Snow water equivalent retrieval using satellite sensors and climate trends of snow mass

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Snow water equivalent retrieval using satellite sensors and climate trends of snow mass

Contents:

1) **Snow water equivalent retrieval using satellite sensors**

2) Current efforts to improve state-of-the-art satellite-based SWE retrieval

3) Bias-correction method & improved knowledge of the NH Snow Mass

Background on Passive microwave SWE monitoring

- Typical empirical SWE algorithms utilize channel difference (basis Chang et al. 1987)
  - 37 – 19 (V or H pol)
  - 19 – 10 (V pol)

- Currently available satellite-based Hemispherical SWE datasets
  - GlobSnow daily SWE from 1980 – present (FMI)
  - AMSR-E daily L3 Global SWE dataset from 2002 – present (NASA/NSIDC)

- Instrument record: SMMR (1978-1987), DMSP SSM/I, SSMIS (1987->), AMSR-E/AMSR-2
  - Continuity: US/DMSP, JAXA GCOM, Chinese FY-3-series include similar sensors

- SWE Retrieval issues
  - Coarse resolution
  - Performance for shallow and deep snow packs (saturation of 37GHz scatter on deep snow)
  - Varying vegetation, land use and lakes effect SWE retrievals (challenge of resolution)
  - Regional adaptations do not perform on global scale

Snow Water Equivalent retrieval using data assimilation approach

- An approach published in Remote Sensing of Environment by Prof. Pulliainen (2006), refined in Takala et al. 2011
- Nature (2020) publication on NH Snow mass trends builds on this method
- The method utilizes
  - Microwave Radiometer data (SMMR, SSM/I, SSMIS)
    - 19 GHz (V-pol) & 37 GHz (V-pol and H-pol)
    - Time-series for 01/1979 – present day
  - Weather station-based snow depth observations
  - HUT snow emission model (Pulliainen et al. 1999)

ESA GlobSnow algorithm by FMI (applies data assimilation)

Dataset	Source
Brightness temperature (18.0/19.4, 37 GHz, H and V polarizations)	SMMR, SSM/I, SSMIS L3 EASE gridded brightness temperatures
Snow mask	IMS and/or NPP VIIRS
Global forest fraction	Derived from ESA GlobCover
Global Forest Biomass	Global average 70 kg/m^3 (v2.0) ESA BIOMASAR (v2.01)
Land, ocean and ice mask	Derived from ESA GlobCover
Mountain mask	Derived from ETOPO5 data (Etopo5 1988)
Snow depth from weather stations	Synoptic weather station observations

- Based on inversion of physical snow emission model (Pulliainen et al., 1999)
- Physical model calibrated over weather station locations (effective grain size)
  - Grain size field extended over area of interest using Kriging technique
- Final step includes assimilation of snow depth background field and radiometer derived SWE estimates

References:
Pulliainen et al., 1999
Pulliainen, 2006
Takala et al., 2011

Data assimilation method (I)

- A Bayesian data assimilation approach:
  - By searching the maximum value of the conditional probability of SWE for the location under investigation given the time series of radiometer observations and *in situ* observations:

max ρ (*SWE* | *radiometer observations, in situ SD observations*)

  - Requires that radiometer observation can be modeled as a function of snow depth and snow density (SWE)
  - Spatial data analysis methods (kriging interpolation) applied for interpolating spatially continuous snow depth values from discrete *in situ* observations

Data assimilation method (II)

- A three step procedure:

First step: Estimation of SD at the locations of reference (*in situ*) stations

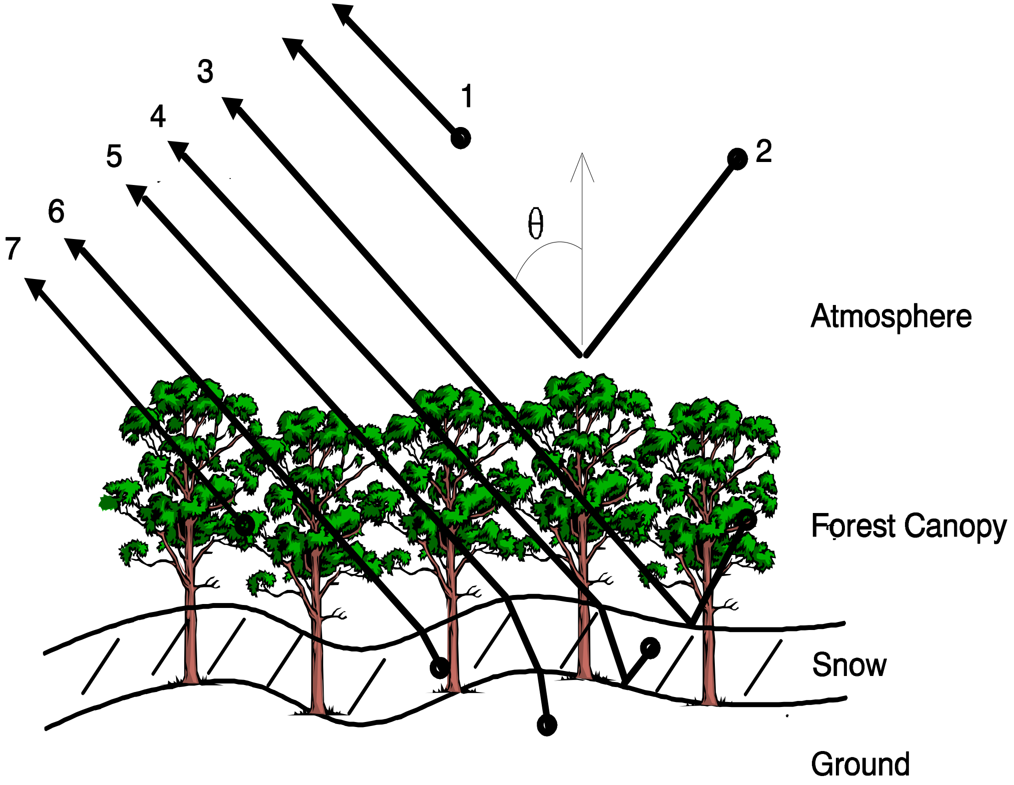
  - By fitting the modeled brightness temperature difference between two channels ($T_{b,18.7GHz,V\text{-}pol} – T_{b,36.5GHz,V\text{-}pol}$) to the corresponding true SSM/I observed channel difference by **optimizing the value of snow grain size**
  - Yields information on the spatial behavior of snow grain size: **average snow grain size** and **its variance** for **different dates** for any location (x,y)
    - the variance is estimated through linearizing the relation between brightness temperature and snow grain size (Taylor series)

Second step: Determination of SD estimate and its variance from *in situ* data for any location (x, y) by kriging interpolation

Third step: Estimation of SD and SWE for the location (x,y) and for the moment of time (day) by weighing different data sources by their estimated variances

The HUT snow emission model

- Background
  - Semi-empirical model simple enough to be used for parameter retrieval from space-borne or airborne data
- Basic characteristics
  - scalar radiative transfer model for single snow layer
  - semi-empirical formulas for snow permittivity and extinction coefficient
  - empirical coefficient for radiation contribution scattered in snow layer
  - incoherent approach used for medium boundary effects
  - soil-snow reflectivity by empirical soil emission models
  - empirical formulas for atmospheric and forest cover effect



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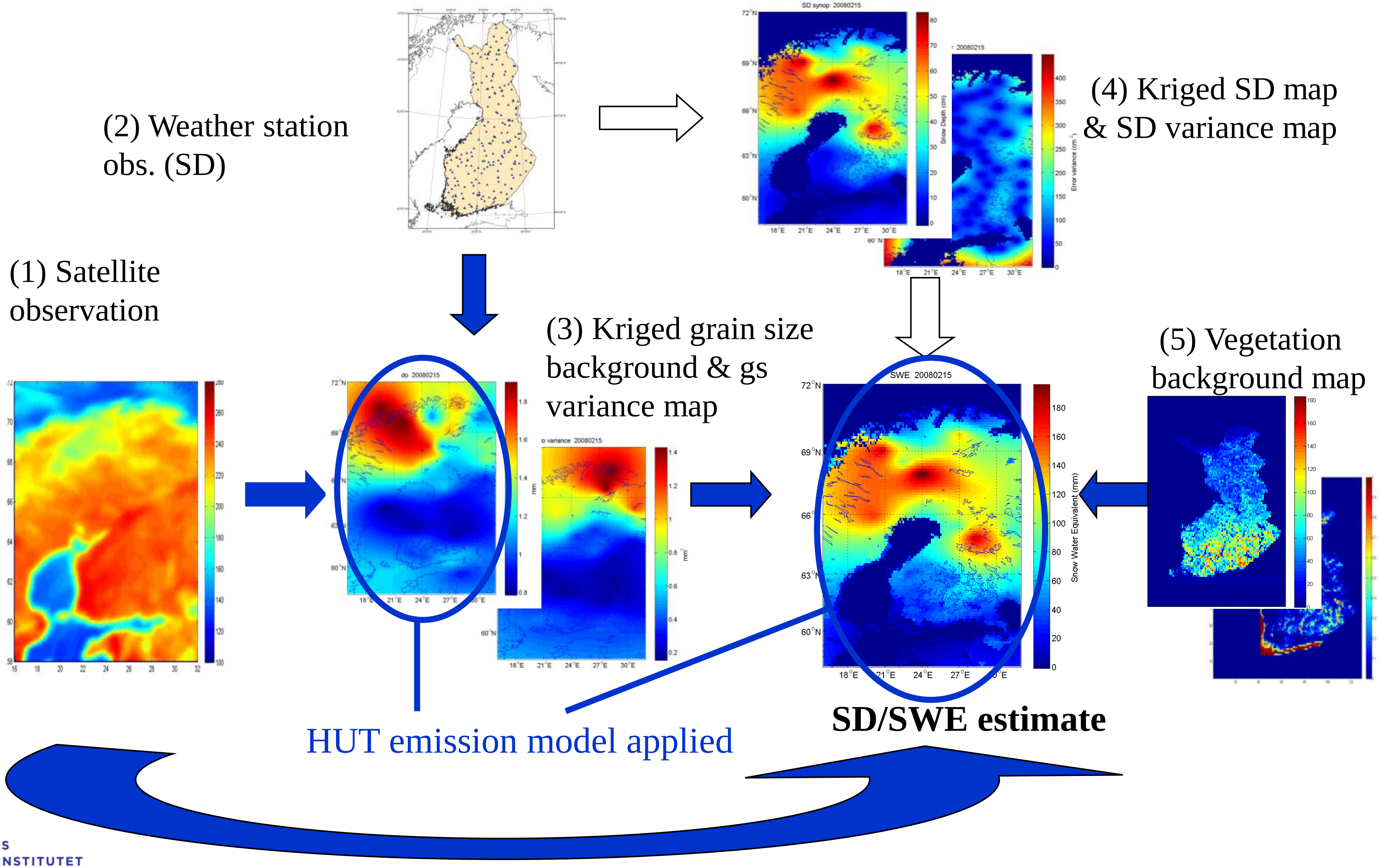
Flowchart of the retrieval approach



(2) Weather station obs. (SD)

(4) Kriged SD map & SD variance map

(1) Satellite observation

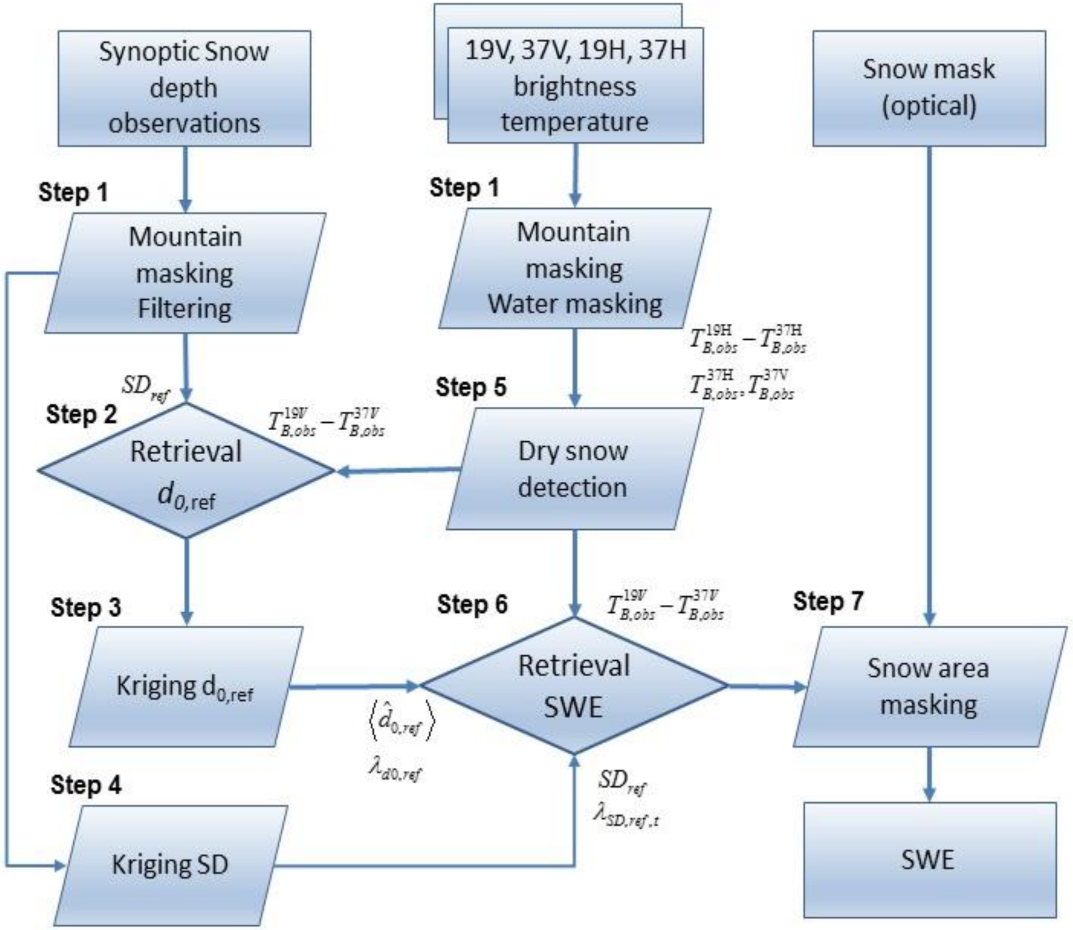
(3) Kriged grain size background & gs variance map

