Efforts to Improve the Northern Hemisphere Snow Water Equivalent Retrievals in the ESA CCI+ Snow Project

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Efforts to improve Snow Water Equivalent retrievals from satellite-data

Contents:

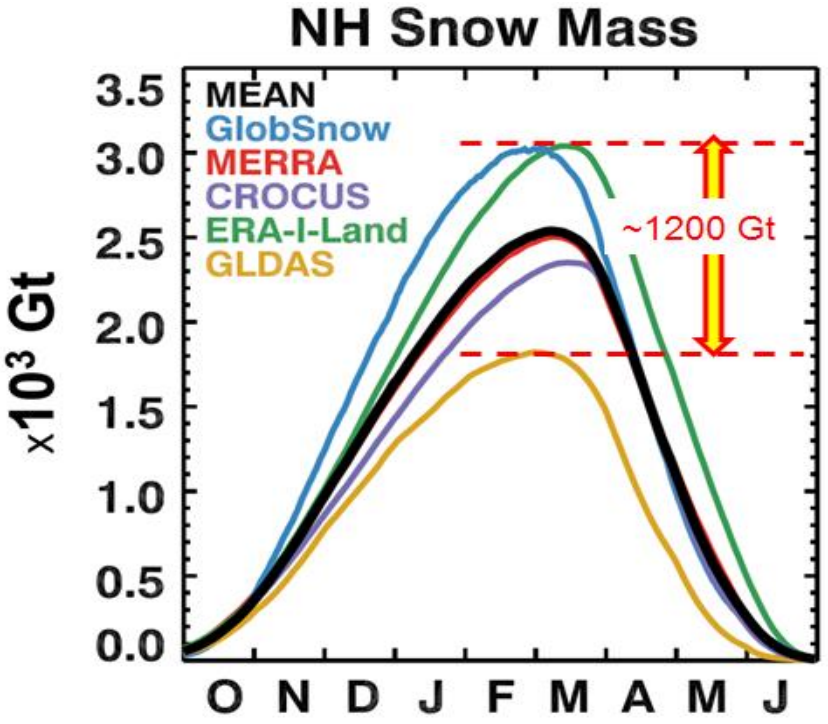
1) What do we know about Northern Hemisphere Snow Mass

2) Our current efforts to improve satellite-based SWE retrieval methodologies

Uncertainty in NH Seasonal Snow Mass

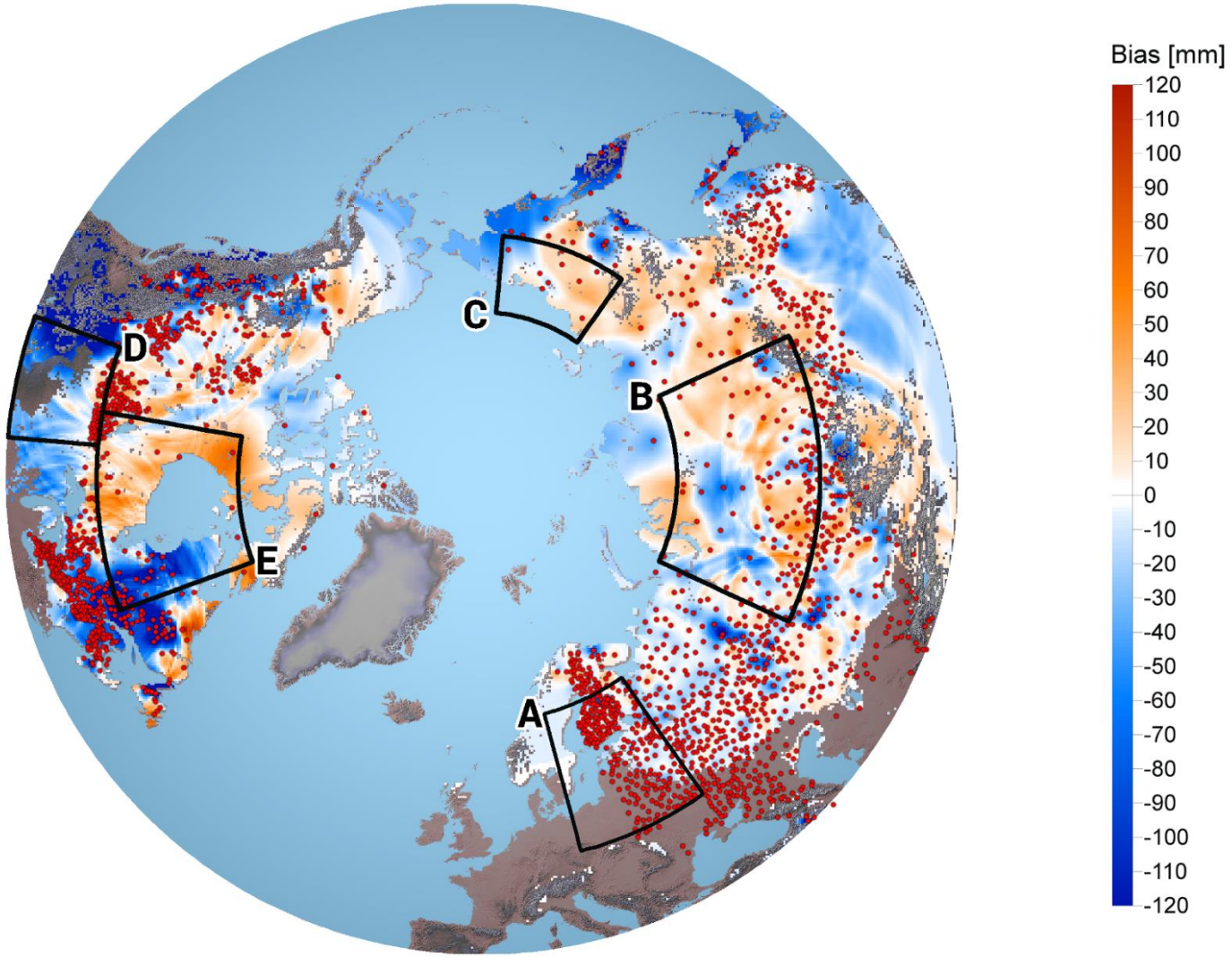
Goal: Accurate determination of the NH snow mass and its changes over the past 40 years
(using available satellite-, model- & surface-based obs.)

- Satellite & model estimates show a high uncertainty with NH Peak SWE conditions:
  - ESA SnowPEx-1 ~1900-3100Gt
  - ESA SnowPEx-2 indicate higher snow masses (and still large overall spread) with next generation snow models
- With high uncertainties – reliable trend analysis has been very challenging!
- A new approach: Bias correction of the satellite-based data with surface-based reference data (snow transect data from Fin/Can/Rus)



Improving the accuracy of snow mass estimation by correcting the systematic error = bias-correction

Bias-correction is done by analyzing and quantiying the difference between SWE estimates and independent hydrological snow course observations of FSU/Russia, Canada and Finland

