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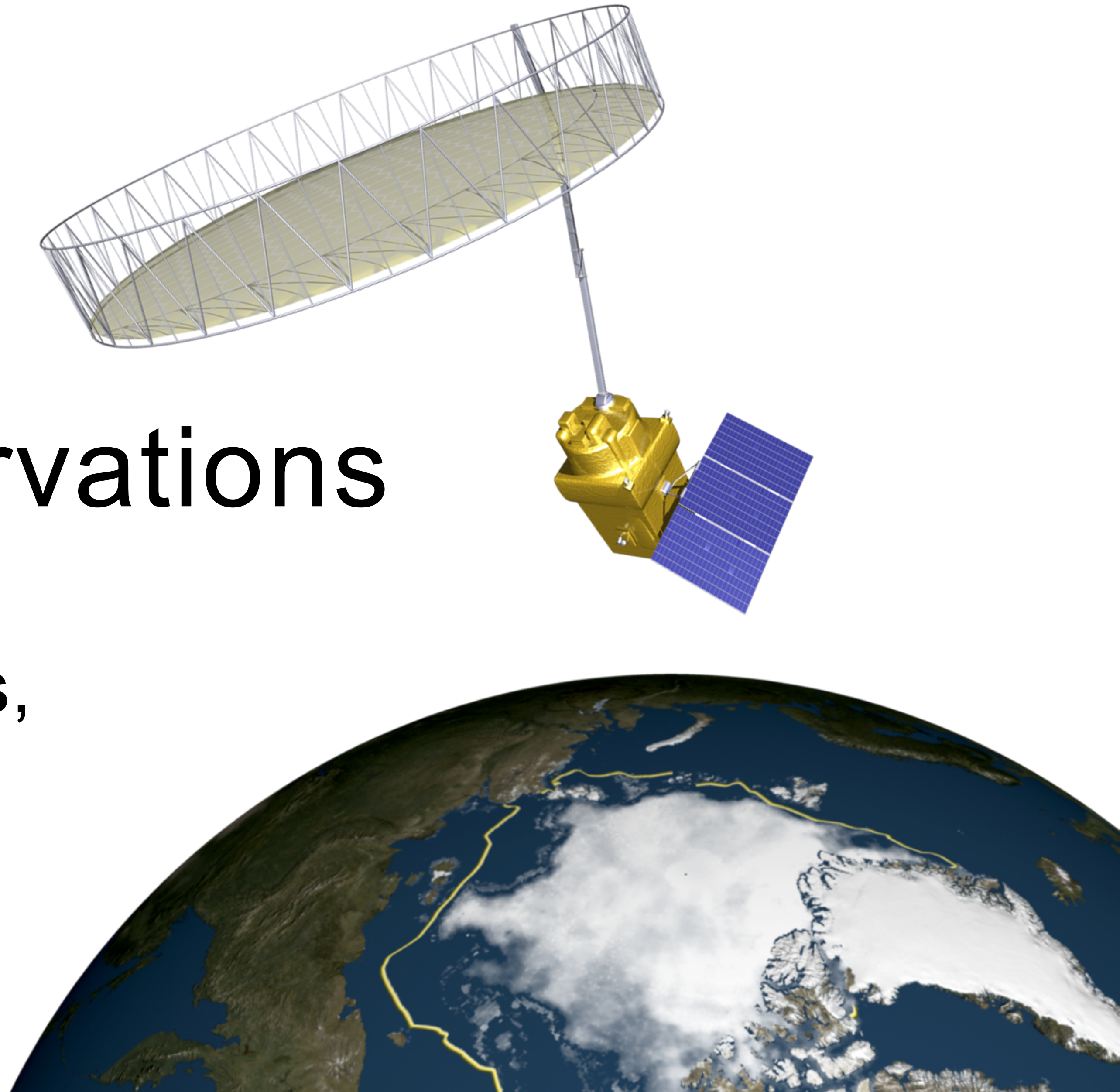


# Sea Ice Observations

## Overview,
## Recent Developments,
## and Uncertainties

Gunnar Spreen
ECMWF Annual Seminar 13.09.2021

# Outline Sea Ice Observations

- Microwave Sensors
  - Longest time series from MW radiometer since more than 40 years
  - Multiple sea ice parameters: **sea ice concentration**, ice type, snow depth, ice drift, thin ice thickness (since 2010)
  - Recent years: strong increase in Synthetic Aperture Radar (SAR) data with almost daily coverage of Arctic
- Altimeter
  - Sea ice freeboard ➔ **ice thickness** ➔ ice mass
  - Laser + radar altimeter: **snow depth**
- Optical Sensors
  - Albedo and melt pond fraction
  - Synergy with microwave sensors
- Field observations
  - More autonomous observations (“buoys”) measuring more parameter
  - Dedicated campaigns like **MOSAiC** for model parametrization

# Remote Sensing of Sea Ice – Where are we?

- **Sea Ice Area:** since more than 40 years (since 1972)
- **Motion:** daily since >20 years (coarse resolution)
  high resolution (SAR) since >15 years (sporadically)
- **Thickness:** 2003–2009 (ICESat), 2010–today (CryoSat, SMOS)
  2018–now (ICEsat-2)
  (since 1994 until 81.5°N with large pole hole)
- Snow thickness, melt cycle length, ice type, deformation, melt ponds, albedo, polynyas, sea ice production, roughness, ice age, lead statistics

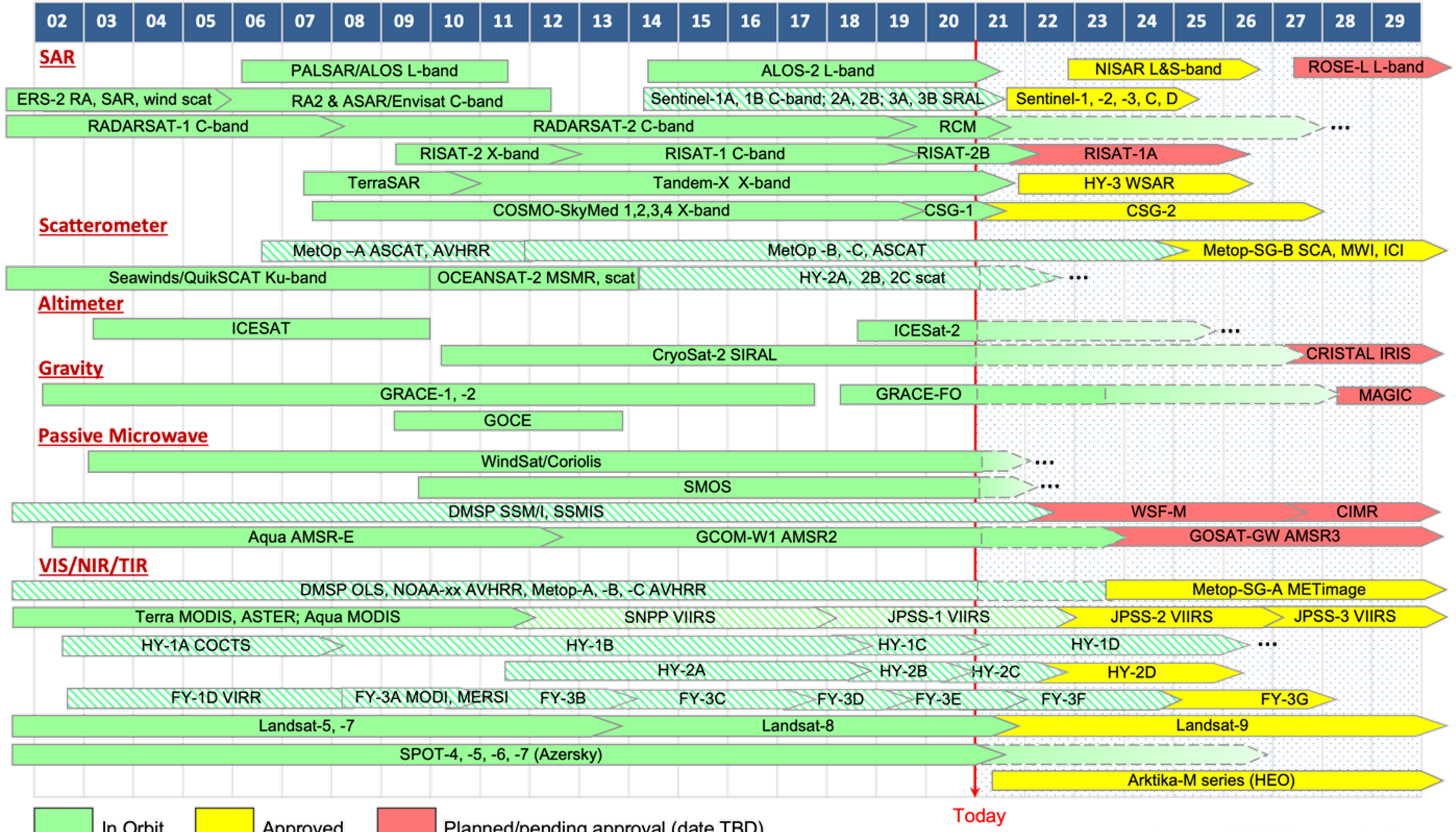
# Satellite Missions for Observing the Cryosphere

Sea ice extent and concentraton, ice sheet elevation, glacier velocity, snow accumulation

Ice sheet elevation, sea ice thickness

Ice sheet mass change

Sea ice extent and concentration, glacier area, surface albedo and temperature, radiation budget




In Orbit — Approved — Planned/pending approval (date TBD)

Solid = R&D; Hatched = operational mission. *For current missions, length of service beyond "Today" is unknown.*

*Courtesy of M. Drinkwater and J. Key*

http://globalcryospherewatch.org

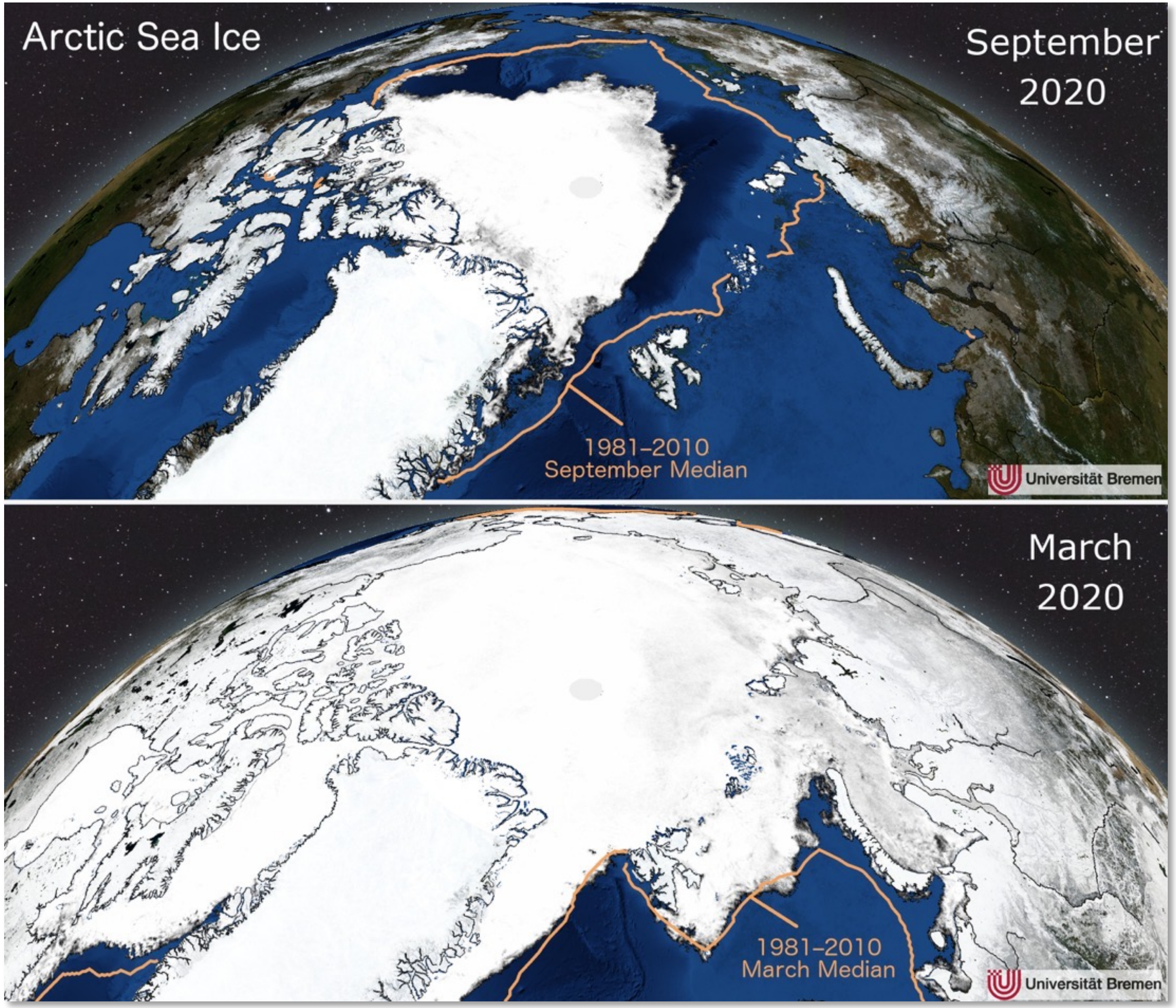
→ Many (>20) satellites in space

→ Frequency spectrum covered from microwave to visual

→ Plus: Altimetry, Gravimetry, Interferometry

→ New EU Copernicus Sentinel and EUMETSAT satellites for polar regions: CIMR, CRISTAL, ROSE-L, Metop-SG-B

