Remote Sensing of Snow on Sea Ice

Robert Ricker

ESA Advanced Training Course on Remote Sensing of the Cryosphere

Leeds, 12.09 –16.09.2016

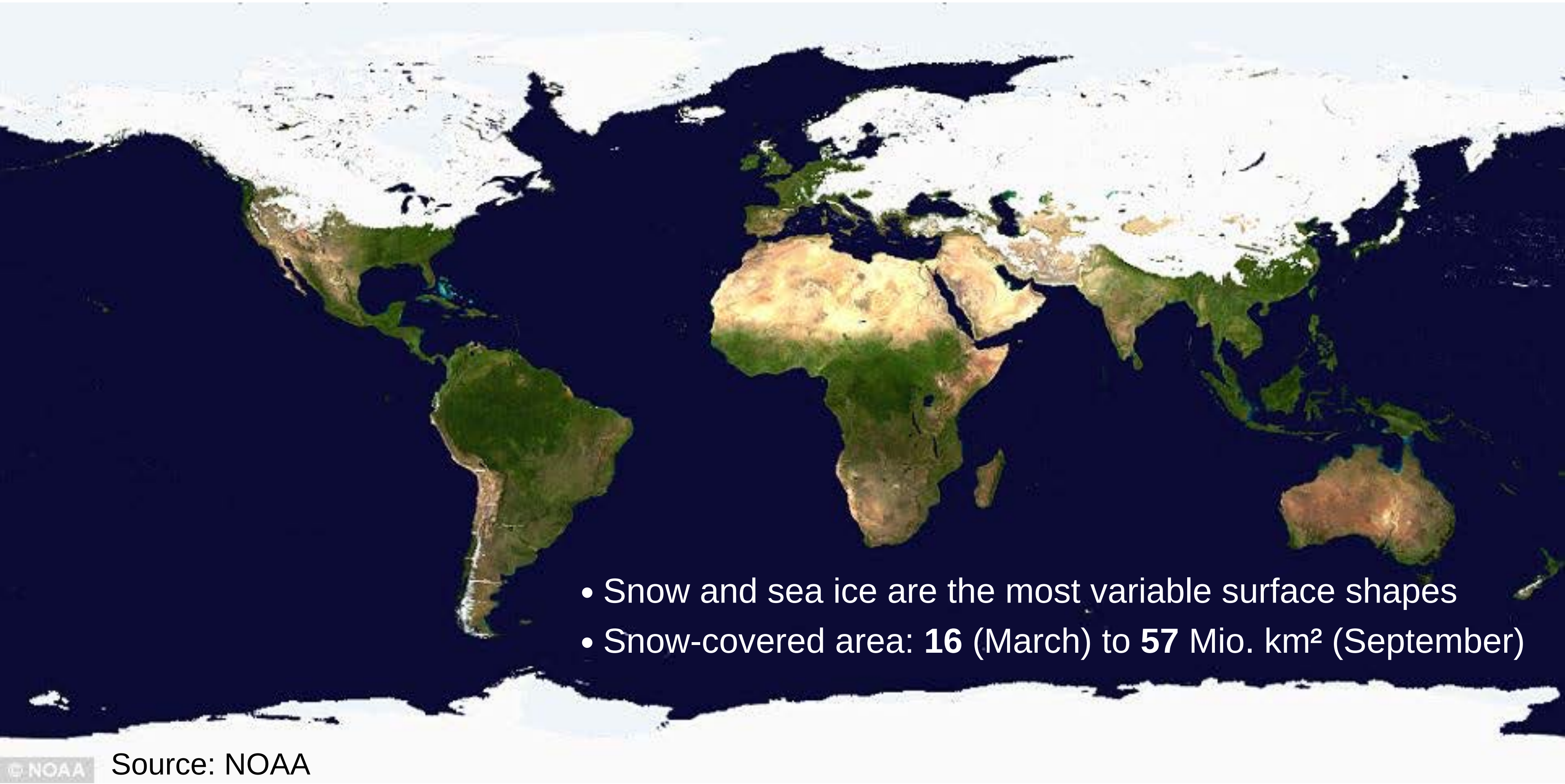
Outline

- Introduction - The far-reaching Impact of Snow
- Snow on Sea Ice - Characteristics
- Remote Sensing of Snow, Climatologies, and Products
- Validation
- The Impact of Snow on Ice Thickness Retrievals
- Outlook

Outline

- **Introduction - The far-reaching Impact of Snow**
- Snow on Sea Ice - Characteristics
- Remote Sensing of Snow, Climatologies, and Products
- Validation
- The Impact of Snow on Ice Thickness Retrievals
- Outlook

The Snow Cover of the Earth

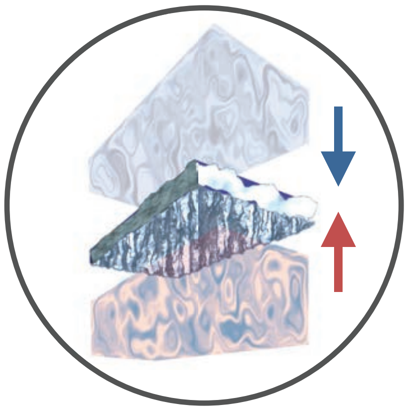


- Snow and sea ice are the most variable surface shapes
- Snow-covered area: **16** (March) to **57** Mio. km² (September)

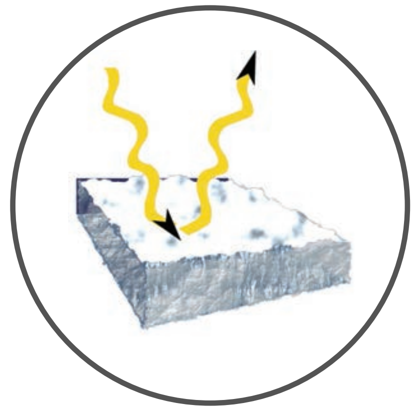
Source: NOAA

Snow on Sea Ice

Insulator between Ocean and Atmosphere

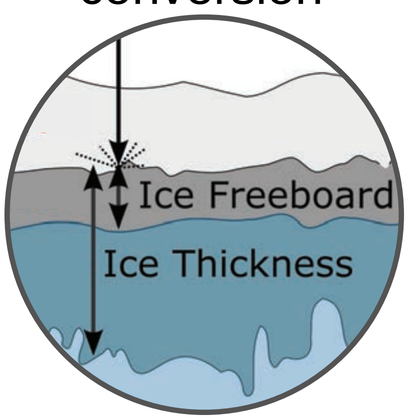


High albedo

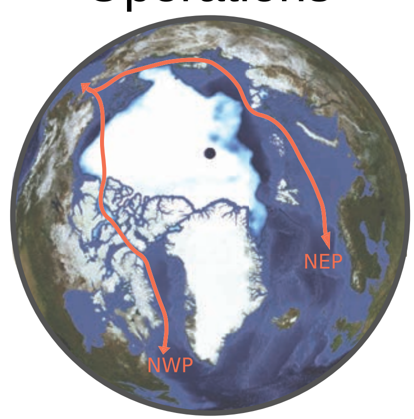


Fresh Water Input

Freeboard-to-Thickness conversion



Maritime Operations



Biology

Snow amplifies Sea Ice Properties

- **Thermal conductivity:**

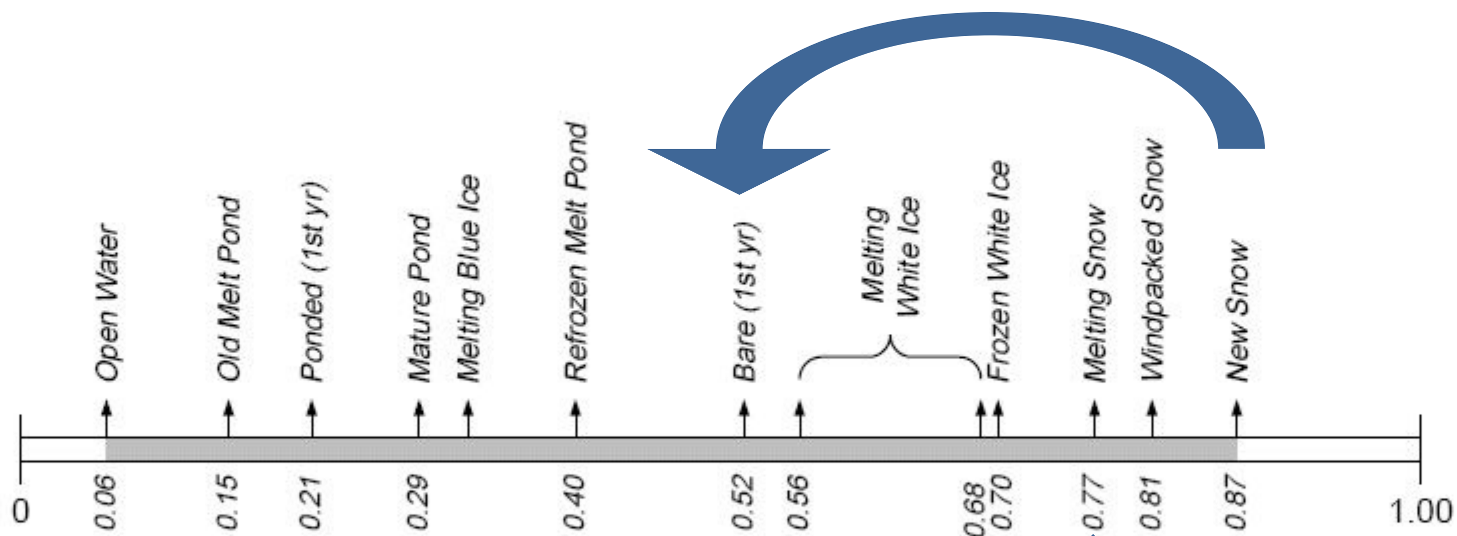
  Snow: 0.11 to 0.35 W m^{-1} K^{-1}

  Sea ice: ca. 2.3 W m^{-1} K^{-1}

  × 10

- **Albedo:**

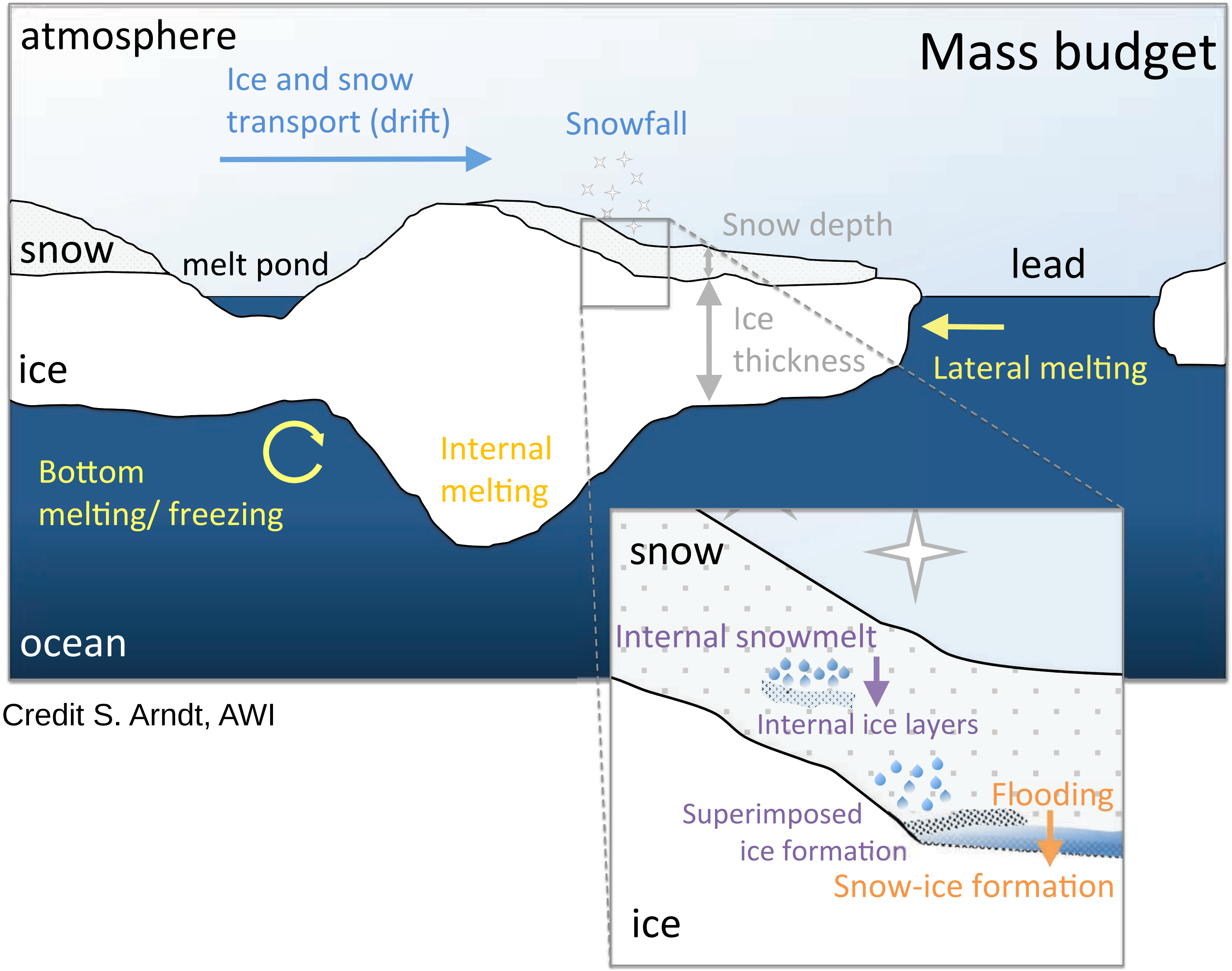
-0.45 ~ 4-fold energy entry



***D.K. Perovich (1996)**, The Optical Properties of Sea Ice*

-0.10 ~ 2-fold energy entry

Snow characterizes the Sea-Ice Cover



Credit S. Arndt, AWI

Outline

- Introduction - The far-reaching Impact of Snow
- **Snow on Sea Ice - Characteristics**
- Remote Sensing of Snow, Climatologies, and Products
- Validation
- The Impact of Snow on Ice Thickness Retrievals
- Outlook

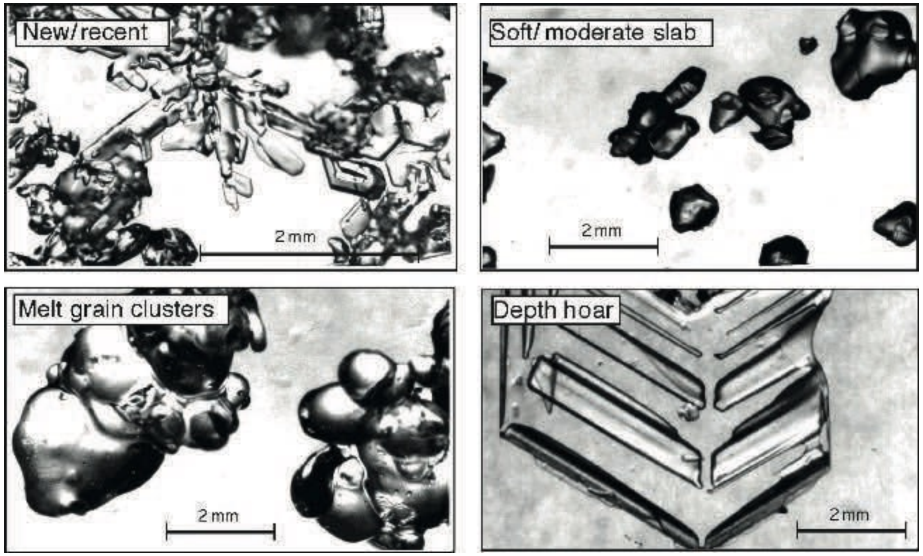

Credit S. Hendricks, AWI


Source: R. Ricker

General Characteristics of Snow

- Snowflakes
- Snow Metamorphism
- Snow Grain Types:
    1. New and recent snow
    2. Fine-grained snow
    3. Wind slab
    4. Faceted grains & depth hoar
    5. Icy layers
    6. Damp/wet snow and slush

***Sturm et al. (2002)**, Winter snow cover on the sea ice of the Arctic Ocean at the surface heat budget of the Arctic Ocean, JGR*

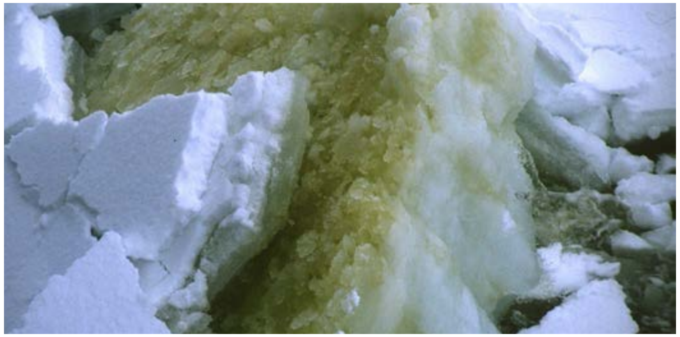


***Sturm et al. (1998)**, The winter snow cover of the West Antarctic pack ice: its spatial and temporal variability*

Arctic vs. Antarctic

Arctic		Antarctic
Complete melt (even at 90°N)	Seasonal snow cover	Persists through summer (e.g. at 68°S)
Melt ponds, deteriorated sea ice	Surface processes	Ice layers, superimposed ice
High latitudes, Basin, surrounded by continents	Geography	Lower latitudes, Open ocean, Central continent
Dominated by radiation fluxes, Warm and moist lows	Meteorology	Turbulent fluxes, Dry and cold wind

