On the synergy of space-borne active and passive microwave sensors for snowfall retrieval: Recent advances, challenges, and perspectives towards the future European missions

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EUMETSAT H SAF

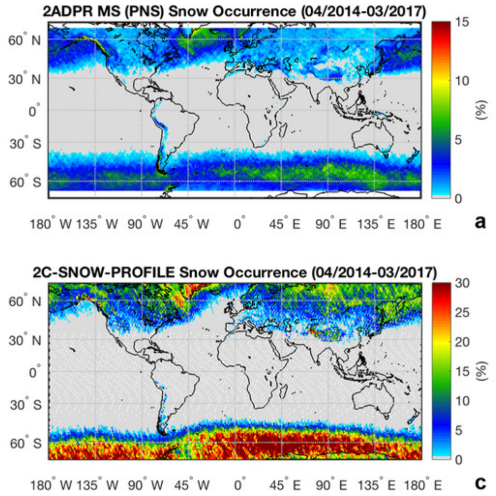
MW radiometry and snowfall: A few key points

Satellite-based precipitation detection and estimation at higher latitudes (mainly snowfall) is one of the main challenges in precipitation retrieval from space

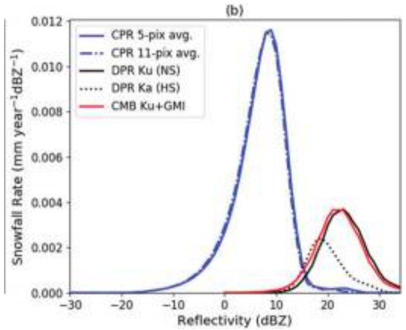
Complementarity of spaceborne radars:

- ***GPM DPR (Ku/Ka band)***: better coverage (large swath but up to 65°N/S) *valuable for medium/heavy snow conditions*; low sensitivity hampers detection/quantification capabilities of light precipitation
- ***CloudSat (and EarthCare) CPR (W band)*** **:** provides by far the most complete view of snow systems (up to 82°N/S) thanks to high sensitivity but is affected by attenuation

Current state of the art satellite products show large discrepancies in snowfall climatologies, in particular at higher latitudes



Snowfall occurrence percentage for (a) DPR MS and (c) CloudSat CPR



PDF DPR and CPR calibrated reflectivities in terms of snowfall rate

(Skofronick-Jackson et al., 2019)

Spaceborne radars do not provide the needed coverage for snowfall global monitoring -> need to rely on PMW radiometers (GPM constellation concept)

Large fraction of *higher latitudes snowfall* is missed by DPR (mostly due to sensitivity limits).

DPR vs. CPR (V04)	**DPR-Ku**	**DPR – Ka MS**
%missed snowfall events	92.5%	95.2%
% snowfall mass detected	28.08%	33.09%

(Casella et al., 2017, Atmos. Res.)

PMW Remote Sensing of Snowfall: Challenges

Challenge 1

The *PMW spectral signature in presence of snowfall* is highly dependent on the complex scattering properties of snowfall

Need to have a high-quality, global snowfall database to be used as a priori or training information in the PMW retrieval process

***Use of CloudSat-PMW radiometer* coincidence dataset (e.g., 2B-CSATGPM, Turk et al., 2021, Rem. Sensing) for analysis of PMW snowfall observation capabilities and PMW snowfall retrieval algorithm development**

Challenge 2

Snowfall scattering signal is weak and tends to be *masked by the water vapor and supercooled cloud liquid water (SCLW) emission*

Need to characterize atmospheric moisture and SCLW at the time of the overpass

- **Model-based ancillary variables**
- **Alternative. Exploitation of all WV sounding channels and 90 GHz channels and use of observational datasets**

Challenge 3

Significant effects of background surface on the upwelling microwave signal in presence of snowfall (especially in dry conditions/high latitudes)

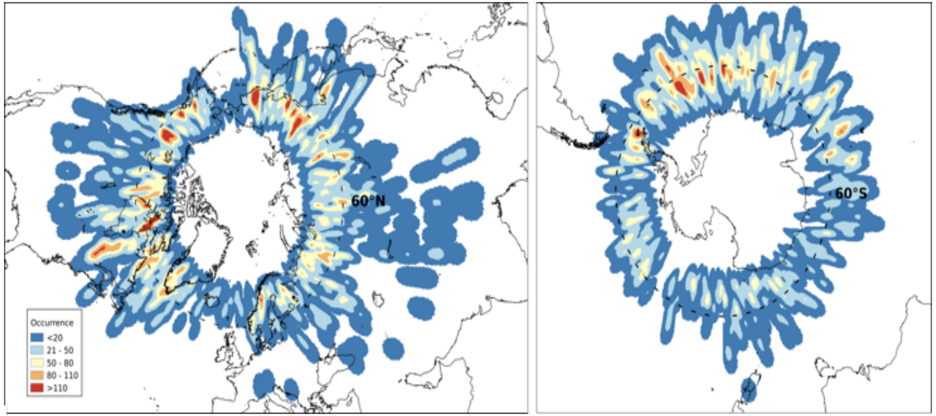
Sea ice and snow-covered land surface emissivity is extremely variable due to rapid changes of sea ice and snow properties of snow cover extent, snow accumulation on the ground, and snowpack and sea ice physical properties.

Exploitation of low frequency MW channels in precipitation retrieval at the time of the overpass

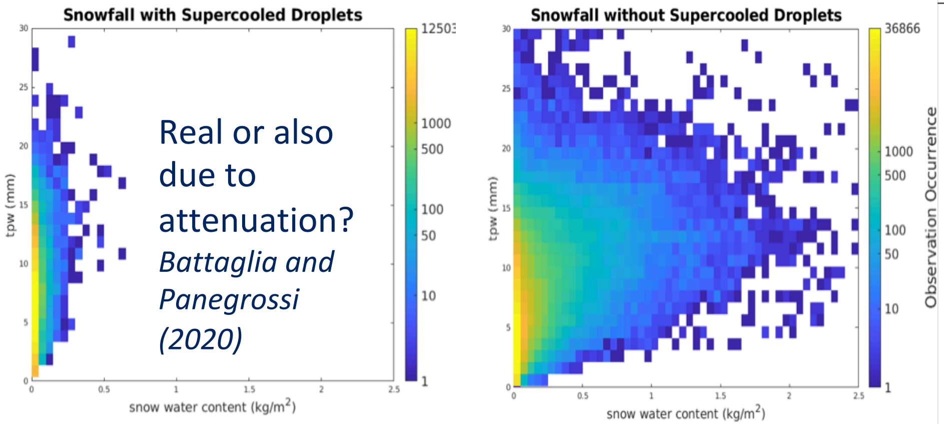
CloudSat/GMI and CloudSat/ATMS coincidence datasets

CloudSat/Calipso-GMI (extension of NASA 2B-CSATGPM v4)

Period	10/03/2014 – 01/09/2016
Geographical area	65 °S–65° N, 180° W–180° E
Number of GMI orbits	6,502
Number of triple coincidences (GPM-CPR-ATMS)	5,801
Number of elements	5,870,903
Number of elements with snowfall	400,145
Number elements with snowfall and SLCT	289,905 70% of snowfall elements



Geographical distribution of GPM/CPR coincidences
(Panegrossi et al., 2017)



Real or also due to attenuation?
Battaglia and Panegrossi (2020)

CPR 2C-SNOW +Calipso

CloudSat/Calipso-ATMS

Period	1/01/2015 – 1/09/2016
Geographical area	90°S–90° N, 180° W–180° E
Number of ATMS orbits	3,049
Number of elements	4,670,442
Number of snowfall elements	745,533
Number of snowfall elements with SLCT	456,391 60% of snowfall elements

SLALOM: CloudSat-based PMW snowfall retrieval

(in preparation for EUMETSAT H SAF EPS-SG MWI day-1 precipitation product)

Machine Learning approach based on the GMI/CloudSat/Calipso coincidence observational dataset; CPR 2C-SNOW-Profile product is used for training (*dry snowfall only (liquid fraction < 15%, no mixed phase or liquid precip.*)

Input: GMI L1c TBs (all channels) and auxiliary ECMWF analysis variables on atmospheric state (T2m, moisture profiles)

No auxiliary info on background surface conditions but exploitation of all GMI low frequency channels