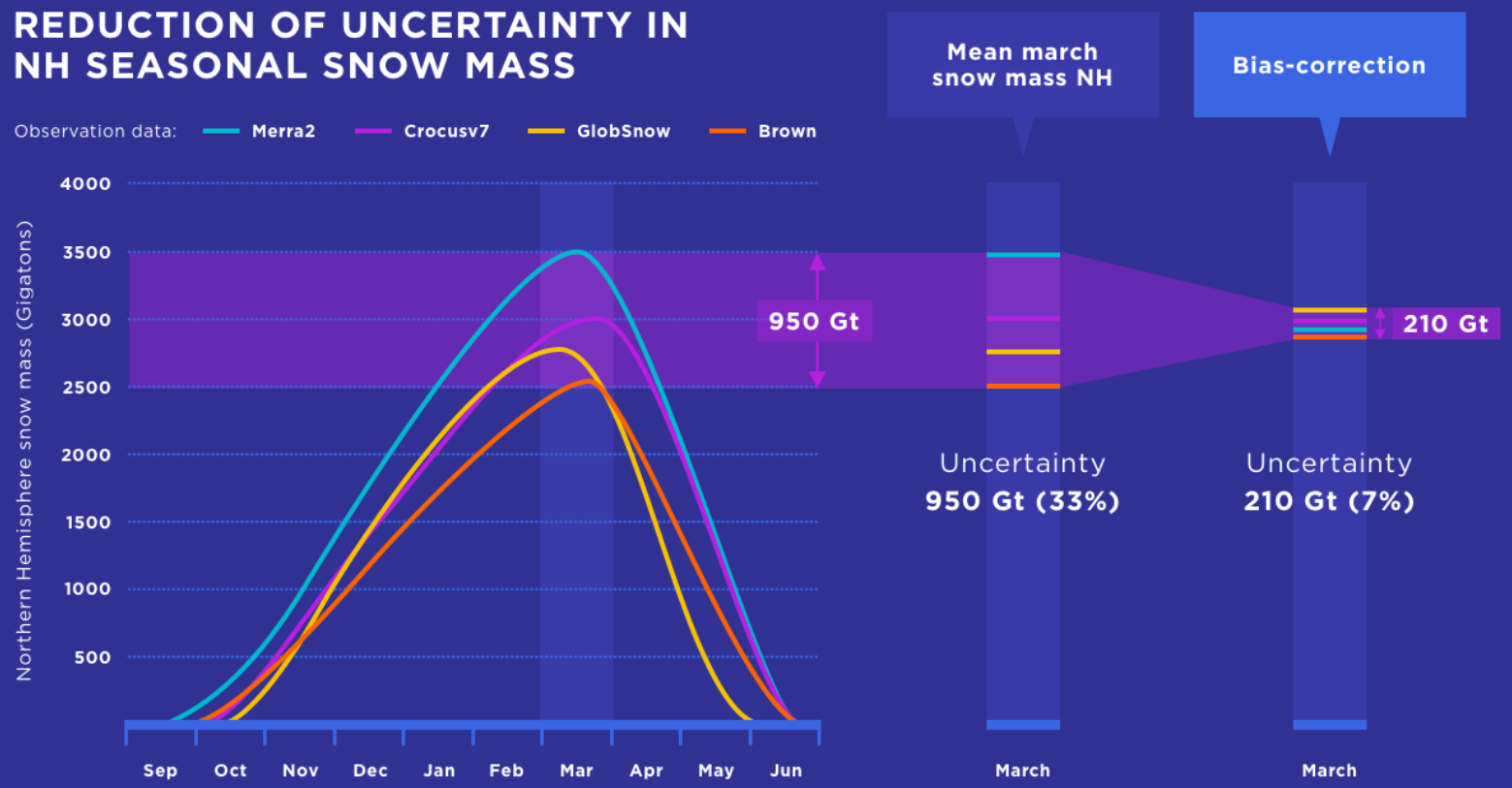


First reliable assessment of Northern Hemisphere (NH) snow mass and its evolution

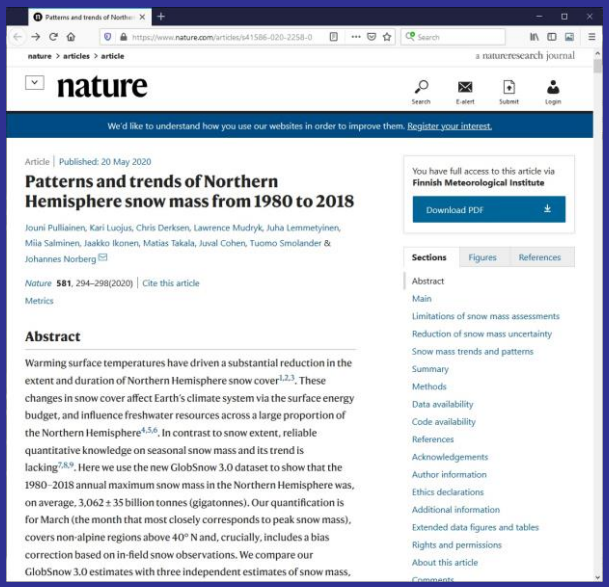
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Pulliainen, J., Luojus, K., Derksen, C. et al. Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. Nature 581, 294–298 (2020). https://doi.org/10.1038/s41586-020-2258-0

- Large spread earlier in NH snow mass between satellite and reanalysis/model-based estimates
  - → The developed bias-correction decreases the spread when applied to different products
  - → The introduced GlobSnow v3.0 assimilation product is uniquely positioned for trend analyses (stable bias)

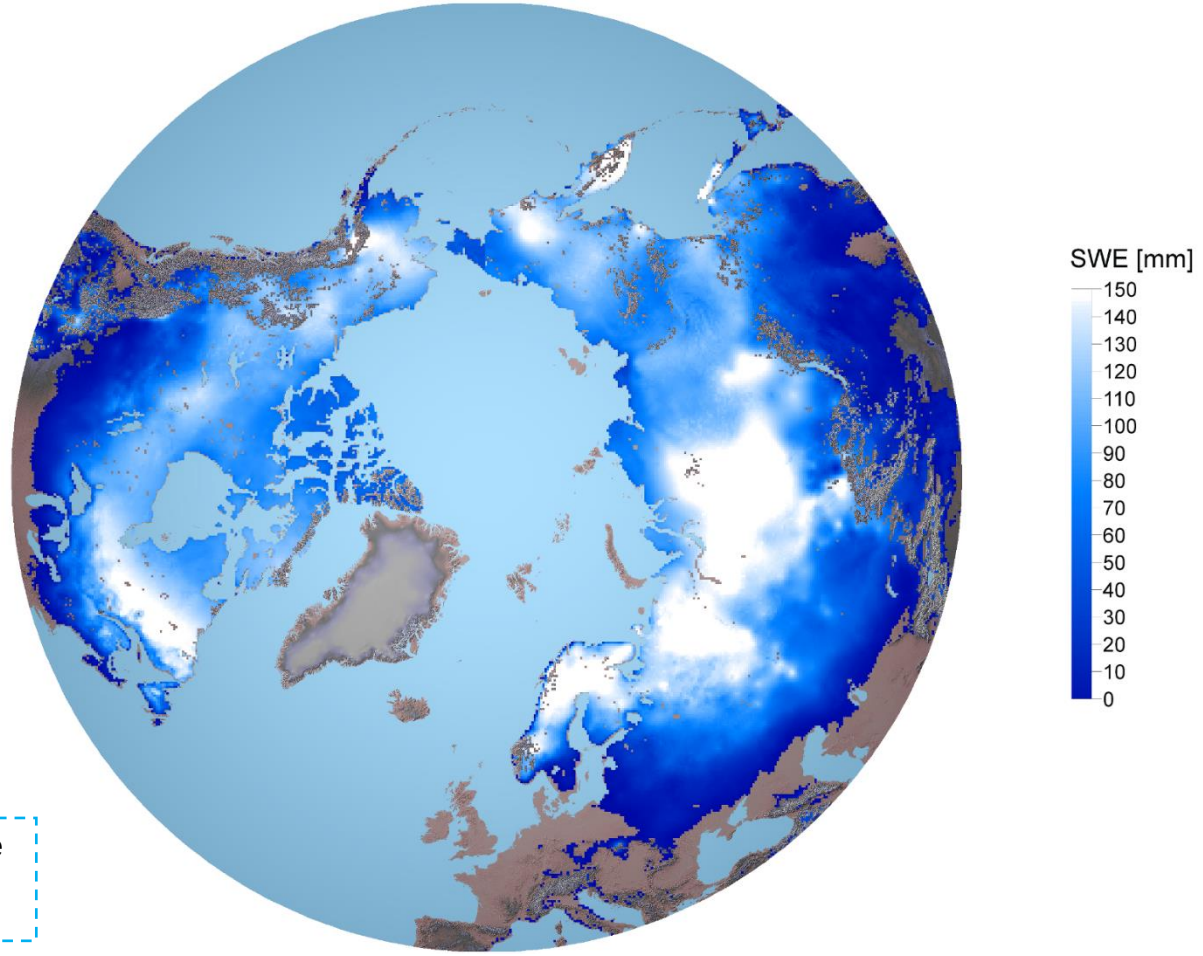






Maximum seasonal snow mass across 1980-2018 and its spatial distribution

- March SWE [mm] based on GlobSnow v3.0 / Snow CCI v1.0 data
- Fusion of satellite and in situ data on snow depth (from synoptic weather stations)
- Alpine regions excluded
    - Due to the use of satellite data with a coarse spatial resolution (microwave radiometers)

