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EO-BASED RETRIEVAL OF SNOW COVER, OVERVIEW OF SELECTED SNOW PRODUCTS AND THEIR QUALITY ASSESSMENT

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Environment Canada

SYKE

enveo

Contents

1. **EO-Based retrieval of snow cover**
   - Snow Cover Extent (SCE) and Snow Water Equivalent (SWE) retrieval using optical and PMW-based approaches
   - Examples from EUMETSAT HSAF, ESA Snow CCI+ and others
2. **Validation & quality assessment (ESA SnowPEx, Snow CCI, …)**
   - Assessment of SWE & SCE products
3. **Long term changes of the Northern Hemisphere snow mass**
   - Snow cover mass for NH 1979 – 2018 and its trend

1. EO-based retrieval of snow cover information:

Snow Cover Extent (optical)
&
Snow Water Equivalent (PMW)

Background on Optical SCE/FSC monitoring

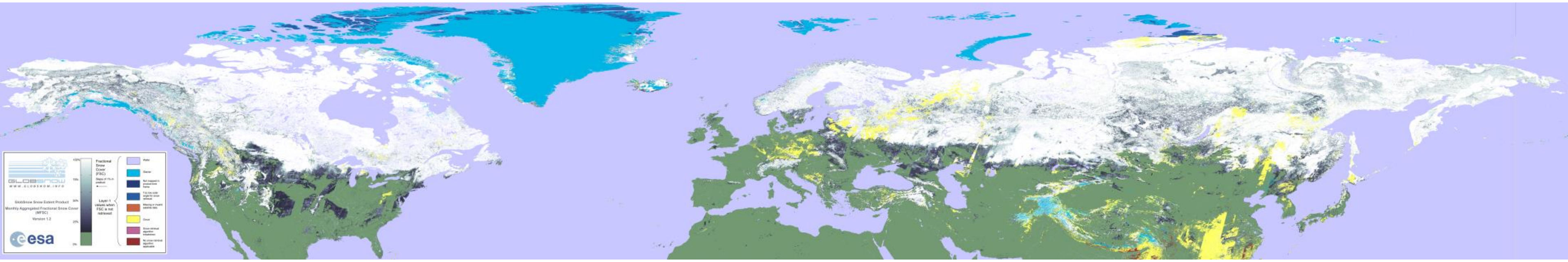
- Typical algorithms use optical to FIR bands, e.g. S3 SLSTR 550nm – 12.7µm
  - Polar orbiting sensors provide a good spatial resolution (MODIS 250m / SLSTR 500m) and typically a daily coverage which is however limited by clouds & polar darkness
  - Retrieval approaches rely on large difference in surface reflectivity between snow covered and other surfaces, e.g. NDSI = (Band4-Band7) / (Band4+Band7)

- Some established Global (NH) SE datasets
  - GlobSnow daily FSC from 1995 – present (FMI)
    - Snow CCI SCE 1982 – 2018 (prototype version ready)
  - MODIS daily FSC from 2000 – present (NASA, D. Hall)
  - Rutgers University, NOAA CDR snow record 1967 to present
  - NOAA IMS operational NRT SCE (NOAA/NESDIS)

- Instrument record: AVHRR, MODIS, (A)ATSR, SLSTR, VIIRS, etc…
  - Global coverage with AVHRR since 11/1978, MODIS 2000

GlobSnow Snow Extent (SE) dataset

- 17 years SE data record produced using optical imagery from ESA ATSR-2 (1995-) and AATSR (2002-2012) on a hemispherical scale.
- SYKE's SCAmod method for fractional snow cover mapping implemented for Northern hemisphere covering all non-mountainous terrain, mountains estimated using NLR algorithm developed by NR
- A novel Cloud detection algorithm by SYKE & ENVEO (snow – cloud discr.)
- Retrieval methodology developed especially for forested regions – basically a challenge for optical methodologies



After GlobSnow efforts → development now continues within ESA Snow CCI

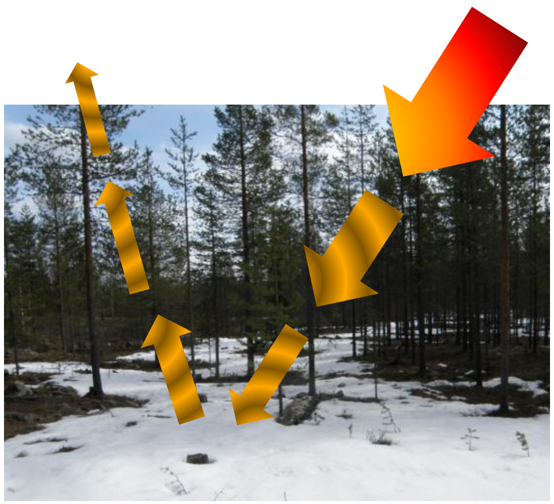
GlobSnow based on SYKE SCAmod (reflectance model)

Volume scattering / surface scattering

$$\rho_{\lambda,obs}(FSC) = \underbrace{(1-t_{\lambda}^{2}) * \rho_{\lambda,forest}}_{\text{Volume scattering}} + \underbrace{t_{\lambda}^{2} * \left[FSC * \rho_{\lambda,snow} + (1-FSC) * \rho_{\lambda,ground}\right]}_{\text{surface scattering}},$$

$$FSC = \frac{\frac{1}{t_{\lambda}^{2}} * \rho_{\lambda,obs} + (1-\frac{1}{t_{\lambda}^{2}}) * \rho_{\lambda,forest} - \rho_{\lambda,ground}}{\rho_{\lambda,snow} - \rho_{\lambda,ground}}.$$

$\rho_{\lambda,obs}$	observed reflectance from unit area
$\rho_{\lambda,snow}$	reflectance of wet snow
$\rho_{\lambda,ground}$	reflectance of snow-free ground
$\rho_{\lambda,forest}$	reflectance of forest canopy
$\hat{t}$	forest canopy transmissivity for unit area
FSC	fraction of snow covered area

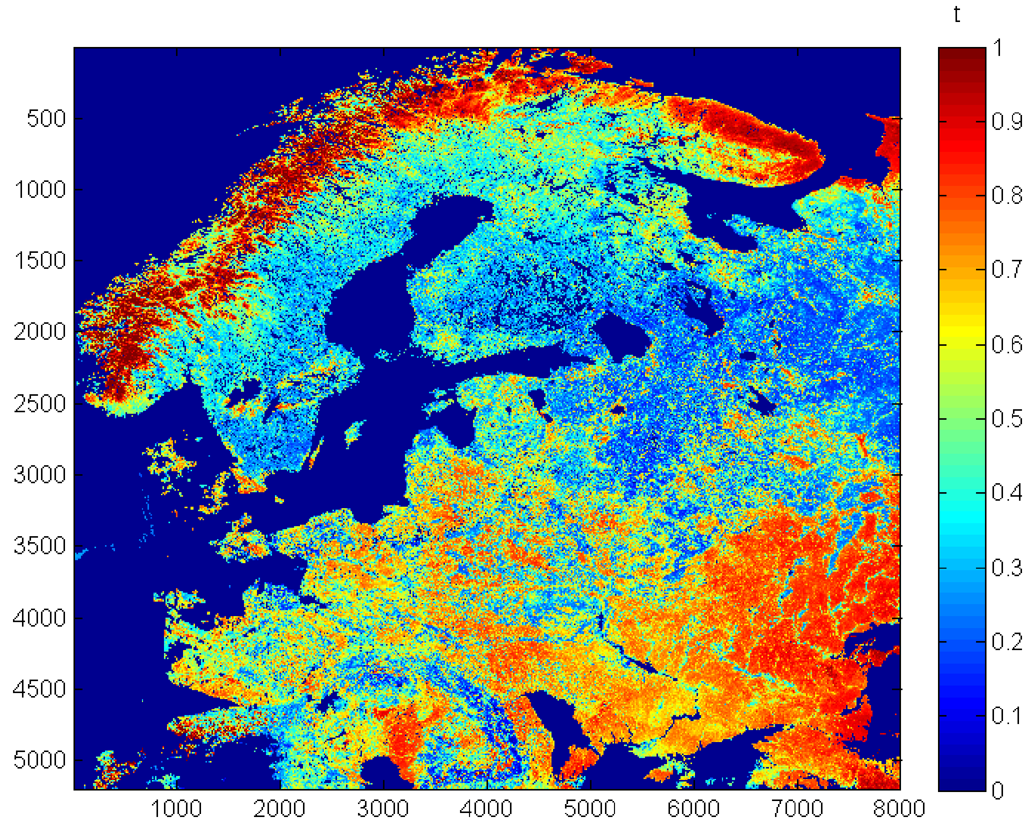


Forest transmissivity

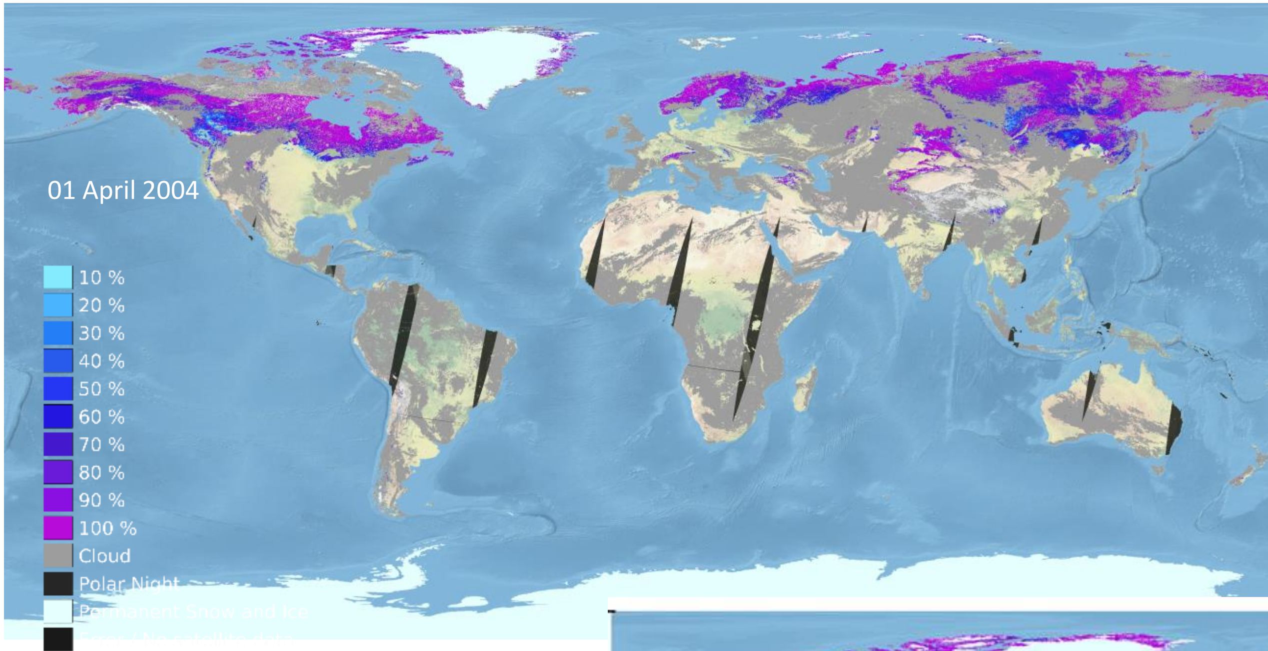
Forest transmissivity map for 0.01°×0.01° grid:

$$\hat{t}^2 = \frac{\rho(SCA=100\%) - \rho_{forest}}{\rho_{snow} - \rho_{forest}}$$

- How much the canopy blocks the two-way radiation
- Can be calculated for each cell using optical data at full dry snow cover conditions



