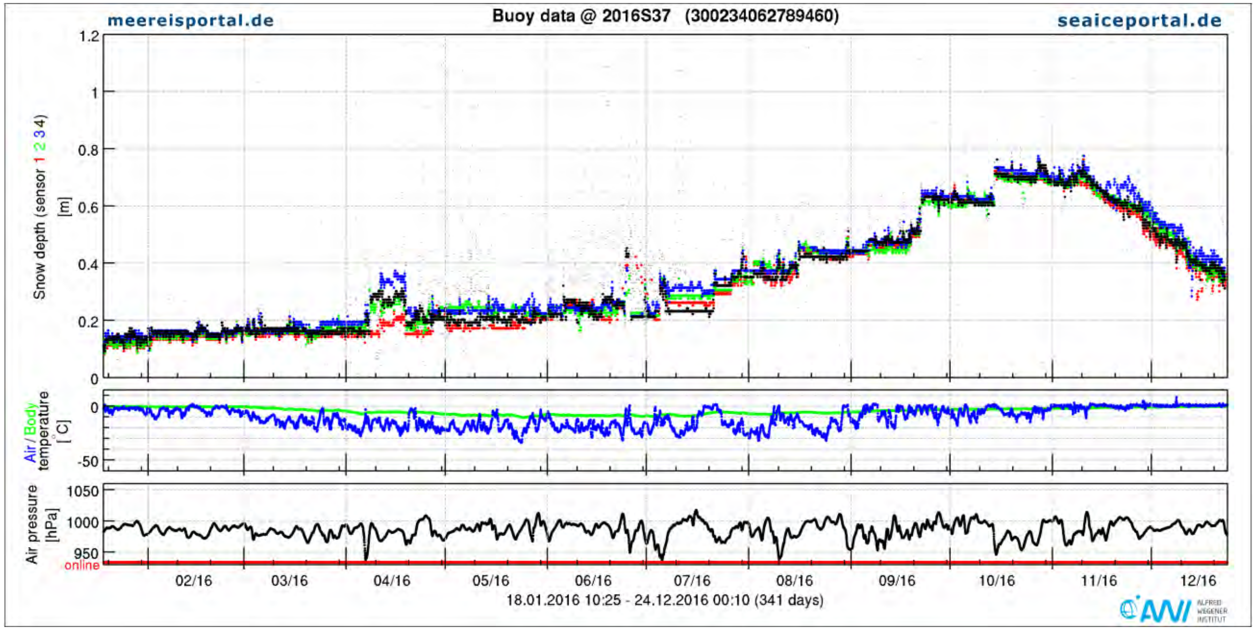
Dual Altimeter

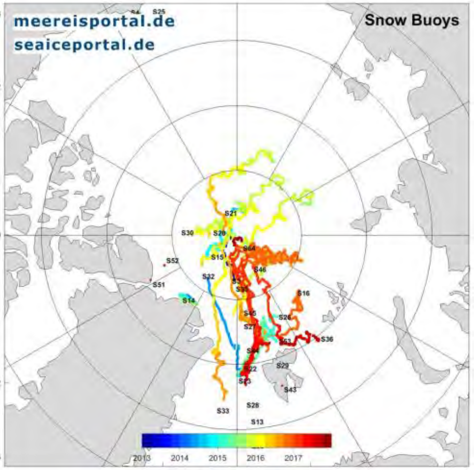
- Monthly
- Envisat/IceSat
- CryoSat-2/AltiKA

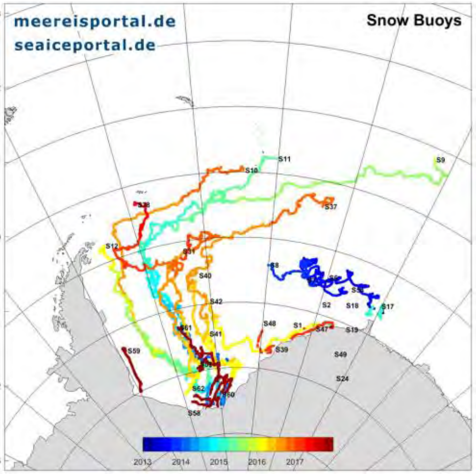
Accurate snow depth information (observation) is an issue

Lawrence, I., Tsamados, M., Stroeve, J., Armitage, T., and Ridout, A.: Estimating snow depth over Arctic sea ice from calibrated dual-frequency radar freeboards, The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-54, in review, 2018.