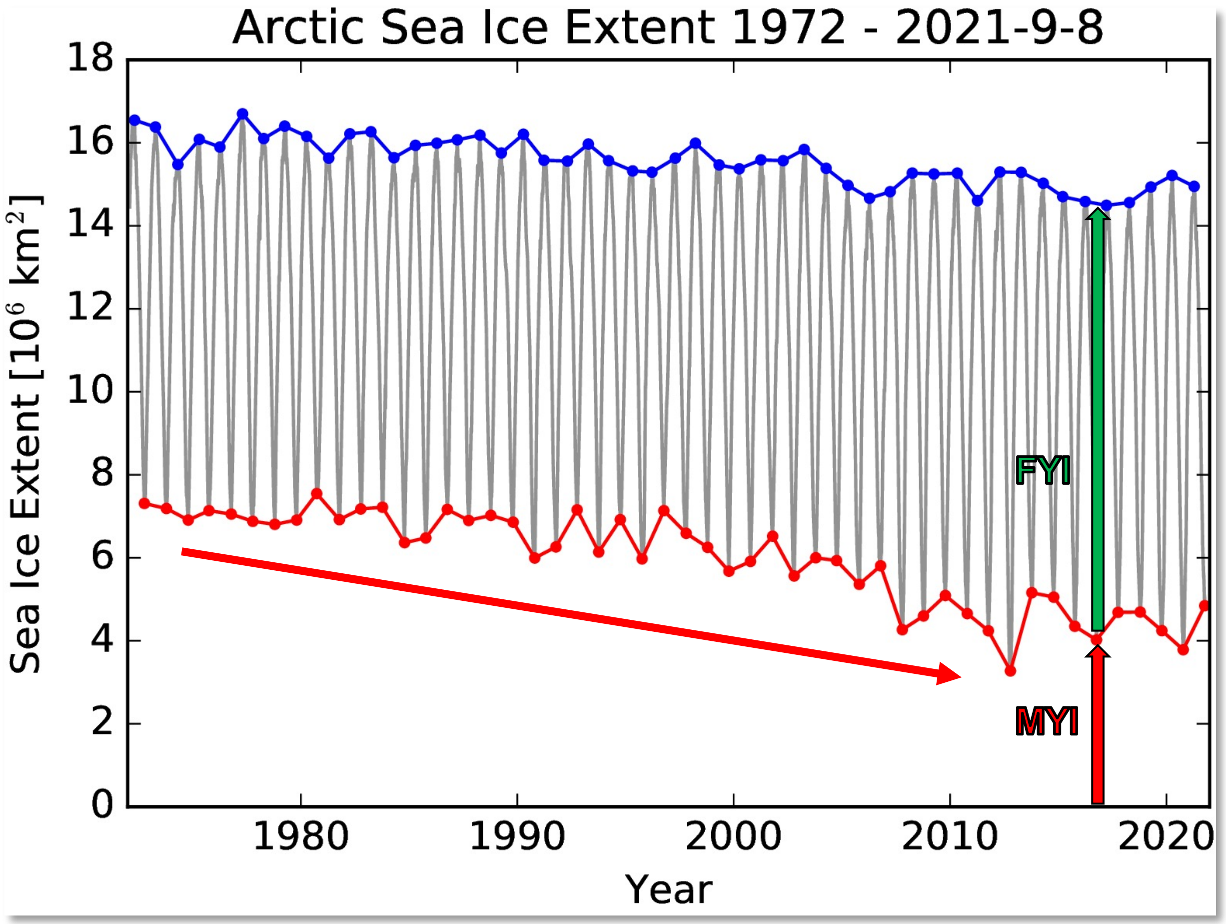
# Sea Ice Concentration Time Series

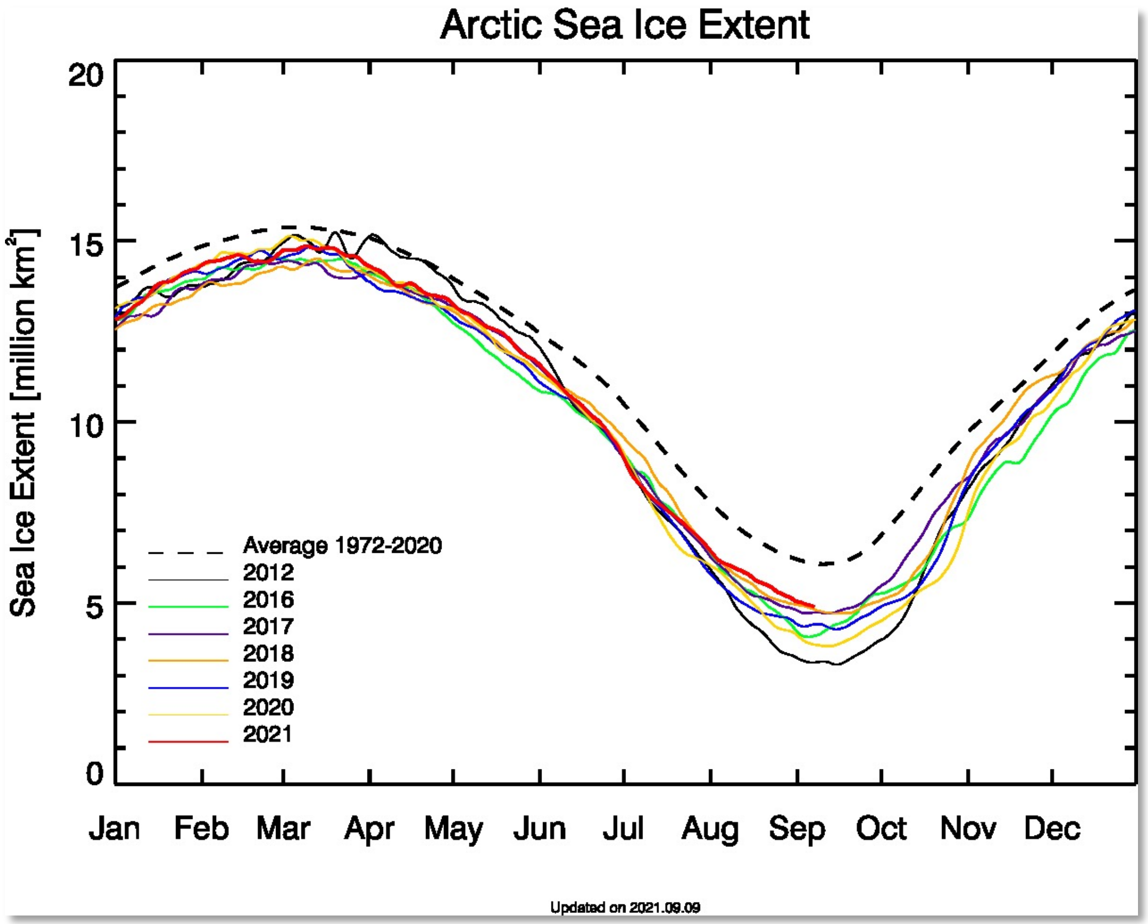



www.seaice.uni-bremen.de,
www.meereisportal.de

# Sea Ice Concentration Time Series





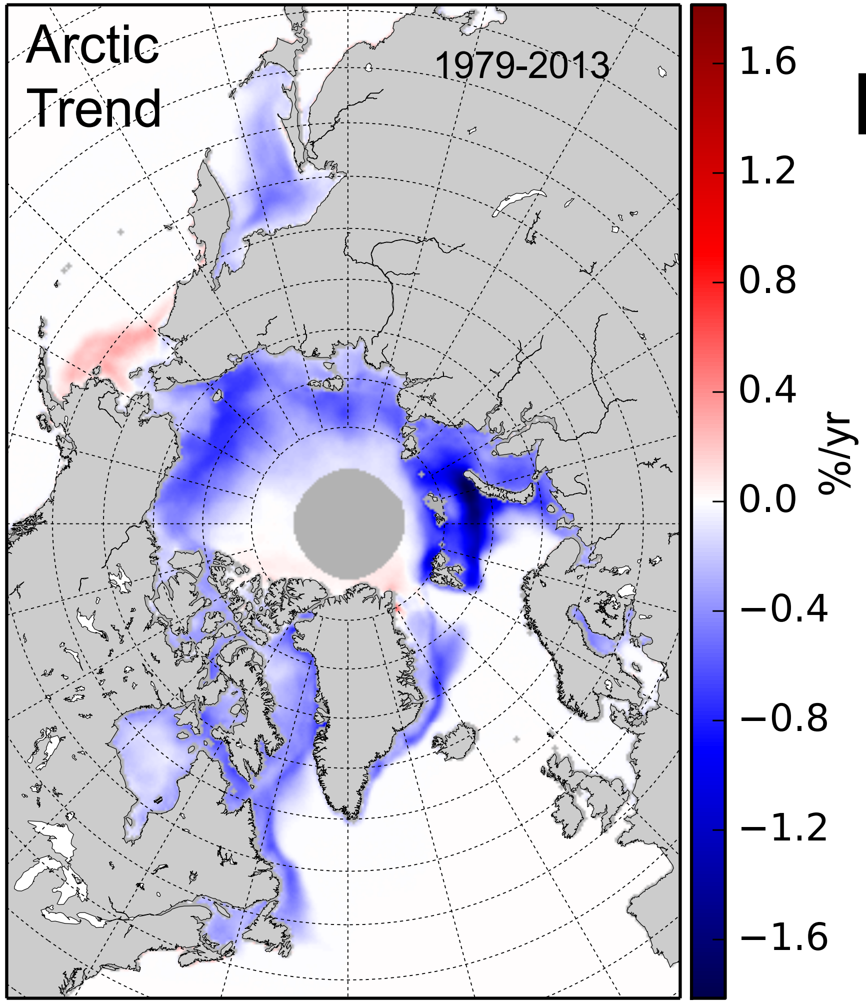



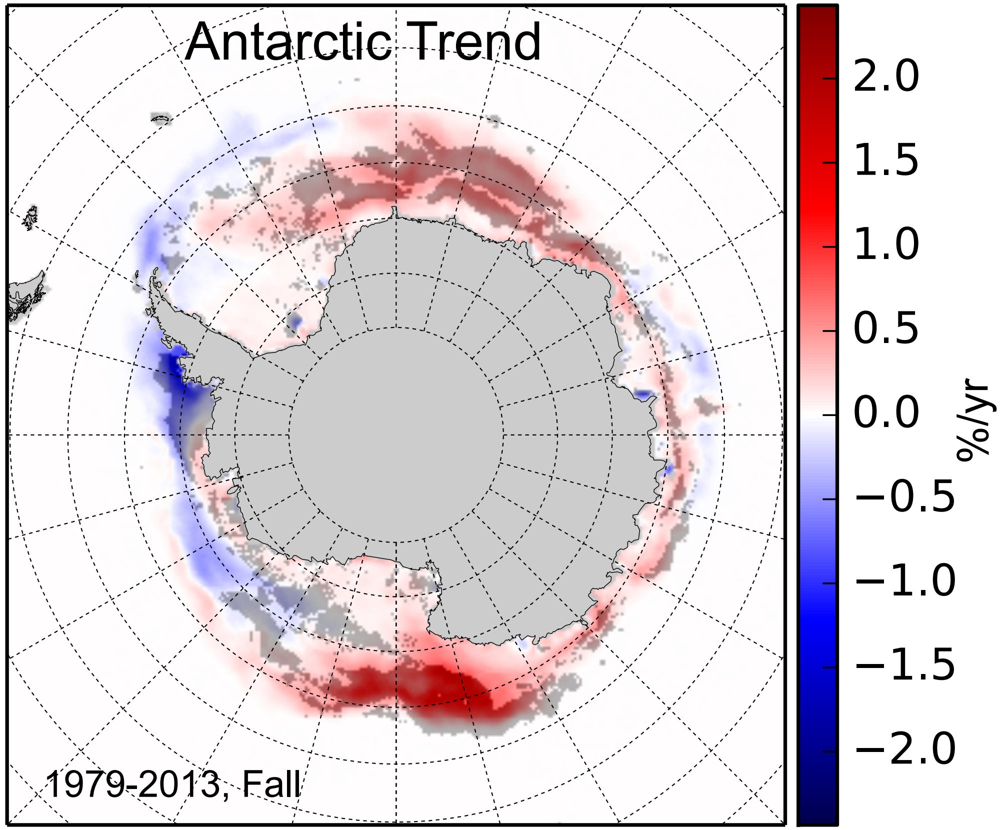

- Time series since 1972
- Annual trend: –4.5%/decade
- Summer trend: –13%/decade

www.seaice.uni-bremen.de,
www.meereisportal.de

# Sea Ice Area Trends

## Spatial Distribution




→ Arctic: Strongest negative trends in marginal seas: e.g., Barents, Beaufort Sea

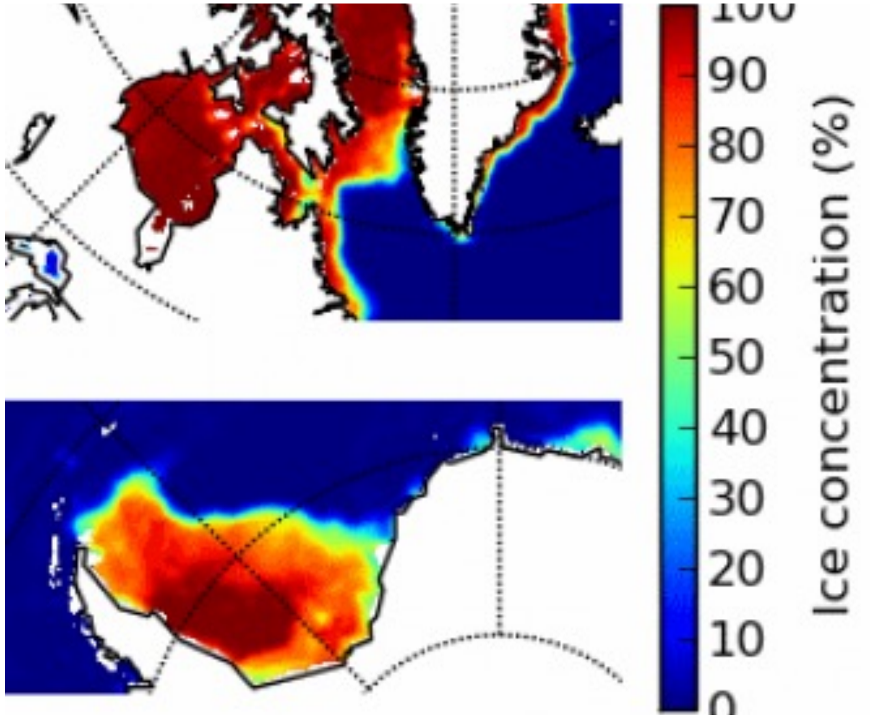
- Antarctic: contrasting patterns depending on location
- negative: Antarctic Peninsula, Bellinghausen, Amundsen Seas
- positive: everywhere else

EUMETSAT OSI SAF OCEAN AND SEA ICE

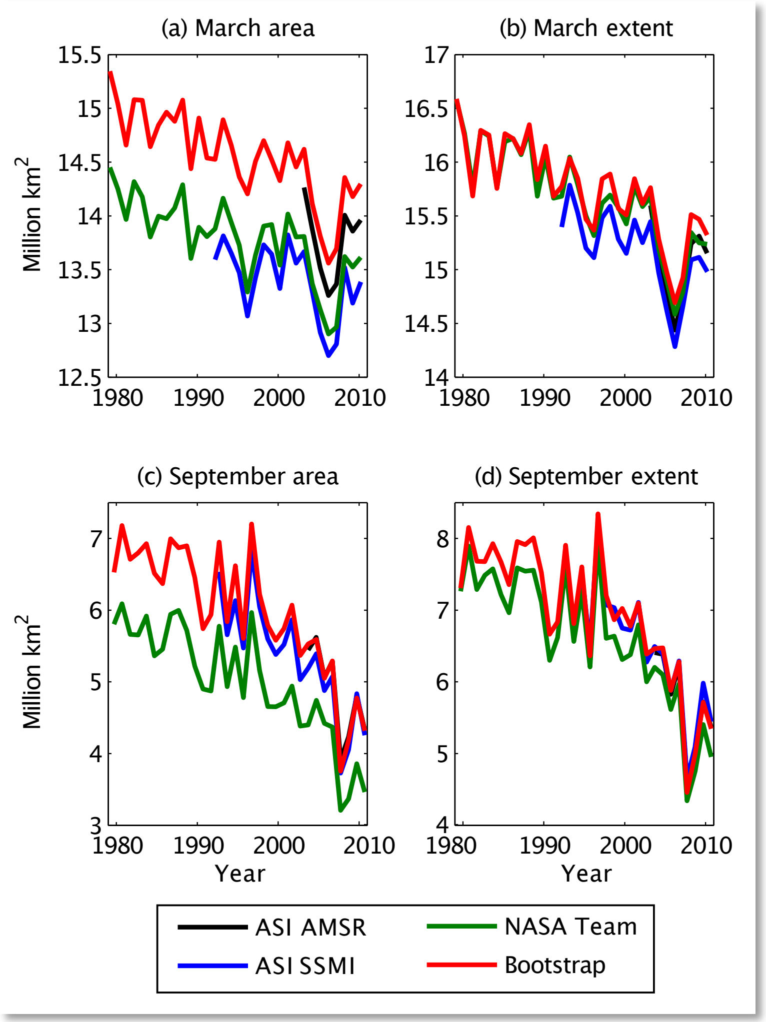
# OSISAF Near Real Time

## Level 2 Sea Ice Concentration

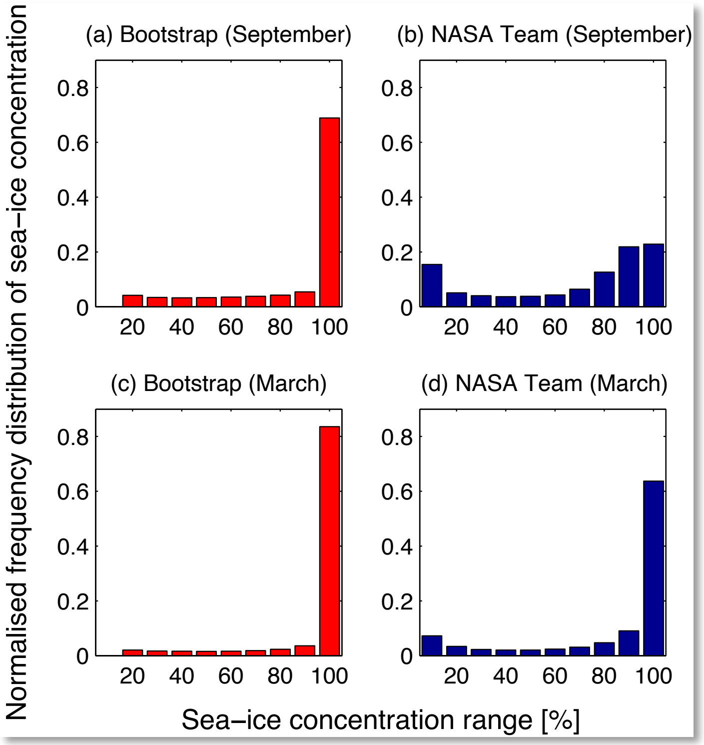
→ Swath based
→ Up 15x per day from AMSR-2 and SSMIS
→ 10 km resolution for AMSR2 (25 km for SSMIS)
→ Target accuracy: 10 % for NH-product
15 % for SH-product
→ Usage: NWP and Ocean/Ice models,
operational Met and Sea Ice services.
→ Product OSI-410;
https://osi-saf.eumetsat.int/products/osi-410



# Significant differences exist between sea ice concentration retrievals

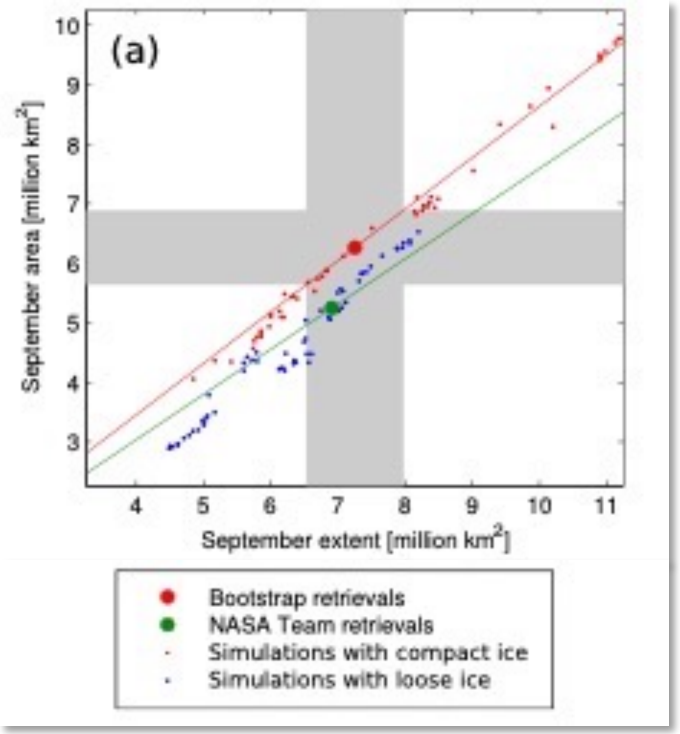



4 satellite retrievals:
ice area & extent




PDF for 2 retrievals:
compact vs. loose ice

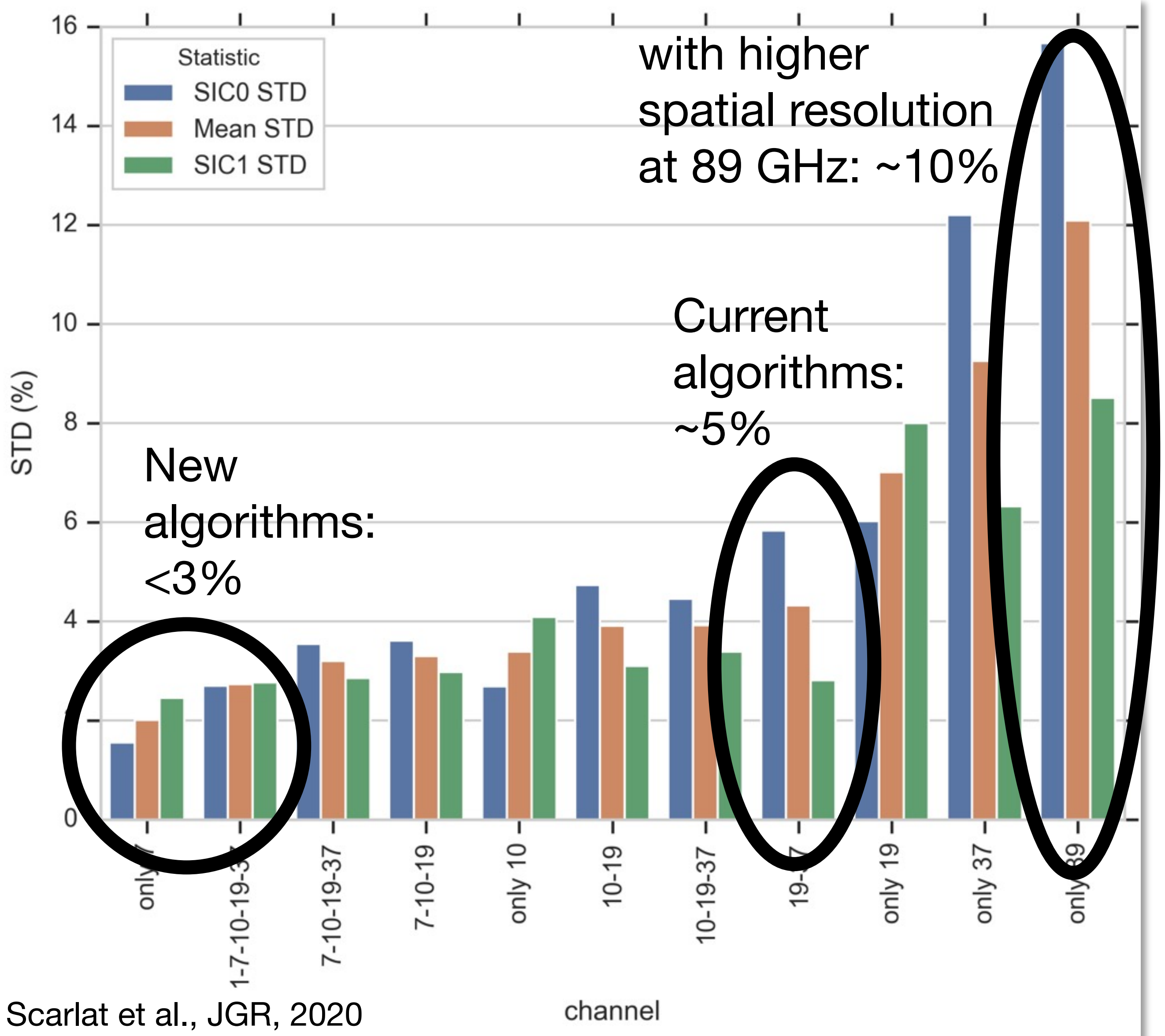
*Notz, D.: Sea-ice extent and its trend provide limited metrics of model performance, The Cryosphere, 2014.*




→ CMIP5 models (red and blue dots) can be either closer to the compact (red) or loose ice (green) retrieval
→ Satellite total ice area and extent are not useful metrics for model evaluation

# Uncertainties

- Current ice concentration algorithms have significant uncertainties
  1. Atmospheric influence on retrievals → use lower frequencies → lower spatial resolution or new satellite (CIMR)
  2. High variability of sea ice emissivity
- Better microwave emission modeling needed
- Derive new parameters like snow depth and better ice thickness
- New satellites (e.g. ICESat-2, CIMR, MetOp-SG, CRISTAL) and methods can help