(5) Vegetation background map

HUT emission model applied

SD/SWE estimate

Flowchart of the retrieval approach



Step 1: mountain mask, water mask & filtering

Step 2: Retrieval of effective grain size

Step 3: Kriging interpolation of effective grain size

Step 4: Kriging interpolation of weather station snow depth

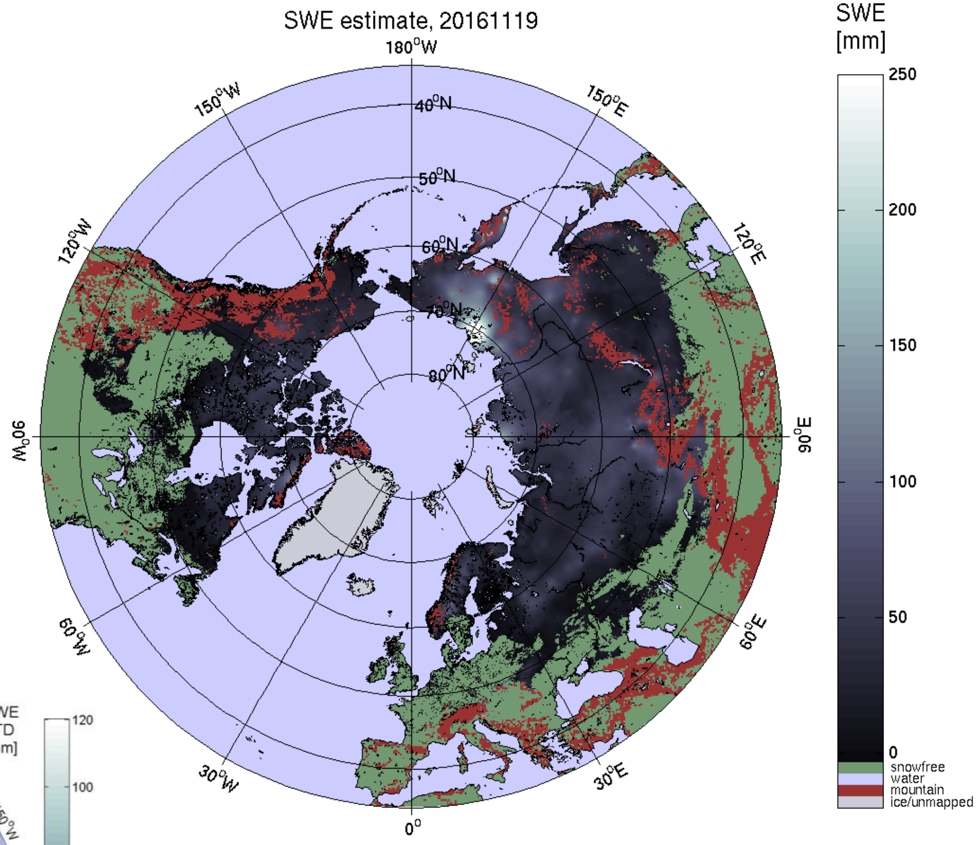
Step 5: Dry snow detection

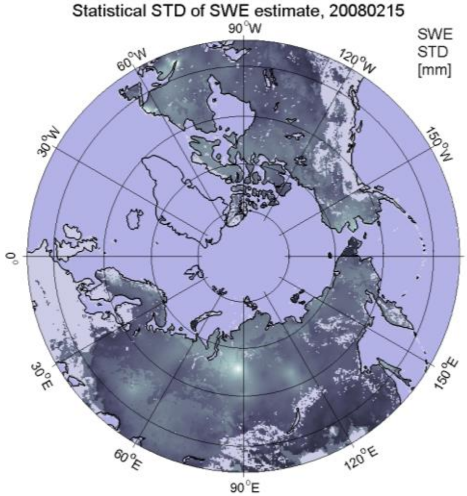
Step 6: Retrieval of SWE

Step 7: Snow area masking

40 year-long CDR time-series of Northern Hemisphere snow conditions (ESA GlobSnow / Snow CCI SWE)

- First time reliable daily spatial information on SWE (snow cover):
  - Snow Water Equivalent (SWE)
  - Snow Extent
  - 25 km resolution (EASE-grid)
  - Time-series for 1979-2019
- Passive microwave radiometer data combined with ground-based synoptic snow observations
- Greenland, glaciers & mountains masked out
- Openly available (CCI data repository)
- Demonstration of NRT production started on October 2010 (now within EUMETSAT / Copernicus services)


SWE estimate, 20161119


Statistical STD of SWE estimate, 20080215

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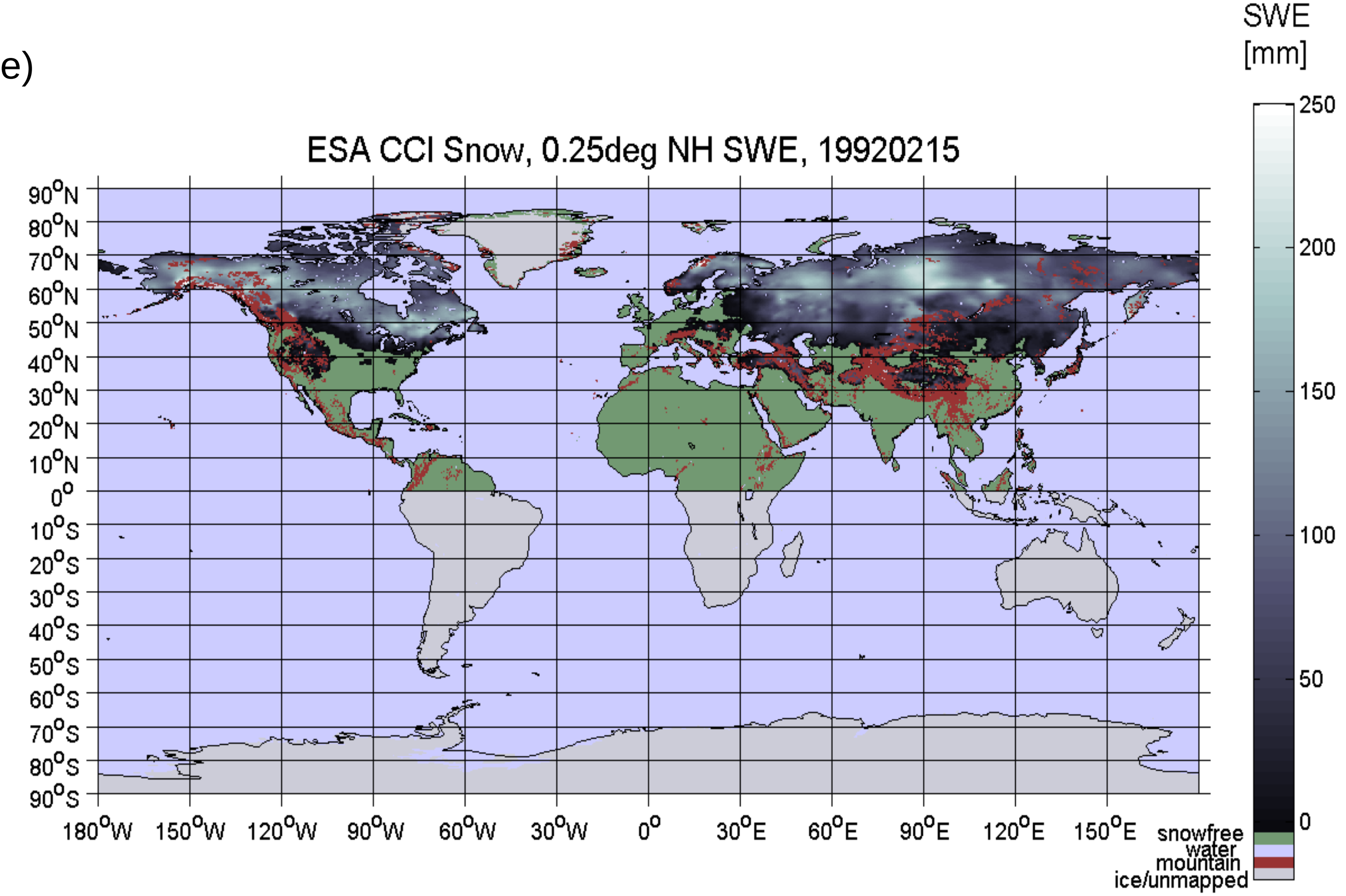
snow cci

Snow CCI SWE v1.0 product time series

- Snow variable:
  - Snow water equivalent (SWE)
  - Uncertainty estimate (STD of SWE estimate)
  - Retrieval algorithm: GlobSnow v3.0 (publication in review)
- Time series:
  - Start: 6 January 1979
  - End: 31 May 2019
- Spatial:
  - Coverage: Northern Hemisphere
  - Grid size: 0.25°
  - Projection: Geograph. (lat/lon)
  - Datum: WGS 84
- Temporal resolution: 1 day
  - Aggregation: Monthly (+bias correction)
- File format: NetCDF4, CF-v1.7
- Metadata: Land/sea mask, SWE uncertainty



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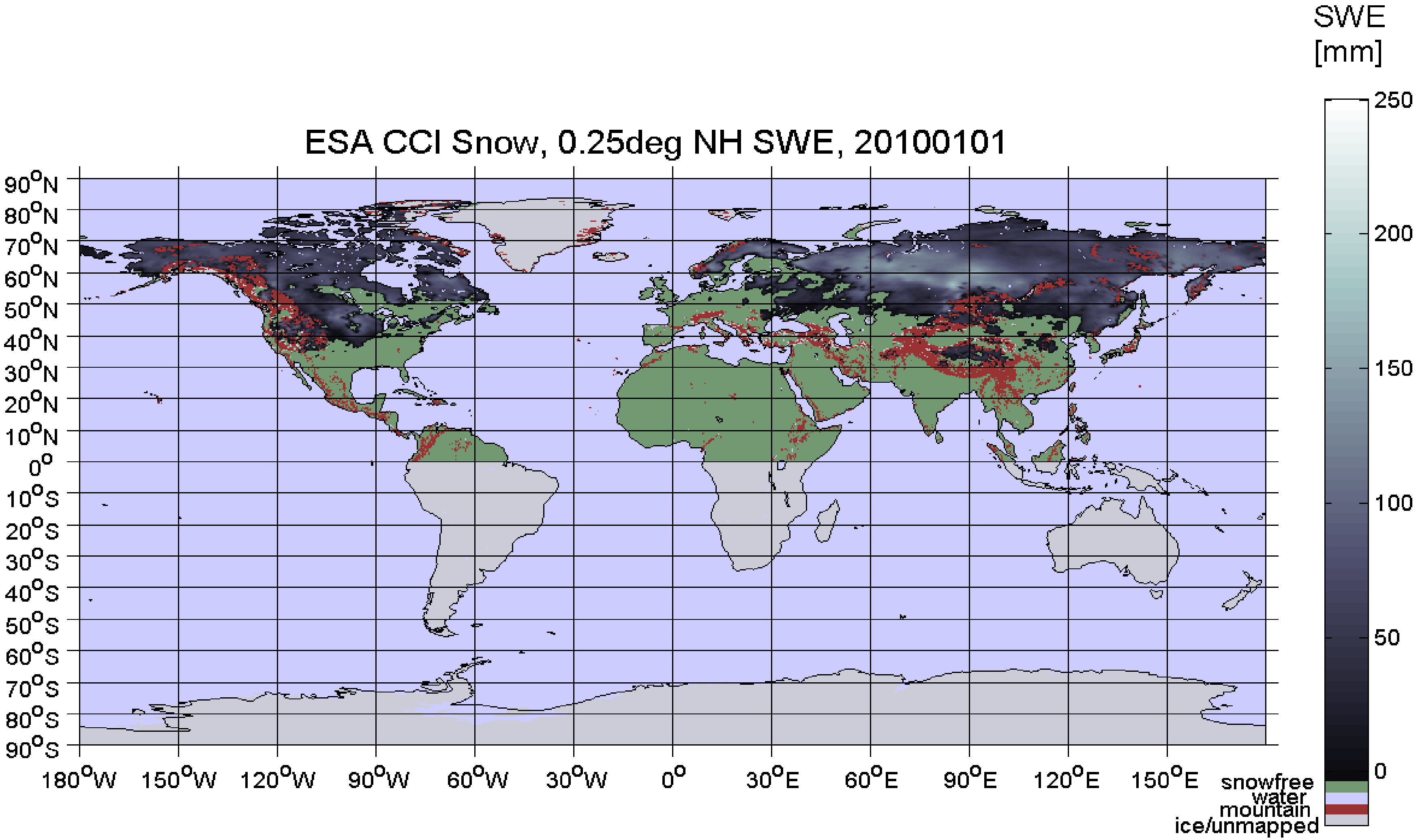
snow cci