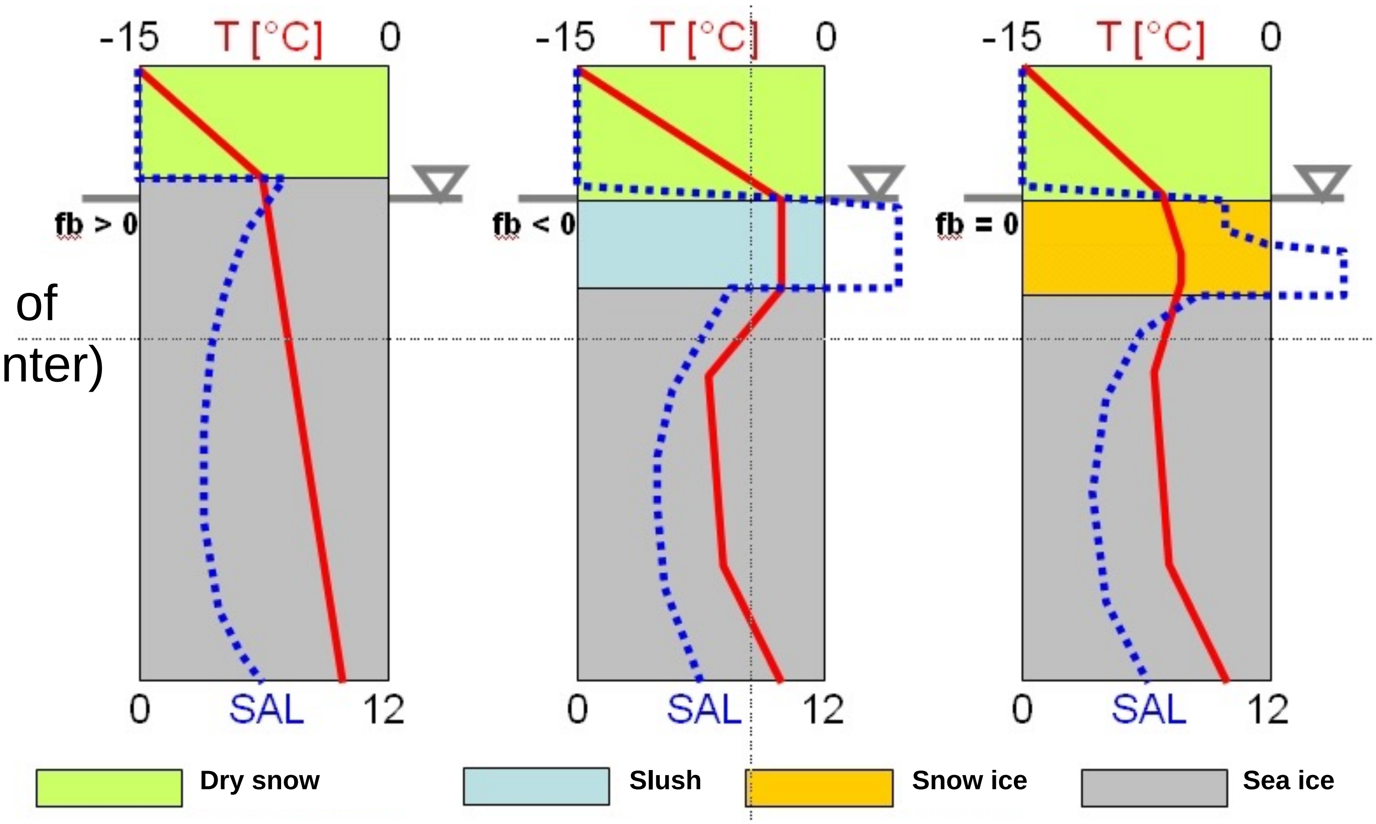
Credit AWI-Sea ice physics



Credit C. Haas, AWI

Contribution to Sea Ice Mass Balance

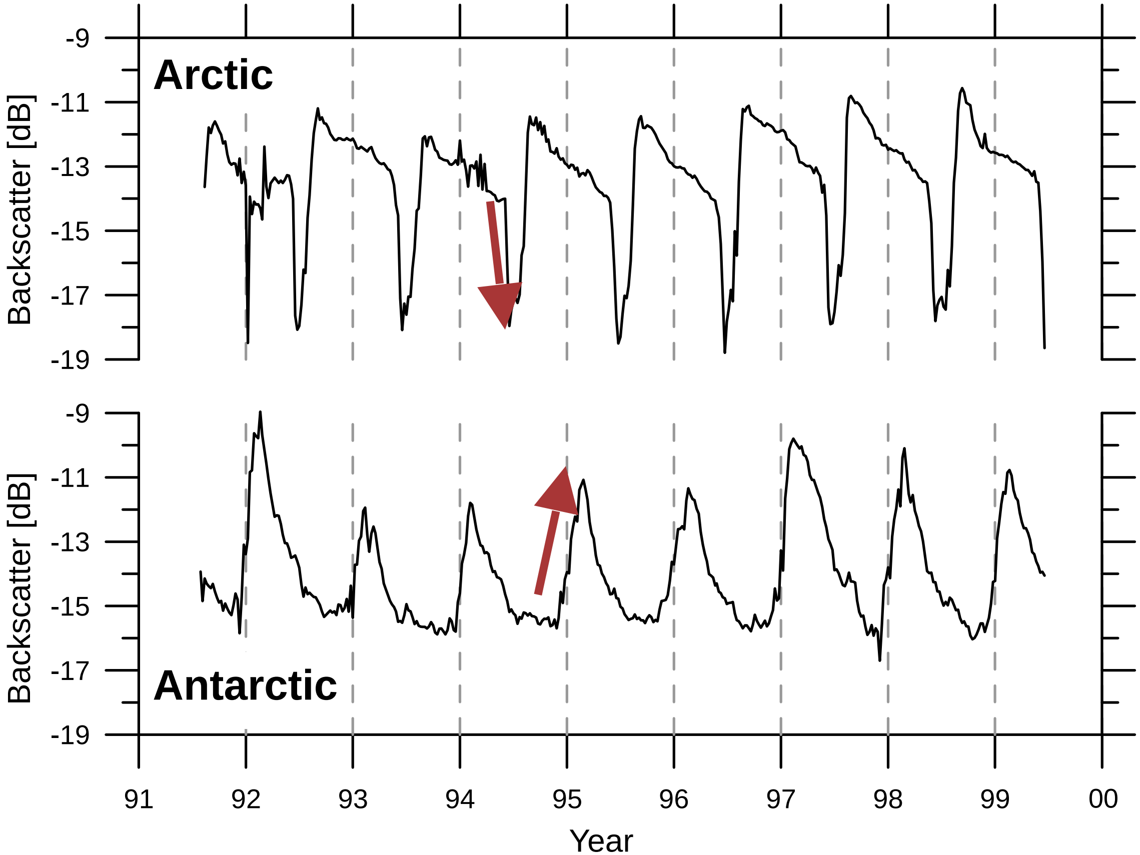
Formation of
snow ice (winter)



Credit M. Nicolaus, AWI

- Absorption of short-wave radiation
  - Sub-surface warming / melting
  - Affecting biological processes
    (PAR activity of algae and micro organisms)

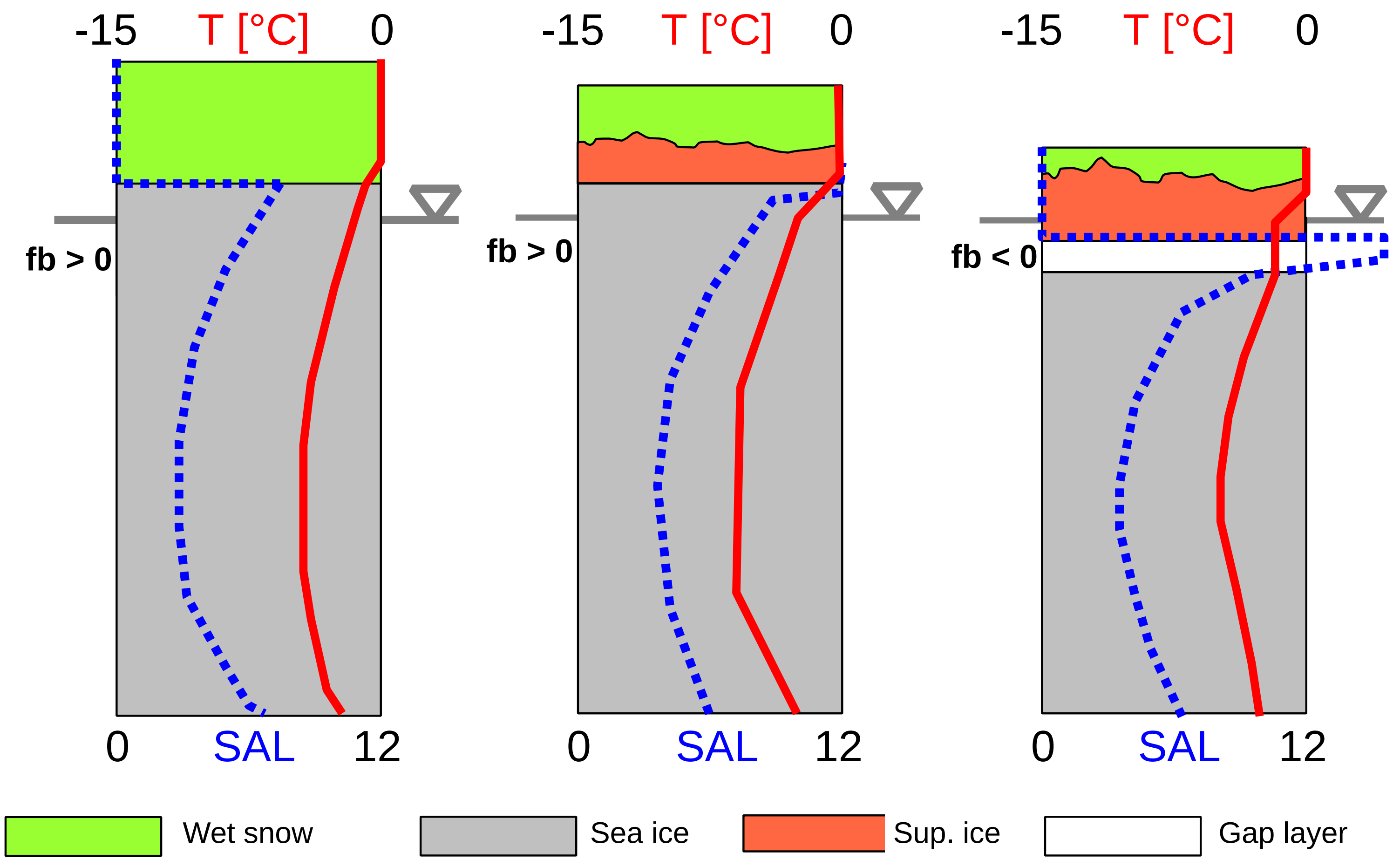
Radar backscatter in both Polar Regions



***Haas et al. (2001)**: Surface properties and processes of perennial Antarctic sea ice in summer, Journal of Glaciology*

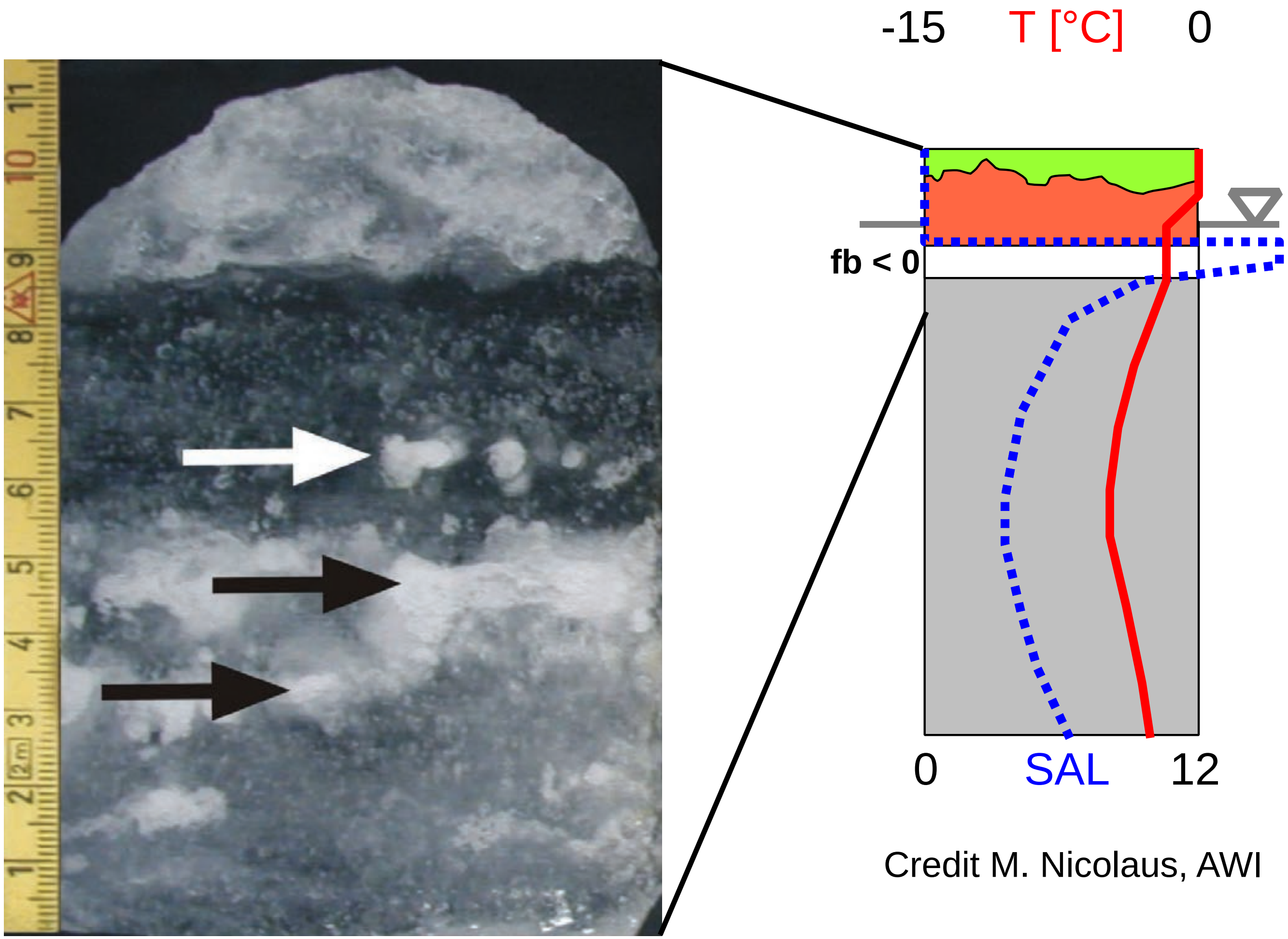
- Arctic: strong decrease followed by strong increase
- Antarctic: strong increase => Melt-freeze cycles, superimposed ice

Formation of superimposed Ice (Summer)



Credit M. Nicolaus, AWI

Formation of superimposed Ice (Summer)



Credit M. Nicolaus, AWI

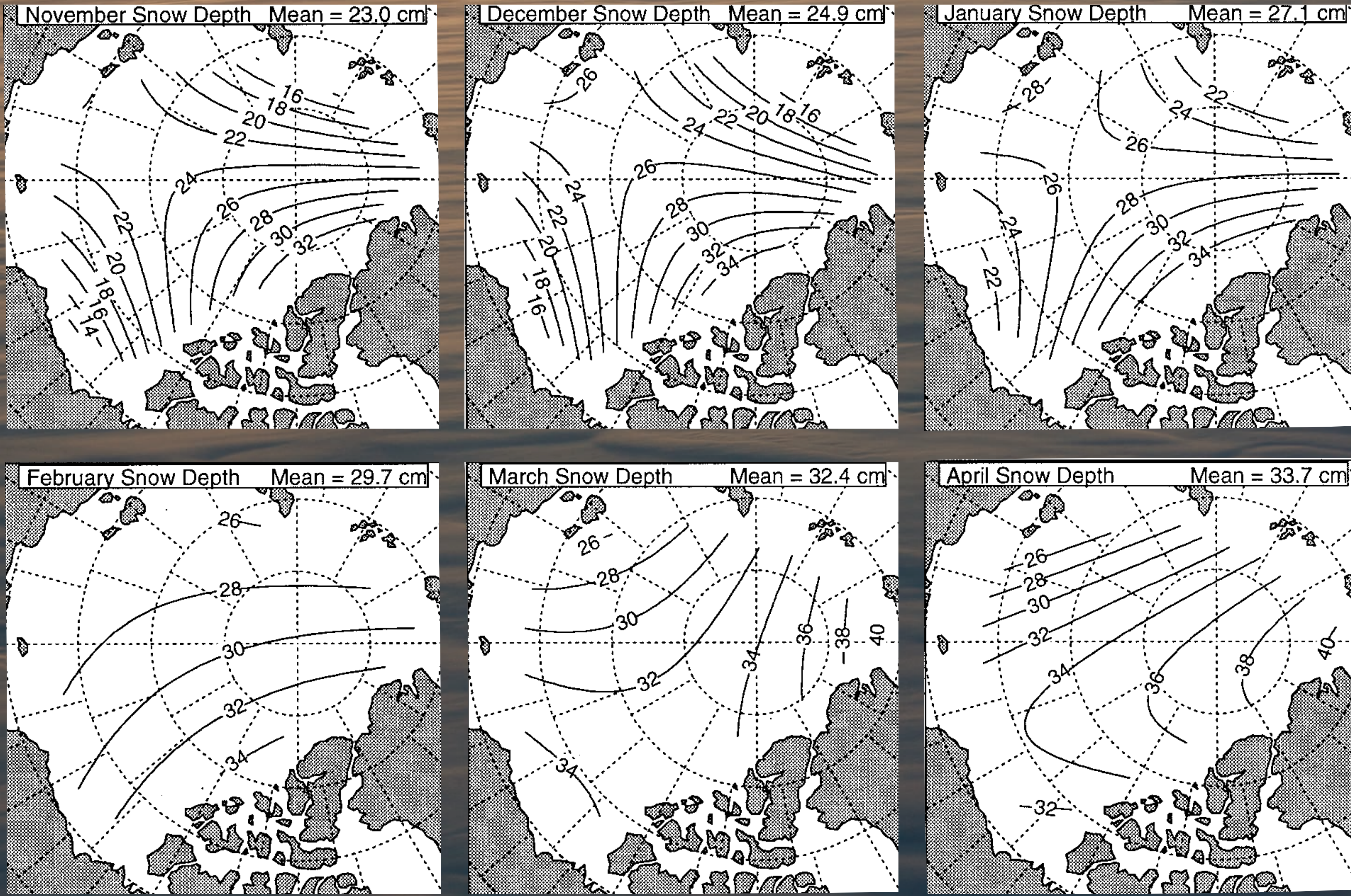
Outline

- Introduction - The far-reaching Impact of Snow
- Snow on Sea Ice - Characteristics
- **Remote Sensing of Snow, Climatologies, and Products**
- Validation
- The Impact of Snow on Ice Thickness Retrievals
- Outlook