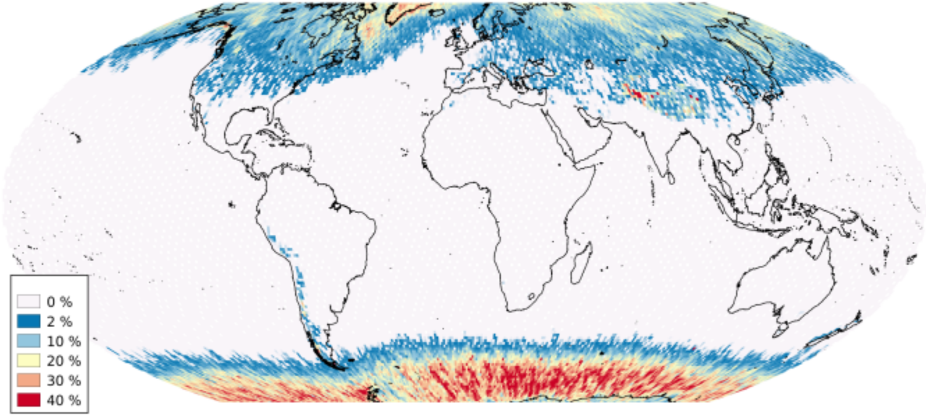
Random forest modules for snowfall detection and supercooled liquid water detection;

Multi-linear regression module: snow water path (SWP) estimates

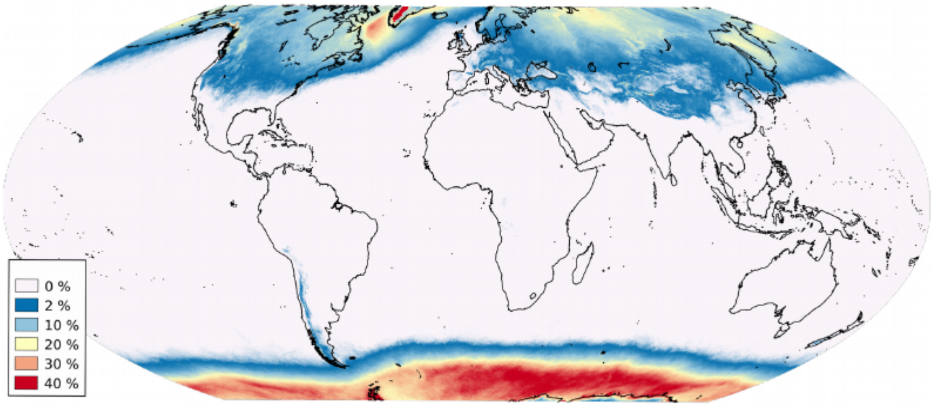
Gradient boosting module: Surface snowfall rate (SSR)

Global snowfall Occurrence 05/2014 - 05/2016

CPR



SLALOM



Good agreement with CloudSat CPR, with the advantage of wide swath coverage versus the nadir-only view of CloudSat

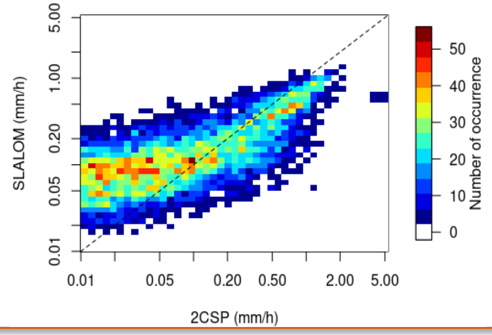
Rysman et al., 2018, 2019

SLALOM: CloudSat-based PMW snowfall retrieval

(in preparation for EUMETSAT H SAF EPS-SG MWI day-1 precipitation product)

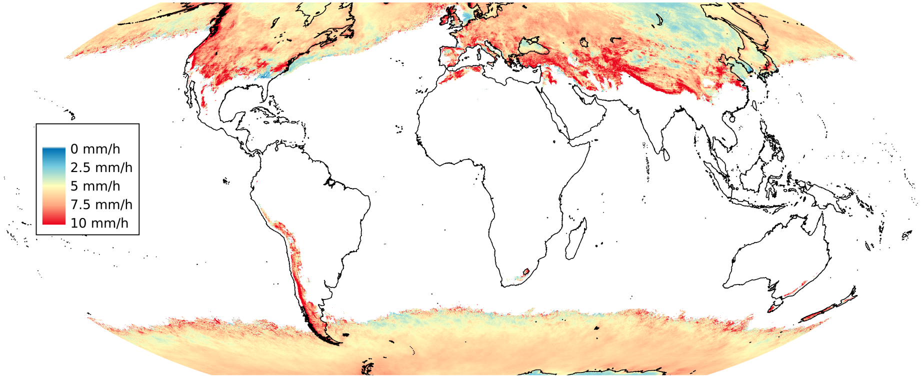
SLALOM main limitations:

- **SLALOM fully relies on the 2C-SNOW-PROFILE CPR product (V04);**
- GMI/CPR observations mostly occur around 60°N/S;
- Overestimation lower snowfall rates (< 0.1 mm/h) (sensitivity issues) and **underestimation of higher rates (not well represented in the training dataset)**

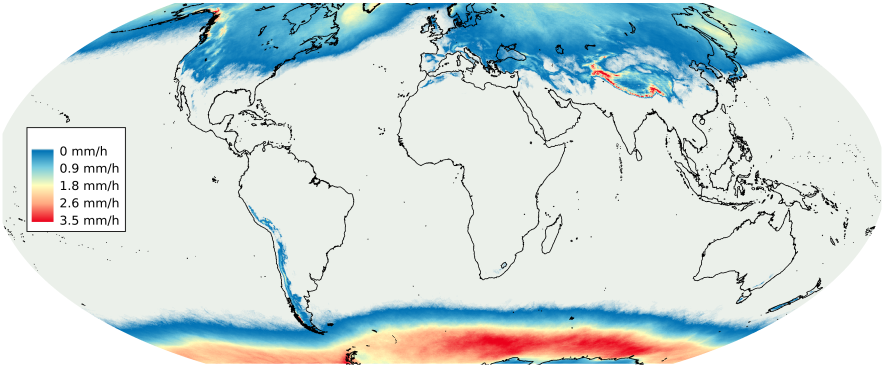


Mean SSR (mm/h) between May 2014 and May 2017

Conditioned (SSR > 0 mm/h)



Unconditioned



Good agreement with CloudSat CPR, with the advantage of wide swath coverage versus the nadir-only view of CloudSat

Rysman et al., 2018, 2019

4-year SLALOM and GPM products validation over CONUS

(Mroz et al., JHM, 2021)

Ground-based radar reference data

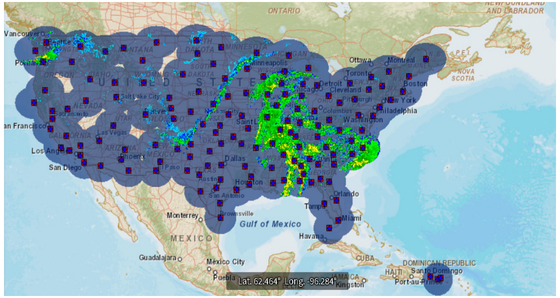
MRMS: Multi-radar-multi-sensor (*Zhang, et al. 2011, Zhang, et al. 2016; Tang et al. 2020*) https://blog.nssl.noaa.gov/mrms/

- ***Products***: Cartesian gridded level II and III radar products over US and Canada
- ***Resolution***: 1 x 1 km horizontal, 2 min time sampling

Variables considered:

- Instantaneous precipitation rate (*S*)
- Radar quality index (RQI)
- Phase precipitation flag

- ***Case studies analysis***
- ***Statistical analysis: 4 year dataset from Jan 2016 to March 2020***



Satellite Snowfall products

GPM Microwave Imager (GMI and Dual-frequency Precipitation Radar (DPR) products:

SLALOM for GMI

GPROF V05 for GMI (NASA GPM)

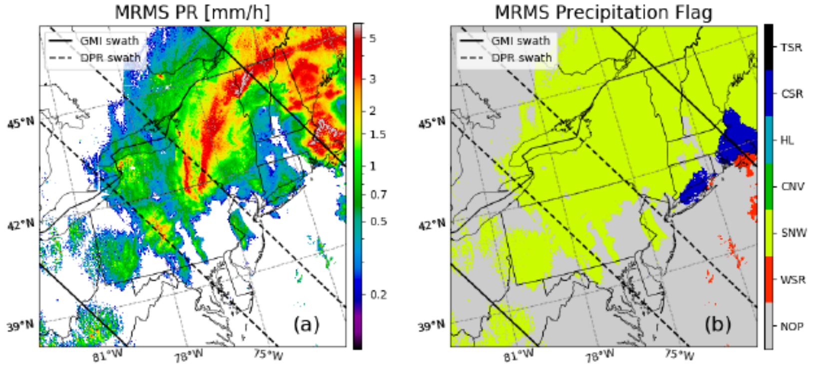
DPR, Ku, Ka V06 (NASA GPM)

