# Advantages of low frequency microwave radiometry for sea ice observation - from research to operational applications

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Low Frequency Passive Microwaves
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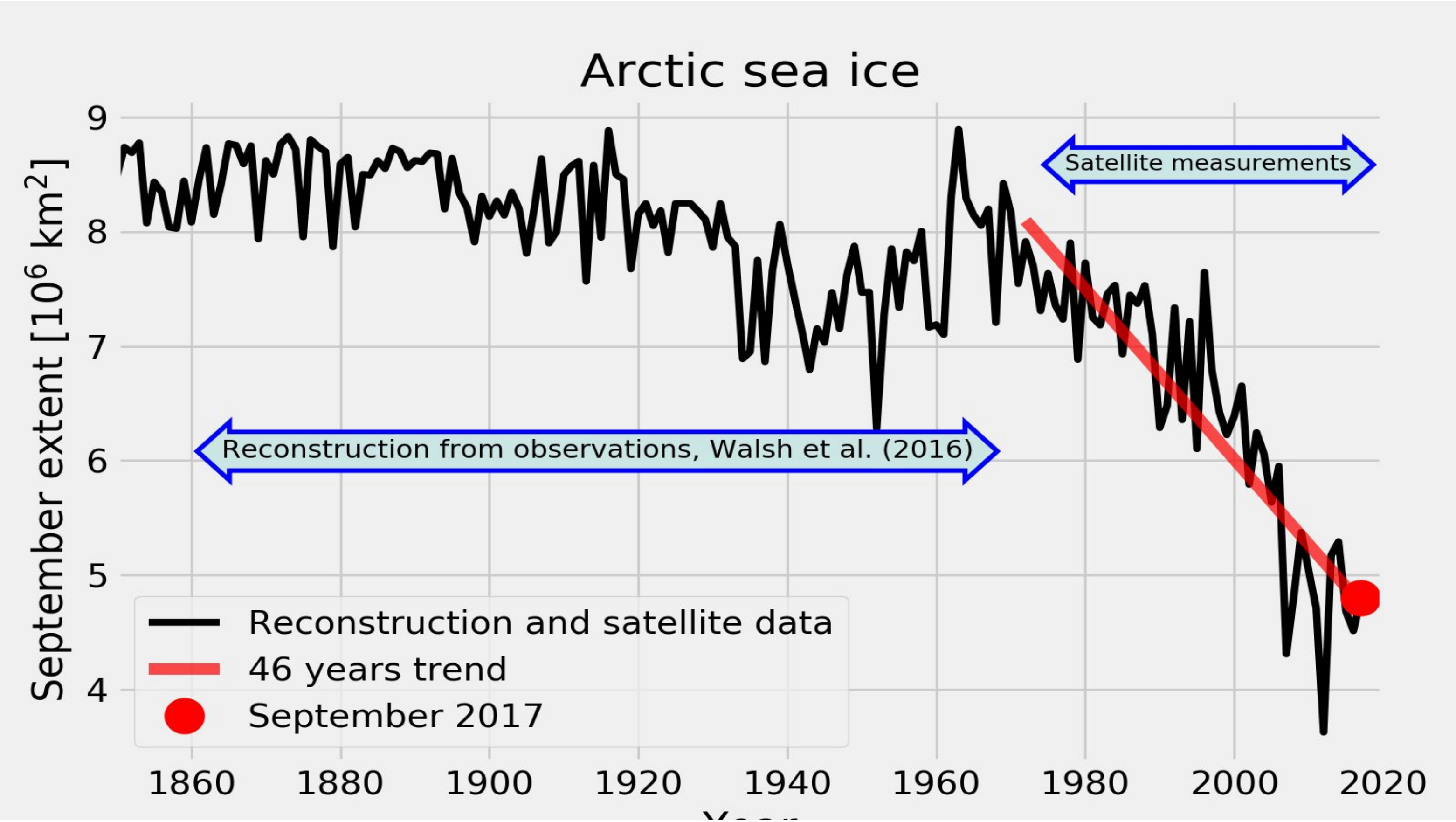
# Overview

- **Introduction and motivation**
- **SMOS sea ice thickness product**
- **Validation campaign**
- **Application: sea ice forecast and ship route optimization**
- **Combination of CryoSat2 and SMOS**
- **Outlook: future missions**
- **Summary and conclusion**

# Impact of warming: observation of iconic Arctic sea ice decline

Importance and societal impact of these passive microwave data?

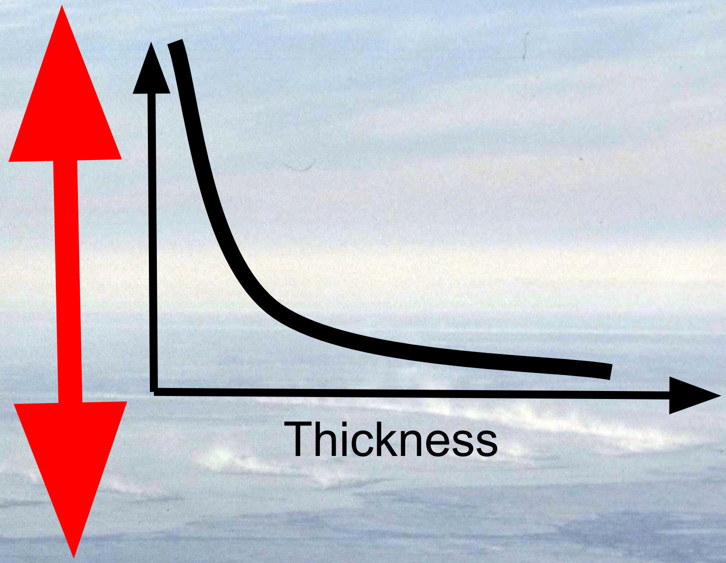



Sea Ice Concentration (%)
100
75
50
25
0
20/08/2017

Exchange of

- energy
- momentum
- moisture
- trace gases

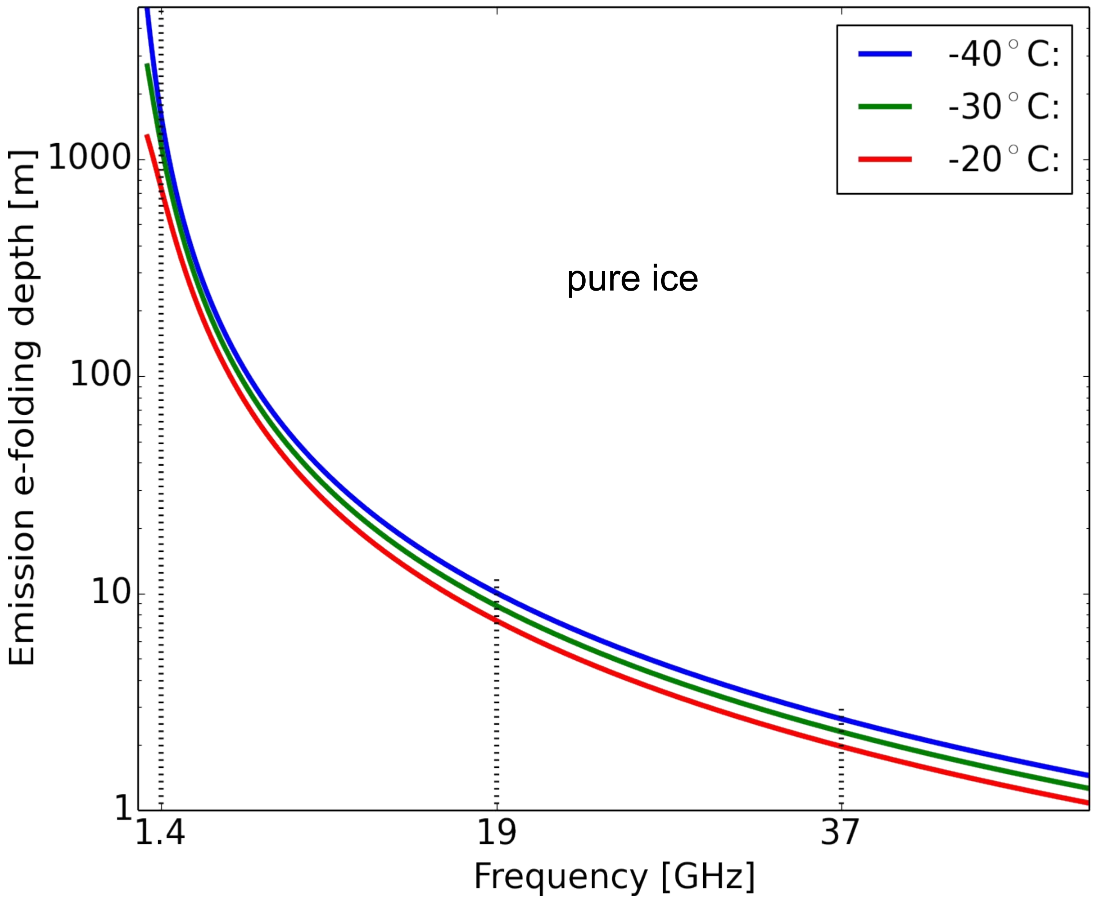
between ocean and atmosphere depends on **sea ice thickness**



# Advantage of L-band radiometry for the cryosphere

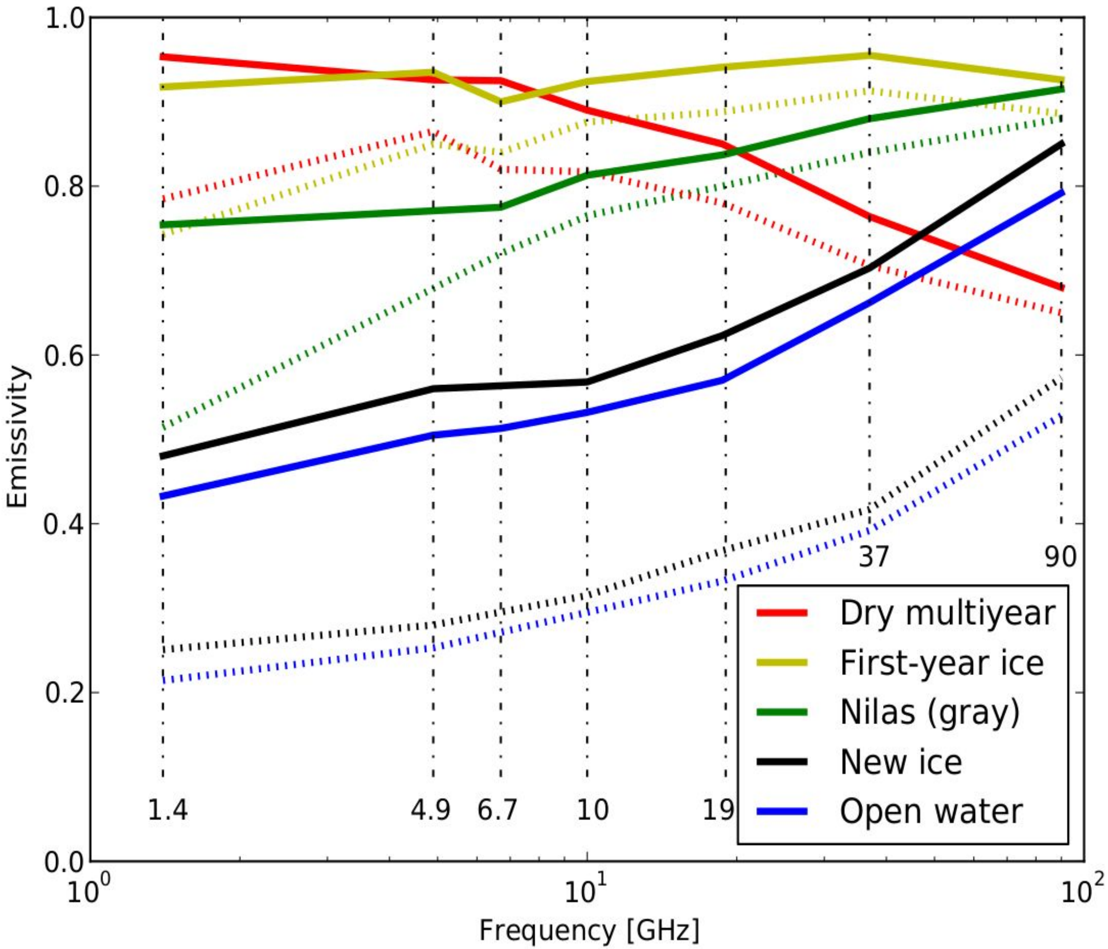
Ice is a very low-loss medium with a minimum of absorption at 1 GHz

- Absorption/emission increases with increasing temperatures and concentration of impurities (e.g. salt ions in sea ice)
- SMOS measures the emission from very deep ice sheet layers
- Retrieval of cryospheric parameters