ESA Snow CCI SCF prototype products

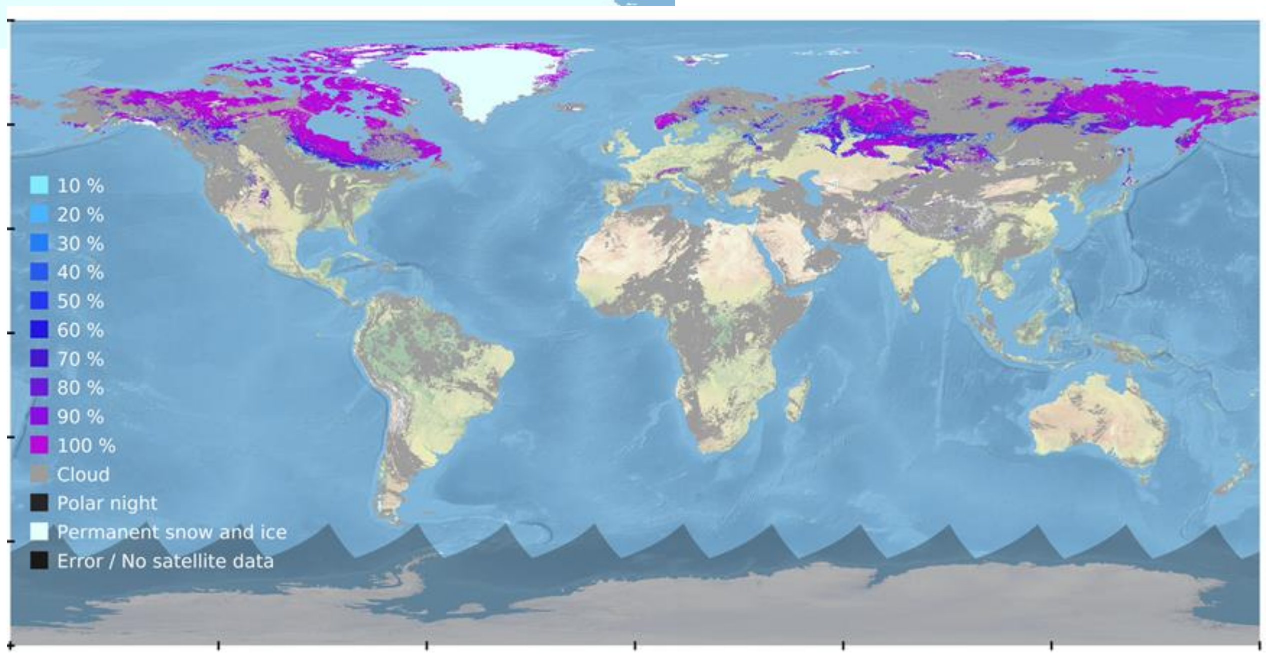


MODIS 1km

Time series: 2000-2018

AVHRR 5km

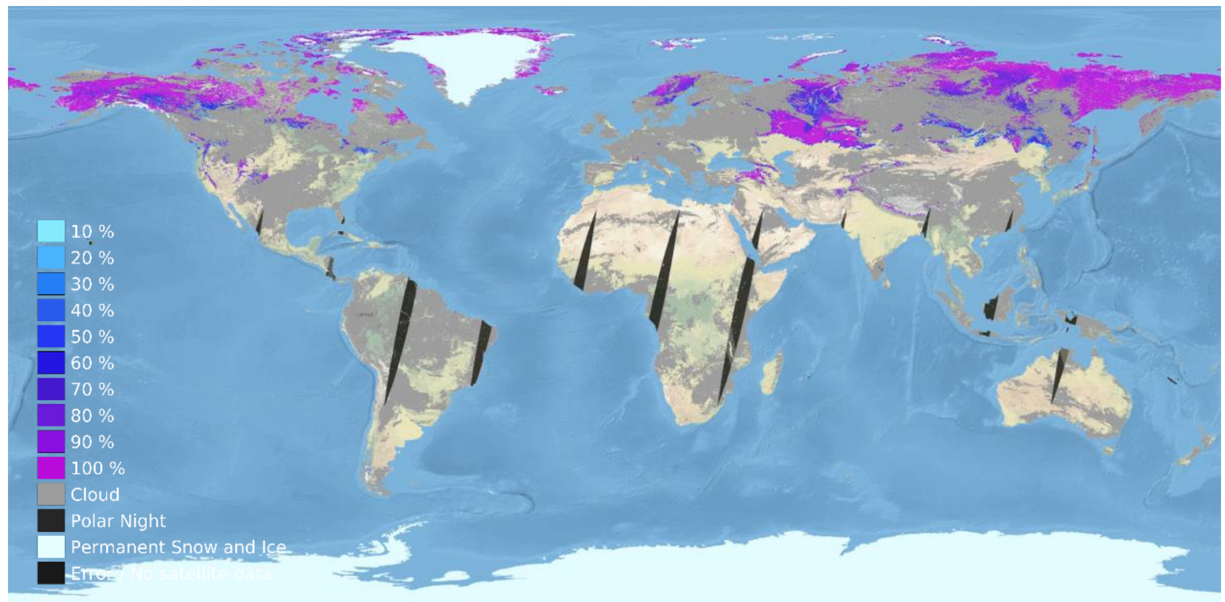
Time series: 1982-2018



1 km MODIS SCF Product Time series

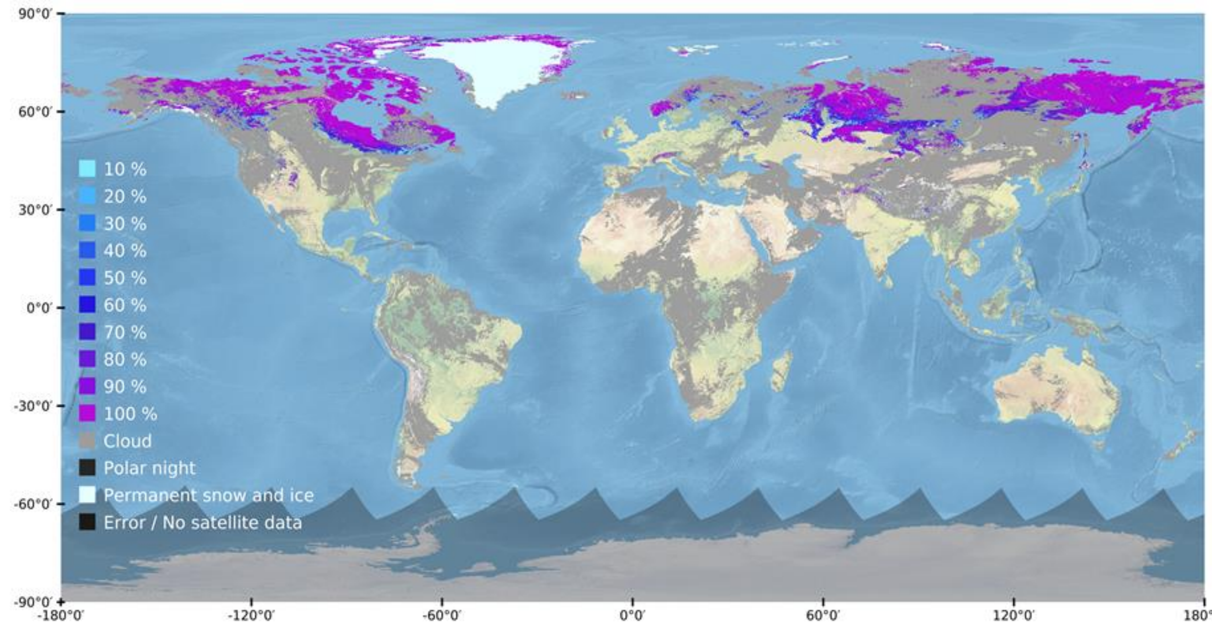
- Snow variable:
  - Snow cover fraction (SCF) – viewable
  - Accuracy target: <20% unbiased RMSE
  - Retrieval algorithm: NDSI Based
- Time series:
  - 14.03.2000 - 31.12.2018 (6808 days)
- Spatial:
  - Coverage: Global
  - Grid size: 0.01° (1 KM)
  - Projection: Geographical (lat/lon)
  - Datum: WGS 84
- Temporal:
  - Resolution: 1 day
- File:
  - Representation: 16 bits (0-255)
  - Format: NetCDF4, CF-v1.7
- Input data
  - MODIS L1B MOD02, MOD03

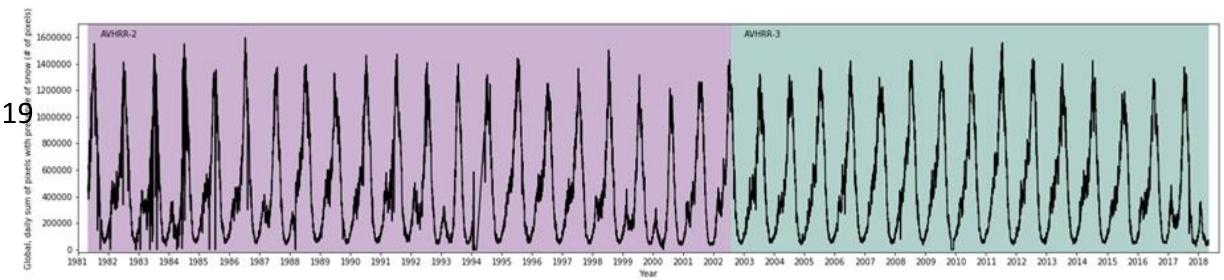
1st April



5 km AVHRR SCF Product Time series

- Snow variable:
  - Snow cover fraction (SCF) – viewable
  - Accuracy target: <20% unbiased RMSE
  - Retrieval algorithm: NDSI Based
- Time series:
  - 1982 - 31.12.2018
- Spatial:
  - Coverage: Global
  - Grid size: 0.05° (5 KM)
  - Projection: Geographical (lat/lon)
- Temporal:
  - Resolution: 1 day
- Product:
  - Representation: 16 bits (0-255)
  - Format: NetCDF4, CF-v1.7
- Input Data
  - AVHRR-2: NOAA-7, NOAA-9, NOAA-11, NOAA-14
  - AVHRR-3: NOAA-16, NOAA-18, NOAA-19
  - Pre-processed using PyGAC by ESA CCI Cloud consortium

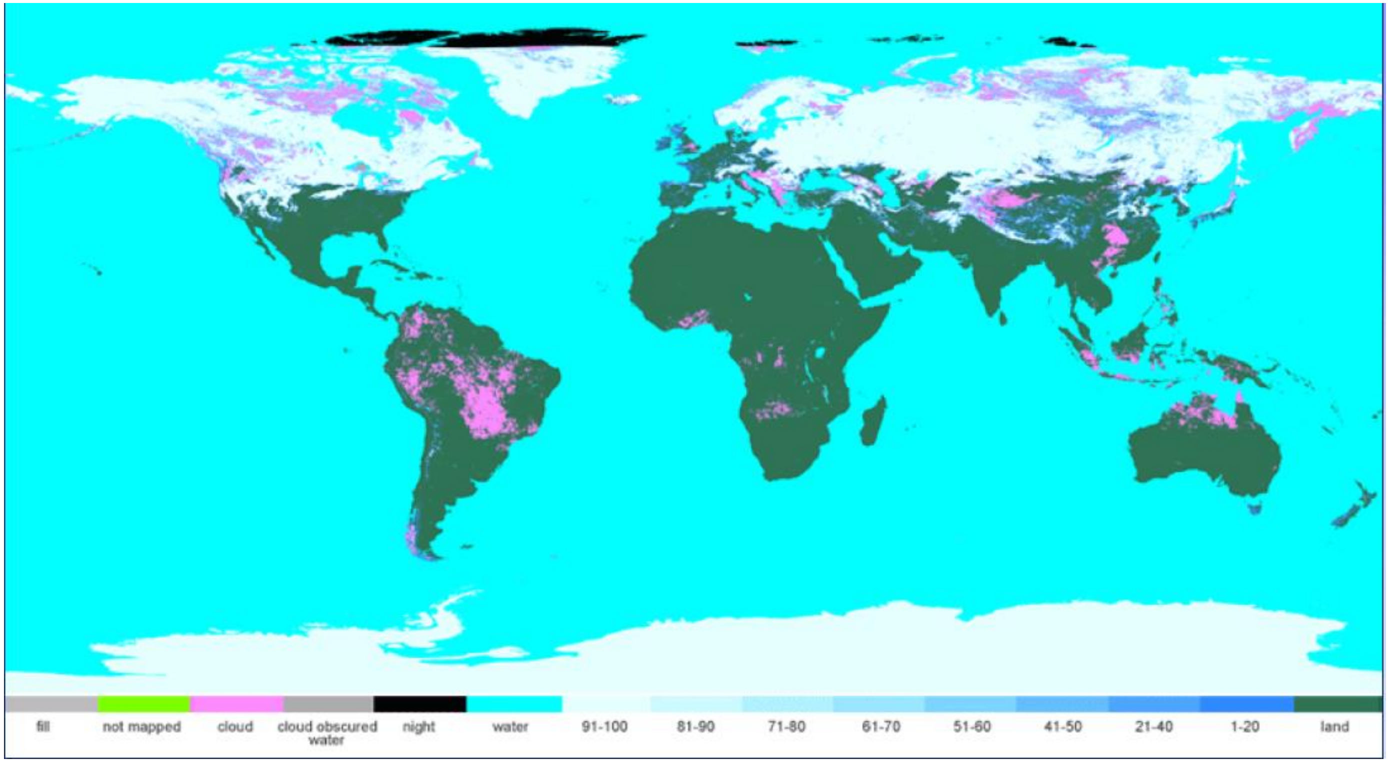




Number of pixels with snow

NASA MODIS FSC/SE (2000-present)

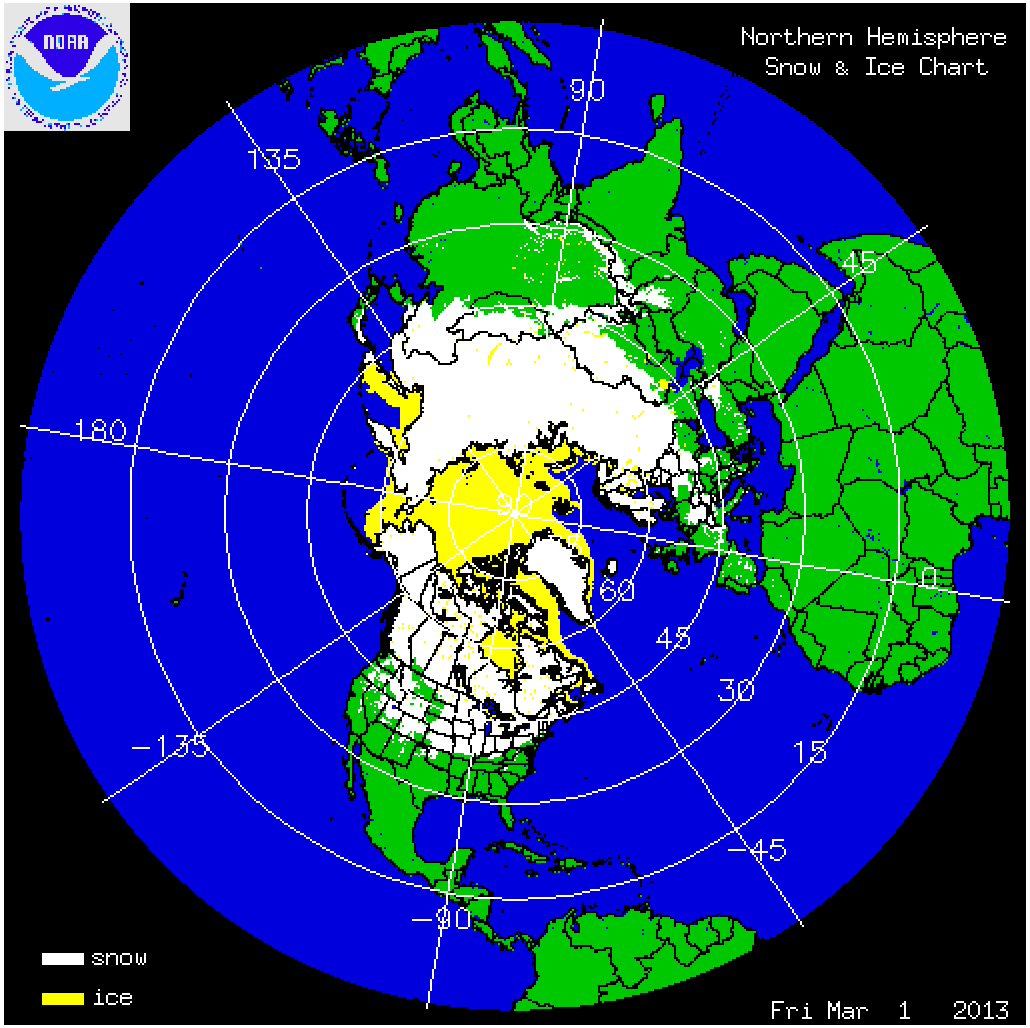
- Daily 500m / 5km SCE NDSI-based product from Terra/MODIS
- One of the ”benchmark” optical FSC/SE products, spanning 19 years
- MODIS: great spatial resolution & coverage; follow-up with NPP VIIRS



5-km 8-day composite climate-modeling grid (CMG) snow cover

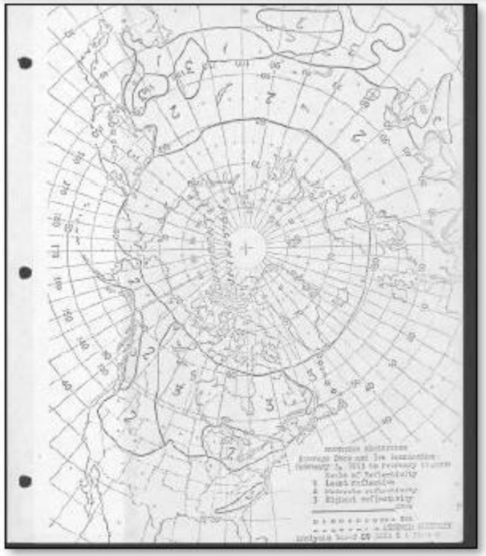
NOAA/NESDIS IMS Snow/Ice (NRT "since 1966")

- Daily/weekly multi-resolution SE product based on **multisensor data and human analyst interpretation**
- Satellite + ground-based + modelled data
- Combines optical, PMW and SAR data + **analyst interpretation**
- Cloud filling
- Binary (SE) product
- 190km / 24km / 4km / 1km
- Operational focus, numerous methodology improvements since 1966
- Weekly 1966-1997, Daily 1997->
- Basis for the Rutgers NOAA CDR

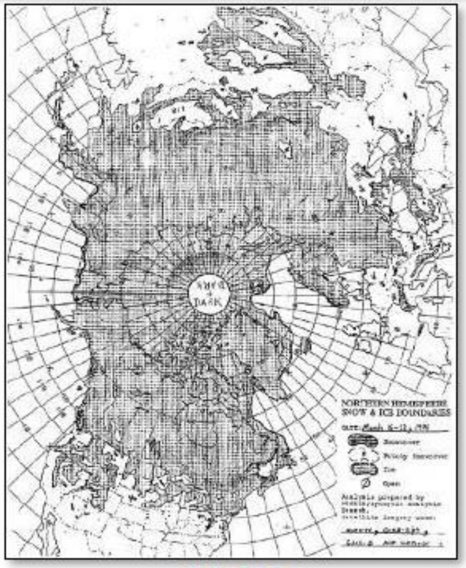


IMS as a source Rutgers NOAA CDR snow chart

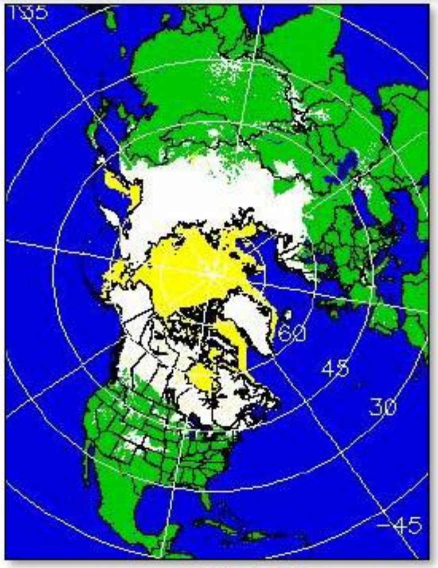
- **NOAA weekly optical snow charts for 1966-1999, NOAA IMS since 1999.**