CORRA (2B-CMB) V06 (NASA GPM)

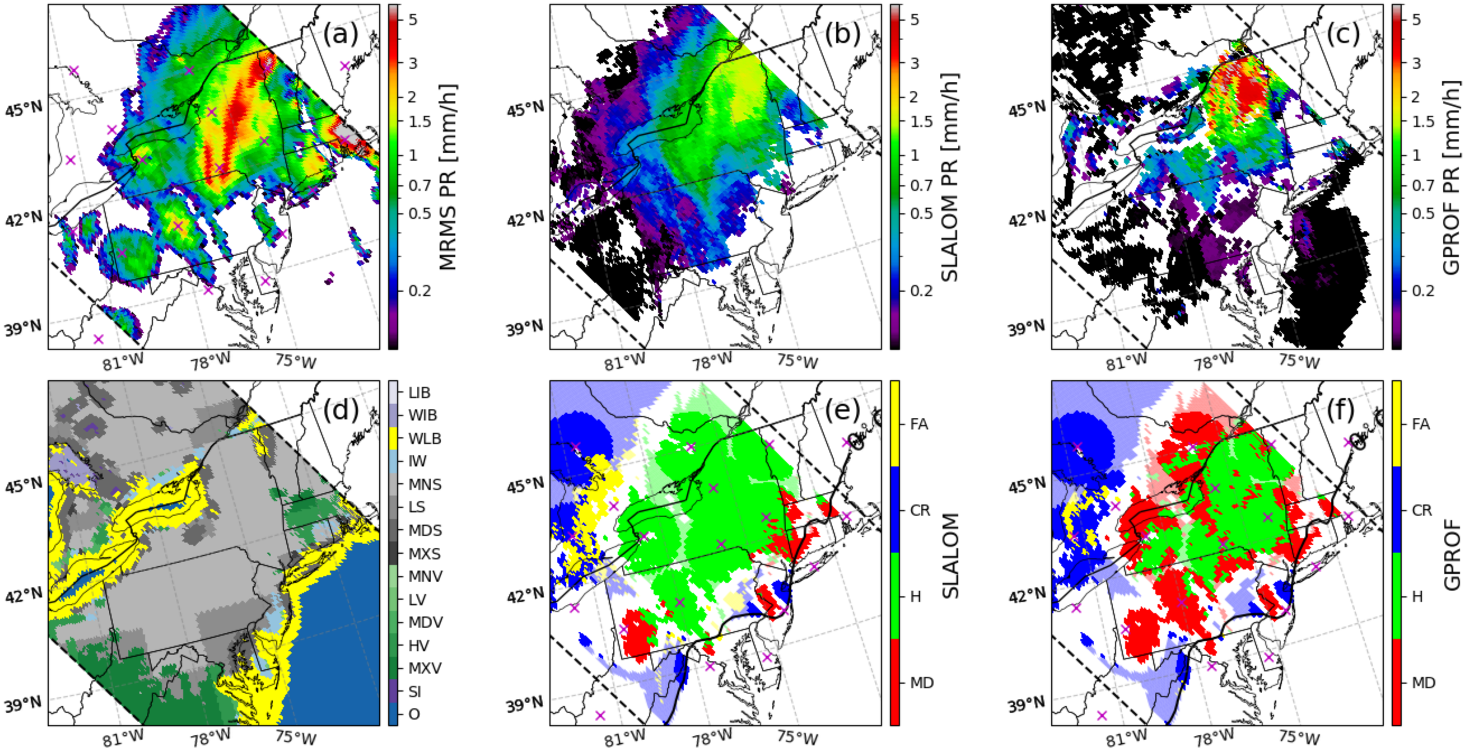
CloudSat CPR product

2C-SNOW-PROFILE (NASA)

Snowfall event 14 March 2017 20:02 UTC



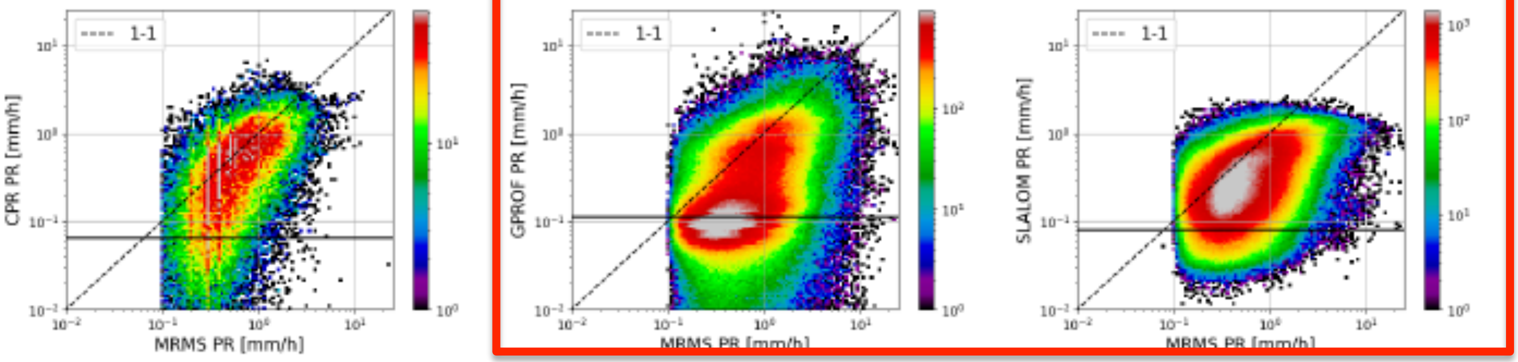
Snowfall event 14 March 2017 20:02 UTC



(Mroz et al., JHM, 2021)

Frozen precip. 2D histograms:
4-year analysis over all surface types (2016-2020)

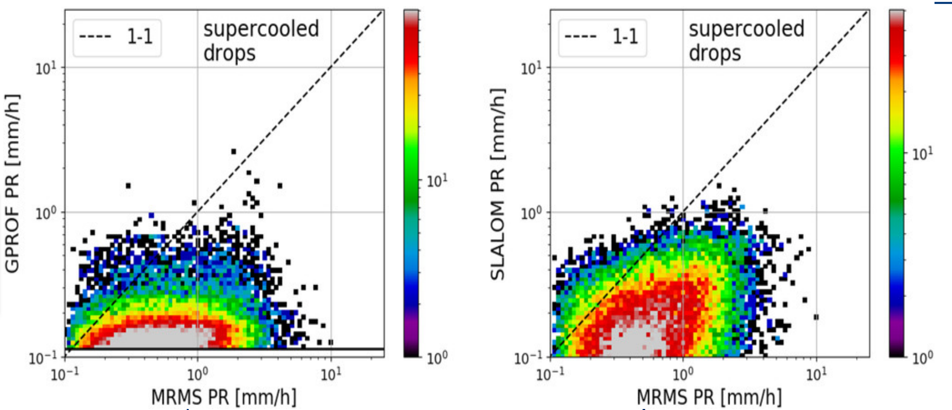
(Mroz et al., JHM, 2021)



Black horizontal lines show the limit on the satellite product that optimizes precipitation detection matching with MRMS

	ME (mm/h)	RMSE (mm/h)	CC	MB %	# of hits
DPR	-0.56	1.08	0.43	56.3	175581
Ku	-055	1.02	0.53	57.3	175274
Ka	-094	1.78	0.38	54.3	30589
CORRA	-0.53	1.07	0.44	57.2	185982
GPROF	-0.54	1.08	0.39	48.4	570736
SLALOM	-0.38	0.74	0.43	48.5	1166181
2C-SNOW	-0.21	0.68	0.45	73.0	50541

The best ; second best



Frozen precipitation detection scores over different surface types *(Mroz et al., JHM, 2021)*

4-year analysis over all surface types (2016-2020)

Score	GMI SLALOM	GMI GPROF	CPR 2C-SNOW
POD (%)	57.3	28.1	70.0
FAR (%)	26.3	39.6	25.5
HSS (%)	58.7	31.3	68.3
CSI (%)	47.6	23.7	56.4