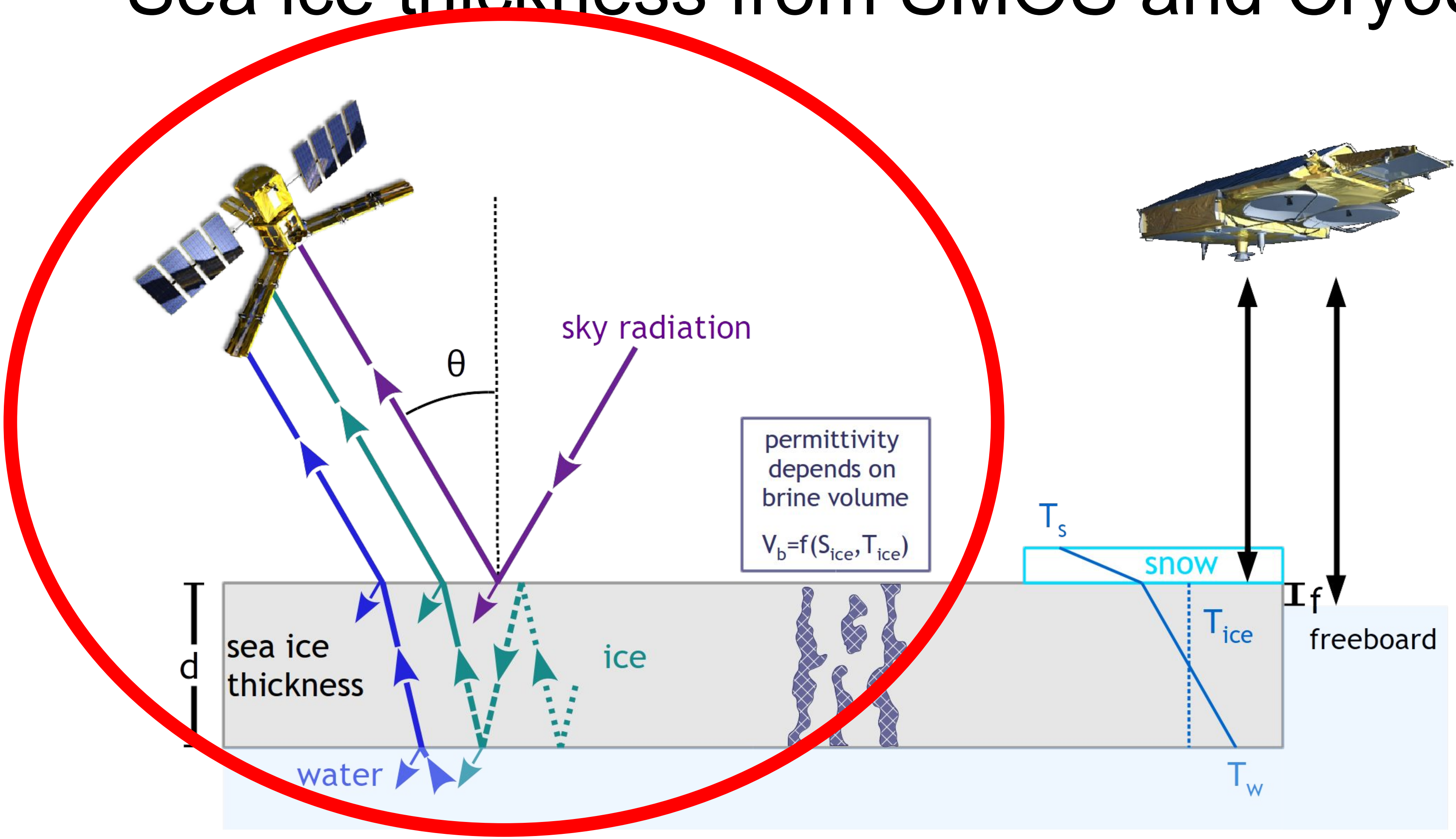


# Sea ice emissivity in the microwave range

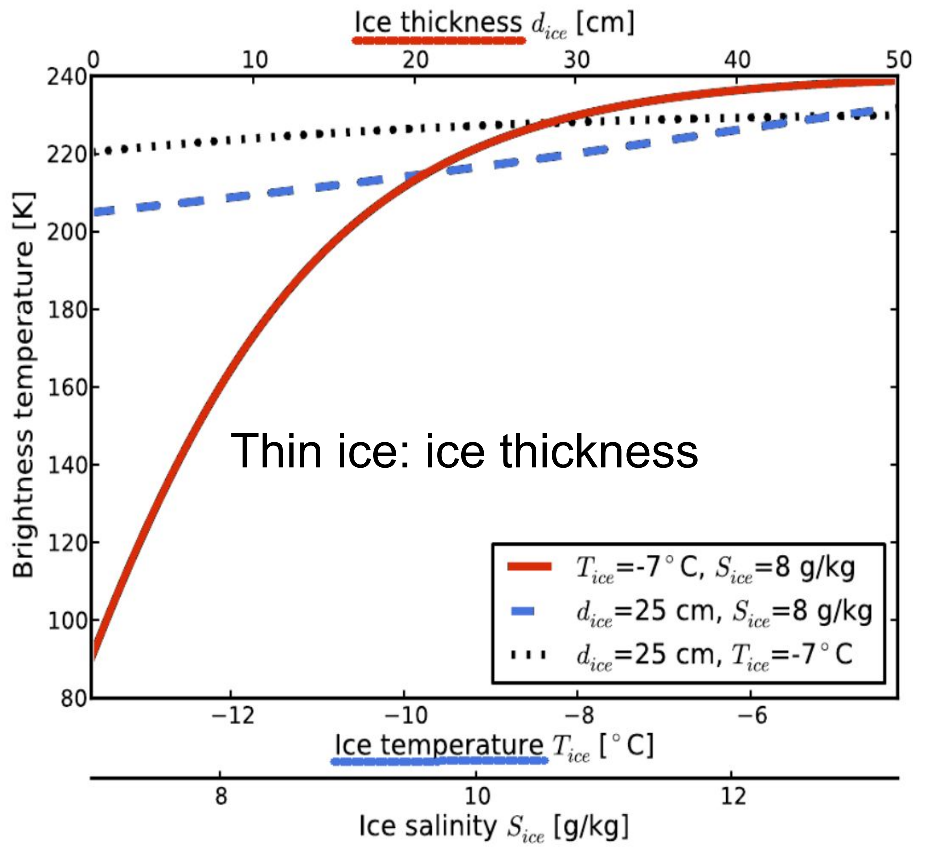
- Emissivity of multiyear ice decreases with increasing frequency
- Emissivity of open water increases with increasing frequency
- Largest range at low frequency

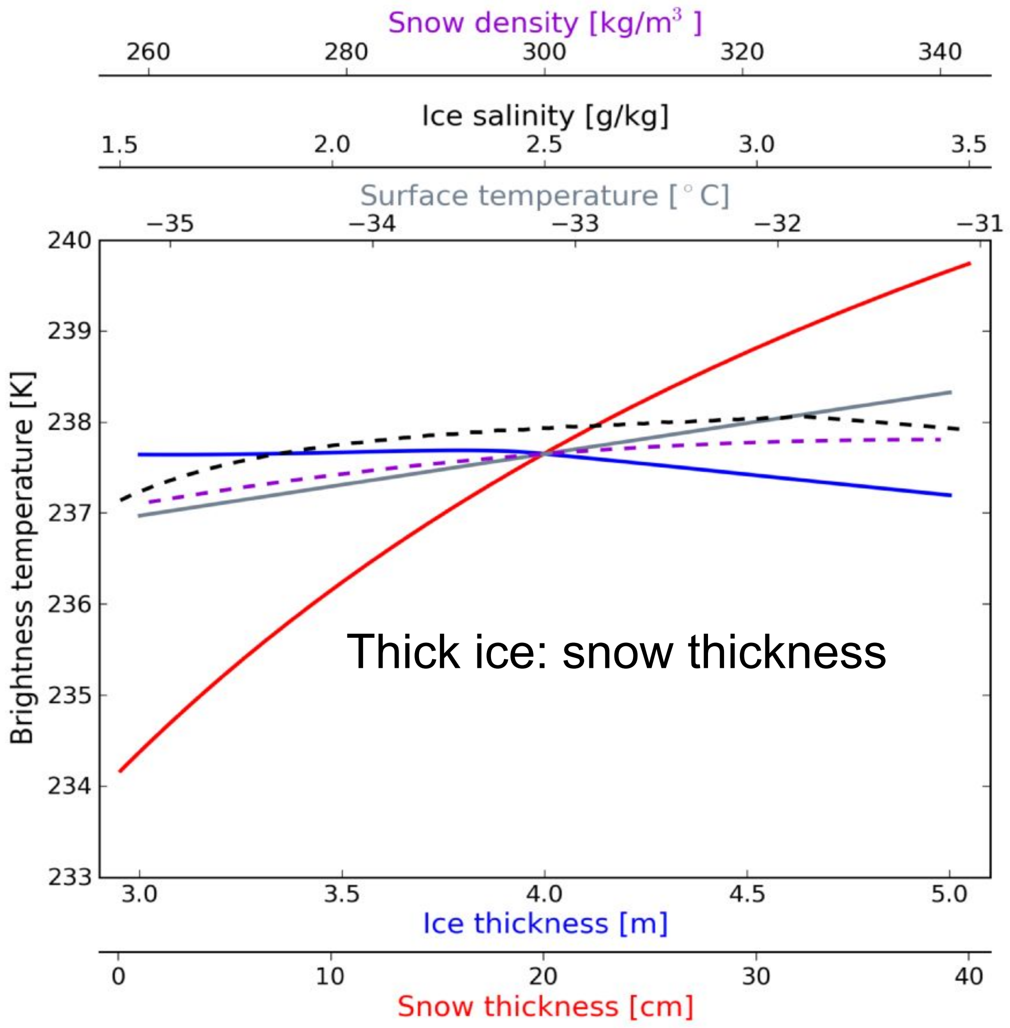


# Sea ice thickness from SMOS and CryoSat2



# Sensitivity @ 1.4 GHz

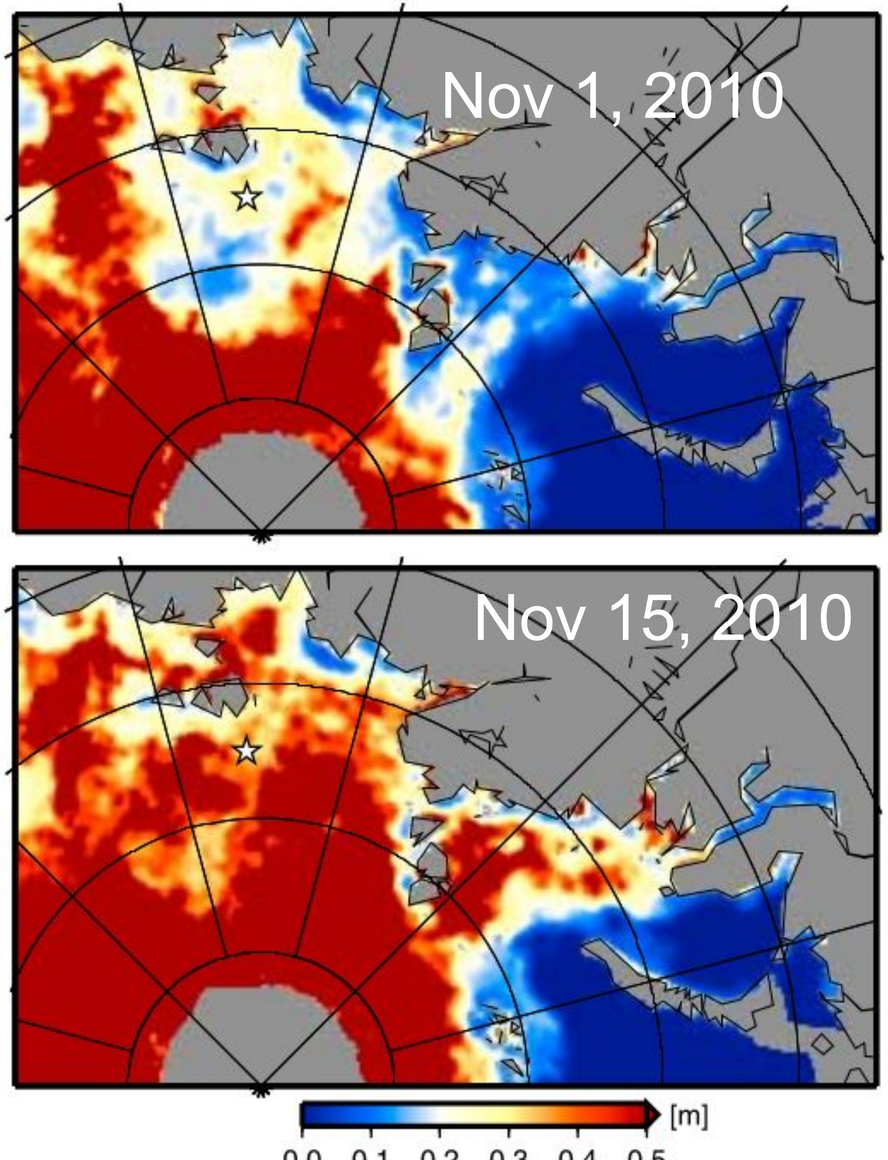


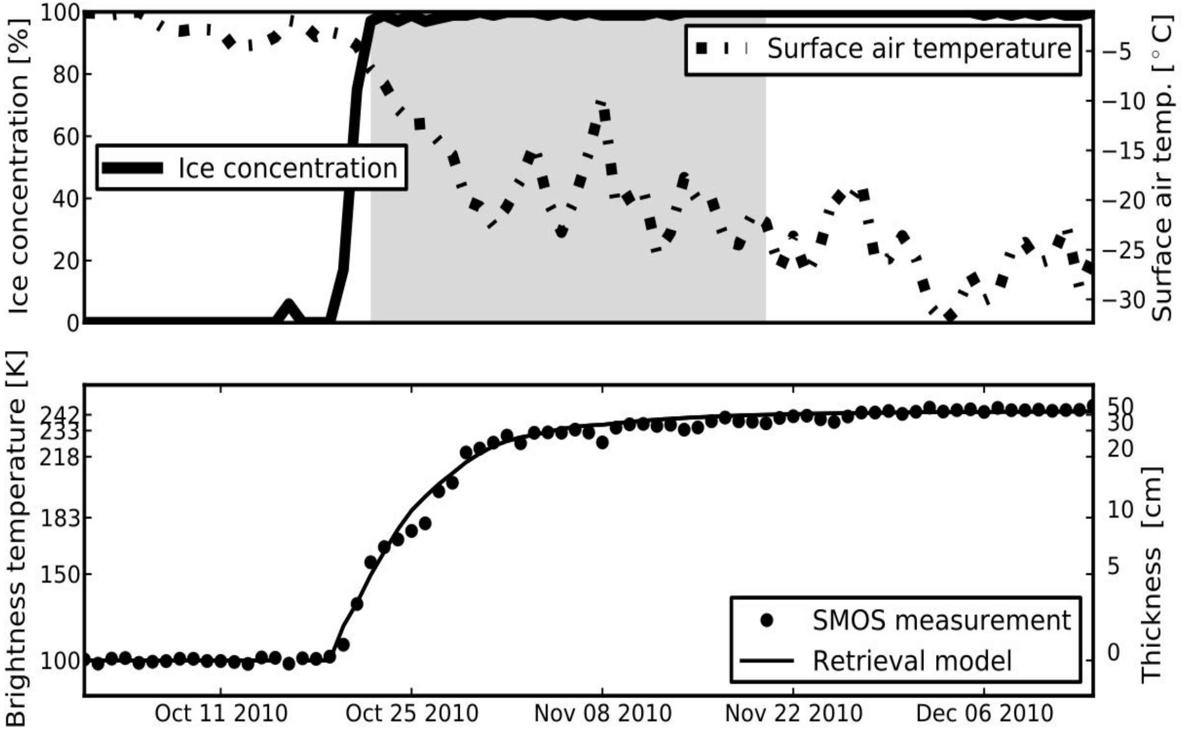


Kaleschke, L., X. Tian-Kunze, N. Maaß, M. Mäkynen, and M. Drusch (2012), Sea ice thickness retrieval from SMOS brightness temperatures during the Arctic freeze-up period, Geophys. Res. Lett., doi:10.1029/2012GL050916

Maaß, N., Kaleschke, L., Tian-Kunze, X., and Drusch, M.: Snow thickness retrieval over thick Arctic sea ice using SMOS satellite data, The Cryosphere, 7, 1971-1989, doi:10.5194/tc-7-1971-2013, 2013.