Challenges for Seasonality

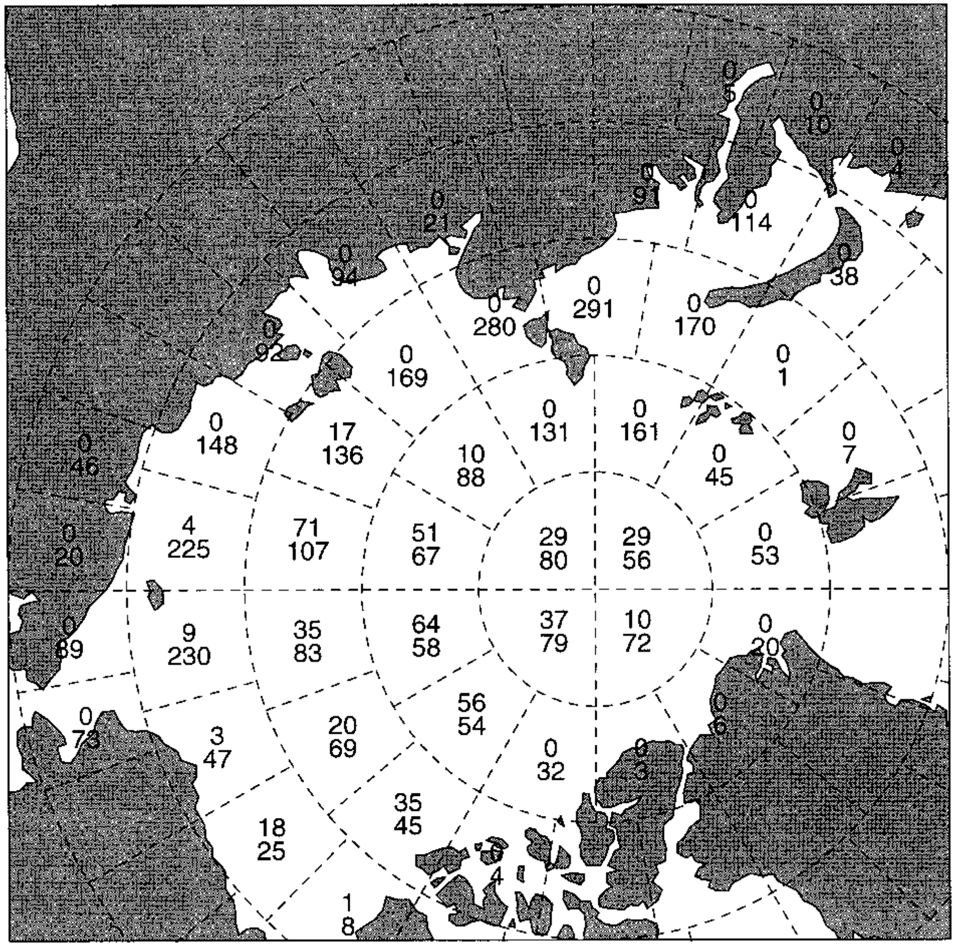
	Arctic	Antarctic
Snow Climatology	✔	x
Few multi-seasonal studies	✔	x
Passive microwave snow depth product	✔	✔
Ship-based Observations data set (ASSIS, ASPeCt)	(✔)	✔

ASPeCt
aspect.antarctica.gov.au/data



Warren et al. (1999): Snow Depth on Arctic Sea Ice

Snow Climatology by Warren et al. (1999)

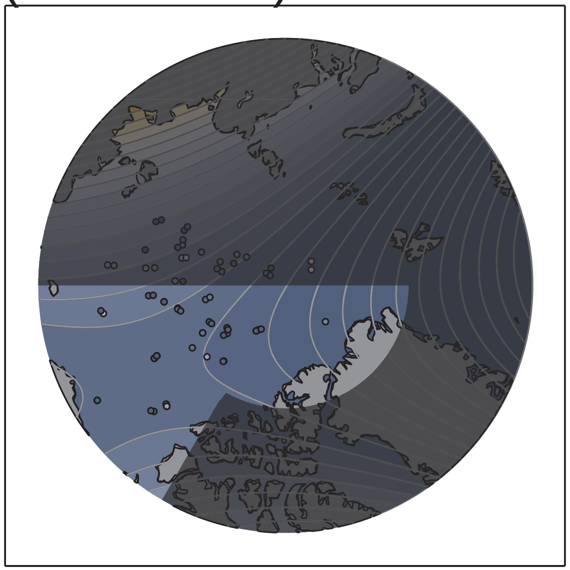


Number of snow lines measured at North Pole drifting stations **(upper number** in each grid box), and number of aircraft landings providing snow depth reports in spring **(lower number)**

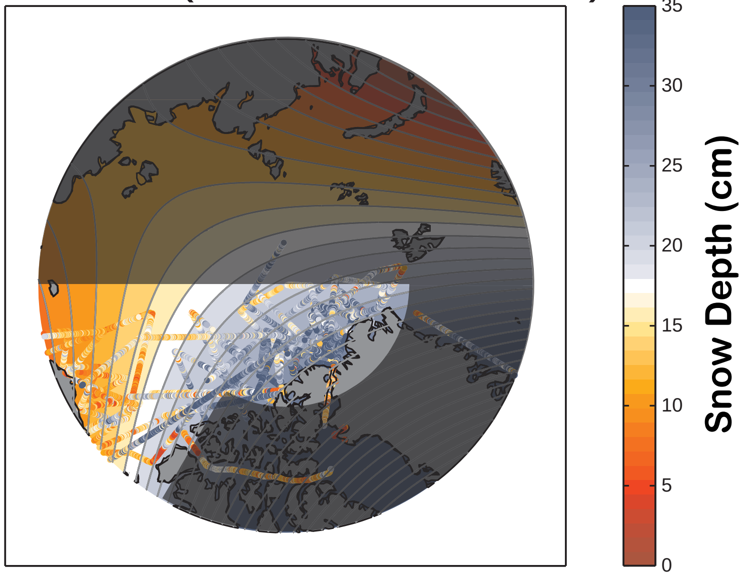
***Warren et al. (1999)**: Snow Depth on Arctic Sea Ice, Journal Of Climate*

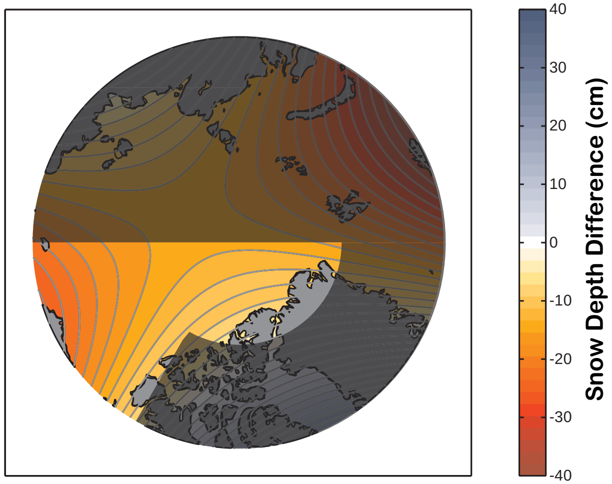
Interdecadal Changes in Snow Depth

IceBridge snow depth fit (2009–2013)



W99 fit (1937, 1954–1991)



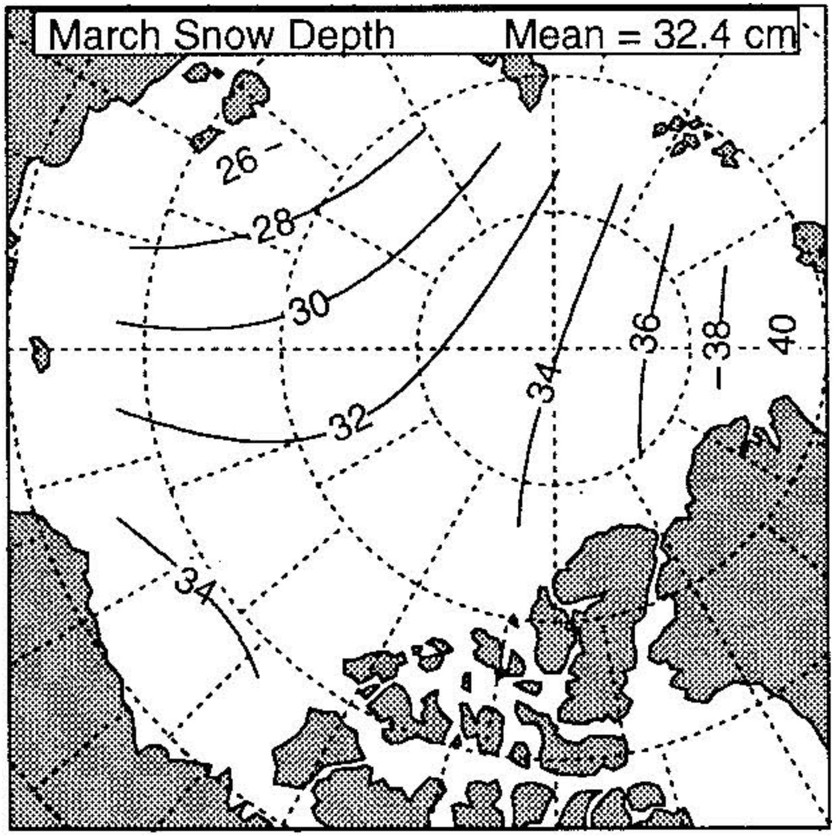


Difference between IceBridge snow depth distribution and W99 climatology

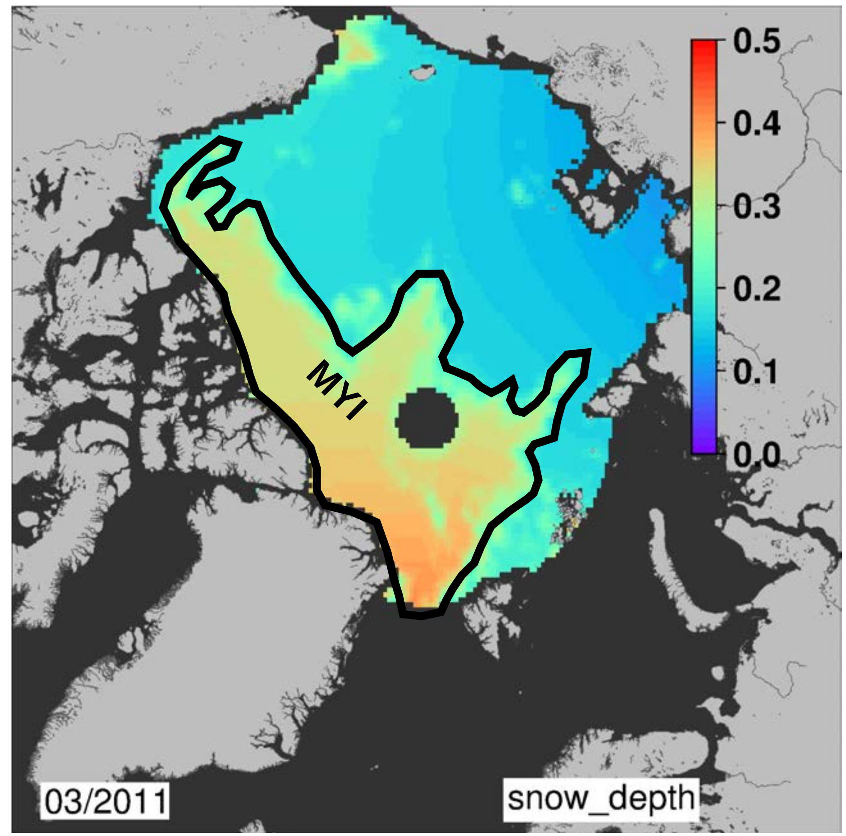
***Webster et al. (2014)**: Interdecadal changes in snow depth on Arctic sea ice, JGR Oceans*

Modified W99 Climatology

W99 (March), snow depth (cm)

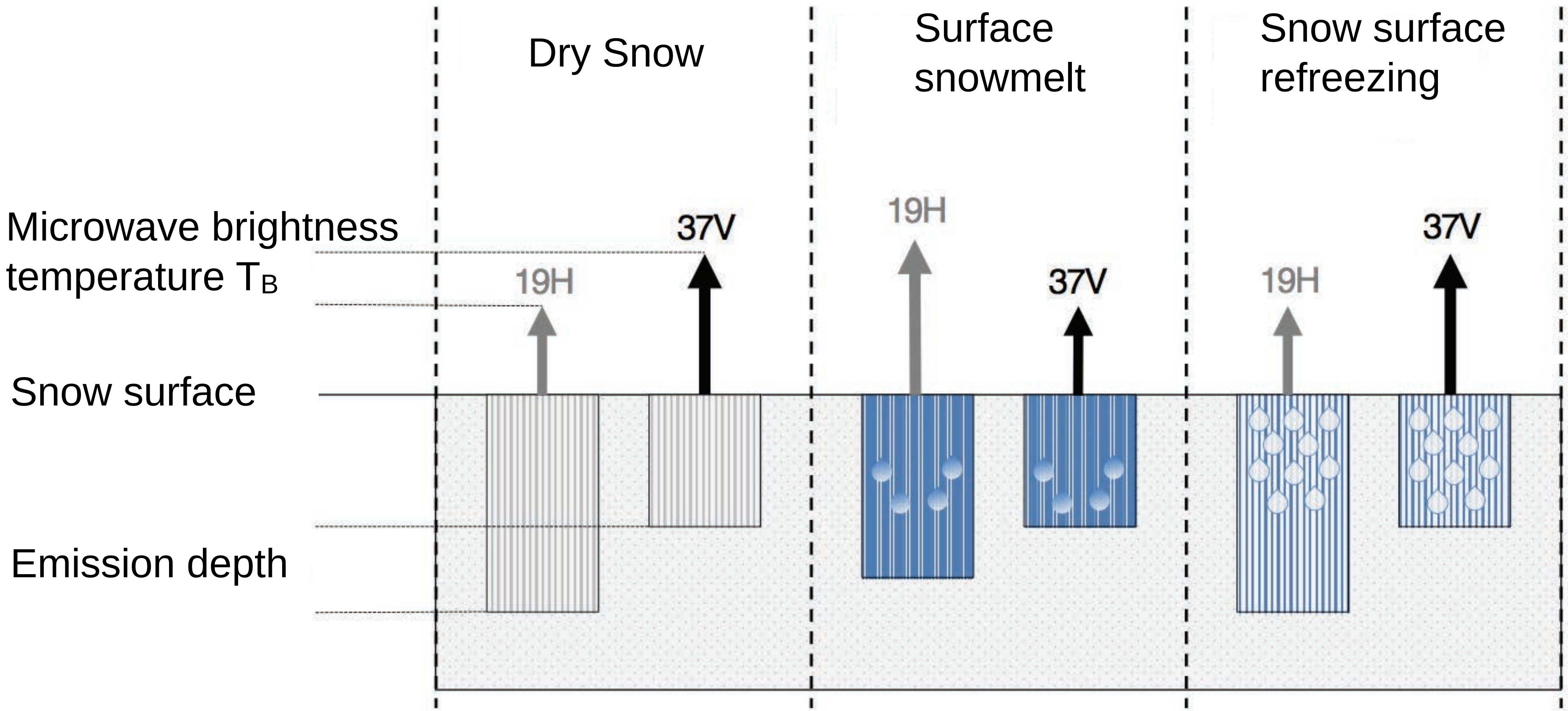


Modified climatology, snow depth (m)



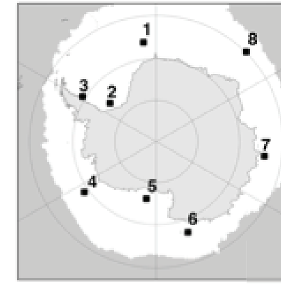
***Warren et al. (1999)**: Snow Depth on Arctic Sea Ice, Journal Of Climate*