In SLALOM the exploitation of low frequency channels allows to better constrain the snowfall retrieval (based on high frequency channels) over all surfaces

Sea ice

Snow cover

Surface type	HSS (%)		POD (%)		FAR (%)		no. of MRMS pixels	
	SLALOM	GPROF	SLALOM	GPROF	SLALOM	GPROF	"no-snow"	"snow"
Ocean	46.1	18.9	49.5	22.7	24.8	39.5	66219	30940
Sea-Ice	54.4	15.2	59.0	12.3	37.6	48.6	93201	15158
Maximum Vegetation	57.1	31.3	49.1	21.3	18.9	9.1	799283	113169
High Vegetation	54.6	31.3	45.1	21.0	19.2	11.2	1381112	154952
Moderate Vegetation	56.2	28.8	45.8	18.8	16.1	7.5	473357	51387
Low Vegetation	60.6	32.3	50.2	21.7	16.3	16.5	24855	2007
Minimal Vegetation	63.4	24.4	53.0	16.9	12.4	30.3	8109	857
Maximum Snow	58.0	14.0	68.5	26.8	41.7	77.8	309380	38151
Moderate Snow	58.8	30.5	63.0	33.1	33.1	52.3	1641016	291043
Low Snow	60.5	28.2	63.9	29.6	30.9	51.7	1404417	258627
Minimal Snow	61.2	37.3	61.0	33.9	24.0	32.4	3448465	798754
Standing Water and Rivers	53.8	30.5	45.1	21.5	17.1	13.7	203484	33633
Water/Land Coast Boundary	49.4	19.0	45.9	14.1	20.7	12.9	731055	225411
Water/Ice Boundary	54.1	12.3	54.0	8.4	27.1	11.1	80445	20491

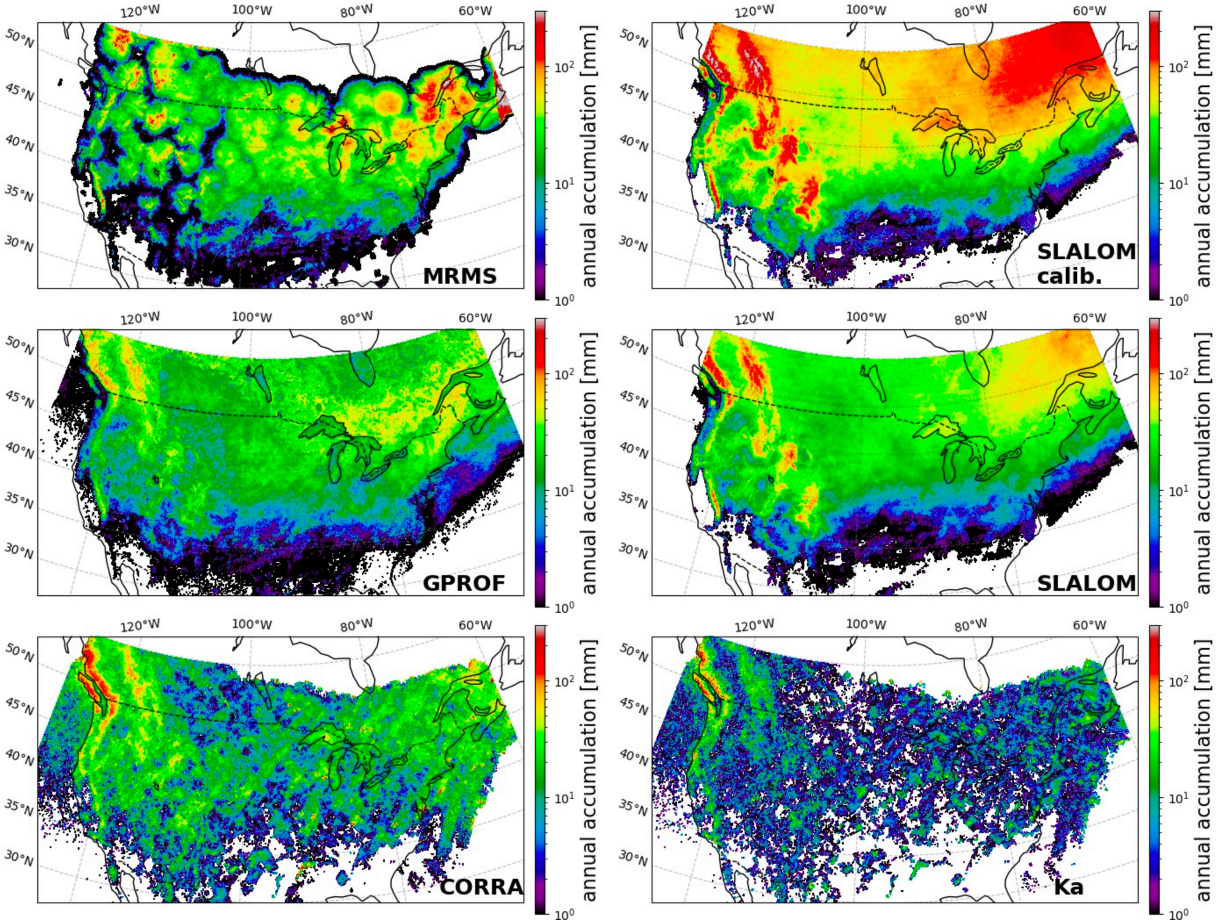
(sfc classes are based on GPROF surface classification)

Mean annual snowfall accumulation (2016-2019) *Mroz et al., JHM, 2021*

Only GPM coincident scans are considered in MRMS climatology

GPROF and MRMS are computed for the pixels where the frozen fraction exceeds 90%

The Ka-only and CORRA retrievals are accumulated over profiles where snow is detected in the lowest clutter free radar bin



The "SLALOM calib." product shows the climatology of the SLALOM algorithm calibrated with the MRMS data at close ranges following the procedure of Meng et al. (2020).

Maps at 1°x1°

PESCA: Passive microwave Empirical cold Surface Classification Algorithm (for ATMS and GMI in preparation for EPS-SG MWS and MWI)

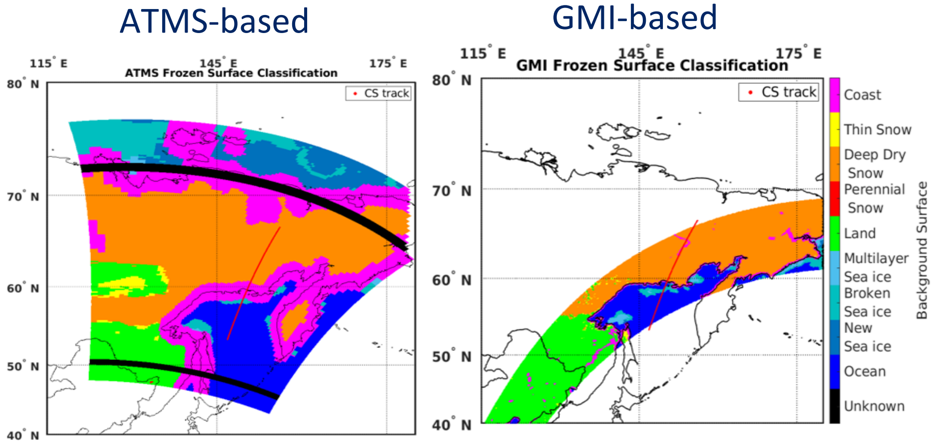
(Camplani et al., JHM, 2021)

The microwave signal related to snowfall is strongly influenced by the **different surface conditions** (e.g., wet or dry snow cover, snow depth, sea ice concentration and type, etc.). The use of surface classification climatological datasets results inadequate for the **extreme variability of the frozen surface conditions**.