# Arctic freeze-up observed with SMOS




Kaleschke, L., X. Tian-Kunze, N. Maaß, M. Mäkynen, and M. Drusch (2012), Sea ice thickness retrieval from SMOS brightness temperatures during the Arctic freeze-up period, Geophys. Res. Lett., doi:10.1029/2012GL050916

# What is the maximal retrieval thickness?

Kaleschke, L., et al., Sea ice thickness retrieval from SMOS brightness temperatures during the Arctic freeze-up period, Geophys. Res. Lett. (2012):

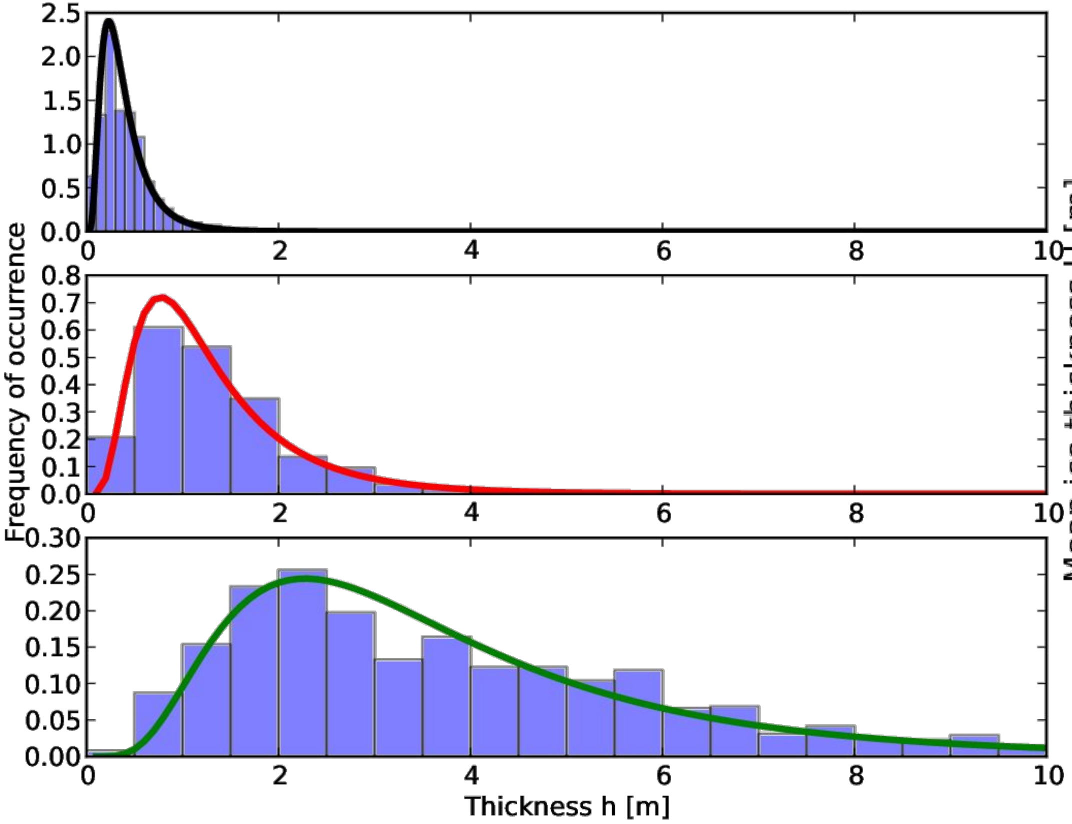
*The results confirm that SMOS can be used to retrieve sea ice thickness up to*
***half a meter***

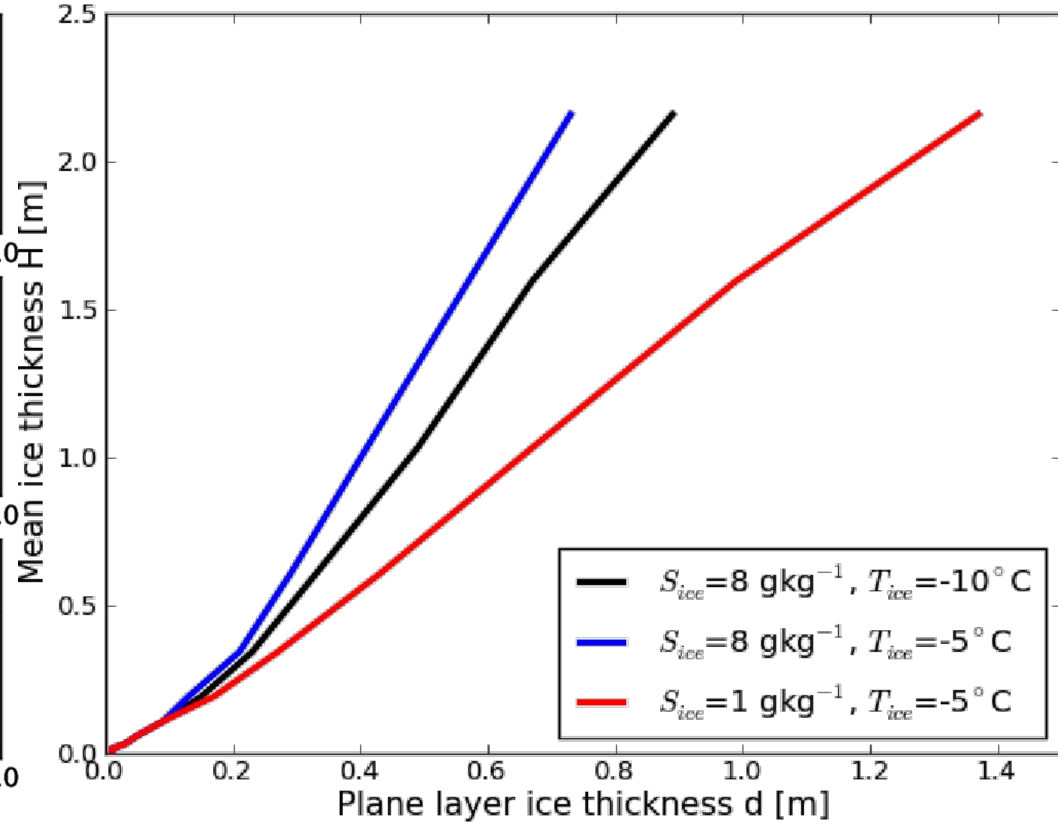
Kaleschke, L., et al., SMOS sea ice product: Operational application and validation in the Barents Sea marginal ice zone, Remote Sensing of Environment (2015):

*Ice thicknesses derived from the surface elevation measured by an airborne laser scanner and from simultaneous EMIRAD-2 brightness temperatures correlate well*
***up to 1.5 m***

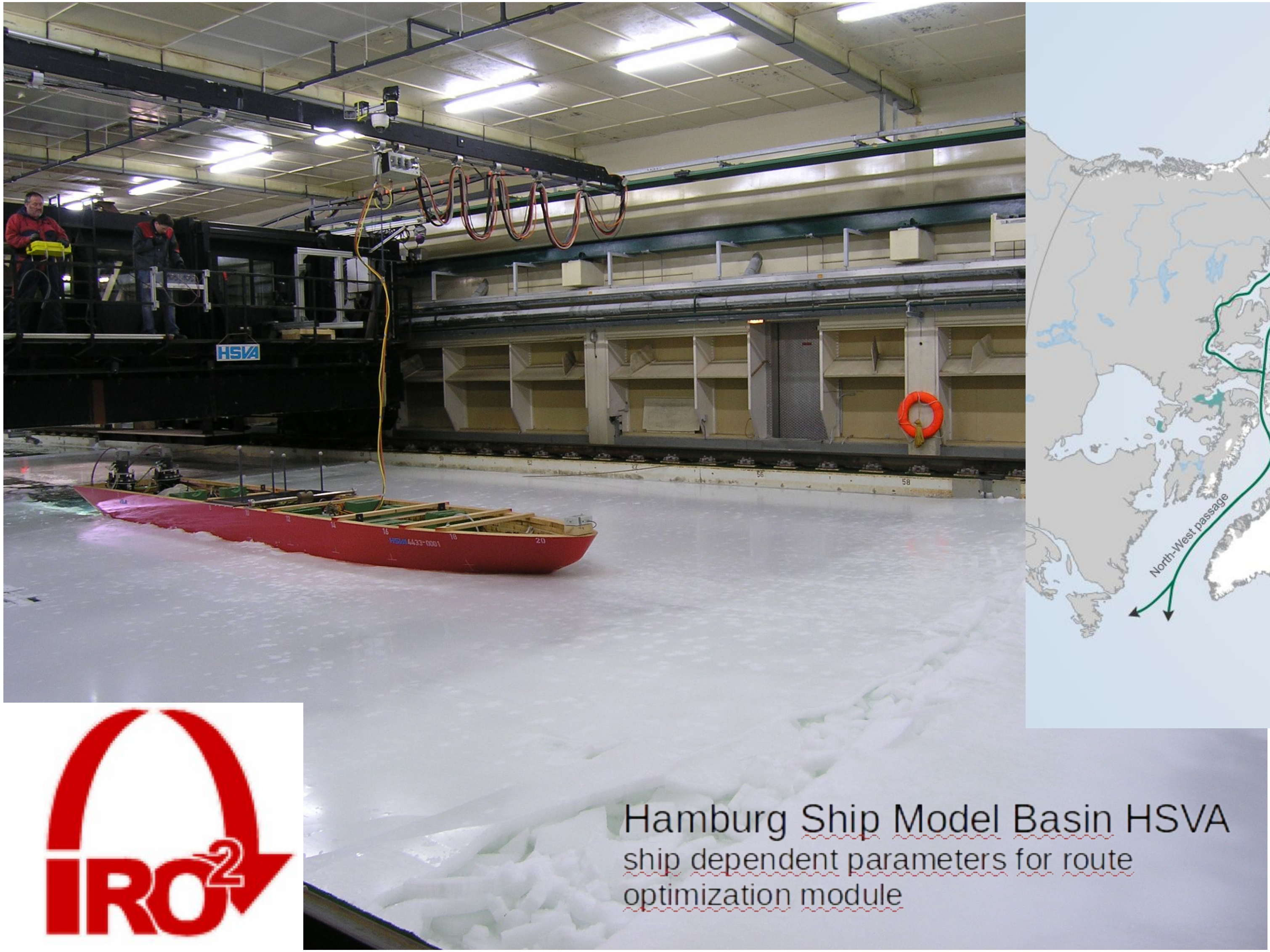
?

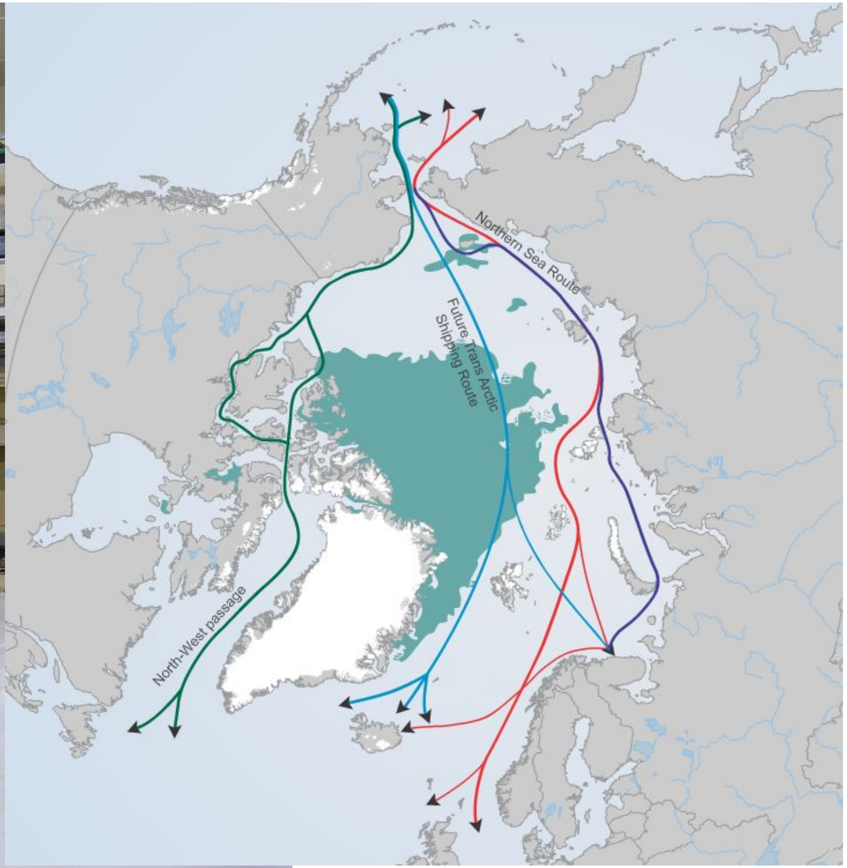
# Sea ice is not a plane surface: statistical thickness distribution




Tian-Kunze, X. et al. , SMOS-derived thin sea ice thickness: algorithm baseline, product specifications and initial verification, The Cryosphere, 8, 997-1018, doi:10.5194/tc-8-997-2014, 2014.