Characteristics of snowmelt from passive microwave satellite observations



Credit S. Arndt, AWI, modified after Willmes, 2007

Derived Variables

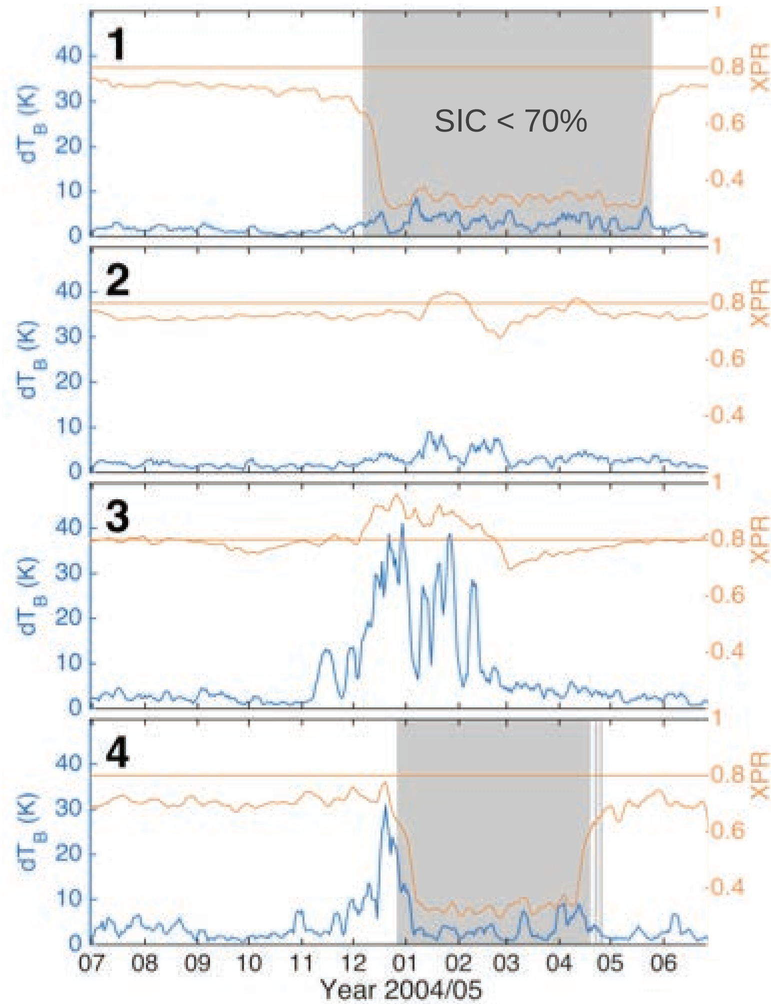


- **Diurnal variation in brightness temperatures, dT_B**
  EASE-Grid brightness temperature data (NSIDC), 37 GHz, vertically polarized

- **Cross-polarized ratio, XPR**

$$XPR = \frac{T_B(19\mathrm{GHz}, H)}{T_B(37\mathrm{GHz}, V)}$$

- **Further data set:**
  Sea-ice concentration, SIC
  Bootstrap data (SSM/I)



Arndt et al. (2016): Timing and regional patterns of snowmelt on Antarctic sea ice from passive microwave satellite observations, JGR Oceans

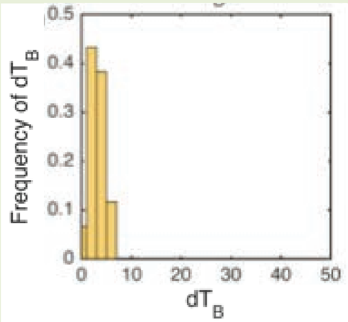
Method Scheme

Continuous time series of SIC > 70% for at least 21 days from 1 Oct onwards

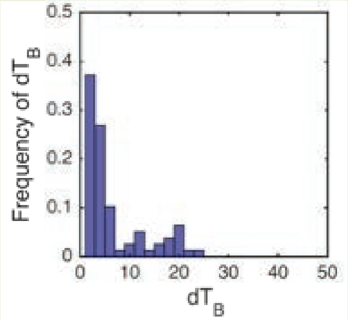
Diurnal variation in brightness temperature **(dT_B)**

Cross-polarized ratio **(XPR)**

Uni-modal



Multi-modal



Credit S. Arndt

Results

Individual thresholds

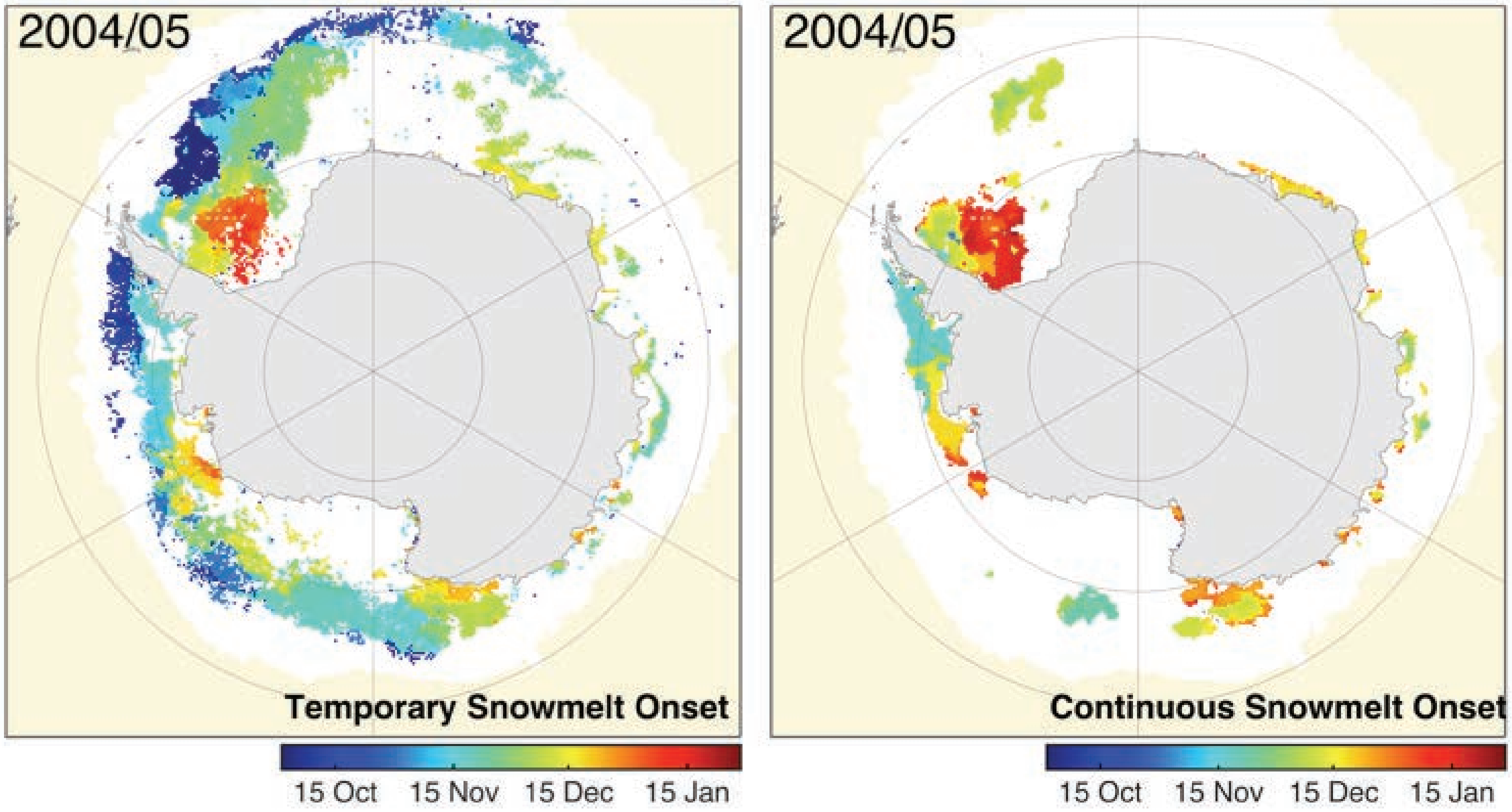
Fixed threshold: XPR = 1

Surface snowmelt onset

Continuous snowmelt onset

Characteristic snowmelt types

Spatial Variability of Snowmelt Patterns



Arndt et al. (2016)

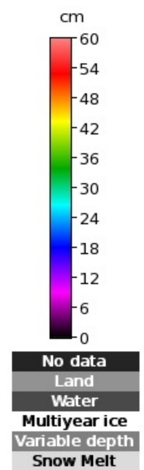
- Temporary snowmelt shows a **latitudinal dependence**
- Continuous snowmelt is usually **17 days after** temporary snowmelt onset observed

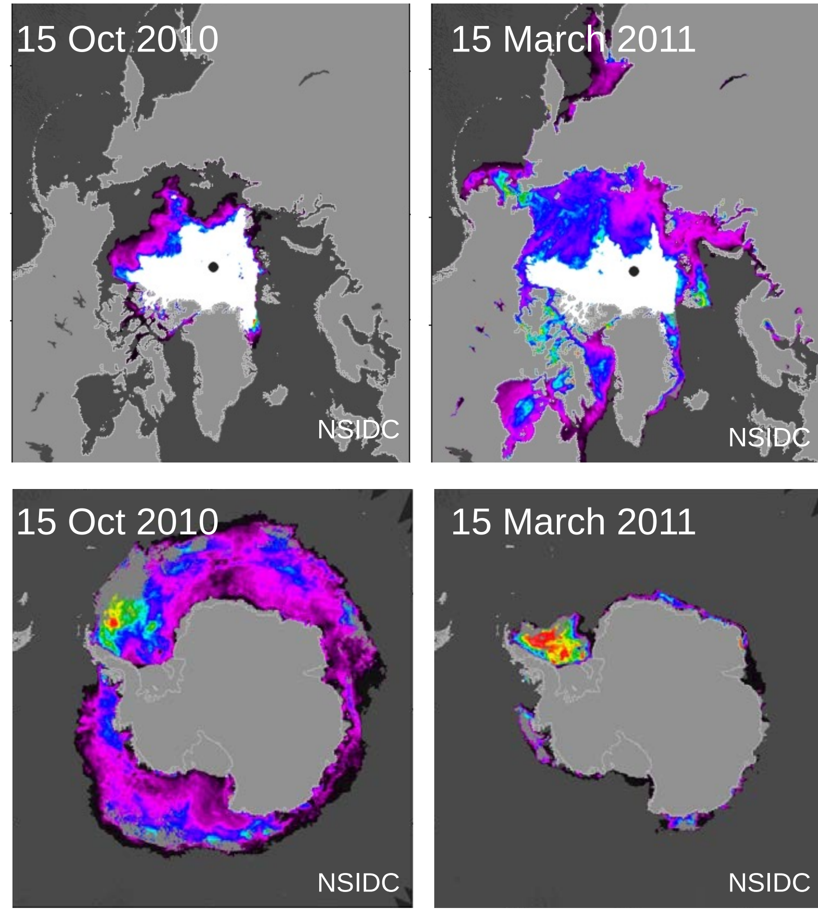
Passive Microwave Remote Sensing of Snow Depth - AMSR-E

$h_s = 2.9 - 782 \times GRV$

Coefficients derived from linear regression of h_s measurements and microwave data

GRV: Spectral gradient ratio corrected for the sea ice concentration





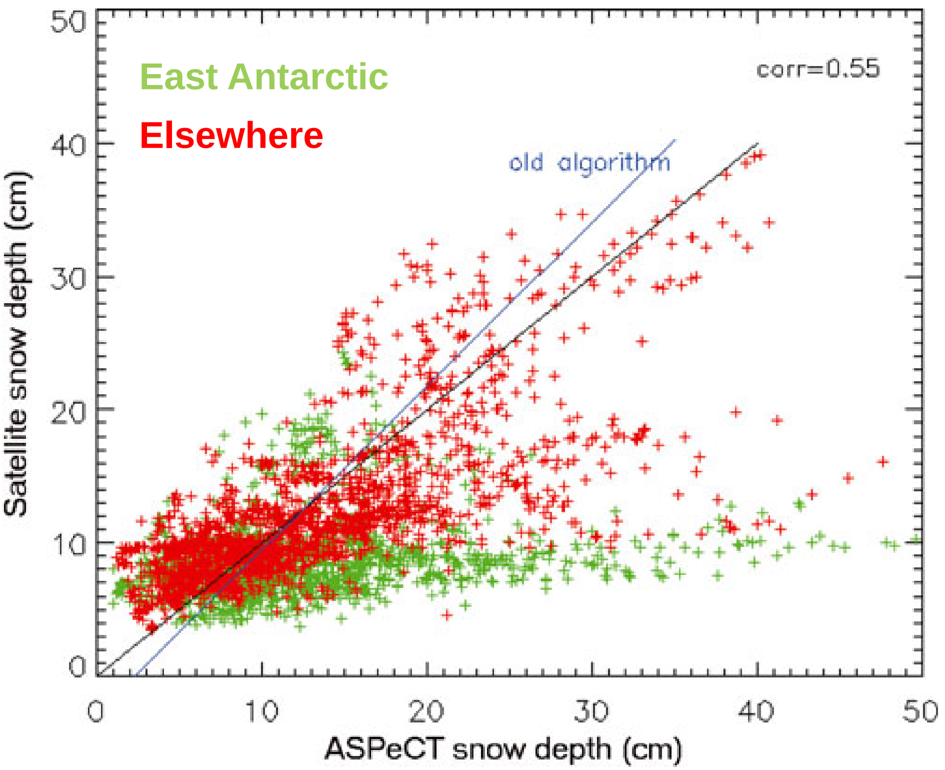
National Snow & Ice Data Center (NSIDC)
http://nsidc.org/data

Markus, T. and D. 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, Antarctic Research Series*

Passive Microwave Remote Sensing of Snow Depth - AMSR-E

- Comparison between in situ observations from *Antarctic Sea Ice Processes and Climate* (ASPeCt) and AMSR-E derived snow depth

- AMSR-E underestimates Snow Depth over rough sea ice



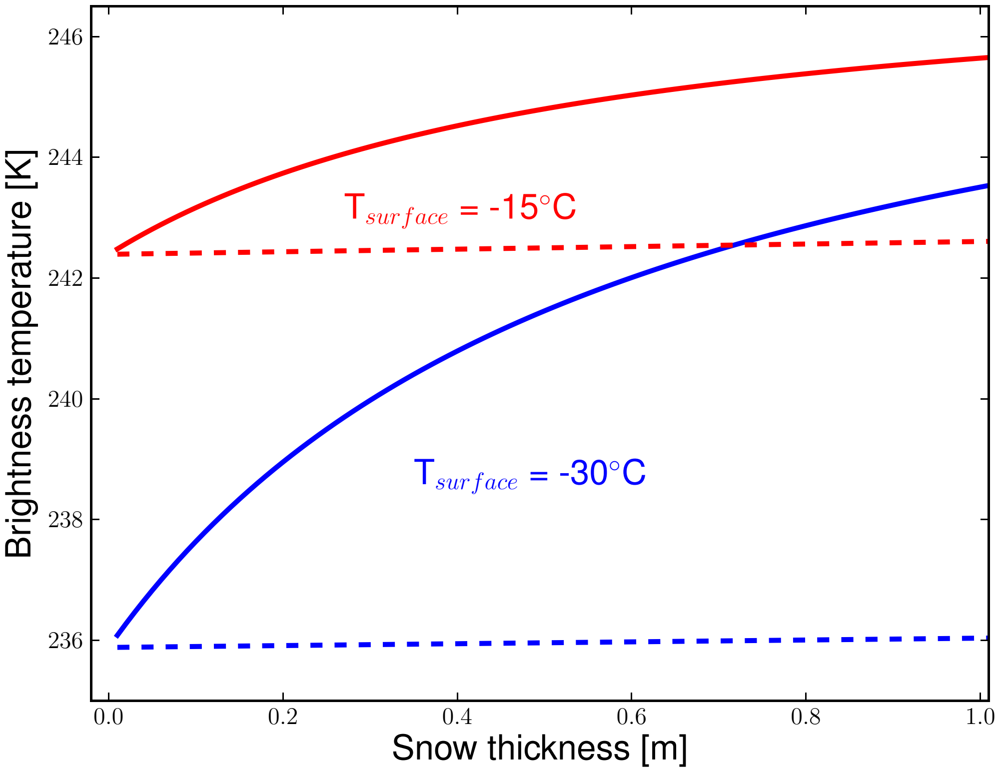
Markus et al. (2011)*: Freeboard, snow depth and sea-ice roughness in East Antarctica from in situ and multiple satellite data, Annals of Glaciology*

Remote Sensing of Snow Depth - SMOS

Soil Moisture and Ocean Salinity (SMOS) satellite mission evaluates surface emissivity in L-Band

- Sea Ice,covered by a thick snow layer, is warmer than covered by a thinner snow layer