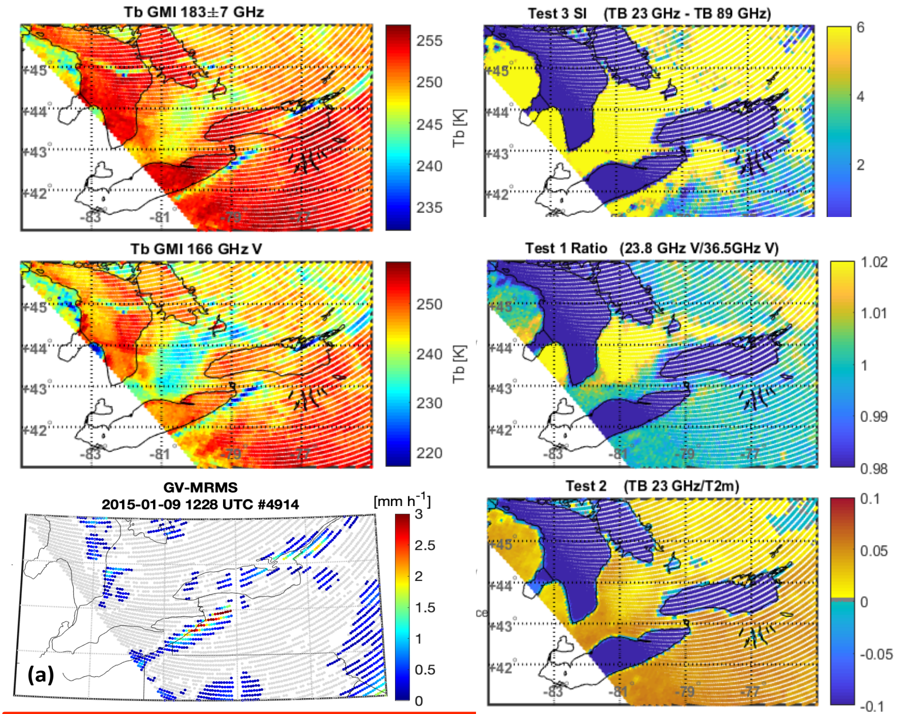
PESCA:

- Empirically-based algorithm for frozen background surface characterization (different types of sea ice and snow cover)
- **Use of low-frequency (<= 90 GHz) channels common to most radiometers;**
- Applicable to both cross-track and conically scanning spaceborne microwave radiometers *at the time of overpass* (for TPW < 10 kg/m^2)

Siberia 30 April 2014

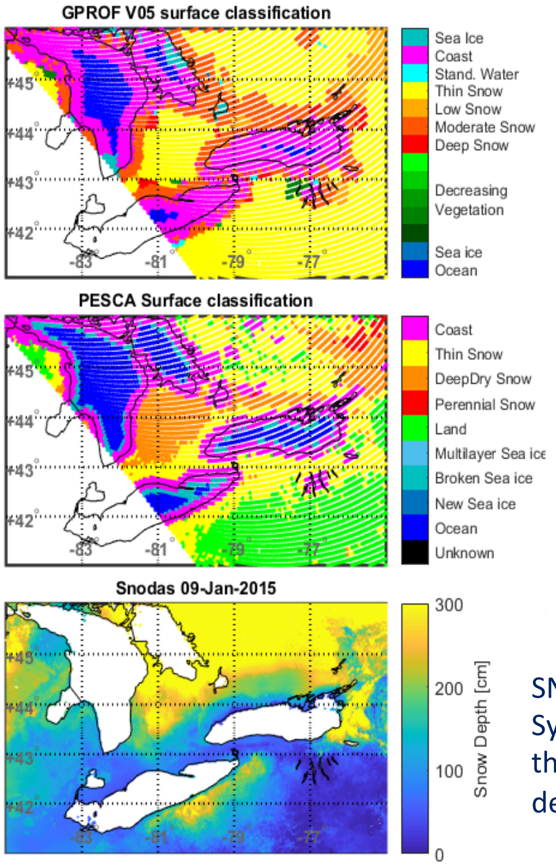


Snowfall vs. background surface conditions at the time of the overpass



Multi-channel TBs respond to both snowfall and snow cover (and sea ice) properties (especially in very dry conditions)

GMI overpass at 12:26 UTC for Extreme Lake Effect Snow event on 9 January 2015 (Milani et al., JHM, 2020)



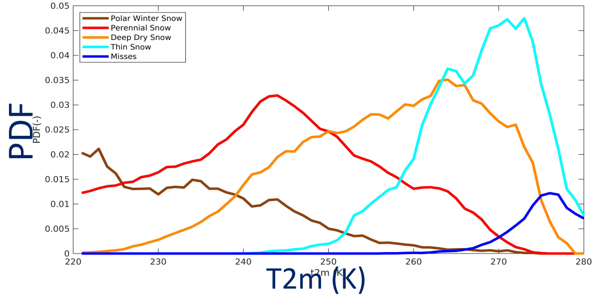
Need for better characterization of frozen surface (sea ice and snow cover) conditions:

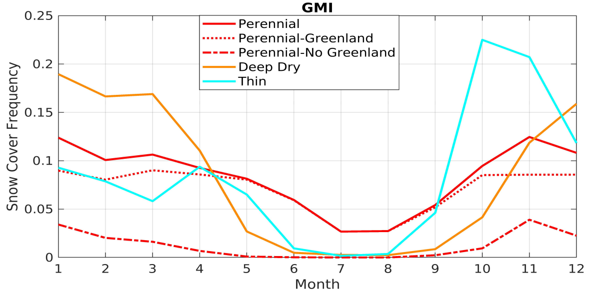
- Improved emissivity models
- Improved climatological/daily sea ice and snow cover products

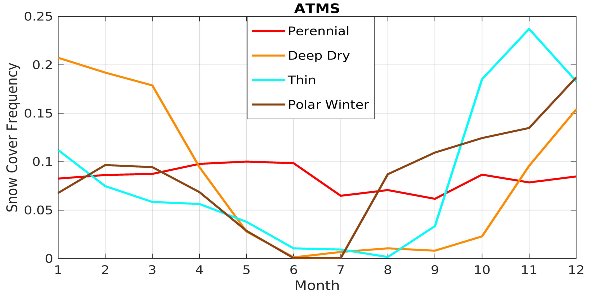
SNOw Data Assimilation System (SNODAS) from the NOHRSC) snow depth