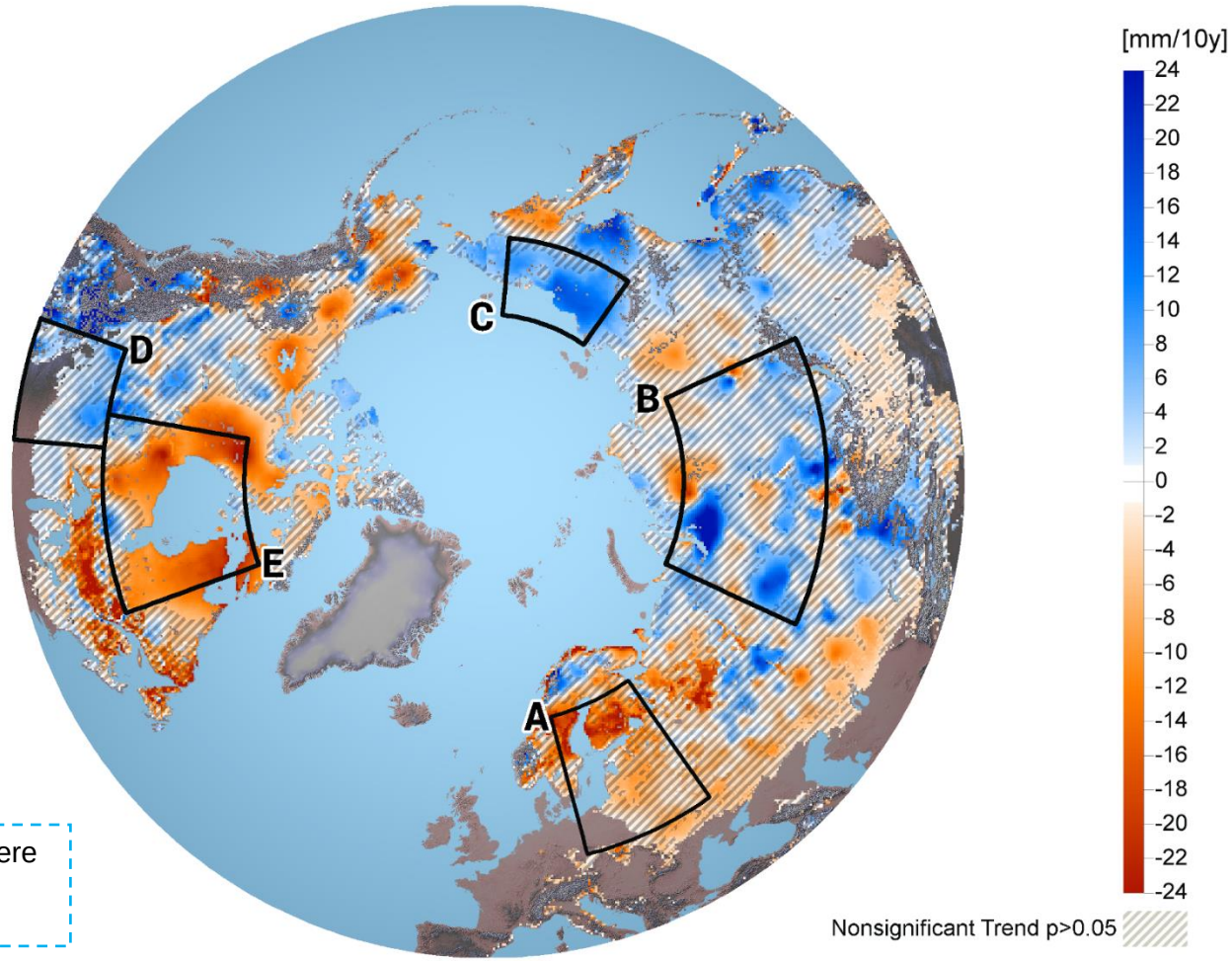


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Region above 40° N: non-alpine snow area (minimum/average/maximum) ($\times 10^6$ km^2)	Mean monthly snow mass 1980–2018 (with error bounds)[a] (Gt)	Average SWE[b] (mm)	Snow mass trend and 95% confidence interval (Gt decade^{-1})	*P*-value of trend line
Northern Hemisphere (29/32/35)				
GlobSnow v3.0	3,062 ± 5	97	−49 ± 49	0.048
Average (range), all four products[c]	2,938 (2,846–3,062)	(90–97)		
Average (range), all without bias correction	2,867 (2,433–3,380)	(77–107)		
Alpine areas, average (range)[d]	709 (482–937)	(96–187)		

Long term changes in NH seasonal snow mass

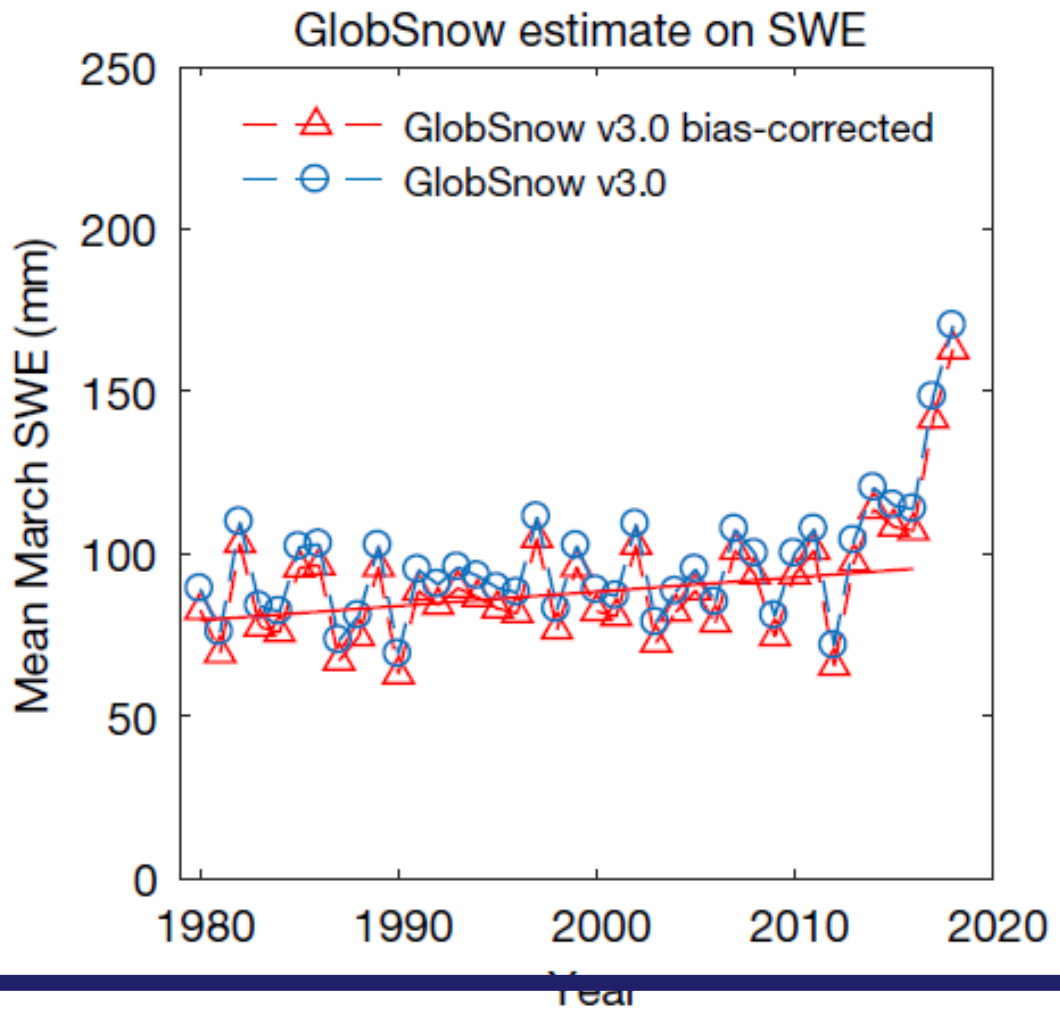
- Decadal trend in NH snow mass [mm/10 years] based on GlobSnow v3.0
- Determined from a period of 39 years (1980-2018)
- Regional differences are strong
- Negligible overall trend in Eurasia
- Declining trend in North America