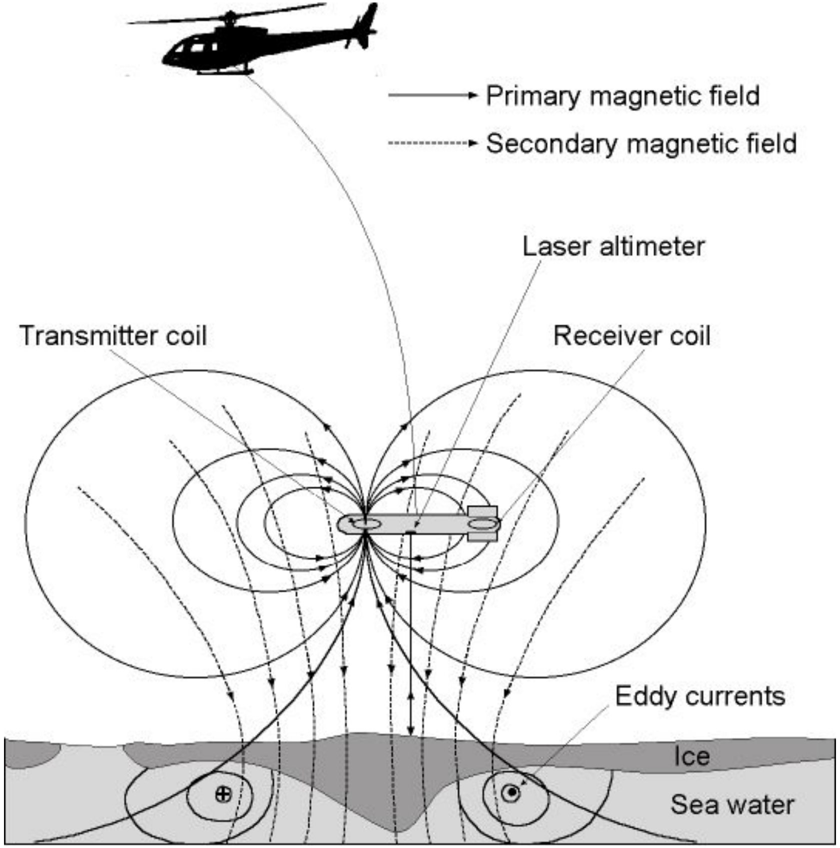

IRO2

# Hamburg Ship Model Basin HSVA

ship dependent parameters for route optimization module

# Ice thickness from Electromagnetical Induction (EM)

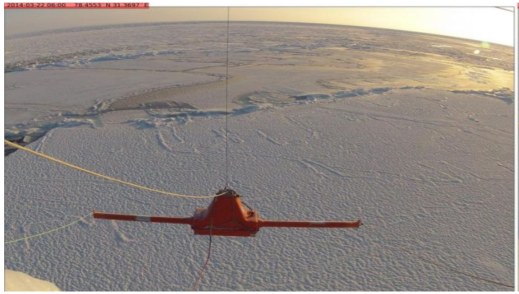
N. Fuchs




C. Haas

**Kaleschke, L., et al., SMOS sea ice product: Operational application and validation in the Barents Sea marginal ice zone, Remote Sensing of Environment (2016)**

# Validation experiment SMOSice+IRO2 March 2014



**Kaleschke, L., et al., SMOS sea ice product: Operational application and validation in the Barents Sea marginal ice zone, Remote Sensing of Environment (2016)**

# SMOSIce Airborne Campaign, March 2014


Polar 5 aircraft, S. Hendricks

# SMOSIce Airborne Campaign, March 2014


**EMIRAD2 L-band radiometer**
**N. Skou, Steen S. Kristensen & Sten S. Søbjærg**
**DTU Space, Technical University of Denmark**

Polar 5 aircraft, S. Hendricks

# SMOSice Campaign Svalbard, March 2014

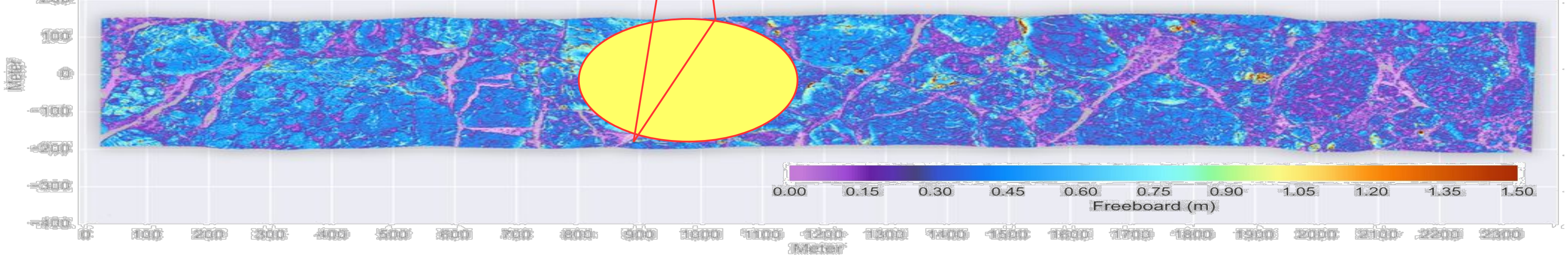
## EMIRAD2 L-band radiometer

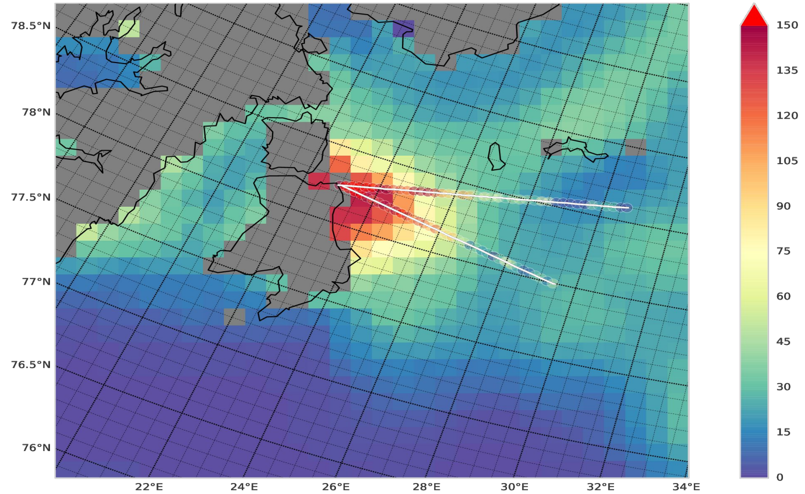
N. Skou, Steen S. Kristensen & Sten S. Søbjærg
DTU Space, Technical University of Denmark

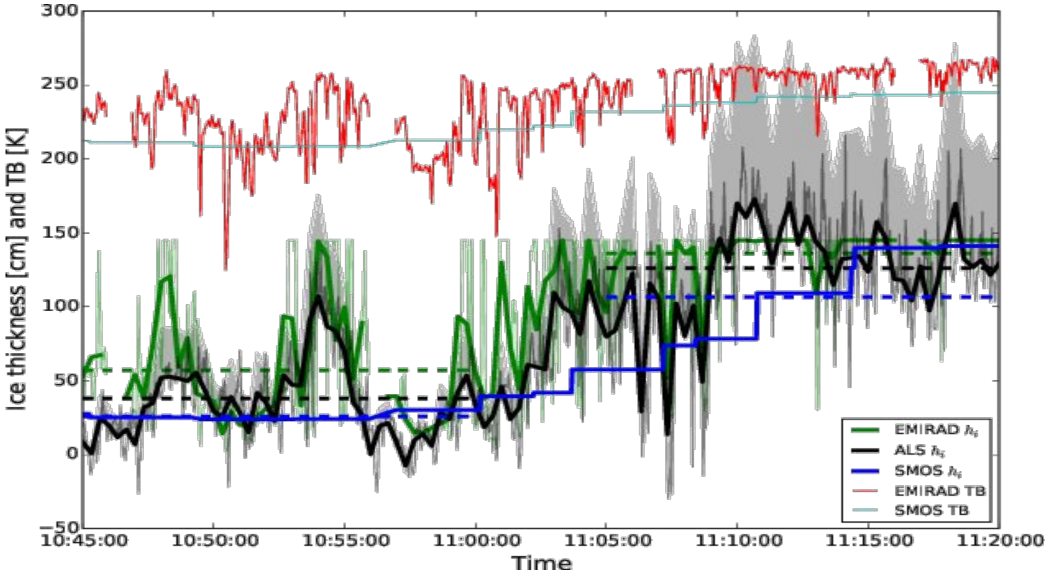
## Airborne Laserscanner (ALS)

S. Hendricks, D. Steinhage, V. Helm, G. Birnbaum, AWI

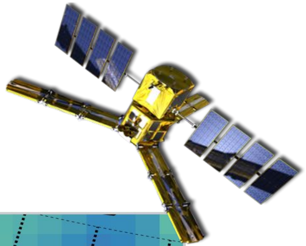
## Snow Radar

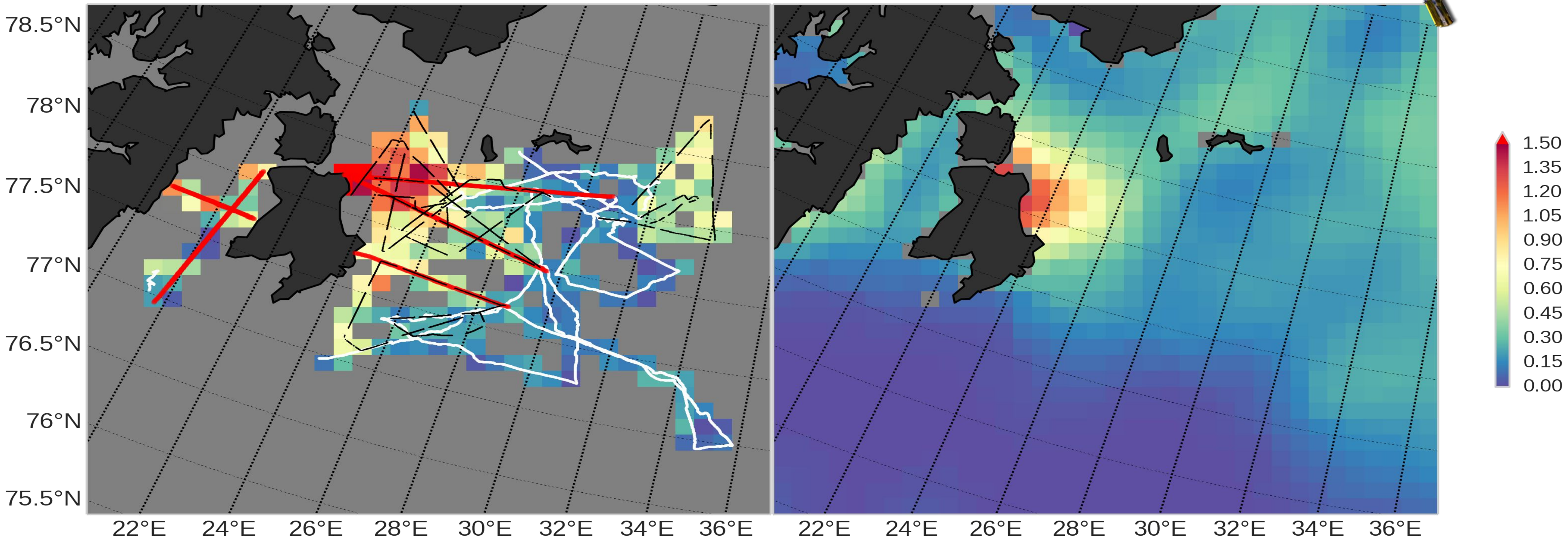


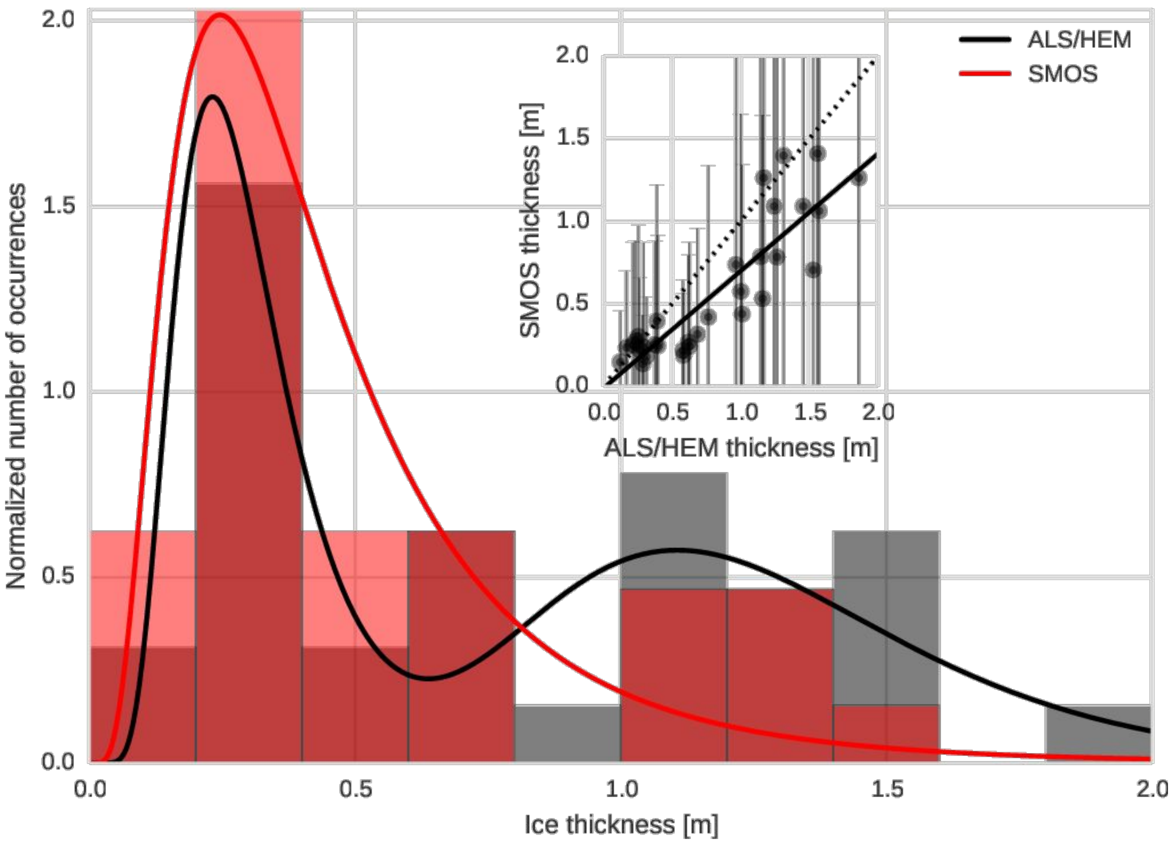
# Validation experiment, March 2014






**Kaleschke, L., et al., SMOS sea ice product: Operational application and validation in the Barents Sea marginal ice zone, Remote Sensing of Environment (2016)**

# Validation experiment, March 2014




Newly formed sea ice with a mean thickness of 17 cm sampled by the shipborne EM on Lance in agreement with SMOS retrieval:
MD=1 cm  RMSD=14 cm

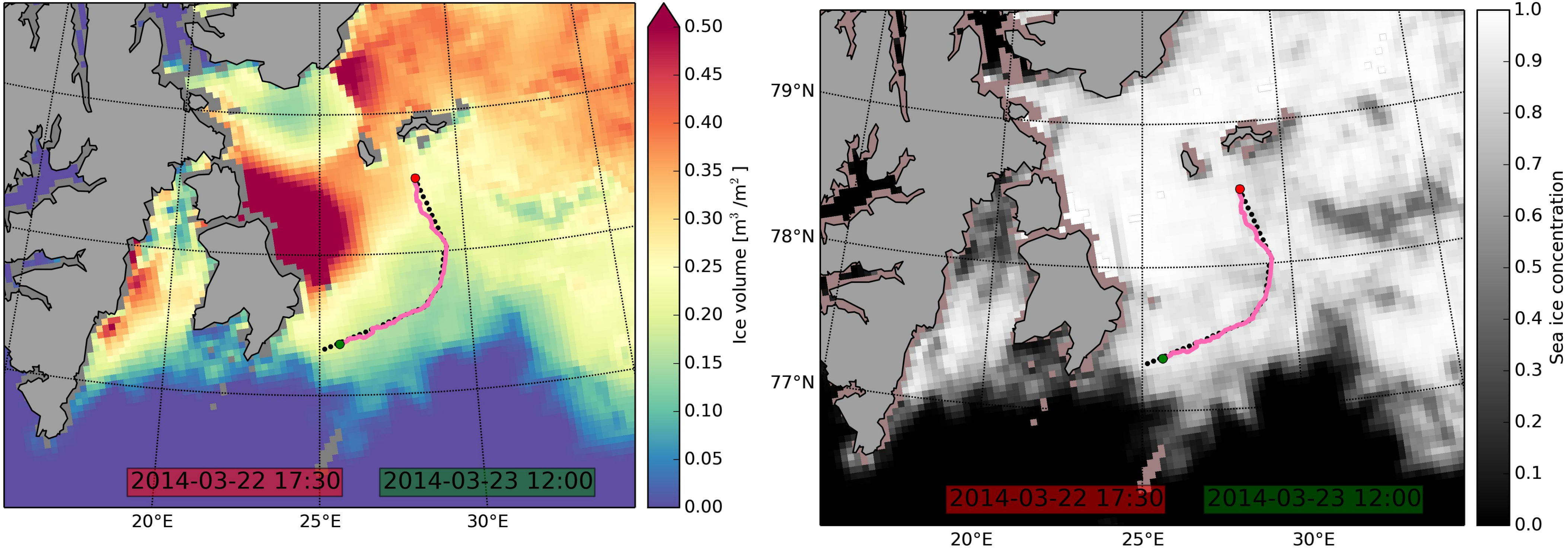
SMOS retrieval underestimates the thickness of deformed thick ice.