Scarlat et al., JGR, 2020

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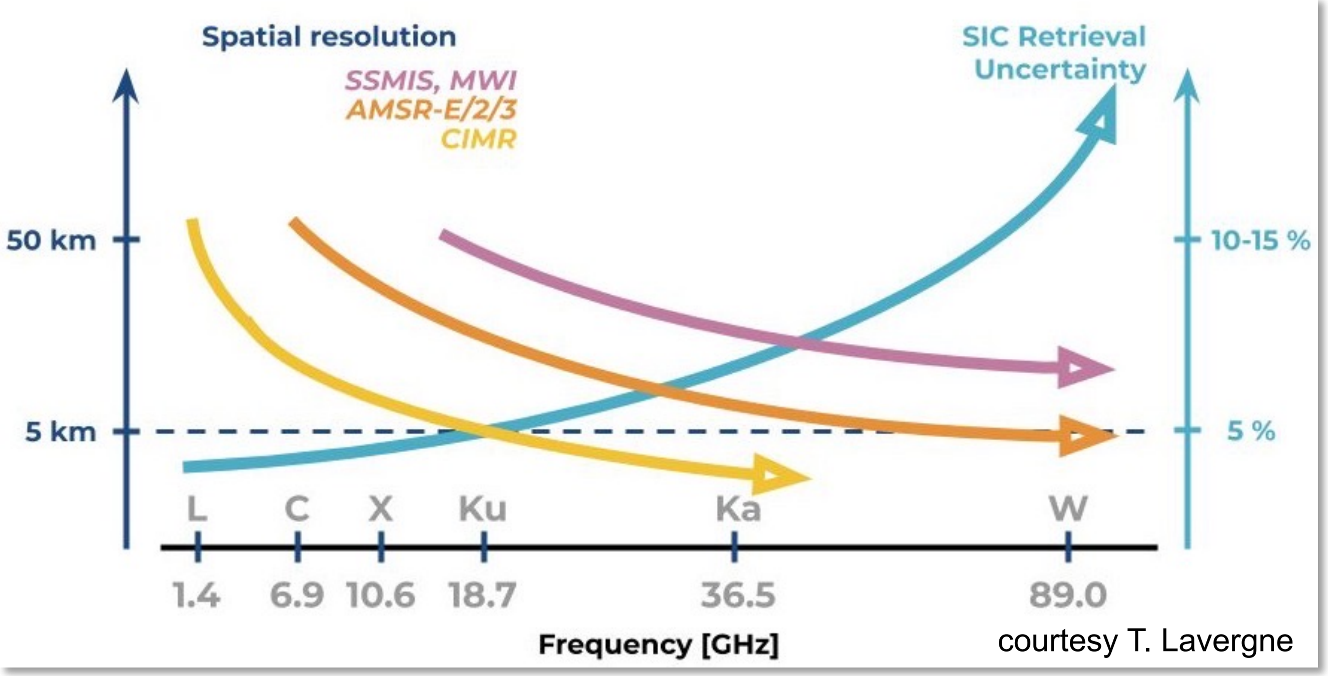

courtesy T. Lavergne

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# One way forward: Multiparameter Retrieval

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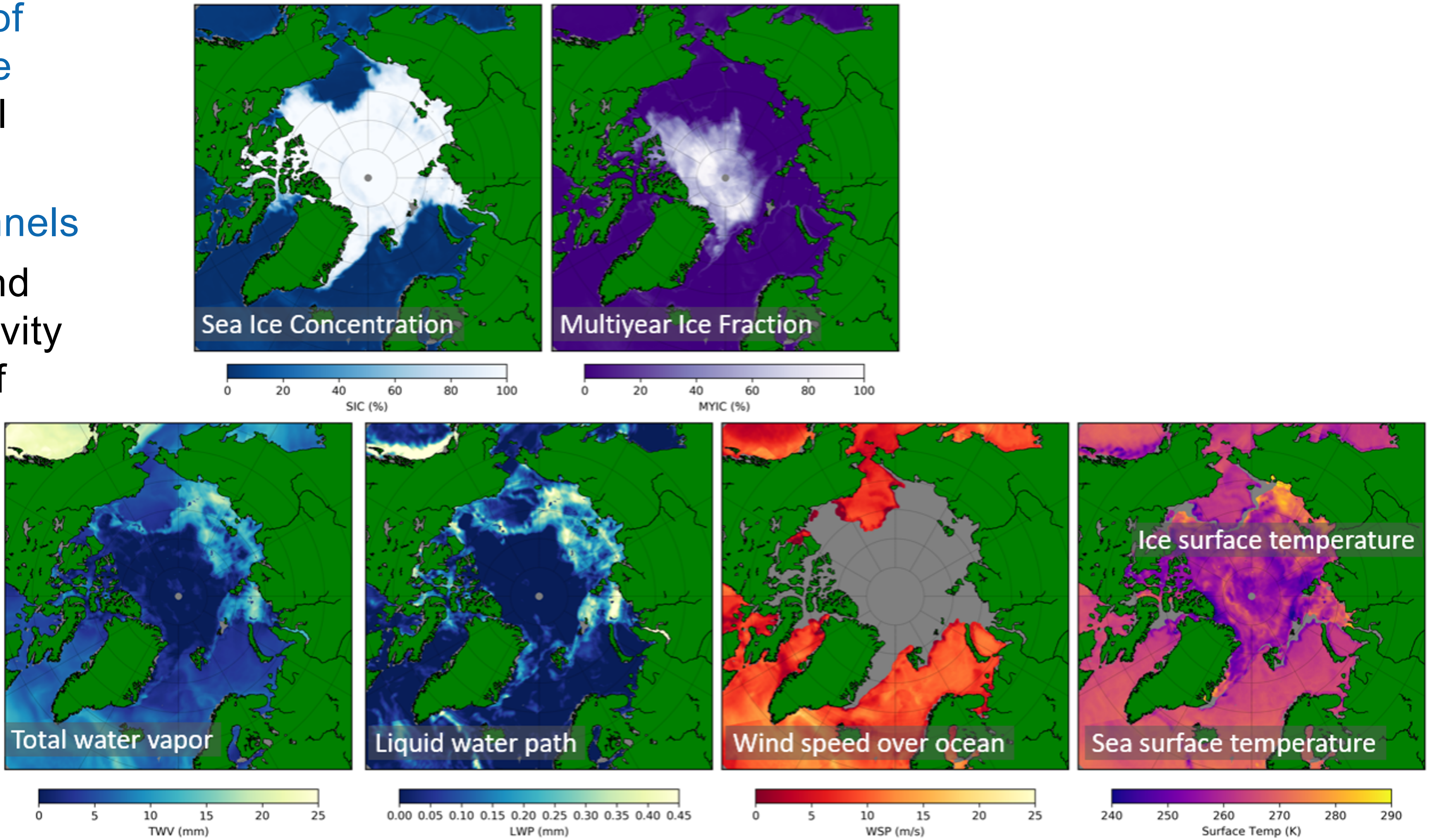
ECMWF Annual Seminar 2021

- → Simultaneous retrieval of surface and atmosphere properties using optimal estimation (OE)
- → Using all available channels
- → Physically consistent and adaptive surface emissivity allows better retrieval of atmospheric properties
- → Here shown for JAXA's AMSR2 MW radiometer (7 – 89 GHz)




6 Nov 2019

Scarlat et al., JGR, 2020

# One way forward: Multiparameter Retrieval

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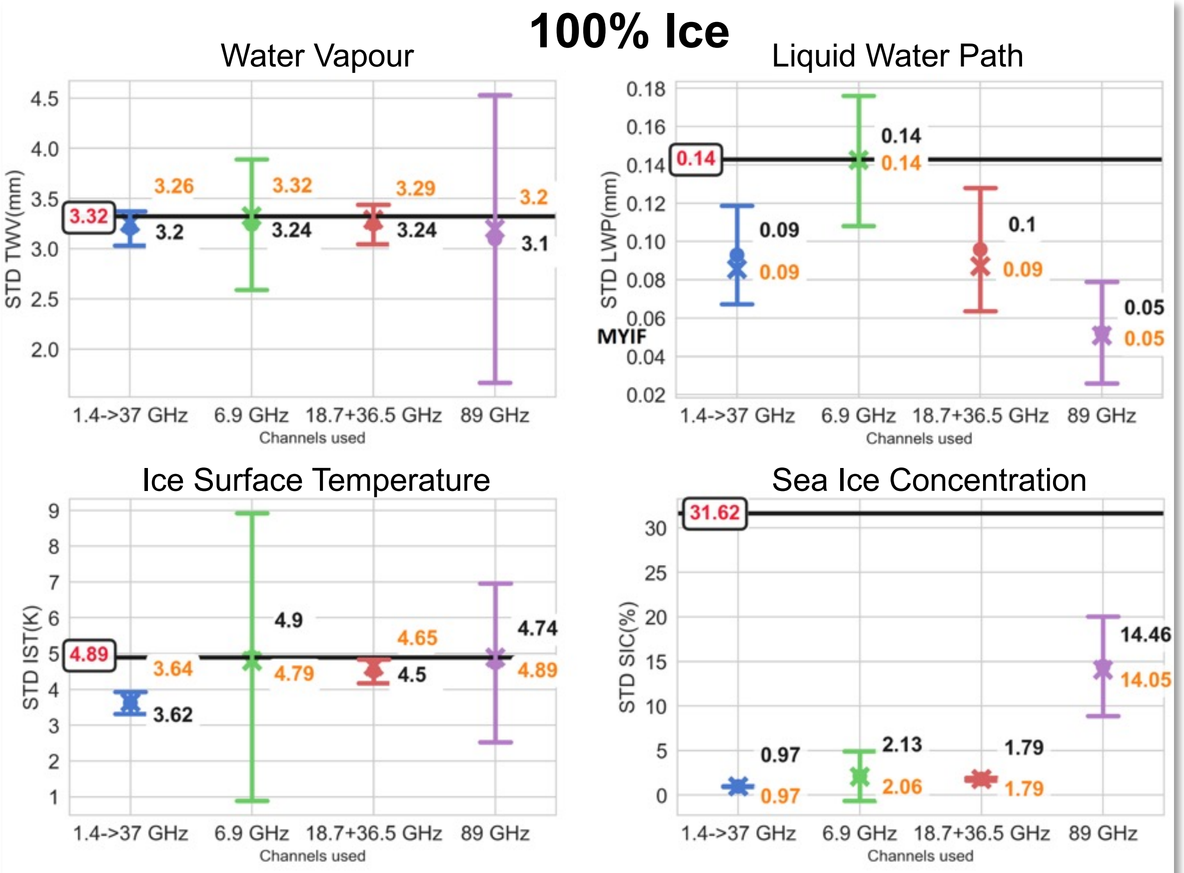
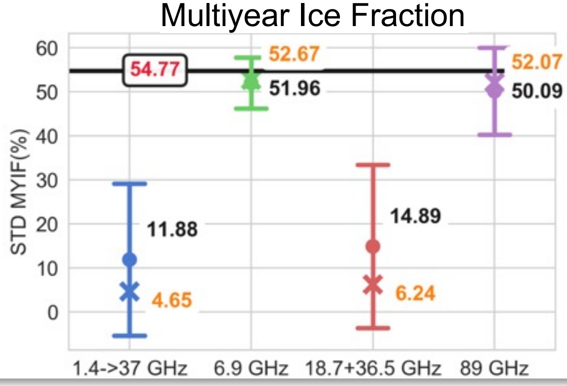
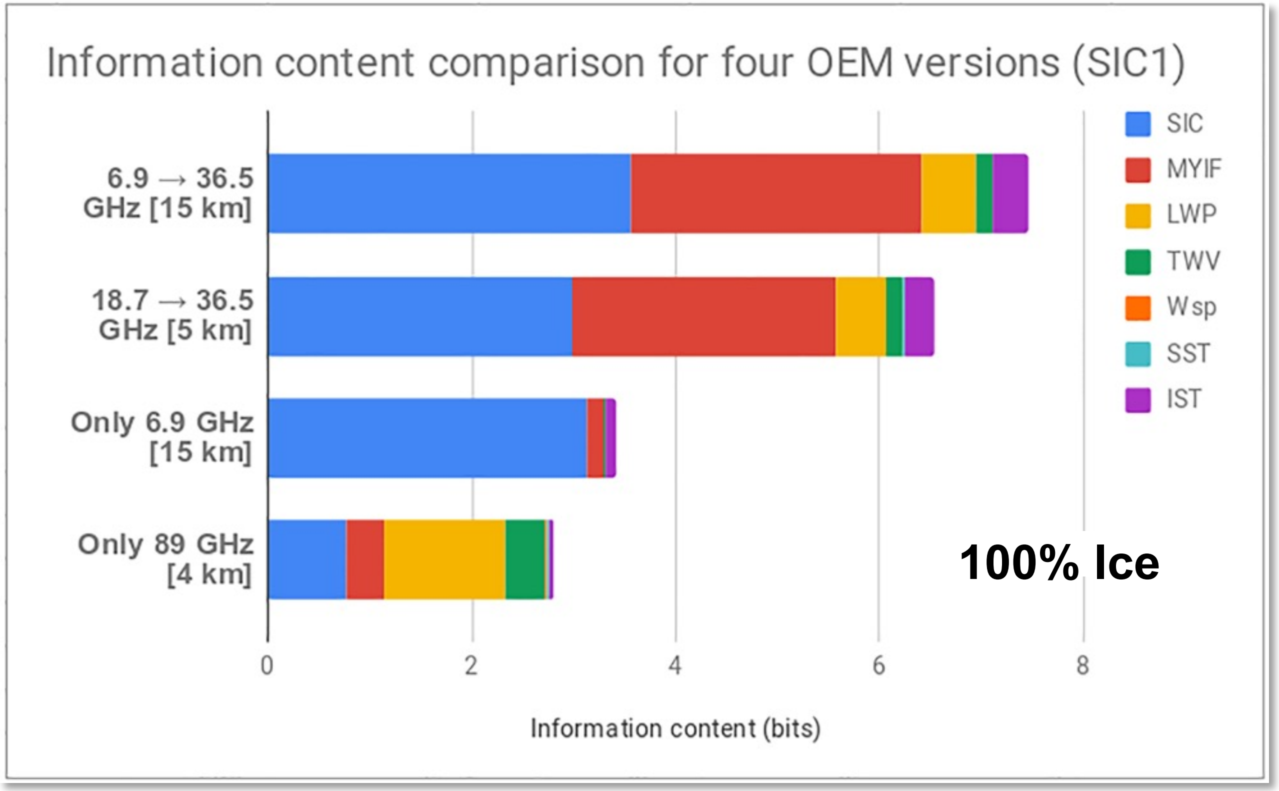



Uncertainties for different frequency combinations used in the OEM

## Uncertainties and Information Content from Optimal Estimation




Information content regarding the different geophysical parameters

Scarlat et al., JGR, 2020

# One way forward: Copernicus CIMR

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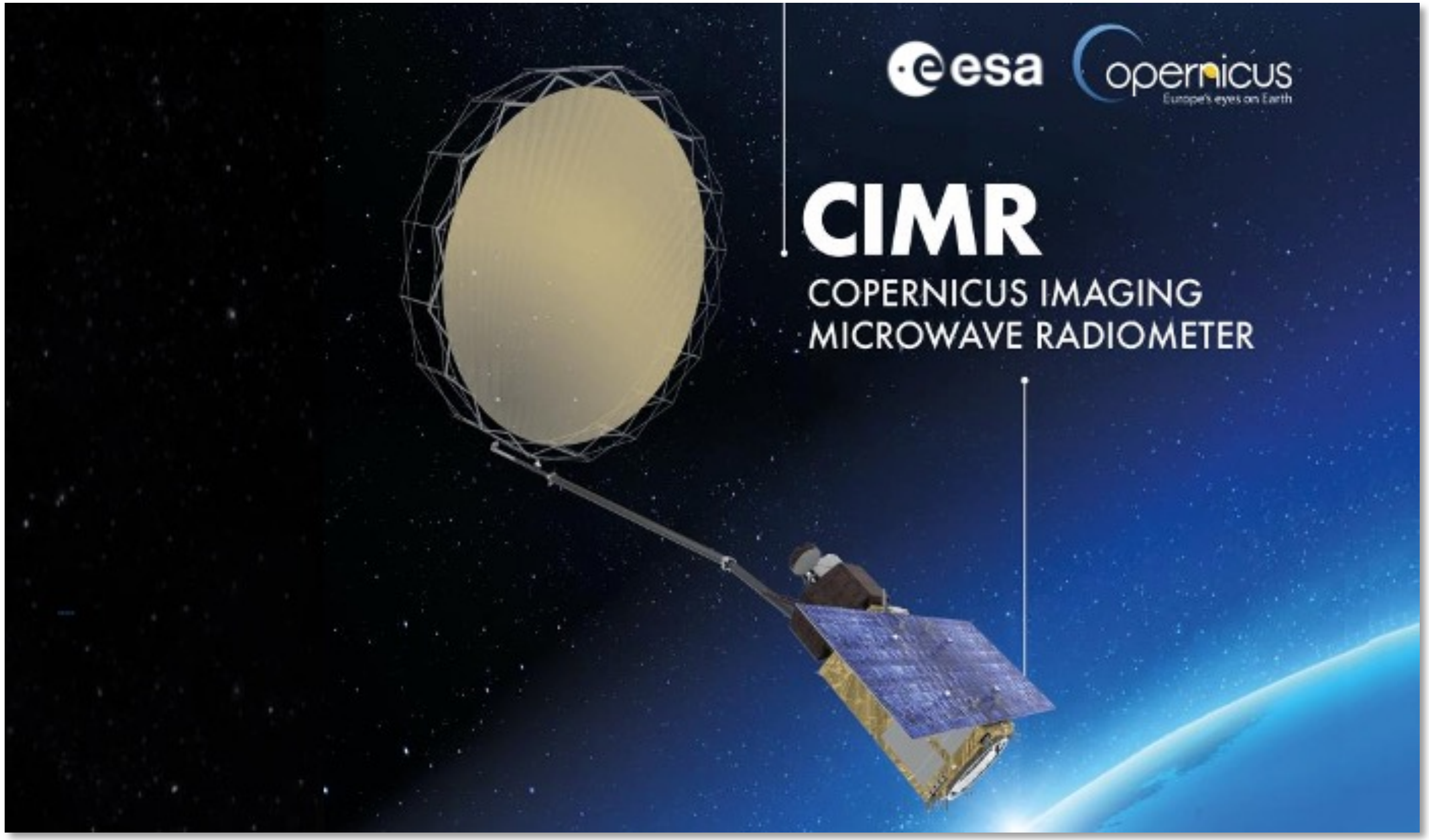
ECMWF Annual Seminar 2021

- → Copernicus Imaging Microwave Radiometer – CIMR
- → Large deployable antenna
- → Will add higher spatial resolution and better radiometric accuracy
- → Adds 1.4 GHz (like SMOS / SMAP) channel: 1.4 – 37 GHz
- → Launch 2027
- → Higher accuracy sea ice concentration
- → More sea ice parameters: thin ice, ice type, ice drift, ice temperature, snow depth
- → Shown here: AMSR2 + SMOS OEM (Scarlat et al., 2020); many more proposed methods: Kilic et al, 2018, 2020; Prigent et al., 2020; Lavergne et al., 2021 and more