Snow Buoys


meereisportal.de
Buoy data @ 2016S37 (300234062789460)
seaiceportal.de
Snow depth (sensor 1 2 3 4) [m]
Air / Body temperature [C]
Air pressure [hPa]
online
02/16
03/16
04/16
05/16
06/16
07/16
08/16
09/16
10/16
11/16
12/16
18.01.2016 10:25 - 24.12.2016 00:10 (341 days)


meereisportal.de
seaiceportal.de
Snow Buoys
2013
2014
2015
2016
2017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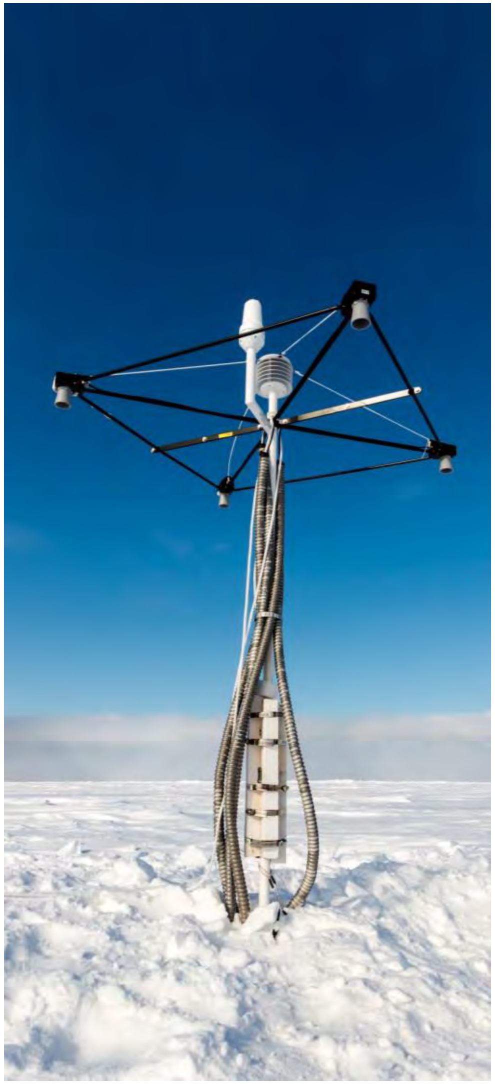
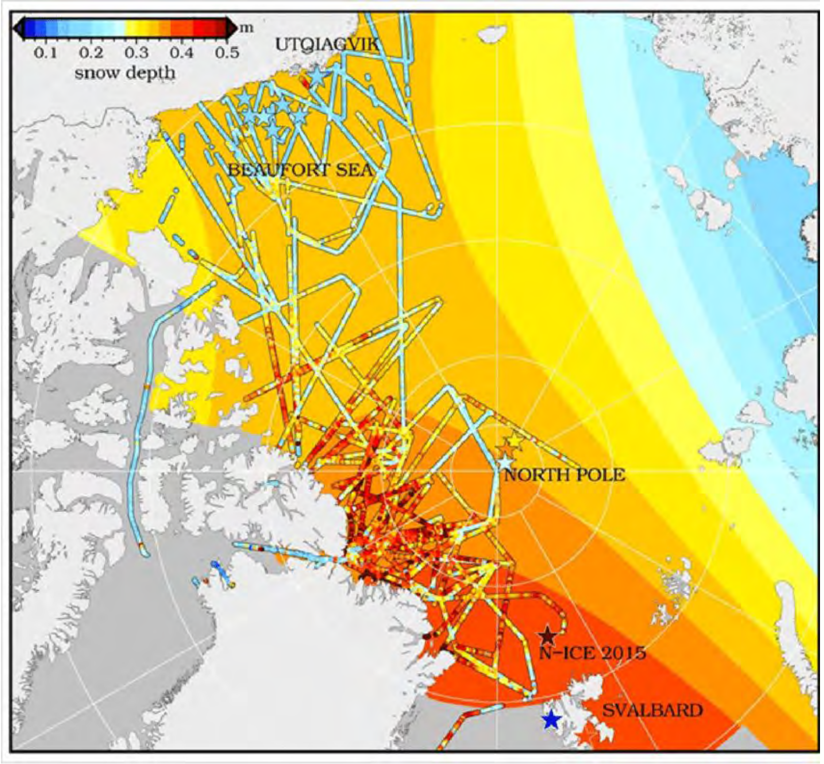
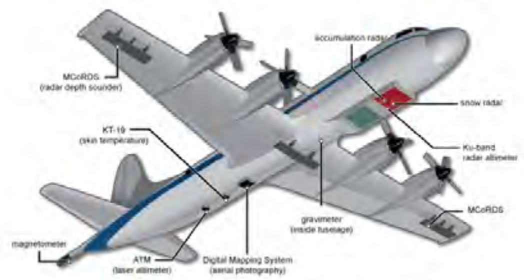
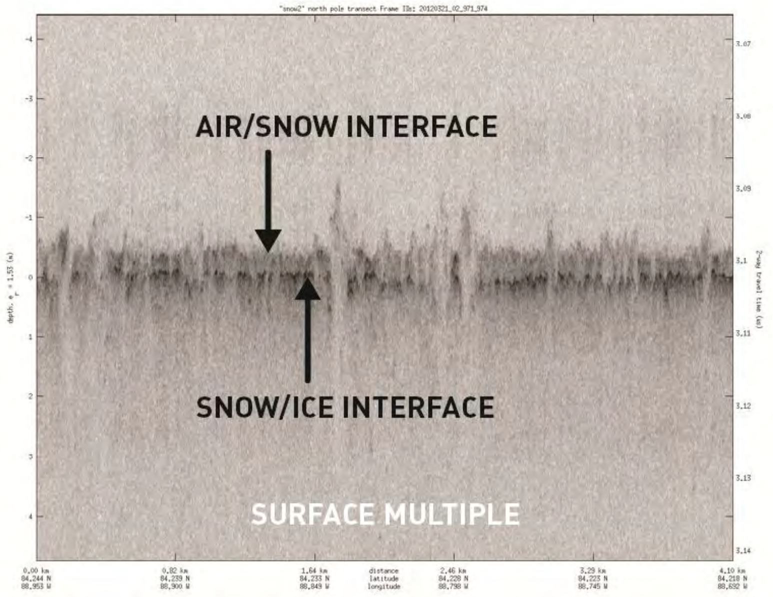
seaiceportal.de
Snow Buoys
2013
2014
2015
2016
2017