Thickness gradient between new thin ice and thick ice is well represented by airborne sensors ALS+HEM and SMOS

**Kaleschke, L., et al., SMOS sea ice product: Operational application and validation in the Barents Sea marginal ice zone, Remote Sensing of Environment (2016)**

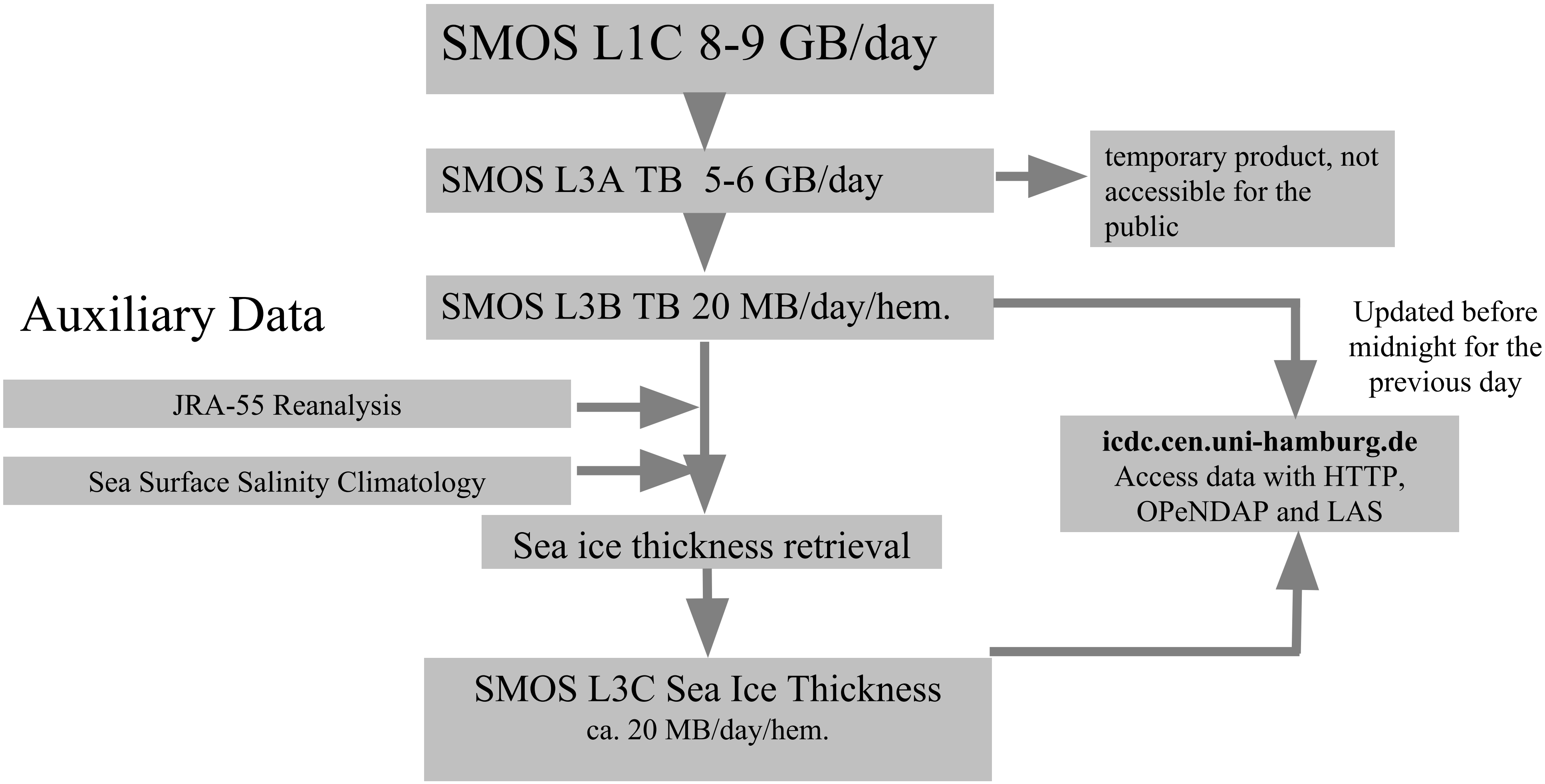
# Sea ice forecast and route optimization tested with RV Lance

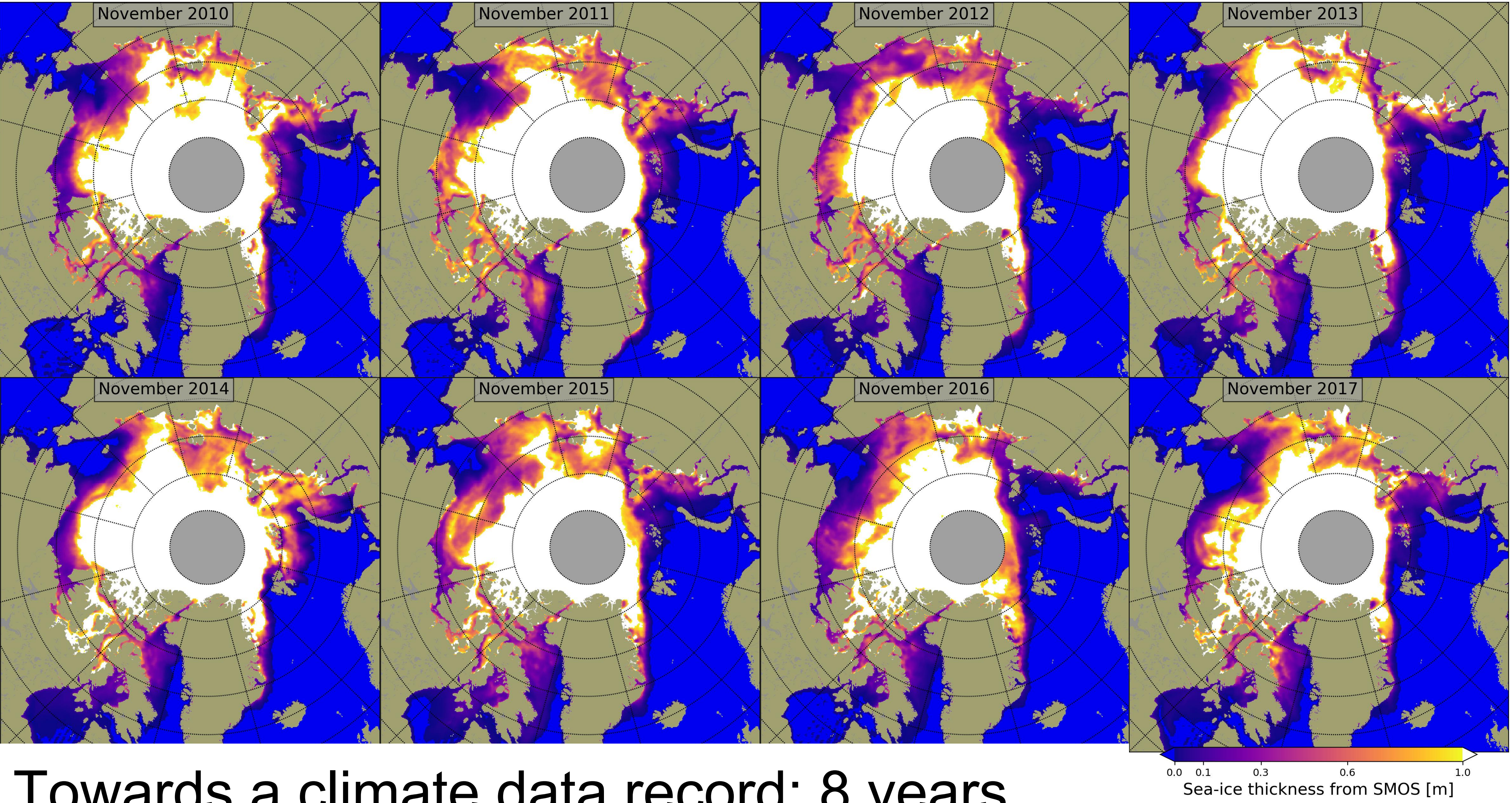
Arctic-wide variational assimilation system ICEDAS (based on NAOSIM) generates a 7 day forecast (0.5° grid) used as boundary and initial values for the nested, regional model system HAMMER (Hamburg System for Mesoscale ice forecast and Route optimization), consisting of coupled MESIM/METRAS and HAMSOM  models. SMOS and AMSR2 were used for sea ice initialization.




**Kaleschke, L., et al., SMOS sea ice product: Operational application and validation in the Barents Sea marginal ice zone, Remote Sensing of Environment (2016)**

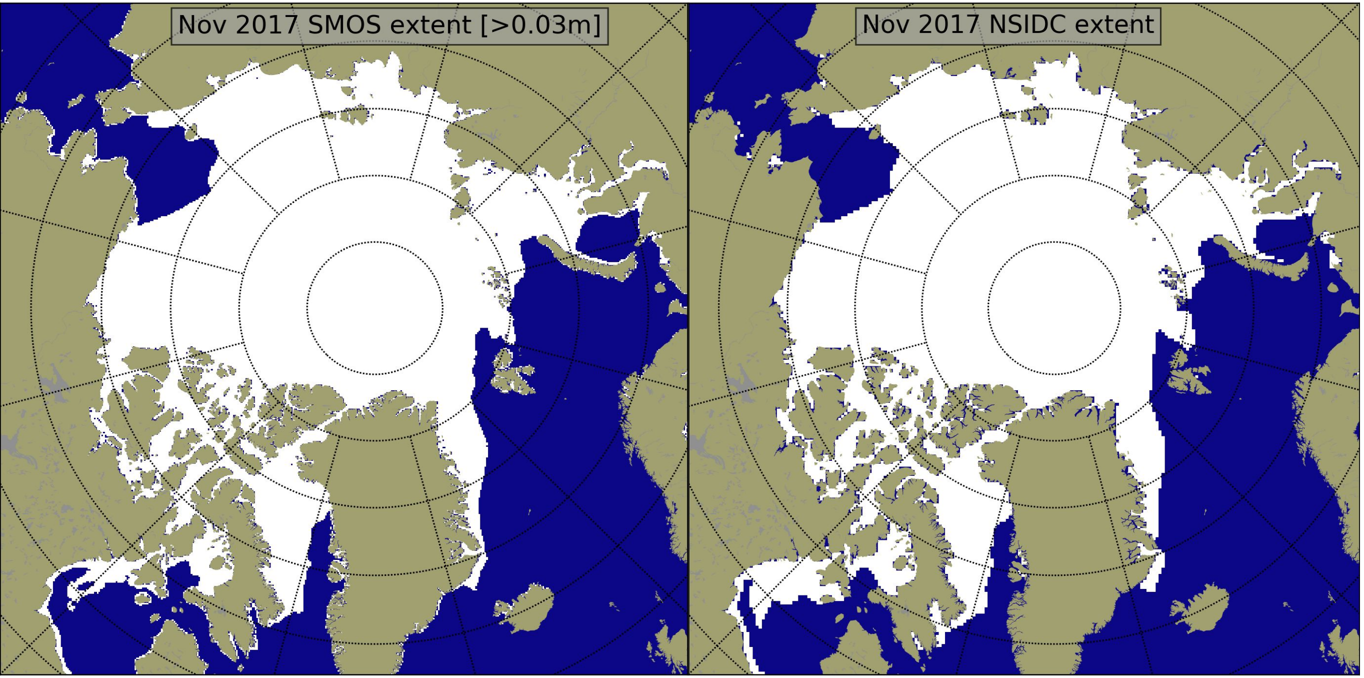
# SMOS processing at the University Hamburg