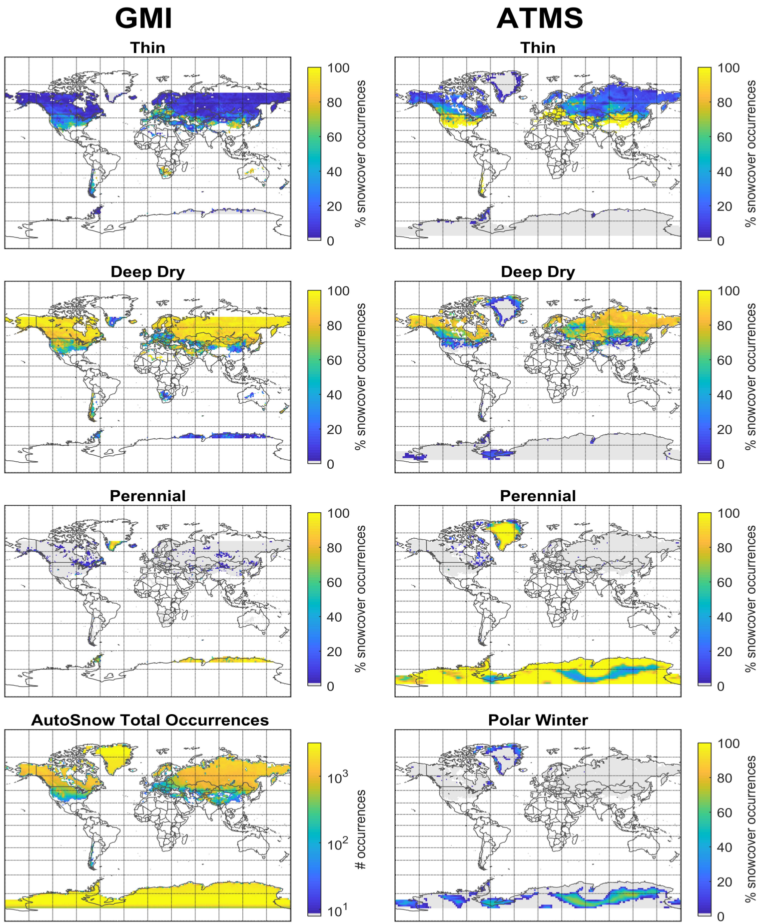
Turk et al., JHM, 2021

PESCA Snow Cover categories *(Camplani et al., JHM, 2021)*



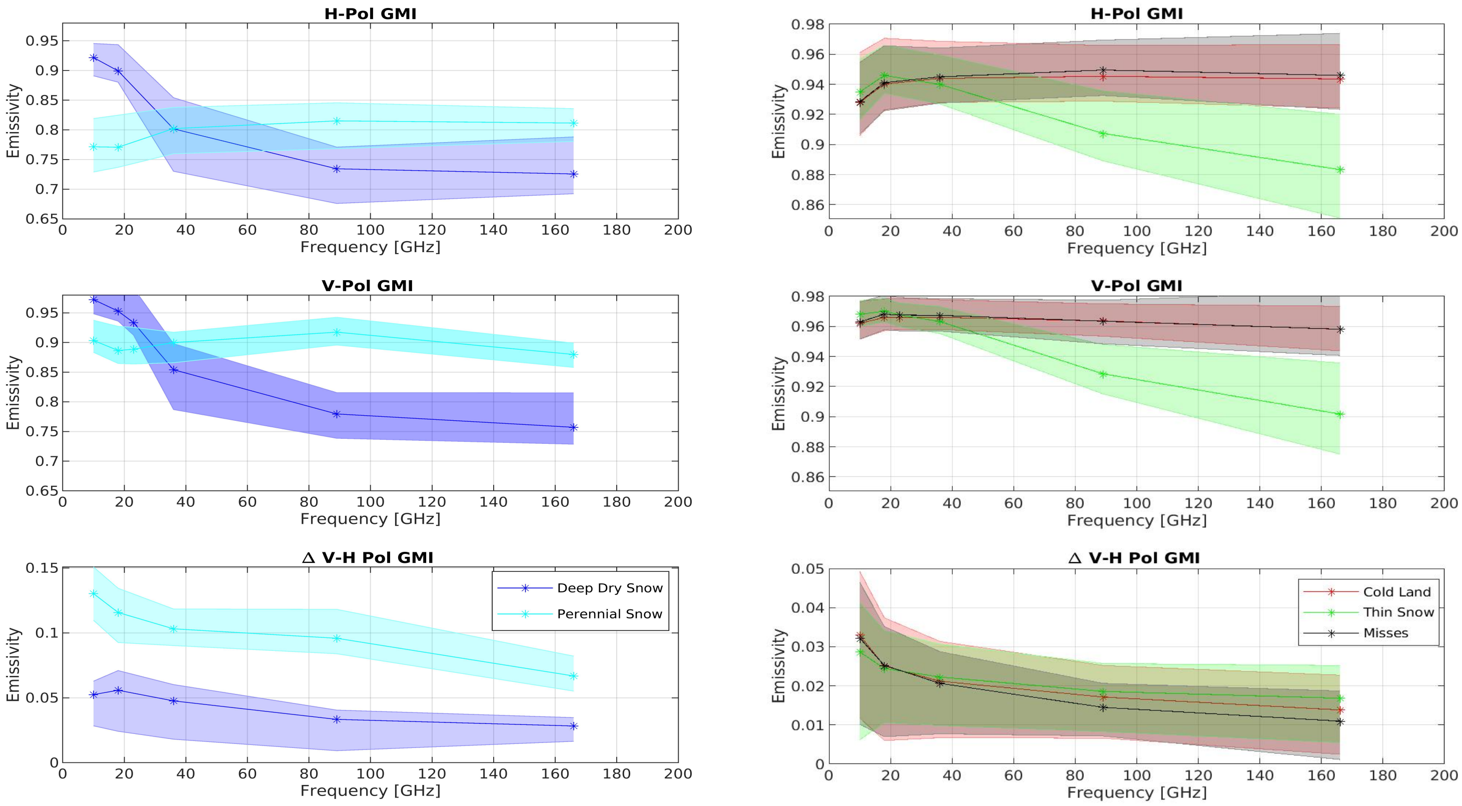






GMI channel emissivity for PESCA snow cover categories

(Camplani et al., JHM, 2021)



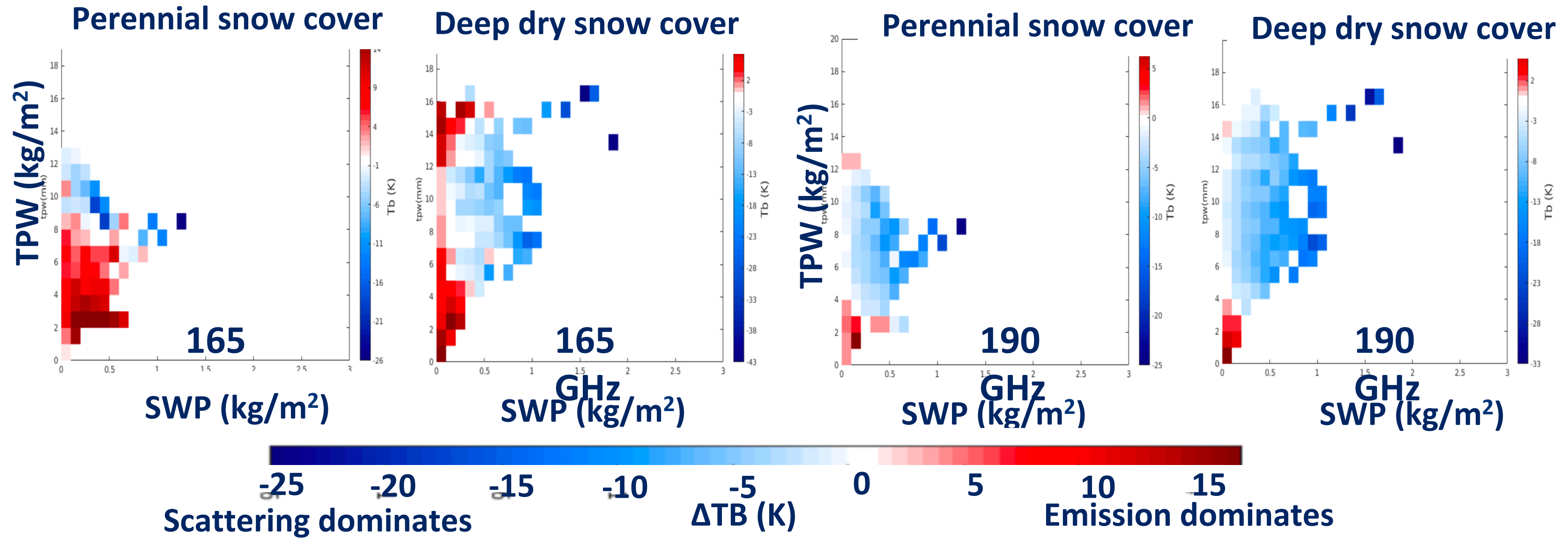
Median GMI channel emissivity (50th percentile) and 25th and 75th percentiles as a shaded area for each class

Distinct behaviour between Deep Dry and Perennial at 90 and 166 GHz (especially V-Pol). Deep Dry lightly polarized, Perennial strongly polarized

Large variability of thin snow emissivity.

Misses behavior is similar to cold land.

Global analysis: TB dependence on Snow intensity, Water vapour and snow-cover type (for ATMS)



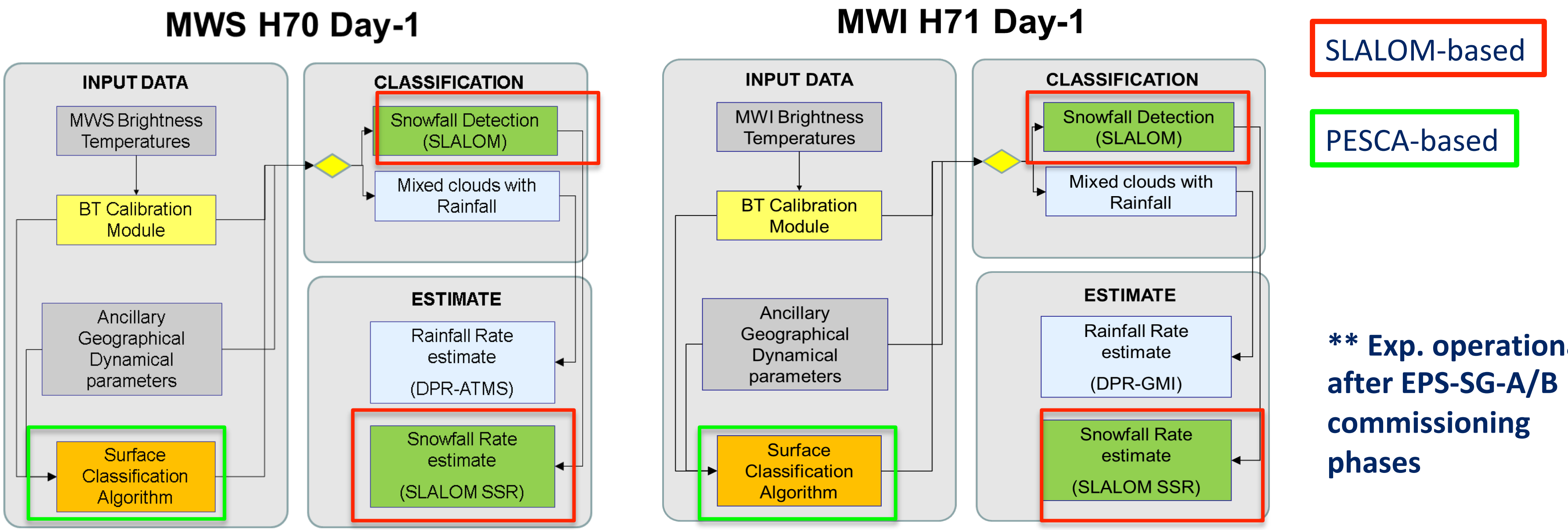
Mean TB difference in TWP/T2m/SWP bins with respect to "clear sky conditions" (SWP=0 kg/m²) for different snow cover categories in CloudSat/ATMS dataset