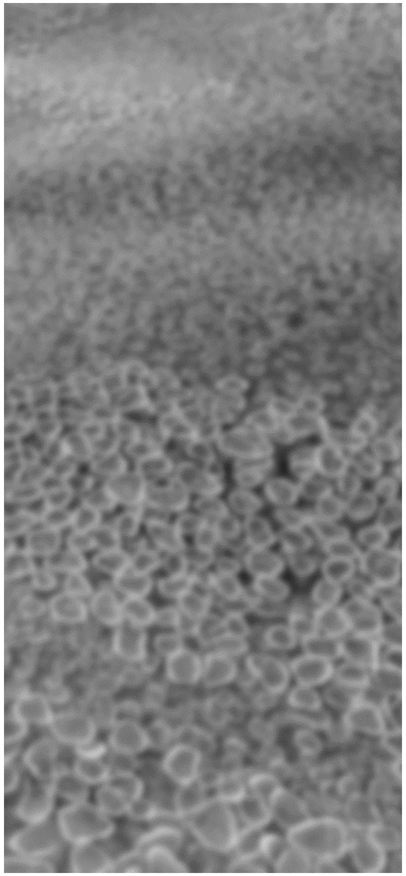
Airborne Snow Data





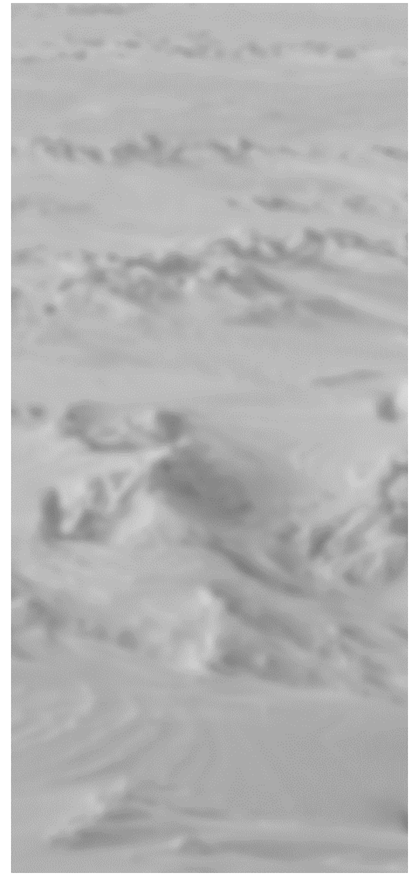


Kwok, R., et al..: Intercomparison of snow depth retrievals over Arctic sea ice from radar data acquired by Operation IceBridge, The Cryosphere, 11, 2571-2593, https://doi.org/10.5194/tc-11-2571-2017, 2017.