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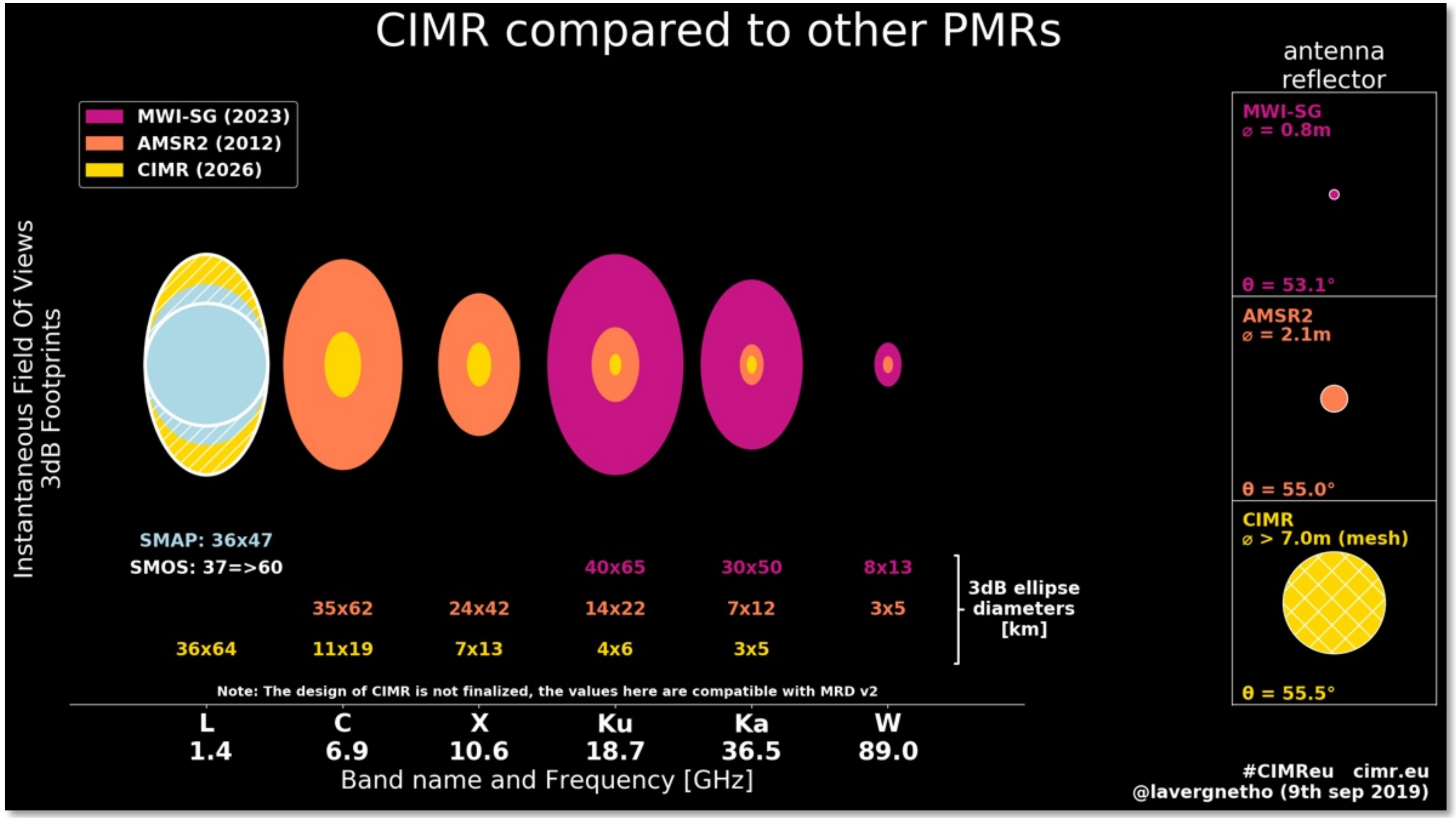

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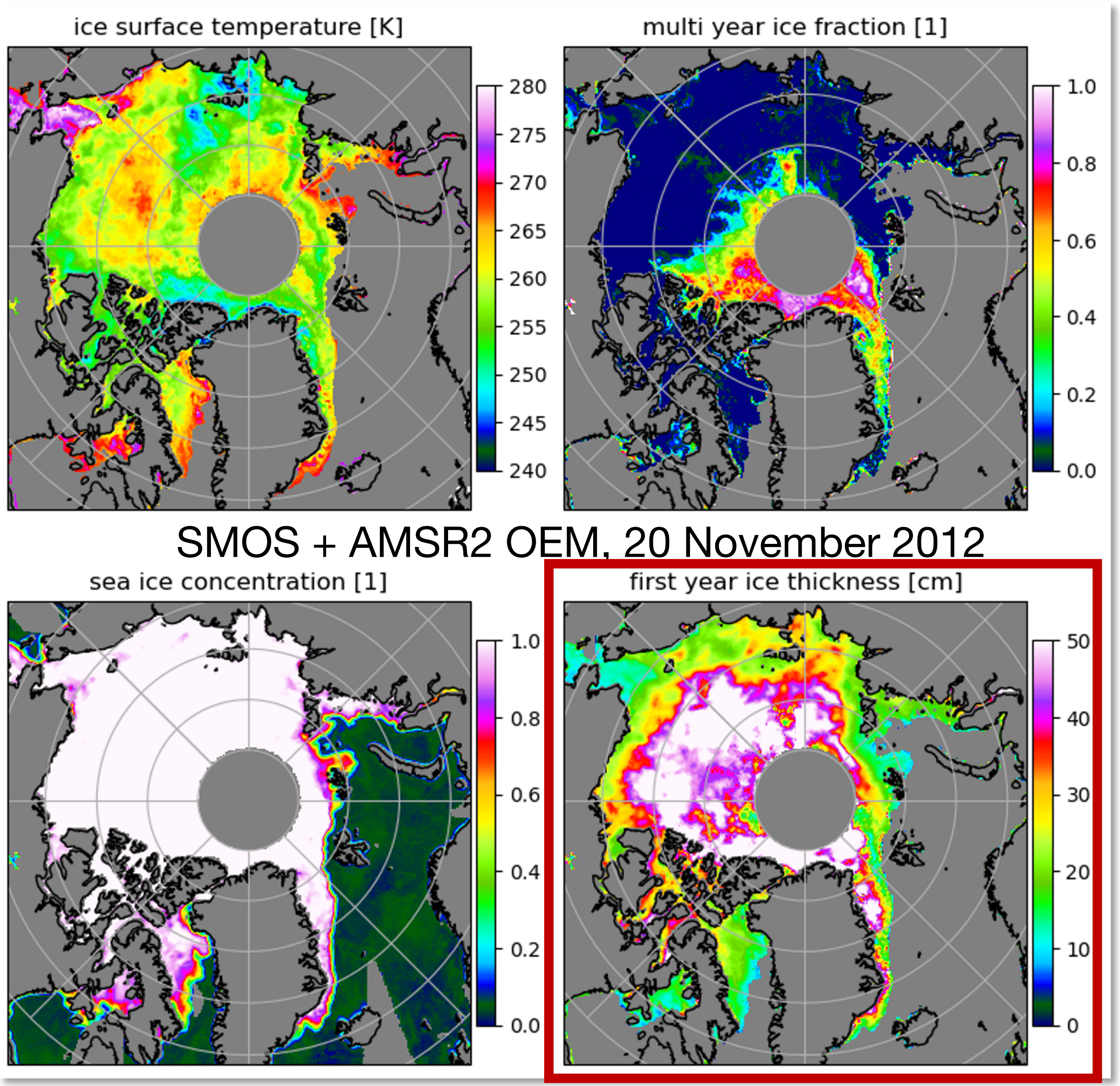

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# Modelling of microwave emission and scattering of sea ice and snow

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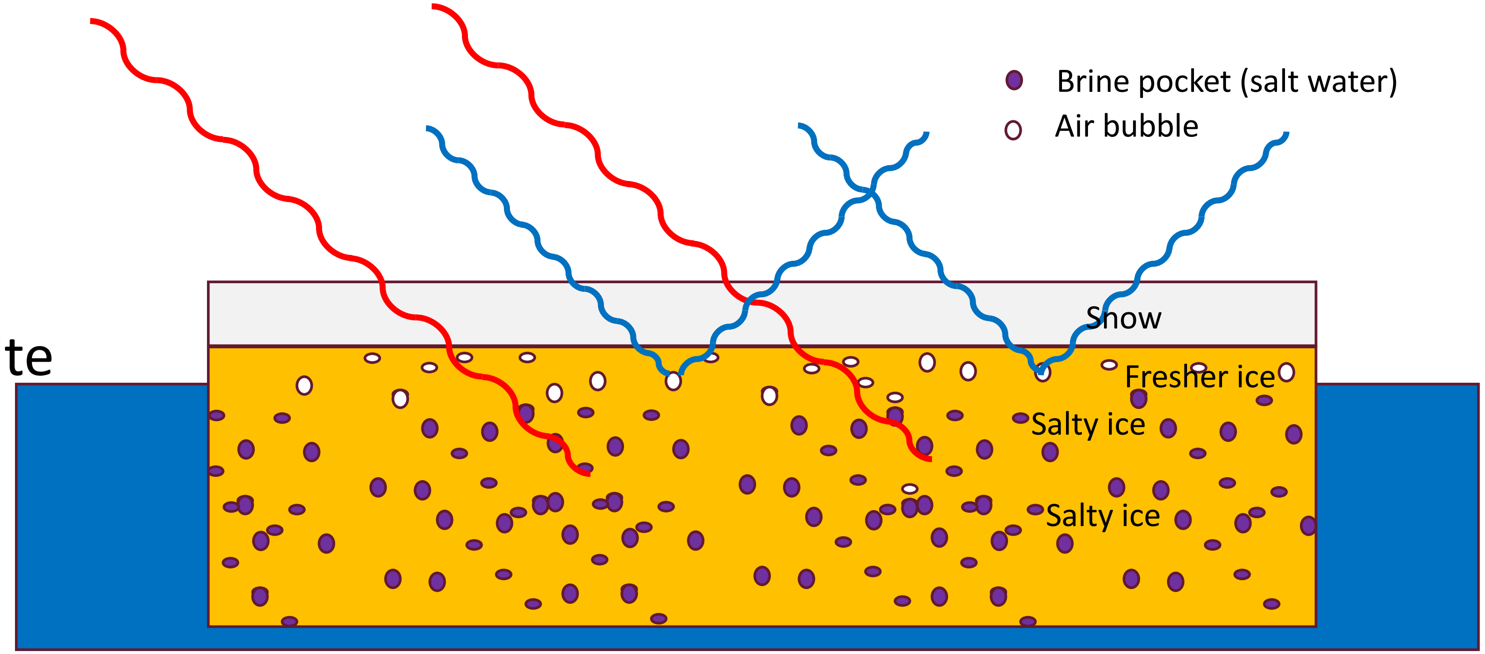
ECMWF Annual Seminar 2021

- Sea ice and snow are complex to model in the microwave domain
- Snow/ice MW models exists (e.g., MEMLS, SMRT) but need many not well constrained input parameters
- In comparison, atmospheric MW forward models are reliable
- However, at frequencies <90 GHz sea ice dominates the brightness temperature measured at the satellite
- For satellite data assimilation in climate/weather models a MW forward operator for sea ice and atmosphere is needed

➢ Field observation needed for development

E.g., Multiyear Ice
- Absorbs almost all incoming radiation at longer wavelengths – nearly a black body (emissivity ~0.9)
- Scatters radiation at shorter wavelengths (<2 cm) – Lower emissivity



# Way forward: Include Sea Ice/Snow Forward Model in Retrieval

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→ MEMLS snow/ice emission model in OEM retrieval

→ Will allow to retrieve properties like snow depth, snow/ice interface temperature

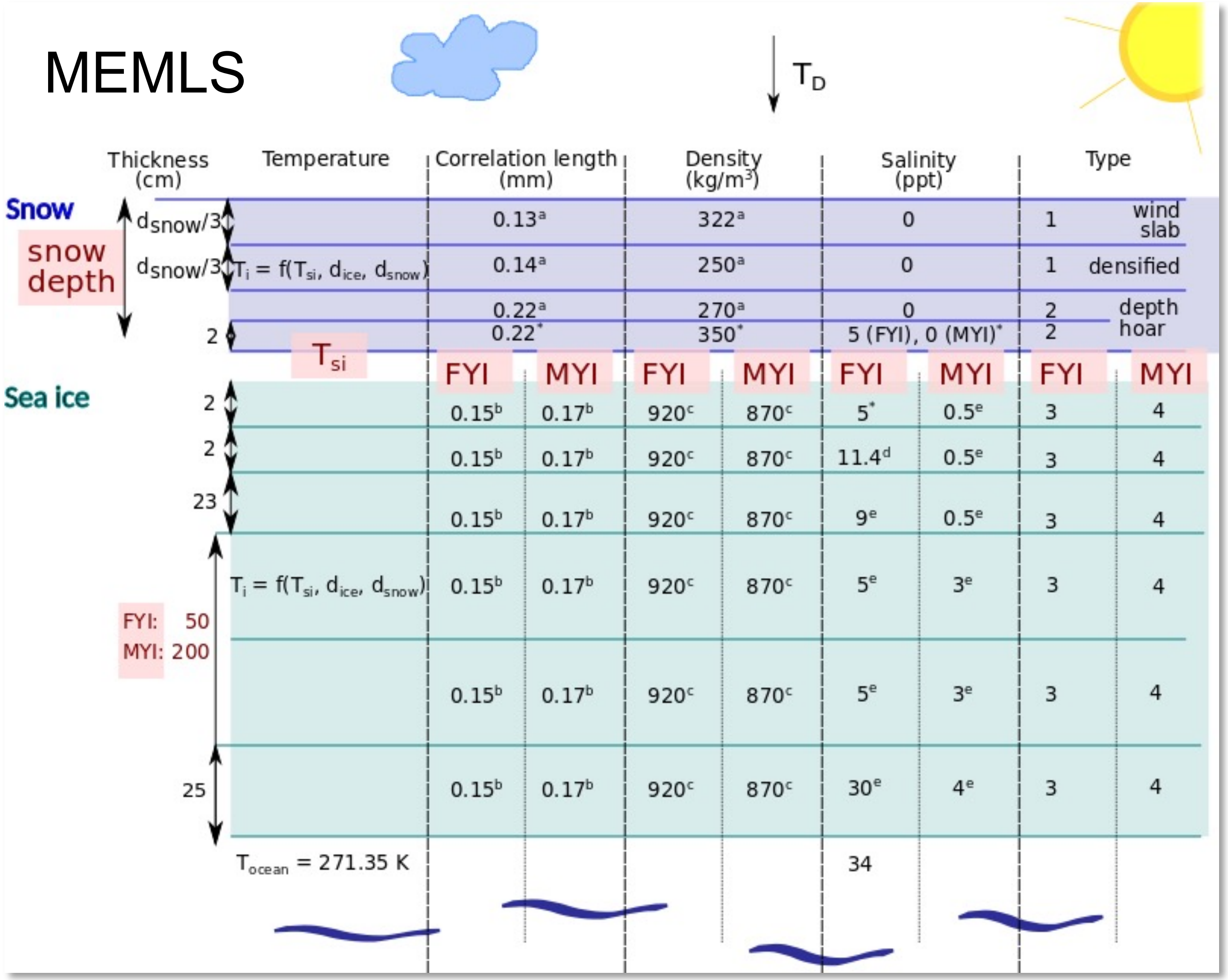
→ Because variability of sea ice emissivity is better represented also other variables like ice concentration, type, cloud liquid water and water vapor should improve

→ Problem: many MEMLS input parameters like snow density, salinity, or correlation length scale are poorly constrained

→ First, preliminary results are promising:

→ Realistic snow depth and temperature distribution

→ Inclusion of MEMLS increases variability of surface brightness temperatures (TB) especially at 89 GHz → more realistic ice TB




Rückert et al., under preparation

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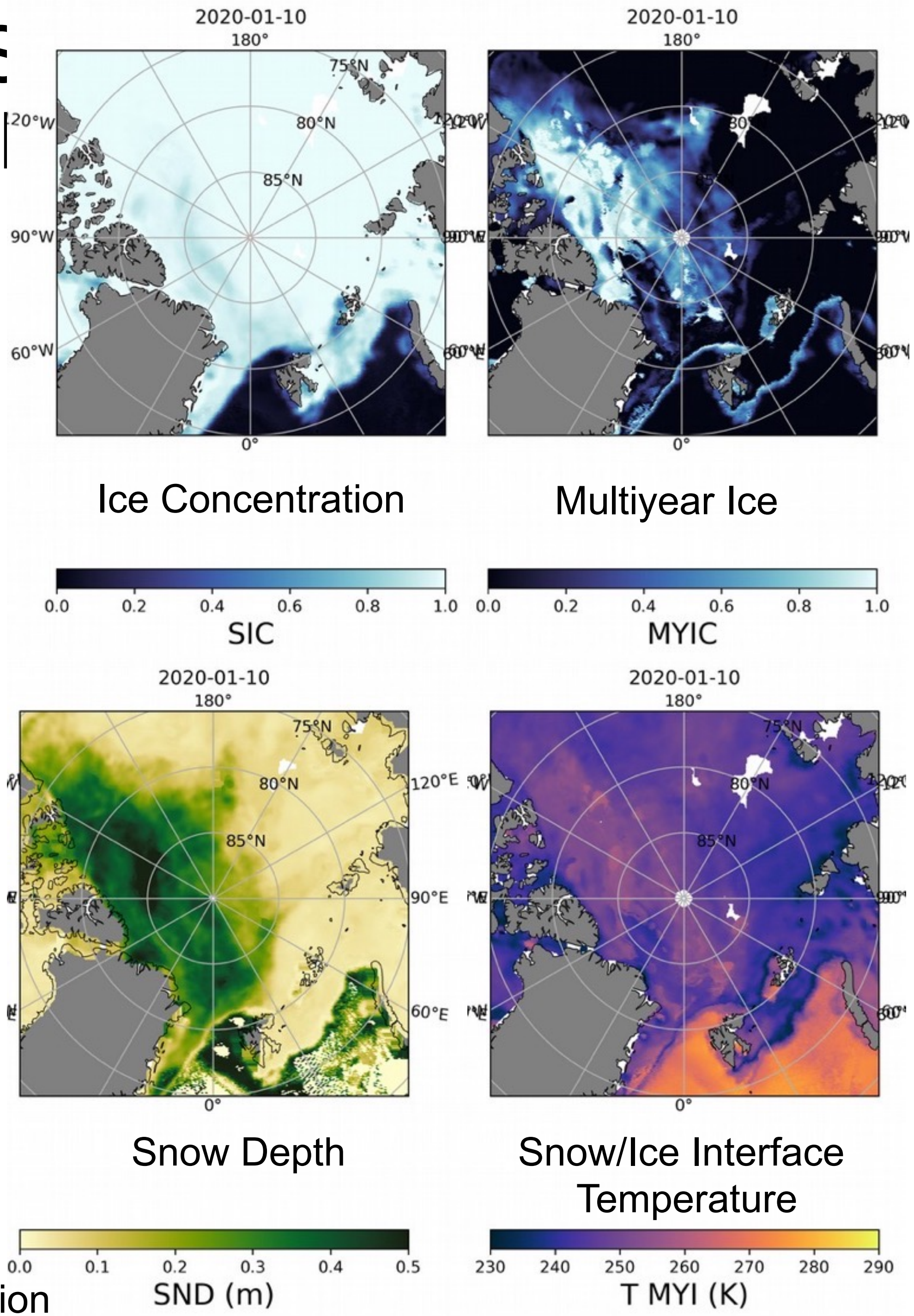