- **At 183.3±7 GHz *a scattering signal is always observed except for very low values of TPW* for both surfaces;**
- **At 165.5 GHz a transition from emission signal to scattering signal** is evident.
- **For deep dry snow and higher TPW, emission/scattering transition** depends on the SWP (when scattering from the frozen hydrometeors dominates over the atmospheric emission)

Outlook to EPS-SG MWS and MWI (EUMETSAT H SAF products)

ML-based precipitation products

Day-1 EPS-SG Level 2 Precipitation rate products



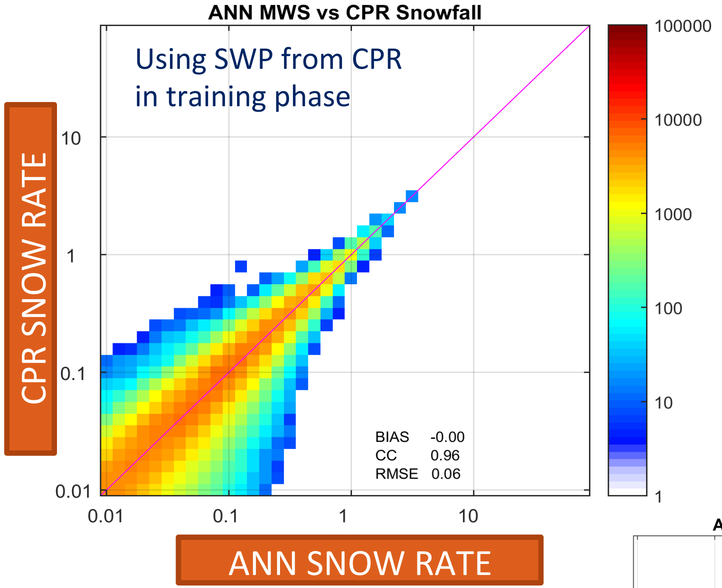
**** Exp. operational after EPS-SG-A/B commissioning phases**

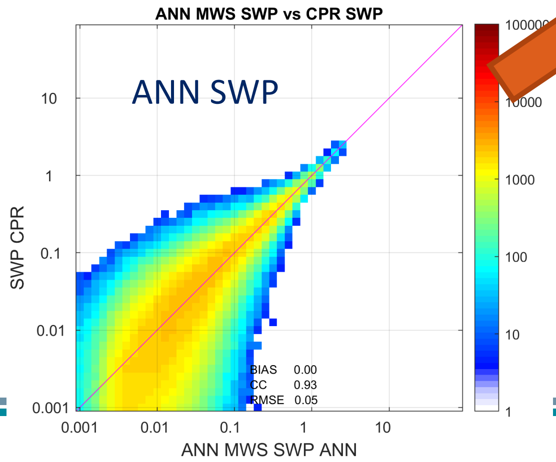
Observational training dataset built from global coincident measurements of existing PMW radiometers (ATMS and GMI) with GPM DPR and CloudSat CPR

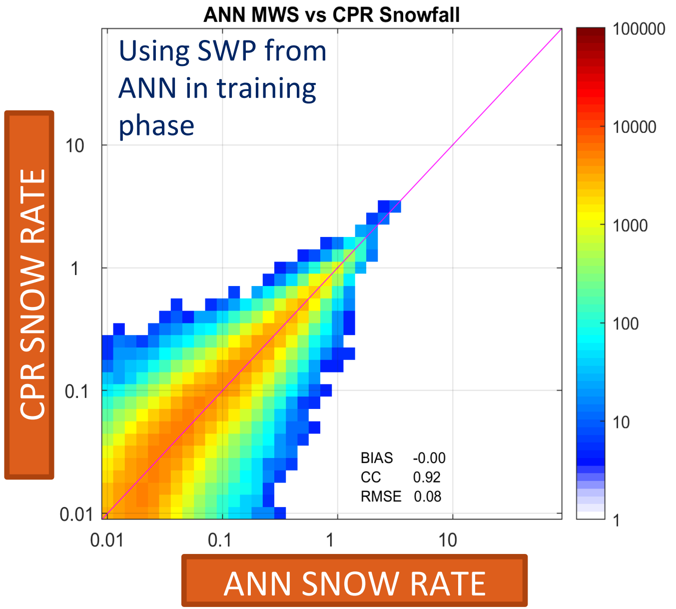
Day-2 EPS-SG products will be developed during CDOP-4 with actual MWI/ICI and MWS data

EPS-SG MWS day-1 product (based on ATMS)

Preliminary results



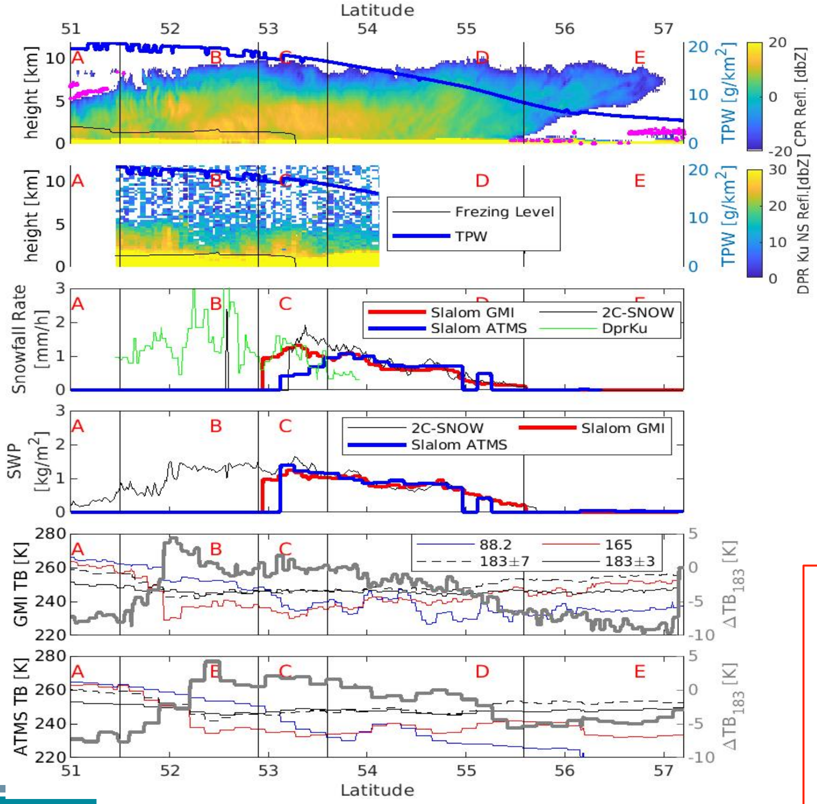


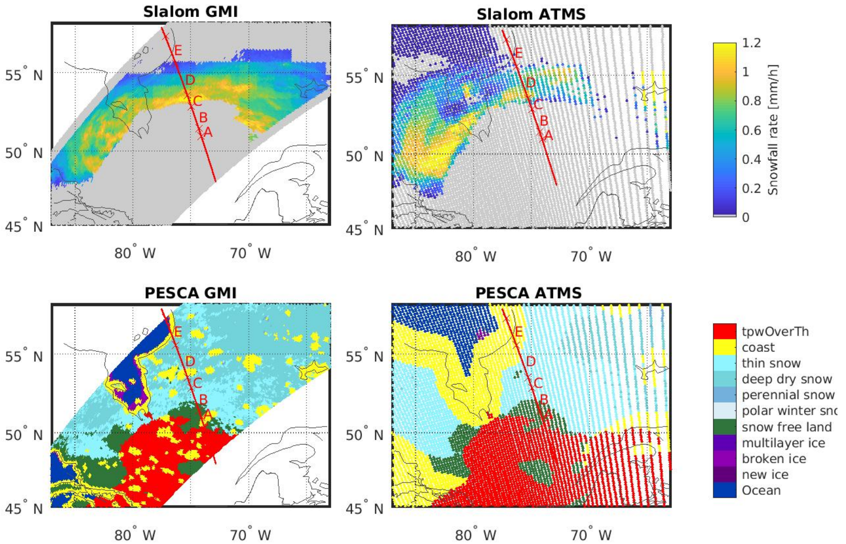


Outlook to EPS-SG MWS and MWI (EUMETSAT H SAF products)