Snow CCI SWE - spring 2010 animation

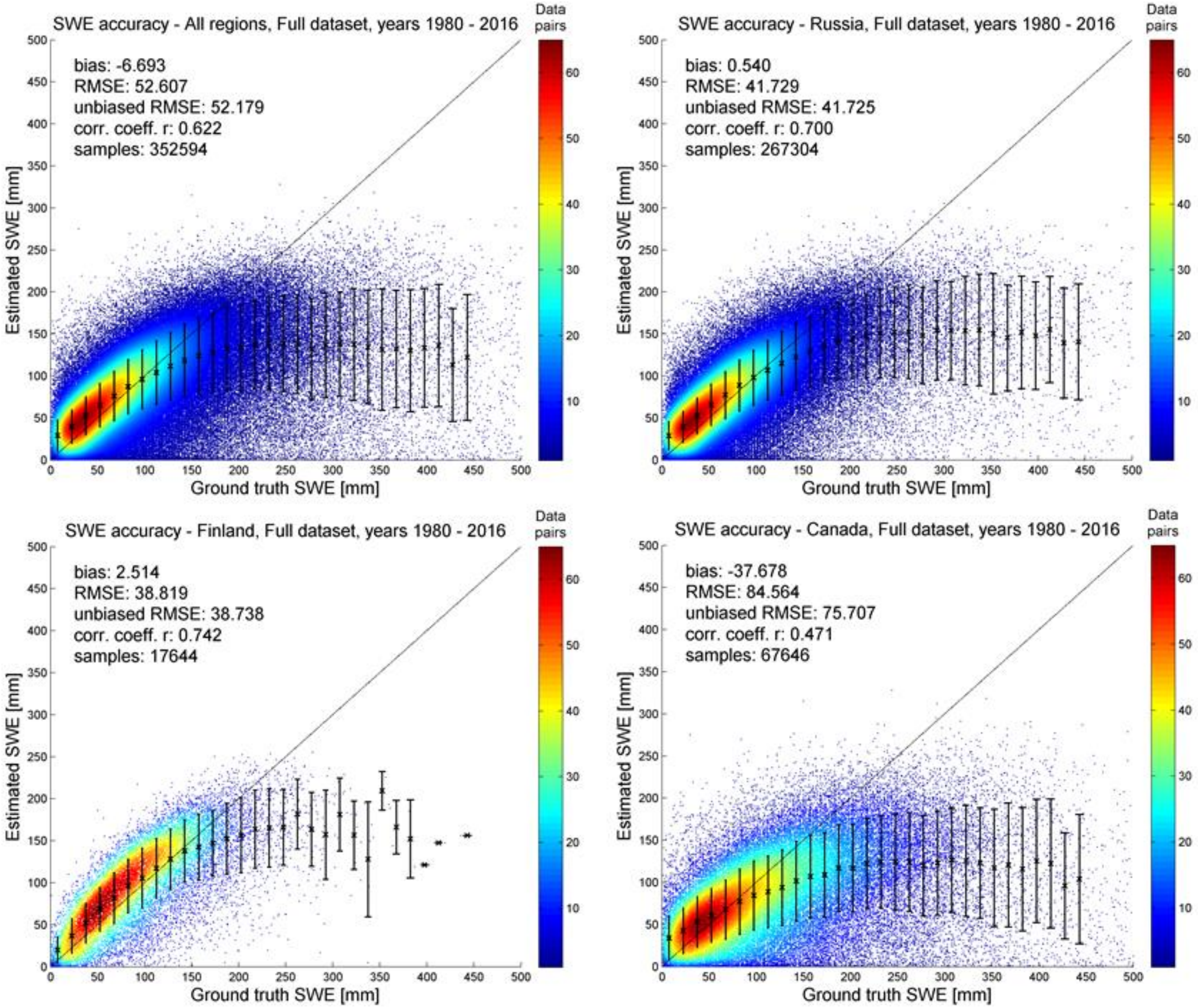


Accuracy characterization of the SWE product

- Product absolute accuracy determined from independent multi-decadal (1980-2016) snow transect dataset from Russia, North America and Scandinavia

All samples	Number of data pairs	Bias [mm]	RMSE [mm]	Correlation (r)	Mean SWE [mm]
All regions	352 594	-6.7	52.6	0.62	89.0
Russia	267 304	0.5	41.7	0.70	79.9
Finland	17 644	2.5	38.8	0.74	93.9
Canada	67 646	-37.7	84.6	0.47	123.7

SWE <150mm	Number of data pairs	Bias [mm]	RMSE [mm]	Correlation (r)
All regions	298 138	6.4	32.7	0.66
Russia	240 041	8.2	30.5	0.70
Finland	14 839	10.0	32.4	0.74
Canada	45 597	-4.3	42.5	0.46



SWE product accuracy against snow transect data from 1980 to 2016

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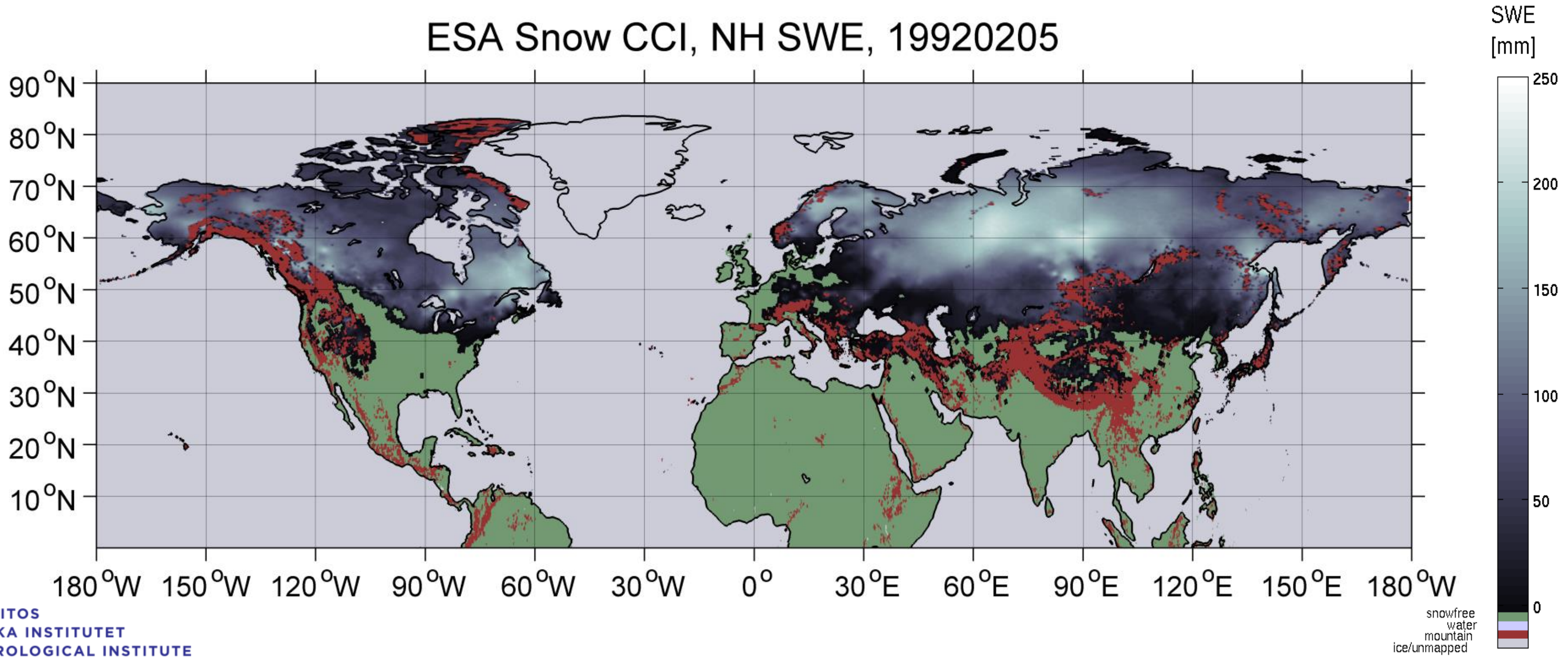
ESA Snow CCI - SWE retrieval updates (up to date)

- Processing chain adaptation to lat/lon gridding and to cover full NH (0-90°N latitudes)
- Improved snow emission model within SWE retrieval (improved forest & lake considerations)
- Updated SD synop database: significantly more consistent long term time-series of SD data from mutliple sources (ECMWF, NCDC, RIHMI-WDC, Canada, etc.)
- Utilization of SCE information to augment SWE retrieval
- The ESA Snow CCI SWE v1.0 CDR (1979-2018) available via the ESA CCI data portal



ESA Snow CCI, NH SWE, 19920205

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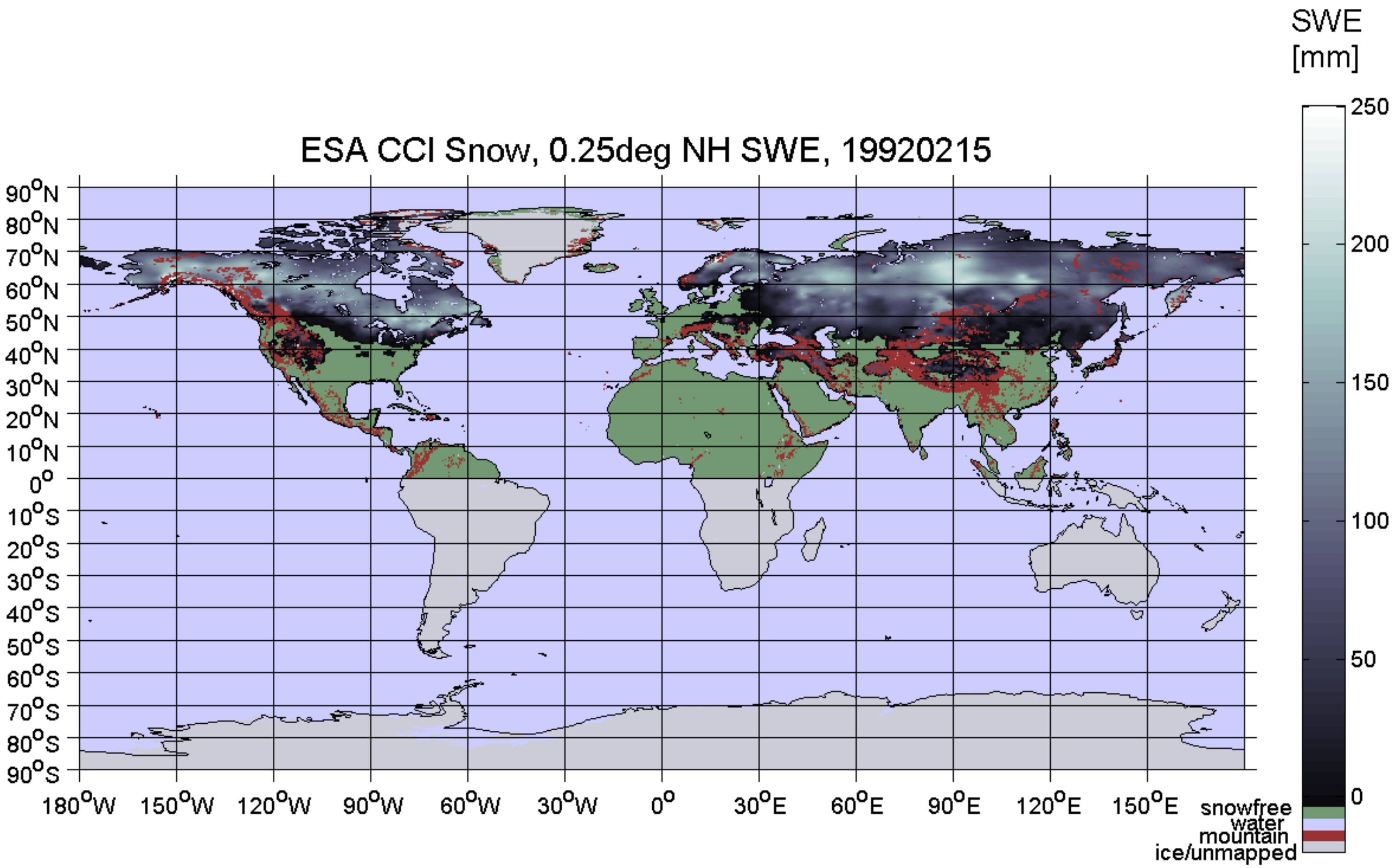
ESA Snow CCI - further development of SWE retrieval for climate applications

Further development efforts for SWE:

- Improved spatial resolution (0.10°)
  - Utilization of enhanced resolution input data
  - 12.5km EASE2 “SIR” data
- Dynamic snow density
  - Utilization of spatially and temporally dynamic snow density in SWE retrieval
- Synergistic utilization of optical snow extent data in SWE retrieval
  - JAXA & Snow CCI SCE datasets applied to enhance SWE retrieval
- Updated/homogenized input datasets
- Monthly bias-corrected product


ESA CCI Snow, 0.25deg NH SWE, 19920215

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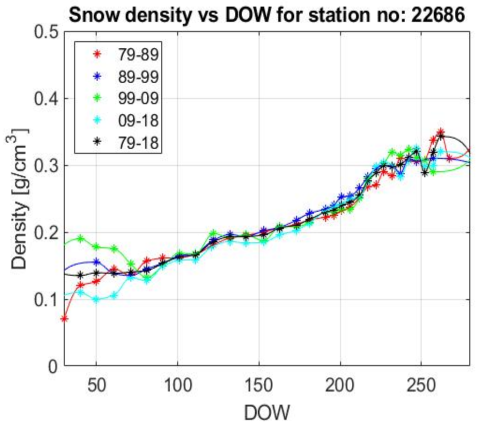
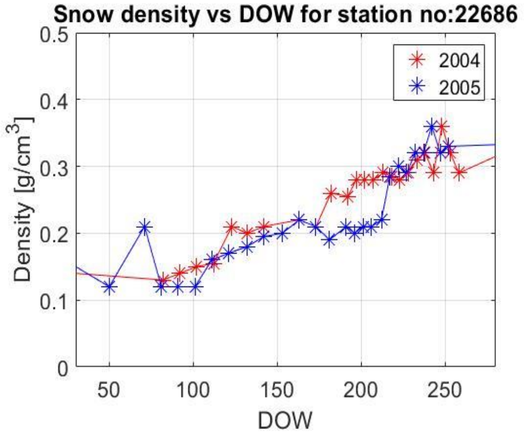
esa