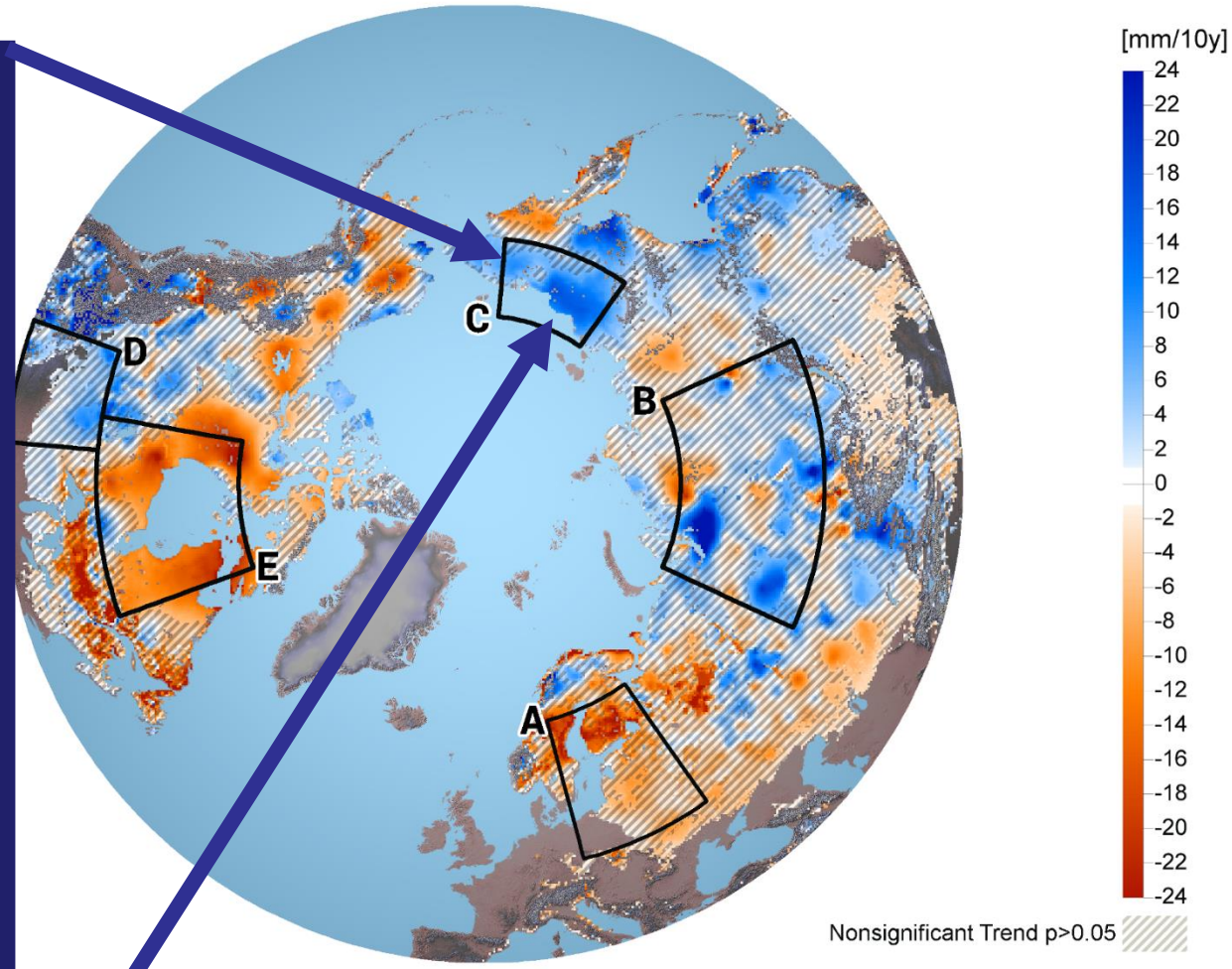


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GlobSnow v3.0 based regional trends	Latitude–longitude grid (°)	SWE trend with 95% confidence interval (mm decade^{-1})	*P*-value of trend line
A. Europe (Baltic)	50° N to 65° N, 15° E to 35° E	−6.3 ± 5.3	0.020
B. Siberia (western-central)	55° N to 70° N, 65° E to 115° E	3.1 ± 2.9	0.038
C. East Siberia	65° N to 73° N, 145° E to 175° E	8.6 ± 4.9	0.001
D. Prairie (USA, Canada)	40° N to 50° N, 110° W to 95° W	2.8 ± 2.7	0.039
E. Hudson Bay area	50° N to 65° N, 100° W to 70° W	−8.5 ± 3.9	0.000

Unlike other regions, region C shows an abrupt increase during the recent years





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Efforts to improve Snow Water Equivalent retrievals from satellite-data

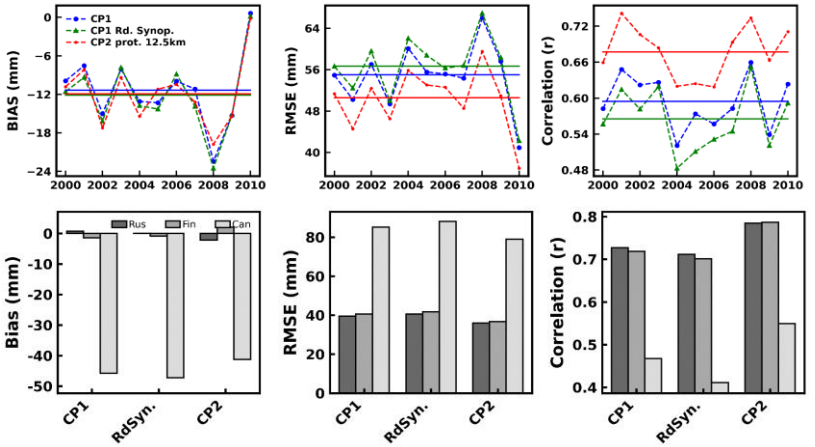
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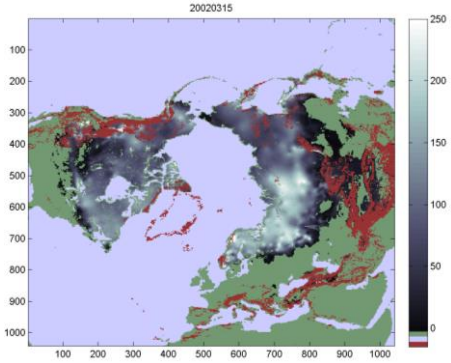
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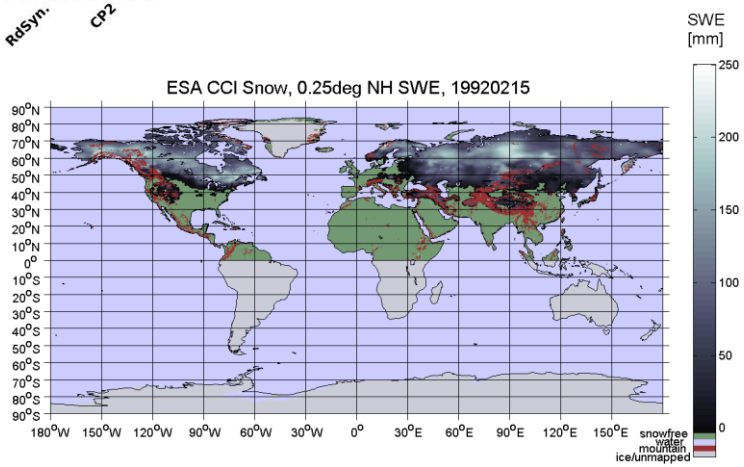
ESA Snow CCI – Updated PMW SWE v2 dataset
(published in Q1/2022)

Validation shows improved performance compared with CCI v1 data



Enhanced resolution
12.5km “SIR” input data





Snow CCI v2 SWE data record:

- Improved spatial resolution (0.10°)
  - Utilization of 12.5km EASE2 “SIR” enhanced resolution input data
  - Geographical (lat/lon) projection, provided in a global grid
- Time series: 6 Jan. 1979 – 31 May 2020
- Dynamic snow density
  - Utilization of spatially and temporally dynamic snow density in SWE retrieval (post-processing)
- Synergistic utilization of optical snow extent data in SWE retrieval
  - Snow CCI & JAXA SCE datasets applied to enhance SWE retrieval
- Updated/homogenized input datasets

“Venäläinen, P., Luojus, K., Lemmetyinen, et al. (2021): Impact of dynamic snow density on GlobSnow snow water equivalent retrieval accuracy, The Cryosphere, 15, 2969–2981, https://doi.org/10.5194/tc-15-2969-2021

Mortimer et al. (2022) Benchmarking algorithm changes to the Snow CCI+ snow water equivalent product, Remote Sensing of Environment, (274)112988, https://doi.org/10.1016/j.rse.2022.112988