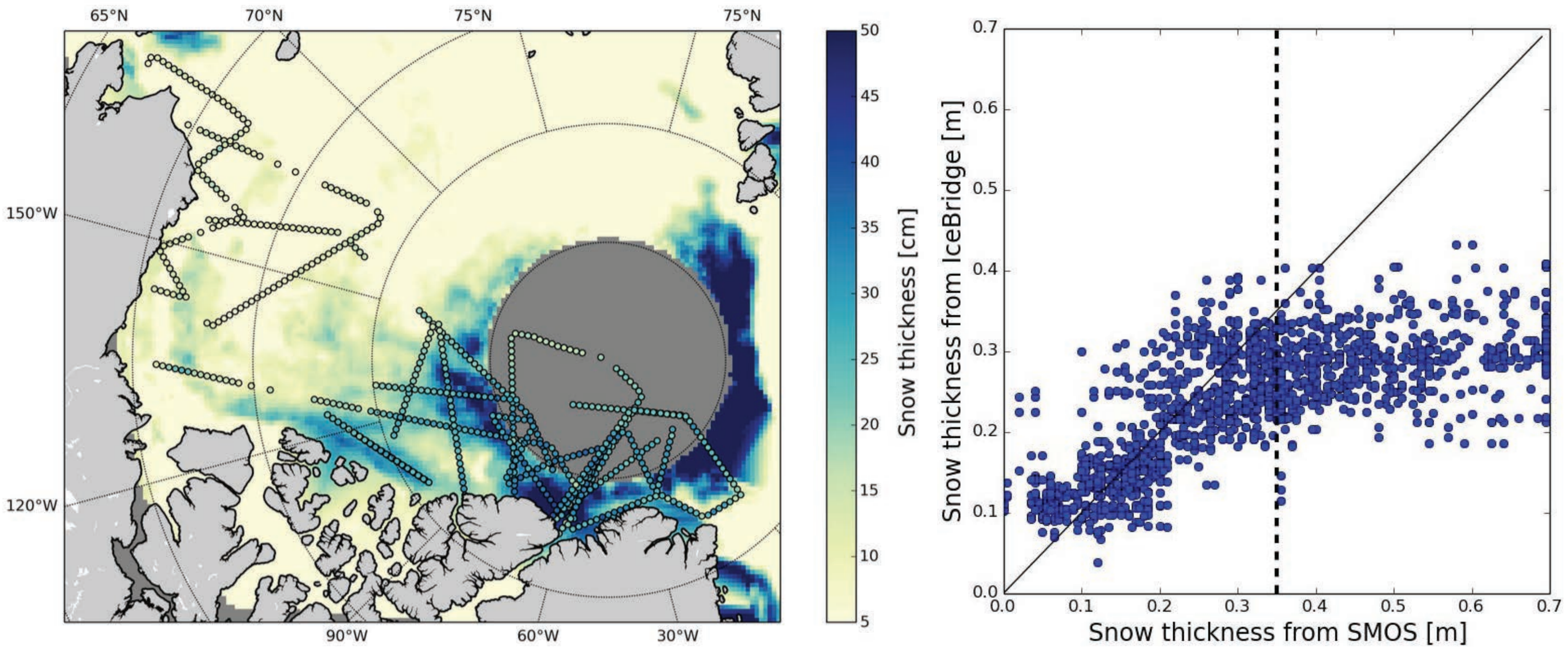
- Snow thickness estimation from horizontally polarized SMOS brightness temperatures over thick sea ice (1-1.5 m) under cold conditions



***Maaß et al. (2014)**: Snow thickness retrieval over thick Arctic sea ice using SMOS satellite data, The Cryosphere*

Remote Sensing of Snow Depth - SMOS

- Mean snow depth averaged over 14–31 March 2012, compared with IceBridge snow depth retrieval



__Maaß et al. (2014)__: Snow thickness retrieval over thick Arctic sea ice using SMOS satellite data, The Cryosphere

Simple Model Simulations

$$h_s = h_{s(sf)} + h_{s(as)} + h_{s(os)} + h_{s(f)} + h_{s(ad)} + h_{s(r)}$$

Total

h_s, model snow depth

Sources

$h_{s(sf)}$, snowfall rate (9.4 cm swe a^{-1})

$h_{s(r)}$, residual term (snow accumulation in leads, wind redistributed, blowing snow sublimation)

Sinks

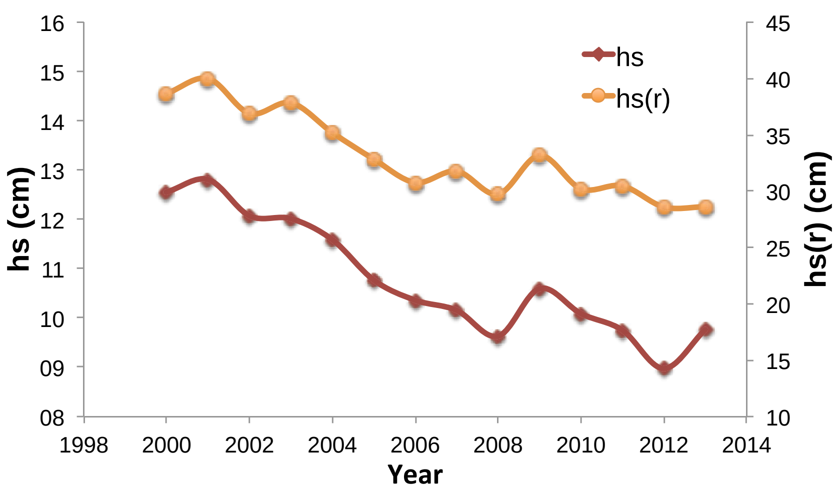
$h_{s(as)}$, snow loss due to heat transfer between atmosphere and snow

$h_{s(os)}$, snow loss due to heat transfer between the ocean and snow

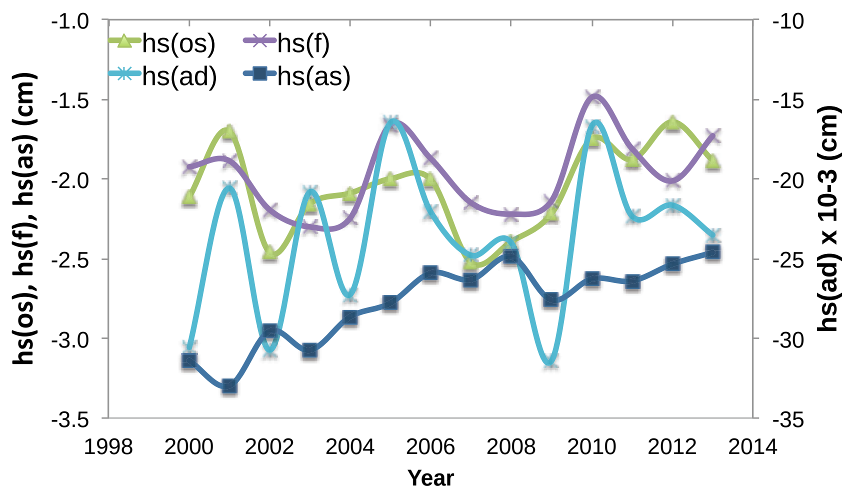
$h_{s(f)}$, loss of snow by flooding

$h_{s(ad)}$, loss of snow by advection

Sources and total

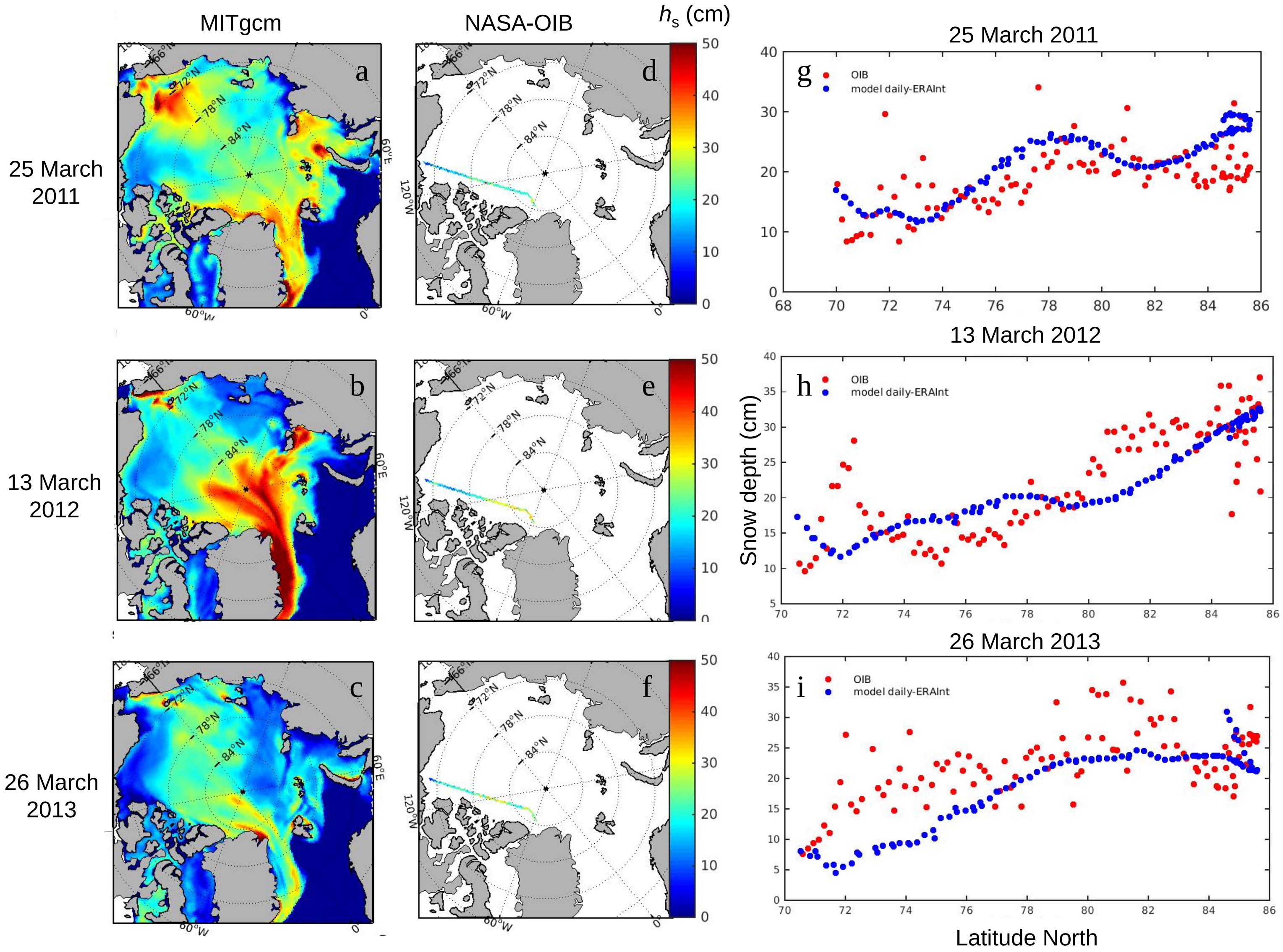


Sinks



***Castro-Morales et al. (2015)**: Snow on Arctic sea ice: Model representation and last decade changes, The Cryosphere Discussions*

Model Validation with OIB Snow Depth



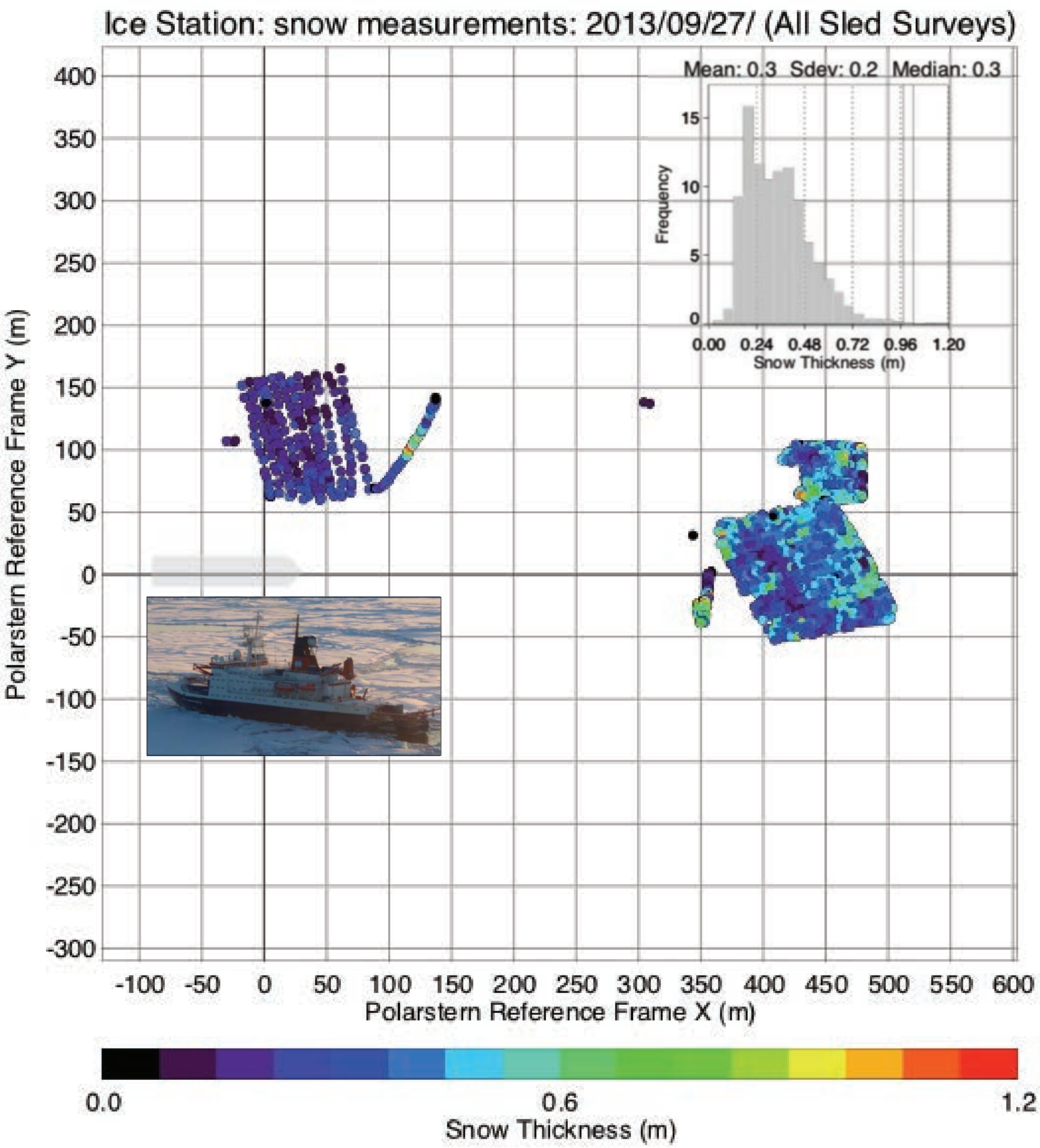
Castro-Morales et al. (2015)

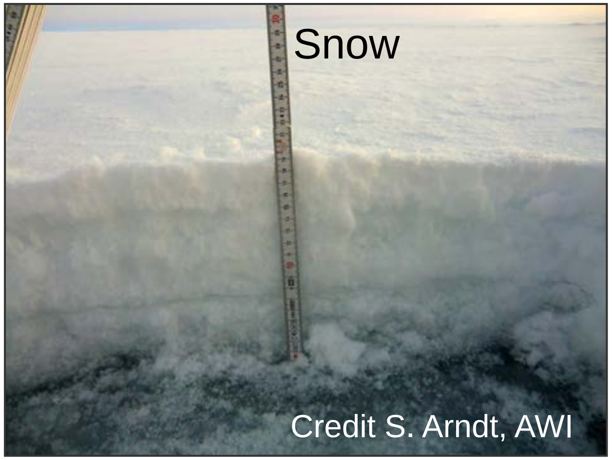
Outline

- Introduction - The far-reaching Impact of Snow
- Snow on Sea Ice - Characteristics
- Remote Sensing of Snow, Climatologies, and Products
- **Validation**
- The Impact of Snow on Ice Thickness Retrievals
- Outlook


© Martin Schiller

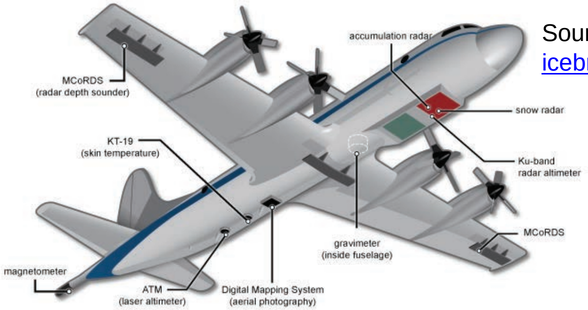
In-Situ Measurements





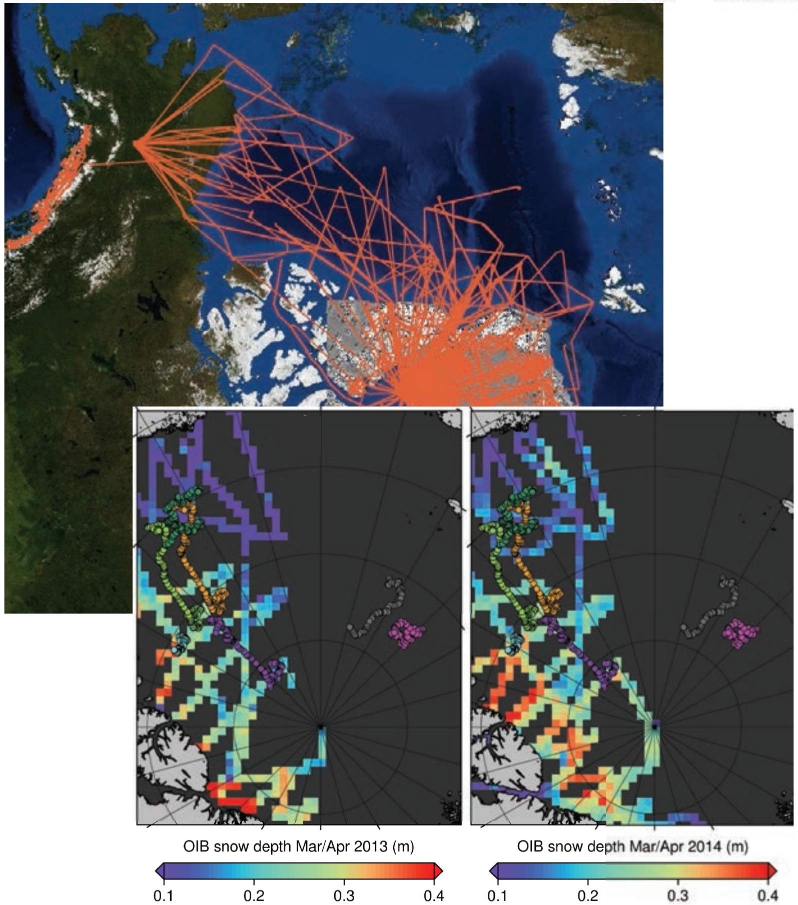
Data Publisher for Earth & Environmental Science: https://www.pangaea.de/