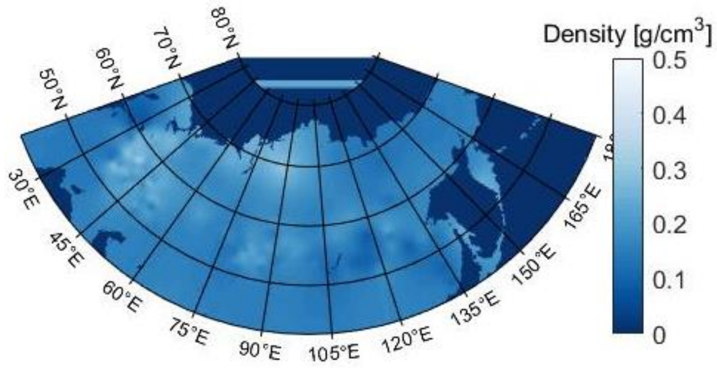
snow
cci

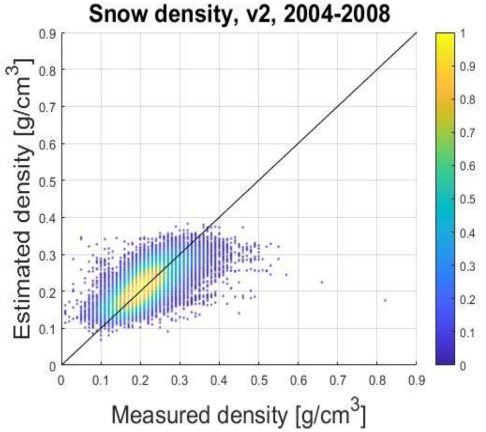
Dynamic snow density in SWE retrieval

- Temporally and spatially dynamic snow density reconstructed from multidecadal snow transect data (Eurasia & North America)
- Applied in SWE retrieval (instead of constant snow density)

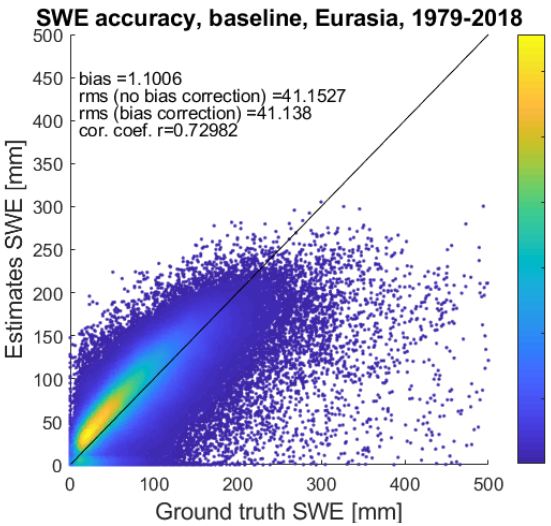


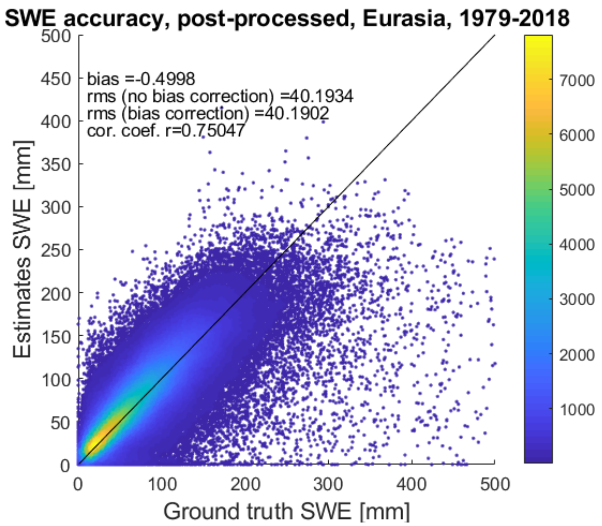






- Applied as post-production step (implemented)
- Applied within SWE retrieval (efforts on-going)





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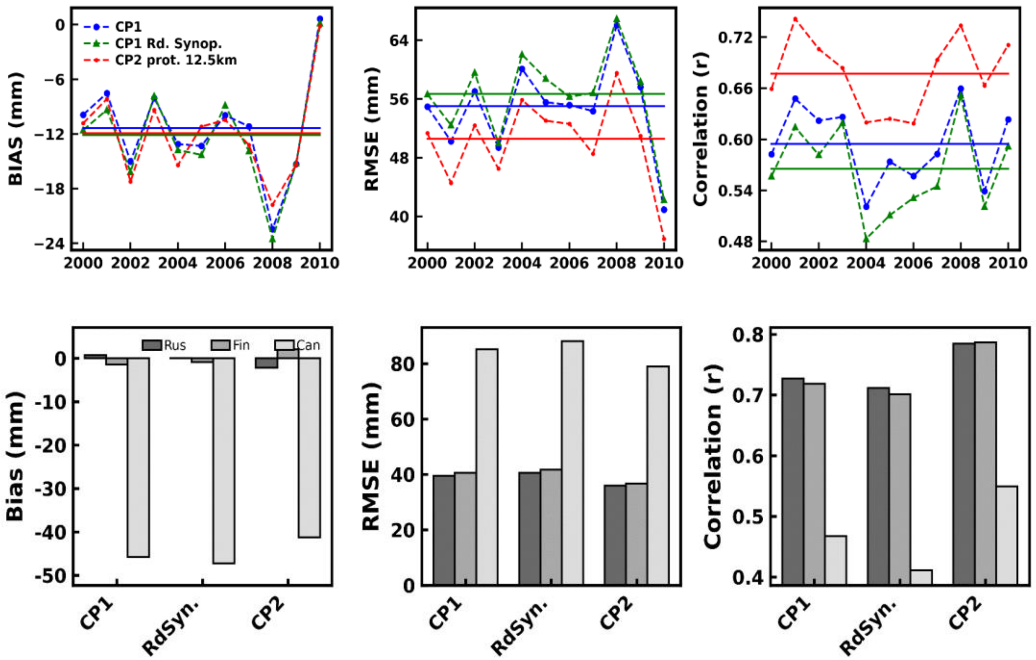
Improved spatial resolution:
25 km EASE-grid -> 12.5km EASE2

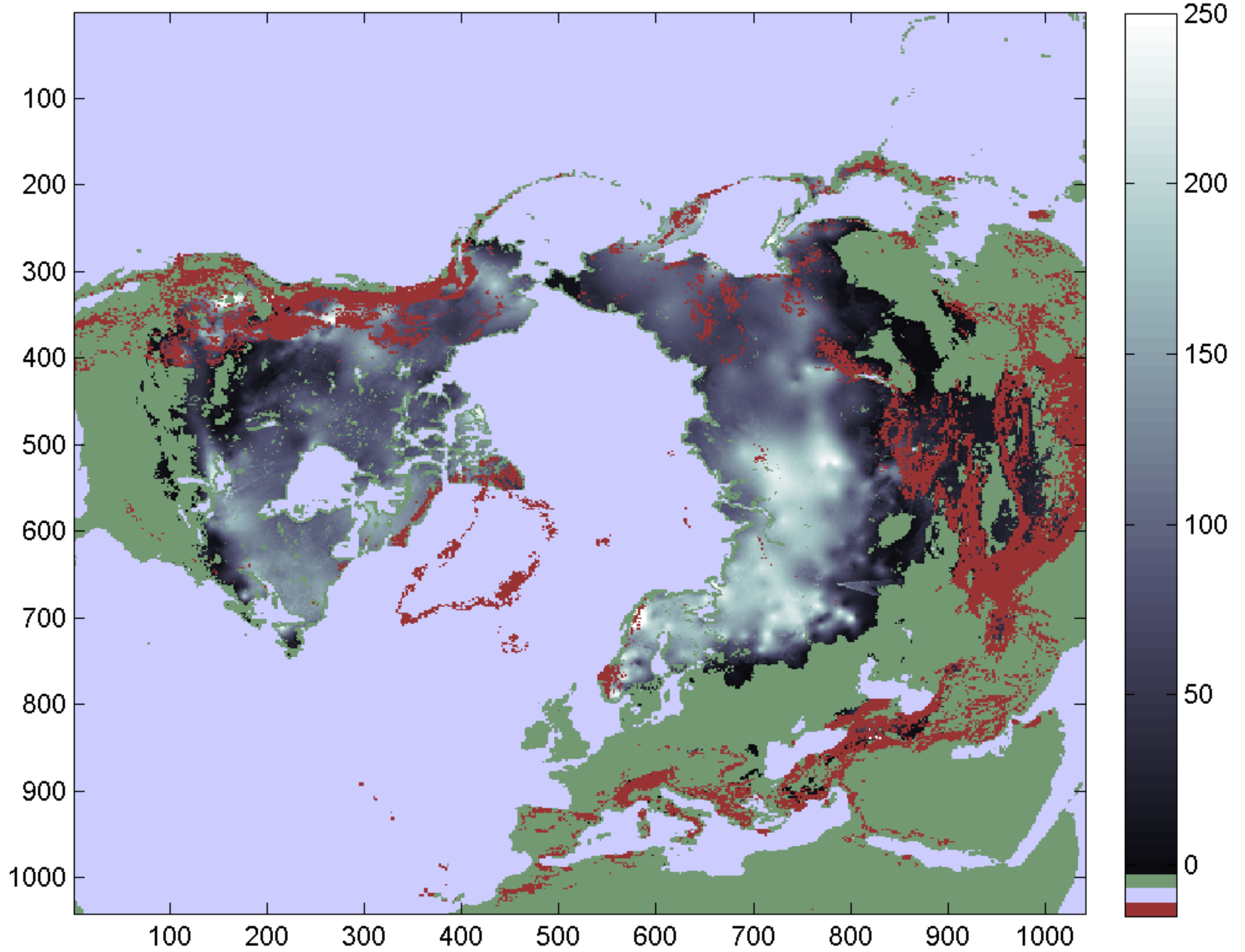
- Utilization of the SIR enhanced resolution input Tb data from NSIDC *(Brodzik et al. 2016)*
- Preliminary validation results below:
  -> (significantly improved SWE retrieval accuracy!)

Snow CCI preliminary validation: Oct.–May 2000 – 2010
- 25km vs. 12.5km dynamic snow density product



12.5km enhanced resolution SWE product

20020315



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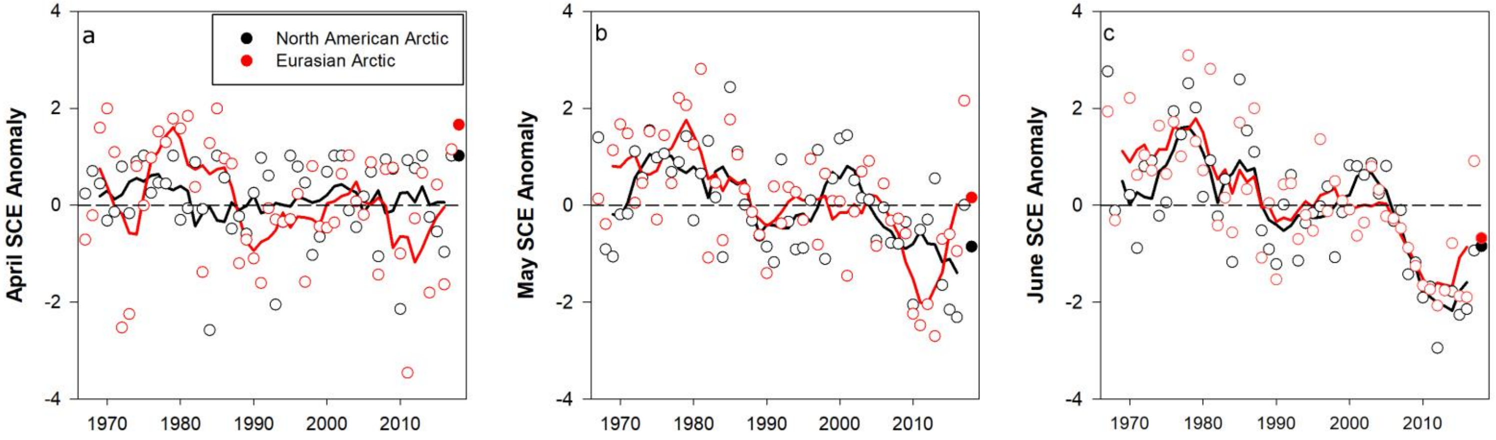
Changes in Snow Cover Extent: - Arctic & Northern Hemisphere

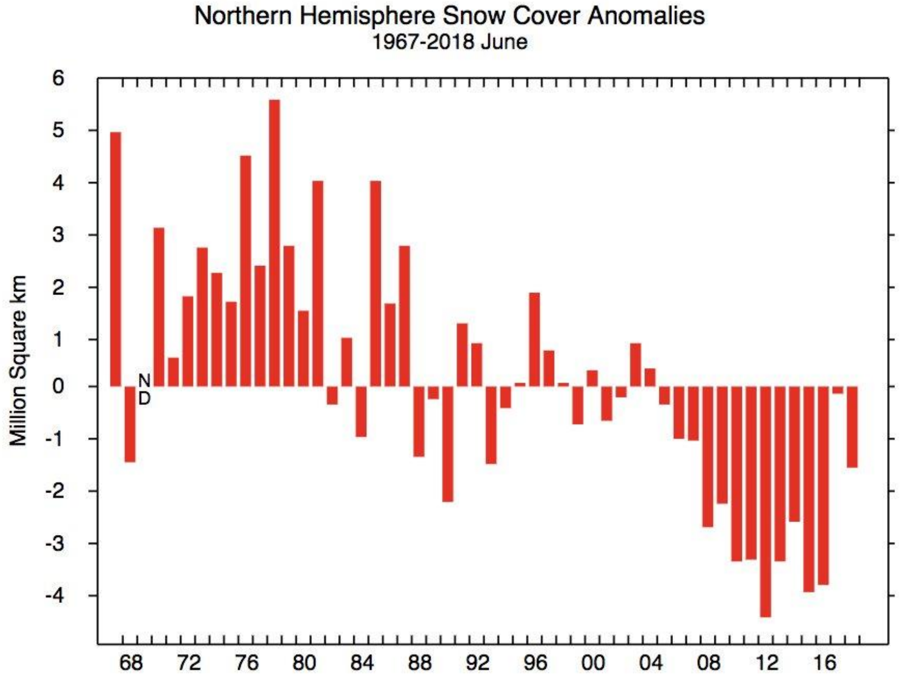
Arctic Snow Cover Anomalies 1967-2018



The Arctic snow cover extent has been declining in the past decades, especially in May and June

Source: NOAA Artic Report Card (C. Derksen & L. Mudryk)

Snow Cover Extent is significantly decreasing!