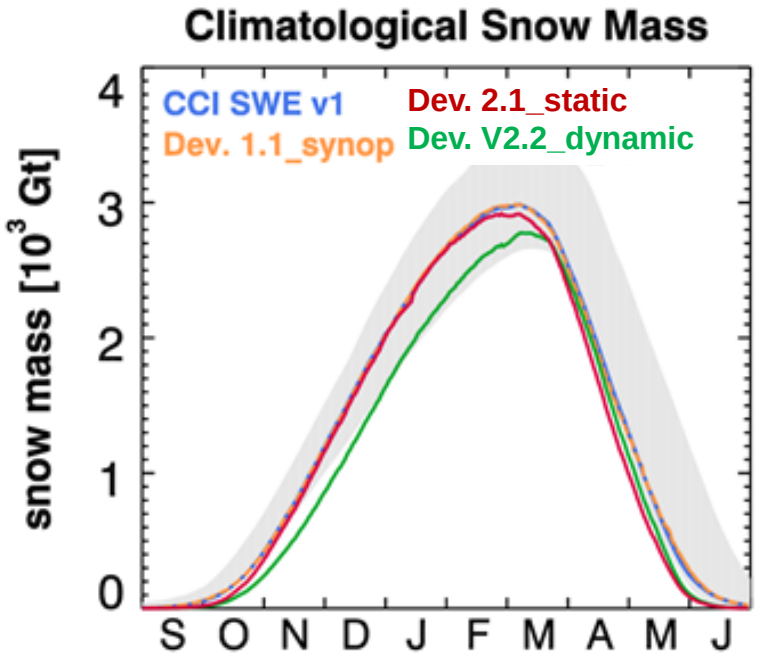
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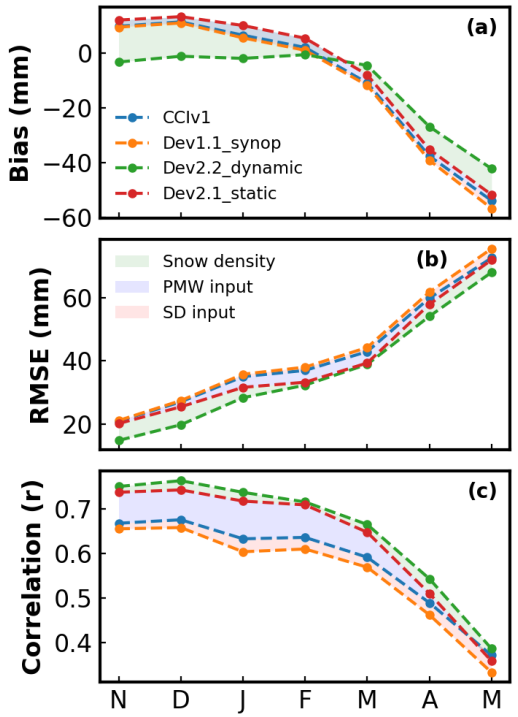
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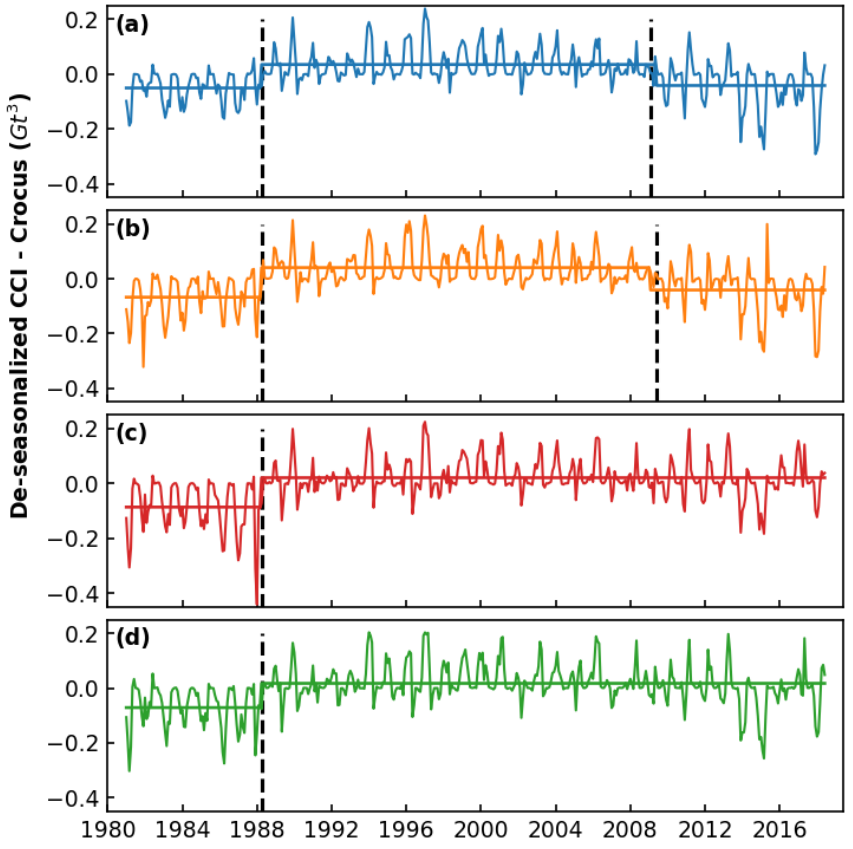
esa snow cci

Snow CCI v2.0 SWE improvements

- PMW **data/grid spacing** and **dynamic snow density** modifications are implemented in CCI v2.0
- **Updated PMW** data and **snow density** contributed **equally** to improvements in RMSE and correlation. **Step change** in previous CDR from **SSM/I to SSMIS transition corrected**.
  -> Long term stability of the SWE data record further improved.
- **Snow density** alters the seasonal evolution of snow mass (issue caused by its application in post-processing -> to be fixed with v3.0).



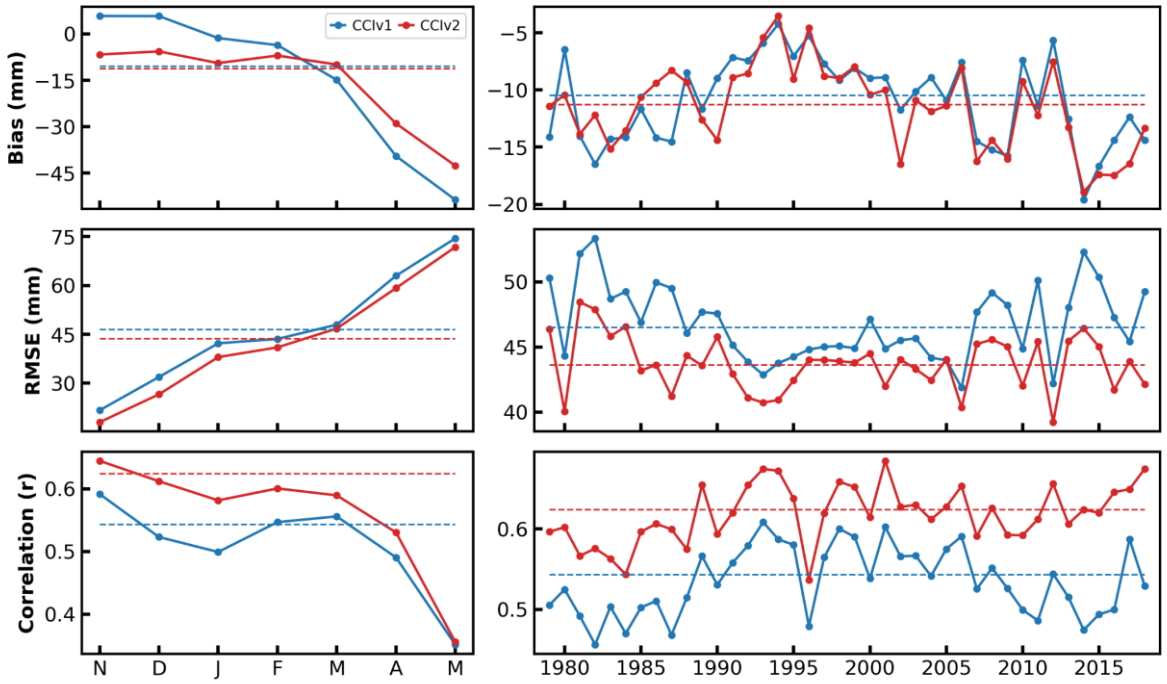




Mortimer et al. (2022) Benchmarking algorithm changes to the Snow CCI+ snow water equivalent product, Remote Sensing of Environment, (274)112988, https://doi.org/10.1016/j.rse.2022.112988

Snow CCI v2.0 SWE (0.1° x 0.1°)