Snow Depth from NASA Operation IceBridge

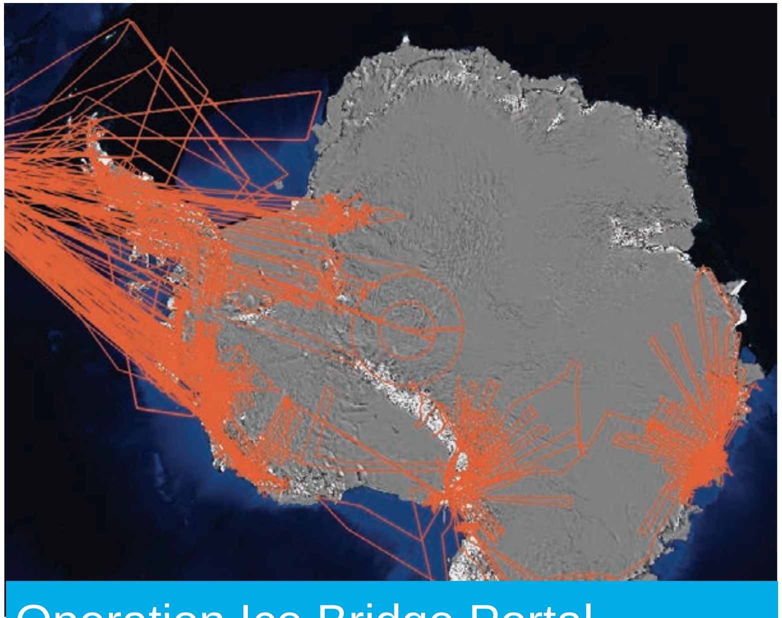


Source:
icebridge.gfsc.nasa.gov

Arctic



Antarctic

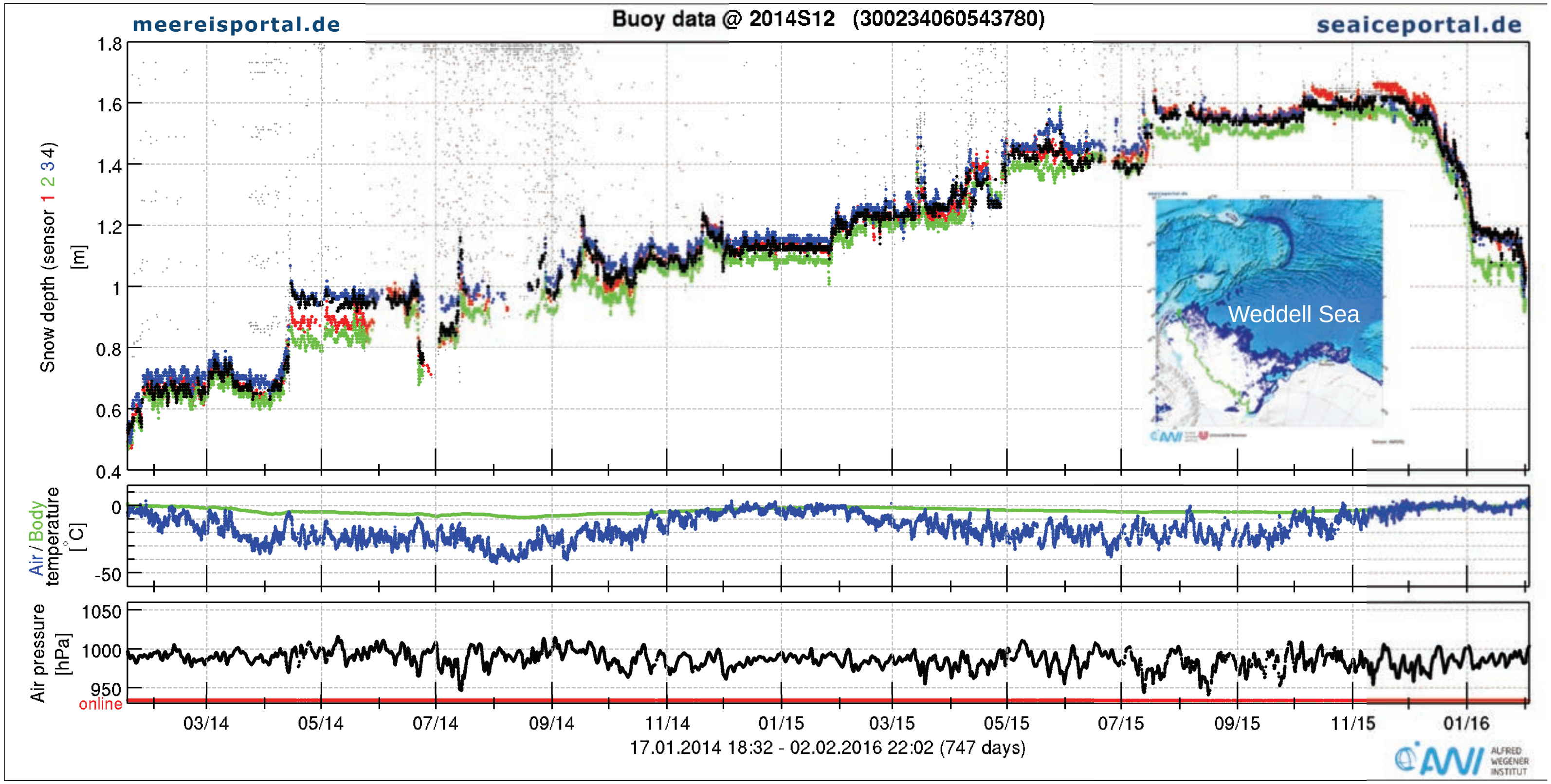


Operation Ice Bridge Portal
http://nsidc.org/icebridge/portal/

Kurtz et al. (2012), Sea ice thickness, freeboard, and snow depth products from Operation IceBridge airborne data, The Cryosphere

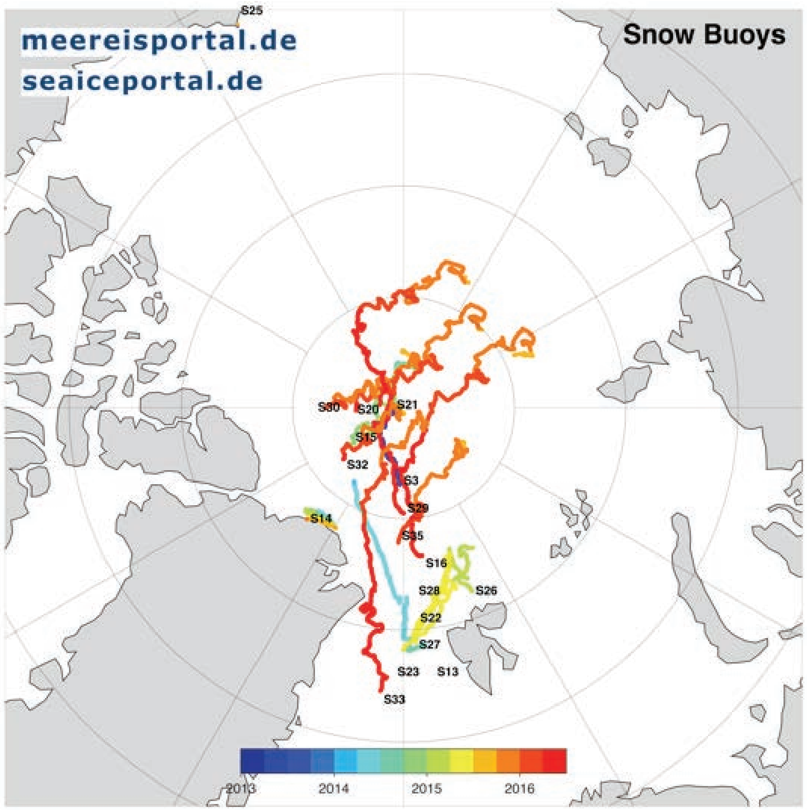
Autonomous Stations

- Ice Mass Balance Buoys: ice and snow thickness changes, thermistor strings
- Snow Buoys

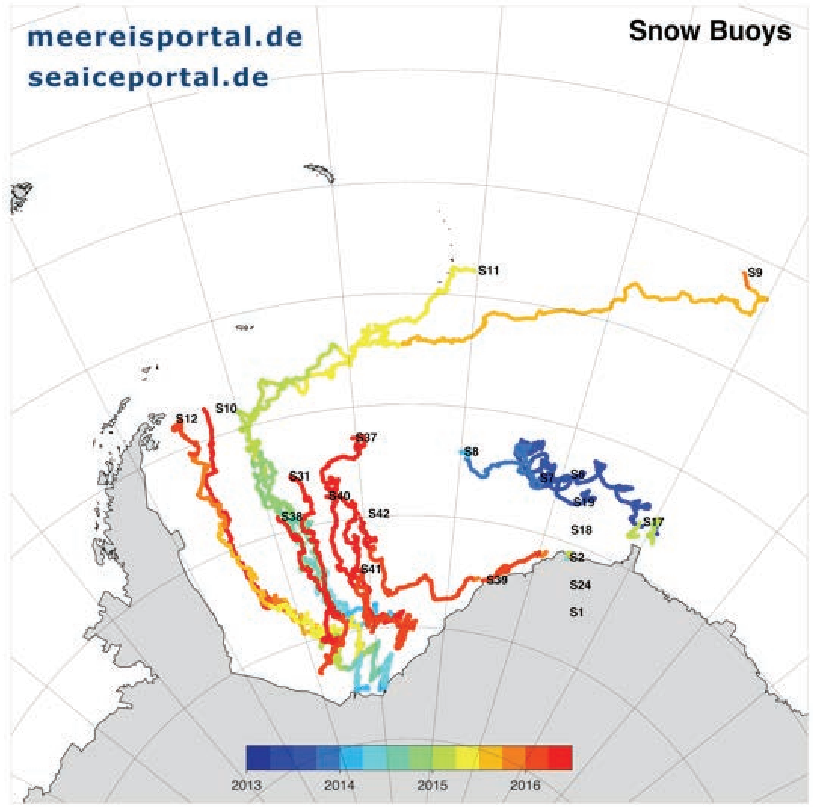


Autonomous Stations

Arctic



Antarctic



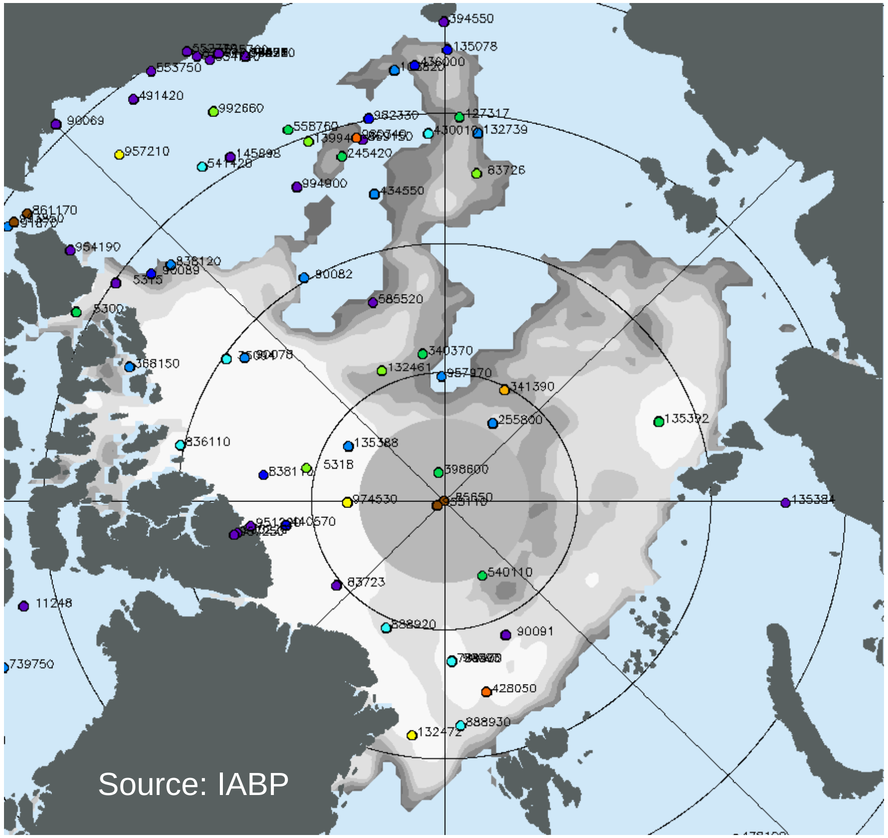
Sea-Ice Portal:
http://data.seaiceportal.de

Further Buoy Data Websites providing Snow Depth

International Arctic Buoy Program (IABP):
http://iabp.apl.washington.edu/

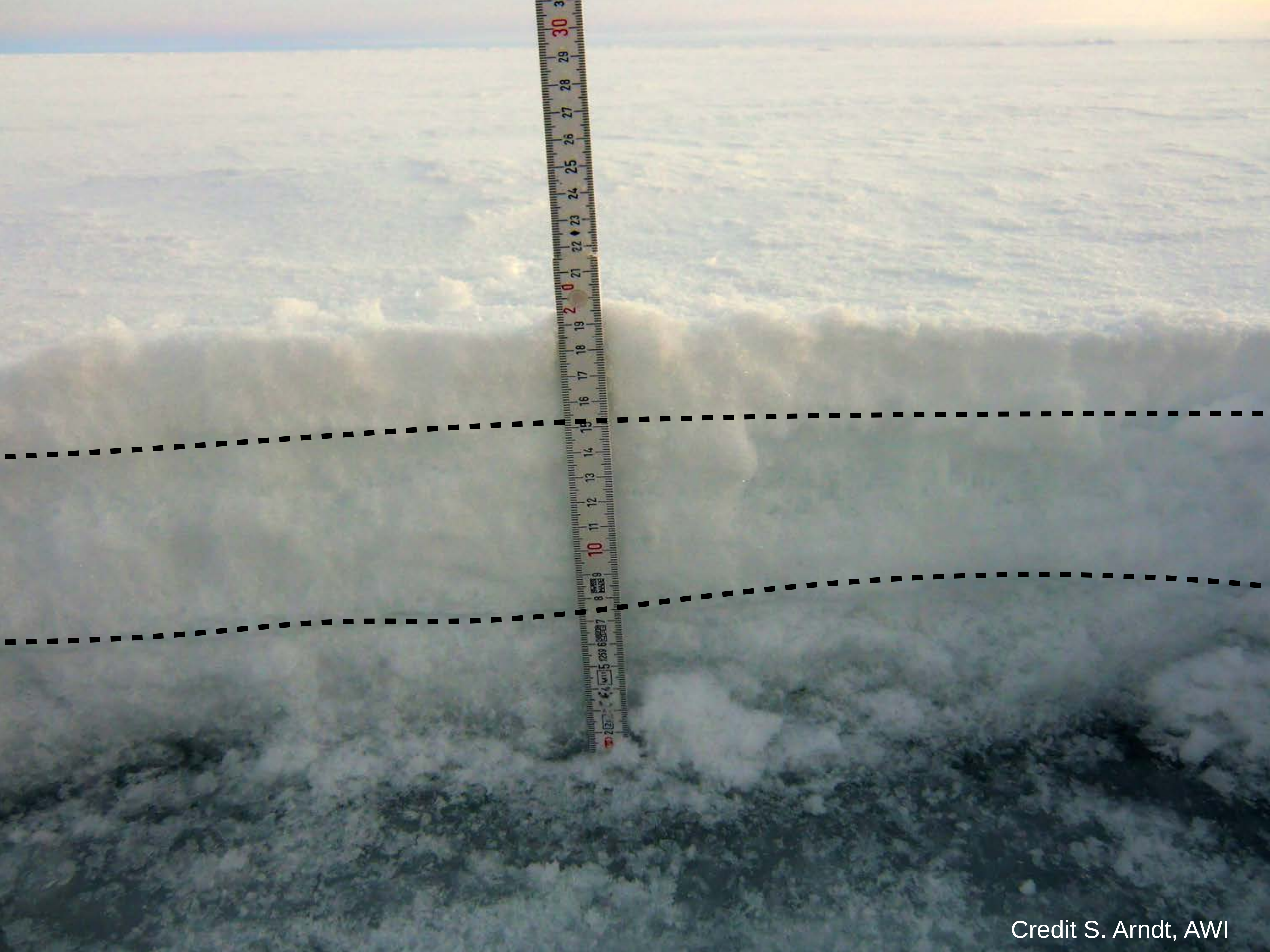
International Program on Antarctic Buoys (IPAB):
http://www.ipab.aq/