Formation
& Growth

Redistribution



Snow Surface
Processes

Melt

Sea Ice Melt

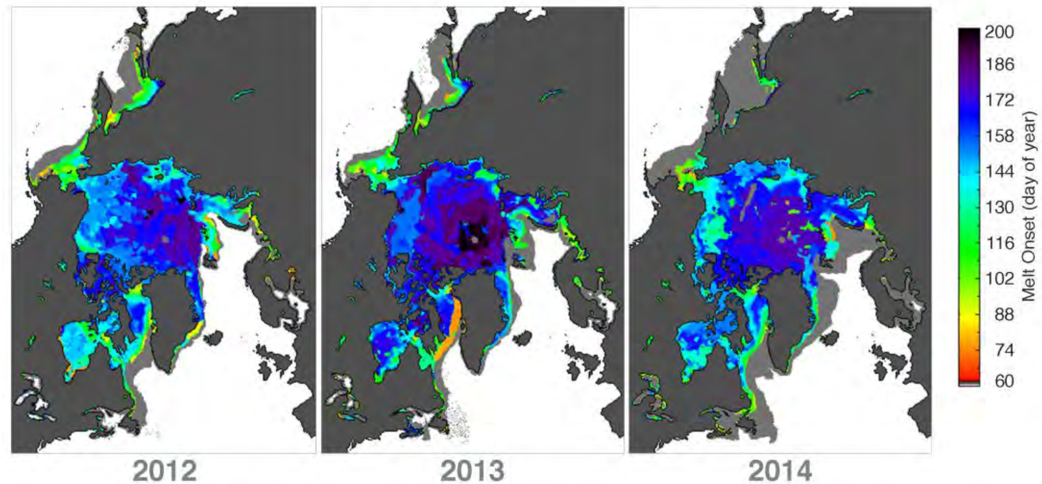
Melt Progress

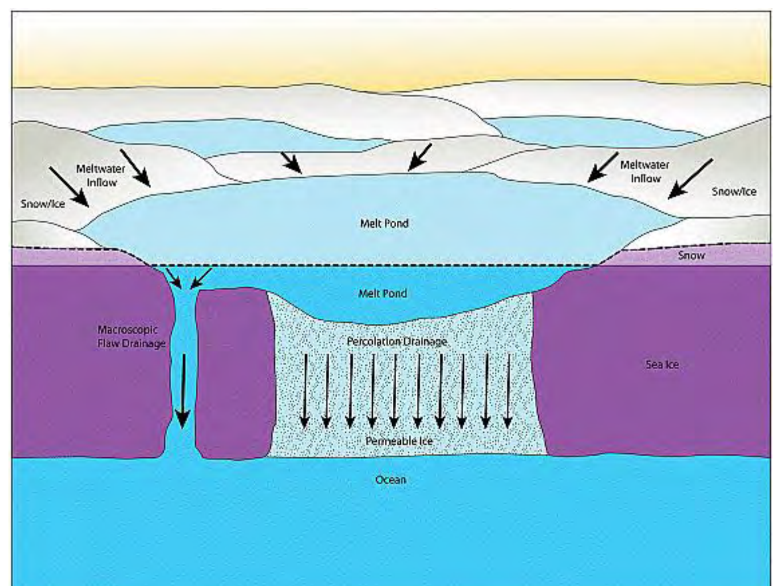
1. Onset: Melting Snow
2. Melt ponds when snow is completely melted
3. Amplification of melt (albedo)
4. Melt pond drainage through sea ice