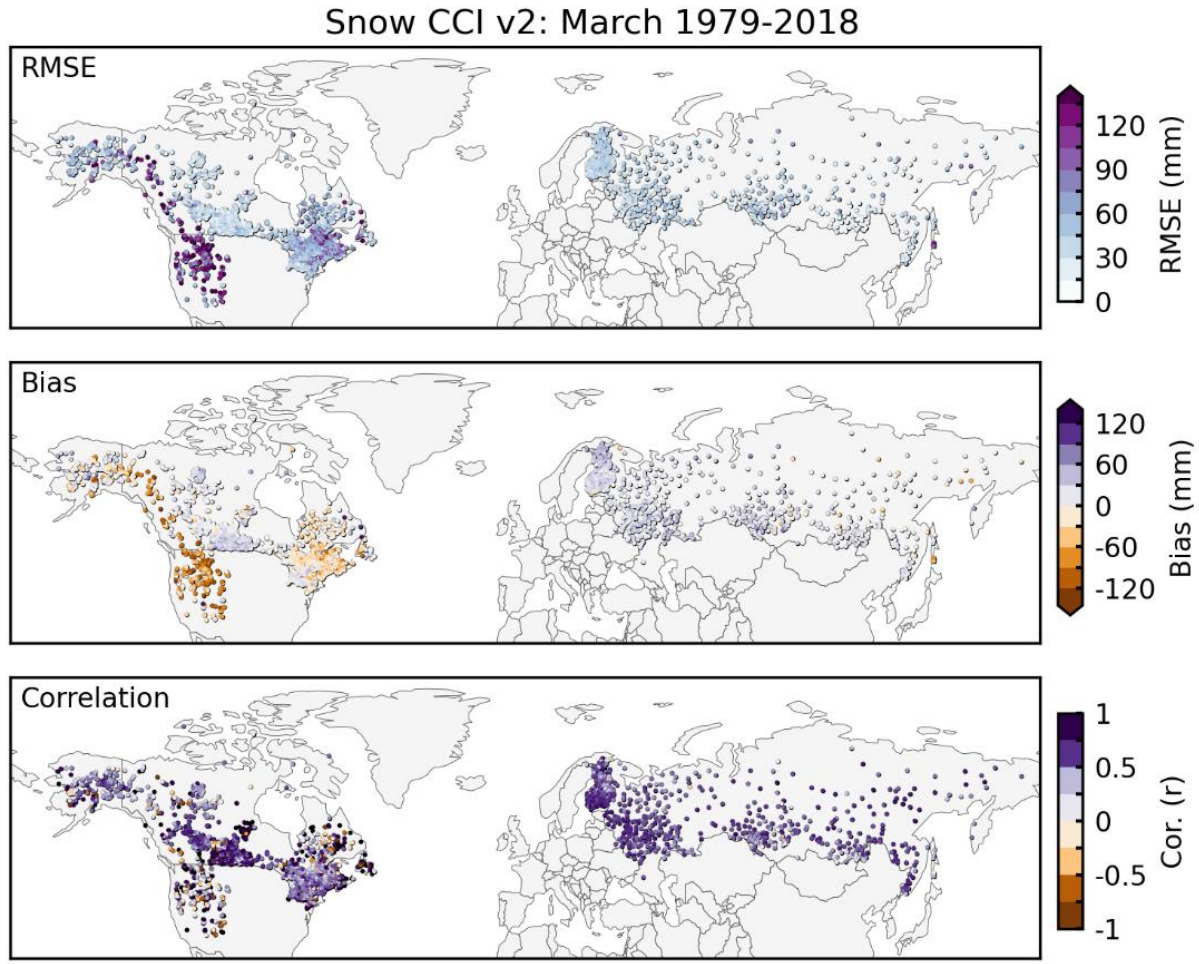
- Assessed against snow courses for SWE ≦ 200 mm.
- Performance is best over Finland and Russia and poorest over the western United States and Alaska where the terrain is complex and SWE magnitude is high.



Mortimer et al. (2022) Benchmarking algorithm changes to the Snow CCI+ snow water equivalent product, Remote Sensing of Environment, (274)112988, https://doi.org/10.1016/j.rse.2022.112988

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ESA SNOW CCI 2 – further SWE development

ESA Snow CCI 2
2 phases
-> 2 new SWE CDRs

Currently on-going algorithm development items:

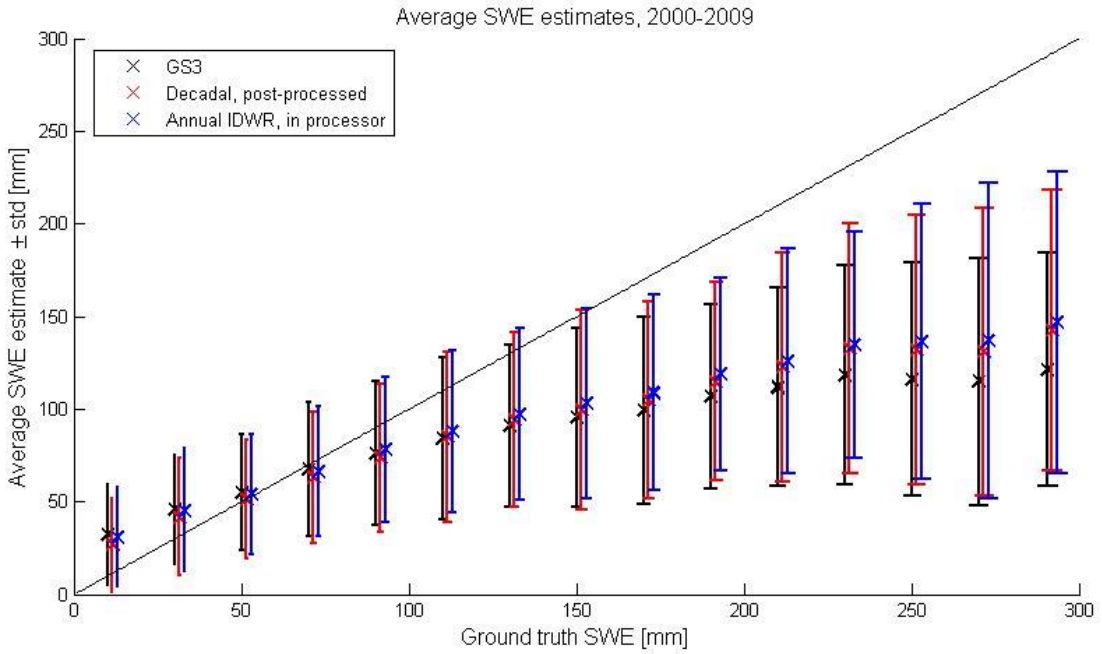
- SWE development is a **joint collaboration** between **FMI** & **ECCC**

1. Synergistic use of optical-based SCE and PMW-based SWE data
2. Improved estimation of early winter SWE retrieval (improved PMW-based snow detection)
3. Dynamic Snow Density within SWE retrieval (currently applied in post-processing)
4. Assessment of the impact of the input Tb spatial resolution change from 25 to 12.5 to 6.25km
   - Initial studies to move towards ~6.25km resolution
5. Feasibility study of improved SD background field, e.g. using 3D-kriging for SD field determination
6. Updated auxiliary datasets (improved mountain mask for NA + Eurasia)
7. Uncertainty update & update of systematic bias in uncertainty
8. Update of bias-correction (Nature method) + updated monthly SWE product & trend analyses

Dynamic Snow density (in retrieval) SWE retrieval accuracy

- Implementing IDWR interpolated densities into the algorithm improves RMSE and MAE by about 4 mm (8 % gain) and 5 mm (16 % gain) when compared to the previous GlobSnow product with static snow density

- Varying snow densities reduce underestimation of large SWE values and overestimation of small SWE value as SWE values are scaled with dynamic densities.