Northern Hemisphere Snow Cover Extent
->June SCE has seen a dramatic decrease!

Source: Rutgers University Snow Lab

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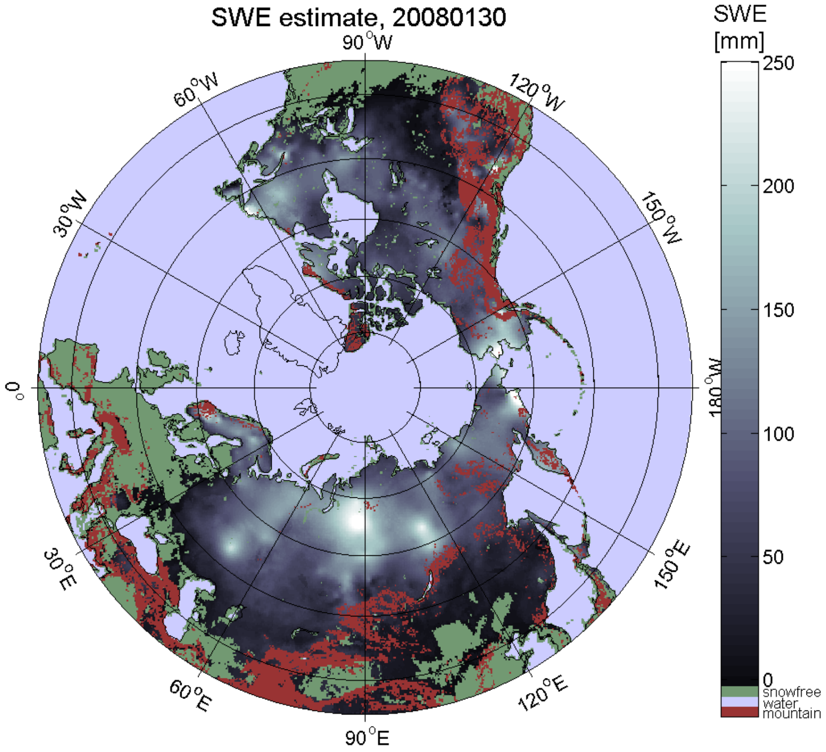
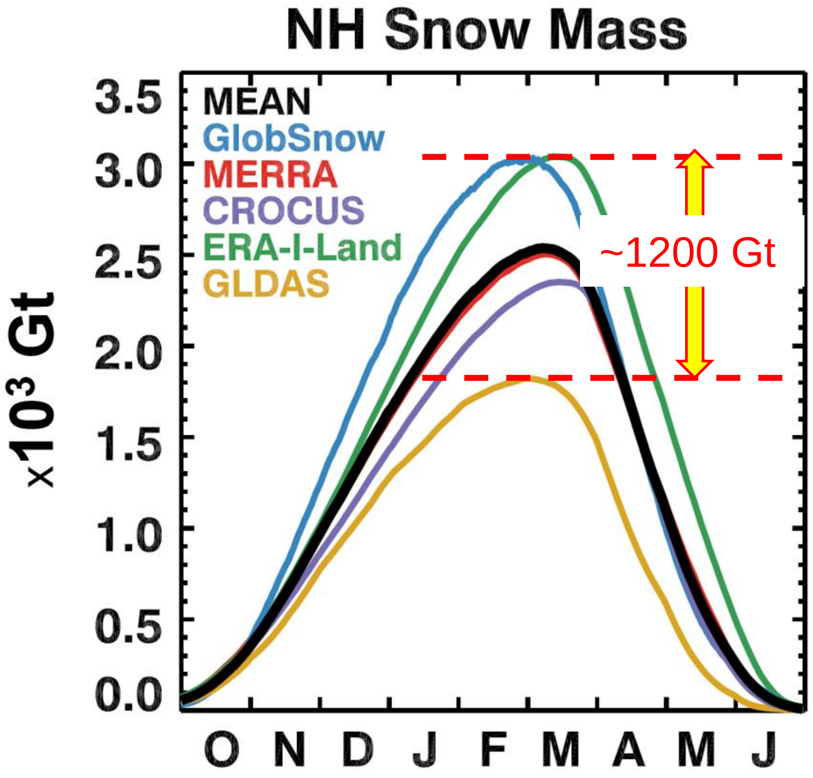
Uncertainty in NH Seasonal Snow Mass

Spread in NH snow mass between **model-based** and **Satellite-based** estimates (ESA SnowPEx)
-> One of the key goals of the SnowPEx & Snow CCI projects was to reduce this uncertainty!



Satellite-based GlobSnow/Snow CCI SWE estimate



Models vs. “Satellite-based“ data

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esa snowpex snow cci

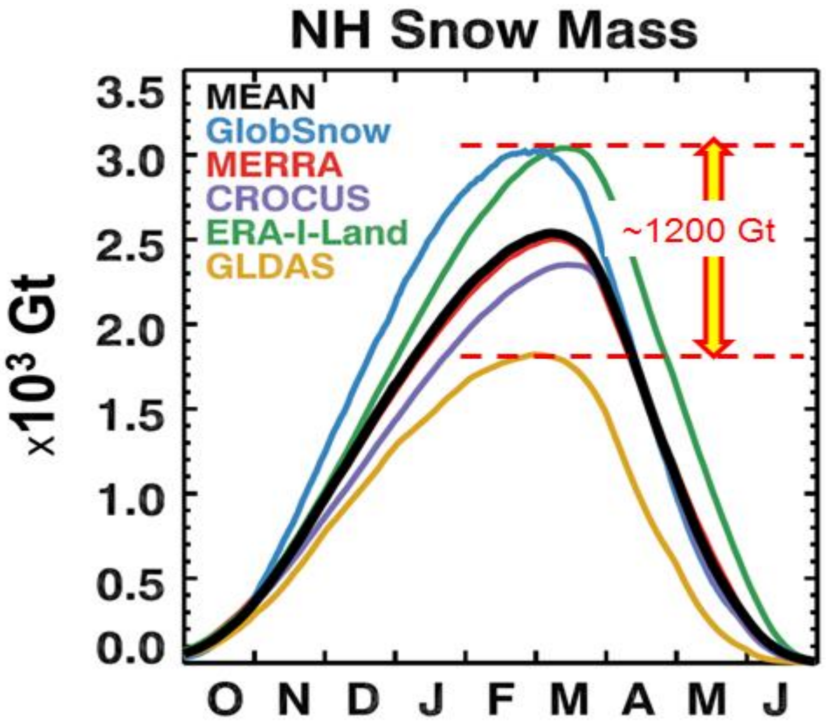
Uncertainty in NH Seasonal Snow Mass

Goal: Accurate determination of the NH snow mass and its changes over the past 40 years
(using available satellite-, model- & surface-based obs.)

- Satellite & model estimates disagree
  -> Peak-SWE uncertainty: ESA SnowPEx ~1900-3100Gt

- With such a high uncertainty – reliable trend analysis is very challenging!

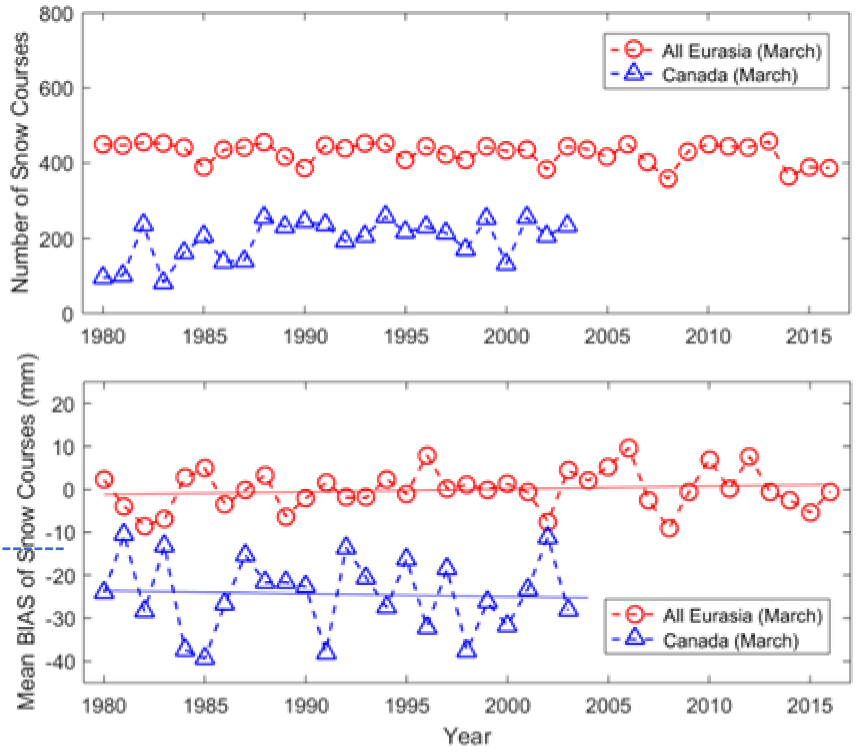
- A new approach: Bias correction of the satellite-based data with surface-based reference data (snow transect data from Fin/Can/Rus)

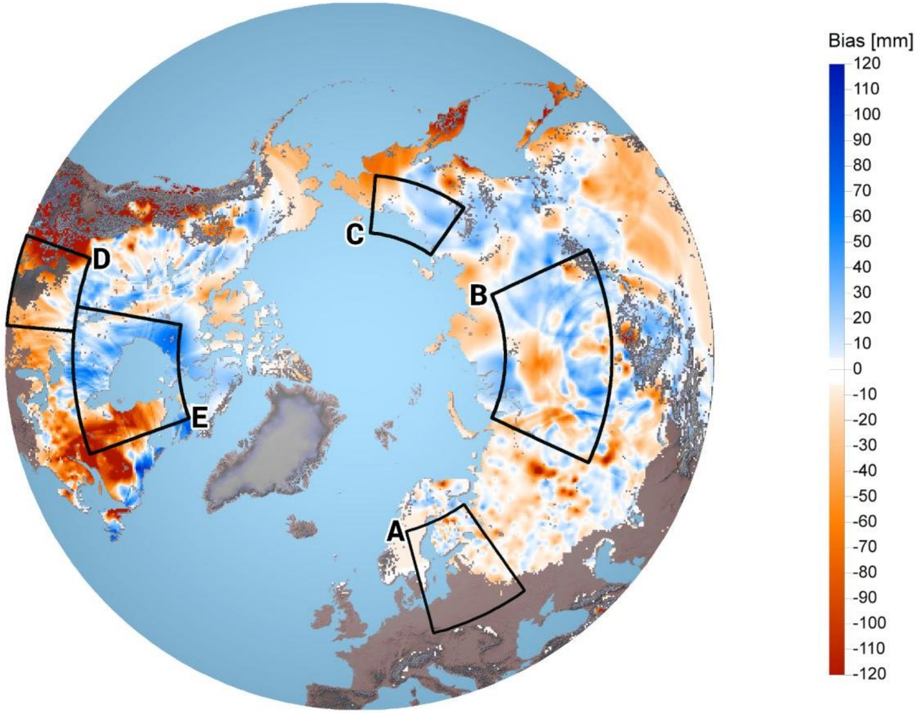


Bias-correction of the SWE CDRs (satellite + models)

- A bias-correction procedure that utilizes independent snow course observations has been developed and applied to the satellite-based SWE CDR (~2200 snow courses over NH)
- Assessment of model-based data records undertaken as well -> overall uncertainty of the overall NH snow mass conditions better constrained
- Significantly reduces the overall uncertainty, brings models & satellite-based climatologies to a very good agreement

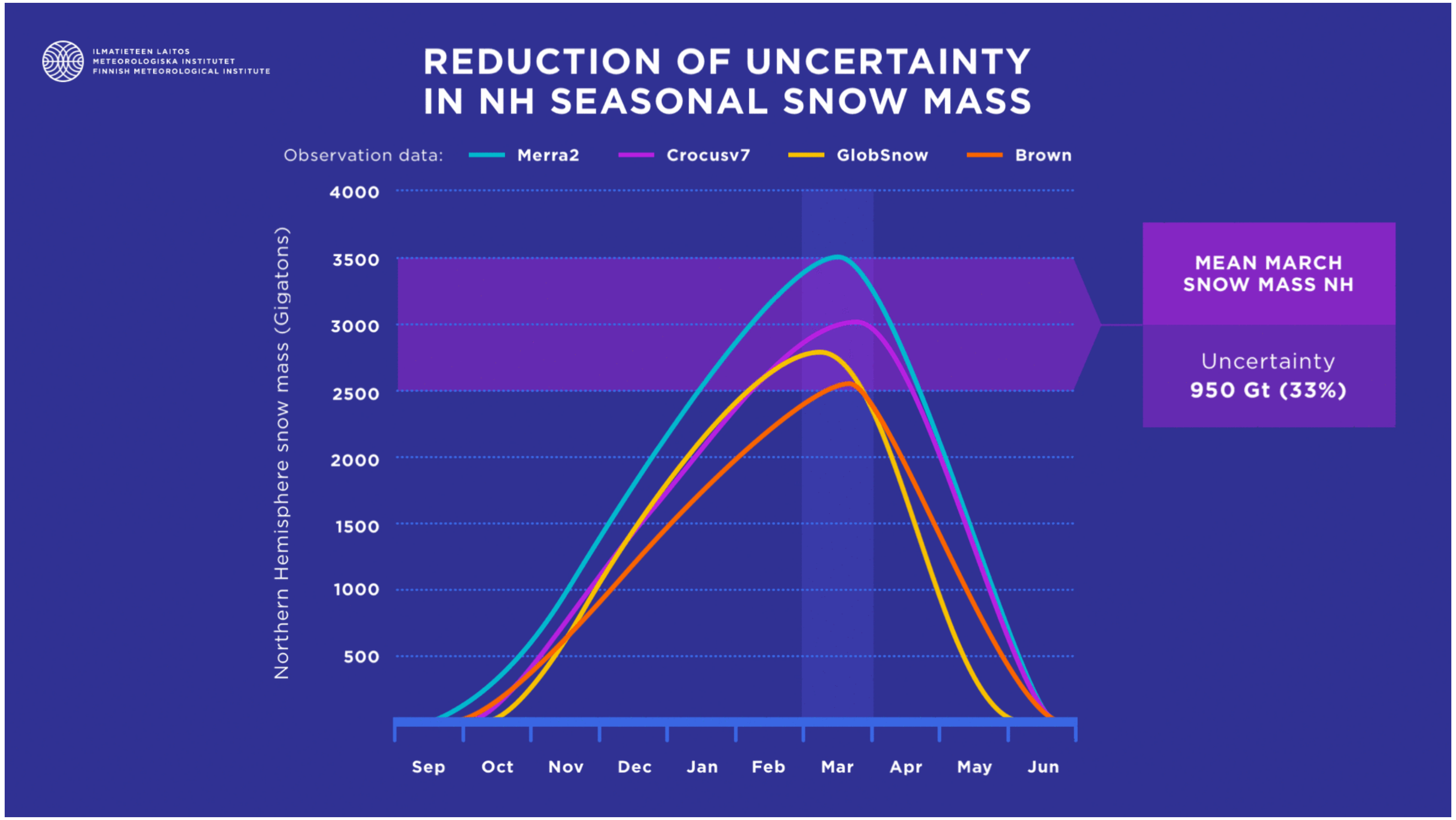
Evolution of the annual bias of GlobSnow SWE estimates for March