Forms of Ice Melt

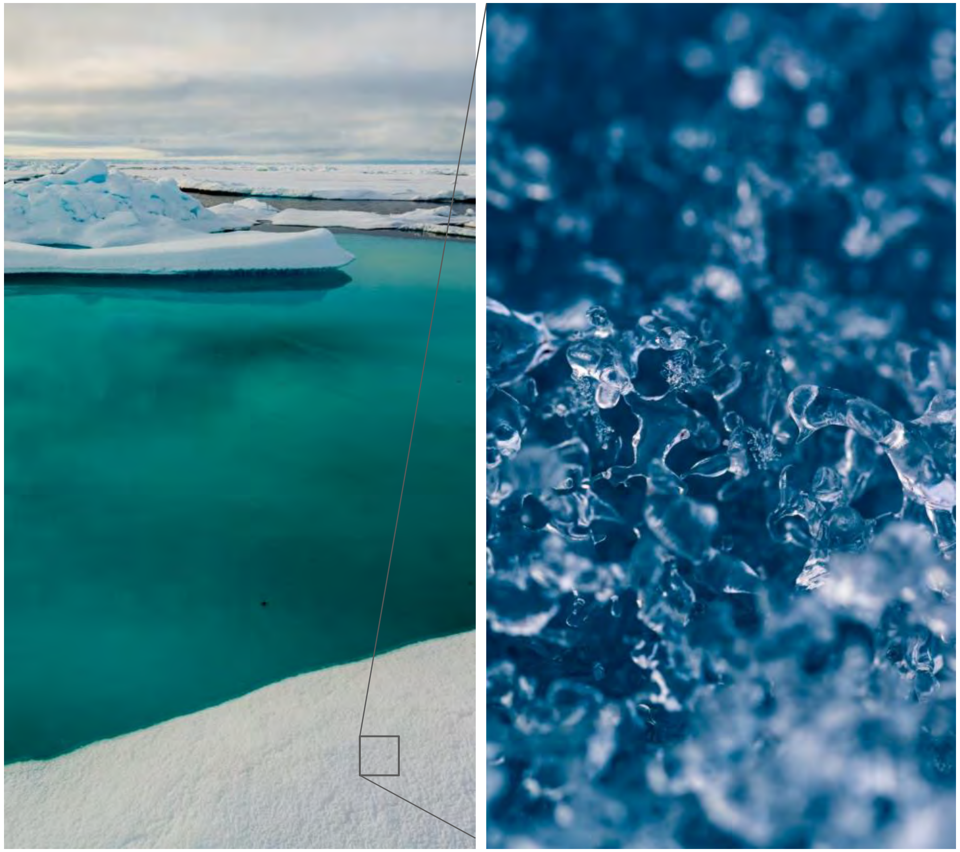
1. Surface
2. Bottom
3. Internal
4. Lateral