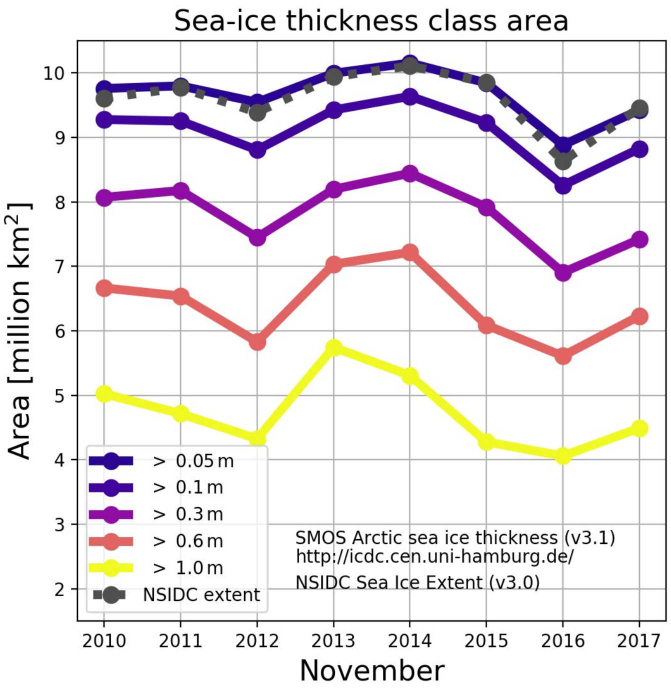





# Towards a climate data record: 8 years

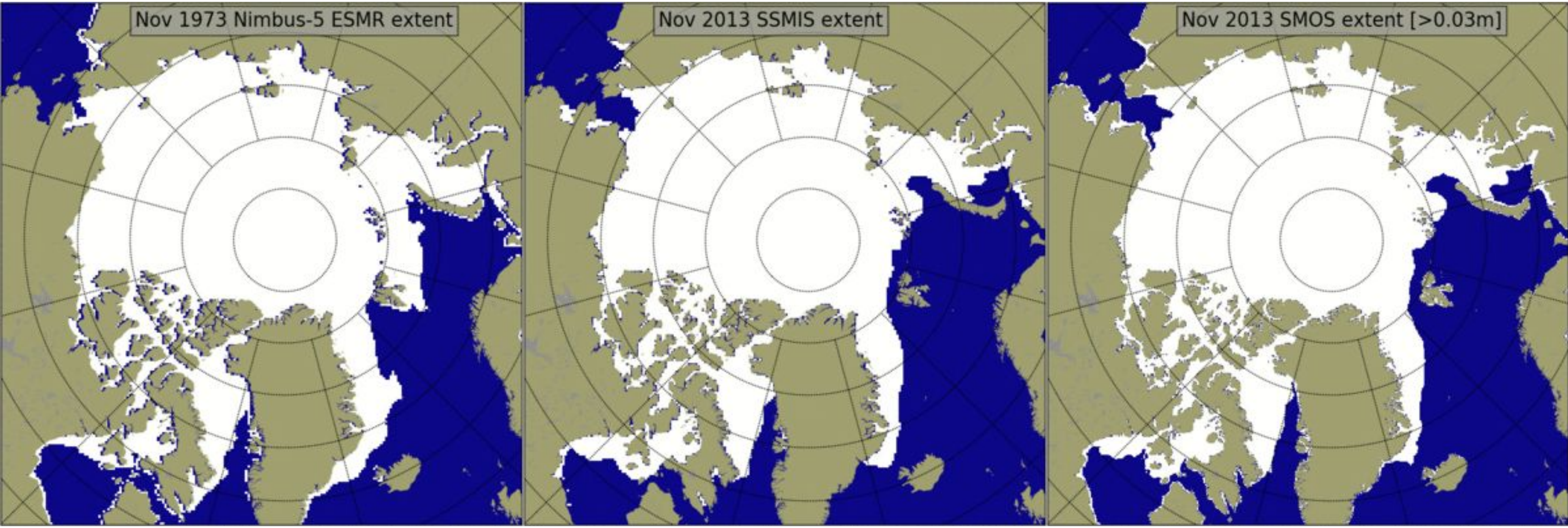
# Sea ice (thickness) extent from SMOS




New metric for comparisons with models -> Steffen Tietsche

# Continuity of measurements? SSMIS? SMOS?

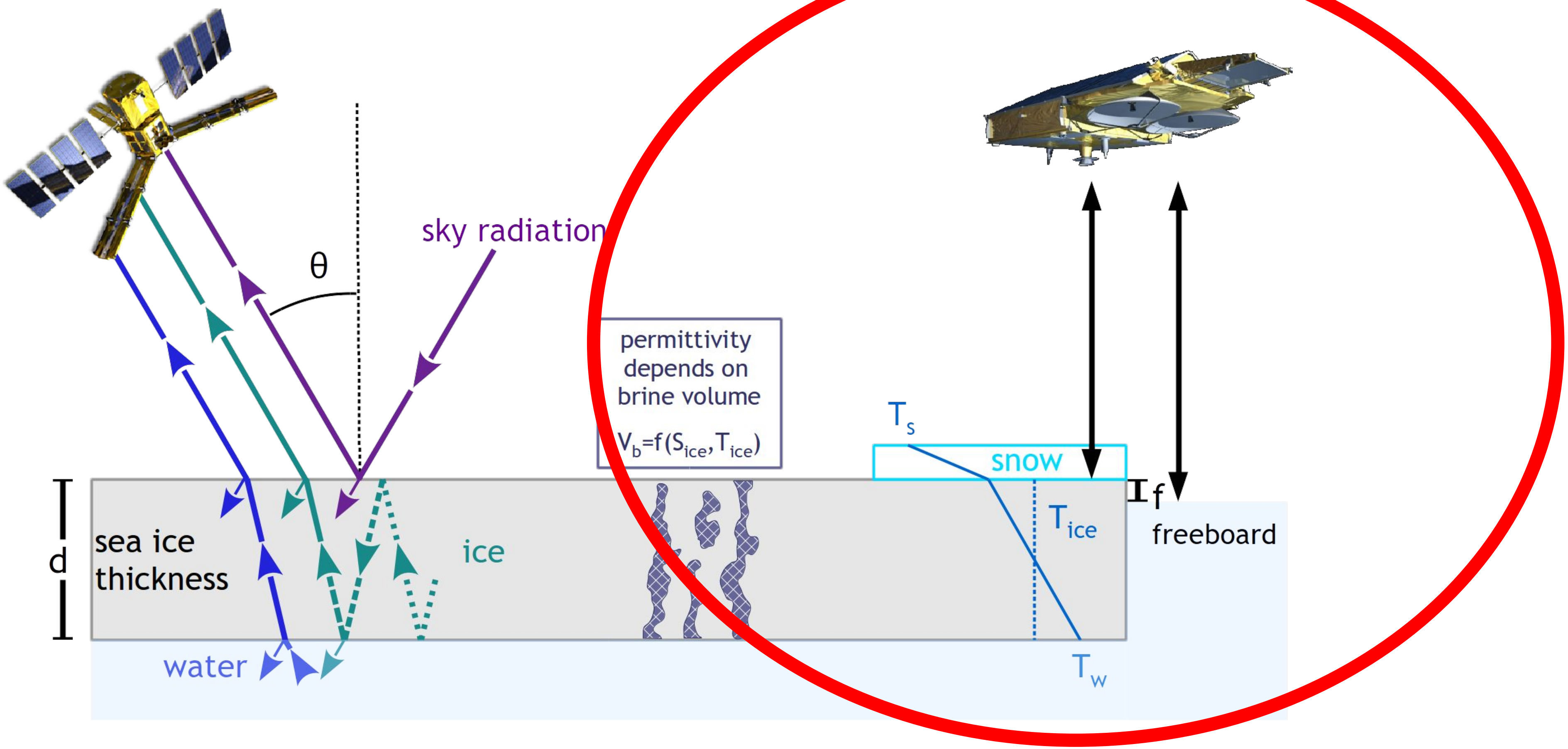



40 years back: NIMBUS-5 ESMR,

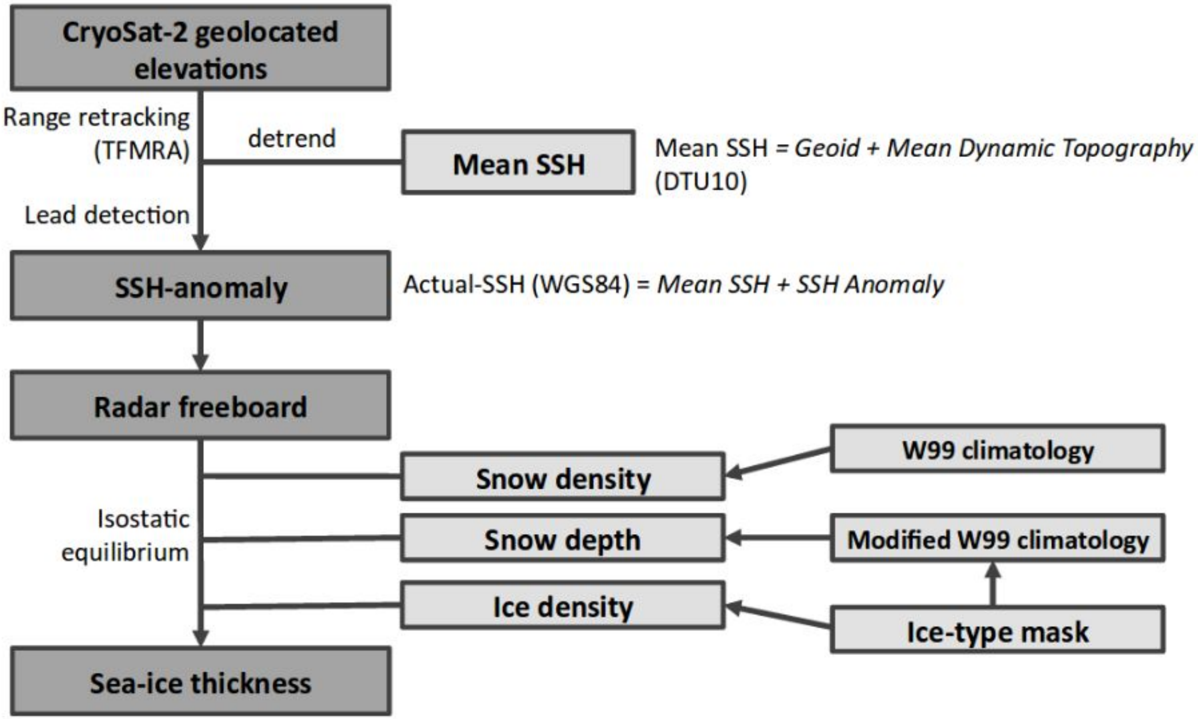
SSMIS F-16 F-18, F19, F20
14, 8 years old

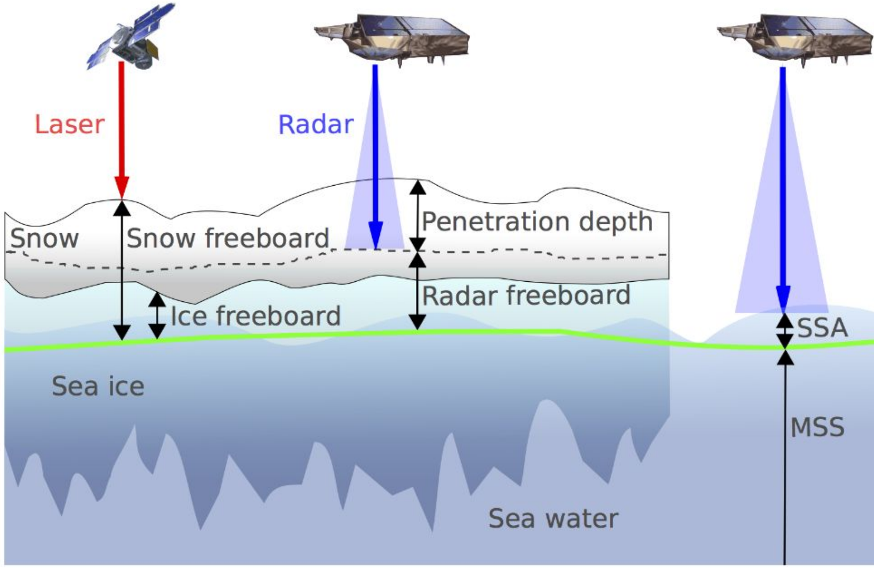
SMOS

# Sea ice thickness from SMOS and CryoSat2



# “AWI” CryoSat-2 data processing algorithm



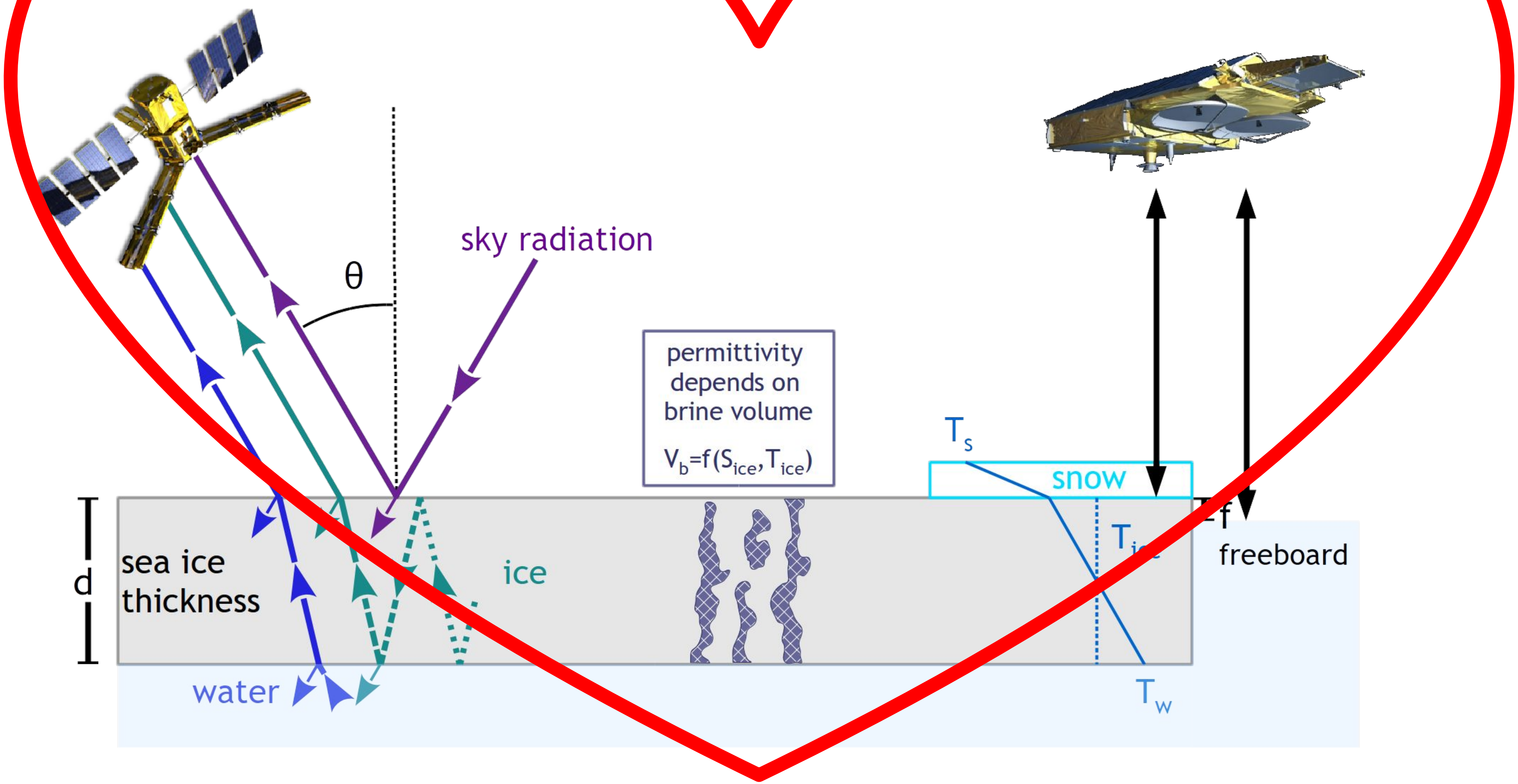




Ricker et al. (2014)