Details in poster by Pinja Venäläinen on Tuesday

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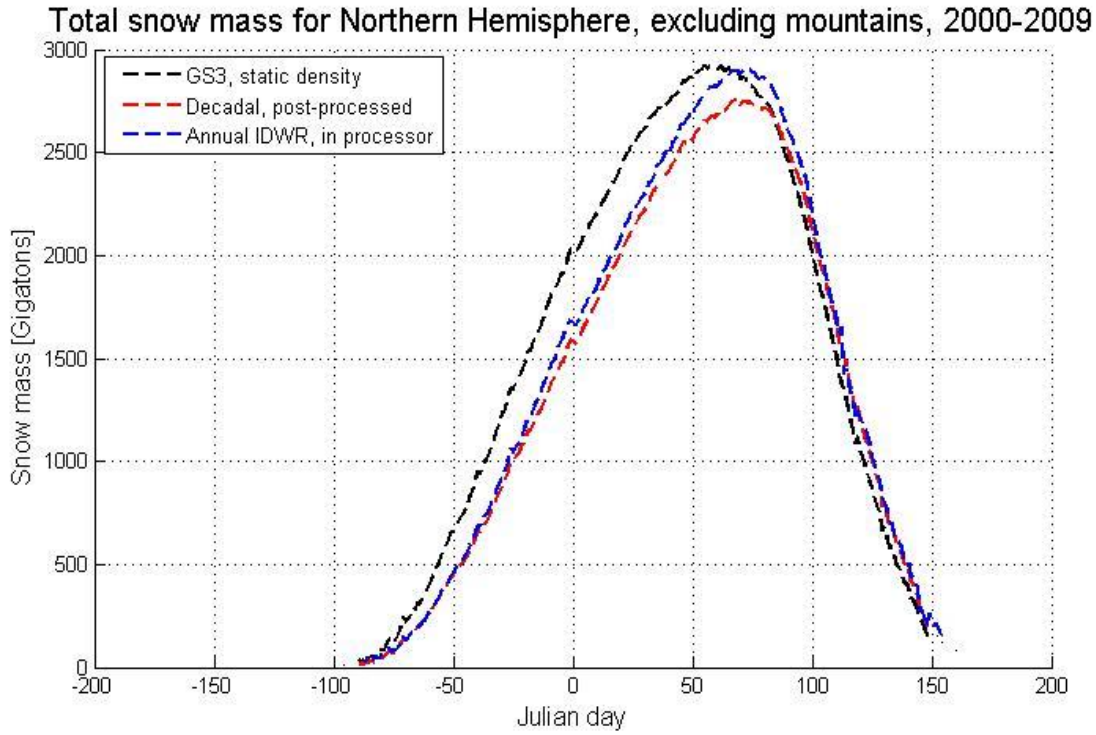
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Dynamic Snow density (in retrieval) Northern hemisphere snow mass

- Post-processing improves SWE retrieval but reduces the total northern hemisphere snow mass when compared to GSv3.0, which itself is biased low.
- Implementing dynamic snow densities into the SWE retrieval fixes this reduction in the northern hemisphere peak snow mass.
- Implementing dynamic snow densities into the SWE retrieval, and using them for post-processing, both delay the timing of the peak snow mass by around two weeks and bring it more in line with other hemispheric SWE datasets.



Details in poster by Pinja Venäläinen on Tuesday

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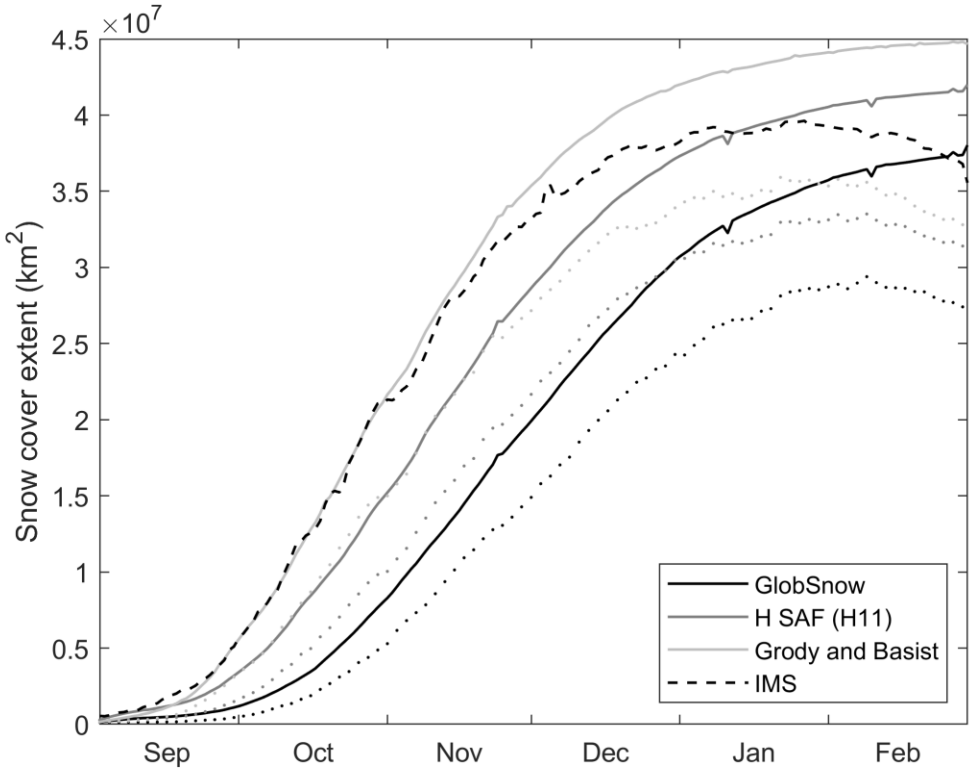
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Assessment of Dry Snow Detection Algorithms

- Comparison of six algorithms
  - using in situ snow depth data
    & spatially complete NOAA IMS snow maps
- Cumulative snow maps
  - retain detected snow throughout season
    → counteract underestimation in snow cover extent
- Decision tree by Grody and Basist (1996)
  - 84% accuracy wrt in situ, 11% difference from IMS
- EUMETSAT H SAF (H11), Pulliainen et al. (2010)
  - 81% accuracy wrt in situ, 15% difference from IMS



Details by Lina Zschenderlein - today 17:20

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Impact of improved snow detection for SWE retrieval performance

- Dry snow detection is a processing step of GlobSnow SWE retrieval
- Cumulative masks applied with snow melt detection
- Validated for 1980–2016 with in-situ snow course SWE data

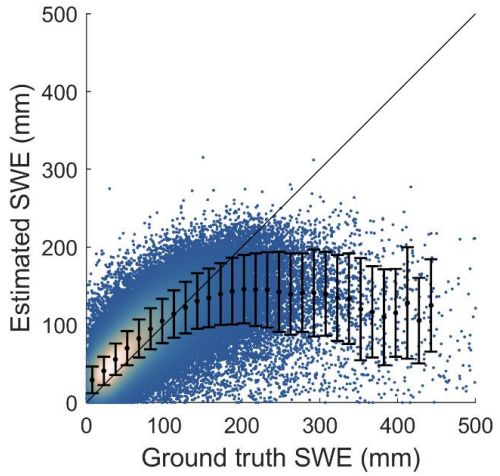
H SAF algorithm improves SWE retrieval, compared to the previous snow detection scheme (Hall et al. 2002)

Bias and RMSE are improved by:

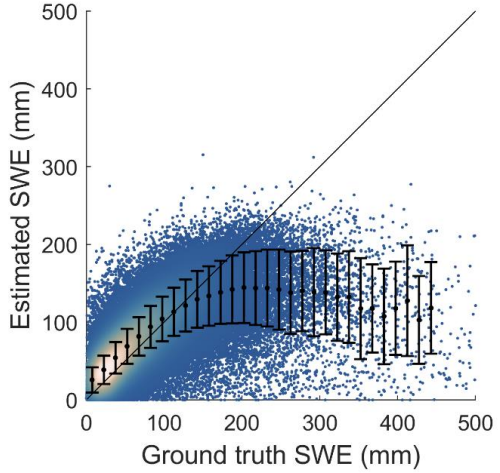
Sep-Feb (SWE ≤ 450 mm):	Bias 0.62 mm	RMSE 0.66 mm
Sep-Dec (SWE < 50 mm):	Bias 2.20 mm	RMSE 1.70 mm

→ especially during shallow snow conditions in autumn

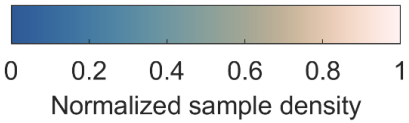
Details by Lina Zschenderlein - today 17:20



(a) GlobSnow (1980-2016)



(b) H SAF (1980-2016)