Melt onset dates



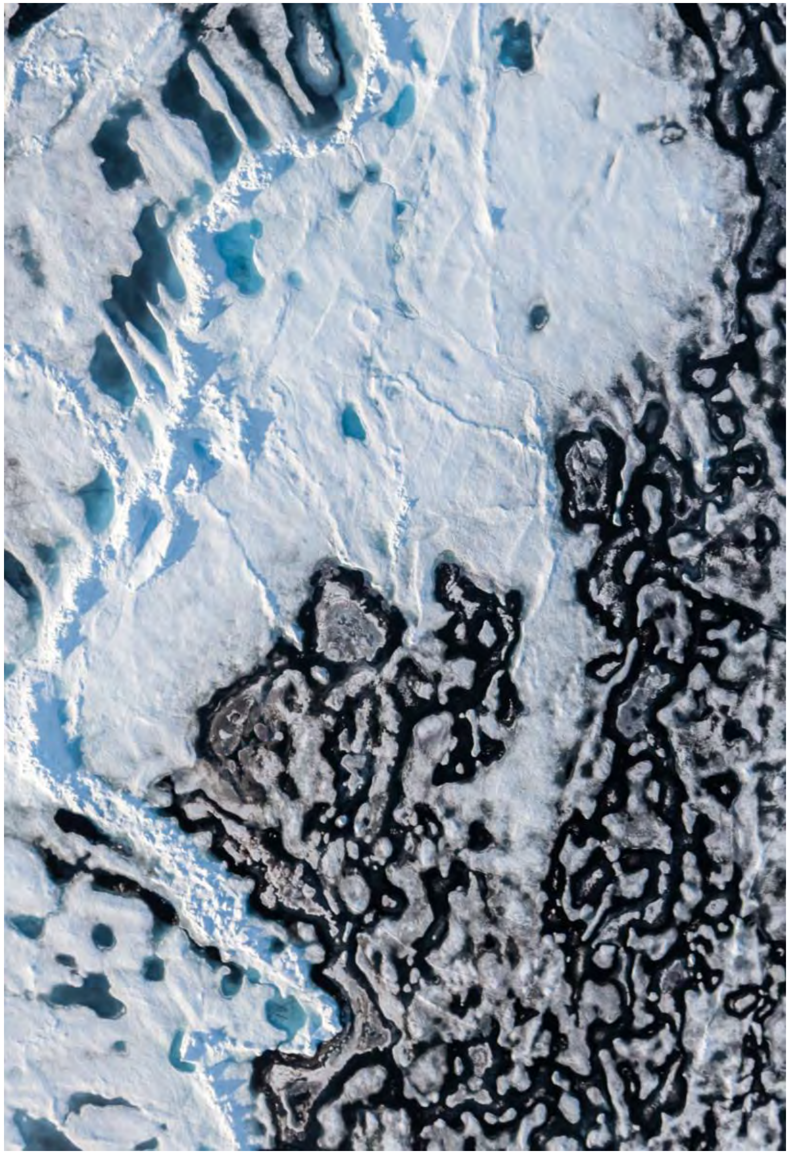


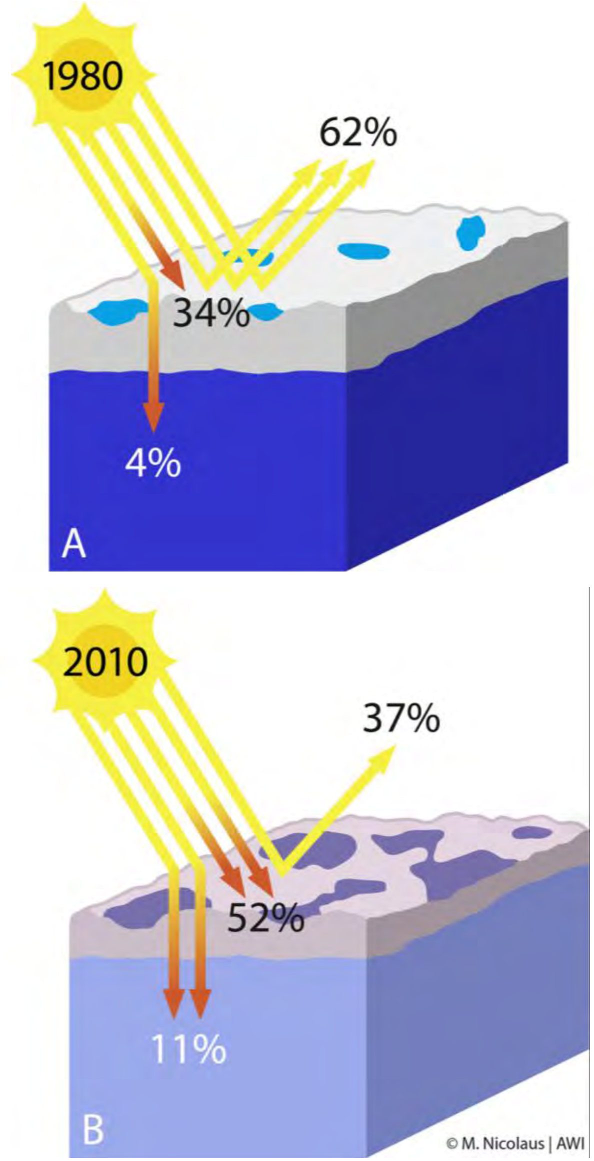
Arctic vs. Antarctic



	Arctic	Antarctic
Snow	melts completely	survives summer
Processes	melt ponds scattering layer (rotten ice)	ice lenses Aufeis