1973



1998



2007

Nov 1966 | Oct 1972 | May 1975 — ESSA, NOAA, GOES Series

1980-81 — Weekly 190 km digitized

METEOSAT & GMS added

1990s — May 1999 — Reanalysis of 1966-71

Feb 1997 — IMS 24 km

Feb 2004 — IMS 4 km

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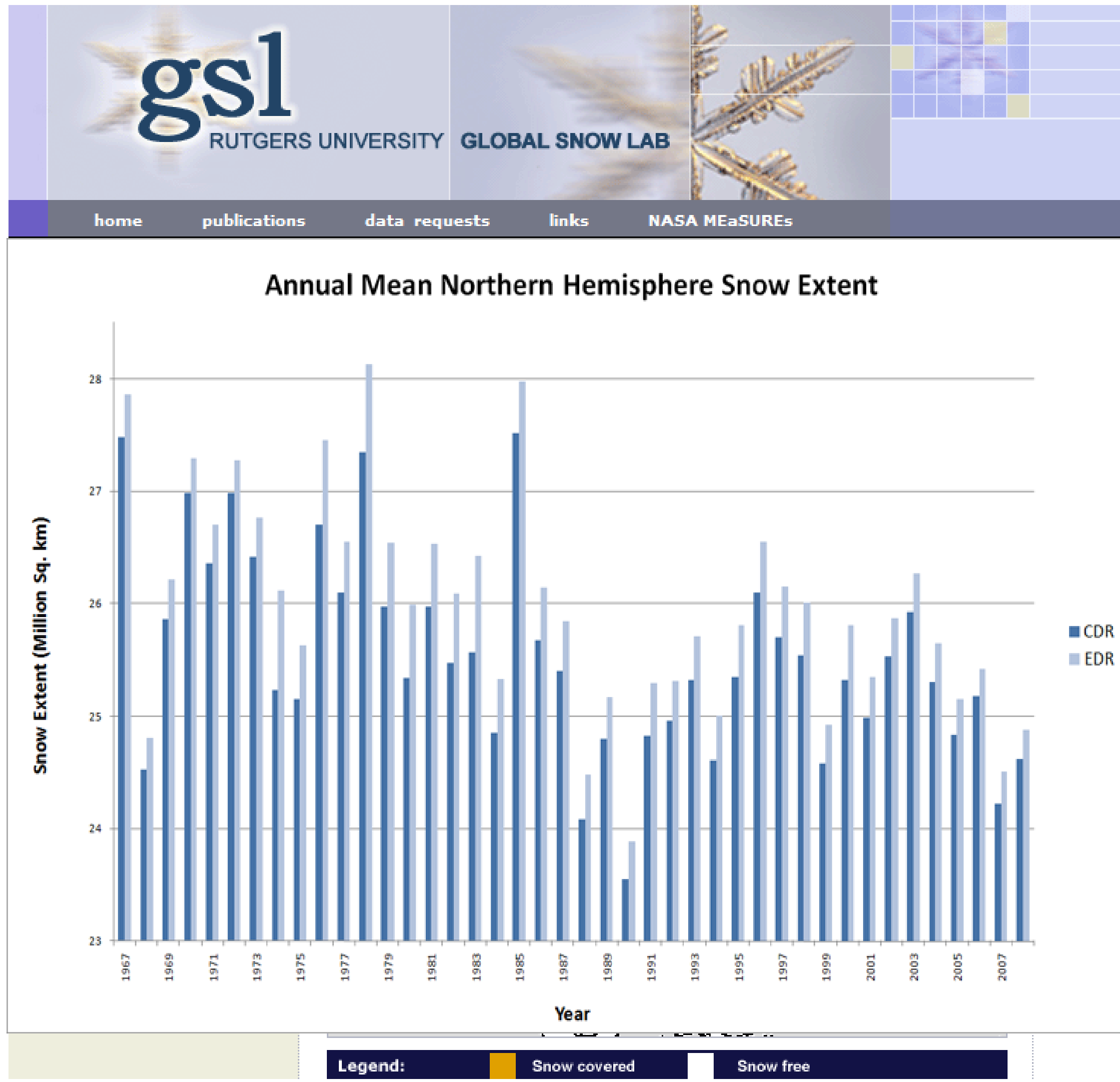
Rutgers NOAA CDR snow chart (1966 – present)

- **Weekly SE product based on NOAA/NESDIS IMS (89x89 grid ~190x190km²)**
- **Consistency checked**
- **Climate Data Record**
- **~190km spatial resolution**
- **Weekly product allows an uniform product to span October 1966 – present**
- **Binary cloud filled SE**

- **Benchmark satellite snow cover product, e.g. IPCC reports**



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Optical product recap

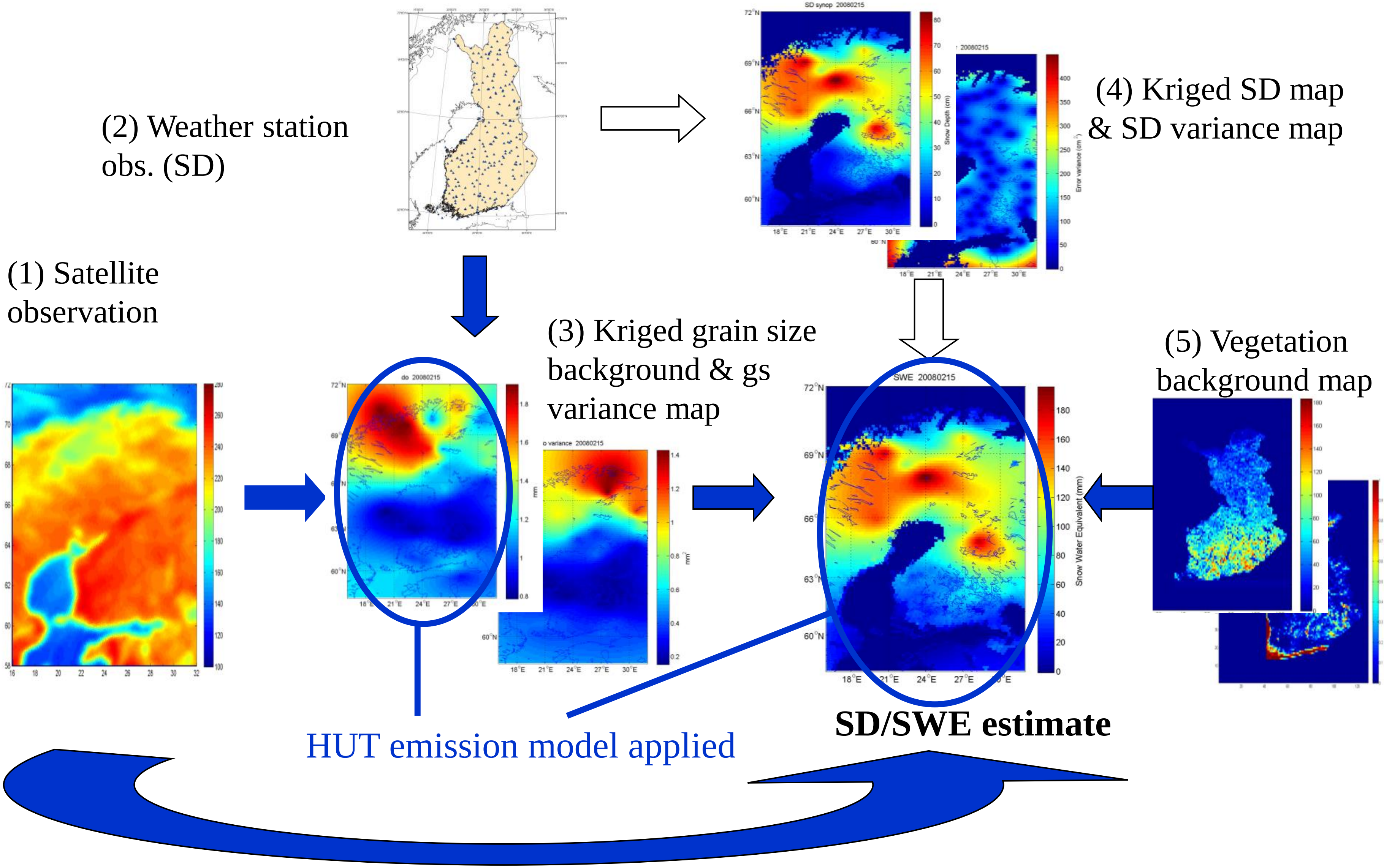
- **Future needs & outlook**
  - Need a wide swath high resolution sensors (250m -> 100m), with full daily global coverage
  - High resolution (S-2/Landsat) continental products/services coming in the future

- Additionally optical products from Geostationary orbit (H SAF), (however, challenges in the high latitudes & coarser resolution)
- SAR-based approaches: wet snow & snow depth

Snow Water Equivalent (SWE) retrieval

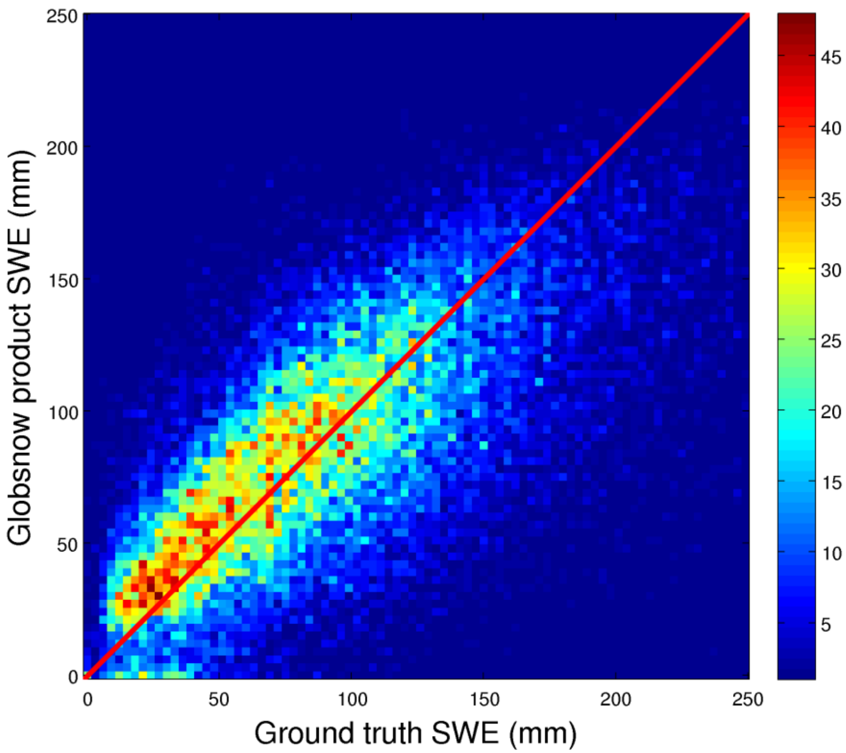
using data assimilation approach

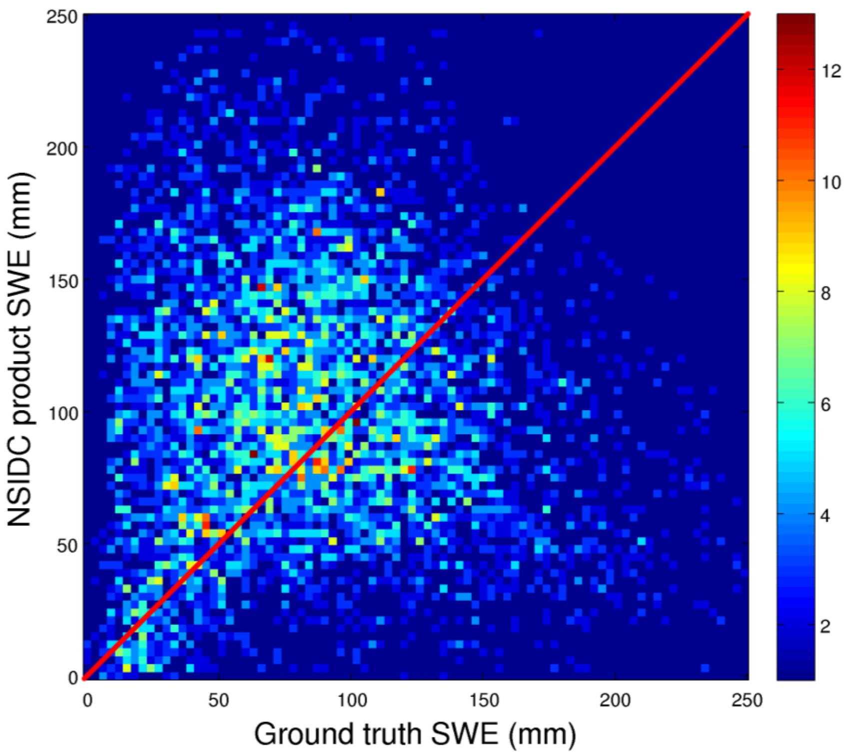
- **An approach published in RSE by Prof. Pulliainen (2006), refined in Takala et al. 2011 & Takala et al. 2017**
- **The method applies:**
  - Microwave Radiometer data (SMMR, SSM/I, SSMIS) [1979 ->]
    - 19 GHz (V-pol) & 37 GHz (V-pol and H-pol)
  - Weather station observations of snow depth
- **Based on inversion of physical snow emission model (Pulliainen et al., 1999), (Lemmetyinen et al., 2011)**
- **Physical snow model calibrated over weather station locations (effective grain size)**
  - Grain size field extended over AOI using Kriging technique
- **Final step includes assimilation of snow depth background field and radiometer observations**


(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
SD synop 20080215
SWE 20080215
Snow Water Equivalent (mm)
HUT emission model applied
SD/SWE estimate

Effect of data assimilation on SWE retrieval accuracy
(data assimilation vs. standalone channel diff. algorithm)

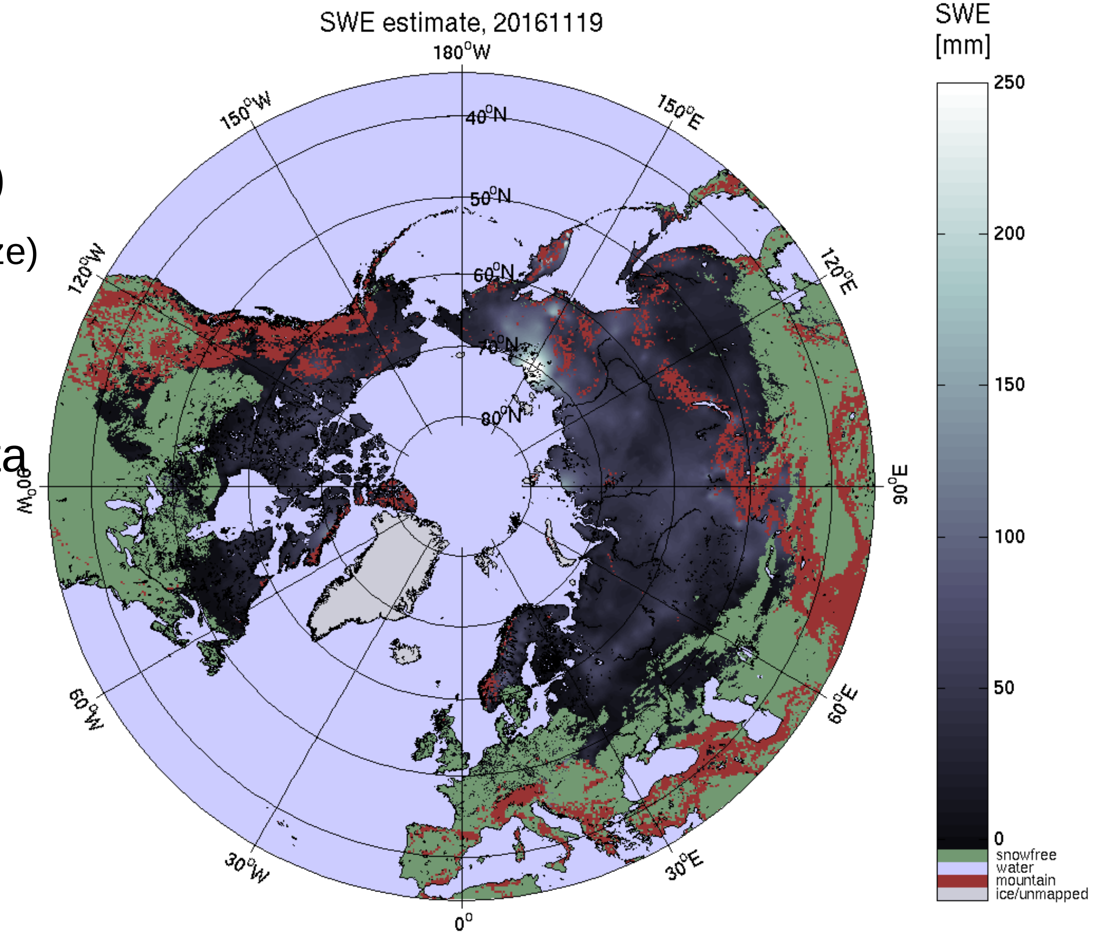
- **Density scatterplot (assimilated vs. satellite only SWE)**
- **Ground truth data is Russian SWE transect data**