SLALOM and PESCA for ATMS and GMI

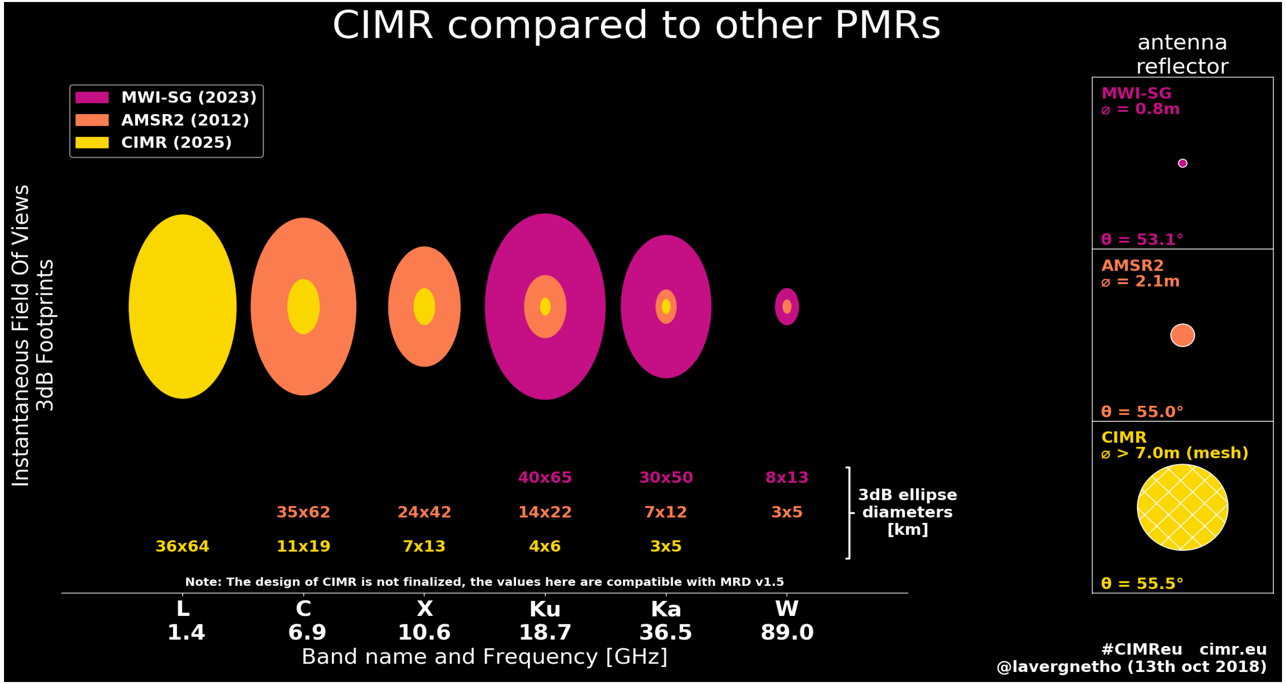
Snowfall event over Quebec and Ontario on 24 November 2014





Use of low frequency channels for background surface characteization at the time of the overpass: *potentials of CIMR channels and high spatial resolution for sea ice and snow-covered land properties to be used in synergy with MWI/ICI for H SAF EPS-SG day-2 precipitation products*

Potentials of Copernicus CIMR high spatial resolution



GMI IFOV size 11x18 km^2 at 19 GHz, and 4x7 km^2 above 89 GHz) (comparable to AMSR-2)
EPS-SG MWI spatial resolution is roughly three times lower (comparable to SSMIS)

CIMR will be able to provided unprecented measurements for sea ice and snow cover properties and to resolve precipitation features over sea as never before (in connections with other ocean state variables, SST, SSS, surface winds)

ESA Arctic Weather Satellite (AWS) mission

- **The future AWS misssion** is the perfect candidate to investigate the applicability and the potential of the SLALOM approach for light snowfall retrieval in extreme Arctic enviromental conditions.
  - Use of the 325 GHz channels combined with the 183.31 GHz channels to improve very light snowfall retrieval at high latitudes
  - The use of the full spectrum of the T and WV sounding channels for the definition of the environmental conditions (T and WV) at the time of the satellite overpass
  - AWS T and WV sounding capabilities, combined with the window channel at 89 GHz channel, for supercooled water droplets detection
  - **Synergy with CIMR or EPS-SG missions for background surface characterization would be very beneficial**

Channel	Frequency (GHz)	Bandwidth (MHz)	Noise Equivalent Delta Temperature (K)	Footprint (km)	Utilisation
11	50.3	180	<0.6	≤ 40	Temperature sounding
12	52.8	400	<0.4	≤ 40	Temperature sounding
13	53.246	300	<0.4	≤ 40	Temperature sounding
14	53.596	370	<0.4	≤ 40	Temperature sounding
15	54.4	400	<0.4	≤ 40	Temperature sounding
16	54.94	400	<0.4	≤ 40	Temperature sounding
17	55.5	330	<0.5	≤ 40	Temperature sounding
18	57.290344	330	<0.6	≤ 40	Temperature sounding
21	89	4000	<0.3	≤ 20	Window and Cloud detection
31	165.5	2800	<0.6	≤ 10	Window/humidity sounding
32	176.311	2000	<0.7	≤ 10	Humidity sounding
33	178.811	2000	<0.7	≤ 10	Humidity sounding
34	180.311	1000	<1	≤ 10	Humidity sounding
35	181.511	1000	<1	≤ 10	Humidity sounding
36	182.311	500	<1.3	≤ 10	Humidity sounding
41	325.15±1.2	800	<1.7	≤ 10	Humidity sounding/cloud detection
42	325.15±2.4	1200	<1.4	≤ 10	Humidity sounding/cloud detection
43	325.15±4.1	1800	<1.2	≤ 10	Humidity sounding/cloud detection
44	325.15±6.6	2800	<1	≤ 10	Humidity sounding/cloud detection

AWS channels

Conclusions

Snowfall products are still burdened by large uncertainties.

- Better quantitative precipitation estimate can only be achieved by improved radar-based products (multi-frequency+Doppler capabilities).
- PMW products (needed for sampling) can hugely benefit from calibration/training by spaceborne radars but the characterization of the background surface and of the atmospheric conditions (near-surface temperature, water vapor content, presence of supercooled droplets) is paramount for improving PMW-based snowfall retrievals. -> **Synergistic multiplatform approach**
- Demonstrated benefits of using CloudSat/Calipso-based Machine Learning SLALOM approach (mostly for higher latitudes) -> **Key role of EarthCare mission and NASA ACCP Radar**

- **Frequency range**: 19 to 190 GHz available in most advanced PMW radiometers (e.g., EPS-SG):
  - 150-166 GHz highly recommended: snowfall sensitivity lower in the atmosphere vs. surface influences -> **Key role for shallow snowfall**
  - The full spectrum of T and WV sounding is needed -> **Definition of environmental conditions (T, WV) (instead of model-derived variables)**
  - Lower frequency channels are needed for the characterization of the frozen background surface –> **Potentials of synergy with the future CIMR mission to be explored**
  - 85-90 GHz channels -> **key role in detection of supercooled liquid cloud droplets**

- Conically scanning is preferable (dual pol., high resolution) but only EPS-SG MWI will be available -> **Need to advance research on cross-track scanning radiometer capabilities (ATMS, MWS, AWS)**

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