Influence of Ice Type on Melt Ponds





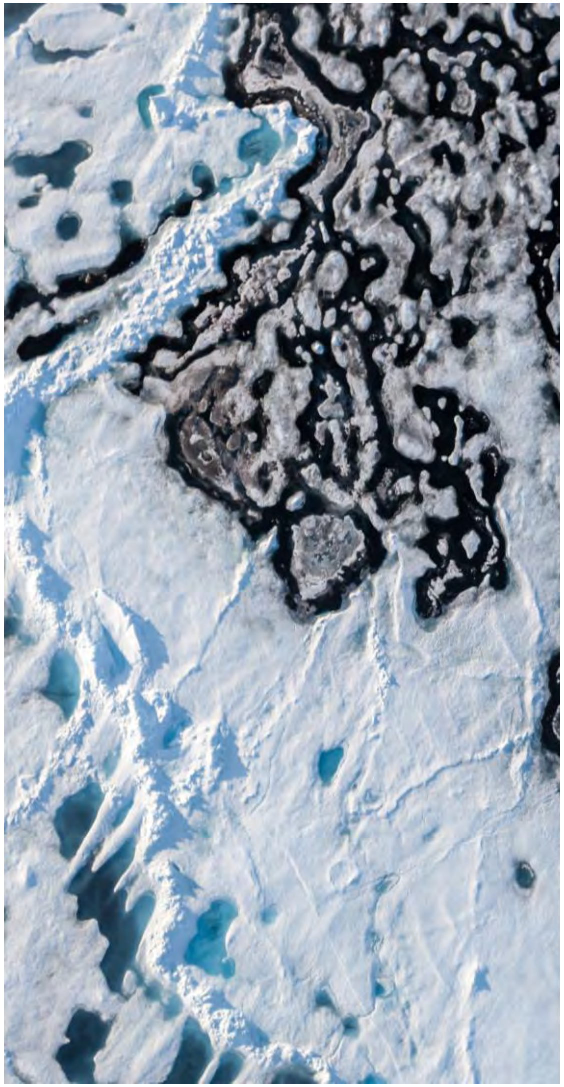
Older Ice

- Rougher Surface
- Less but deeper ponds

Younger Ice

- Level Surface
- Widespread ponding

Impact of Surface Melt on Microwave RS



Wet snow is an efficient absorber of microwave radiation

Melt ponds have similar remote sensing signature to leads

Altimetry

- Ranging biases in wet snow
- Ambiguou lead/ice classification with open melt ponds