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

- First time reliable daily spatial information on SWE (snow cover):
  - Snow Water Equivalent (SWE)
  - Snow Extent and melt (+grain size)
  - 25 km resolution (EASE-grid)
  - Time-series for 1979-2019
- Passive microwave radiometer data combined with ground-based synoptic snow observations
  - Variational data-assimilation
- Greenland, glaciers & mountains masked out
- Openly available (GlobSnow FTP)



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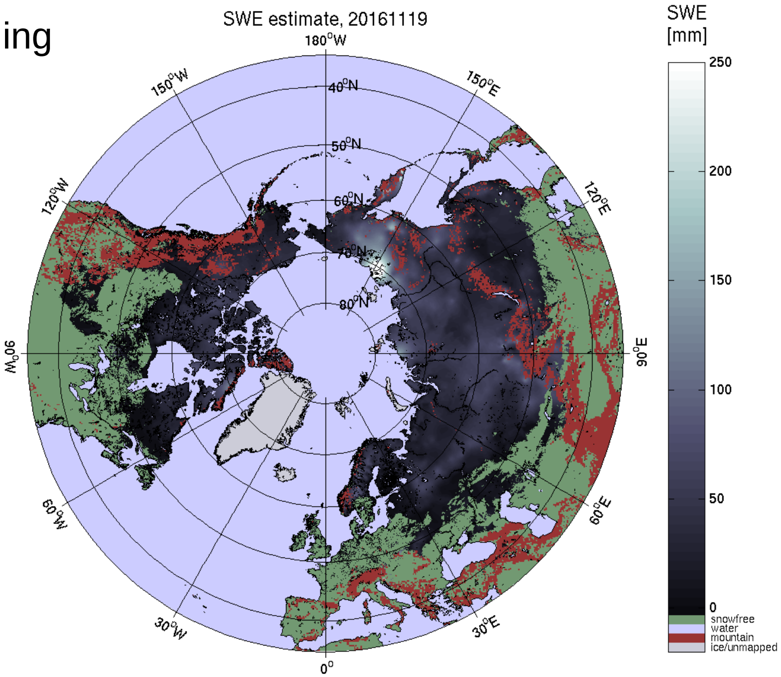
esa snow cci

ESA CCI+ Snow (started on 09/2018)

- Further development of the GlobSnow SWE retrieval methodology
- Re-construction of the long-term satellite SWE climate record

ESA CCI+ Snow SWE goals for 2018-2020:

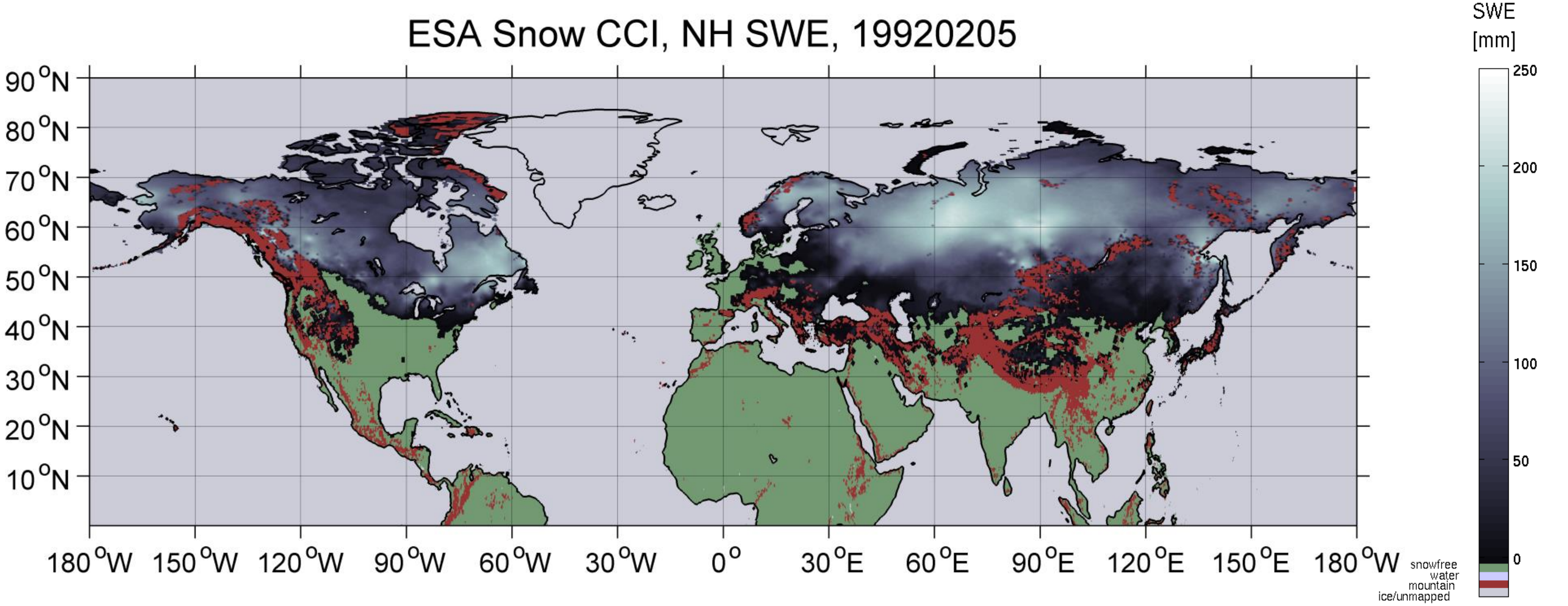
- Advanced snow emission model with improved lake ice handling and land cover influence in snow depth and snow grain size estimation
- dynamic snow density consideration
- Utilization of optical SCE data in SWE retrieval (synergistic SWE/SE product)
- Brightness temperature resolution enhancement
- Super Resolution processing (6.25 / 12.5km resolution)
- Baseline of SMMR, SSM/I and SSMIS FCDR with assessment of AMSR-e, AMSR2 and FY-3 MWRI as additional input data
- Improved consistency consideration for synop SD input data



GlobSnow-CCI SWE v1.0 products to be released by the end of 2019

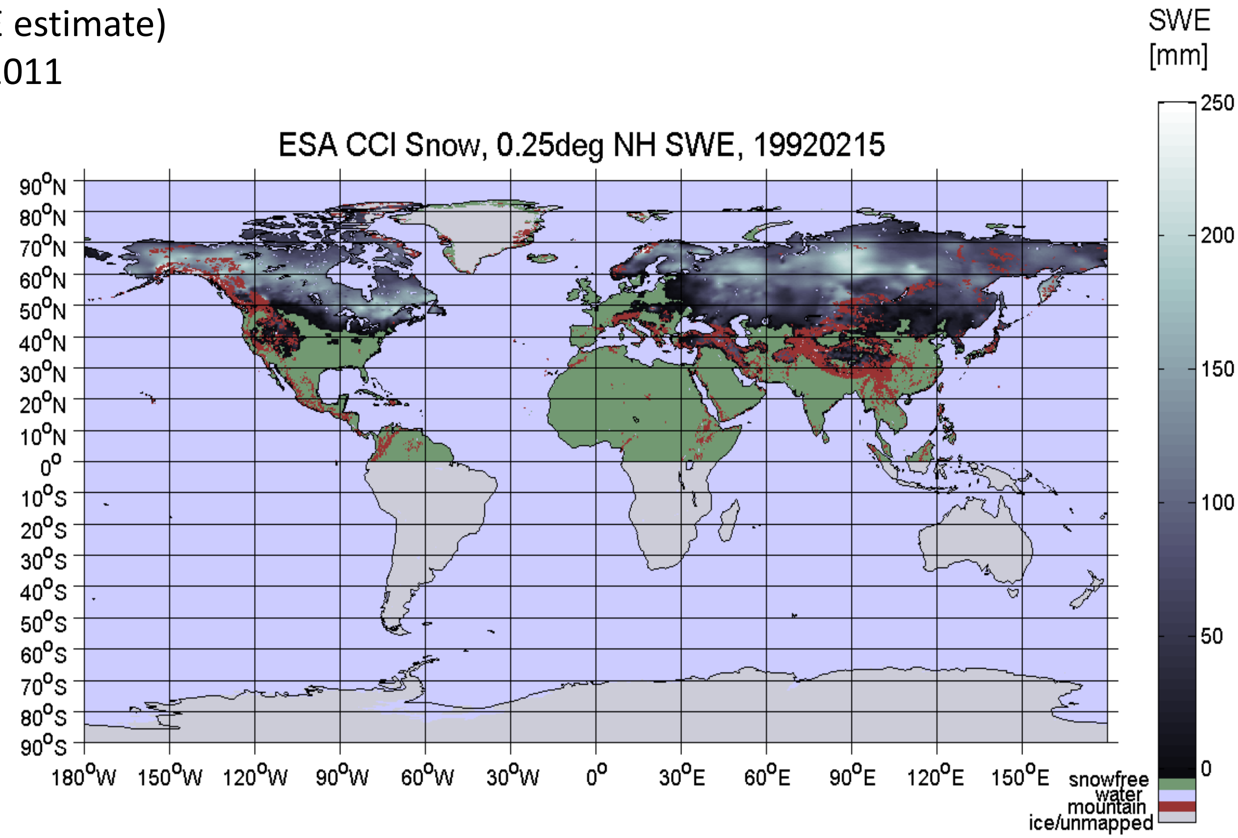
ESA Snow CCI - SWE retrieval updates - Year 1 outcome

- Processing chain adaptation to lat/lon gridding and to cover full NH (0-90°N latitudes)
  - Modifications to code base & updated aux datasets
- 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
- CDR production completed (new 1979-2018 CDR to be released by end of 2019)



Snow CCI SWE v1.0 product time series

- Snow variable:
  - Snow water equivalent (SWE)
  - Uncertainty estimate (STD of SWE estimate)
  - Retrieval algorithm: Takala et al. 2011
- Time series:
  - Start: 6 January 1979
  - End: 31 May 2018
- Spatial:
  - Coverage: Northern Hemisphere
  - Grid size: 0.25°
  - Projection: Geograph. (lat/lon)
  - Datum: WGS 84
- Temporal:
  - Resolution: 1 day
  - Aggregation: None
- File:
  - 32 bit float (SWE: 0-500 mm)
  - Format: NetCDF4, CF-v1.7



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PMW product recap

- **Future needs & outlook**
  - Weather & illumination independence, but coarse resolution
  - Further R&D for retrieval methodology
    - likely path forward: PMW combined with aux data
  - ESA & Copernicus follow-on missions -> CIMR (~5km)
  - EUMETSAT programs -> MetOp-B SG MWI

- Main parameter from PMW is SWE; but also snow status & snow melt products are done (e.g. H SAF)

- Additional products: JAXA AMSR-2 (by R. Kelly)

H SAF Snow Cluster Product Summary

- **H10**: Snow detection (snow mask) by VIS/IR radiometry
- **H11**: Snow status (dry/wet) by MW radiometry
- **H12**: Effective snow cover by VIS/IR radiometry
- **H13**: Snow Water Equivalent
- **H31**: MSG/SEVIRI snow extent
- **H32**: Metop/AVHRR snow extent
- **H34**: Snow detection (snow mask) by VIS/IR radiometry of SEVIRI
  - successor of H10
- **H35**: Snow detection (snow mask) and effective snow cover by VIS/IR radiometry of AVHRR
  - successor product of H12
- **H43**: MTG/FCI snow extent
- **H65**: Snow Water Equivalent
  - successor of H13
- **H85**: Metop-SG/Metimage snow extent

A comprehensive set of operational snow products
optical and passive microwave sensors
+ polar and geostationary satellites!

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2. Validation & quality assessment of snow products

ESA SnowPEx
ESA GlobSnow & Snow CCI

ESA SnowPEx (2014-2018)

ISSPI-1 WS July 2014


ISSPI-2 WS Sep 2015

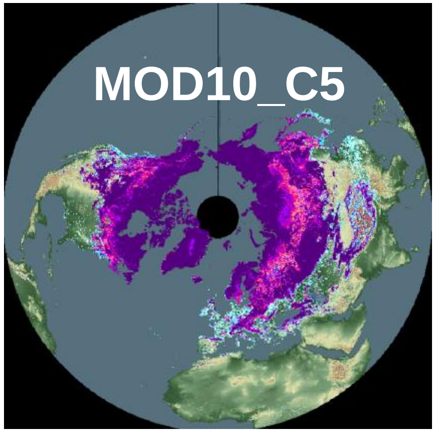
SnowPEx Activities

- **Intercompare** and **evaluate** global / hemispheric (pre) operational **snow products** derived from different EO sensors and generated by means of different algorithms, assessing the product quality by objective means.
- Evaluate and intercompare temporal **trends of seasonal snow parameters** from various EO based products in order to achieve well-founded **uncertainty estimates** for **climate change** monitoring.

SnowPEx Reports are publicly available, publications coming

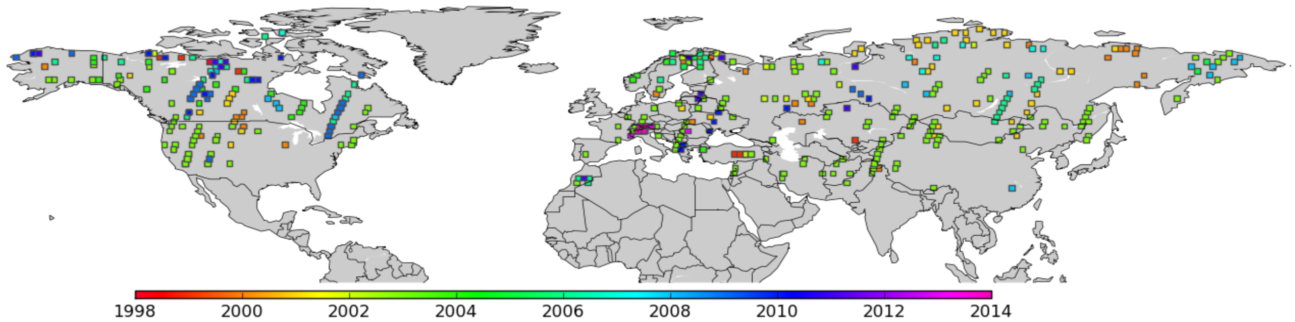
Snow Cover Extent Products evaluated in ESA SnowPEx

ID	Product Name	Thematic Parameter	Period	Projection	Pixel Size	Quantity
CRCLIM	CryoClim	Binary, Global	1982 - present	Ease-Grid 2.0	5km	Snow on Ground
GLSSE	GlobSnow v2.1	Fractional, NH	1996 - 2012	Geographic Coordinates	1 km	Snow on Ground
IMS01	IMS	Binary, NH	2014 - present	Polar Stereographic	1 km	Snow on Ground
IMS04	NOAA IMS	Binary, NH	2004 - present	Polar Stereographic	4 km	Snow on Ground
IMS24	NOAA IMS	Binary, NH	1997 - present	Polar Stereographic	24 km	Snow on Ground
MEASU	MEaSUREs	Binary, Global	1999 - 2012	Ease-Grid 2.0	25 km	Snow on Ground
PATHF	AVHRR Pathfinder	Binary, NH	1985 - 2004	Ease-Grid North	5 km	Snow on Ground
SCAG	SCAG	Fractional, US/ Himalaya/Andes	2000 - present	Sinusoidal	0.5 km	Snow on Ground
ASNOW	Autosnow	Binary, NH	2006 - present	Geographic Coordinate	4 km	Viewable Snow
JXAM5	JASMES GHRM5C	Binary, NH	1979 – 2013	Geographic Coordinates	5 km	Viewable Snow
JXM10	JASMES MDS10C	Binary, NH	2000 – 2013	Geographic Coordinates	5 km	Viewable Snow
M10C05	MOD10_C5	Fractional, Global	2000 - present	Sinusoidal	0.5 km	Viewable Snow
CRYOL	CryoLand	Fractional, PanEU	2000 - present	Geographic Coordinates	0.5 km	Snow on Ground
EURAC	EURACSnow	Binary, Alps	2002 - present	Geographic Coordinates	0.25 km	Snow on Ground
HSAF10	HSAF H10	Binary, PanEU	2009-present	Geostationary Projection	5 km	Viewable Snow
HSAF31	HSAF H31	Binary, PanEU	2009-present	Geostationary Projection	5 km	Viewable Snow