Rückert et al., under preparation

# Way forward: observation operator for model evaluation

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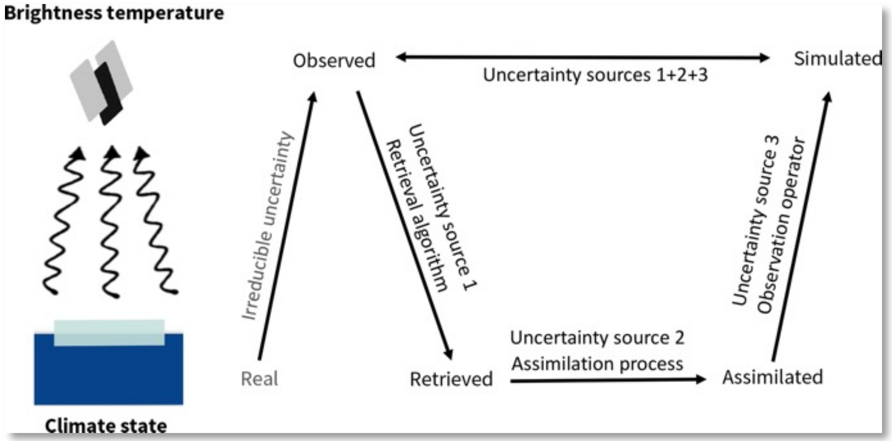
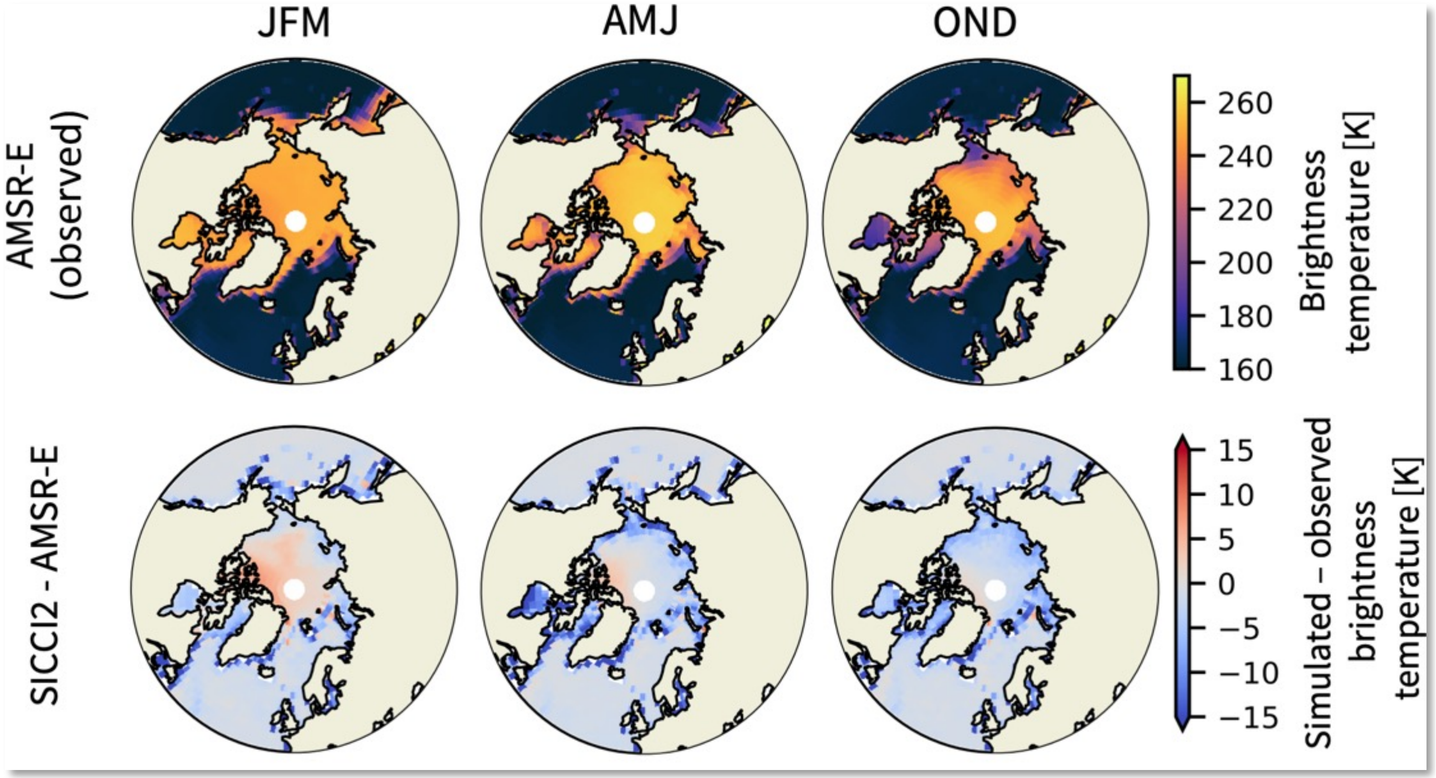
- → Uncertainties in satellite sea ice concentration make model evaluations challenging (Notz, 2014)
- → Better evaluate model directly with measured brightness temperatures (TB)
  ➜ removes influence of satellite retrieval (but introduces uncertainty of observation operator)
- → Model provides consistent sea ice physics
- → Burgard et al., TC, 2020a,b developed a observational operator for 6.9 GHz V
- → Applied to MPI-ESM GCM and compared to AMSR-E
- → Difference between observed (AMSR-E) and modeled TB overall is small (<5 K)
- → Some spatial variability: overestimation for older, thick ice; underestimation in MIZ



# Microwave Radiometer

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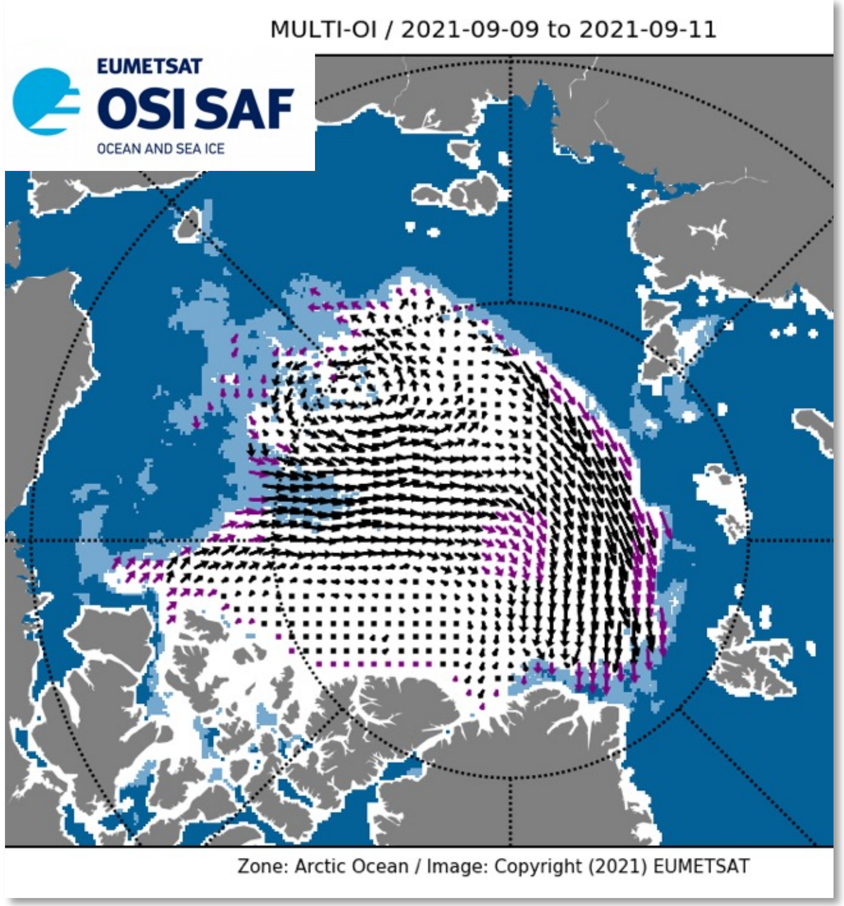
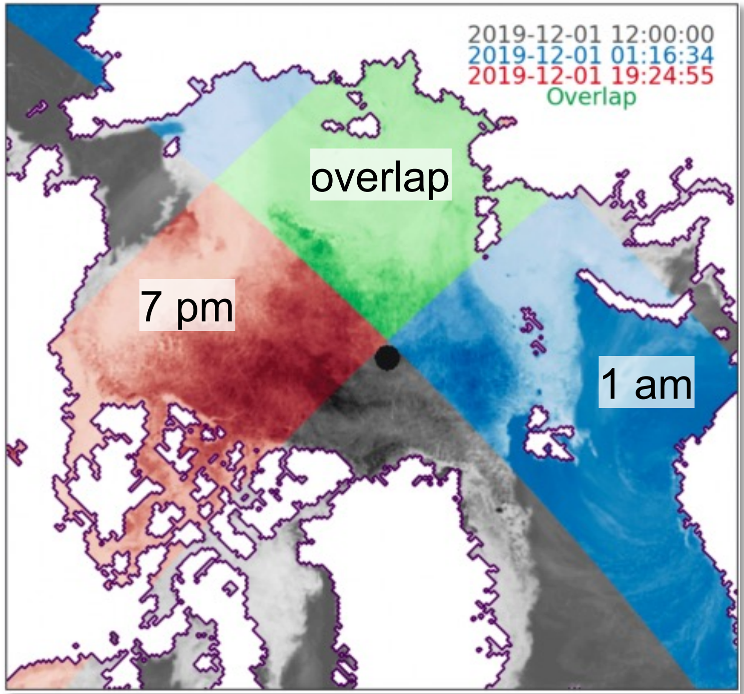
## Sea Ice Drift

→Several datasets (OSISAF, NSIDC, IFREMER …) from SSM/I and AMSR-E/2
→Long time series starting 1979
→Cross-correlation of TB pattern with 1, 2, or 3 days time difference
→ Spatial resolution >50 km




**Recent Developments**

→Swath-to-swath ice drift (Lavergne et al., TC, 2021)

→Demonstrated with AMSR2; in preparation for CIMR

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# Microwave Radiometer

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## Snow Depth

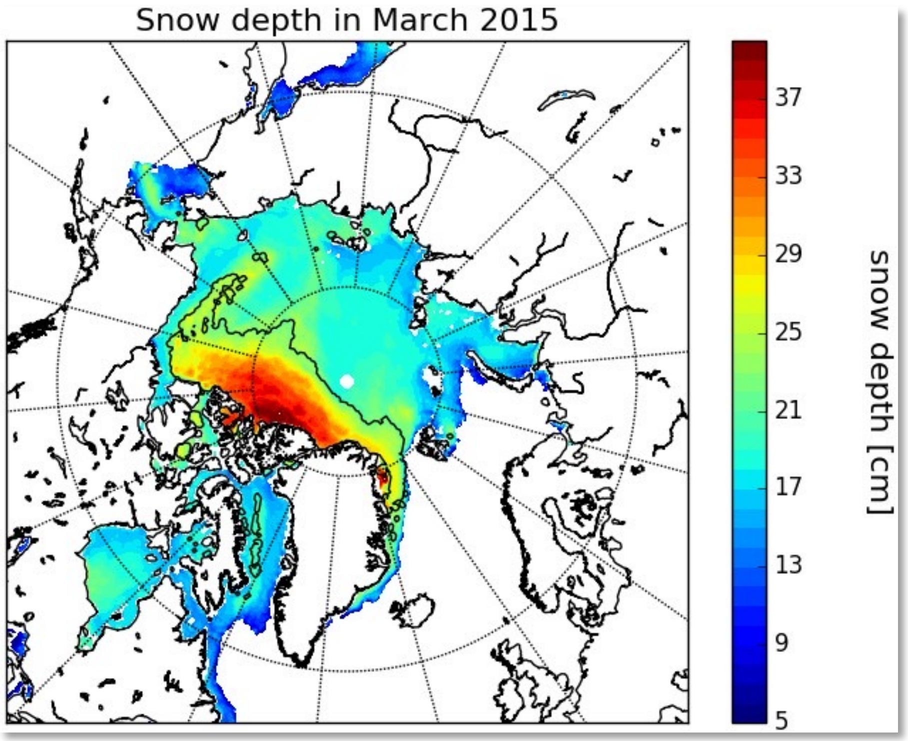
→ Empirical relation for MW volume scattering at different frequencies to snow depth
→ Long time series from SSMI and AMSR-E/2 using 19 and 37 GHz (Marcus & Cavalieri, 1998)
→ Only for first-year ice

**Recent Development**

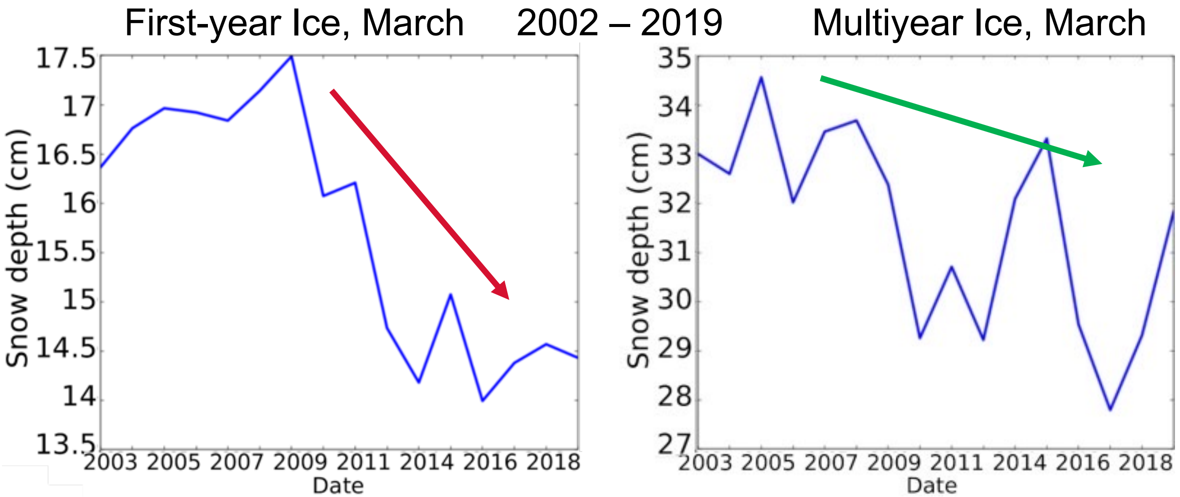
→ Extension to multiyear ice using 7 GHz channels from AMSR-E/2 (Rostosky et al., JGR, 2018)
→ Several new algorithms (Braakmann-Folgmann & Donlon, 2019; Kilic et al., 2019; Liu et al., 2019) mainly exploiting NASA Operation IceBridge airborne data for retrieval training

**Challenges**

→ Variability of ice/snow emissivity depends on other parameters: ice type, salinity, grain size, wetness
→ Missing evaluation and training data for fall




Rostosky et al., 2018, 2019



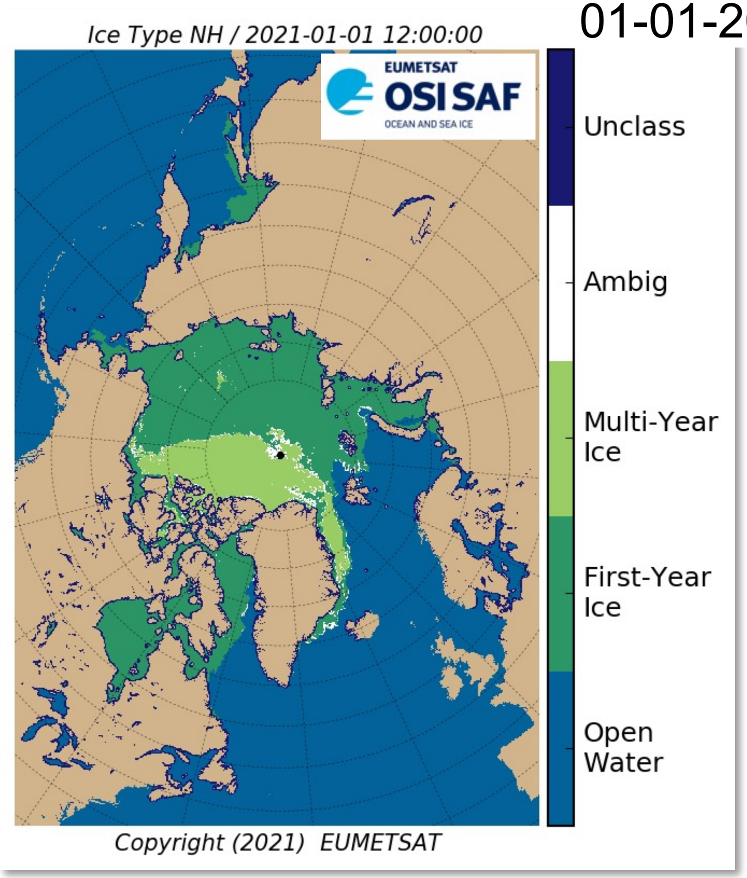
# Microwave Radiometer

## Ice Type

→ Retrieval of multiyear ice fraction
→ Long time series (since 1979) using microwave radiometer only (SSMI, AMSR; NASA-team algorithm, Cavalieri et al.)
→ Scatterometer only timeseries from QuikSCAT since 1999 (Kwok et al., Haarpaintner et al.)

**Recent Development**

→ Combining radiometer and scatterometer data
→ Sea ice type mask (OSISAF) or concentration (Yu et al., 2016; seaice.uni-bremen.de)

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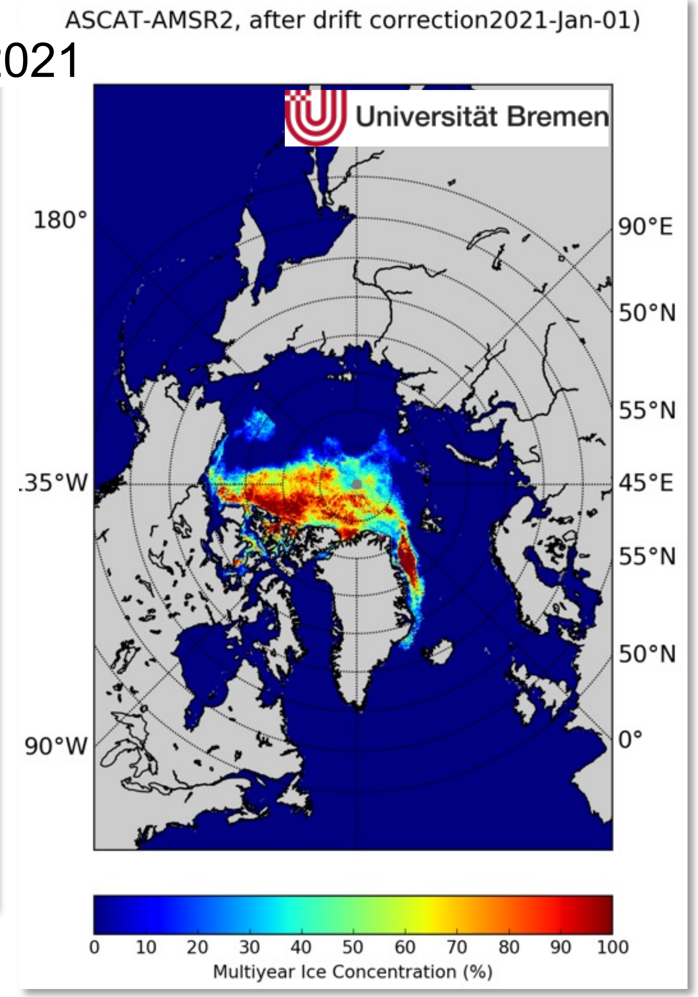



**Challenges**

→ Ambiguities for deformed, rough ice in the marginal ice zone
→ High surface roughness (deformation, pancake ice) has similar MW signature as multiyear-ice

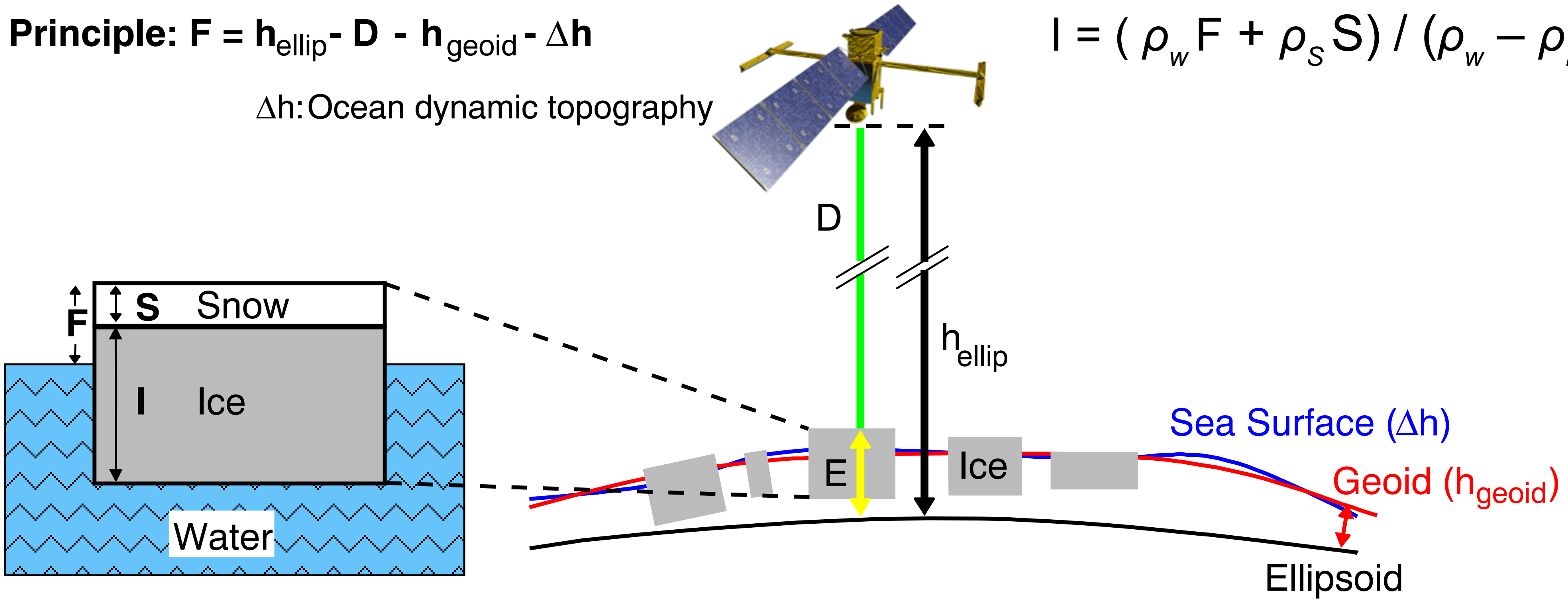
# Altimeter: Sea ice Thickness

- Measure distance to ice (radar) or snow (laser) surface + SSH → freeboard
- Conversion to ice thickness under assumption of hydrostatic balance