# CryoSat2 uncertainties over thin ice and marginal ice zones

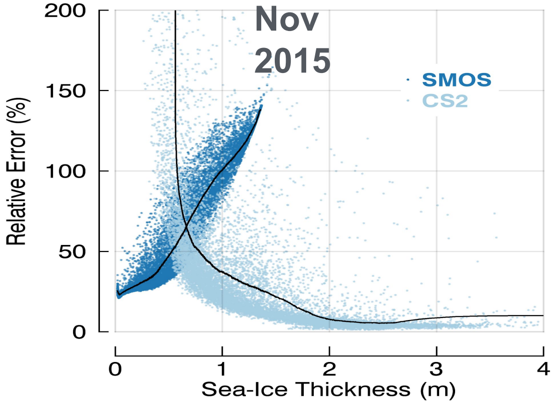
- Thinner ice rather occurs in lower latitudes where due to the CryoSat-2 orbit inclination, the density of measurements is lower than closer to the pole where ice is thicker.
- Measurement uncertainties are reduced by spatial averaging and the uncertainty reduction depends on the number of available measurements.
- The relative uncertainty increases over thin ice, as measurement uncertainties do not decrease over thinner ice
- In the marginal ice zones, when ice concentration decreases, many openings in the sea ice cover can lead to an underrepresentation of (thin) sea ice.
- With many openings in the sea ice (as in the marginal ice zones), so called “snagging” leads to increased uncertainties in the range measurements (Armitage and Davidson, 2014)

# Sea ice thickness from SMOS and CryoSat2

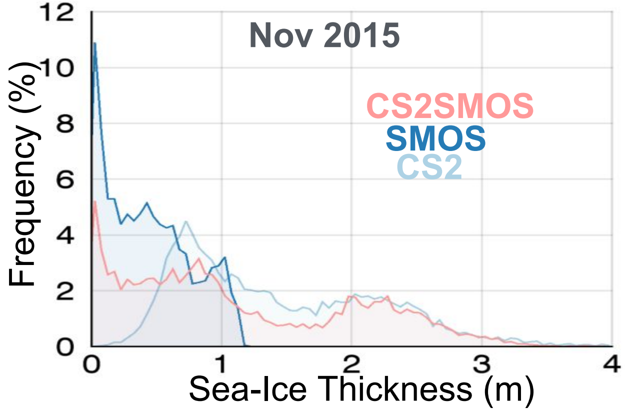


# Merging CryoSat-2 and SMOS data: CS2SMOS

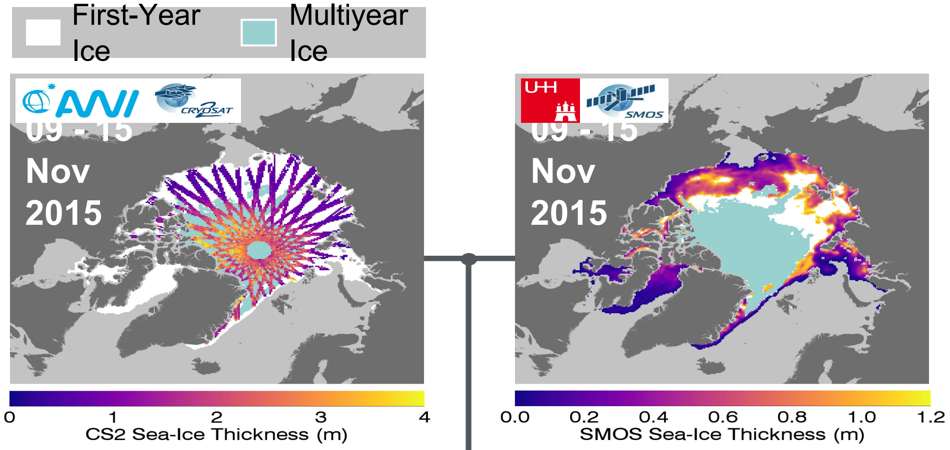
Complementary uncertainties and sampling

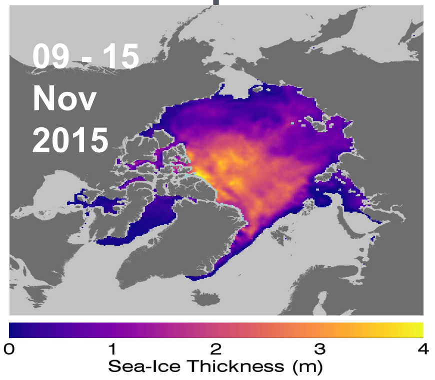



Thickness distribution

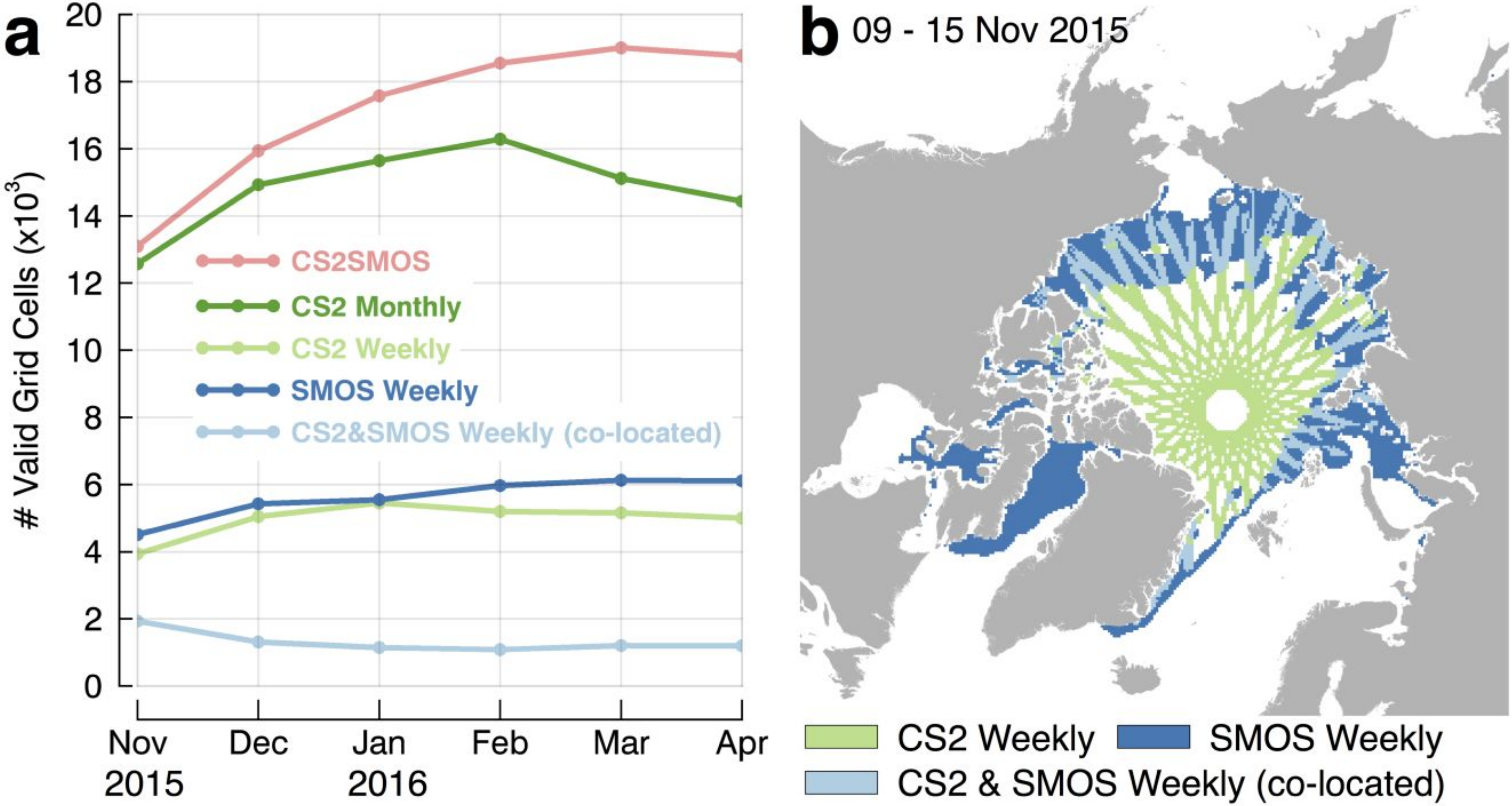



Merging weekly CryoSat-2 and SMOS sea-ice thickness retrievals using Optimal Interpolation



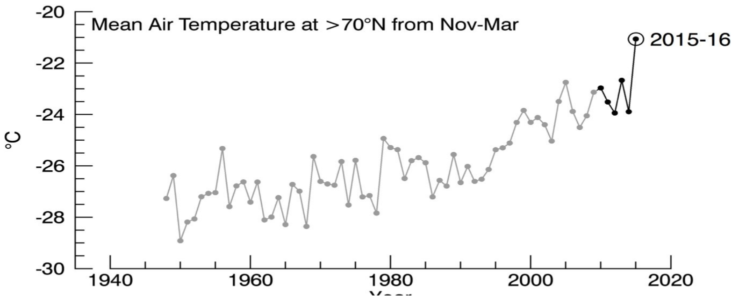




Ricker, R., Hendricks, S., Kaleschke, L., Tian-Kunze, X., King, J., and Haas, C.: A Weekly Arctic Sea-Ice Thickness Data Record from merged CryoSat-2 and SMOS Satellite Data, The Cryosphere Discuss., doi:10.5194/tc-2017-4, in review, 2017.



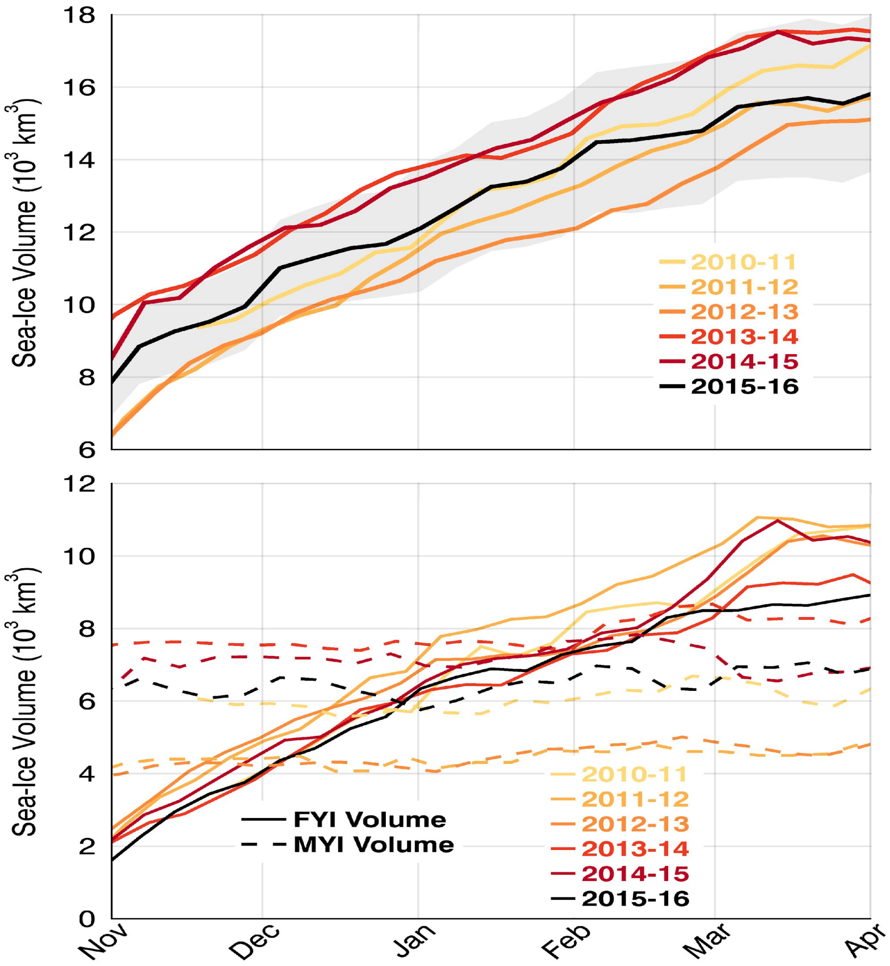
a
20
18
16
14
12
10
8
6
4
2
0
# Valid Grid Cells (x10$^3$)
CS2SMOS
CS2 Monthly
CS2 Weekly
SMOS Weekly
CS2&SMOS Weekly (co-located)
Nov 2015
Dec
Jan 2016
Feb
Mar
Apr
b
09 - 15 Nov 2015
CS2 Weekly
SMOS Weekly
CS2 & SMOS Weekly (co-located)