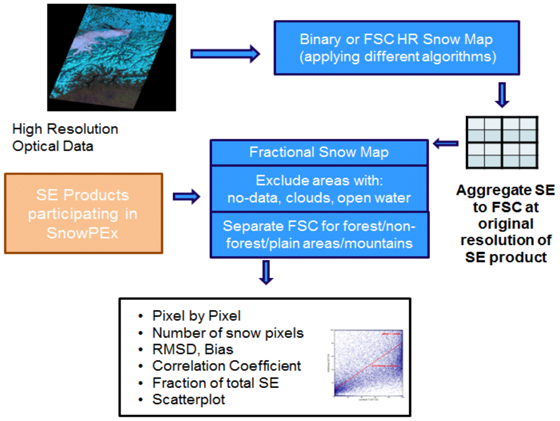


Validation of SE products – different approaches

Validation using High resolution (S-2/Landsat) reference data

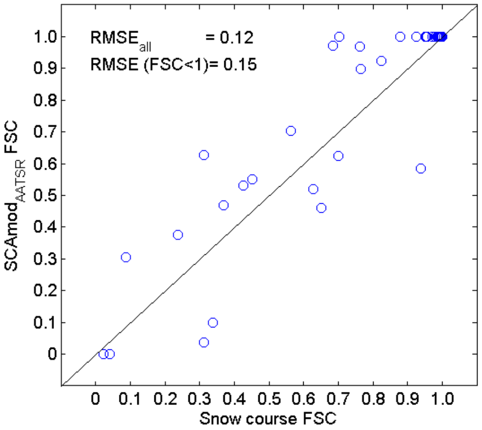


Intercomparison of Snow products



In-situ validation:

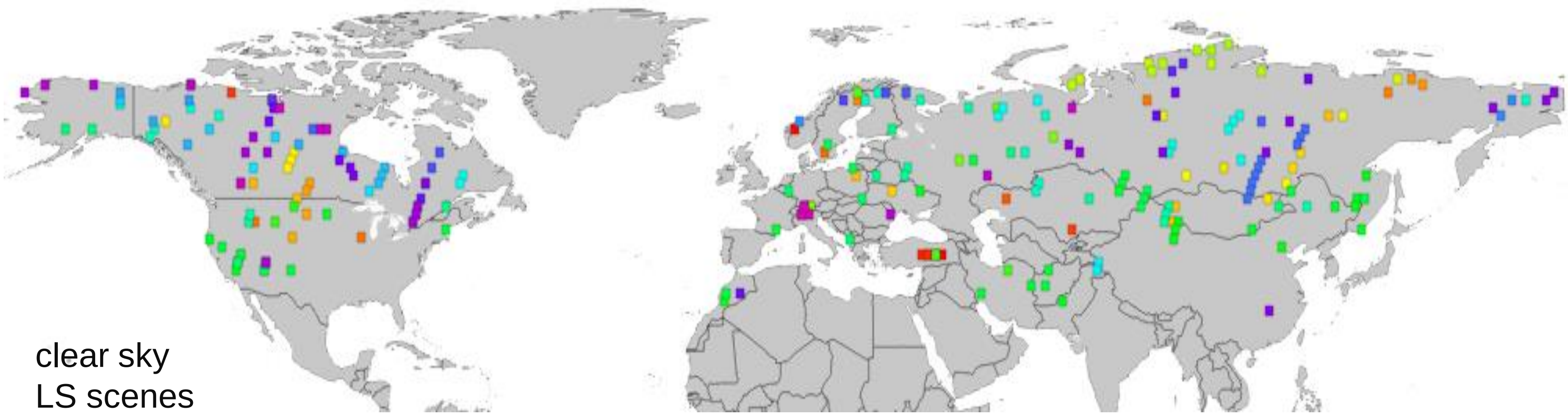
Snow courses / synop data



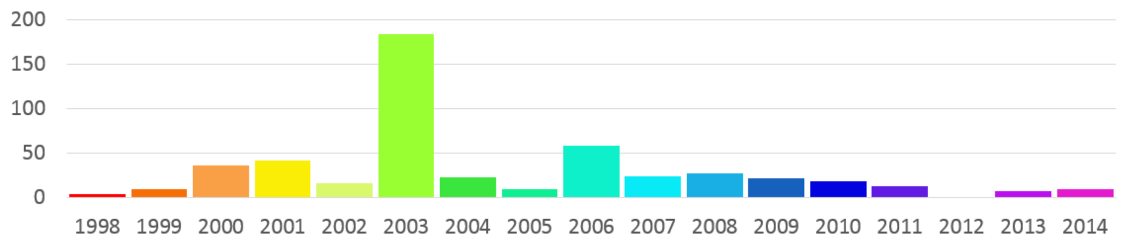
High resolution (Landsat) reference Data

→ Landsat reference dataset: 498 Landsat scenes

- Landsat-5 (217)
- Landsat-7 SLCon (265)
- Landsat-8 (16)

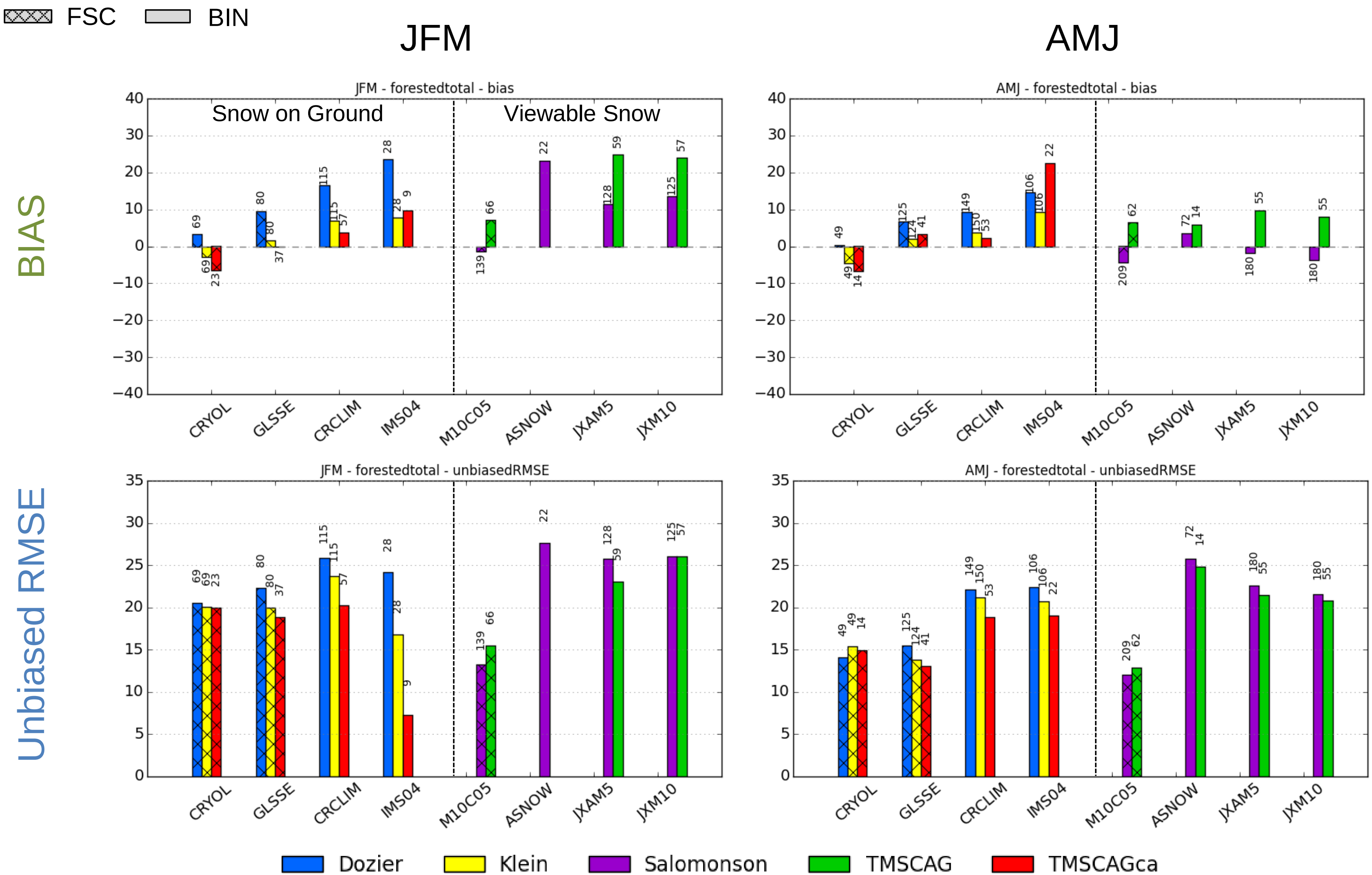


clear sky
LS scenes



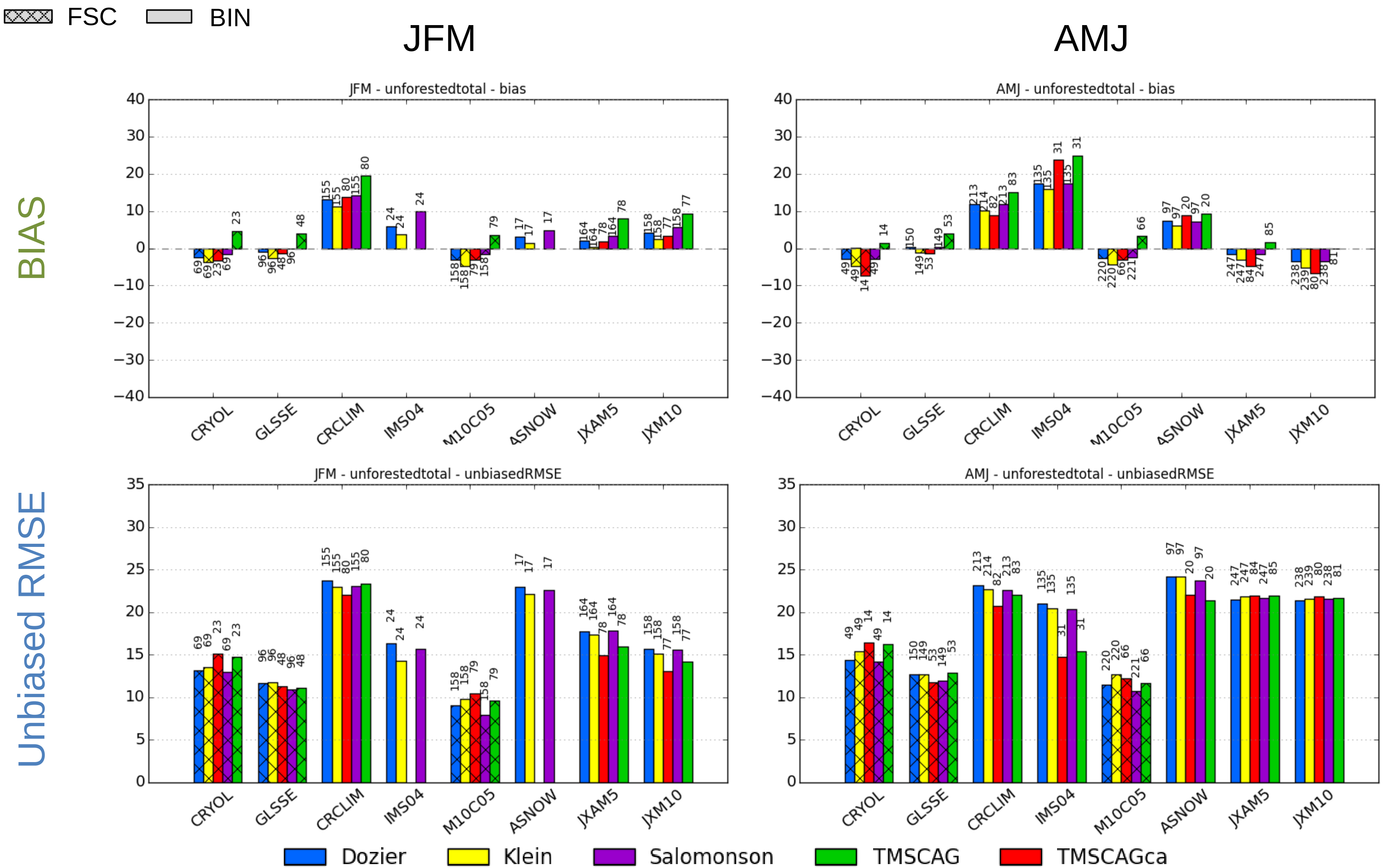
Validation Results

Forested area



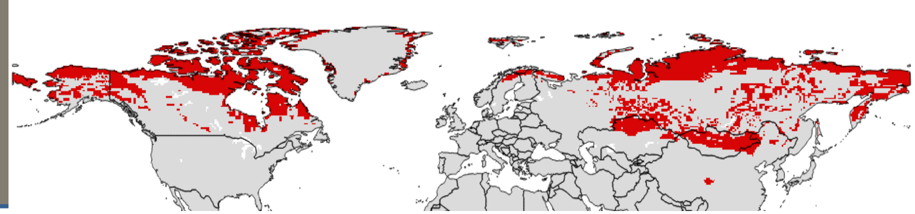
Validation Results

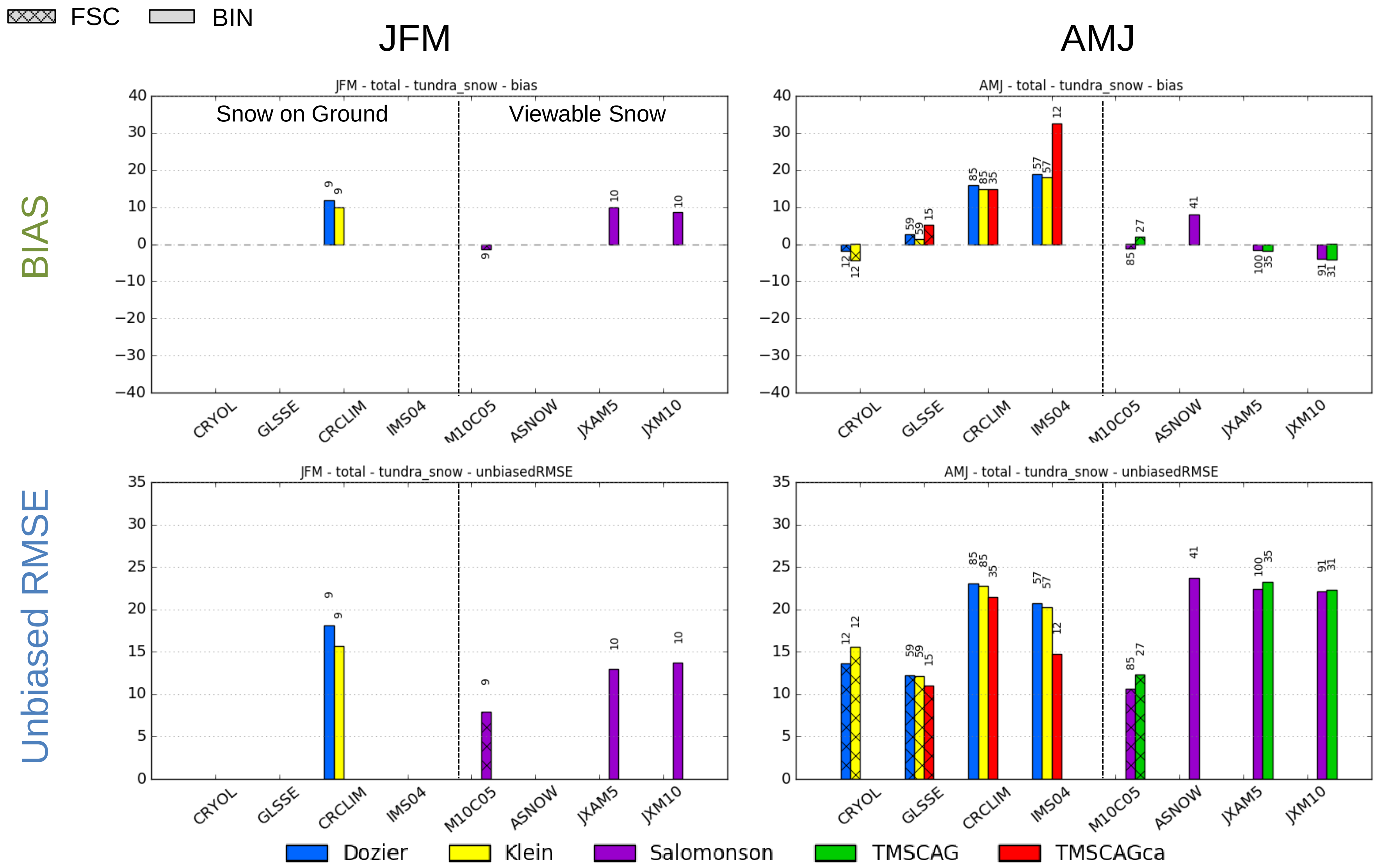
Unforested area



Validation Results

STURM tundra snow (124)