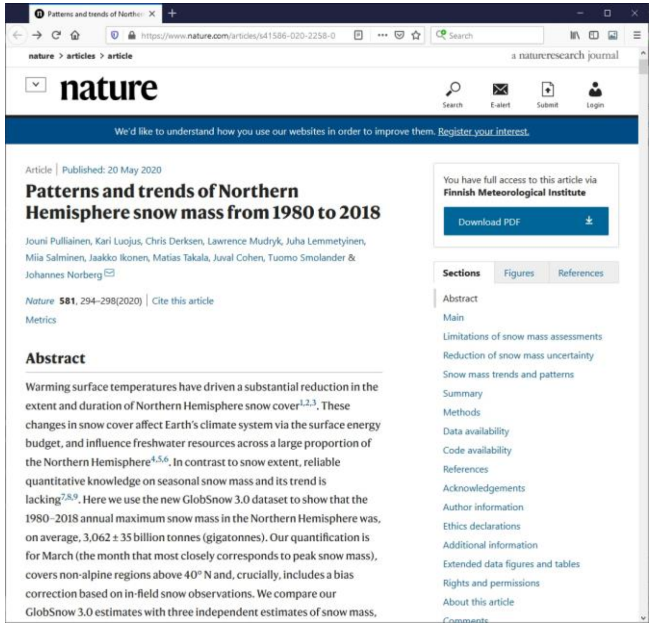




Nature publication on NH snow mass: Reduction of the overall uncertainty

The significant spread in NH snow mass between the Satellite and model-based estimates.
-> Development of a new bias-correction methodology.





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Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018

Jouni Pulliainen, Kari Luojus, Chris Derksen, Lawrence Mudryk, Juha Lemmetyinen, Miia Salminen, Jaakko Ikonen, Matias Takala, Juval Cohen, Tuomo Smolander & Johannes Norberg

Nature **581**, 294–298(2020) | Cite this article

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About this article

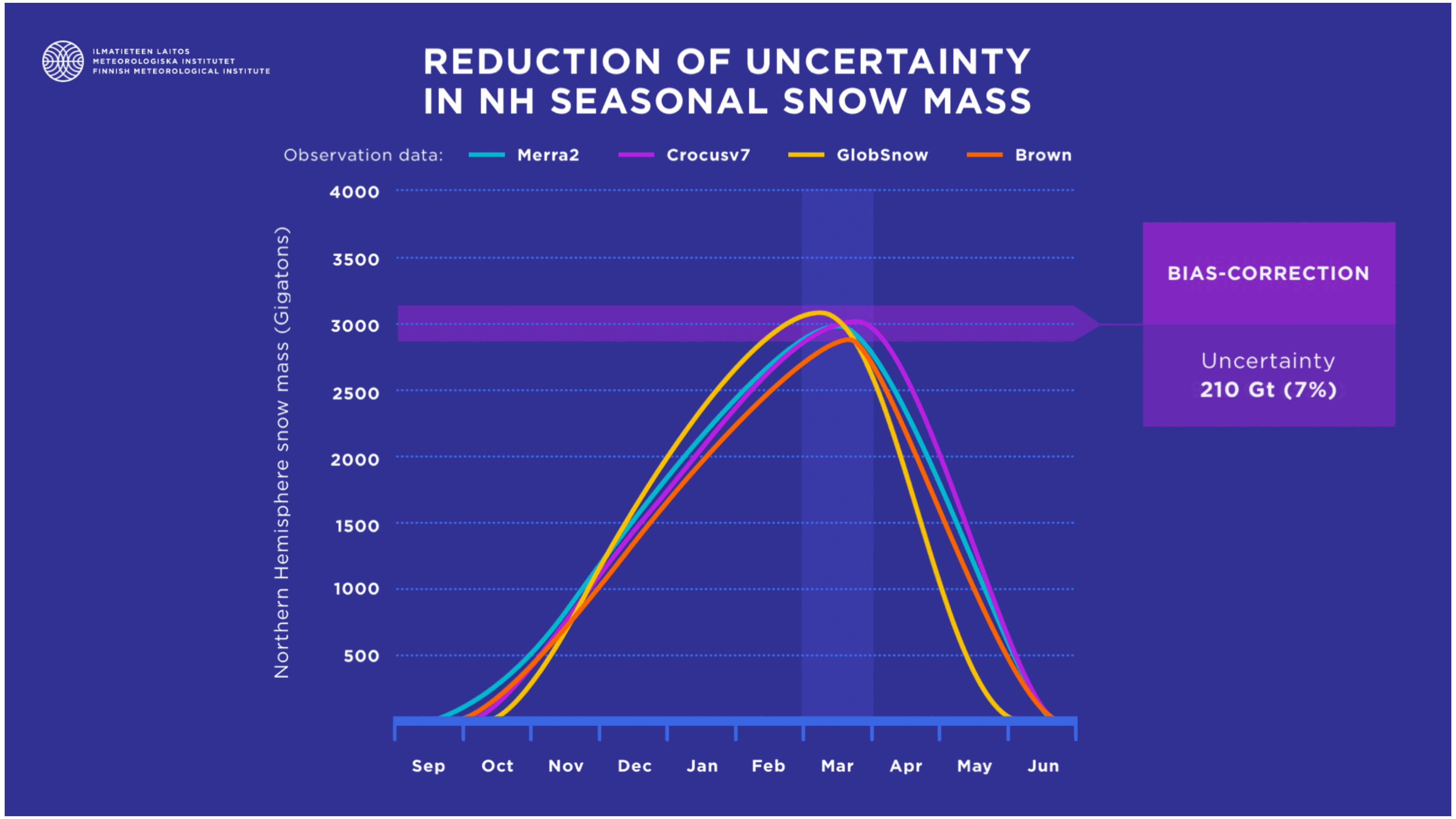
Abstract

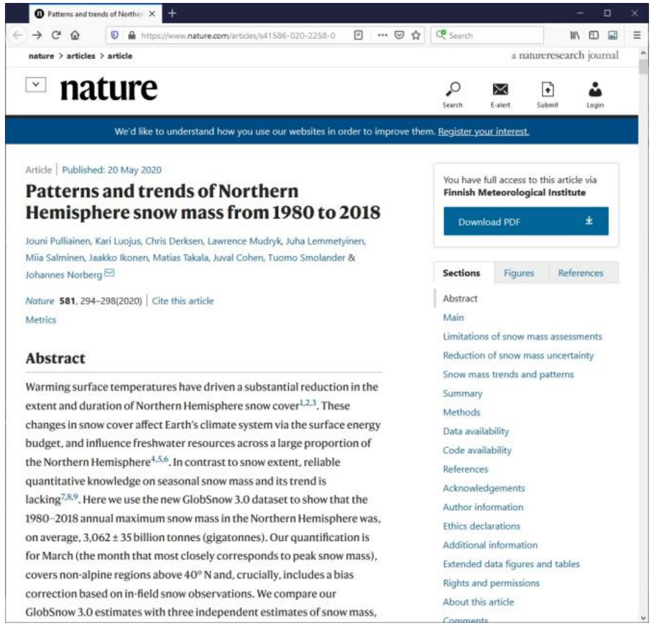
Warming surface temperatures have driven a substantial reduction in the extent and duration of Northern Hemisphere snow cover[1,2,3]. These changes in snow cover affect Earth's climate system via the surface energy budget, and influence freshwater resources across a large proportion of the Northern Hemisphere[4,5,6]. In contrast to snow extent, reliable quantitative knowledge on seasonal snow mass and its trend is lacking[7,8,9]. Here we use the new GlobSnow 3.0 dataset to show that the 1980–2018 annual maximum snow mass in the Northern Hemisphere was, on average, 3,062 ± 35 billion tonnes (gigatonnes). Our quantification is for March (the month that most closely corresponds to peak snow mass), covers non-alpine regions above 40° N and, crucially, includes a bias correction based on in-field snow observations. We compare our GlobSnow 3.0 estimates with three independent estimates of snow mass,

Pulliainen, J., Luojus, K., Derksen, C. et al. Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. Nature 581, 294–298 (2020). https://doi.org/10.1038/s41586-020-2258-0

Nature publication on NH snow mass: Reduction of the overall uncertainty

The new bias-correction methodology, significantly reduces the uncertainty.
-> Allowing us to determine for the first time reliably the trends and patterns of the NH snow mass for 1980-2018!





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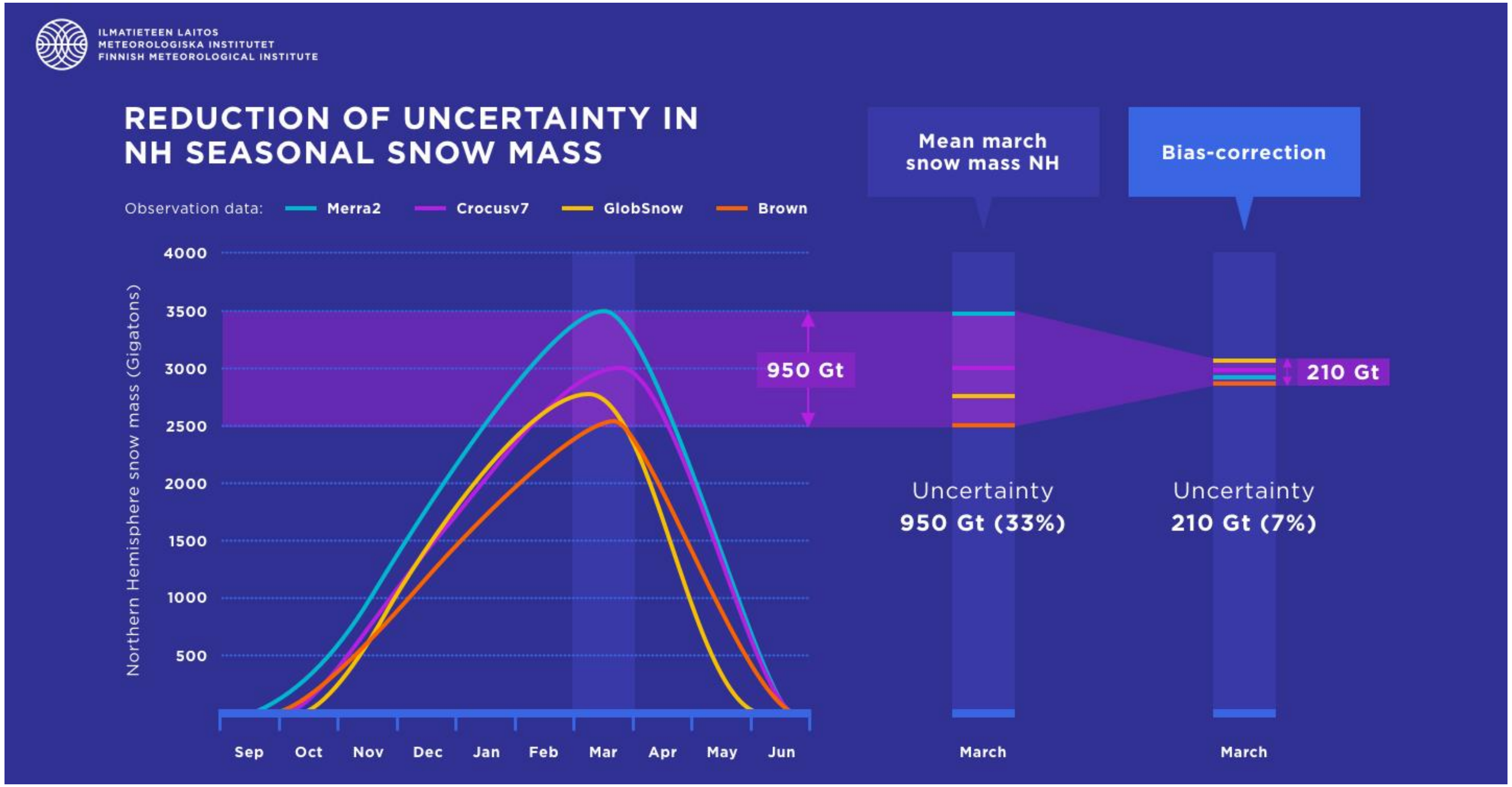
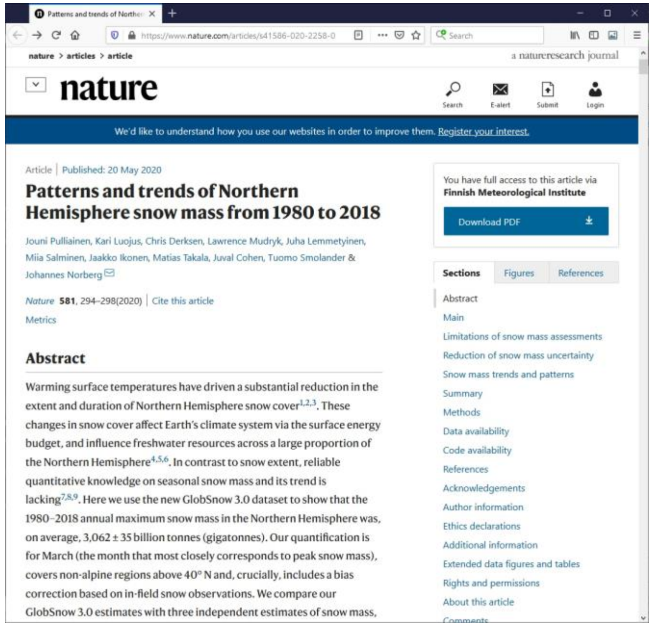
Nature publication on NH snow mass: Reduction of the overall uncertainty

The bias-correction methodology decreases the overall uncertainty significantly.
Allows determination of the trends and patterns of the NH snow mass for 1980-2018!