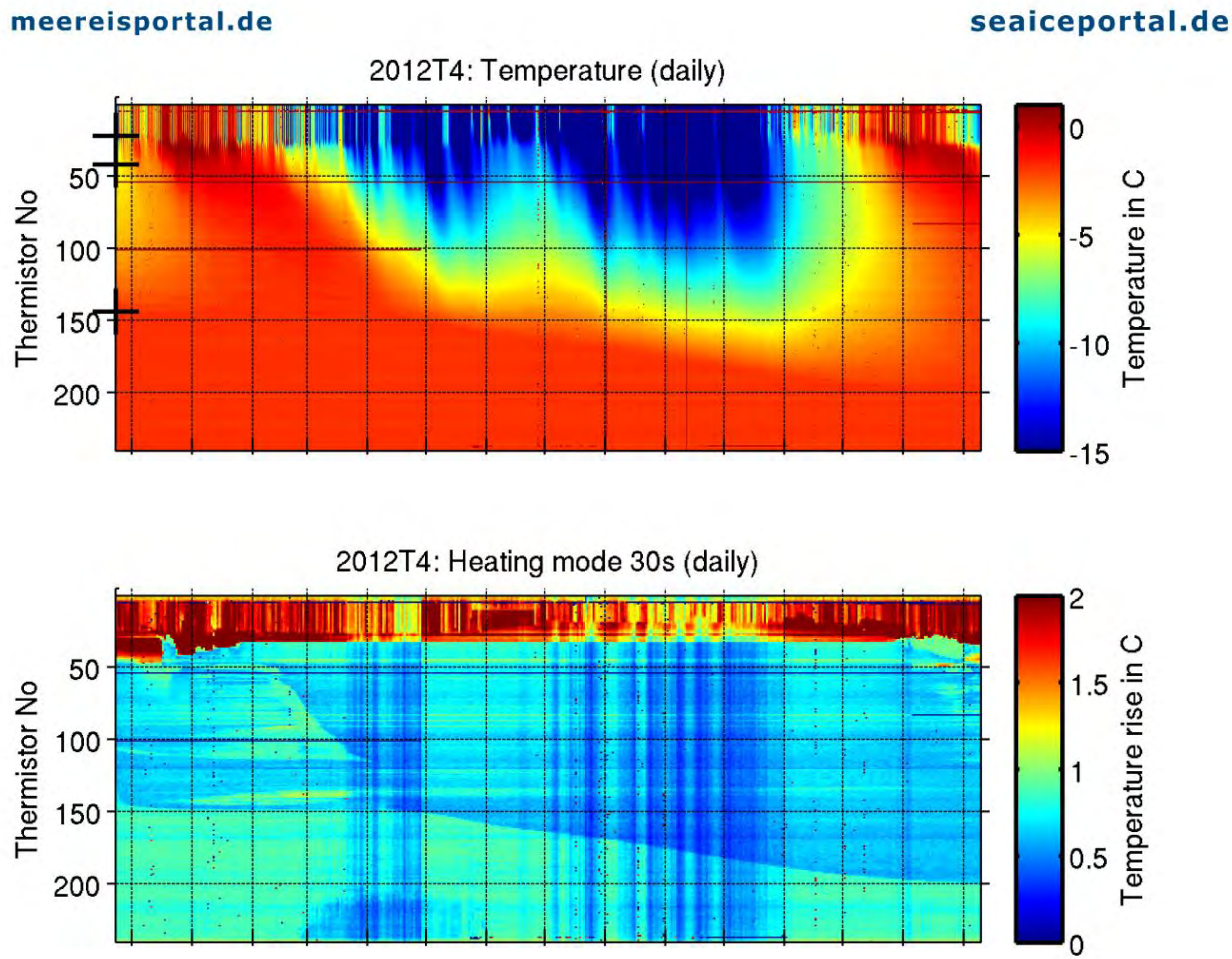
Passive Microwave

- Changes of brightness temperatures (desaliniation, melt ponds)

Backscatter (SAR)

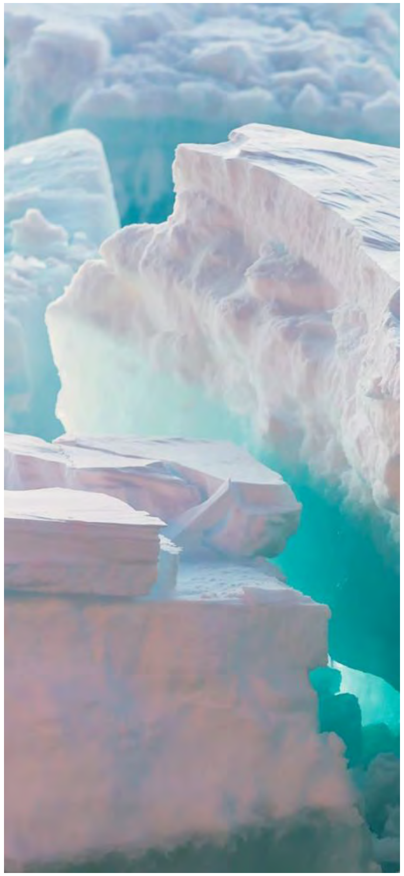
- Loss of contrast between ice types

Ice Mass Balance Buoys



Sea ice temperatur and thermal conductivity measured by thermistorstring with heating function

Summary



Take Home Message

Sea ice and related processes are very heterogenous on spatial and temporal scales

A lot of variability not resolved by current remote sensing footprints

Challenge in the future:

- to include this variability in analysis of existing analysis algorithm
- to improve capability of high resolution observations for sea ice and its snow cover

Sea Ice – Public Data Sources

Unified Sea Ice Thickness Climate Data Record	Polar Science Center, Applied Physics Laboratory, University of Washington	Arctic	Sea Ice Thickness	Various	Link
Ice Mass Balance (IMB) Buoy Program	Cold Regions Research and Engineering Laboratory	Arctic	Sea Ice Thickness, Snow Depth, Sea Ice Temperatur	Buoys	Link
NASA OIB data portal	NASA, NSICD	Arctic Antarctic	Snow Freeboard, Snow Depth, Sea Ice Thickness	Aircraft	Link
meereisportal.de	Alfred Wegener Institute	Arctic Antarctic	Snow Depth, Sea Ice Thickness	Buoys Aircraft	Link
Beaufort Gyre Exploration Project	Woods Hole Oceanographic Institution	Arctic	Sea Ice Draft	Moorings	Link
ESA Earth Observation Campaign Data (CryoVEx)	European Space Agency	Arctic	Sea Ice Thickness, Snow Freeboard	Aircraft	Link
Antarctic Sea Ice Processes & Climate (ASPECT)	Australian Antarctic Division	Antarctic	Sea Ice Thickness, Snow Depth, Snow Properties, Ice Surface Properties	Visual Observations	Link
IceWatch (ASSIST)	International Arctic Research Center	Arctic	Sea Ice Thickness, Snow Depth, Snow Properties, Ice Surface Properties	Visual Observations	Link
National Snow & Ice Data Center – Sea Ice Data	National Snow & Ice Data Center	Arctic Antarctic	Sea Ice Draft, Various	Submarine Various	Link
PANGAEA	Alfred Wegener Institute & Center for Marine Environmental Sciences, University of Bremen (MARUM).	Arctic Antarctic	Sea Ice Thickness, Snow Depth, Various	In-Situ Aircraft	Link
.... to be expanded					

MOSAIC Observatory

Multidisciplinary drifting Observatory for the Study of Arctic Climate

http://www.mosaicobservatory.org/