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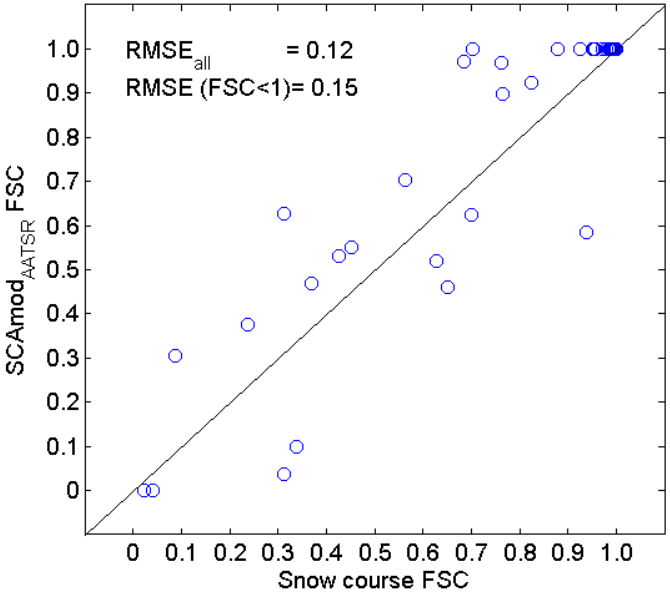
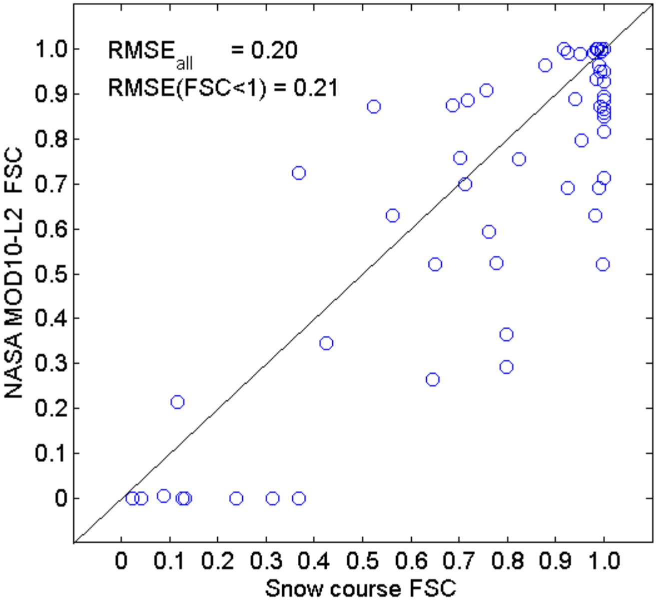
Validation of FSC products with in-situ data - snow transects

SYKE SCAmod



NASA MODIS

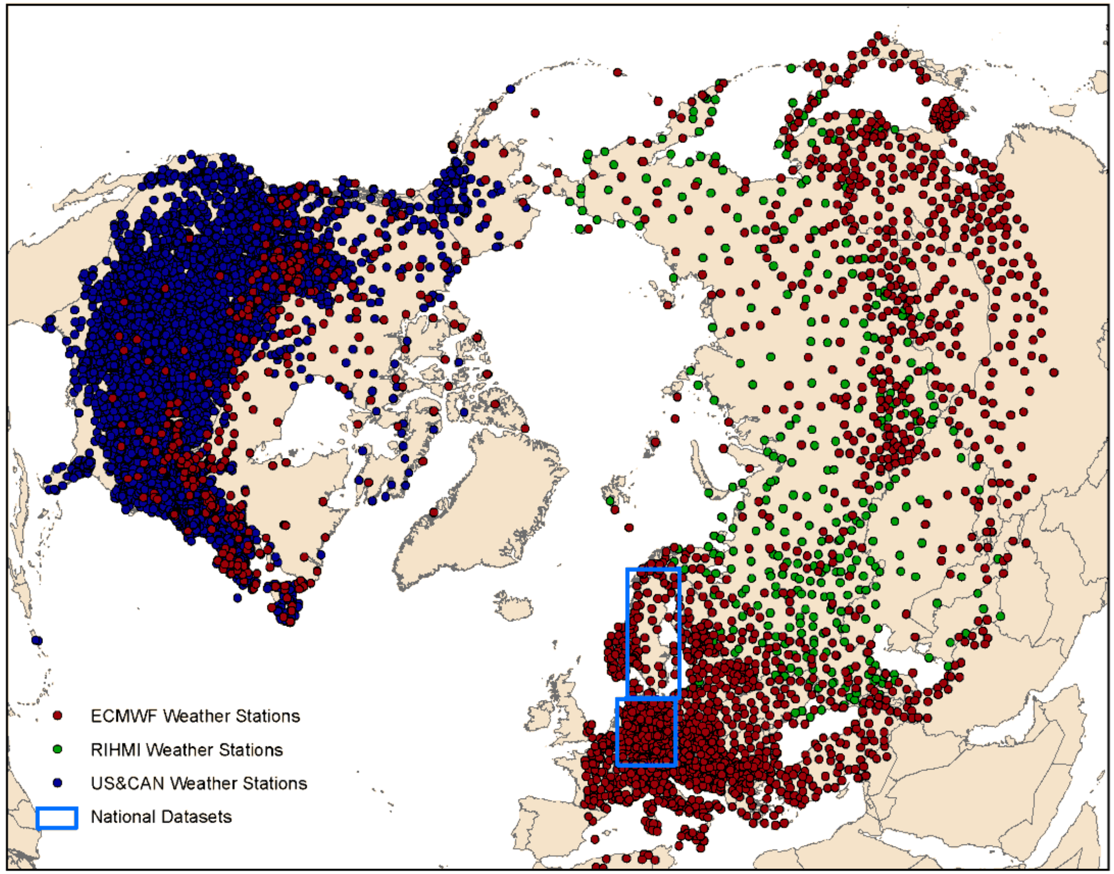


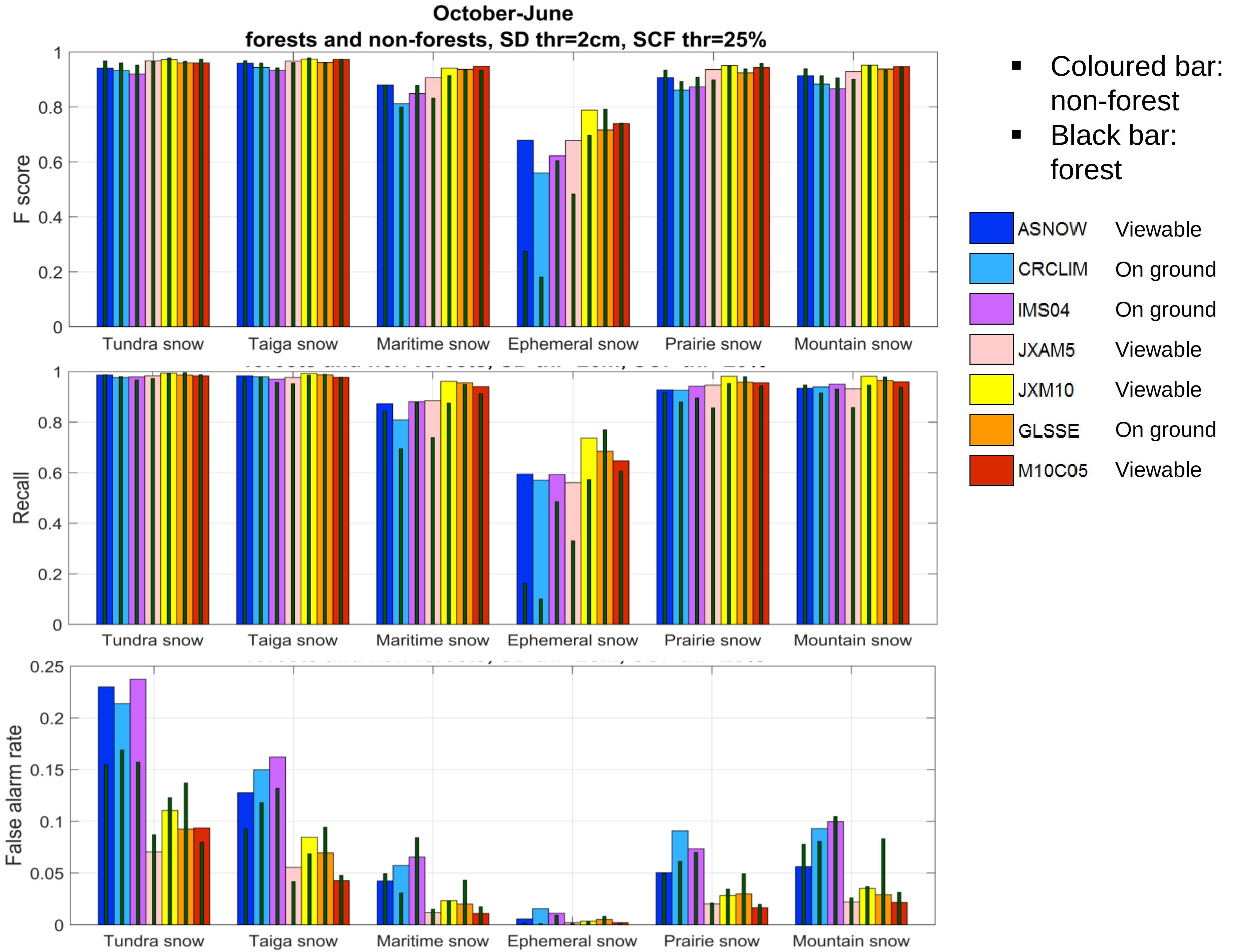
4km transect where FSC is observed at 80 locations. Average FSC is used for validations

Validation of NH products, using synop SD data

- Period 2000-2001, 2003-2004, 2005-2006 and 2007-2008 analyzed

ASNOW
CRCLIM
IMS04
JXAM5
JXM10
GLSSE
M10C05

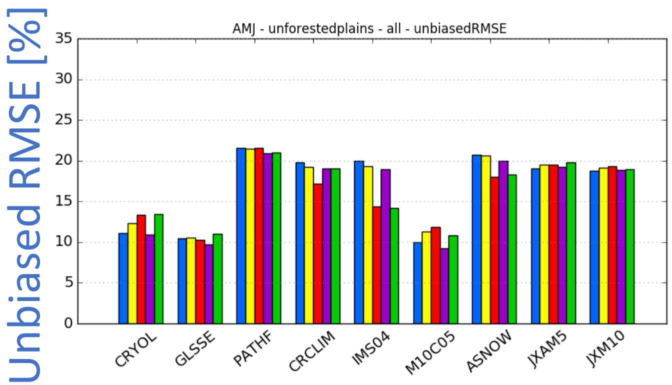


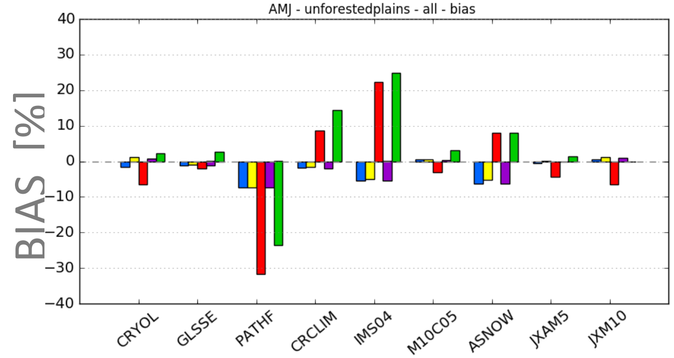


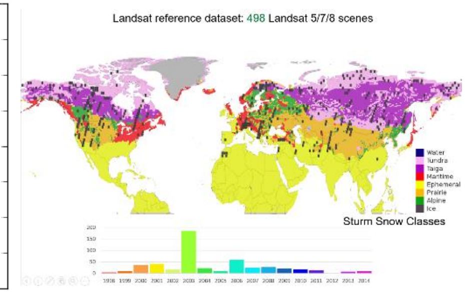
October-June
forests and non-forests, SD thr=2cm, SCF thr=25%
F score
Recall
False alarm rate
Tundra snow
Taiga snow
Maritime snow
Ephemeral snow
Prairie snow
Mountain snow
Coloured bar: non-forest
Black bar: forest
ASNOW Viewable
CRCLIM On ground
IMS04 On ground
JXAM5 Viewable
JXM10 Viewable
GLSSE On ground
M10C05 Viewable

SCF algorithm assessments
Snow CCI alg. decision

Unforested Areas







Snow CCI SCE Algorithm	Thematic information	Required spectral band(s)	Tested with data from
Ext. SCAmod (CryoLand, Metsämäki et al., 2005, 2012)	Snow on Ground (Viewable Snow?)	~550 nm, ~1.6 µm, 11µm	AVHRR, AATSR / ATSR-2, MODIS, VIIRS, (SLSTR draft)
NDSI based (Salomonson & Appel, 2004, 2006)	Viewable Snow	~550 nm, ~1.6 µm	AVHRR, MODIS, VIIRS, (SLSTR draft)

Determining SWE product accuracy

- Several SWE datasets readily available but constraining uncertainty and quantifying product accuracy remains a challenge, efforts in ESA SnowPEx have improved our knowledge on the topic

- **In-situ** data availability is an issue, data are sparse and often not spatially or temporally fully representative
- **Inter-comparison** of products provides a measure of agreement but agreement does not necessarily mean accuracy

- Multiple approaches for SWE product assessment were employed

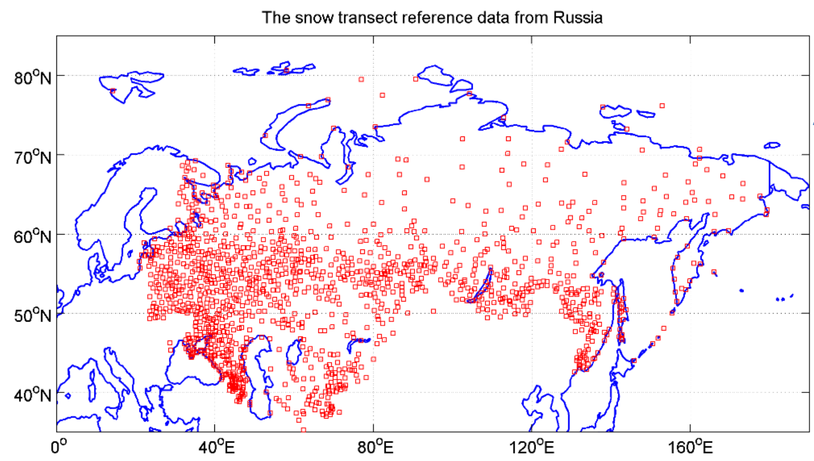
Assessment of 3 groups of SWE products (2002-2010) – dictated by data availability

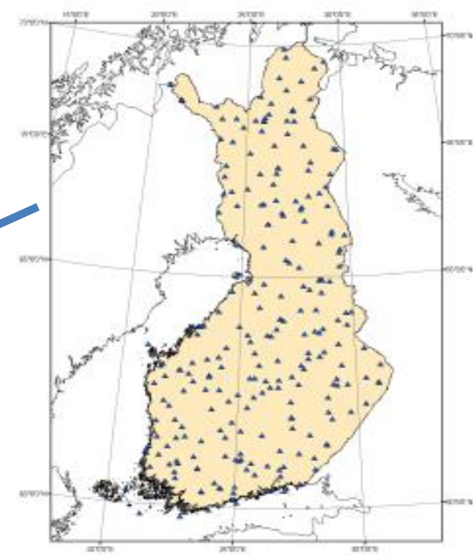
	Dataset	Method	Ancillary/ Forcing Data	Resolution	Time Series	Reference
PMW + in situ	GlobSnow v2.0	Passive microwave + in situ	Weather station snow depth measurements	25 km	1979-2015	Takala et al (2011)
Standalone PMW	NASA AMSR-E historical	Standalone passive microwave		25 km	2002-2011	Kelly (2009)
	NASA AMSR-E operational	Microwave + ground station climatology	Weather station snow depth climatology	25 km	2002-2011	Tedesco and Jeyaratnam (2016)
Land surface models & reanalysis	ERA-land	HTESSEL land surface model	ERA-interim	0.75° x 0.75°	1981-2010	Balsamo et al (2013)
	MERRA	Catchment land surface model	MERRA	0.5° x 0.67°	1981-2010	Rienecker et al (2011)
	Crocus	ISBA land surface + Crocus snow model	ERA-interim	1° x 1°	1981-2010	Brun et al (2013)
	GLDAS-2	Noah 3.3 land surface model	Princeton Met.	1° x 1°	1981-2010	Rodell et al (2004)