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Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018

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Metrics

Abstract

Warming surface temperatures have driven a substantial reduction in the extent and duration of Northern Hemisphere snow cover[1,2,3]. These changes in snow cover affect Earth's climate system via the surface energy budget, and influence freshwater resources across a large proportion of the Northern Hemisphere[4,5,6]. In contrast to snow extent, reliable quantitative knowledge on seasonal snow mass and its trend is lacking[7,8,9]. Here we use the new GlobSnow 3.0 dataset to show that the 1980–2018 annual maximum snow mass in the Northern Hemisphere was, on average, 3,062 ± 35 billion tonnes (gigatonnes). Our quantification is for March (the month that most closely corresponds to peak snow mass), covers non-alpine regions above 40° N and, crucially, includes a bias correction based on in-field snow observations. We compare our GlobSnow 3.0 estimates with three independent estimates of snow mass,

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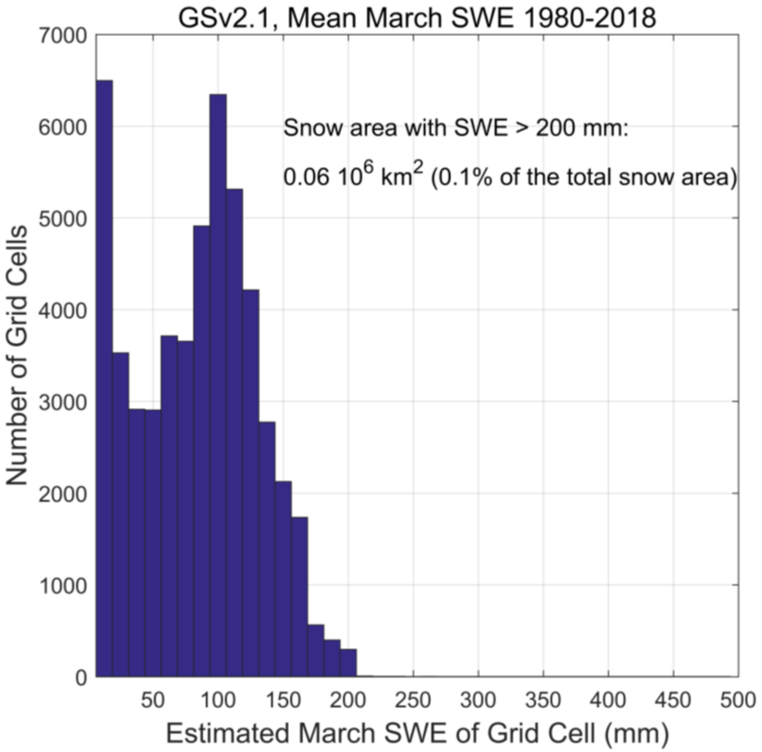
Results from bias-corrected satellite-based SWE CDR for 1979-2018

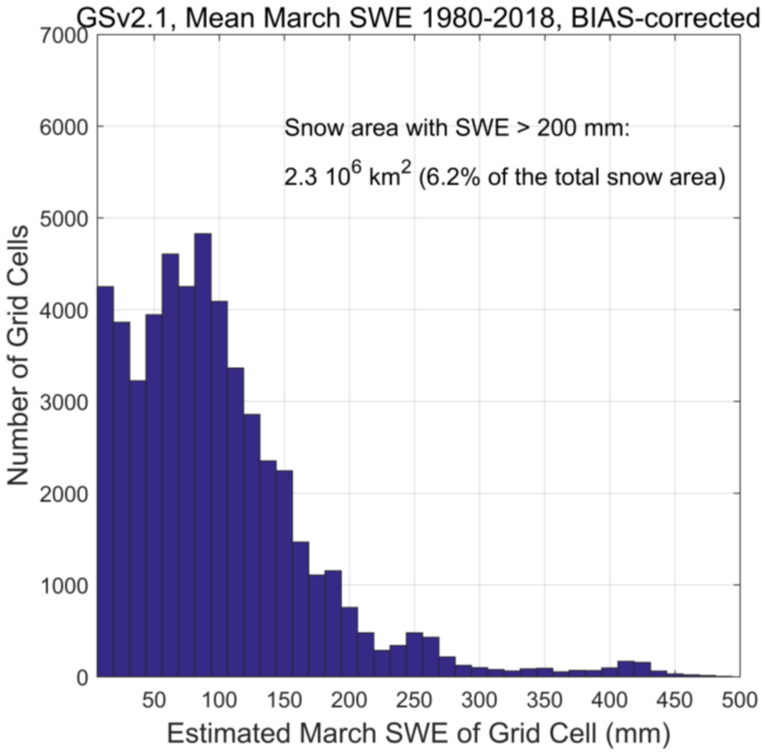
- The bias-correction corrects (increases) especially the problematic ”deep snow” SWE estimates (typical under-estimation of deep snow is corrected to a significant degree)



GSv2.1, Mean March SWE 1980-2018

Snow area with SWE > 200 mm:

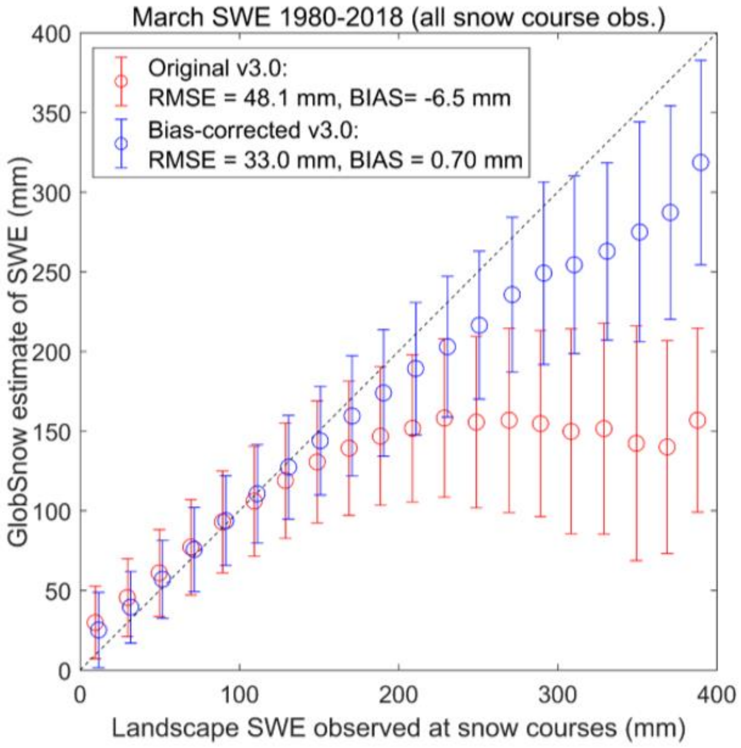
0.06 10^6 km^2 (0.1% of the total snow area)



GSv2.1, Mean March SWE 1980-2018, BIAS-corrected

Snow area with SWE > 200 mm:

2.3 10^6 km^2 (6.2% of the total snow area)



March SWE 1980-2018 (all snow course obs.)

Original v3.0:
RMSE = 48.1 mm, BIAS= -6.5 mm
Bias-corrected v3.0:
RMSE = 33.0 mm, BIAS = 0.70 mm

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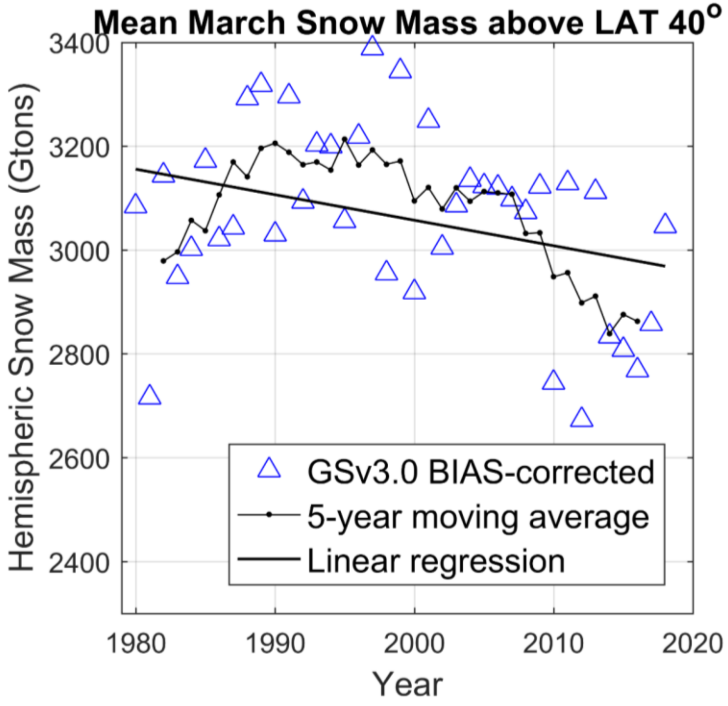
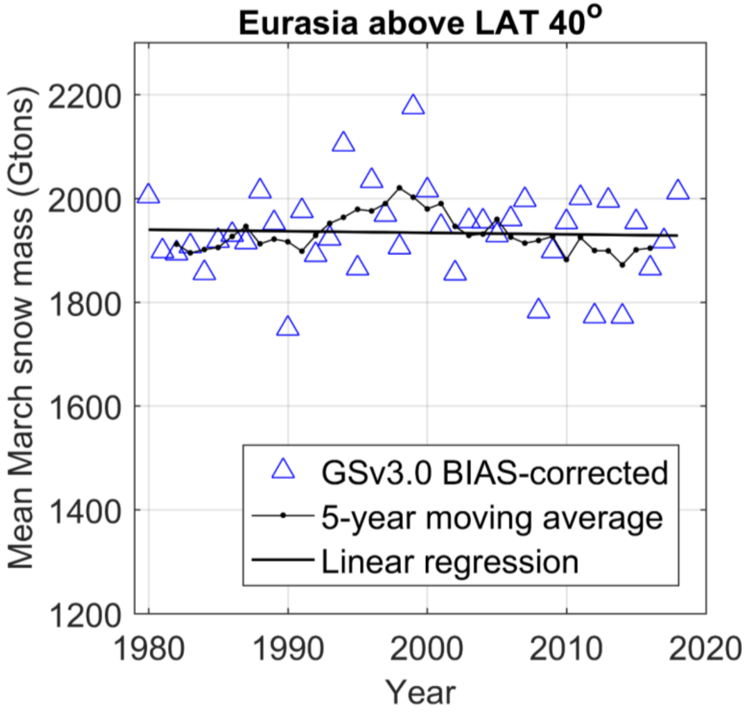
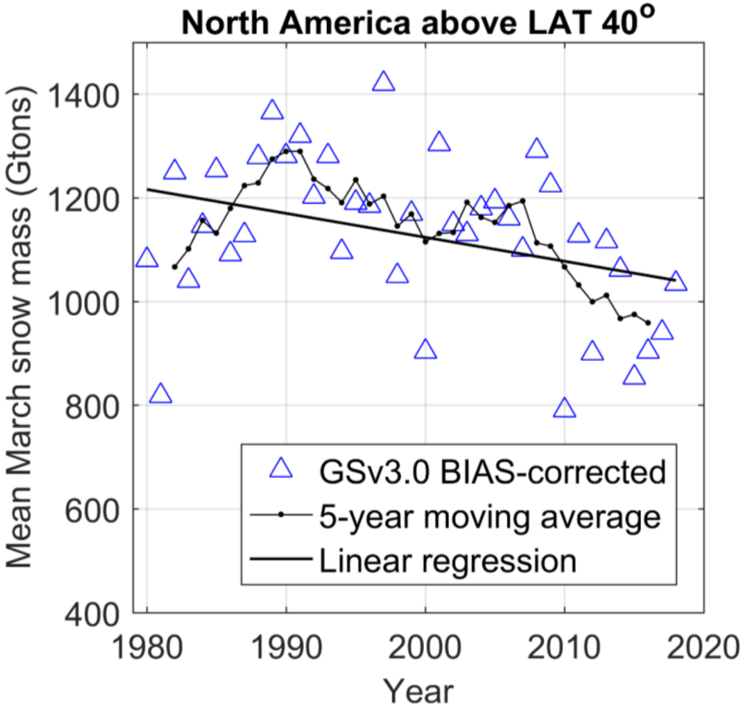
Bias-corrected satellite-based SWE mean March snow mass on northern hemisphere 1980-2018

- The bias-corrected dataset shows: **no significant trend** for **NH for March**
- The dataset shows no trend for Eurasia and **a slightly negative trend** for **North America**
- **Peak SWE hasn’t significantly decreased yet, spring-time snow cover extent has!**