**Principle:** $F = h_{ellip} - D - h_{geoid} - \Delta h$

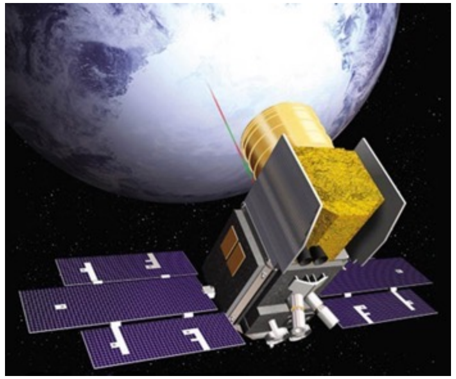
$\Delta h$: Ocean dynamic topography

$$I = (\rho_w F + \rho_S S) / (\rho_w - \rho_I)$$



# Polar Altimeters (past and present)

ICESat

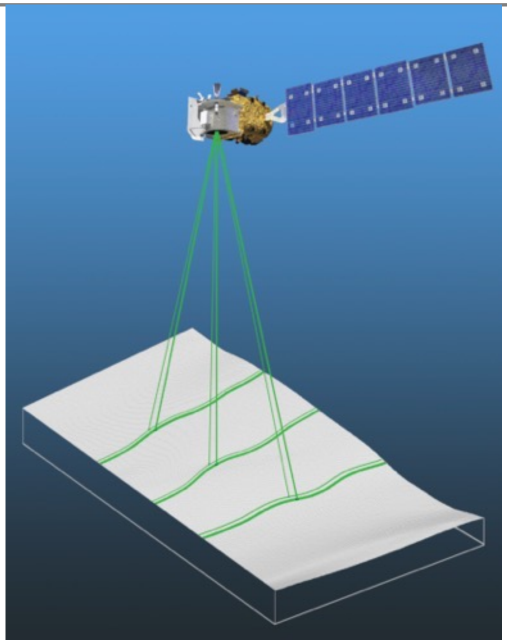


- Laser altimeter
- Two frequencies:
  - infrared 1064 nm
  - green 532 nm
- Launch: Jan. 2003
- Mission end: Oct. 2009
- 94° inclination
- Lasers decayed faster than expected
- 2–3 about one month long measurement periods per year

CryoSat-2

- Radar altimeter
- Ku-band (13.6 GHz)
- Launch April 2010
- 92° inclination
- First Synthetic Aperture Interferometric Radar Altimeter (SIRAL)

ICESat-2



- Laser altimeter
- 6 beams (3 pairs)
- Photon-counting lidar
- Launch September 2018
- 92° inclination
- 13 m footprint

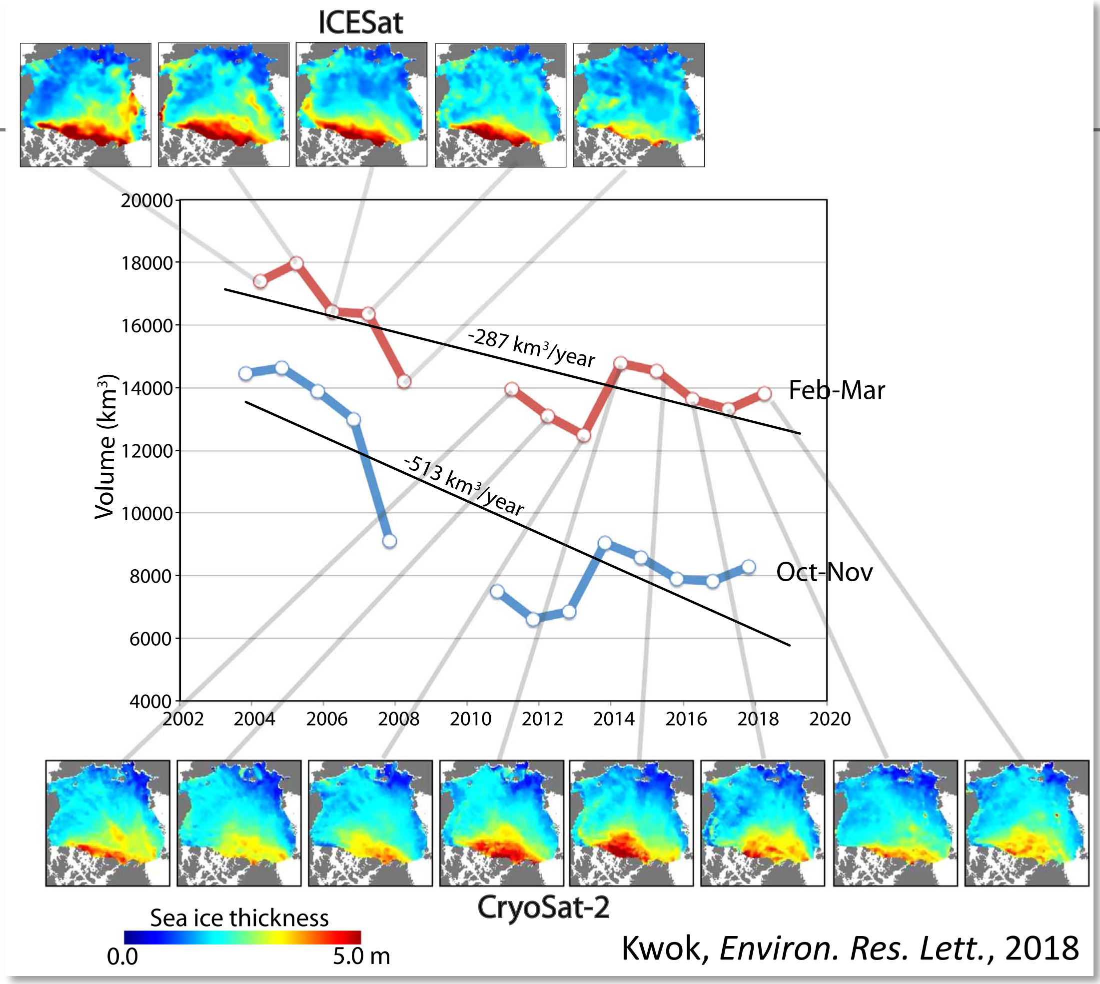
# Upcoming: CRISTAL

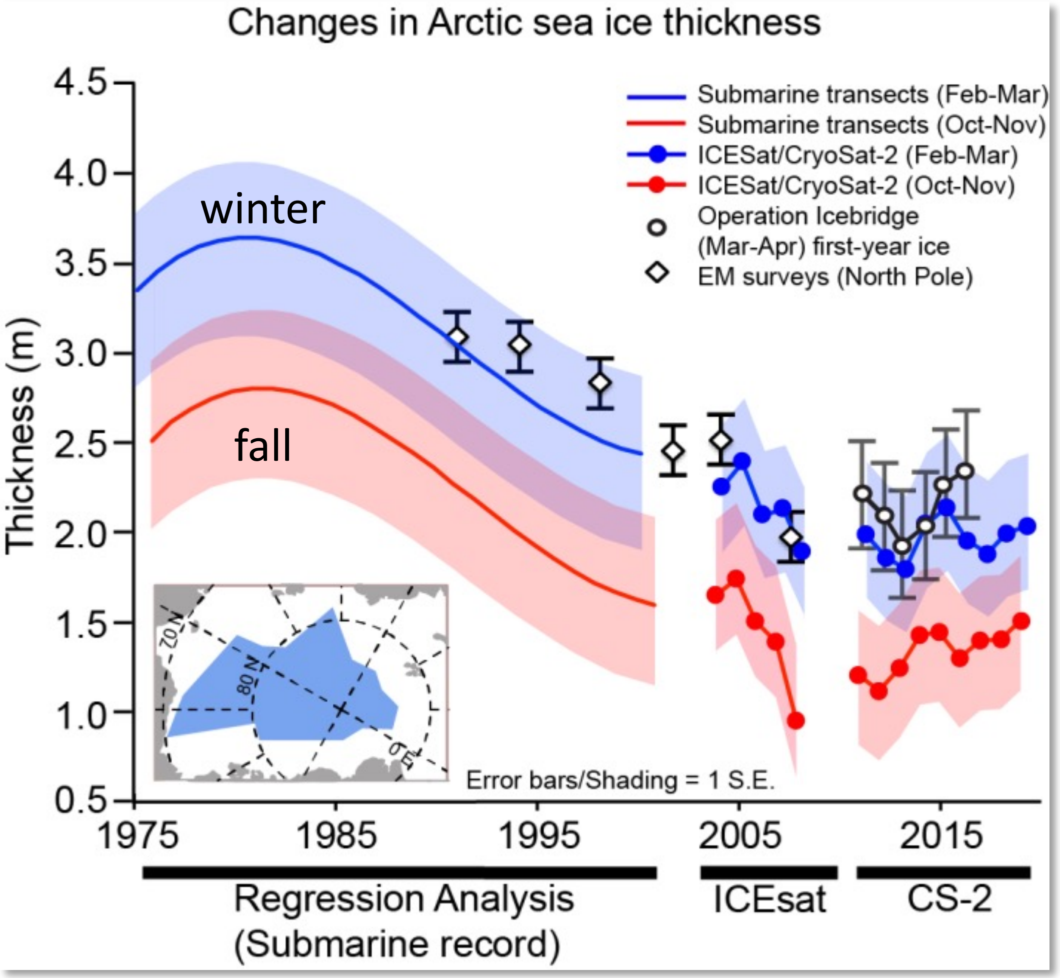
## Copernicus Polar Ice and Snow Topographic Altimeter

→Dual-frequency (Ku & Ka) radar altimeter
→Continuation of CryoSat-2 mission
→Two frequencies: Snow depth in addition to ice thickness
→Launch 2027

opernicus Europe's eyes on Earth
esa
AIRBUS

# Altimetry Example: ICESat + CryoSat-2



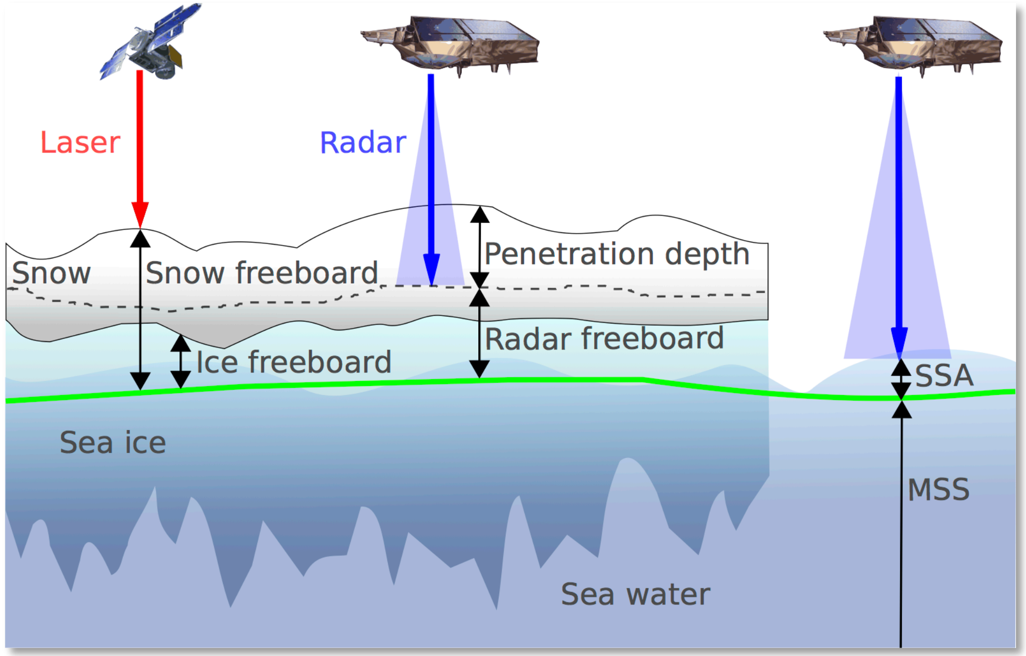




IPCC AR 6, 2021

- Combined ICESat (laser) and CryoSat-2 (radar) time series → thickness decrease
  - ➢ How Consistent are the ICESat and CryoSat record? Envisat can help.
- Combined with submarine record: strong decrease in ice thickness for 1976–2019.
- Recent years, however, show strong variability and no decreasing trend.

# Freeboard to Thickness Conversion

- Convert freeboard to thickness: assume hydrostatic balance
- Different for laser and radar altimeters:




**Laser:** $$I = F_S \frac{\rho_W}{\rho_W - \rho_I} + S \frac{\rho_S - \rho_W}{\rho_W - \rho_I}$$

**Radar:** $$I = F_R \frac{\rho_W}{\rho_W - \rho_I} + S \frac{\rho_S}{\rho_W - \rho_I}$$

- Snow depth $S$, and ice, snow, and water densities $\rho$ need to be known
- The snow loading and ice densities are large error sources
- For radar altimetry also the snow penetration depth is a large error source


- Giles et al., 2007, Rem. Sens. Env.
- Ricker et al., 2014, Cryosphere

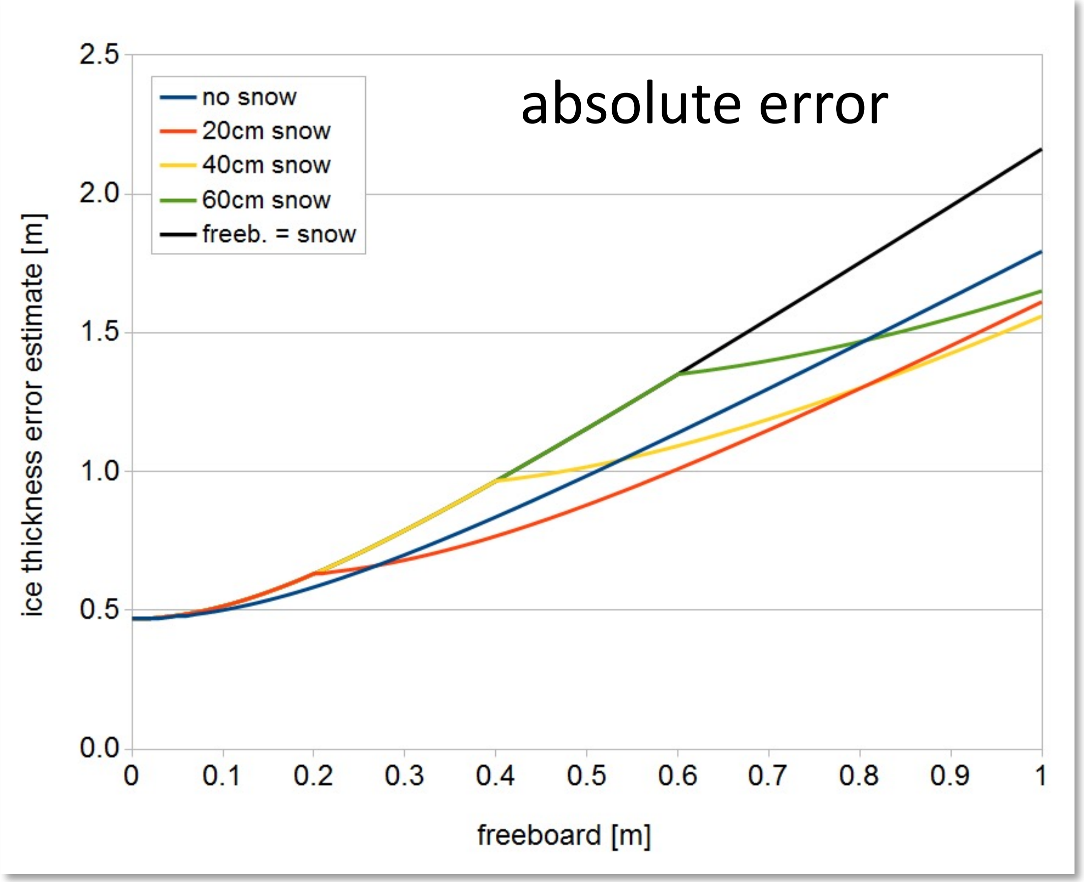
# Altimetry: Geophysical Uncertainties

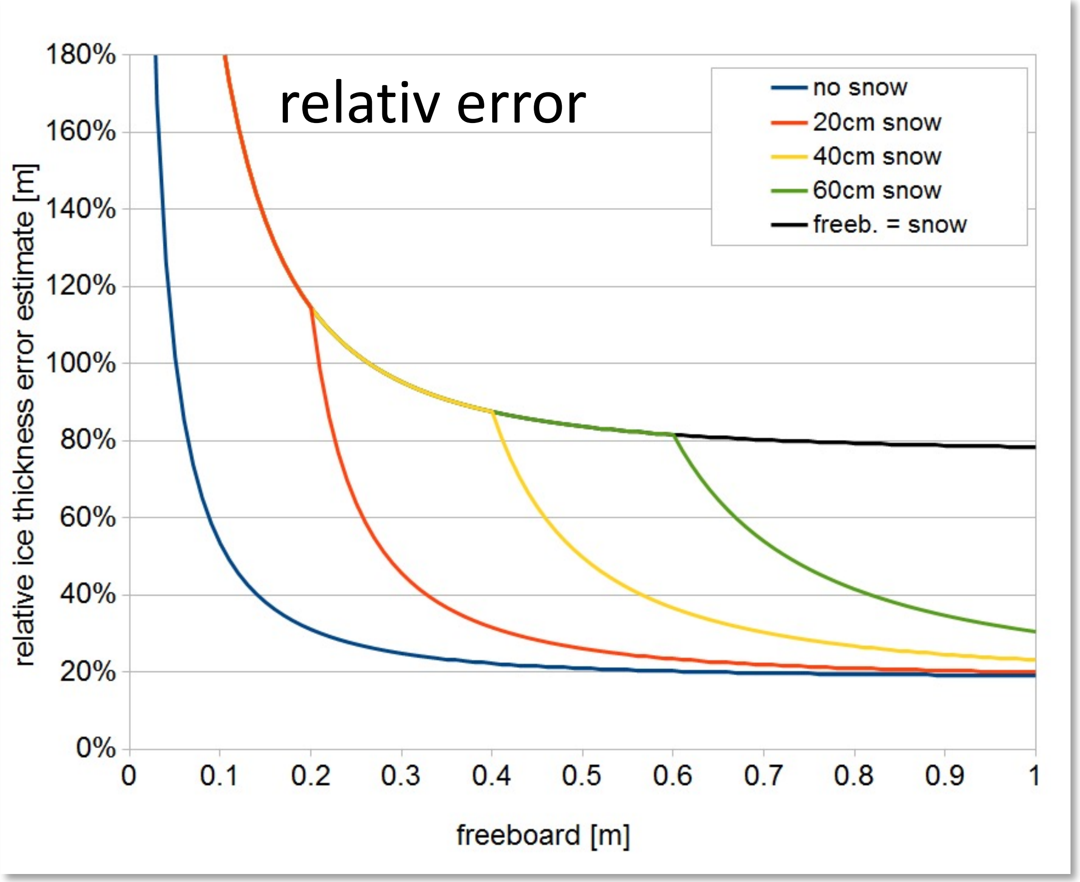
- Snow depth
  - Warren climatology. Outdated? No interannual variability.
  - Microwave radiometer snow depth. Uncertainties? SMOS snow depth?
  - Accumulation and advection of precipitation from atmospheric reanalysis. Quality?
- Ice and snow densities
  - Different depending on age and ice type.
  - Melt-refreeze layers. Flooding.
- Salinity in snow → changes radar penetration depth (~5–15 cm)
- Radar penetration into snow
  - What is the main scattering horizon? Ice surface, snow surface, where inbetween?
  - Sensitivity of different retrackers to snow penetration "problem"?