CRREL:
http://imb.erdc.dren.mil/buoysum.htm



Outline

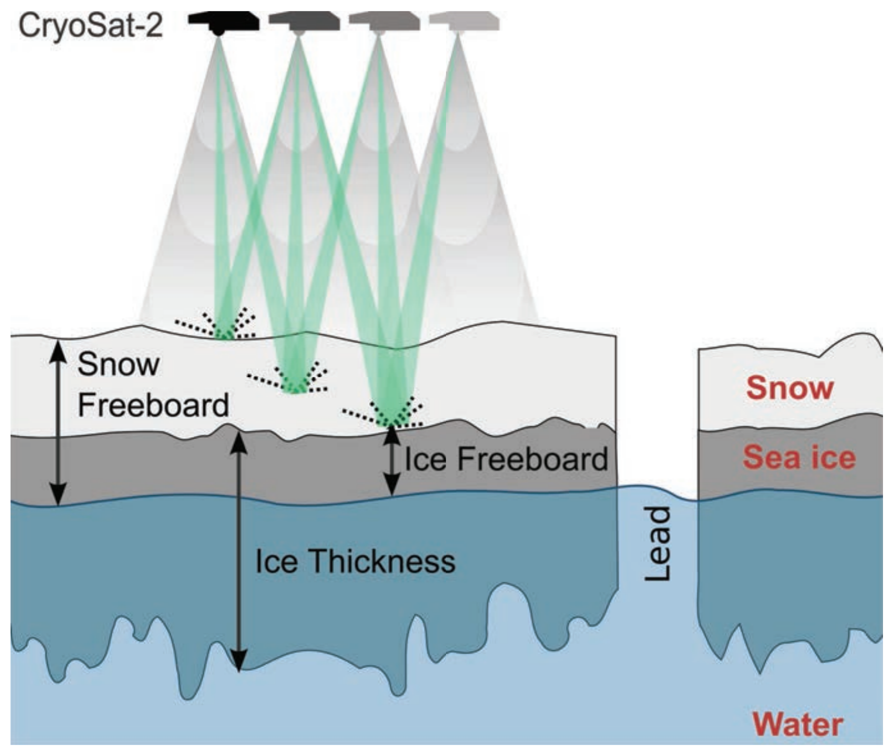
- Introduction - The far-reaching Impact of Snow
- Snow on Sea Ice - Characteristics
- Remote Sensing of Snow, Climatologies, and Products
- Validation
- **The Impact of Snow on Ice Thickness Retrievals**
- Outlook



Credit S. Arndt, AWI

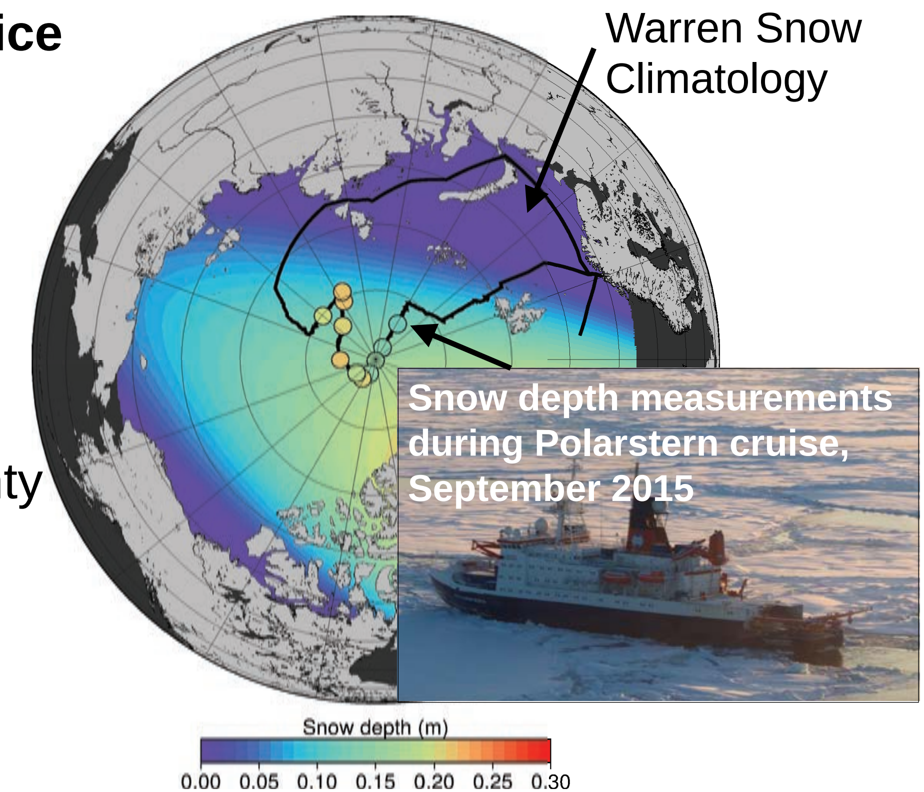
CryoSat-2 Ku-Band altimetry

- Satellite altimeters sense the **sea-ice freeboard**, the height of the ice surface above the water level
- Freeboard can be converted into Thickness by assuming **hydrostatic equilibrium**
- **Snow depth** adds to the uncertainty of the ice thickness retrieval in different ways:



CryoSat-2 Ku-Band altimetry

- Satellite altimeters sense the **sea-ice freeboard**, the height of the ice surface above the water level
- Freeboard can be converted into Thickness by assuming **hydrostatic equilibrium**
- **Snow depth** adds to the uncertainty of the ice thickness retrieval in different ways:
  - it is a key parameter for the conversion



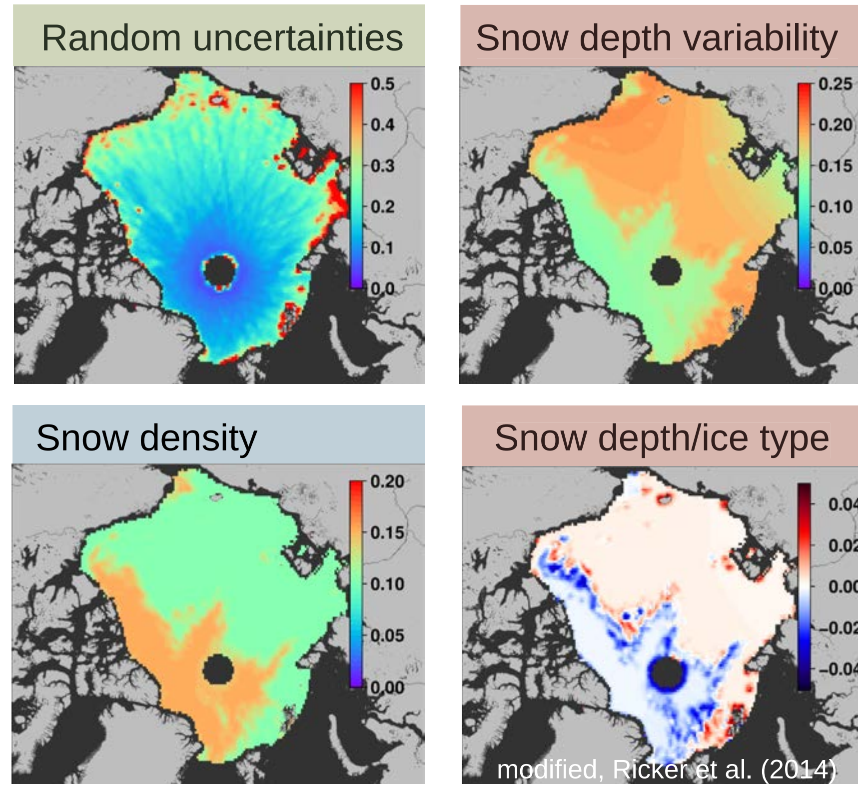
CryoSat-2 Ku-Band altimetry

$$H = F_I \frac{\rho_w}{\rho_w - \rho_i} + S \frac{\rho_s}{\rho_w - \rho_i}$$

- Satellite altimeters sense the **sea-ice freeboard**, the height of the ice surface above the water level

- Freeboard can be converted into Thickness by assuming **hydrostatic equilibrium**

- **Snow depth** adds to the uncertainty of the ice thickness retrieval in different ways:
  - it is a key parameter for the conversion



***Ricker et al. (2014):** Sensitivity of CryoSat-2 Arctic sea-ice freeboard and thickness on radar-waveform interpretation, The Cryosphere*

***Giles et al. (2007)**: Combined airborne laser and radar altimeter measurements over the Fram Strait in May 2002, GRL*

CryoSat-2 Ku-Band altimetry

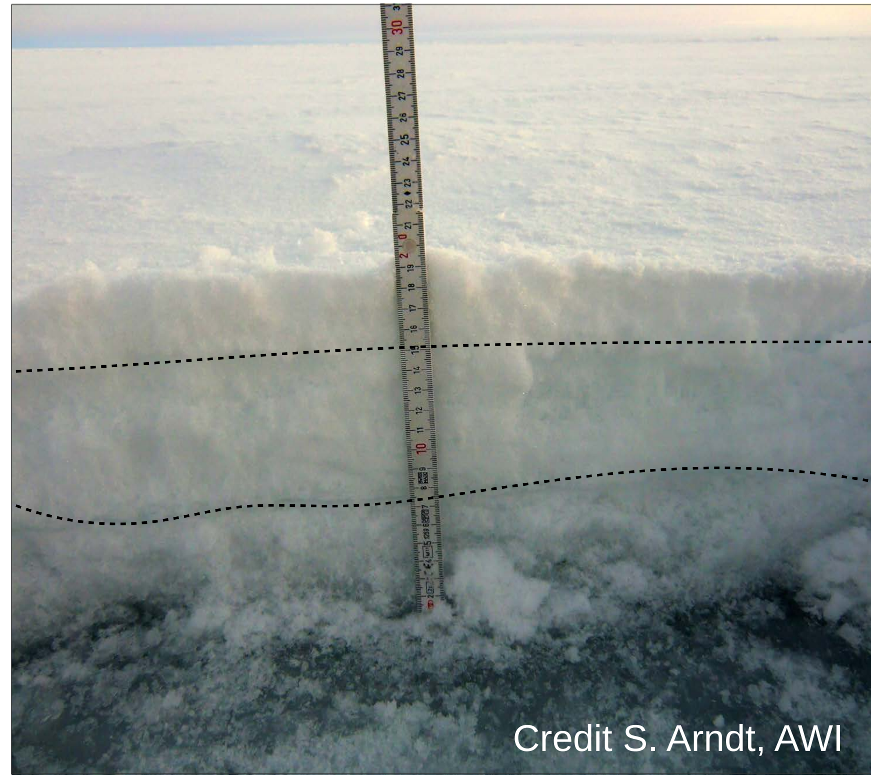
- Satellite altimeters sense the **sea-ice freeboard**, the height of the ice surface above the water level

- Freeboard can be converted into Thickness by assuming **hydrostatic equilibrium**

- **Snow depth** adds to the uncertainty of the ice thickness retrieval in different ways:

  - it is a key parameter for the conversion

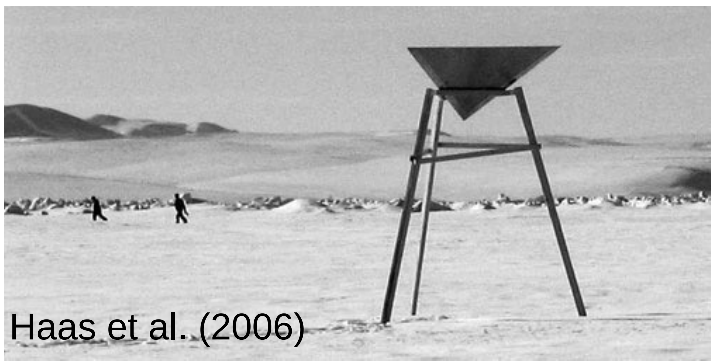
  - recent studies show that a thick snow cover can cause a significant sea-ice thickness bias due to scattering effects in the **snow volume**

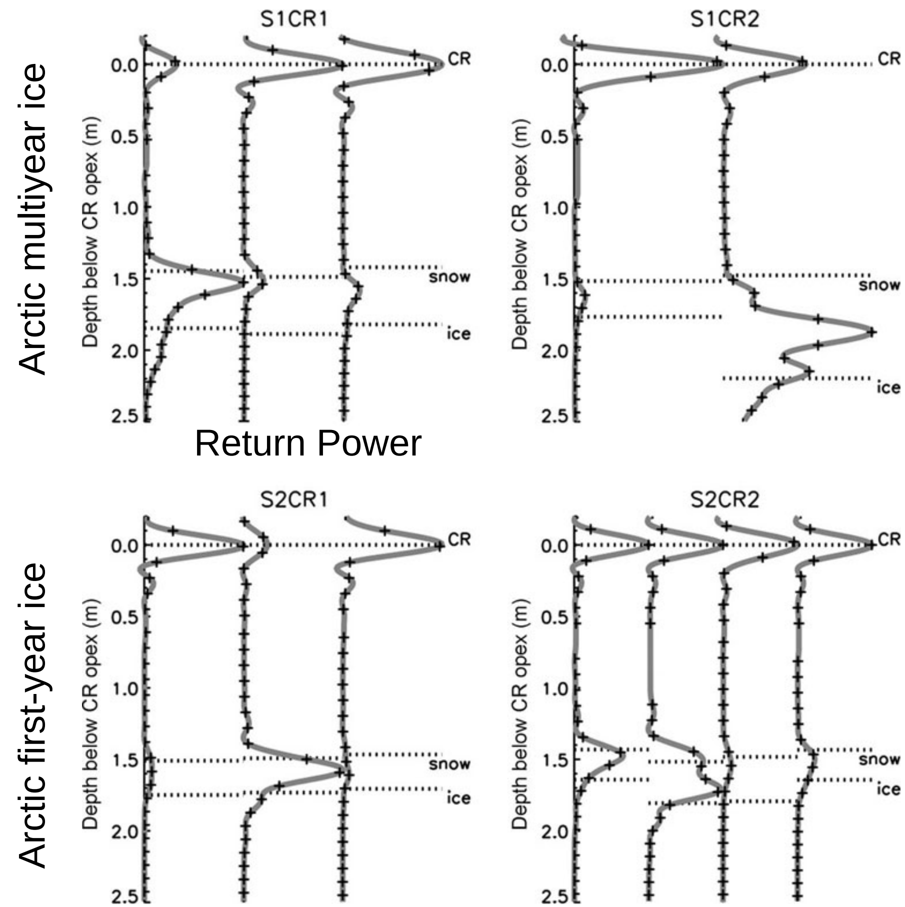


***Kwok, R. (2014)**: Simulated effects of a snow layer on retrieval of CryoSat-2 sea ice freeboard, GRL*

Ku-Band Radar Penetration

- Validation measurements with ASIRAS, an airborne simulator of CryoSat-2, over first- and multiyear ice, using corner reflectors (CR)


Haas et al. (2006)



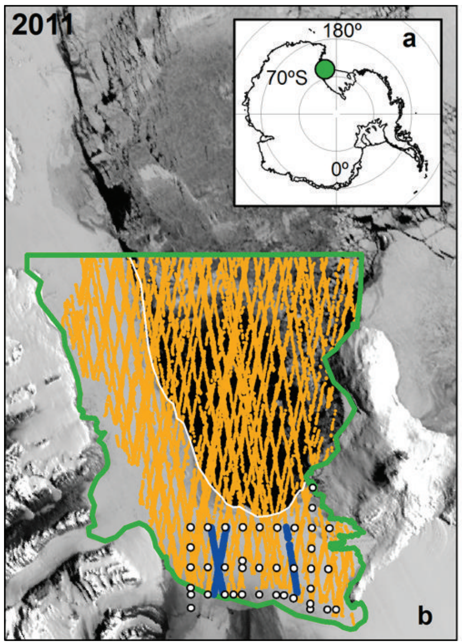
Willatt et al. (2011)

Willatt et al. (2010)*, Field Investigations of Ku-Band Radar Penetration Into Snow Cover on Antarctic Sea Ice, IEEE*

Willatt et al. (2011)*, Ku-band radar penetration into snow cover on Arctic sea ice using airborne data, Annals of Glaciology*

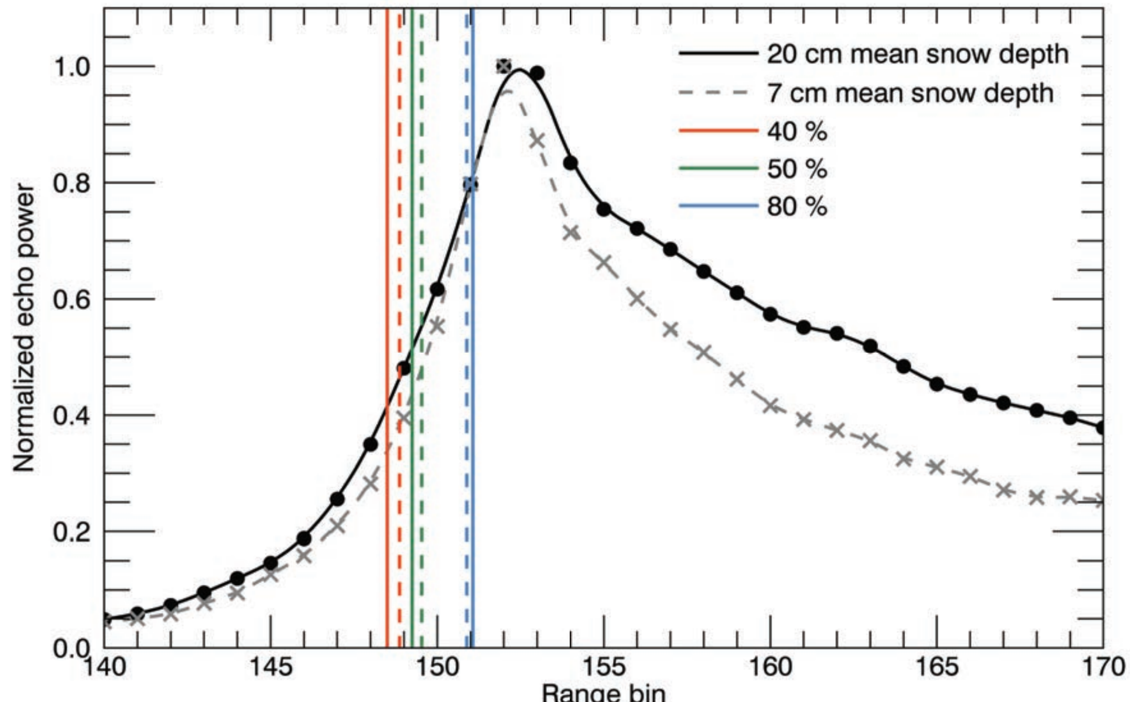
The impact of snow on the waveform

CryoSat-2 validation lines on fast-ice in McMurdo Sound (Antarctica):