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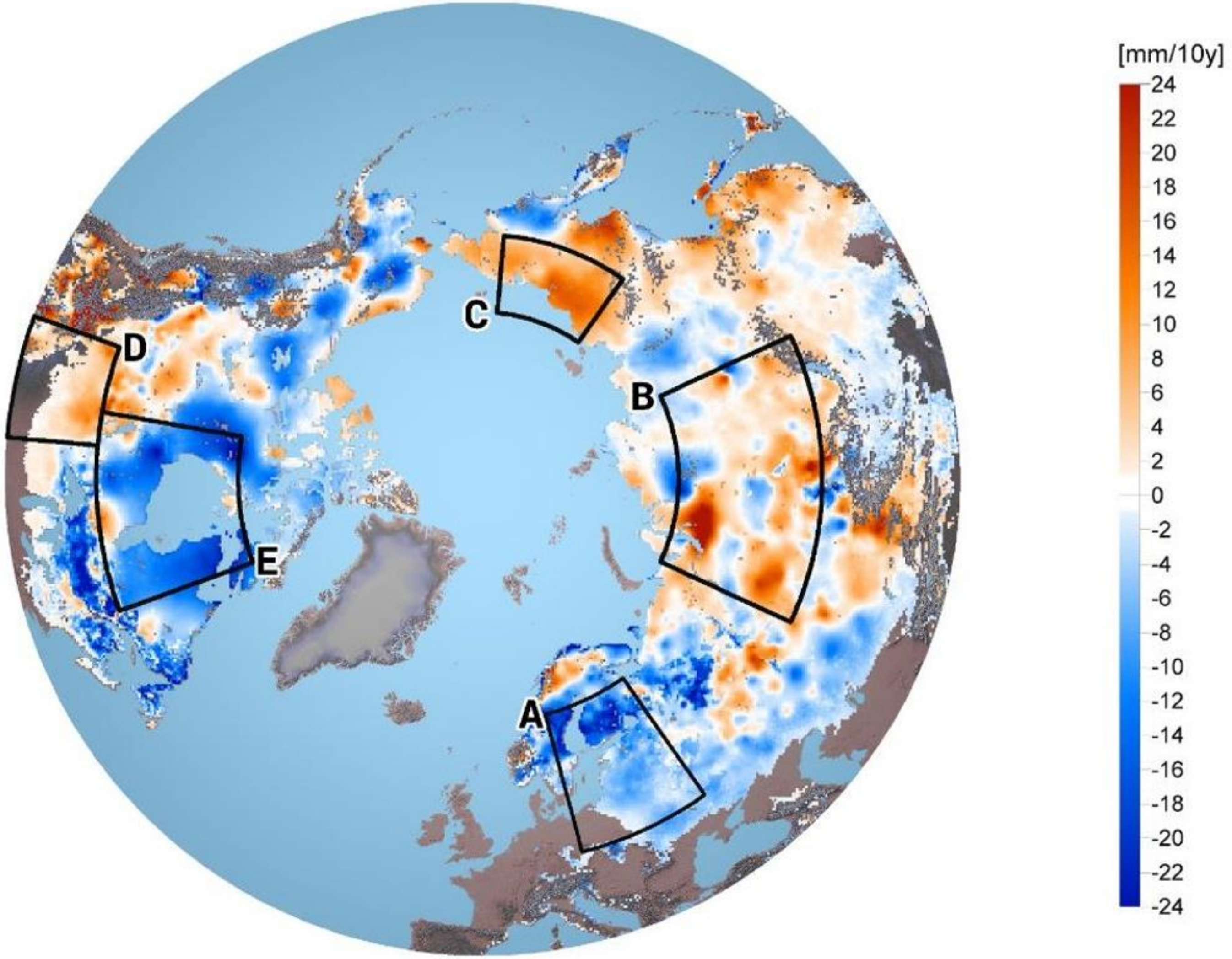
Long term changes in NH Seasonal Snow Mass (from bias-corrected satellite-based SWE)

- Decadal changes in NH snow mass [mm/10 years]
  High regional variability in snow mass trends on both continents are obvious



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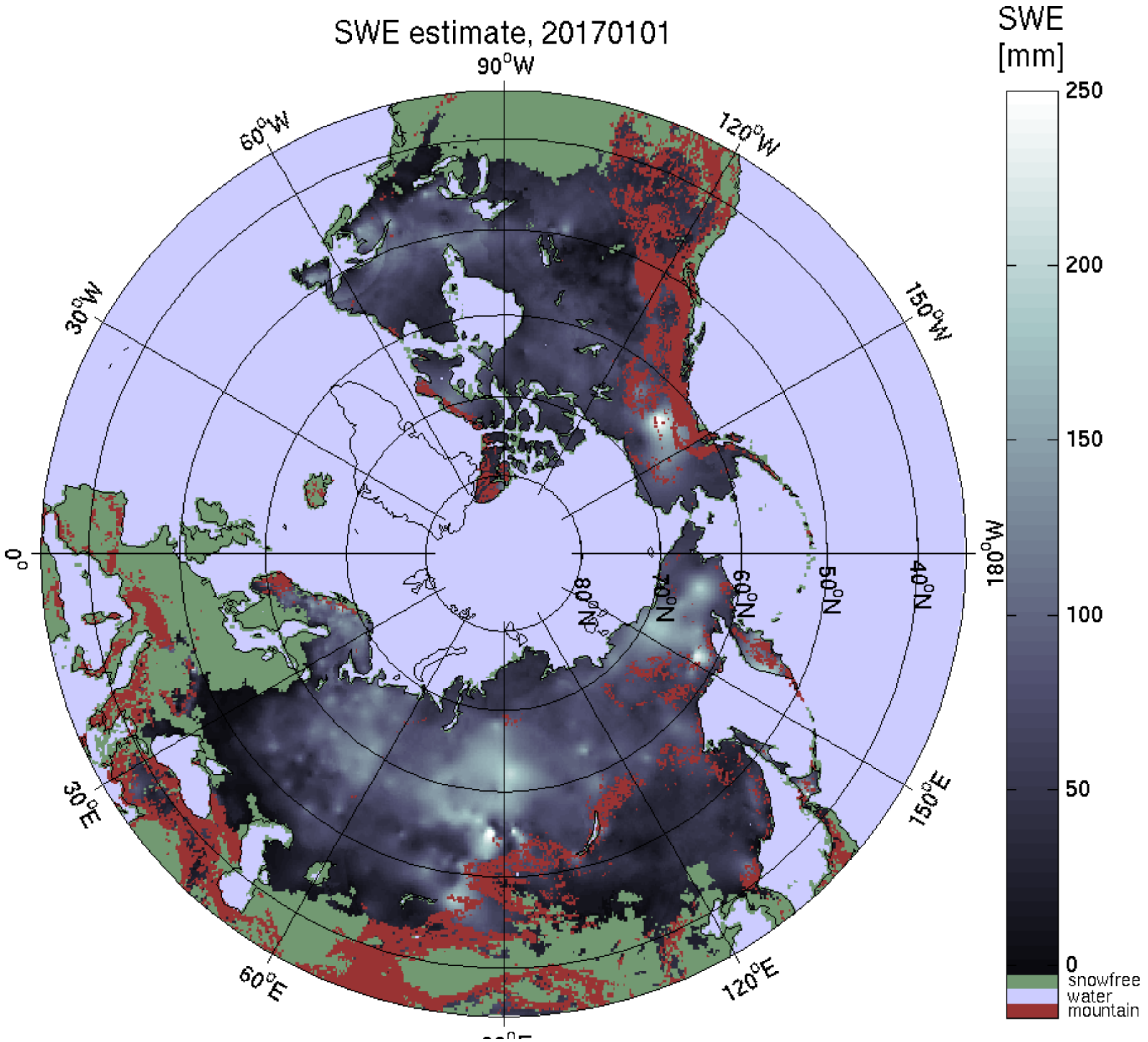
EUMETSAT H SAF H65 SWE NRT product

FMI participates in the EUMETSAT Hydro SAF (Satellite Application Facility) with the Near Real Time SWE product

The current operational SWE product H13 (Pan European region) will be replaced with Northern Hemispherical H65 product (brought online during 2021)

The mountains (in the sample image masked out) will be provided by Turkish State Meteorological Service (TSMS) -> providing a full NH-wide coverage

Once EUMETSAT EPS-SG satellites are launched the H65 product will be based on MWI (Microwave Imager) data



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EUMETSAT
H SAF
SUPPORT TO OPERATIONAL HYDROLOGY AND WATER MANAGEMENT

Copernicus Imaging Microwave Radiometer (CIMR)

Mission Objective

Respond's directly to the ***Integrated EU Arctic Policy***

- Climate Change and Safeguarding the Arctic
- Environment Sustainable Development in and around the Arctic
- International Cooperation on Arctic Issues
- Global SST capability

Characteristics (To be Confirmed)

- Conically scanning multi-frequency microwave radiometer
- Single satellite, Observation Zenith angle 55±1.5°
- Loose convoy flight with MetOp-SG(B) ~300s separation
- ~95% global coverage every day, mean 6 hourly-revisit in Arctic Areas
- In Phase A/B1, Launch: 2025

Channels (GHz, all H&V):	**1.4,**	**6.9,**	**10.65,**	**18.7**	**36.5**
Resolution (km):	**≤55**	**10**	**≤10**	**≤5**	**≤5**
NEΔT (K @150K):	**≤0.3**	**≤0.2**	**≤0.3**	**≤0.3**	**≤0.7**
Swath	> 1900km				

Products (Performance TBC, P=Primary, S=Secondary)

P1: Sea Ice Concentration (≤5 km, 5%)

P2: Sea Surface Temperature (10 km, ~0.2 K)

S: Sea Ice Drift (≤25 km, 3 cm/s)

S: Thin Sea Ice Thickness (~40 km, 10%)

S: Snow on Sea Ice

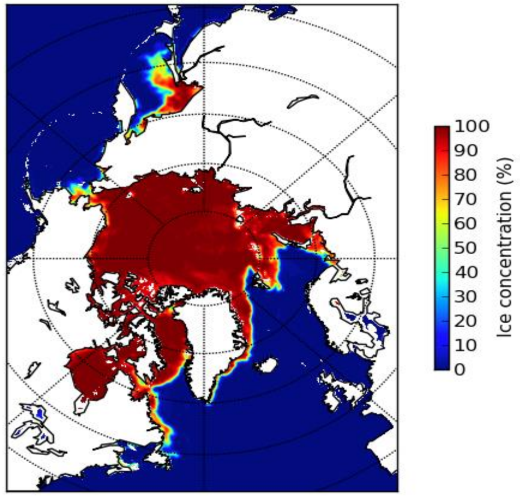
S: Snow Water Equivalent

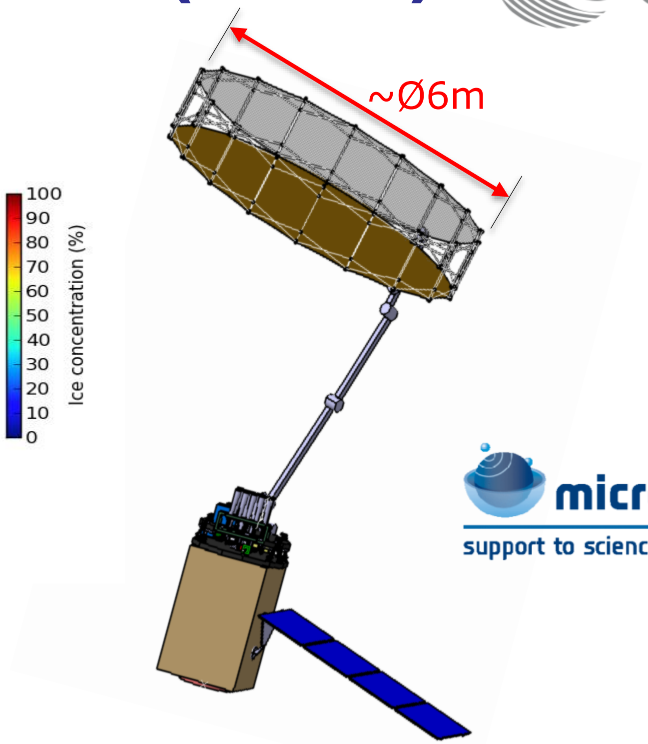
S: Sea Surface Salinity (~40 km)

S: Ice Type (≤5 km)

S: Extreme Wind

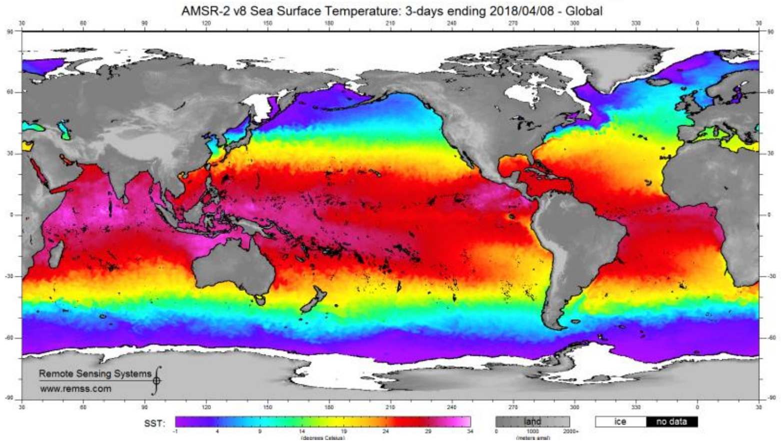
Additional tertiary products (eg. global soil moisture, water vapour, precipitation rate…)





microwat
support to science element

FMI participates the on-going Mission studies. CIMR will be excellent for SWE retrieval!



Conclusions

Efforts in the ESA Snow CCI project are on-going to improve the retrieval of SCE and SWE records from satellite data – several updates to earlier “GlobSnow” SWE retrieval methodology

Further R&D: Dynamic snow density, improved spatial resolution, a new bias-correction method
-> significantly improved satellite-based SWE climate data record!

There has been a significant spread in NH snow mass between the satellite and model-based estimates

-> A new bias-correction methodology significantly decreases the NH snow mass uncertainty -> Allowing us to determine for the first time reliably the trends and patterns of the NH snow mass for 1980-2018

Key results:

- Overall NH SWE uncertainty ~33% -> 7% [950Gt -> 210Gt]
- Slightly decreasing March NH Snow mass trend for 1980-2018, driven by changes in North America

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snow cci