Validation of SWE products

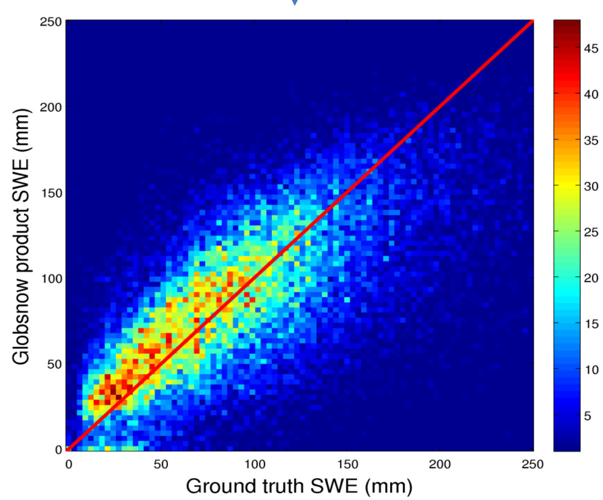
Russia: 1300+ snow transects from a vast geographical domain & diverse conditions

Finland: 100+ snow courses





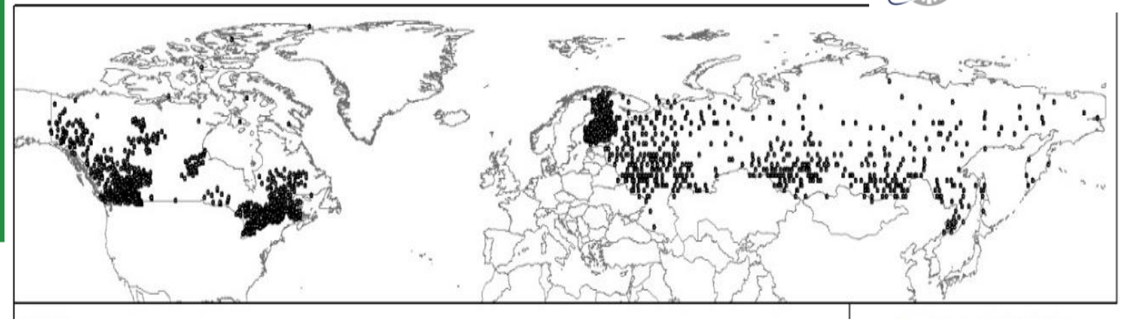
SWE retrieval accuracy



SWE retrieval accuracy should be determined from an independent & diverse temporally extensive reference dataset across NH

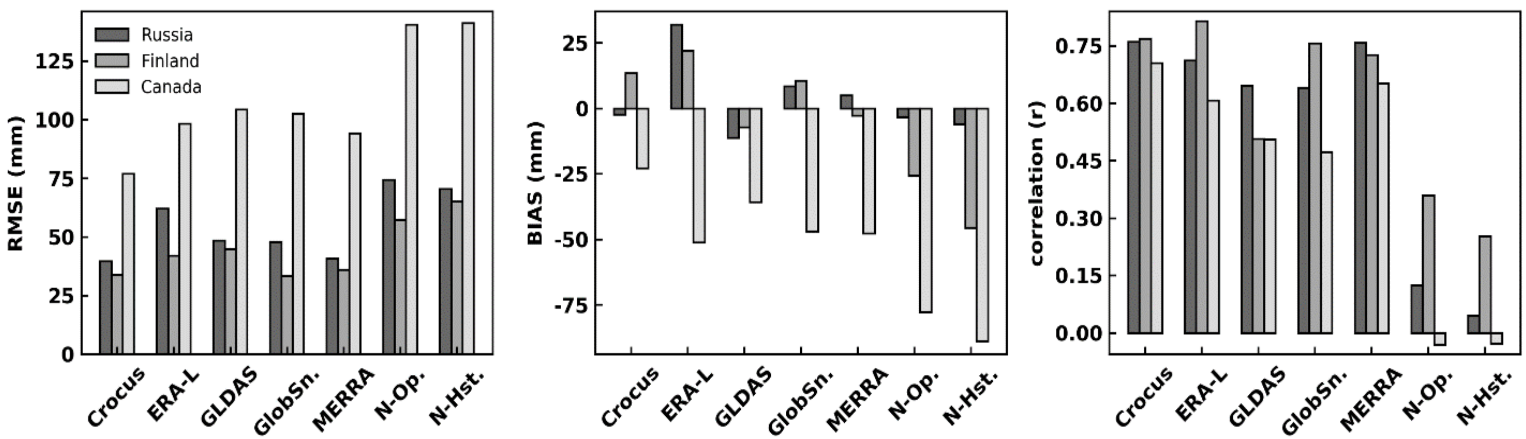
Retrieval performance, long term consistency, bias, trend evaluations

Validation: in situ observations



Spatial distribution of raw (un-gridded) snow course data used for product validation

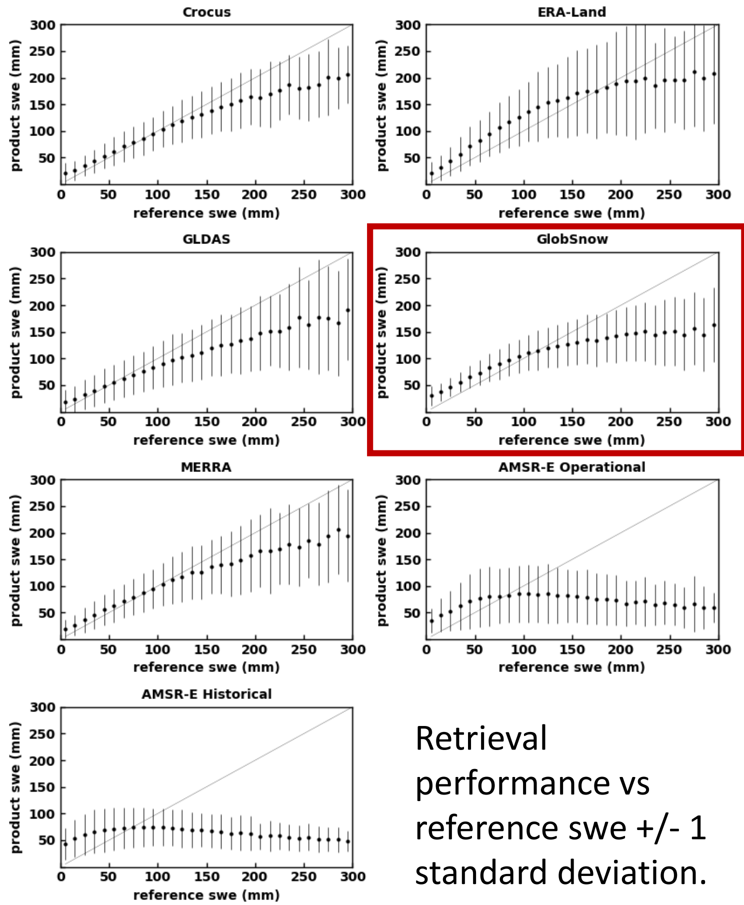
- Uneven spatial distribution of snow courses, especially over Canada
- Gridded snow course dataset: biweekly/10day, 25km grid
- CCI+ - to include additional assessment of temporal stability of snow in situ data prior to validation of 40yr record



Validation statistics for various SWE products (against gridded snow course data), 2002-2010

Validation – SWE magnitude 2002-2010

- GlobSnow and Reanalysis-based products – reasonable agreement up to ~100-150 mm swe
- Standalone PMW products insensitive to magnitude of SWE above ~60-100 mm swe.
- Performance of GlobSnow closely tied to density of synoptic snow depth observations (Larue et al. 2017; Brown et al. 2018) – CCI+ to investigate influence synoptic SD

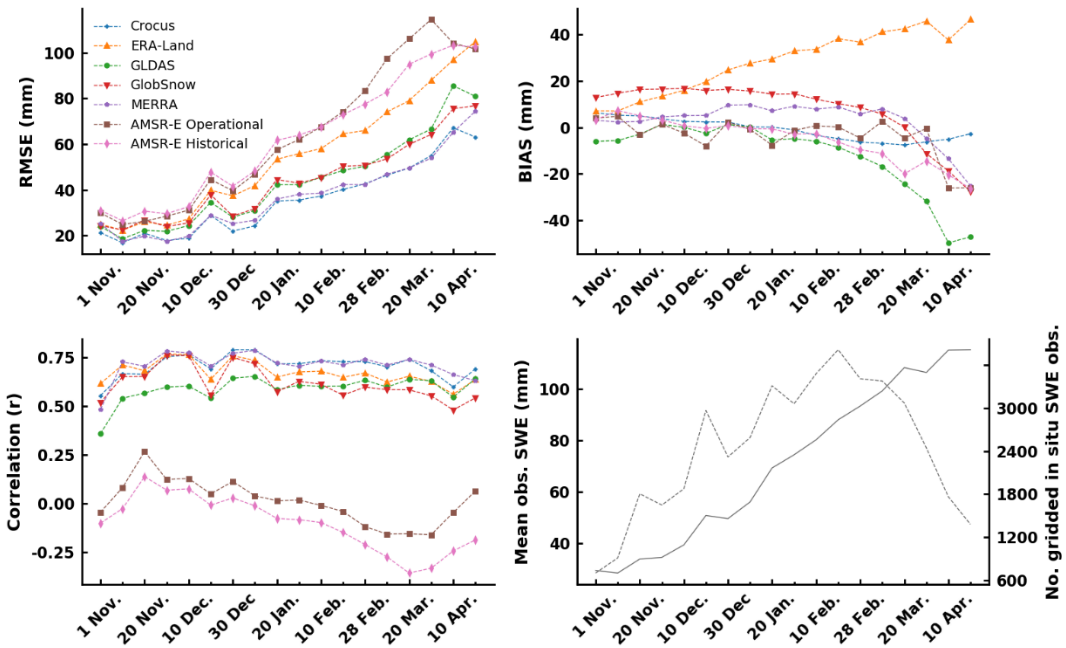


Retrieval performance vs reference swe +/- 1 standard deviation.

snowpex

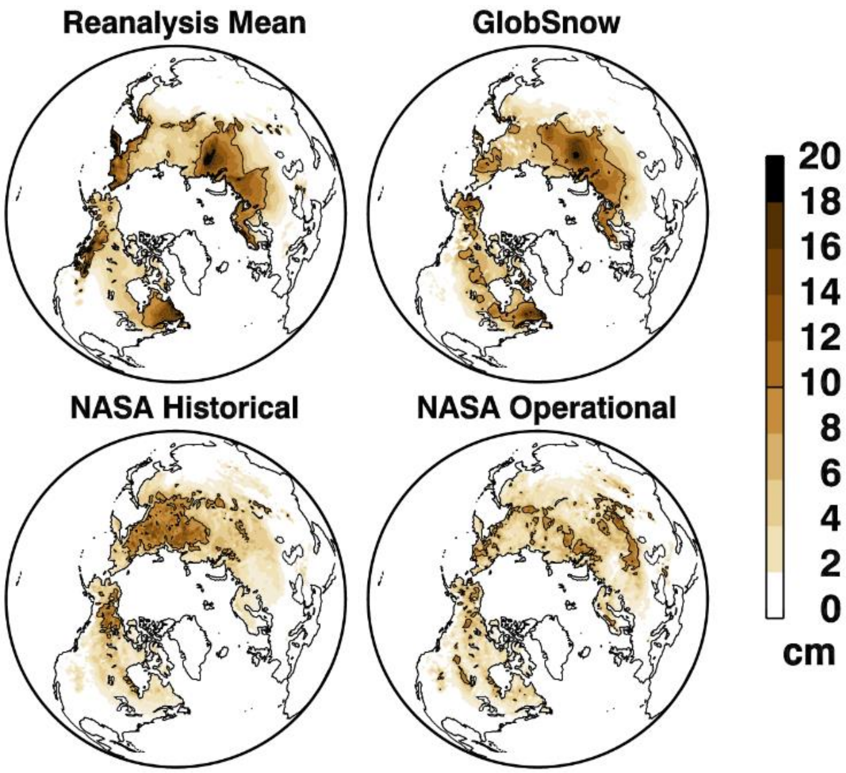
Influence of seasonality on performance (2002-10)

- RMSE and Bias increase over the course of the snow season
- Peak uncertainty late in the season – driven by cumulative errors over the entire season, differences in timing of snow onset, different melt rates
- Correlation for all but the standalone PMW products is stable over the snow season
- Stable correlation – indicates SWE anomalies should be reasonably realistic throughout the season, even if climatological amounts of SWE differ between analyses.



SWE product intercomparison

- Existing SWE products show widely differing climatological SWE

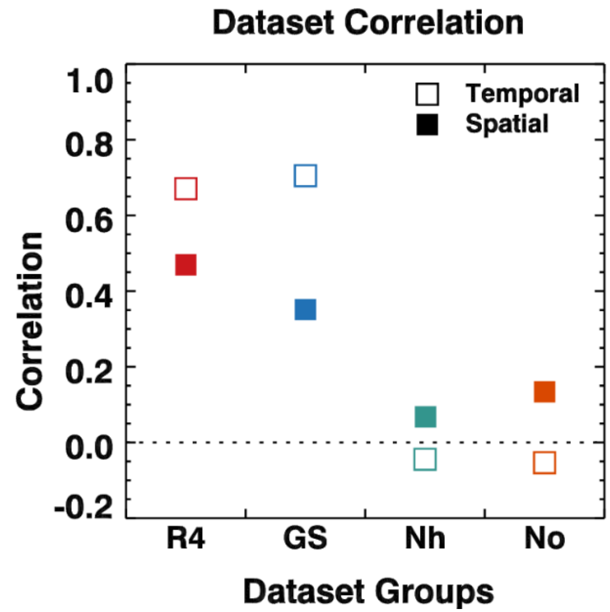


Mean JFM SWE over 2003-10 period
'Reanalysis mean' - 4 reanalysis-driven products (GLDAS-2, ERA-Interim-land, Crocus, MERRA)

Intercomparison

- Snow course – point data and not available everywhere
- Intercomparison - provides measure of agreement over complete spatial and temporal domain
- Good agreement between datasets does not mean lower bias compared to ground truth; rather the datasets are consistent with each other.