***Price et al. (2015)**: Evaluation of CryoSat-2 derived sea ice freeboard over fast-ice in McMurdo Sound, Antarctica, Annals of Glaciology*

Different power thresholds applied on two stacked CryoSat-2 waveforms:

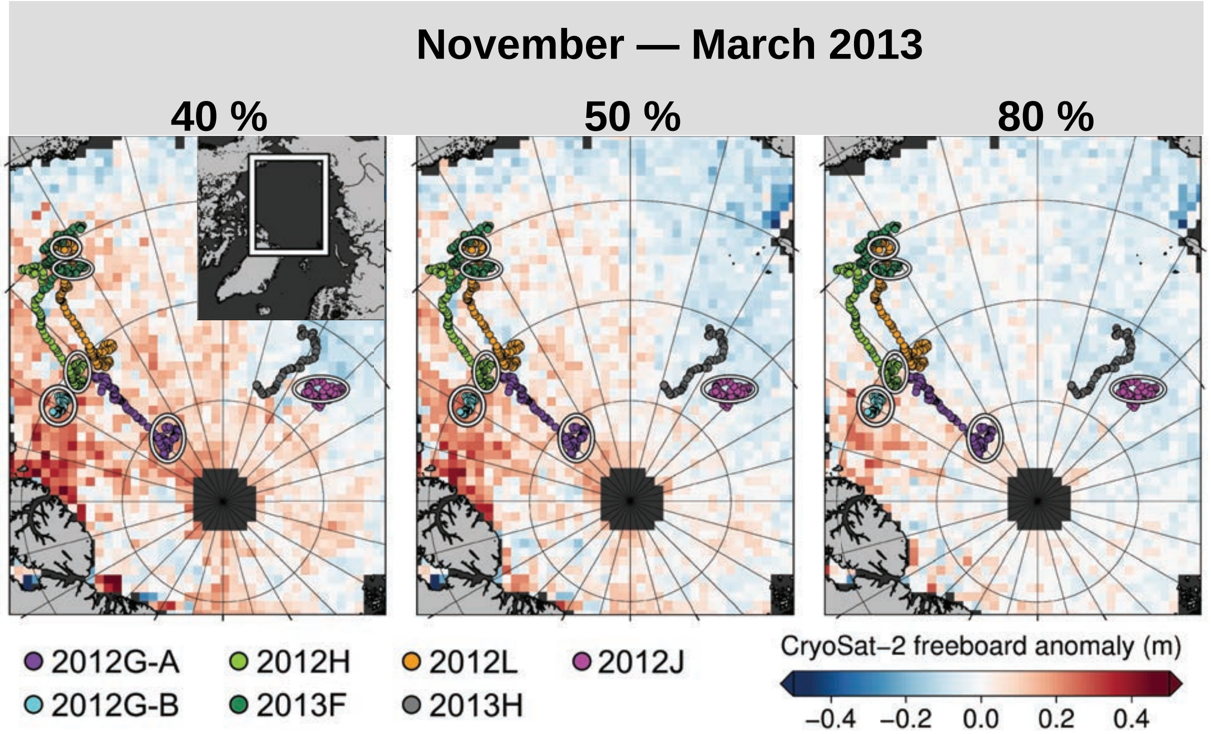


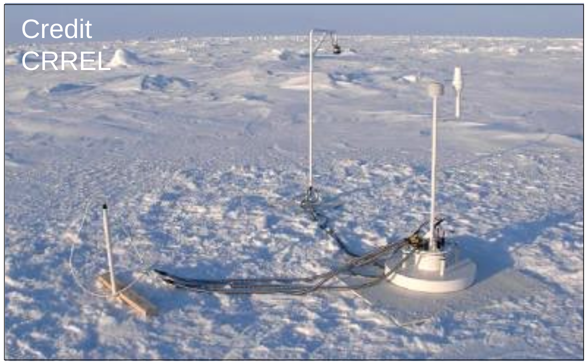
re-plotted, Price et al. (2015)

An observational approach with buoy data

- Differences in gridded CryoSat-2 Arctic modal freeboard between **November** 2013 and **March** 2013 retrievals

- We apply three different retracker **thresholds**: **40 %**, **50 %** and **80 %**

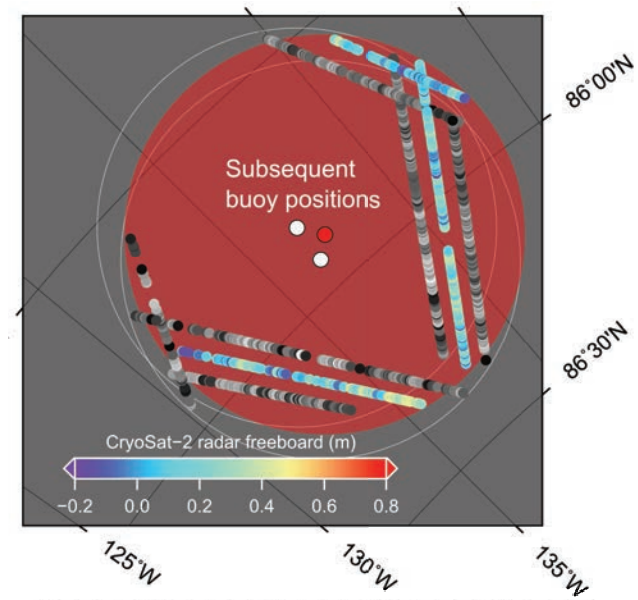




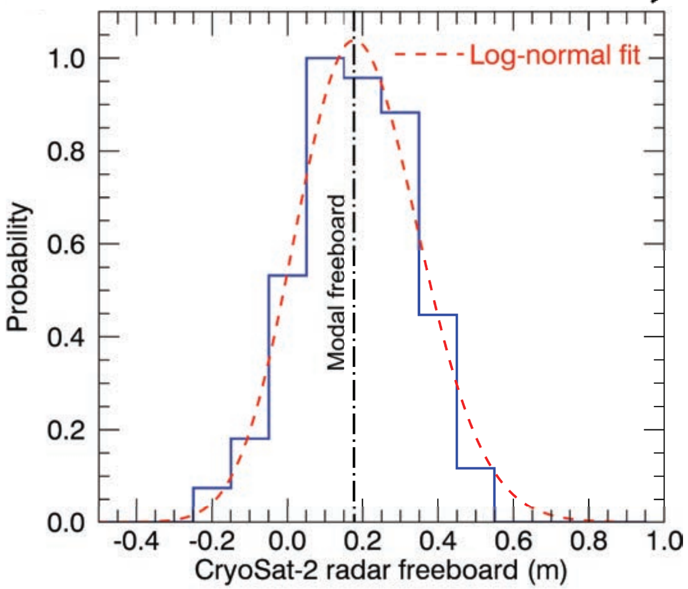
***Ricker et al. (2015)**: Impact of snow accumulation on CryoSat-2 range retrievals over Arctic sea ice: an observational approach with buoy data, GRL*

An observational approach with buoy data

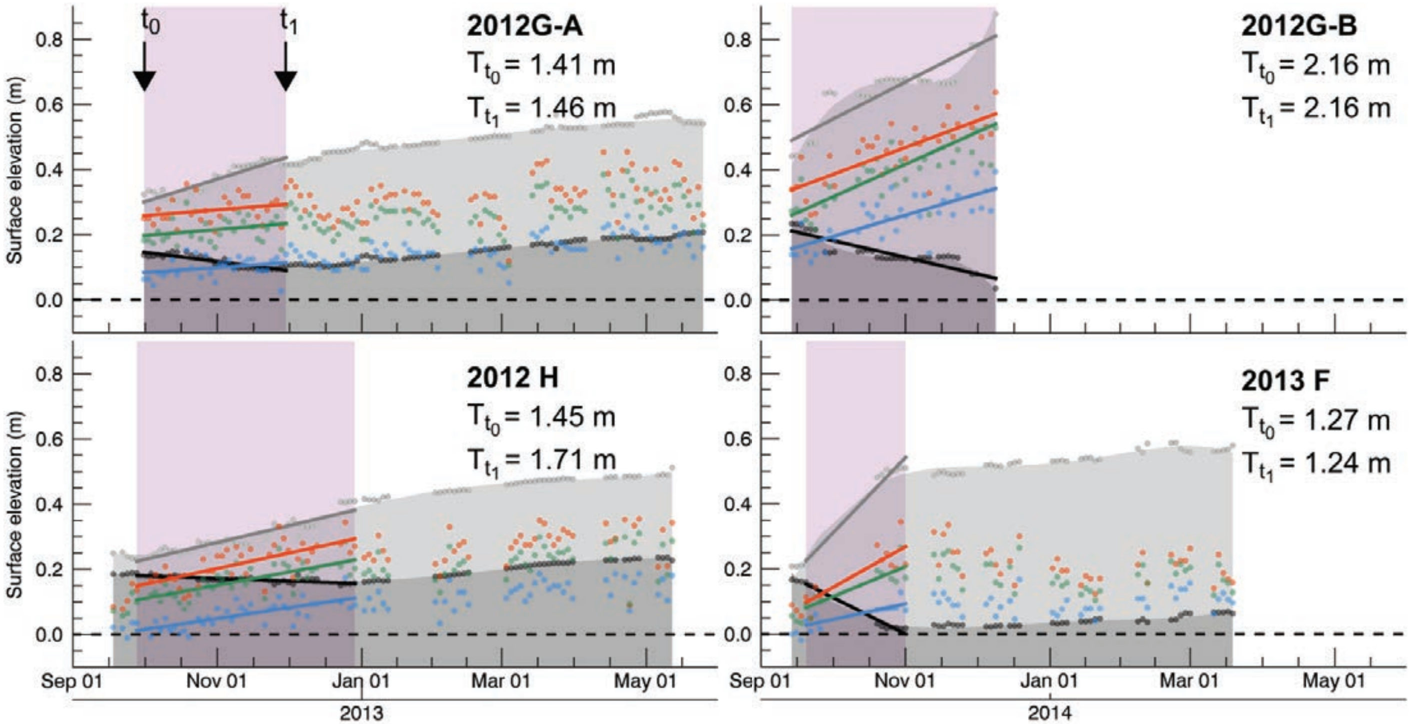
- CryoSat-2 measurements are collected within a **50 km** radius (red circle) around a considered buoy position (red dot)



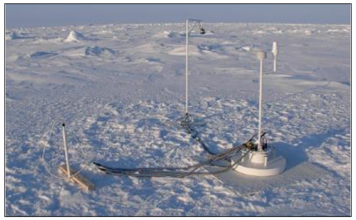
- A log-normal function is fitted to the CryoSat-2 freeboard distribution to retrieve the modal sea ice freeboard



CryoSat-2 and coincident buoy records



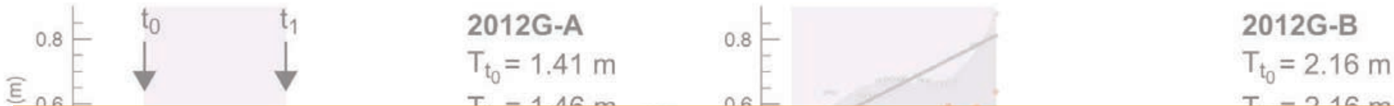
- For substantial snow accumulation on multiyear ice, we estimate a thickness bias up to **1.4 m**



Snow freeboard
Ice freeboard
Event period

CS-2 freeboard 40 %
CS-2 freeboard 40 %
CS-2 freeboard 40 %

CryoSat-2 and coincident buoy records

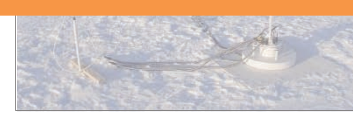


- During the snow accumulation periods we only find **negative trends** for the **IMB ice freeboard** while the **IMB snow freeboard** trends are always **positive**

- Simultaneously we observe only **positive trends** for coincident **CryoSat-2 radar freeboard** estimates

- Ice dynamics in the vicinity of the buoy locations can interfere with these quantifications

accumulation on multiyear ice, we estimate a thickness bias up to **1.4 m**



Snow freeboard
Ice freeboard
Event period

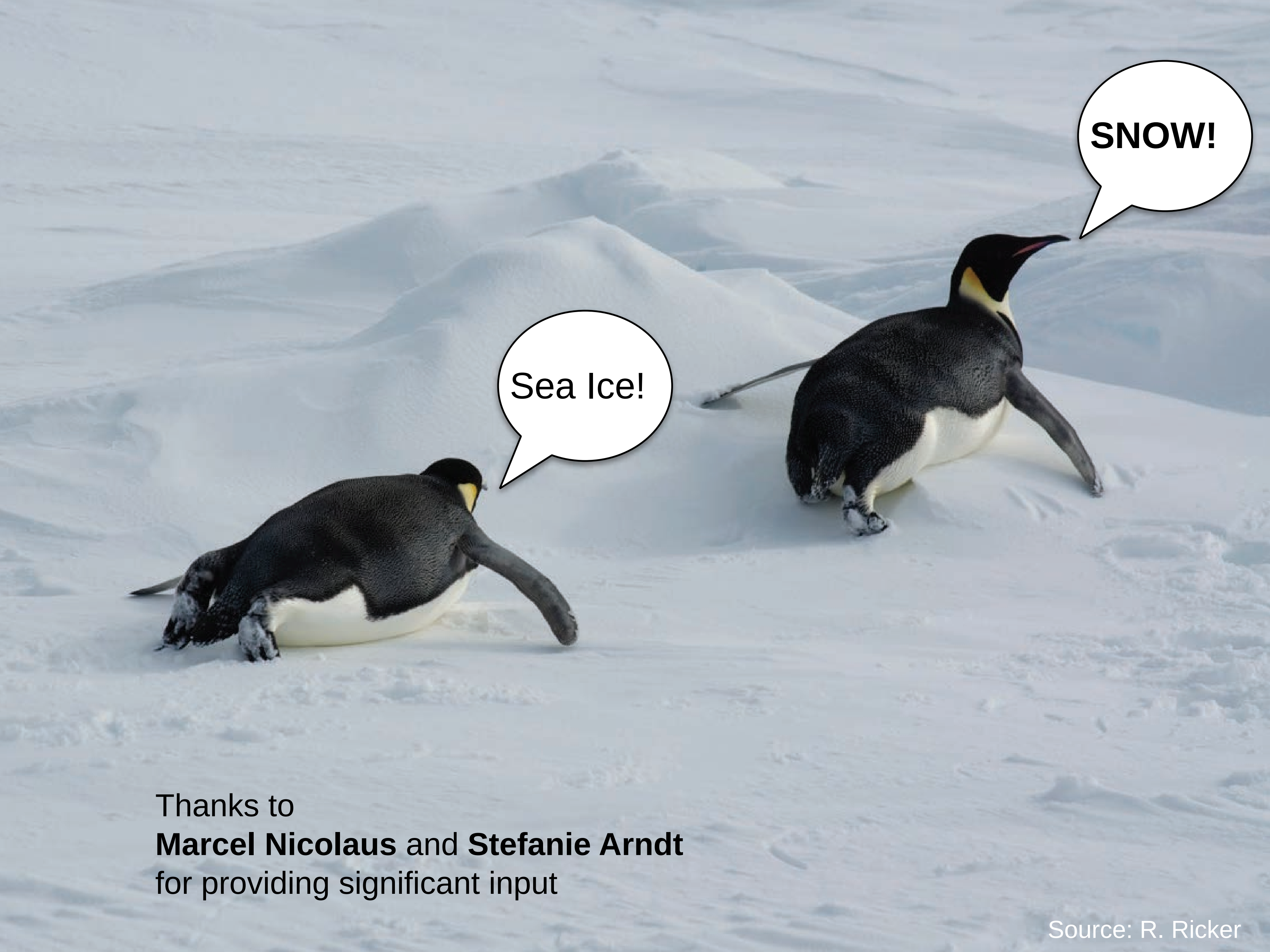
CS-2 freeboard 40 %
CS-2 freeboard 40 %
CS-2 freeboard 40 %

Outline

- Introduction - The far-reaching Impact of Snow
- Snow on Sea Ice - Characteristics
- Remote Sensing of Snow, Climatologies, and Products
- Validation
- The Impact of Snow on Ice Thickness Retrievals
- **Outlook**

What can we work on?

- Systematic validation studies of current snow depth products
- Seasonal in-situ measurements of snow and surface properties (stratigraphy, density, surface roughness)
- Improving snow relevant processes in models
- Improving passive microwave snow depth products
- Optimal Interpolation of different snow depth data sets
- Model studies on the impact of snow volume on Ku-Band radar



Thanks to
Marcel Nicolaus and **Stefanie Arndt**
for providing significant input

Source: R. Ricker