➢ These questions can only be answered by regular field and airborne surveys!

- Other uncertainties: retracker, SSH identification, sampling (for monthly grids)

# Uncertainty Estimation Example for ICESat

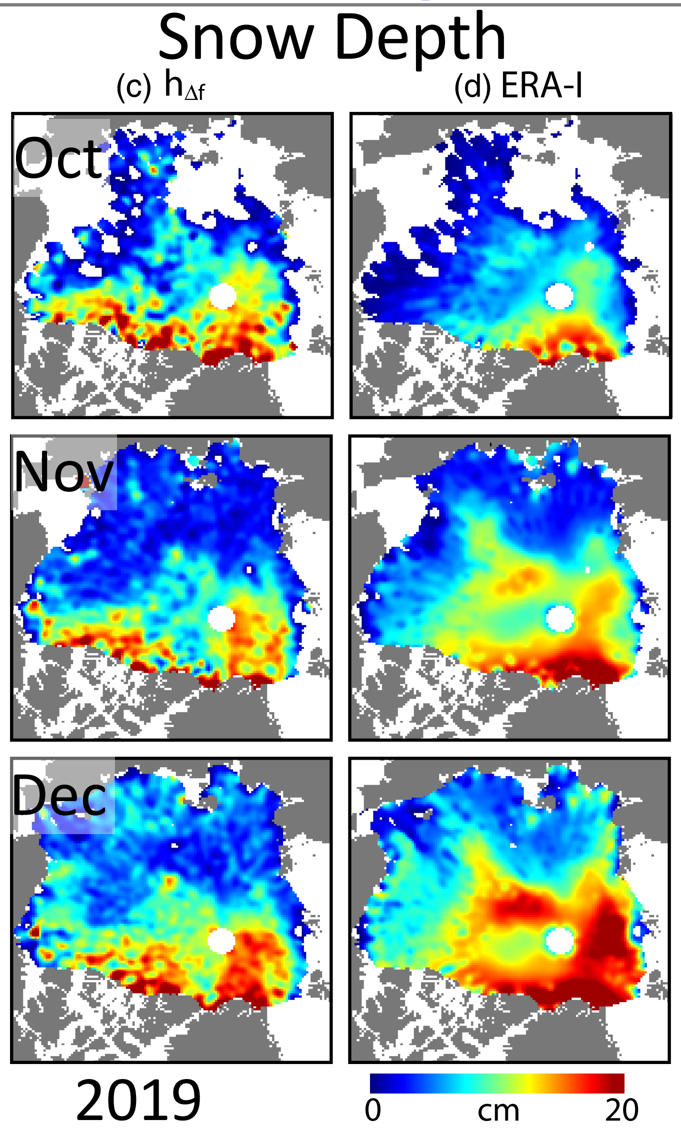



Kern and Spreen, Ann. Glaciol., 2015

- ICESat error estimation using Gaussian error propagation for
  - 5 cm ice freeboard uncertainty
  - 30% snow depth uncertainty
  - $\rho_S$ = 300 $\pm$ 50 kg/m$^3$; $\rho_I$ = 915.1 $\pm$ 20 kg/m$^3$

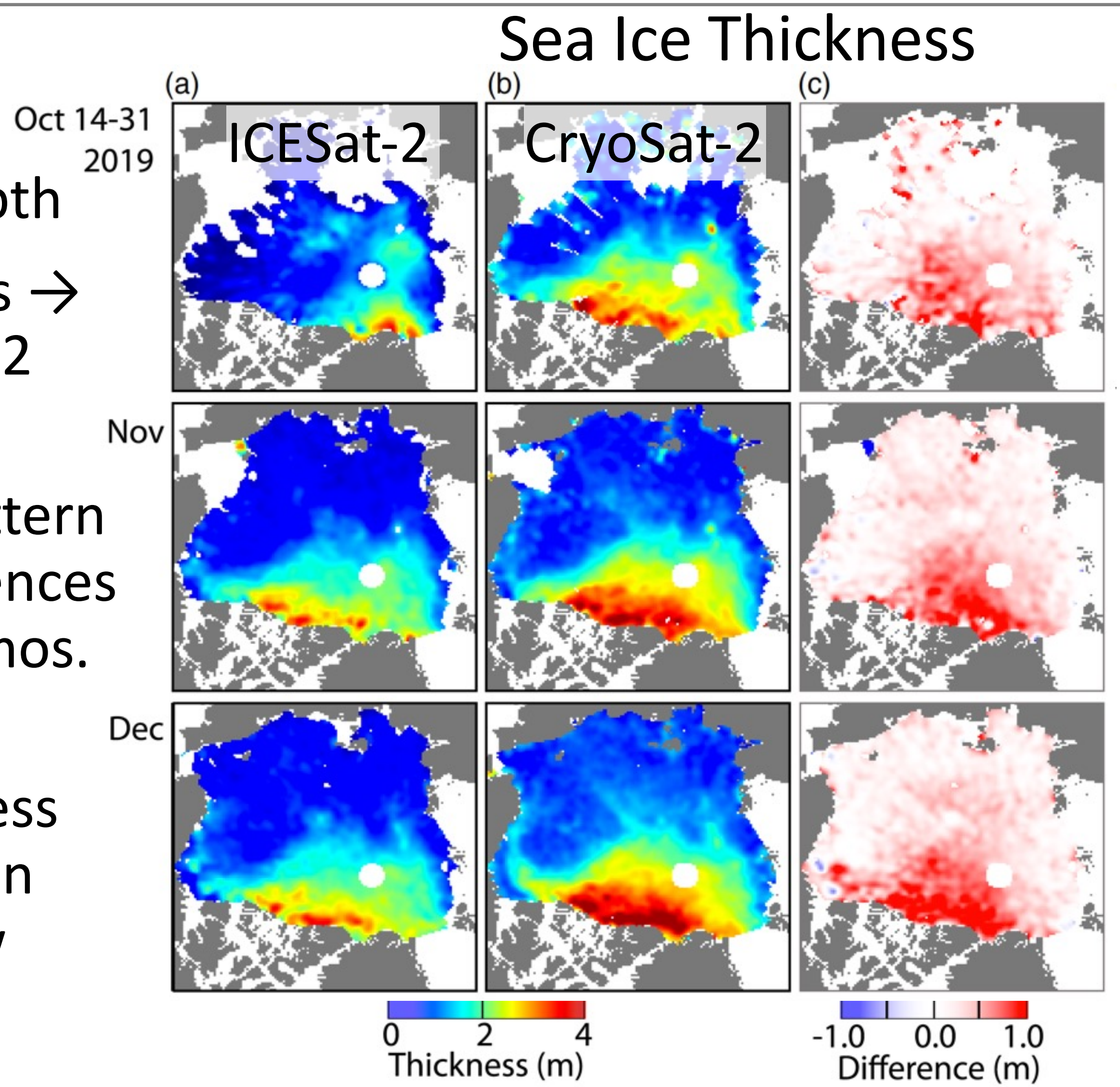
# ICESat-2 first results (with CryoSat-2)




← Snow depth

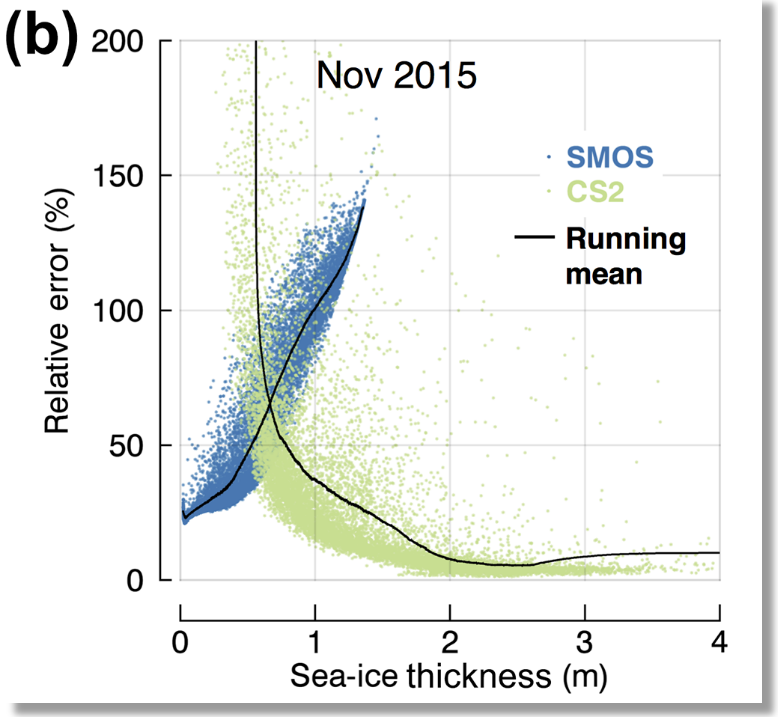
Ice thickness → from ICESat-2

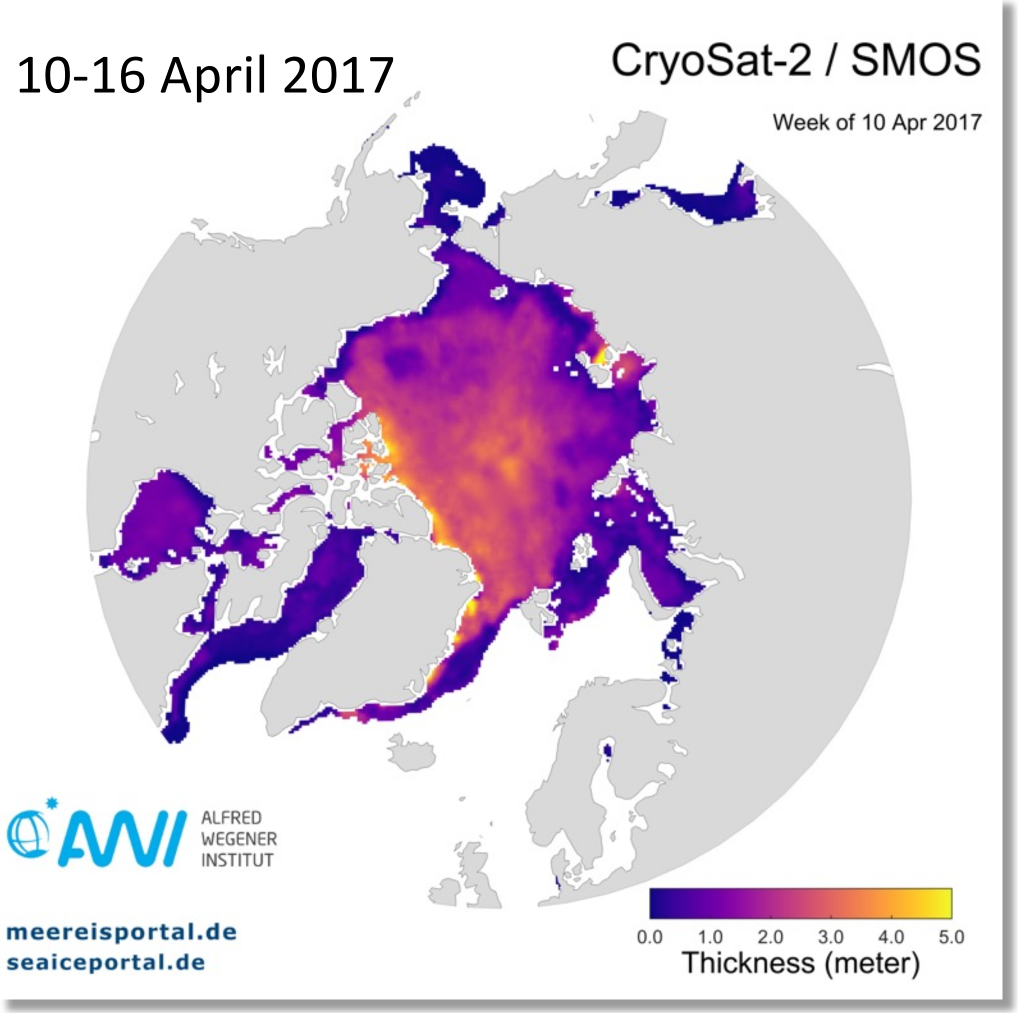
- Snow with similar pattern but differences to ERA atmos. reanalysis
- Ice thickness depends on used snow dataset




- Kwok et al. (2020): Arctic Snow Depth and Sea Ice Thickness From ICESat-2 and CryoSat-2 Freeboards: A First Examination. *JGR-Oceans.*

# Merged Ice Thickness – CryoSat + SMOS



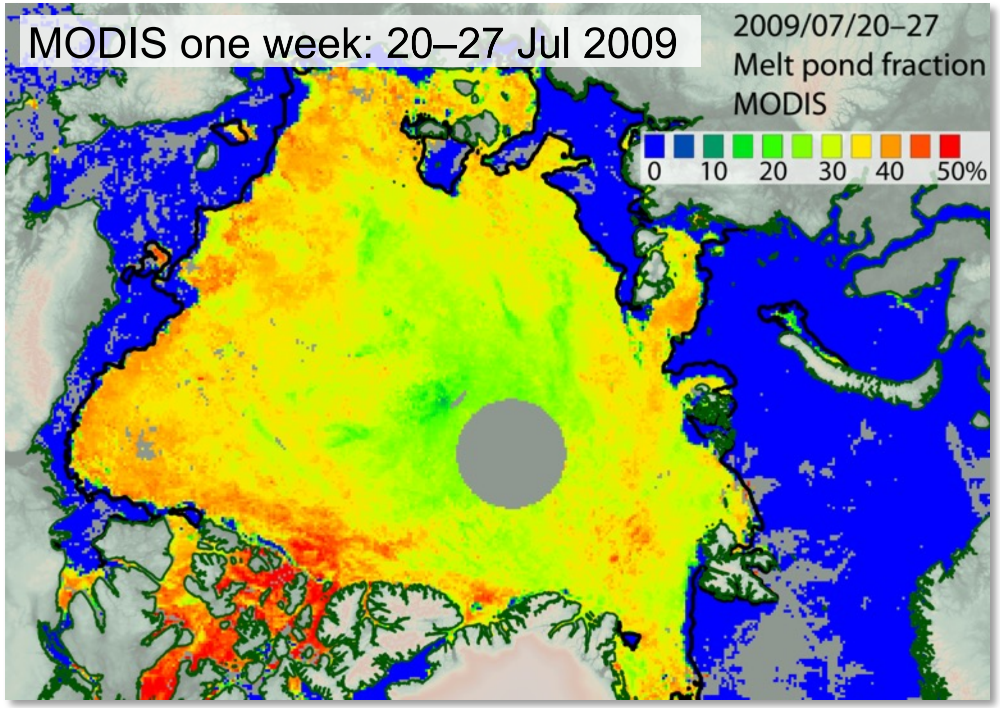




- CryoSat and SMOS have a complementary error behavior:
  – CryoSat: lower uncertainties for thick ice
  – SMOS: lower uncertainties for thin ice
- SMOS daily coverage + sparse CryoSat tracks → weekly merged ice thickness

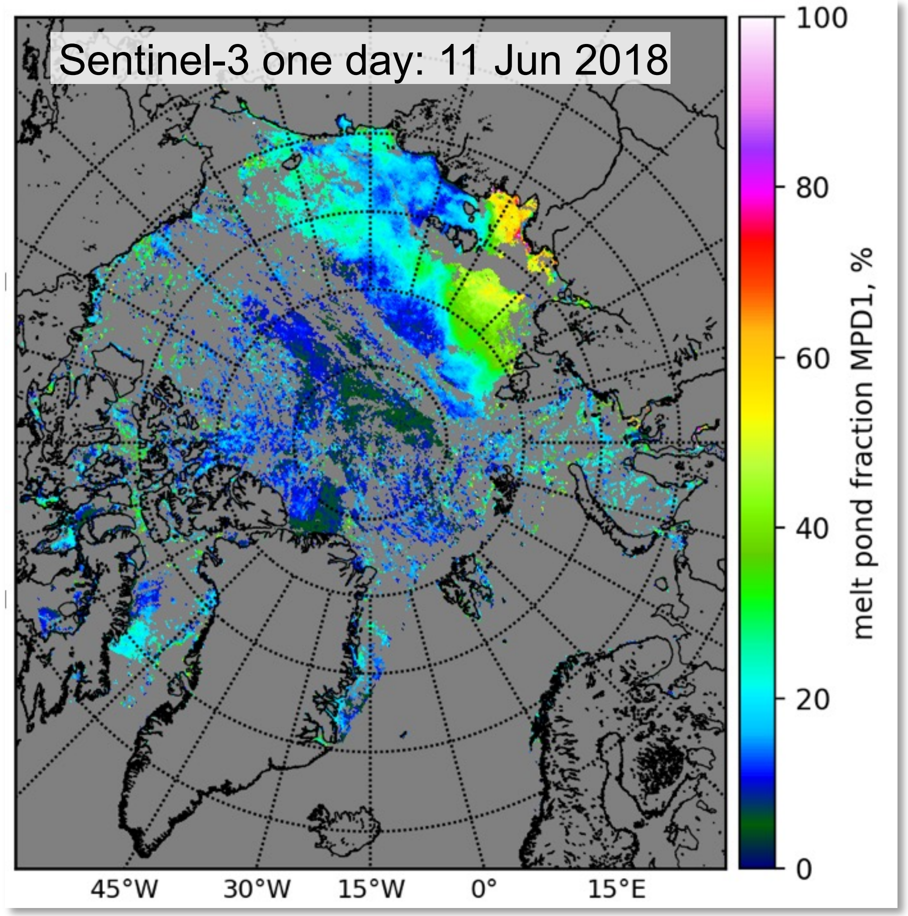
- Ricker et al., 2017, Cryosphere
- data.meereisportal.de

# Optical Data: Melt Pond Fraction (and Albedo)

- 2000–2011: MODIS (Rösel et al., 2012) and MERIS (Istomina et al., 2015) data
- New development 2017 – today: from Sentinel-3 OLCI data



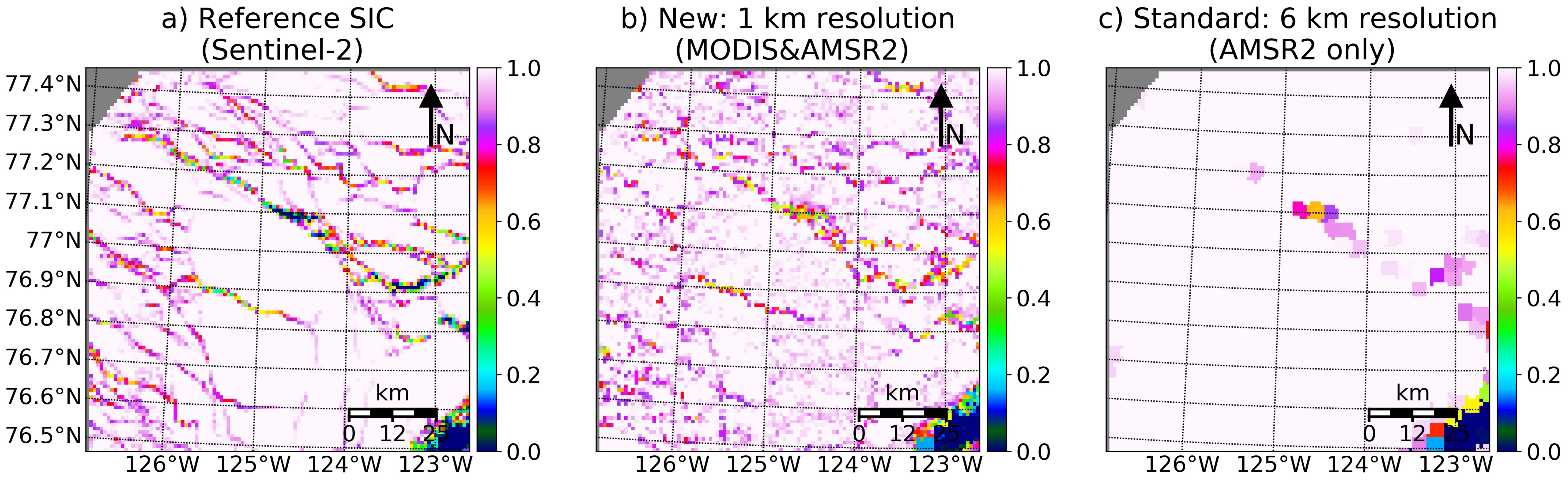

MODIS data (Rösel et al.) from ICDC (www.cen.uni-hamburg.de/icdc.html)