- Pairwise correlations of SWE anomaly:
  - Reanalysis/LSM-based products reasonably well correlated with each other and with GlobSnow
  - Standalone PMW – lack of correlation reanalysis-based products



Representative values for temporal and spatial correlations among groups of products (2003-10)

Intercomparison

- Pairwise SWE anomaly correlations for each grid cell
- Each of the 4 modern era reanalysis products well correlated with the R4 mean
- GS and R4 product mean strong agreement except Arctic Canada & Ephemeral snow zones
- Standalone PMW datasets – weak and even negative correlations with R4; newer 'operational' algorithm slightly better over eastern Siberia

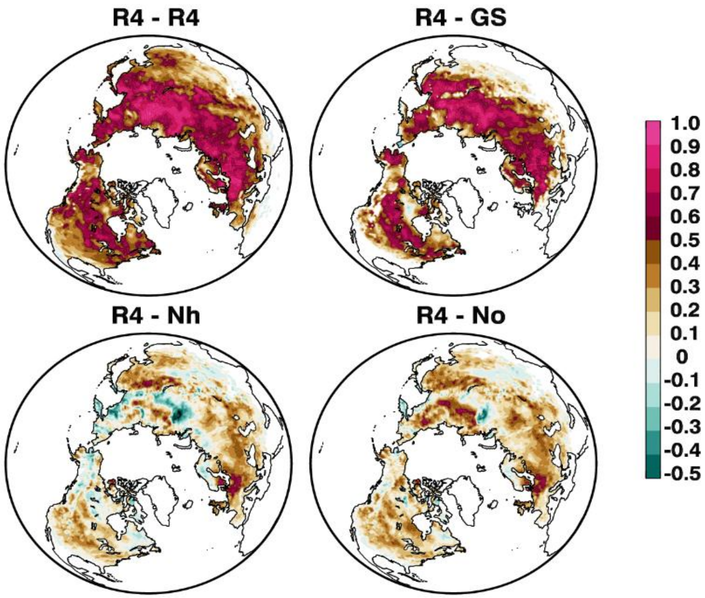


***Fig.** Correlation map of four reanalysis driven products (Crocus, GLDAS2, ERA-Land, MERRA) and each other, Globsnow v2, NASA historical and operational PMW algorithms.*

Long term Snow Extent trend anomalies (from SWE datasets)

snowpex

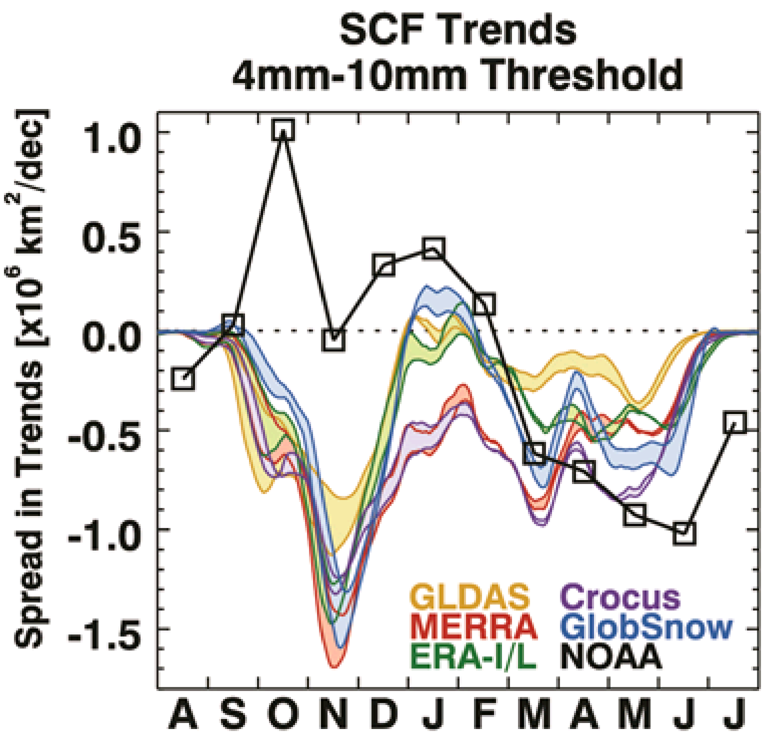
EC

- Trend analysis – from satellite & model-based SWE datasets:

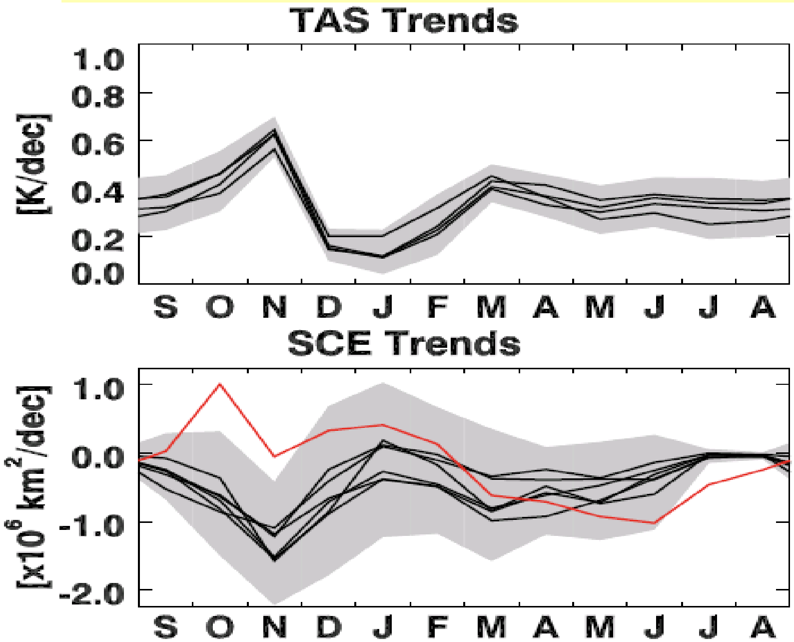
  -Integration of SCE and SWE products: SE used to limit SWE (GlobSnow & JXAM5)

  -SWE products converted to SCE, 1981-2010; monthly spatial trend maps at 1x1 deg; temporal trend statistics.

  -Snow Extent trends from SWE data vs. NOAA_CDR long term trend!



Monthly NH surface temperature trends from CRU, NCDC, GISS and NCEP2m



NOAA-CDR is an outlier, esp. Oct/Nov

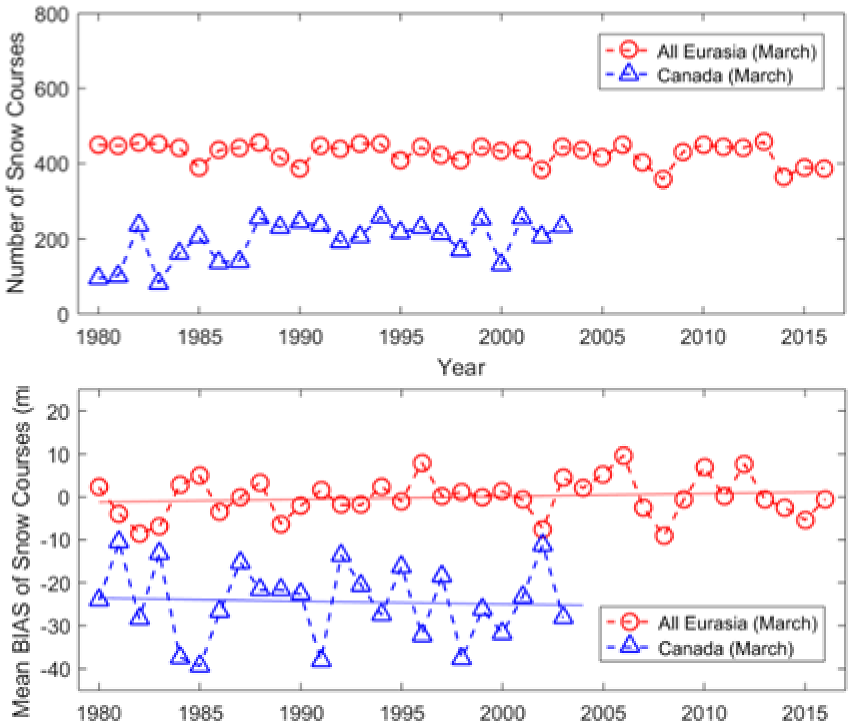
Monthly NH SCE trends from MERRA, ERA-I-Land, Crocus, GLDAS-2, Brown, GlobSnow, and NOAA-CDR

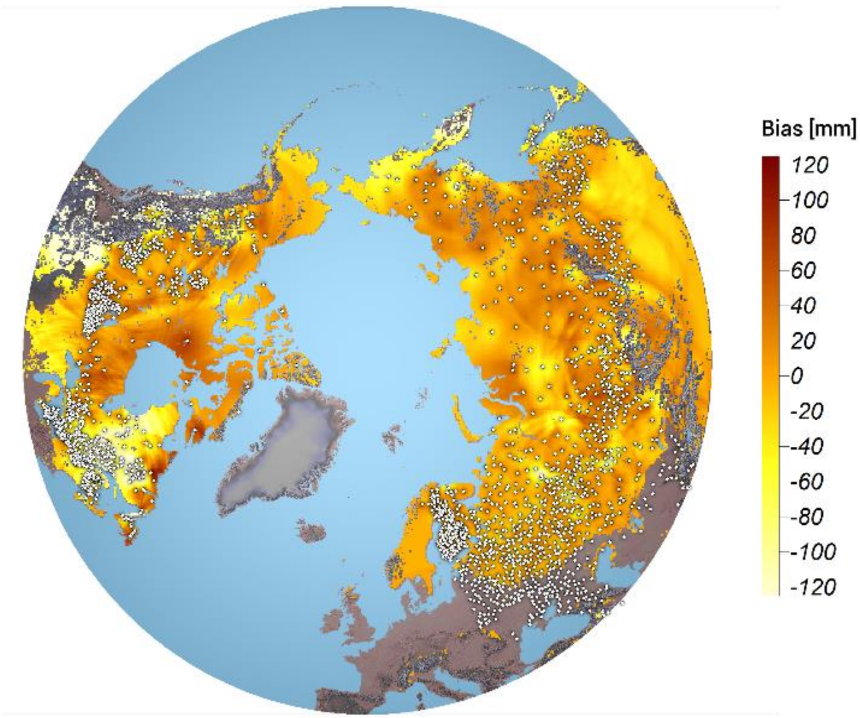
3. Seasonal snow cover mass in Northern Hemisphere

Recent results from bias-corrected GlobSnow SWE CDR
[Pulliainen, Luojus, et al. in review]

Bias-correction of the GlobSnow SWE CDR

- A bias-correction procedure that utilizes independent snow course observations was applied to the GlobSnow SWE CDR (~600 consistent snow courses over NH)
- Bias assessed & corrected for each year & each snow course, bias corrected for SWE with nearest neighbour interpolation

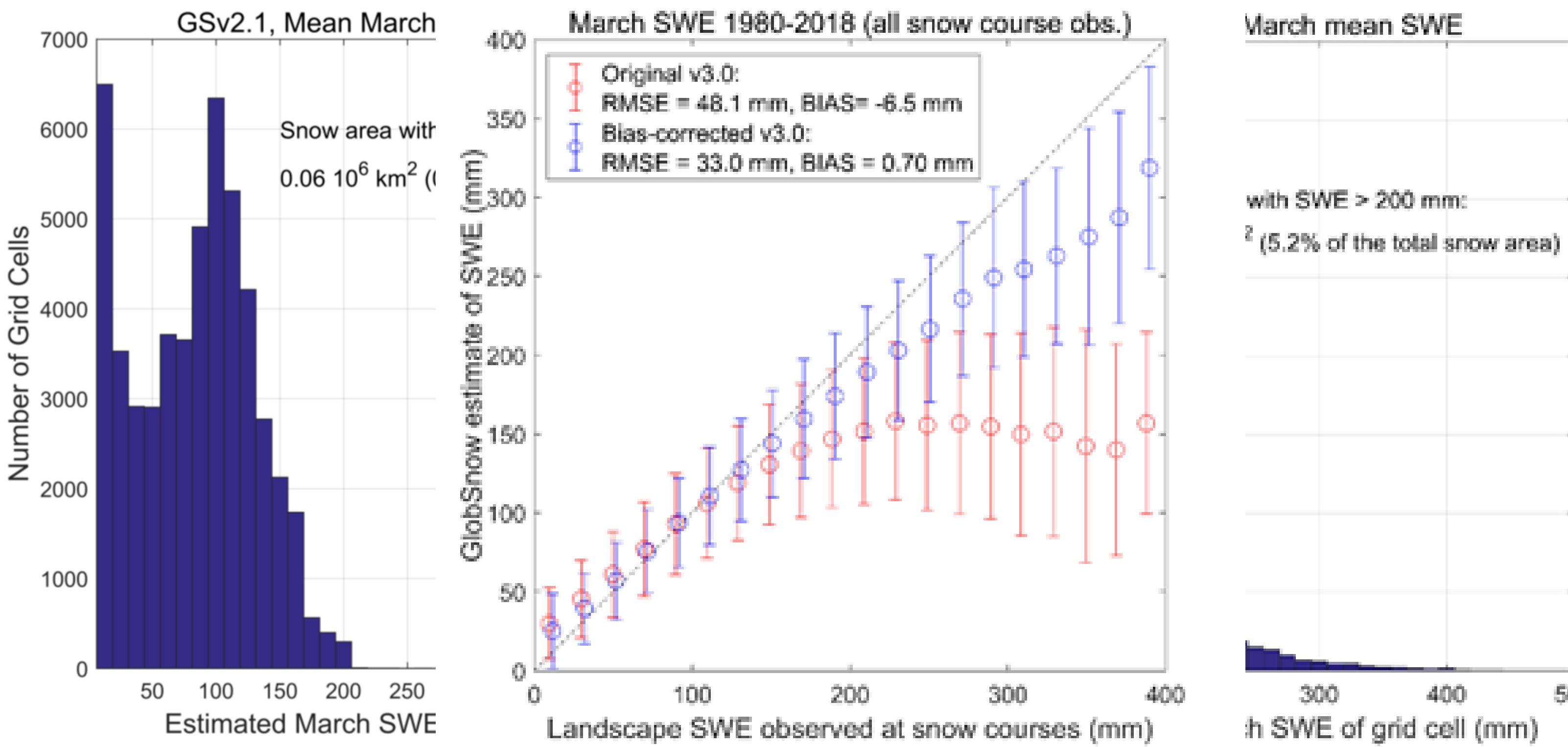




Evolution of the annual BIAS of GlobSnow SWE estimates for March

Recent results from bias-corrected GlobSnow SWE CDR for 1979-2018

- The bias-corrected dataset increases the SWE estimates (typical under-estimation of deep snow is corrected to a degree)



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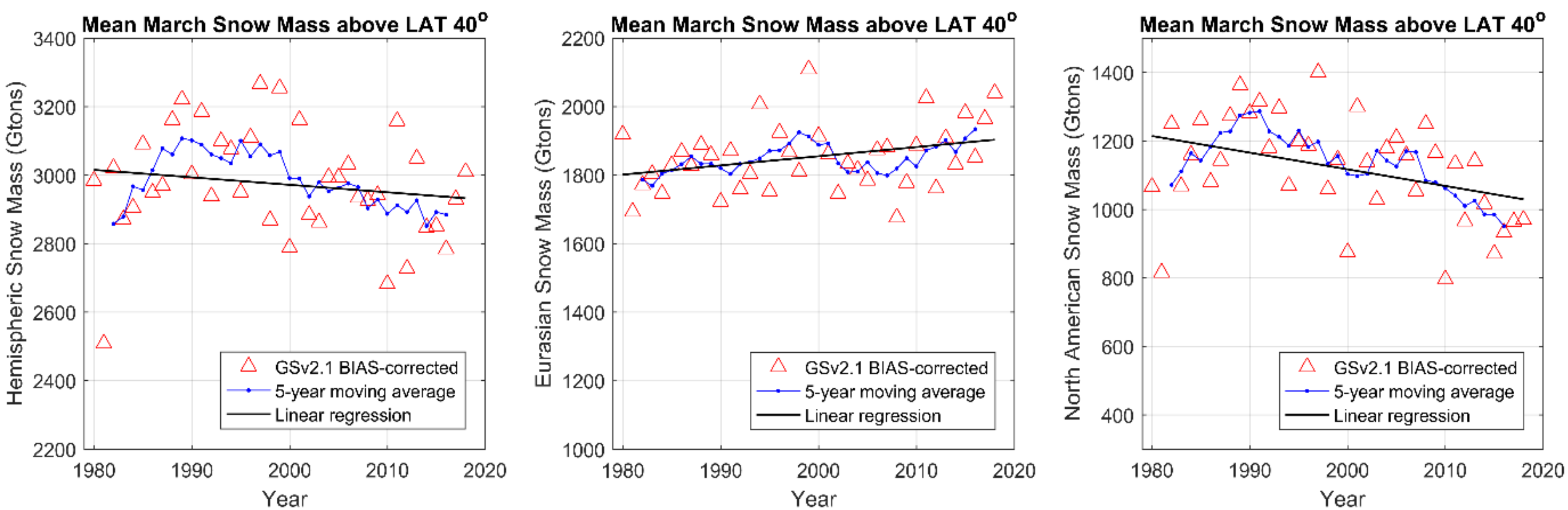
Recent results from bias-corrected GlobSnow SWE CDR for 1979-2018

- The bias-corrected dataset does not show a significant trend for NH for Peak SWE period of March (also non-significant trends for Feb & April)
- Trends in snow mass are very small (compared to trends in Snow Extent)
    - Snow melts earlier, but SWEmax is not affected at the moment



Conclusions

- Optical and Passive MW sensors are well suited for snow cover monitoring, from high resolution regional to moderate/coarse resolution global level
- Different focus for different frameworks; e.g. ESA = long term climate data records; EUMETSAT focus on operational hydrological applications; also Copernicus is gradually building snow and river/lake ice services
- Validation & QA are crucial; a lot of work but needs to be carefully considered

- A number of significant 1) operational services & 2) R&D projects on-going
- Strong European know-how on satellite-based snow remote sensing (built by number of projects by EUMETSAT, ESA, EC), wealth of data and products for different applications, including operational NRT and climate applications
- Current and future satellite sensors (by EUMETSAT, ESA and Copernicus) provide still greatly improving capabilities in the coming years -> multi-sensor / multi-domain approaches (optical + PMW + SAR / polar & geostationary sats) have still plenty of R&D potential