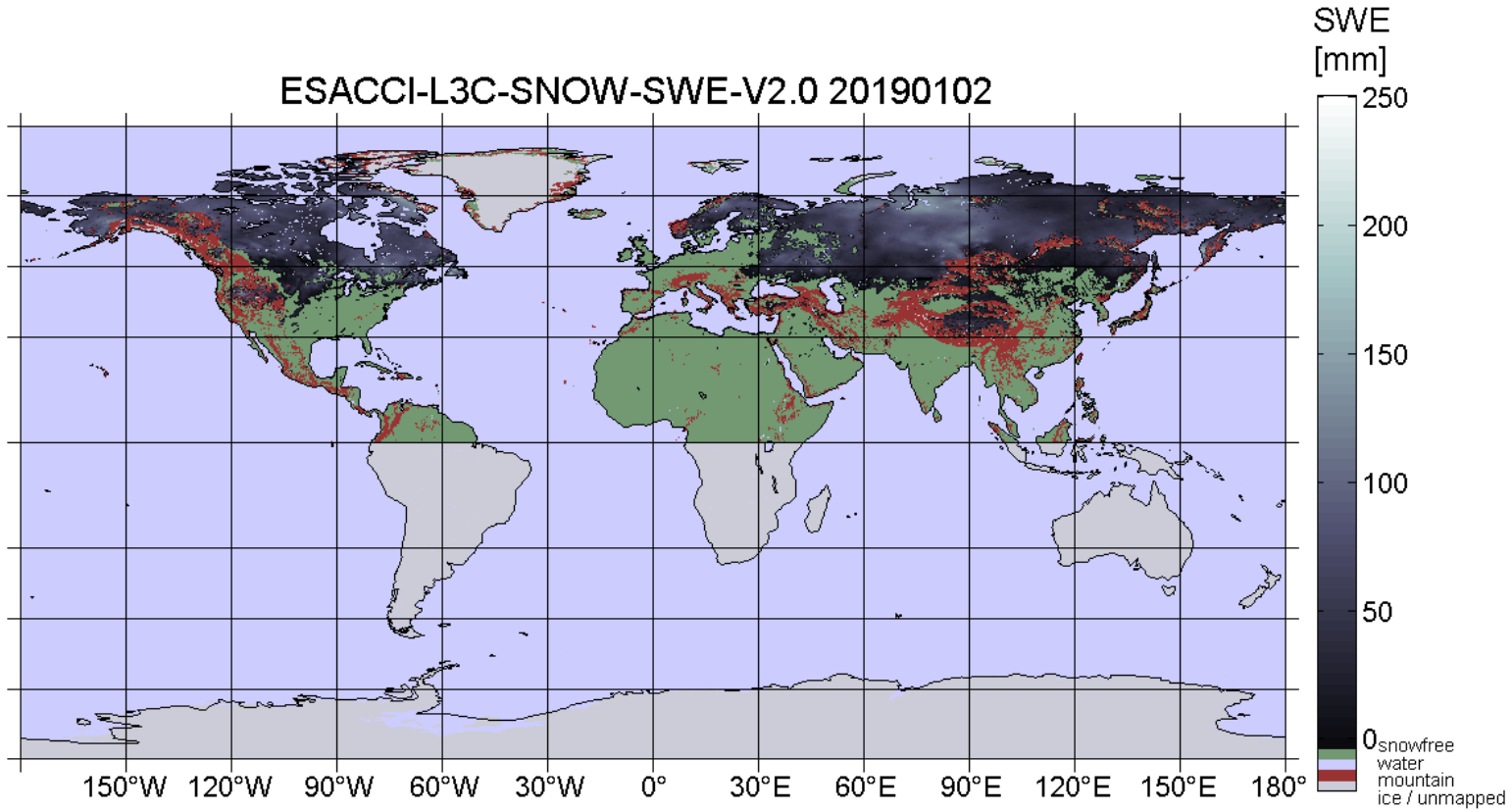


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ESA Snow CCI 2 – planned v3.0 SWE product

- Snow variable:
  - Snow water equivalent (SWE) + Uncertainty estimate (STD of SWE estimate)
  - Retrieval algorithm:
    - Luojus et al. 2021
    - Venäläinen et al. 2023 (in press)
    - Zschenderlein et al. 2023 (in press)
- Time series: 01/1979 – 06/2022
- Dynamic snow density
  - Utilization of spatially and temporally dynamic snow density **within** SWE retrieval
- Temporal specs:
  - Resolution: 1 day
  - Aggregation: Monthly (+ bias correction)
- Format: NetCDF4, CF-v1.9
- Metadata including SWE uncertainty
- Estimated release: Q4/2023



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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

- 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 B2, Launch: 2028

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

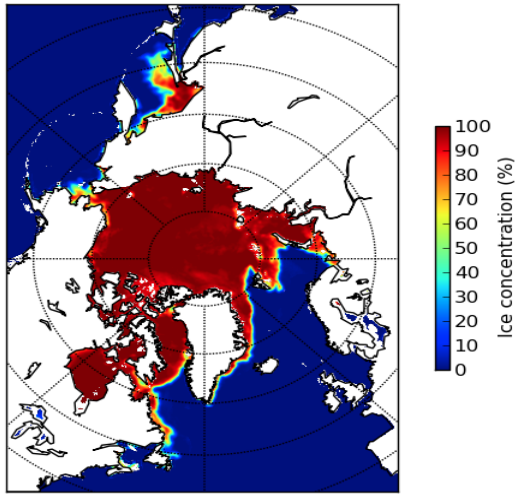
S: Snow Water Equivalent

S: Sea Surface Salinity (~40 km)

S: Ice Type (≤5 km)

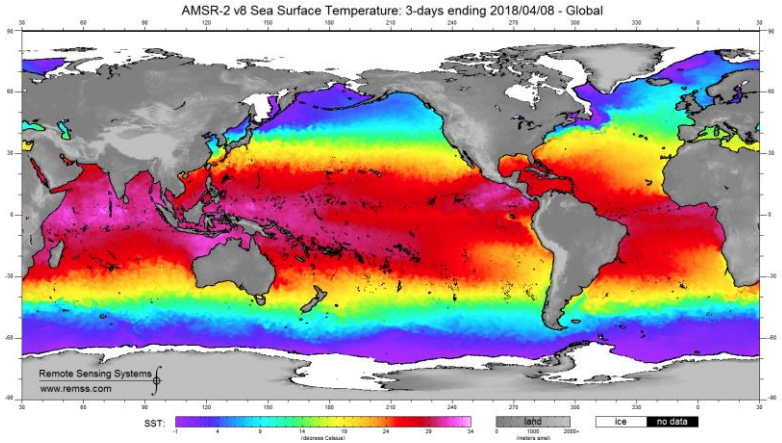
S: Extreme Wind

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





FMI participates the on-going Phase C studies.
CIMR will be a major breakthrough for SWE retrieval!
~5km spatial resolution



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ESA SnowPower project

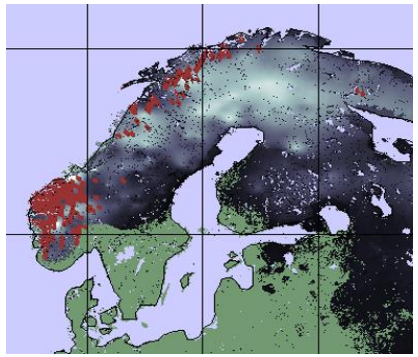
- Feasibility study on utilization of SAR-based SD/SWE estimates for hydropower optimization - *methodology: Lievens et al. 2019 & 2022*
- Project investigates the potential to combine PMW & SAR-based snow retrievals for mountains

SNOWCAP
Expert Snow Service provider (spin-off)

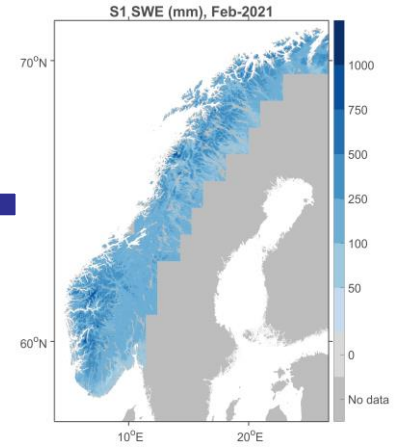
EOMAP
detect more.
Leading EO and IT service provider

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Expert Snow Service provider for Copernicus and ESA

PMW SWE



SAR-based mountain SD





Merged PMW + SAR SWE

Lievens, H., Brangers, I., Marshall, H. P., Jonas, T., Olefs, M., and De Lannoy, G.: Sentinel-1 snow depth retrieval at sub-kilometer resolution over the European Alps, The Cryosphere, 16, 159-177 (2022).

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Conclusions

Efforts in the ESA Snow CCI 2 -project are on-going to improve the retrieval of SCE and SWE records from satellite data – several updates to the established “GlobSnow” SWE retrieval methodology

Further R&D: Dynamic snow density, improved spatial resolution, updated bias-correction method
-> we’re still managing to push the state-of-the-art satellite-based SWE data records forward!

There has been a significant spread in NH snow mass between the satellite and model-based records, still evident in recent SnowPEx-2 results!

-> The bias-correction approach significantly decreases the NH snow mass uncertainty -> Allowing us to improve our estimation of trends and patterns of the NH snow mass for the satellite era (1980-2018)
-> Bias-correction to be updated in ESA Snow CCI 2

<u>Key result in observed NH trends:</u>

- Slightly decreasing trend for March NH Snow mass for 1980-2018, driven by changes in North America



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