Daily Sentinel-3 data from seaice.uni-bremen.de

# Optical data: Merged MODIS or VIIRS with AMSR2 sea ice concentration at 1–km

- MODIS + AMSR2, winter: Ludwig et al., TC, 2019 & Rem. Sens., 2020
- VIIRS + AMSR2, all seasons: Dworak et al., Rem. Sens., 2021
- MODIS/AMSR2 winter time data available (Oct-May) 2019 – 2021




22 May 2019

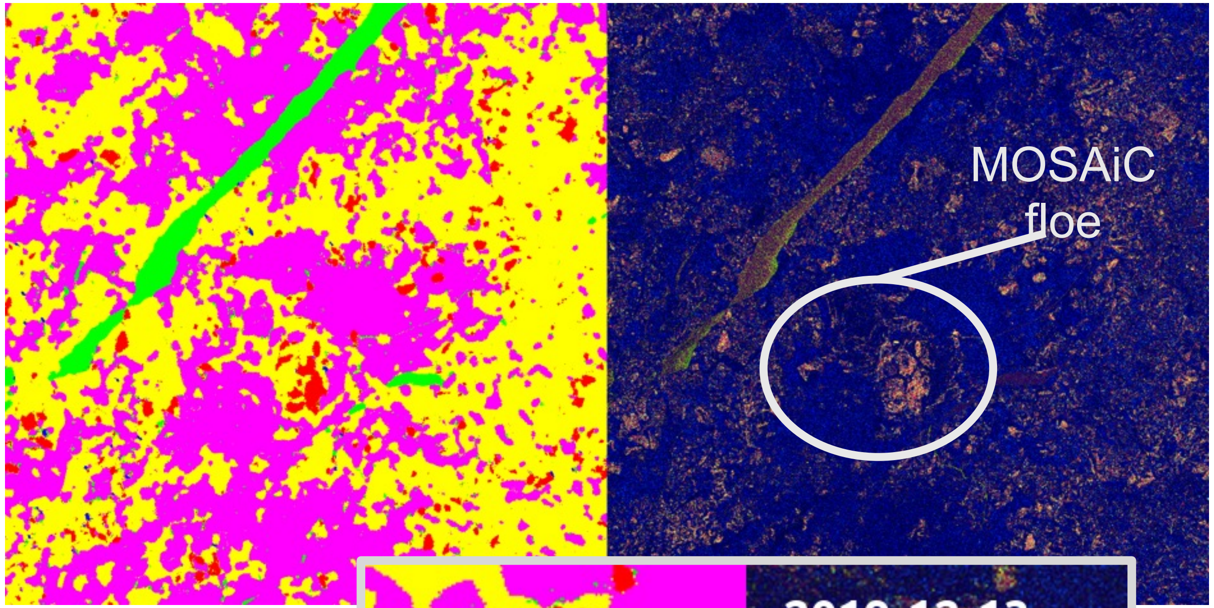
www.seaice.uni-bremen.de

# Ice Type From SAR

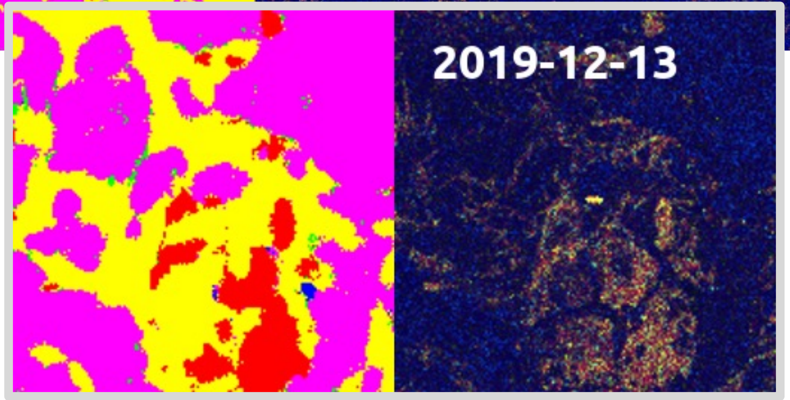


Gunnar Spreen
ECMWF Annual Seminar 2021

- SAR data is now available on an almost pan-Arctic daily scale: Sentinel-1a,b; Radarsat Constellation Mission
- Several automatic SAR ice type classification methods currently developed; here only one example for MOSAiC
- Future development: more frequencies, especially L-band (e.g. ALOS, SAOCOM, ROSE-L) ➜ better classification

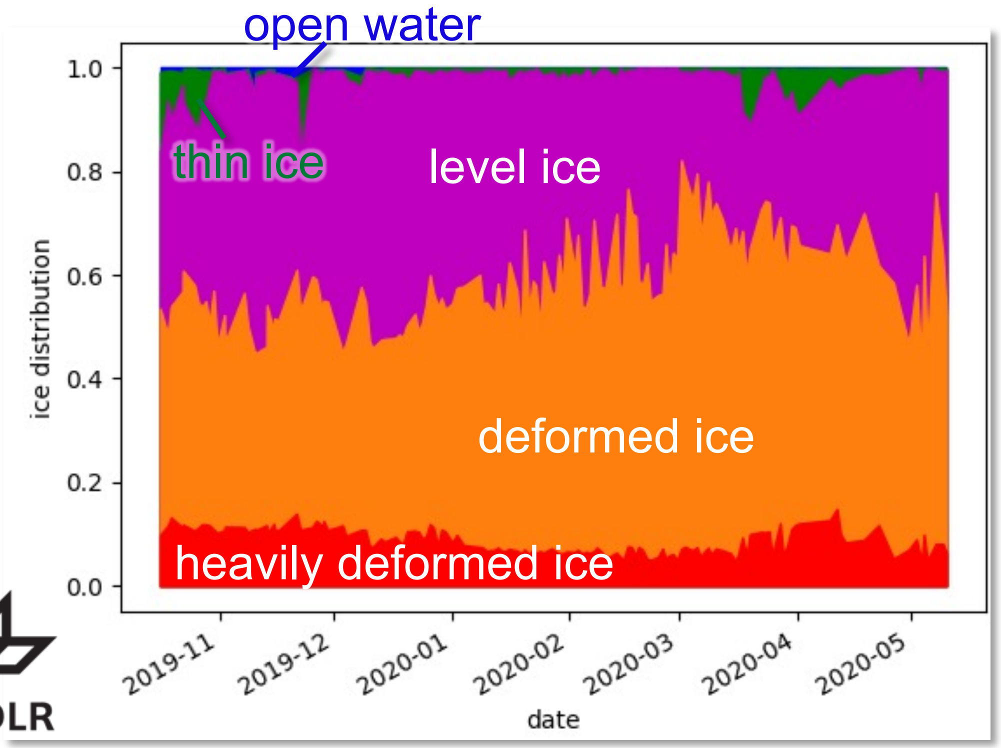



Zoom to floe




Kortum et al., TGRS, submitted

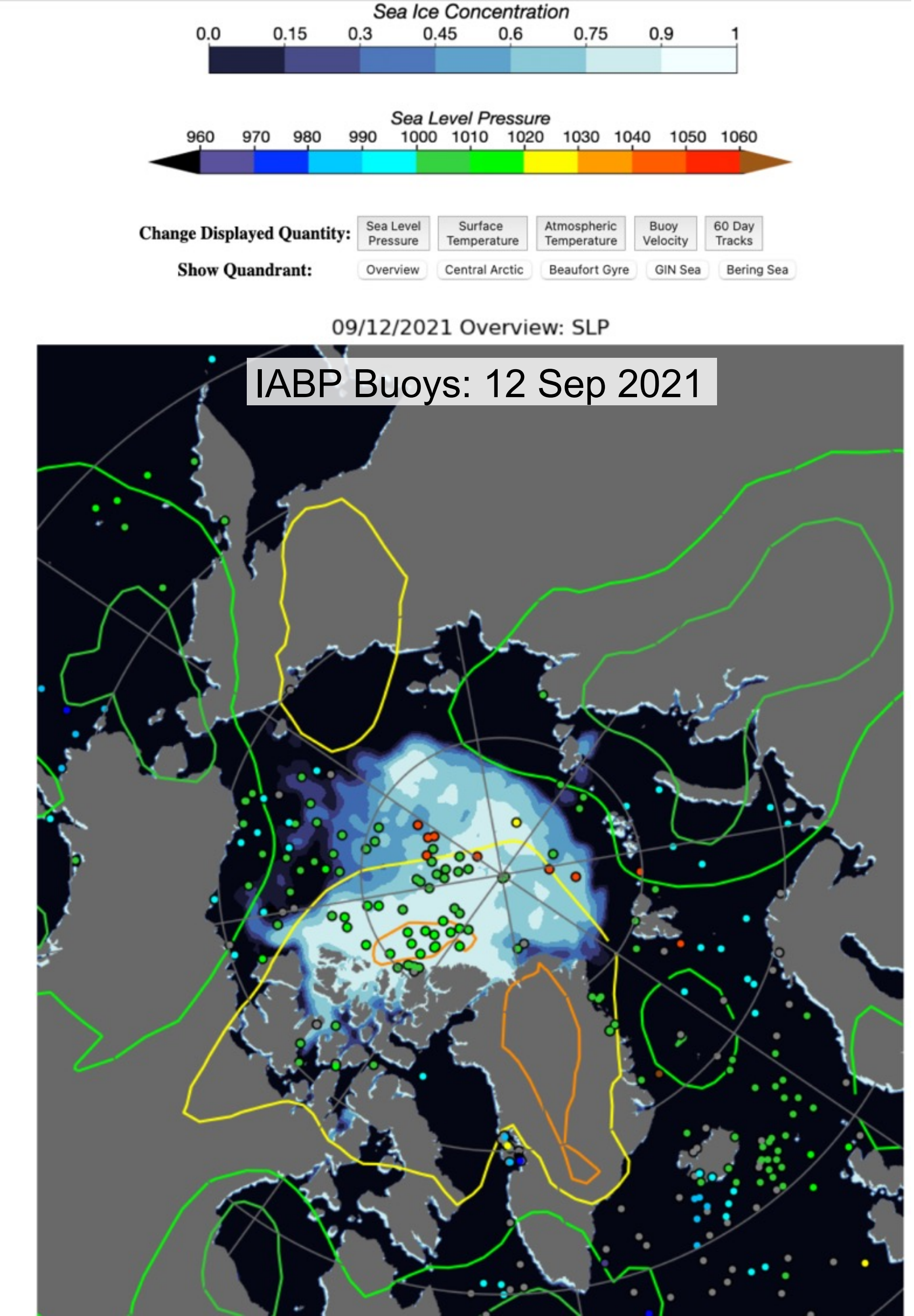
→ Daily TerraSAR-X data provided by DLR
→ Regional distribution of ice types can be monitored throughout the year




Time series of ice types during MOSAiC drift

# Field Observations: Autonomous Buoys

- The number of autonomous measurement platforms deployed on sea ice is increasing
- Traditionally mainly ice drift, surface pressure and temperature
- More parameters added: ice and snow thickness, temperature profiles, near surface oceanography

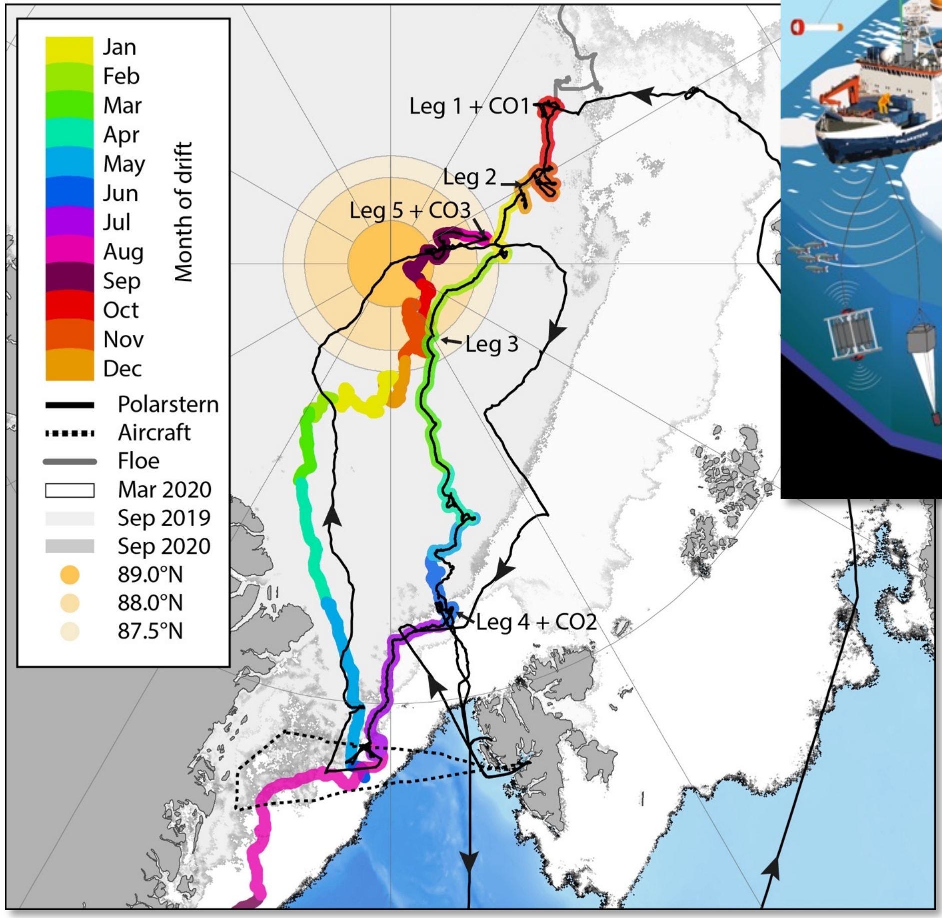



International Arctic Buoy Programme (IABP)
https://iabp.apl.uw.edu

MOSAiC International Arctic Drift Expedition

# Field Observations: Ship Expeditions

## MOSAiC – International Arctic Drift Expedition

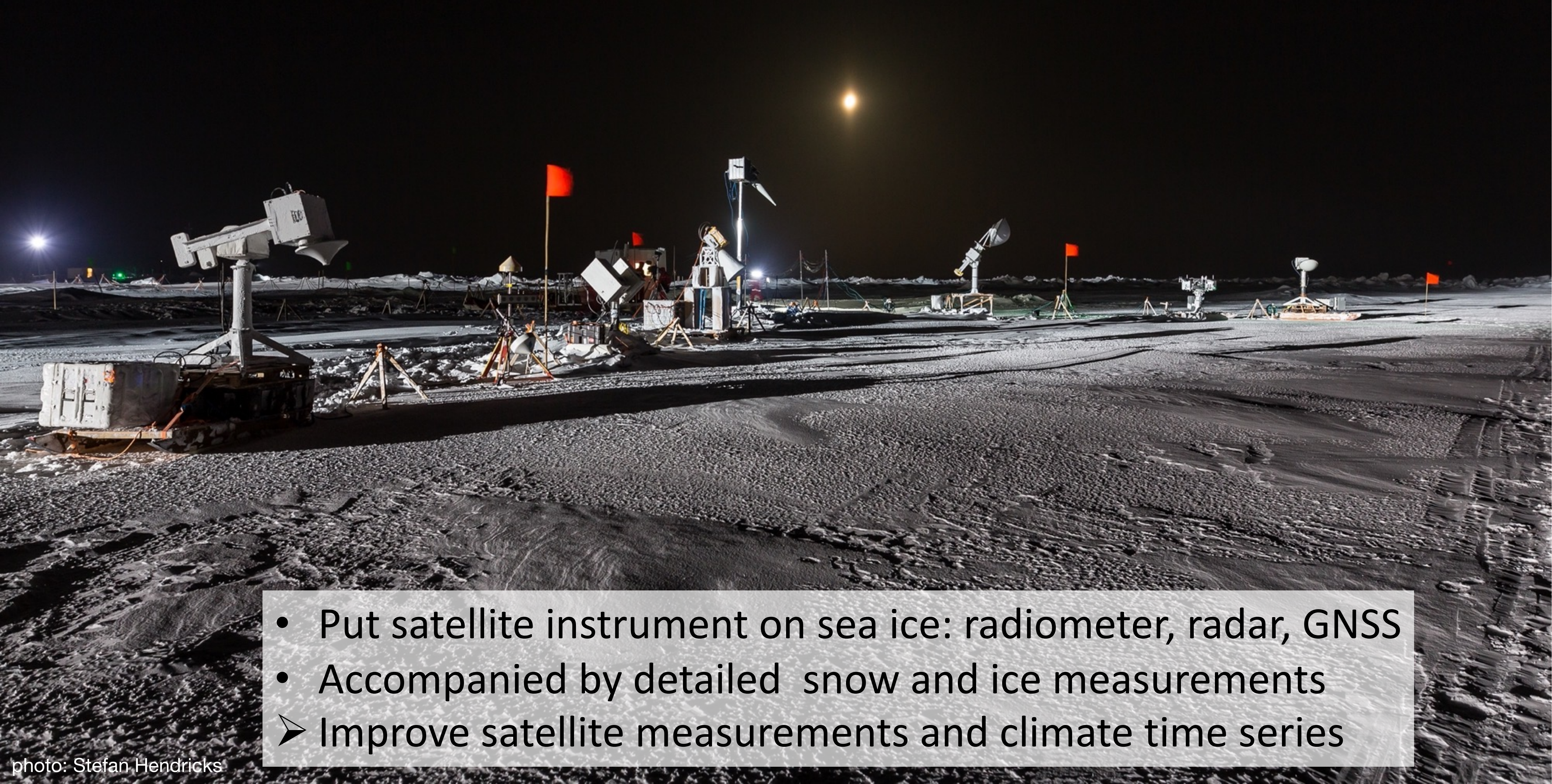



- First time an **icebreaker close to the north pole for a full year**
- More than **70 institutions** from **20 nations**
- September 2019 to October 2020
- Interdisciplinary:
  - Atmosphere • Ocean • **Sea Ice** • Ecology • BGC • **Remote Sensing** • Modeling • Aircraft

- Collect in-situ observations for a full seasonal cycle
- Measurements in a distributed network of 50 km
- **Primary goal**: better process understanding to improve models

www.mosaic-expedition.org

# MOSAiC: Remote Sensing of Sea Ice



- Put satellite instrument on sea ice: radiometer, radar, GNSS
- Accompanied by detailed  snow and ice measurements
- ➢ Improve satellite measurements and climate time series

photo: Stefan Hendricks

# Conclusion Sea Ice Observations

- Satellite data is primary source for pan-Arctic and Antarctic sea ice observations
- Microwave radiometer time series now more than 40 years long
- Sea ice concentration is primary observed variable
  - However, still uncertainties exist mainly due to atmospheric influence and variability of ice/snow emissivity
  - → Move to lower frequencies (6 GHz) ➔ lower special resolution ➔ new satellites (CIMR)
  - → Better modeling of sea ice microwave emission ➔ forward model instead of empirical
- Sea ice thickness time series gets more reliable: radar + laser, snow depth
- Merging of datasets: e.g. altimeter and L-band radiometer for ice thickness; optical and radiometer for ice concentration
- Multi-parameter retrieval (optimal estimation) for consistent datasets
- Field observations critical needed for development and evaluation