# Results:CS2SMOS Arctic Sea-Ice Volume

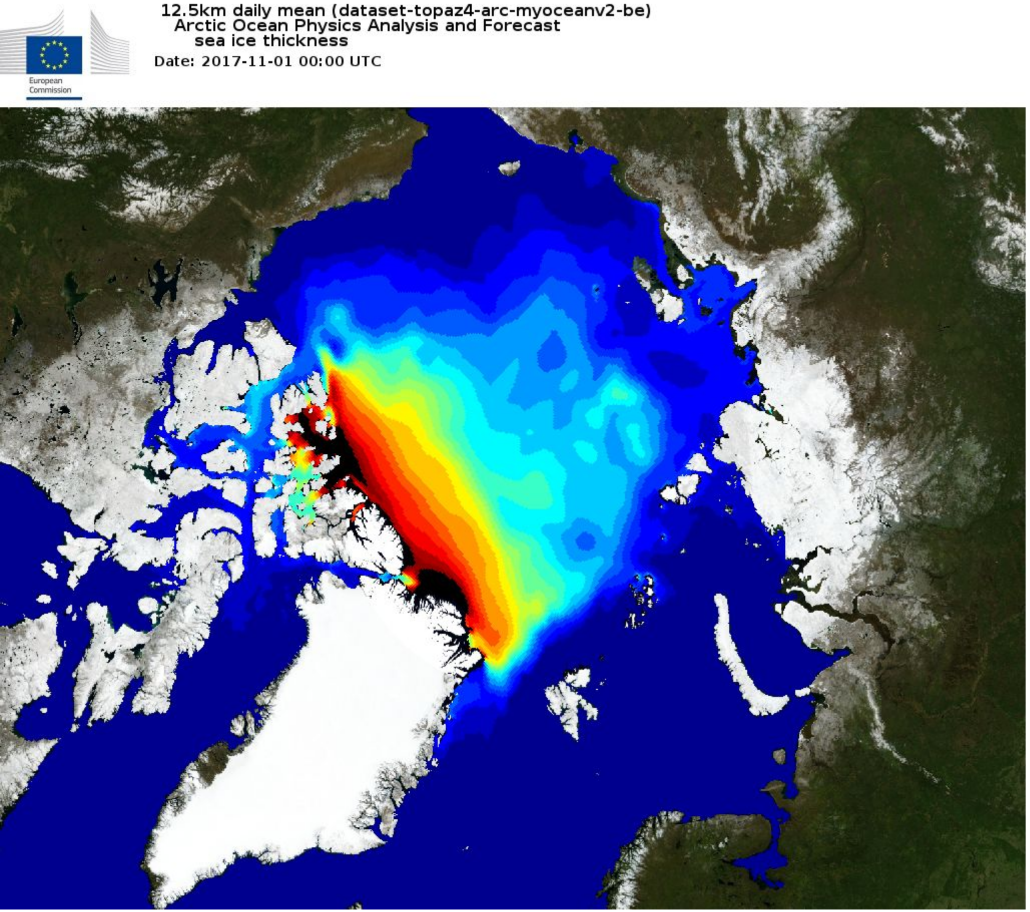


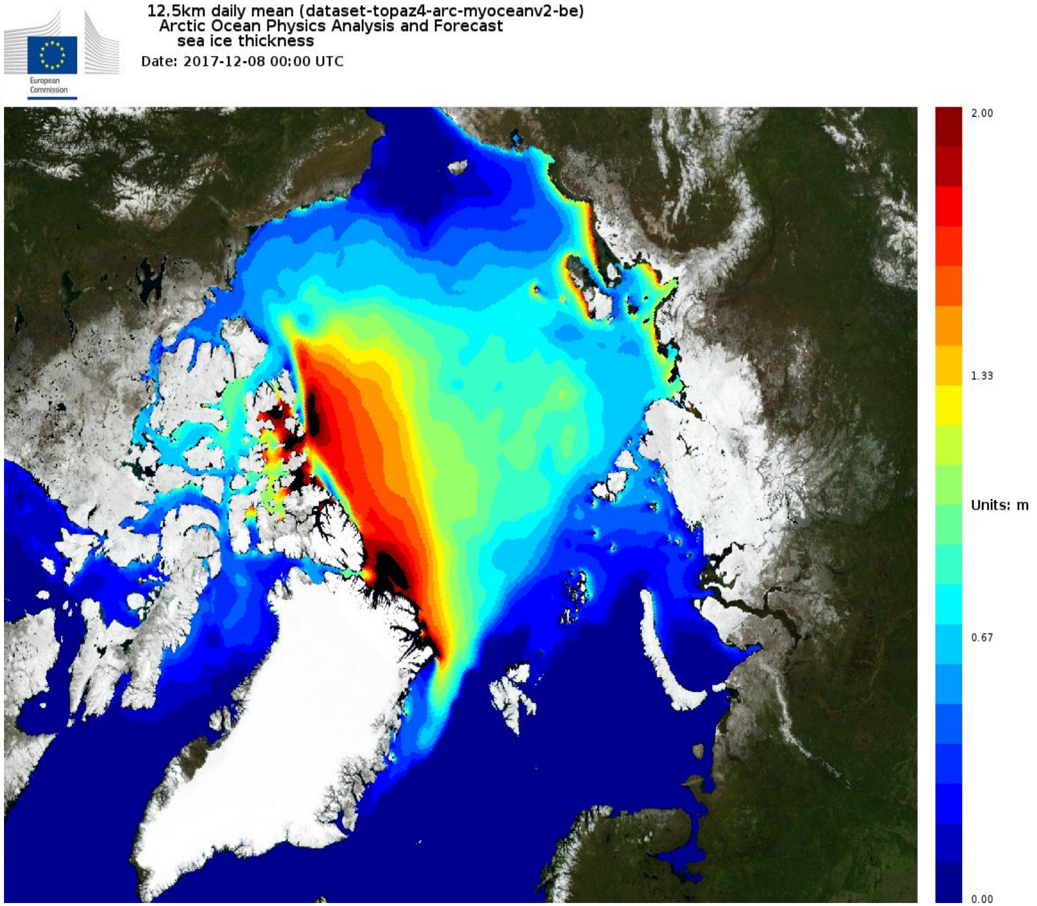

- First-year ice volume variability primarily driven by thermodynamic growth
- Volume reduction in 2015/16 due to reduced summer multiyear ice replenishment and reduced winter-ice growth

*Ricker et al.: Satellite-observed drop of Arctic sea-ice growth in winter 2015-2016, GRL*

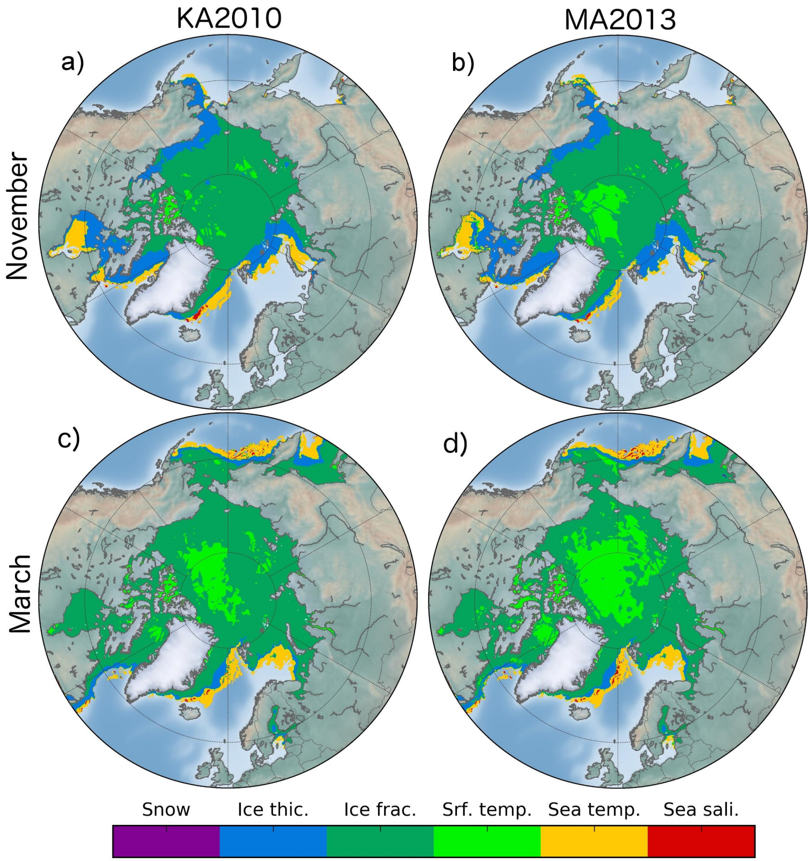


# Copernicus Arctic Marine Services -> Laurent Bertino



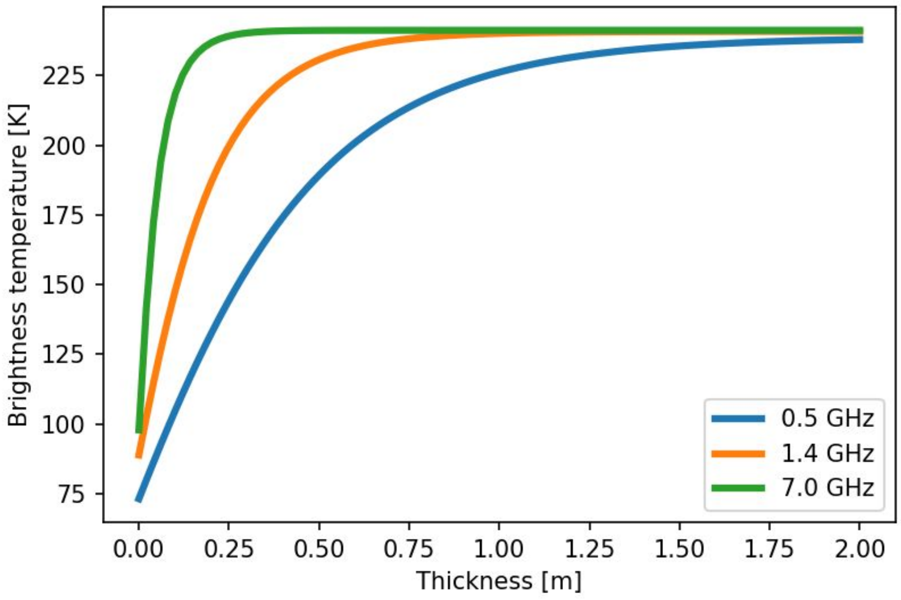
# Outlook: assimilation of brightness temperatures




- Currently the thickness retrieval is based on many assumptions, parameterizations, and auxiliary data
  - Thickness distribution
  - Ice concentration
  - Snow thickness
  - Salinity
  - Temperature
  - ...
- New approach: assimilation of TBs with ocean ice model and radiative transfer model (observation operator)
- Allows quantification of uncertainty covariances

Richter, F., Drusch, M., Kaleschke, L., Maaß, N., Tian-Kunze, X., and Mecklenburg, S.: Arctic sea ice signatures: L-Band brightness temperature sensitivity comparison using two radiation transfer models, The Cryosphere Discuss., https://doi.org/10.5194/tc-2016-273, in review, 2016.

# Outlook: more and lower frequencies

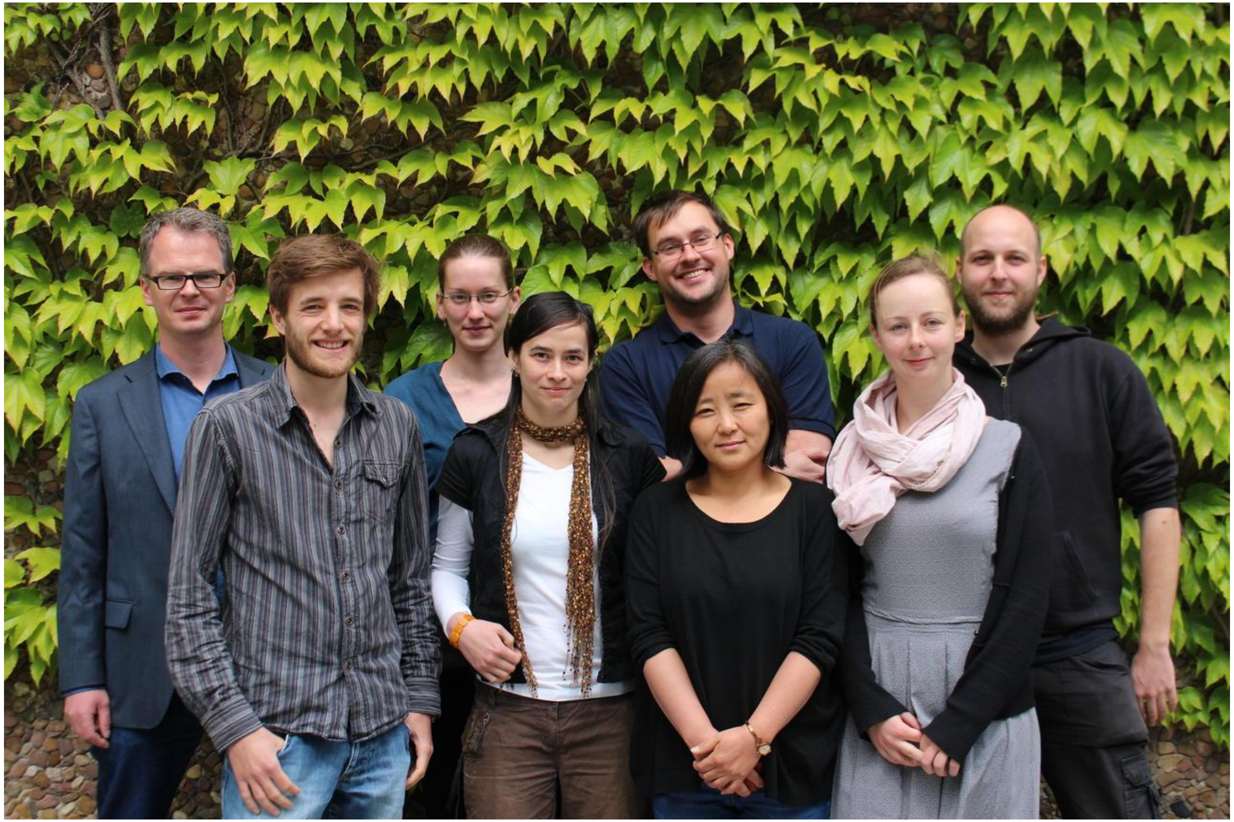



- Much deeper penetration at 0.5 GHz
- Retrieval of sea ice thickness/volume over entire range for undeformed first-year ice
- Airborne campaign with Ultra-Wideband Software-Defined Microwave Radiometer UWBRAD (J.T. Johnson, Ohio State University)
- Radiometer experiment during year-round MOSAiC transpolar ice drift with Polarstern 2019/2020
- CryoRad proposal for EE10 (G. Macelloni, IFAC)

# Summary and conclusion

- Sea ice thickness is one of the key parameters needed for the initialisation of forecast models for short-term and seasonal prediction and can be obtained from SMOS
- Successful test and demonstration of operational short-term forecast and ship route optimization system in Barents Sea, March 2014
- Unique dataset covering thin ice and deformed ice in the marginal ice zone confirms validity of 1.4 GHz sea ice thickness retrieval
- Combination of SMOS and CryoSat2 used for new interpolated weekly product CS2SMOS with reduced uncertainty and better coverage
- Continuing growth of SMOS sea ice thickness data use, e.g. assimilation in Copernicus Arctic Marine Forecast System
- Sea ice extent from SMOS compares well to SSMIS (preliminary analysis)
- Continuity needed for climate research and operational applications
- Outlook:
    - Retrieval of snow thickness
    - In-situ validation data needed: salinity and temperature profiles -> MOSAiC 2019/2020
    - Develop and validate sea ice emissivity community model (observation operator)
    - Assimilation of brightness temperature in forecast models
    - Towards new satellite missions

# Thank you for your attention!



Special thanks to the sea ice remote sensing group, University of Hamburg, 2015

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Ola Gråbak **ESA ESRIN**
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Mike Schwank **Gamma Remote Sensing and Swiss Federal Institute WSL**
Xiaolan Xu, Scott Dunbar **Jet Propulsion Laboratory**
John Kimball, Youngwook Kim **Montana State University**
Alexandre Roy, Alain Royer **Université de Sherbrooke**
Chris Derksen **Environnement Canada**

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